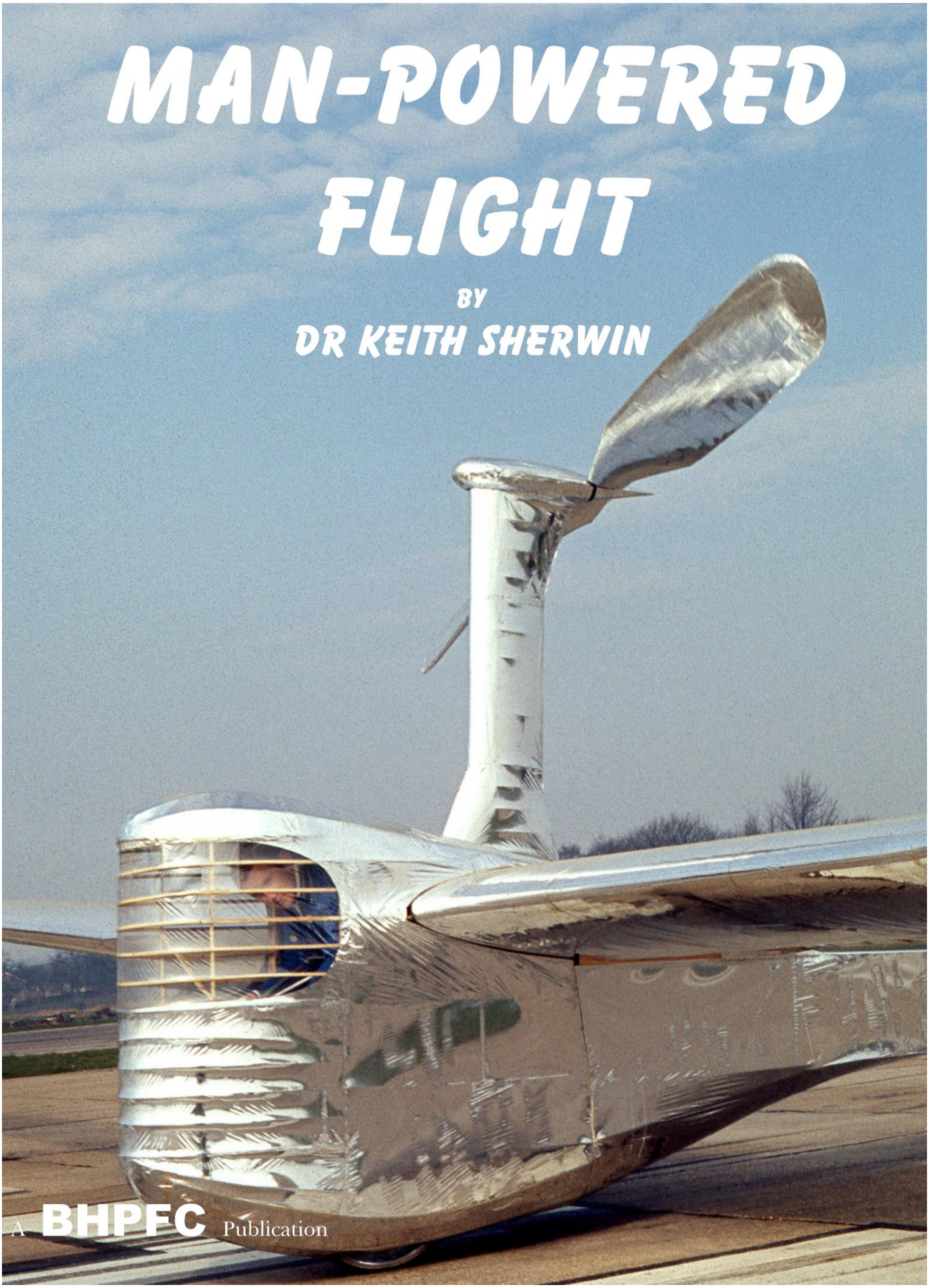
MAN-POWERED FLIGHT

BY

DR KEITH SHERWIN



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MAN-POWERED FLIGHT

K. SHERWIN, Ph.D., B.Sc., C.Eng., A.F.R.Ae.S., M.I.Mech.E.

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Flight Lieutenant John Potter, pilot and engine of Jupiter human powered aircraft

Photograph by Fred To

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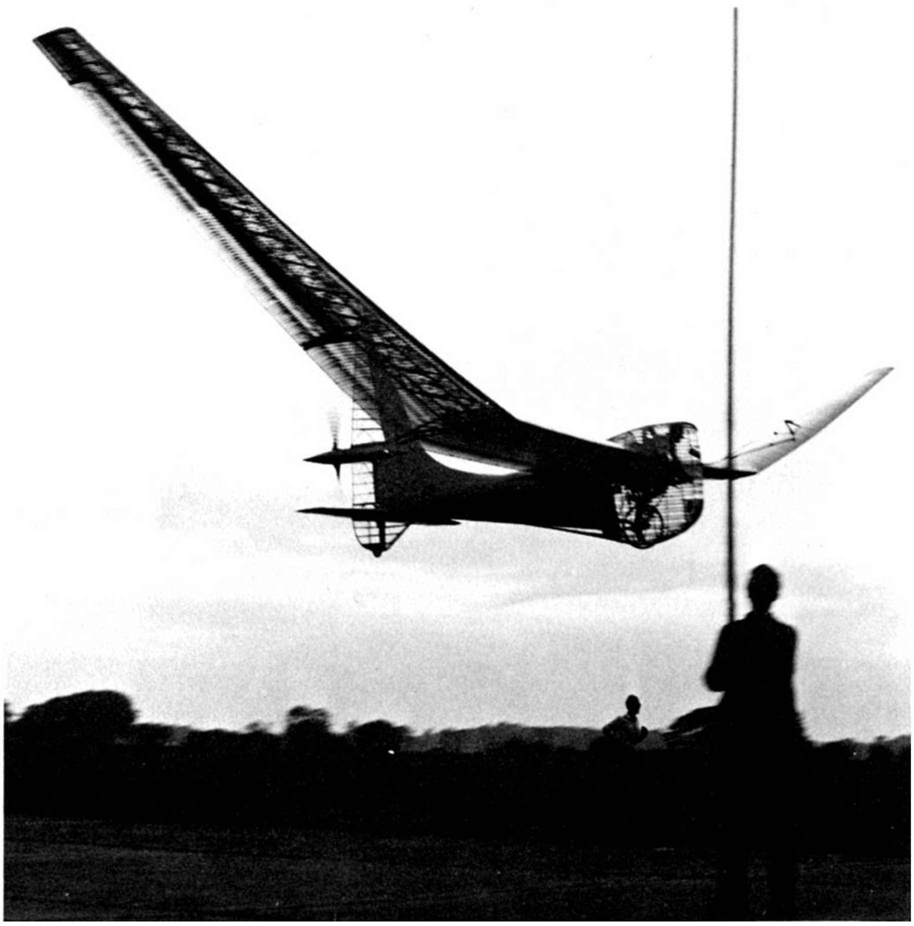
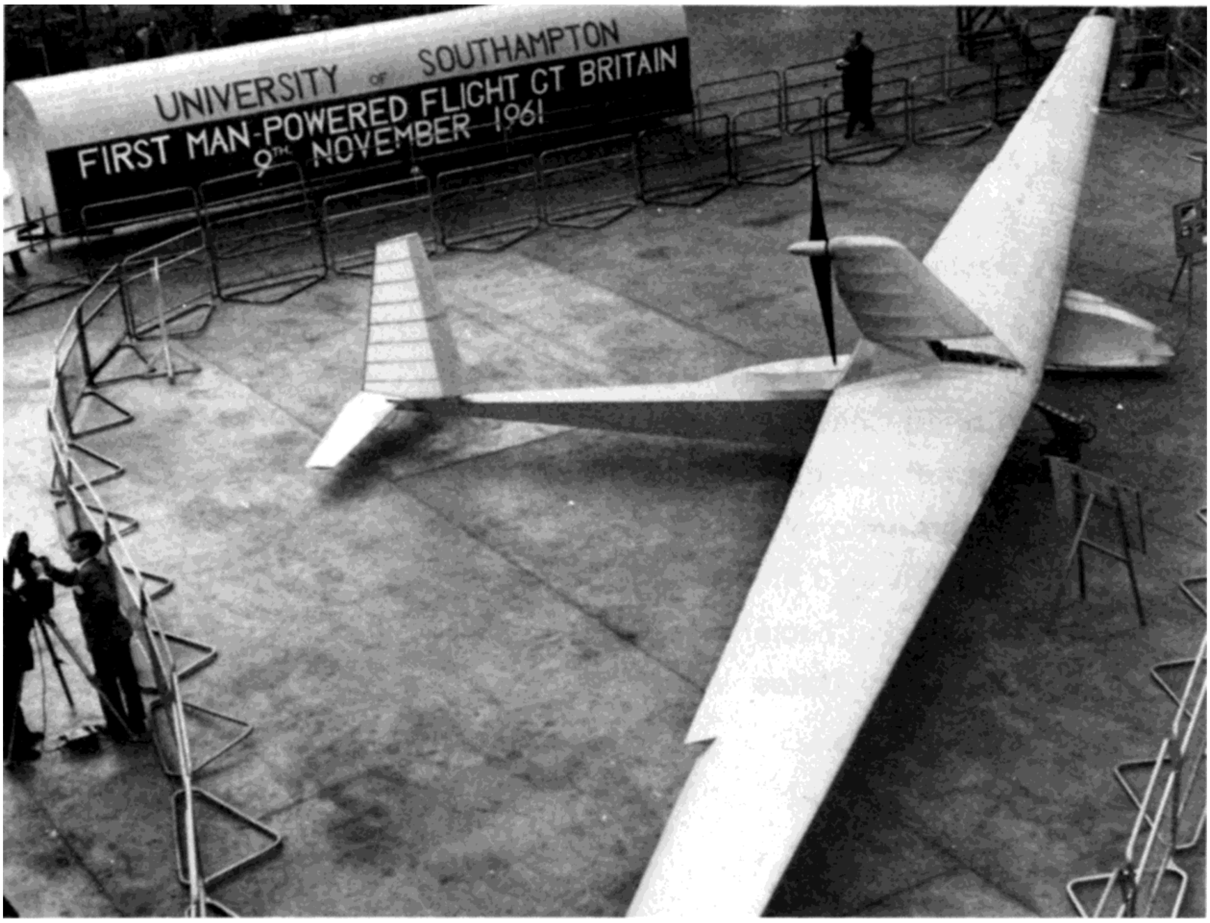


Puffin II flying at 17 ft altitude past a marker-pole in the calm of twilight at Hatfield.



S.U.M.P.A.C., a highly successful project which achieved the distinction of making the first man-powered flight in Great Britain on 9th November 1961.

Preface to the PDF

The book was converted to PDF format by scanning the original book and then O.C.R.ing as much as possible of it. The result was then cut and pasted into Microsoft word. The rest was done the old fashioned way, by hand.

Photos were either copies of the original book or if we had the original photo or something similar then that was used.

The formatting of the original book has mostly been lost.

The result is that while some errors have been corrected, some new errors may have been introduced by the O.C.R process, marks on a well used book is one source. email publishing@bhpfc.org.uk if you spot any so we can correct them.

As this book was originally written in 1971 it uses British units. If you are more used to S.I. units be aware that dividing by 550 is a conversion from foot-pounds per second into horse power (ft-lb/s into h.p.). The book is pre-computer so calculations are generally to 3 significant figures. Today the calculations would be done using a spreadsheet.

The other thing is that some of the photos may have originally been in colour, most are black and white but the book was printed in black and white to keep costs down.

This book was prepared by Malcolm Whapshott, Fred To and John McIntyre for BHPFC Publishing, part of the British Human Powered Flight Club at http://www.bhpfc.org.uk. Proof reading by Chris Roper.

Preface to the reprint

When I wrote the preface to 'Man Powered Flight' in 1971 I little realised that I would be writing a new preface over forty years later.

Over that period there have been well over a hundred man powered aircraft built and flown, some of which are described in my most recent book 'Pedal Powered Planes'. Notable achievements include the winning of the 'figure-of-eight' Kremer prize by Paul MacCready and his team with 'Gossamer Condor'. This was later eclipsed by a flight across the English Channel with 'Gossamer Albatross' and an even longer flight across the Aegean Sea from Crete to Santorini with 'Daedalus'

The original aim of 'Man Powered Flight' was to encourage people to build practical aircraft and this aim continues with this electronic version. Fortunately, the fundamentals remain the same. Many of the photographs in the original book were provided by Ron Moulton, then editor of the magazine 'Aeromodeller'. Unfortunately, Ron is no longer with us but the photographs are of historical interest.

Why people should wish to build man powered aircraft is still open to question. It was a question that was perhaps less relevant in 1971 as there was the objective of the Kramer prize. However, chapter 12 did address the long term future of man powered flight as a sport. To this end it was suggested that compact aircraft such as the 'Malliga' aircraft and 'Liverpuffin' could provide the basis for low cost training aircraft. The idea was further translated into practice with a simple aircraft, 'Aslam', built and flown by students in Singapore using plywood sheets as a runway.

There were several unexpected results of writing 'Man-Powered Flight' including an award of a diploma by the Aero Club de France.

This electronic version is the result of the enthusiasm of Fred To and the hard work of Malcolm Whapshott, to both of whom I express my sincere thanks.

Finally, I should emphasise that 'man' in this context refers to all humans and should not be taken as implying a purely male activity.

Keith Sherwin

January 2015

PREFACE

LEGEND has it that Icarus was the first person to attempt man-powered flight. The story of his attempt is too well known to bear repeating here. Perhaps the most disturbing feature of the legend is that it is too well known. Most people still seem to think of man-powered flight in terms of flapping wings and being rather impractical. It is hoped that this book will dispel these ideas.

At the present time the development of man-powered flight is at a very interesting stage since there is a useful amount of information stemming from past experience yet it is still very much a pioneering activity. Anyone prepared to design and construct a man-powered aircraft can add appreciably to our knowledge of the subject. Sufficient basic information has been presented within this book in order that the reader may design his own aircraft. Also the presentation has been made brief and to-the-point so that the reader may find the relevant information more readily.

I wish to thank all the people who helped with this book: to David Williams of the Southampton group, John Wimpenny and Frank Ogilvy of the Hatfield group and John Elliott of the Farnborough Ornithopter group for the time they gave to helpful discussions; to Herr Josef Malliga for information regarding his aircraft; to Miss Pike, Secretary of the man-powered aircraft group of the Royal Aeronautical Society for information and several of the photographs presented within this book; to Miss Elizabeth Halliday for translating my illegible scrawl into typescript; and above all to my wife for putting up with all my various interests and for seeing so little of me during the writing of the book.

I am indebted to Dr D. L. Marriott for lively discussions regarding man-powered flight and for many of the ideas within this book.

My thanks are also due to the publishers not only for their painstaking work during the preparation of this book but also for having first inspired my interest in aeronautics during the late 40’s through their excellent magazine Aeromodeller.

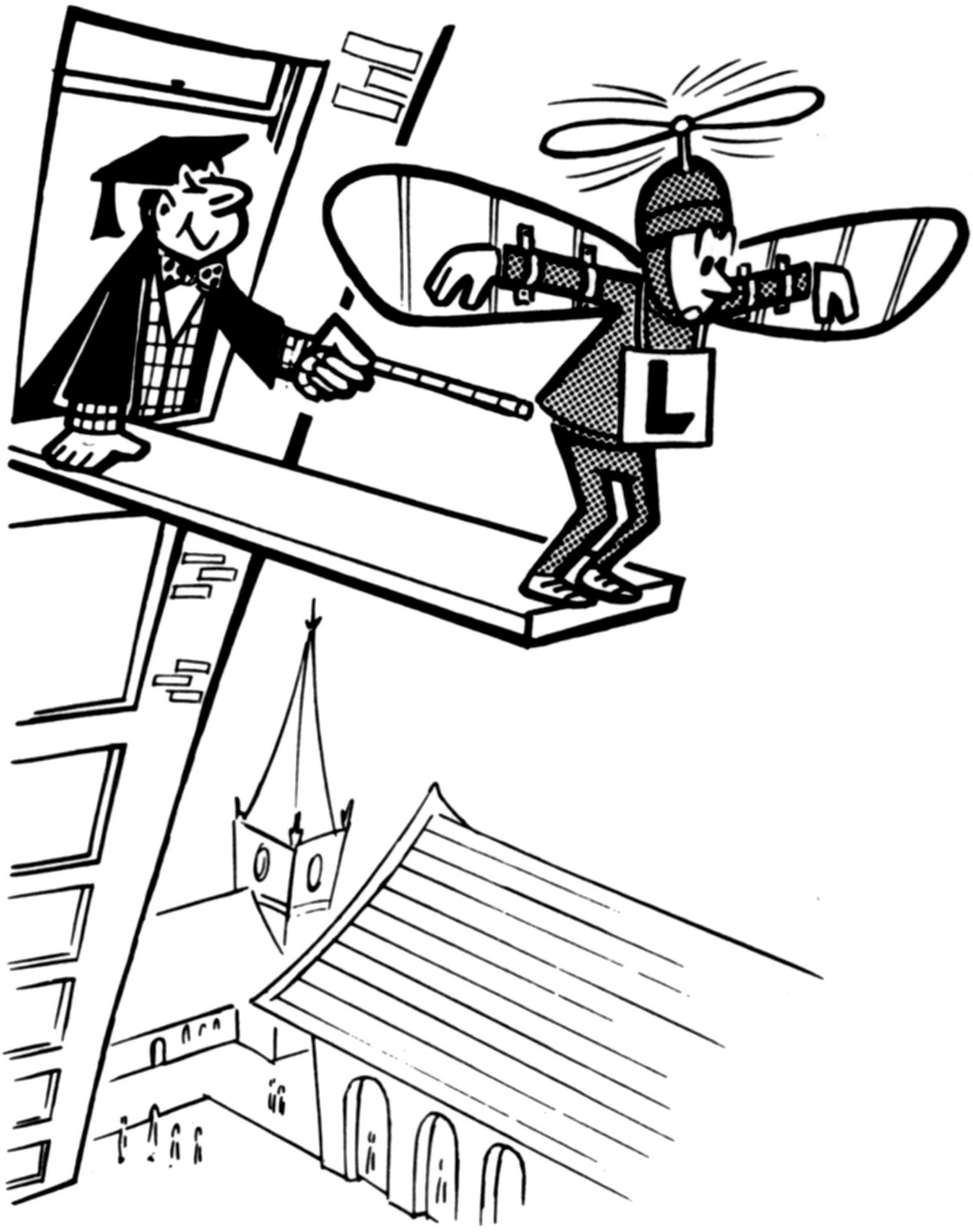
Without the experience gained by the pioneers in the field this book could not have been written. Without the continuation of that pioneering spirit there would probably be no need for such a book. So it is to the pioneers in man-powered flight that this book is dedicated.

Department of Mechanical Engineering,

The University of Liverpool.

February, 1971

To those magnificent men ...



1. INTRODUCTION

1.1 General background

FOR centuries man has wished that he could fly under his own power but only within recent years has man-powered flight become a reality. Previously the nearest approach to this has been through gliding, a branch of aviation where performance requires that the pilot uses his skill in utilising help from the atmosphere in order to extend performance. Unfortunately gliding requires a considerable amount of auxiliary equipment to first get the machine into the air. Man-powered flight overcomes this drawback by utilising the physical effort of the pilot for take-off, but there any comparison with gliding must end for existing man-powered machines leave the pilot little energy for actual flights. Nevertheless the early development in gliding gave no indication of the achievements to follow and it is hoped that man-powered flight may also progress to the point of becoming a sport and it is this possibility that must stimulate the long term study of the problem.

At the present time and within the foreseeable future the development of man-powered flight must rest in the hands of individuals or small groups of people who have the enthusiasm to design and construct their own aircraft. It may be doubted that an individual could attempt such a project but this depends on the person concerned and it is reassuring to consider the achievements of individuals in other fields of endeavour. Without quoting a wide range of examples, it is only necessary to look at some restored veteran and vintage cars to appreciate the many-thousands of man-hours that are devoted by enthusiasts to their particular hobby.

In the allied field of aeromodelling D. A. Russell, one time editor of Aeromodeller designed and constructed a one-fifth flying-scale model of the Westland Lysander. Its design was over-optimistic judged by present day knowledge and it did not fly, yet in 1939 Mr. Russell took as his maxim the old adage '"Tis better to have tried and failed, than not to have tried at all". The work involved in the project was of a similar order of magnitude to that of a man-powered aircraft and was the work of only one man. More recently (over 30 years after the Lysander) S. Holloway has built a 1/5th **all metal** true scale model of the Pup 100 which is radio controlled, duplicates all the full sized structure and flies!

Whether one contemplates construction of a man-powered aircraft or not, the associated design study alone is a fascinating project. To design in detail a machine which, if built, would fly successfully is a source of satisfaction especially if it represents a new approach to the problem and thereby adds to our knowledge concerning the subject. The following chapters provide adequate data to allow such design studies to be performed.

It is envisaged that man-powered flight is a subject of interest to a wide range of people and therefore emphasis has been placed on the physical reasoning behind the relevant design equations as opposed to the theoretical proofs that one generally finds. To those who are more theoretically inclined no apology is made for this approach as there are many text books on aerodynamics that will fill the gaps left by this treatment of the subject. Also it is all too often forgotten that theory simply provides a mathematic model of a physical situation in order that the designer may obtain numerical answers. To the layman it must be pointed out that by using intuition or just plain commonsense there is no reason why he cannot arrive at a valid design. This book provides the necessary technical information to check the validity of his design and, it is hoped, provided in a sufficiently straightforward manner to allow him rapid access to the relevant data.

Design can be defined in many different ways, but one common theme is that design is concerned with results! This is worth remembering especially in this technological age when actual design procedures of most technical devices have reached alarming proportions of complexity. Whatever the required result, whether a piece of hardware or simply a report on some proposed device, it is the result that is important not the method by which it was achieved. There is no one valid method of designing, the designer must use the tools of his trade to the best of his ability whether they be technical or creative. From this point of view it is as permissible for the layman to dream up a design and then use existing data to check its correctness as it is for the expert to use a sophisticated theoretical approach to the problem. In fact the layman could find a new approach to the problem which the expert, with his deep involvement in the subject and the preconceived ideas that can come with such involvement, may have missed. The layman only becomes a "crank" if he proposed a new idea without considering all the implications or fails to check the validity of his proposed design either theoretically or experimentally.

Before discussing the detailed design of man-powered aircraft it is proposed to review the present "state of the art". Although man-power flight is now possible it is nevertheless still in its infancy and from this point of view it is perhaps instructive to briefly review the history of gliding in the hope that it may provide some reassurance regarding achievements that may result in the future. Furthermore gliders and man-powered aircraft have common design problems in that both have limited power available for flight, so that for both performance is dependent on good lift/drag (L/D) ratios. This criteria becomes evident when one considers that with limited power the aircraft weight/power input ratio must be high. The weight is supported by the lift whilst the power absorbed is dependent on the drag.

1.2 History of gliding

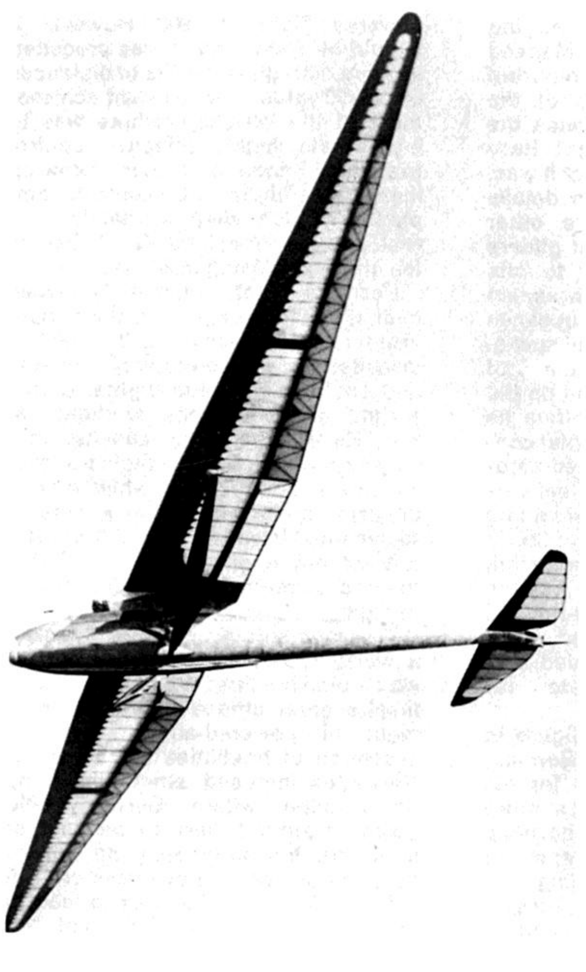
Ignoring the earlier unsuccessful attempts by "birdmen" the history of gliding in its practical form stretches over a century, during most of which time it could be considered to have been in its infancy. This extended infancy stems from the development of gliders during a period for which their primary purpose was the studying of aeronautics alone. When eventually the sporting aspect became apparent, gliding became a valid section of aviation, its by-products including a better understanding of meteorology and aerodynamics whilst it is common knowledge the part gliders played in the Second World War. Present day machines, especially competition sailplanes, are fairly sophisticated and therefore are comparatively expensive, so that their construction has become quite big business.

Sir George Cayley, who is rightfully acknowledged as the father of British aviation, built the first man carrying glider in the early 1850's. Manned flights of up to 500 yards were reported but unfortunately no details of the glider were published, otherwise the development of gliding might have been far more rapid than in fact it was. All that can be inferred from details published regarding Cayley's other experimental machines is that gliders probably conformed largely to kite practice having a wing of low aspect ratio with sail type surfaces between single leading and trailing edge spars. This success came as the climax of some 60 years study of aviation on the part of Cayley during which time he reached some of the fundamental conclusions basic to the low speed aerodynamics discussed later. As early as 1804 he built a machine weighing 56 lb and having a wing area of 300 ft^2 that made short hops carrying a man. It eventually crashed with a boy on board whilst performing experiments with flapping wing propulsion, as a result of which Cayley decided that man-power was inadequate for sustained flight.

After Cayley the next key figure in the history of gliding was a German, Otto Lilienthal, who adopted for his wing form a bird, or perhaps more correctly, a bat type of design having a radiating structural member over which the fabric was stretched. Using this basic form Lilienthal built a series of gliders in which he made more than a thousand glides, covering distances up to 400 yards. Control was by the pilot swinging his hanging body so moving the centre of gravity position of the machine. Lilienthal lost his life in a flying accident in 1896 but his work was to have a far-reaching effect both through his practical demonstration and the sale of his machines to other experimenters.

The work of Lilienthal stimulated the interest of the Wright brothers in America so resulting in the first powered flight of 1903. However it should be stated that it was preceded by some 1000 glider flights of distances up to 200 yards. The greatest achievement of the Wright brothers was to incorporate highly effective control systems in their machines, allowing many of the flights to be made in comparatively high winds. Certainly their first powered machine flew close to the ground in 25 m.p.h. winds.

Powered flight immediately placed gliding in the background, the Wright brothers only returning to it in 1911 to investigate meteorological effects that could help extend flights. Orville Wright made a series or flights at Kitty Hawk often being launched into very high winds. Several flights of over 5 minutes were recorded whilst on one occasion a flight lasted for 9 minutes 45 seconds. It was this flight that without actually ending it, indicated that the end of the infancy of gliding was in sight.



This momentous flight was to remain a world record for 10 years, during which time the First World War was to inspire great strides in the development of powered-aircraft. At the cessation of hostilities the Treaty of Versailles imposed strict limitations on aviation within Germany. No powered aircraft were to be built or imported, but fortunately no similar ban was placed on powerless craft. It was this loophole that was to lead to the subsequent development of sophisticated gliders, and without which one wonders what would have been the present state of gliding since the other air-minded countries concentrated their efforts in the field of powered aircraft.

Designed by Alexander Lippisch and flown by R. Kronfeld, the 'WIEN' of 1929 established many records and its structure has been followed by man-powered aircraft designers, albeit in many *cases unwittingly*

Post-war flying in Germany was concentrated on the Wasserkuppe a hill of some 3000 ft in height in the Rhon-Gebirge area of Central Germany. The first Rhon meeting of 1920 produced considerable interest but a maximum flight of only 2 $^{1}/_{4}$ minutes duration, a performance still a long way from that of the Wright brothers. However, in 1921 the duration record was at last broken by a flight of 13 minutes. This was achieved by Wolfgang Klemperer of the Aachen Aerodynamische Institute flying his “Blaue Maus” glider of 30 ft span 172 sq. ft wing area and a weight of 125 lb. The machine was now a conventional cantilever monoplane design incorporating what was then a very light and refined construction. The weight is of interest as it represents the order of magnitude required for man-powered flight, yet since Klemperer’s day there has been considerable experience concerning design and construction of light-weight structures.

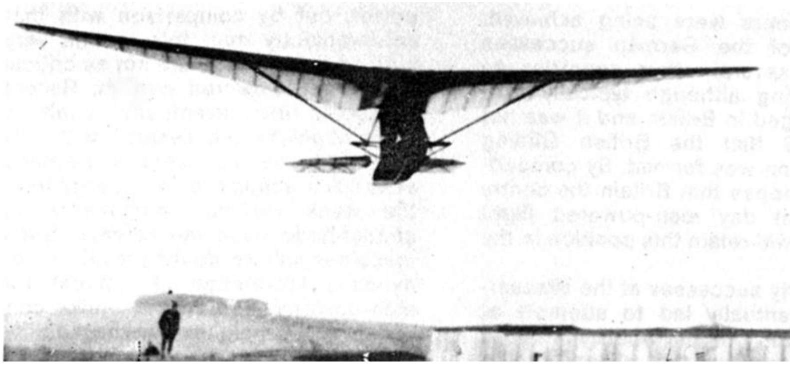
Klemperer’s successful flight was accomplished by gaining duration by loss of altitude down the side of the Wasserkuppe. Nevertheless it inspired others and within a week the record was broken by a flight of nearly 16 minutes whilst a year later flights of several hours were being achieved. Reports of the German successes inspired several other countries to start gliding although typically progress lagged in Britain and it was not until 1929 that the British Gliding Association was formed. By comparison one hopes that Britain the centre of present day man-powered flight activities will retain this position in the future.

The early successes at the Wasserkuppe eventually led to attempts at cross-country flights where the use of thermals required that gliders should be robust and manoeuvrable as well as having good aerodynamic performance. A typical present day sailplane will have a span of 50 ft, an all up weight of 800 lb and a L/D ratio of 40. Such a machine would have a free air power requirement of under 4 horse-power, but by comparison with that achievable by man this is still very high so that designs are not as critical as for man-powered aircraft. Recent proposals may eventually result in more sophisticated designs with L/D ratio of 80+ so that flights can be made at 40,000 ft altitude to use energy from the weak vertical components of atmospheric wave movements. Such machines will no doubt provide aerodynamic knowledge of interest for man-powered aircraft but unlike conventional sailplanes manageability will be low as the requirement of circling within thermals will not apply.

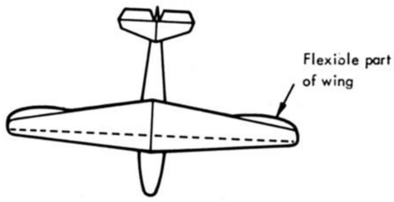
1.3. History of man-powered flight

It is perhaps inevitable that the first serious attempts at man-powered flight should have been carried out in Germany. A flapping-wing man-powered aircraft designed by Lippisch flew in 1929. The layout of this is shown in Figure 1, and incorporated a high wing of some 38 ft span with an open pilot seat and a covered fuselage behind it. The wings were moved by the action of the leg in a similar movement to rowing. Each wing had a triangular strut support underneath and on the end of this strut, cables moved the joint in a guide rail fastened to the fuselage. A diagrammatic representation of the mechanism is shown in Figure 2.

The Slingsby Skylark IV typical of sailplane design and structure in the past decade, in this case ably demonstrated by Derek Piggott, the first Briton to fly a man-powered aircraft in the United Kingdom



The Lippisch machine in flight



Lippisch flapping wing aircraft.
Figure 1

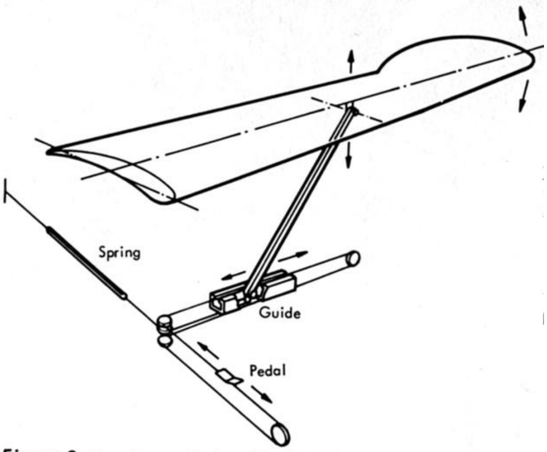


Figure 2 Operating mechanism of the Lippisch aircraft

Control of the machine was by stick for elevator and rudder. There were no ailerons as it was considered that differential speed of flapping of the two wings would give some lateral control. Empty weight was of the order of 110 lb with each wing, without the struts attached weighing 10 lb.

From a shock cord launch, a method in common usage then for gliders, the maximum flight attained was of the order of 300 yards. This could only be counted as a man-assisted flight but nevertheless indicated the possibilities of man-powered flight. More recently[1] Lippisch expressed the view that wing-flapping gives promise of high efficiencies and that an improved version of his machine would give some very interesting results. Amongst other improvements he mentioned that a lighter structure could be achieved by using balsa and an improved mechanical efficiency of the power transmission could be achieved by a stiff lightweight linkage.

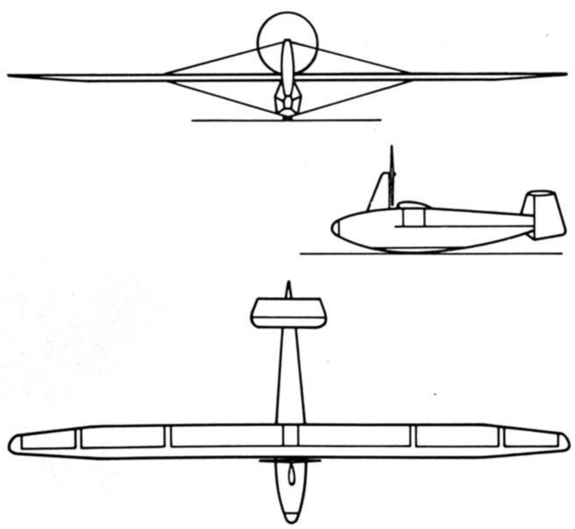
In 1933 Oskar Ursinus in the editorial of Flugsport arranged the offer of a 500 marks prize for the first man-powered flight of 1 km around two pylons set 400 metres apart. The prize was not won but a consolation prize was given to Haessler and Villinger for a flight of 790 yards. Helmut Haessler and

[1] Man-powered flight in 1929, A. M. Lippisch, *Journal of the Royal Aeronautical Society*, July 1960.

Franz Villinger were two engineers with Junkers and started design and construction of their "Mufli" machine in 1935, see Figure 3. The pilot flew the machine in a reclining position, pedalling with his feet, the drive to the propeller using a simple twisted belt scheme. The flight of 790 yards was from an assisted take-off.

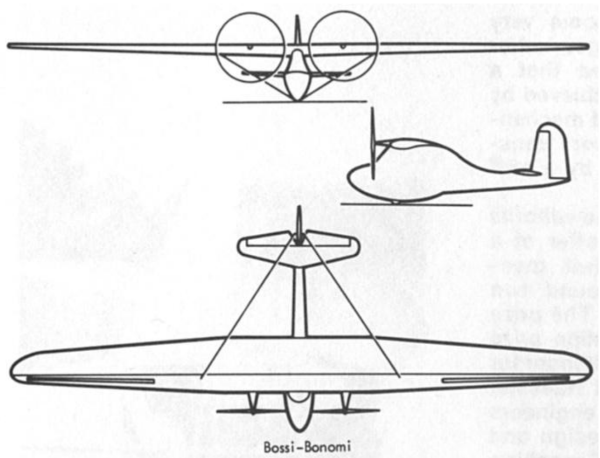
A prize similar to the German one was offered in Italy, as a result of which Enea Bossi and Vittorio Bonomi built and flew their "Pedaliante", see Figure 4. This machine had a best flight of 980 yards from a shock-cord launching but this distance was only achieved by considerable loss of altitude. It is alleged, but certainly not confirmed, that some flights actually took off under man power alone. Certainly the "Pedaliante" incorporated driven undercarriage wheels but the validity of this allegation will be checked against our existing design data later in Chapter 6.

The 'Mufli' with panel removed to reveal drive to the propeller

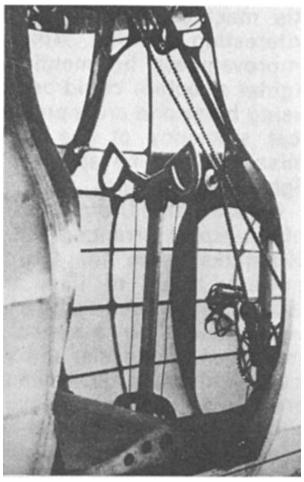


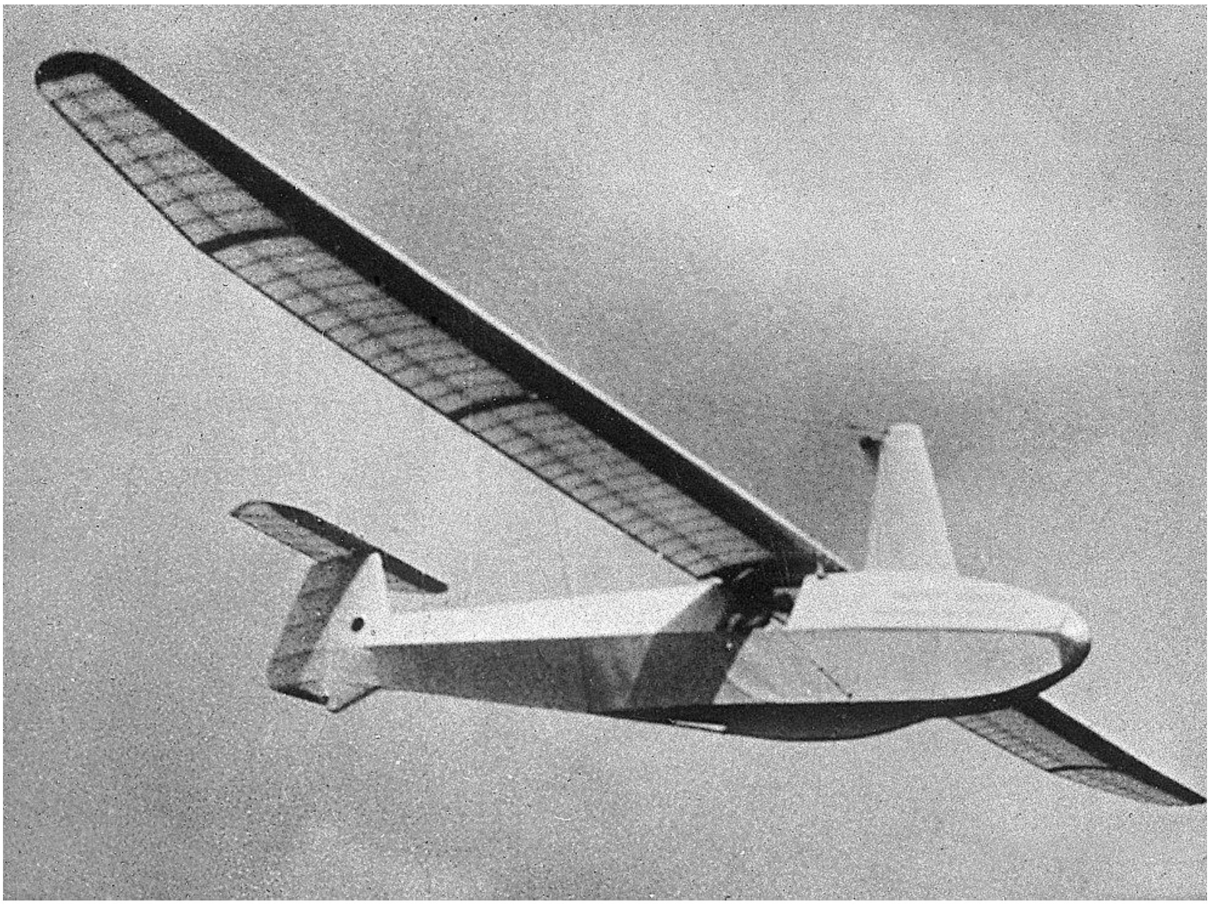
Haessler - Villinger aircraft **Figure 3**

Unfortunately both the Haessler-Villinger and the Bossi-Bonomi machines were destroyed during the Second World War. The problem remained forgotten except for an analysis of man-powered flight in 1948 by B. Worley which indicated slight optimism if full advantage was taken of the latest developments. It was not until 1956 that any real post-war effort was begun when T. R. F. Nonweiler and B. S. Shenstone started writing and talking about it simultaneously. At about this time a Mr. Perkins, a civil servant at Cardington balloon establishment built a man-powered aircraft with an inflatable wing. No flights were recorded with his first machine, but through subsequent developments he managed to fly his Mk. III aircraft a few inches above the floor of the airship hangar at Cardington. This aircraft named the "Reluctant Phoenix" had a delta configuration, wing span of 27 ft., wing area of 250 sq. ft. and a weight of 38 lb.

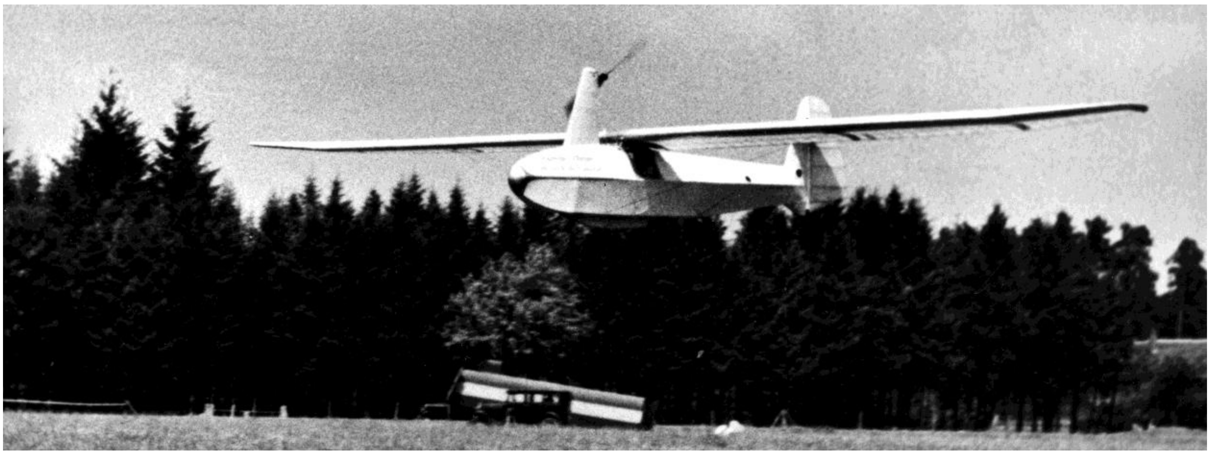


Bossi-Bonomi 'Pedaliante' **Figure 4**

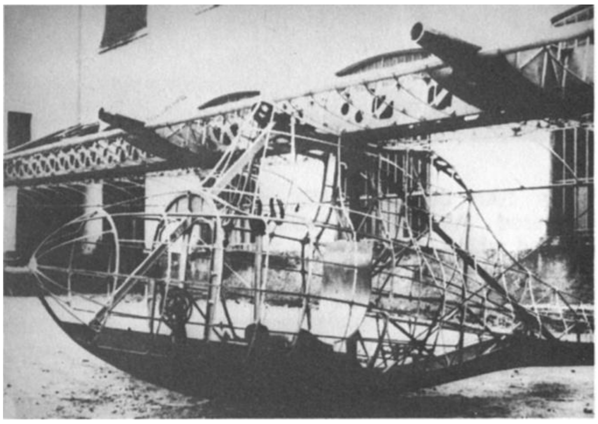


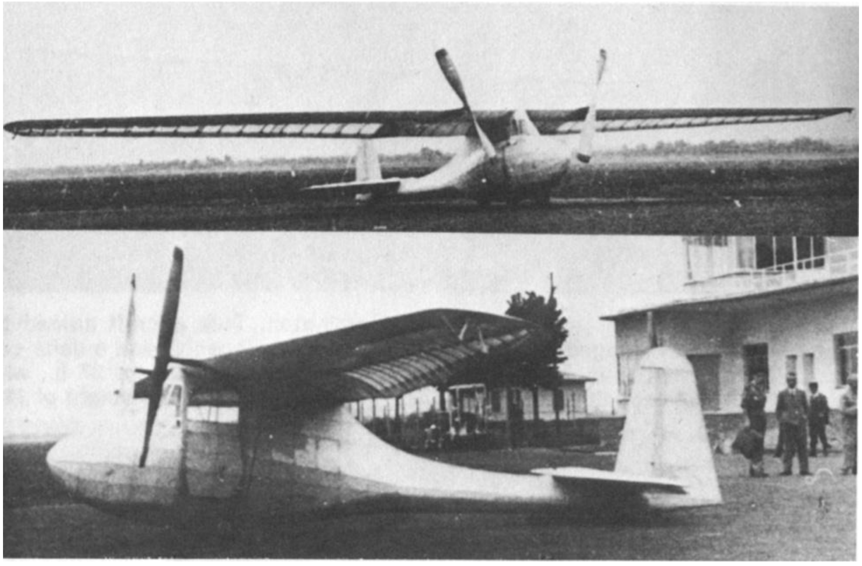


Above, and below, the Haessler-Villinger machine in flight after catapult launch.



Below is the Italian Bossi-Bonomi twin propeller machine in flight, at right is the uncovered airframe and above left the cockpit area with the chain drive exposed.





Two views of the Bossi-Bonomi aircraft illustrate the contra-rotating propellers and the pronounced undercamber of the low speed aerofoil.

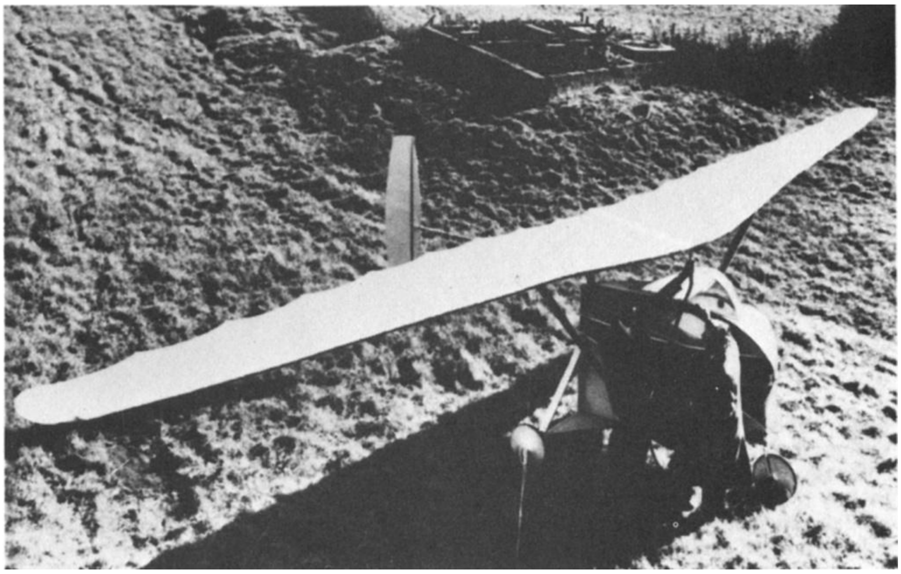
On 10th January, 1957, a Man-Powered Aircraft Committee was formed which later became the Man-Powered Aircraft Group of the Royal Aeronautical Society[2]. Its aim to

[2] Now[2015], the Human Powered Flight Group of the RAeS.

financially assist promising designs and with this end in view a fund of £5000 was finally achieved. Whilst the group were collecting money, Mr. Henry Kremer offered £5000 for the first British man-powered aircraft to fly a "figure of eight" course around two markers, half a mile apart. In 1967 Mr. Kremer doubled the prize money to £10,000 and opened it to all nationalities.

Resulting from this, six projects were proposed, all fixed wing and propeller driven. Construction started on the two most promising designs, proposed by the Southampton and Hatfield Man-Powered Aircraft Groups aided by financial assistance from the Royal Aeronautical Society.

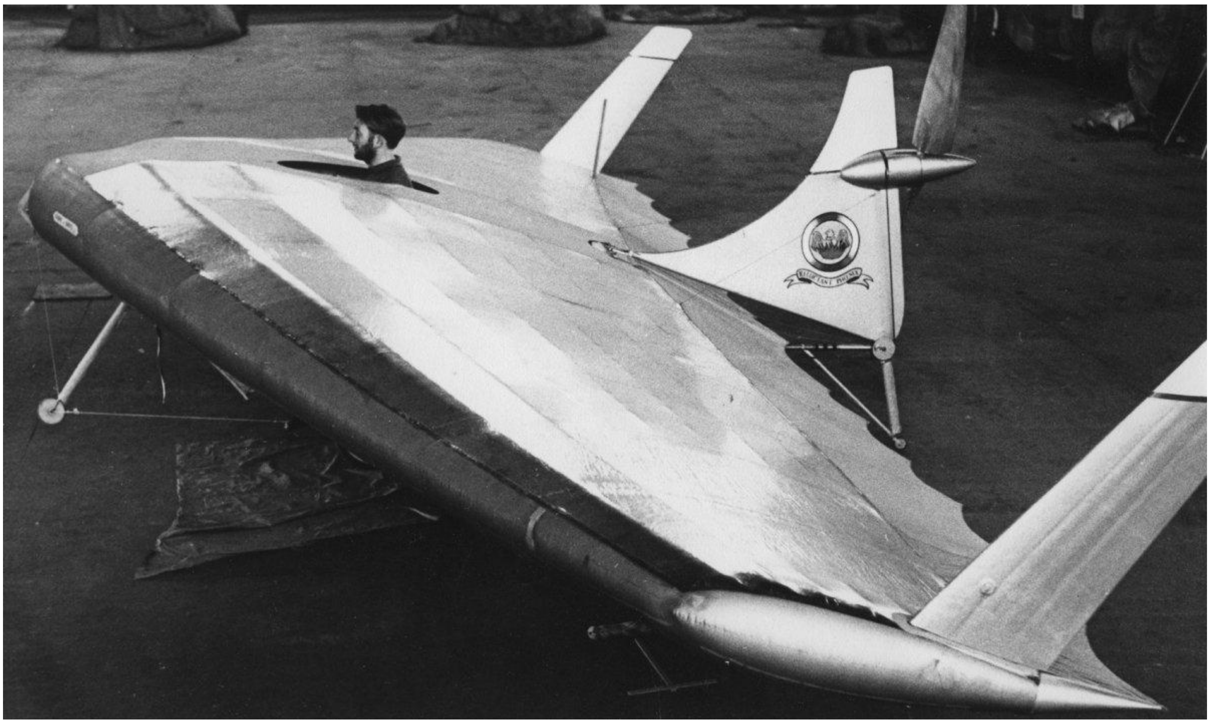
The Southampton aircraft, "SUMPAC"[3] for short, was designed and constructed by three post-graduate students at the University. Actual aircraft configuration, Figure 5, and construction were entirely conventional as the aim was to get the machine flying in the shortest possible time, also it is reassuring to note that the students did not have previous experience of aircraft design. Wing construction embodied two spars as the simplest form for construction, with girder-type ribs of spruce and balsa. Drive mechanism consisted of a Renold chain to drive the back wheel from the pedal cranks and a twisted flat Steel belt to drive the propeller shaft. "Belt-stick" was used to increase the coefficient of friction of the belt.



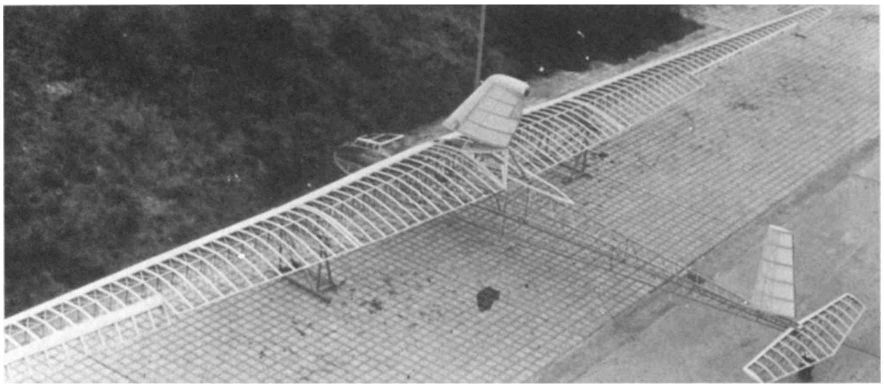
First of four pneumatic airframes made by D. Perkins at Cardington was this tailless project made in the late fifties. It was not successful.

Below: The 'Reluctant Phoenix' last of D. Perkins' inflatable airframes which first flew (indoors) on 18th July 1966 and subsequently made 97 ground effect flights.

[3] *S*outhampton *U*niversity *M*an-powered *A*ircraft

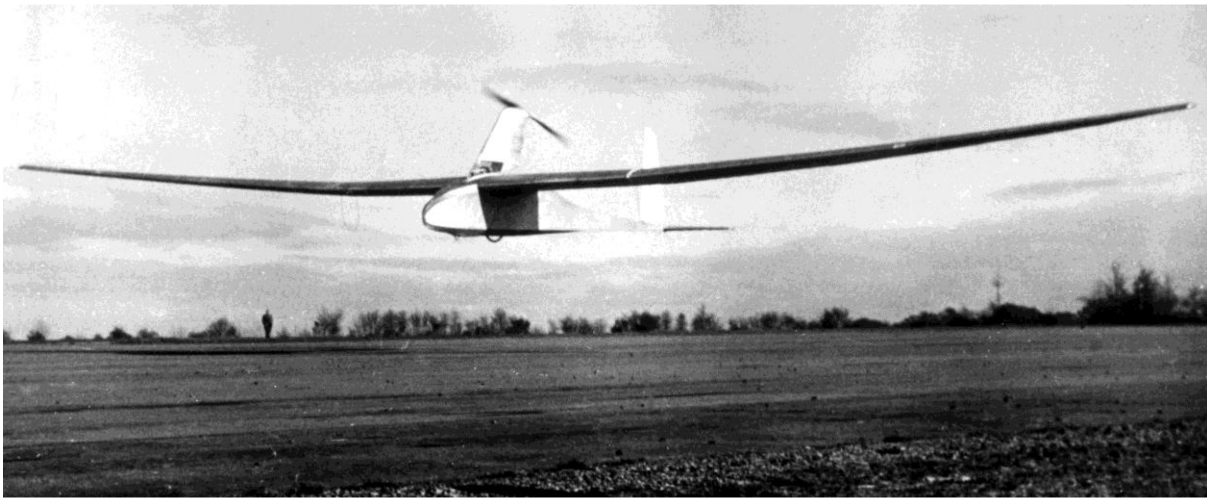


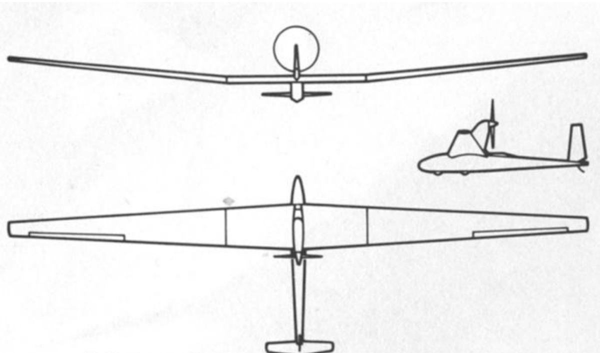
Design of “SUMPAC” commenced in July 1960 whilst construction started in January 1961 and finished in the September of that year. Flight trials were carried out at Lasham Gliding Centre with Derek Piggott, the chief gliding instructor as the pilot. After many ground tests and “hops” the first real flight took place at 4.30 p.m. on Thursday, 9th November, 1961. The flight covered a distance of 50 yards with a maximum height of 6 ft, but most important it proved that man-powered flight was feasible, that such an aircraft could take off using pilot power alone. Most of the flying with “SUMPAC” was of the straight and level variety, and by late 1962 flights up to 650 yards including 80° turns and cross-wind landings had been achieved. In 1964 a London group under the leadership of Alan Lassiere, one of the original members of the Southampton group undertook a partial re-design which largely consisted of an improved drive system with the original Steel belt replaced by a positive drive fabric belt. The aircraft was damaged when, with a cyclist at controls, a gust of wind took it to a height of 30 ft and it then stalled and hit the ground. The aircraft has not been flown since and is on permanent display in the Shuttleworth Collection at Old Warden Aerodrome in Bedfordshire.[4]



[4] Since this book was written, SUMPAC has been moved to Solent Skies museum in Southampton.

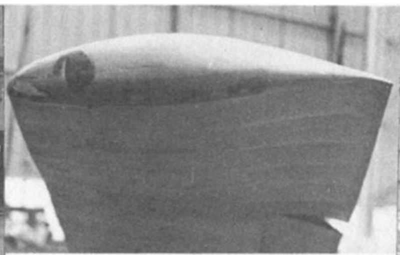
Bare airframe of SUMPAC above and one of the memorable long flights by Derek Piggott at Lasham airfield, below.



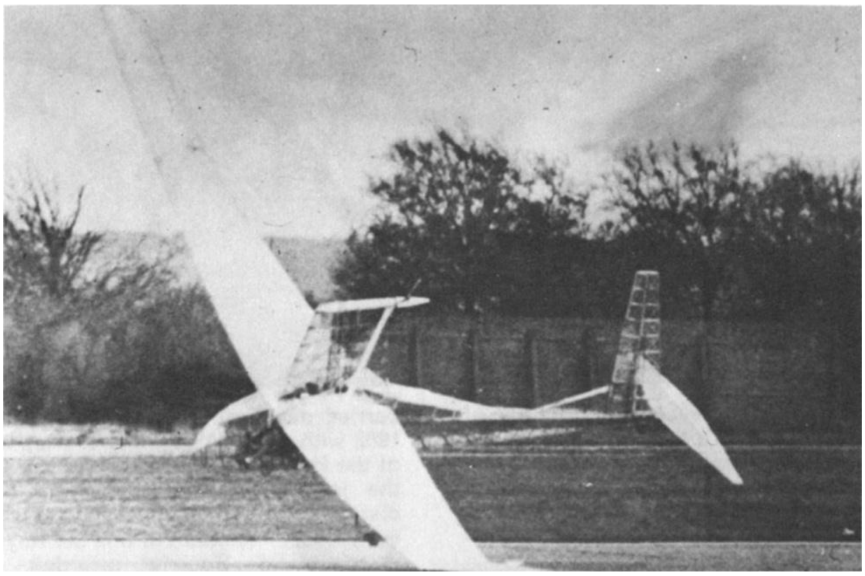


"S.U.M.P.A.C."
Southampton University man powered aircraft
Figure 5

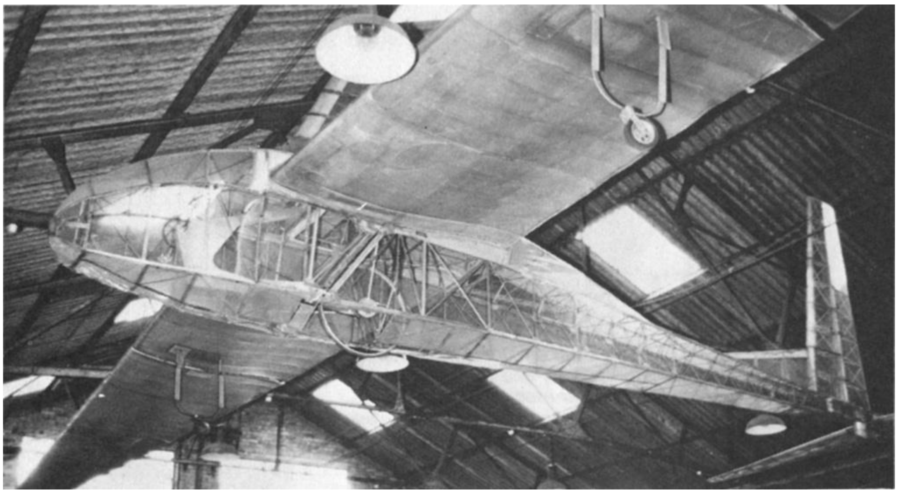
The Hatfield aircraft, "Puffin I", flew shortly after "SUMPAC" on the 16th November, 1961. Flight trials were carried out by J. H. Philips and J. L. Barnes, test pilots of the de Havilland Aircraft Co. and the de Havilland Engine Co. respectively. By the end of 1961 straight flights of up to 700 yards had been achieved and turns had been carried out through 70 to 80°. In May 1962 with John Wimpenny the leader of the Hatfield group piloting, it made the longest flight yet recorded, a distance from unstick to landing of 993 yards. As a result of this the Royal Aeronautical Society awarded a special prize of £50 for the first flight of half a mile by a man-powered aircraft. After successfully completing over 90 flights, "Puffin I" crashed, due to a change of wind direction, in April 1963.



Left: the small tailplane of the SUMPAC and the all-moving rudder later modified. Above is the Block Balsa tip showing aerofoil section and at the right, the nose cowling removed to reveal drive frame.



Moment of disaster, SUMPAC crumples its wing and sustains other damage after stalling from 30ft. It is preserved in a repaired state at the Shuttleworth Collection, Old Warden, Biggleswade, Bedfordshire[5]*, as below.*



SUMPAC is notable for its pylon mounted propeller and conventional control surfaces. A dorsal fin was added, tail area increased and light weight Melinex covering applied during progressive modifications.

[5] Since this book was written, SUMPAC has been moved to Solent Skies museum in Southampton.

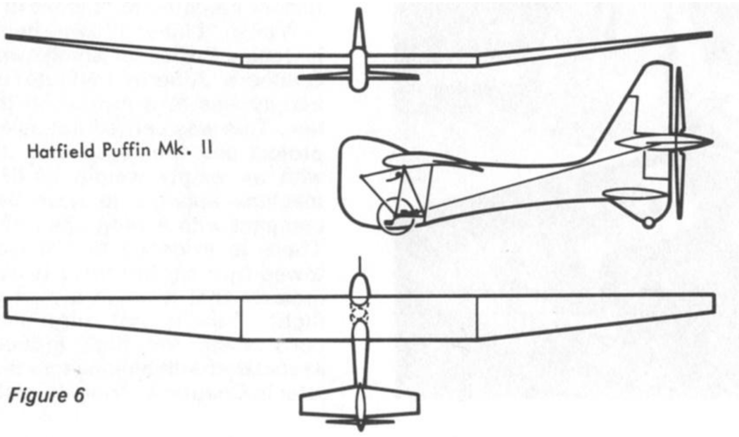


Figure 6

As a result of the damage to "Puffin I" the opportunity was taken to redesign the wing. Span was increased from 84 ft to 93 ft and an improved aerofoil section used. The original Puffin wing was sheeted with balsa over the front section. This proved unsatisfactory as the balsa wrinkled and buckled with changes in humidity and temperature, resulting in aerodynamic inefficiency. The balsa sheet was not used on "Puffin II', the wing of which was aerodynamically improved by using more ribs to maintain a consistent aerofoil section shape.

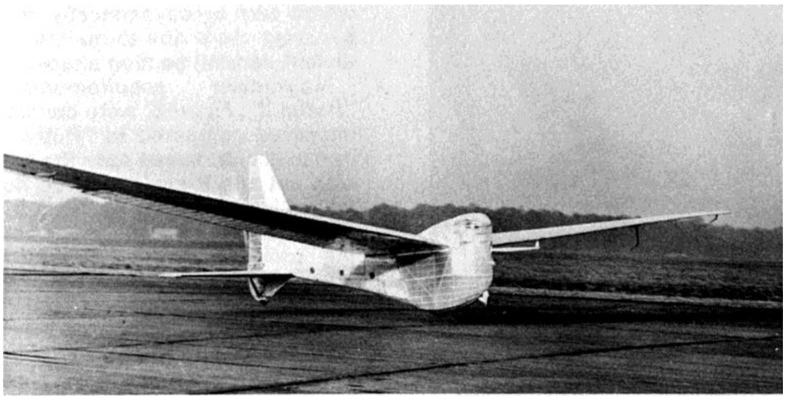
Man-power requirements for "Puffin II", Figure 6, were considerably improved compared to "Puffin I" but due to the increased span the handling was not and it could only be flown in calm air so that flying tended to be restricted to dusk time. After completing some 90 flights "Puffin II" also crashed, in early 1969, the aircraft hitting a landing light on Hatfield airfield when the pilot veered away from a region of turbulent air encountered at a height of 6 ft above the runway at dusk. Since then Liverpool University have taken over the Puffin aircraft and subsequent development of Liverpuffin is described in Chapter 10.

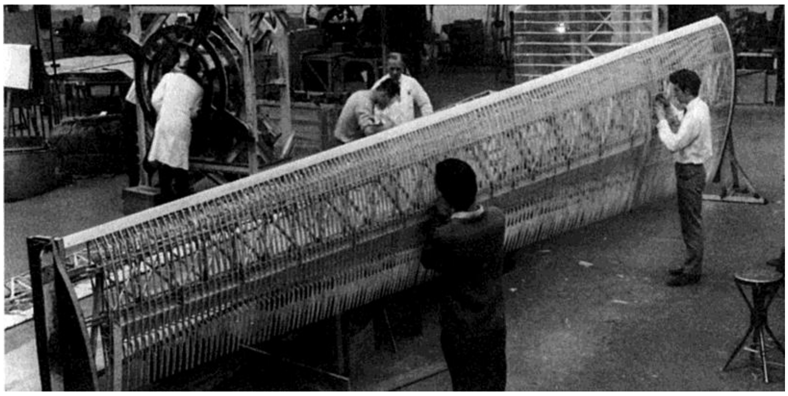
An individual venture by S. W. Vine, a South African, flew in May 1962. Wing span was 40 ft with a wing area of 220 sq. ft and a total flying weight with pilot of 375 lb. Empty weight was 205 lb. The aerofoil section was a modified Go.535 as used for the Haessler-Villinger machine and on pre-war gliders. It was a marginal flier being too heavy and too small for true man-powered flight, but managed to get airborne by running along the runway into a stiff breeze. This gave the necessarily high relative airspeed for take-off but after becoming airborne the machine could not maintain the necessary flying speed so stalled and crashed nose first into the ground.

In 1965 a Japanese man-powered aircraft "Linnet I" shown in Figure 7 made several flights. This was a project at Nihon University built under the leadership of Professor Kimura and the best flight achieved was of 48 yards during March 1966. Later that year it was modified to "Linnet II" Figure 7 with the same wings and basic fuselage layout but with the pilot in a conventional cycling position and a bubble canopy over him instead of the original sitting position. The original shaft drive was modified having the bevel gear units replaced by universal joints. "Linnet II" made 31 flights the longest being 100 yards with a maximum height of 5 ft. Since then the aircraft has been further modified to "Linnet III".

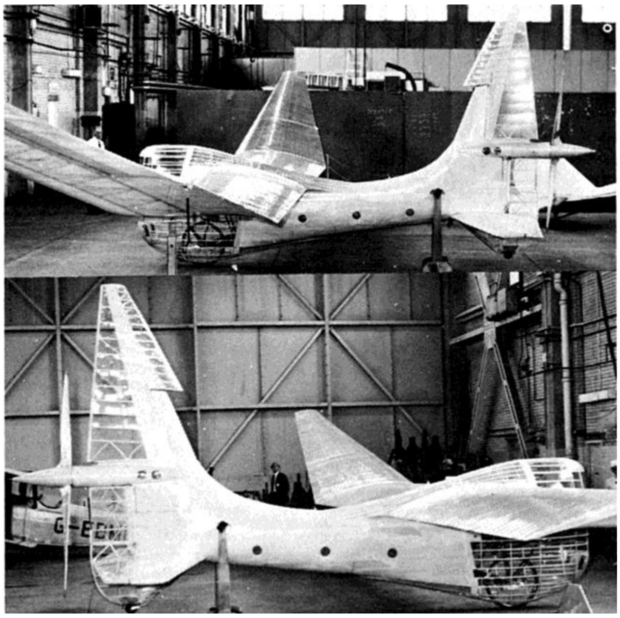
Whilst "Linnet I" was being flown in Japan, Professor Smolkowski of the Southern Alberta Institute of Technology was also looking at the problem. This was carried out as a student project and the result was a biplane with an empty weight of 85 lb. The machine appears to have been very compact with a wing span of 40-50 ft. There is evidence that it was flown towed by a car but there is nothing to indicate that it made a man-powered flight. This is not surprising when considering the high induced drag associated with biplanes, as discussed later in Chapter 4. Wing tip plates were incorporated, presumably as an attempt to reduce the induced drag.

John Wimpenny, design leader on the Puffin, also the successful self-taught pilot for many of the long flights at Hatfield.





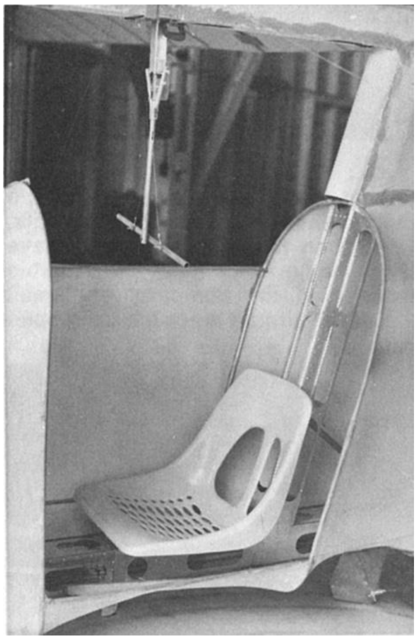
Above top, Puffin MK 1 in flight at Hatfield with the balsa covered wings sheathed in Melinex. Above, the MK II wing under construction with fine pitch rib spacing to conserve the aerofoil. The completed MK II airframe is seen at right, with adjustable dihedral angle, and enlarged rudder giving a saw-tooth leading edge.

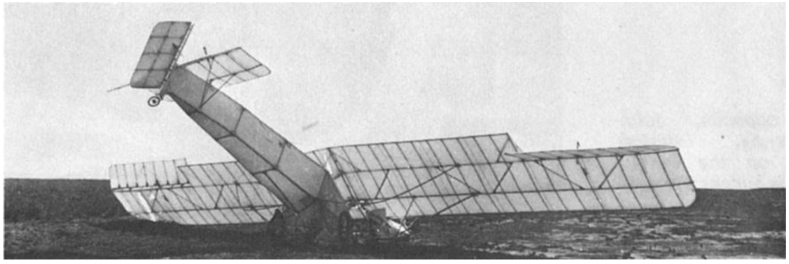


One other man-powered aircraft that has flown is that built by Josef Malliga an Austrian. It made a flight of 220 yards length at a height of 3 ft in the autumn of 1967 with Siegfried Puch, a gliding instructor at the controls. Since then flights of 400 yards have been achieved which is notable because of the comparatively small size of the aircraft since the wing span is 65 ft. However, Malliga was fortunate in finding a suitable pilot who was also light, Puch weighing only 126 lb. More recently a new Japanese aircraft has flown, the Sato-Maeda OX-1. This machine has a wing span of 72 ft. and a weight of 121 lb. Flights of 30 yards at heights of 6 ft. have been reported.

Only one man-powered aircraft project has been reported from the United States, the McAvoy MPA-1 built at Georgia Tech. This aircraft had a 54 ft. wing span and a weight of 110 lb. It featured shrouded contra-rotating propellers at the tail. Unfortunately it was damaged before being flown.

Several other projects either have or are under construction, see Table 1, both one- and two-seater aircraft. The Southend project, shown in Figure 8, was completed in 1968 but mechanical difficulties with the drive mechanism prevented it being flown. Since then dispersal of the interested group members and the difficulty of finding a suitable flying field has caused the project to be given up. Construction of the two-seat aircraft of the Canadian Aeronautics and Space Institution in Ottawa, Figure 9, and the Hertfordshire Pedal Aeronauts "Toucan", Figure 10, has been started. The latter is well advanced which is a particularly notable achievement since most members of the group involved were associated with the Handley Page Aircraft Co. Set-backs to this company naturally retarded the work of the group, nevertheless it is hoped to complete "Toucan" by early 1971.

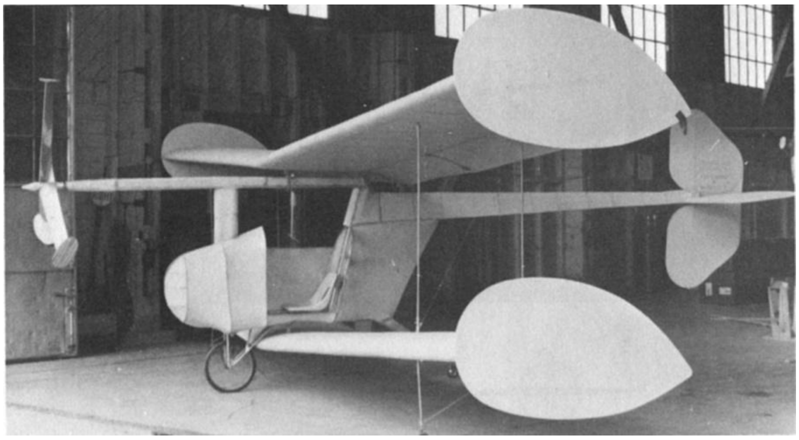


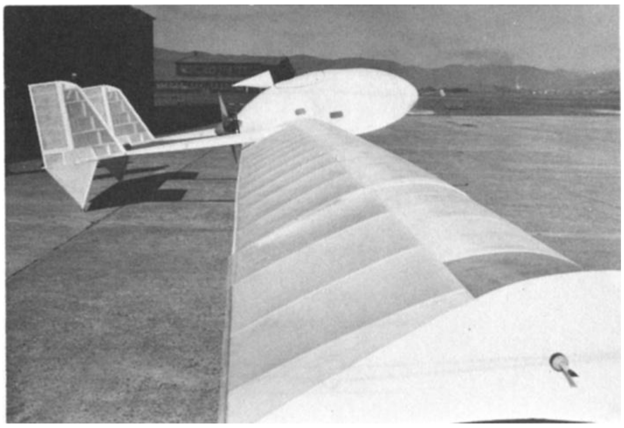


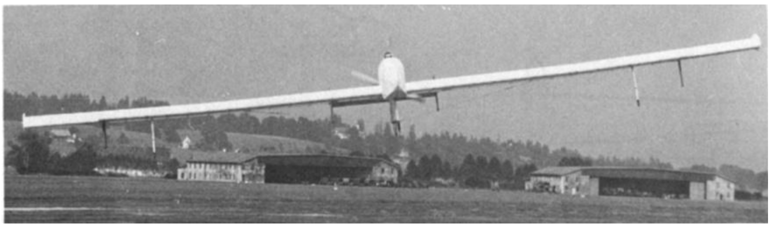
Top and Bottom the 40 ft Parasol wing project by S. W. Vine of Krugersdorp S. Africa before and after flight.

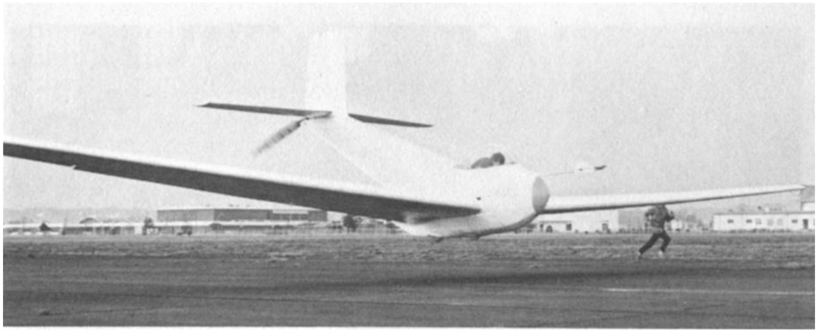
Centre is the pilot seating and controls for the Canadian biplane by Smolkowsky (above) at Calgary, Alberta.

Below, the transverse ailerons and twin boom of the Austrian Malliga machine seen in flight at Herbst, below. Note the deflection of the tip during this flight turn.









Linnet MK II airborne above, distinguished by the cycling attitude of the pilot whereas original MK I (below) had a reclining pilot attitude. The subsequent MK Ill version adopts the same basic configuration of the MK II.

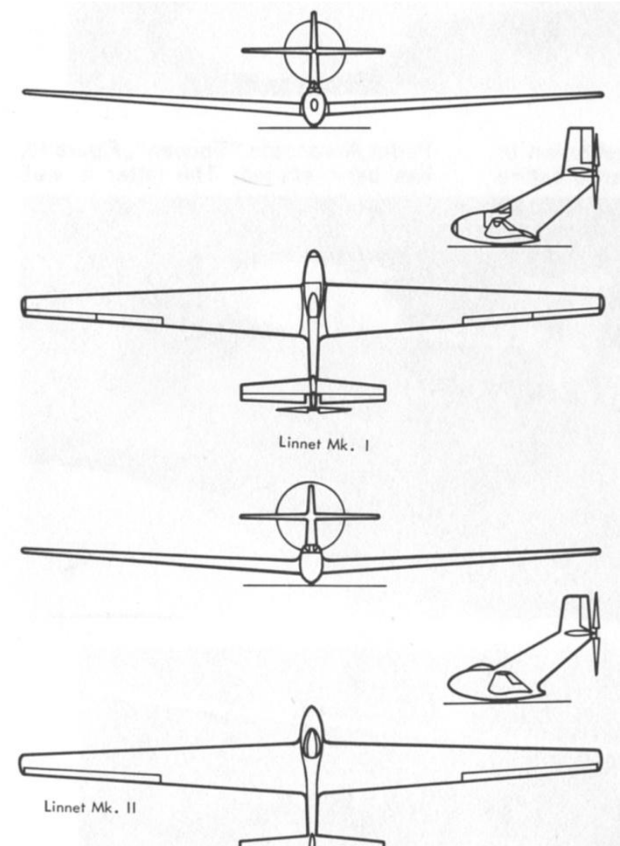
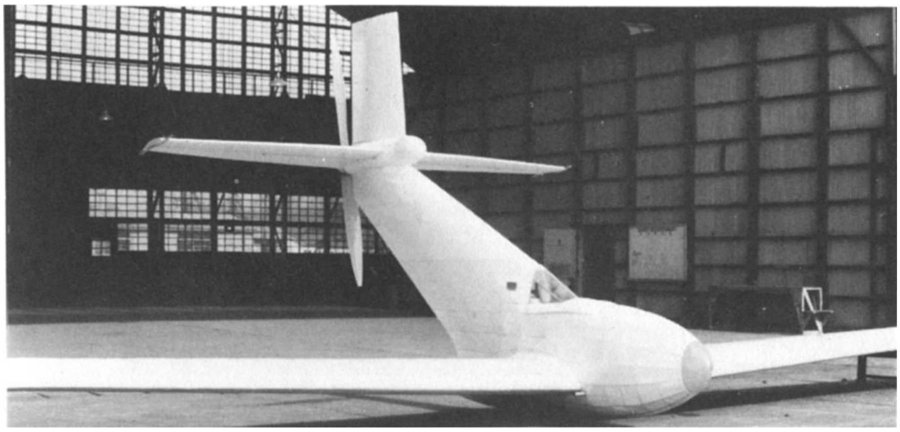
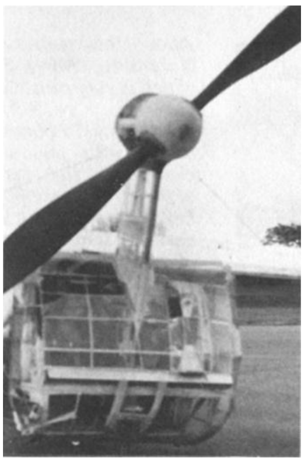
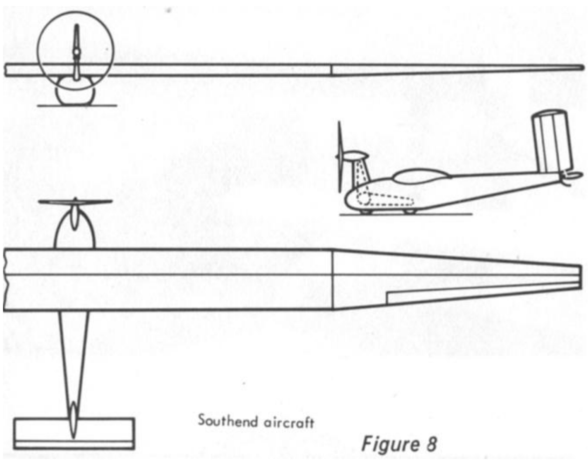


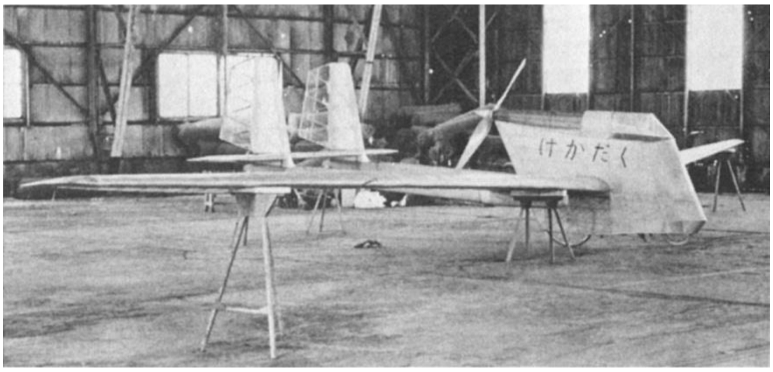
Figure 7







Large diameter propeller and blunt nose enclosing side-by-side propulsion/ pilots on the 'Mayfly' (centre opposite) from Southend. Rear three-quarter view at bottom shows the large tail surfaces and the Aluminised Meculon covering adopted for this, the first of the British 2-man machines.



Above: the Japanese Nakamura MP-X-6 which is very much a one-man project, using the twin boom layout with pusher propeller at the rear of the pilot's nacelle. Underneath, the more successful Sato-Maeda SM-OX which has flown on many occasions in Japan.

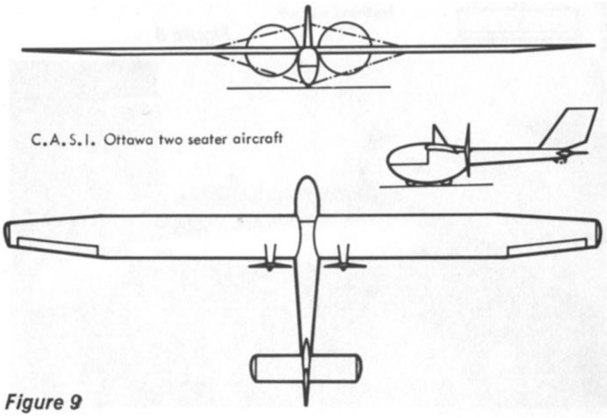
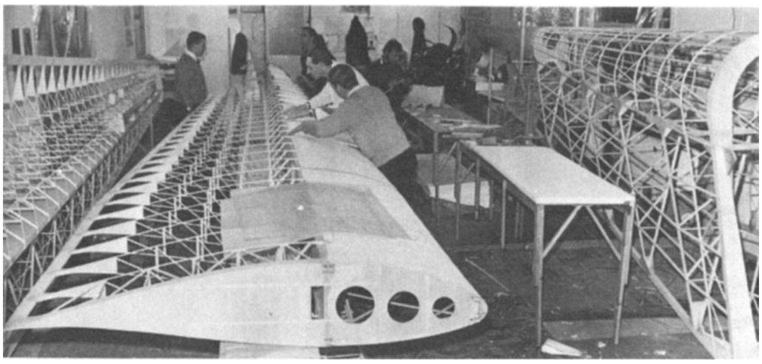


Figure 9

The Woodford project is a single-seater machine with a similar configuration to "SUMPAC" but with the Puffin type of fuselage nose to allow the pilot to operate from a cycling position. This machine was severely damaged by fire in June 1969 and will not now be completed by the original group. The parts are to be taken over by a group at the R.A.F. Apprentice Training School.

Construction of the Weybridge aircraft, Figure 11, a machine built with the Kremer competition as its sole objective, is completed and it is hoped for the first flight in 1971.

The majority of the designs incorporate large wing spans of high aspect ratio, but an exception was the Lippisch 1964 project, Figure 12. This was not built due to the ill health of Dr. Lippisch, during which time the group had dispersed. The design was to have been constructed entirely of balsa wood joined by polyester glue, with braced wings. The entire wings were to have rotated about their spars to give roll and pitch control. Transmission to the propeller used a chain drive with a 90° crossed chain. Referring to this project in comparison with others Dr. Lippisch expressed the view that it is better not to look to these "high hanging grapes" but first build a simple trainer with which one can probably just fly 100 yards and learn how to handle such a craft. He goes on to say that the enterprise must be looked at as a true sport in-line with other athletics. The vehicle is only a means to achieve certain performances. If one can fly every Sunday a few 100 yards it is much better than to have a monster standing in the hangar and waiting for extraordinary weather. A similar point of view must have been used as a basis for the Malliga and Sato-Maeda machines.



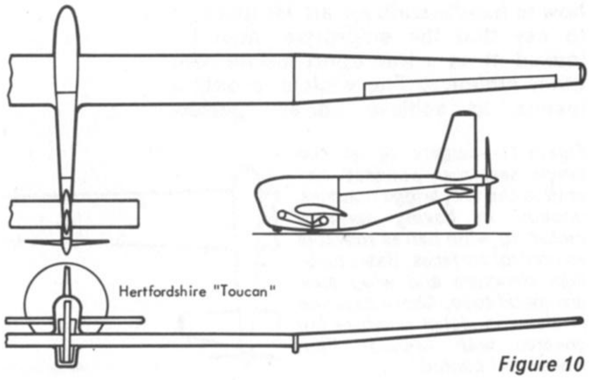
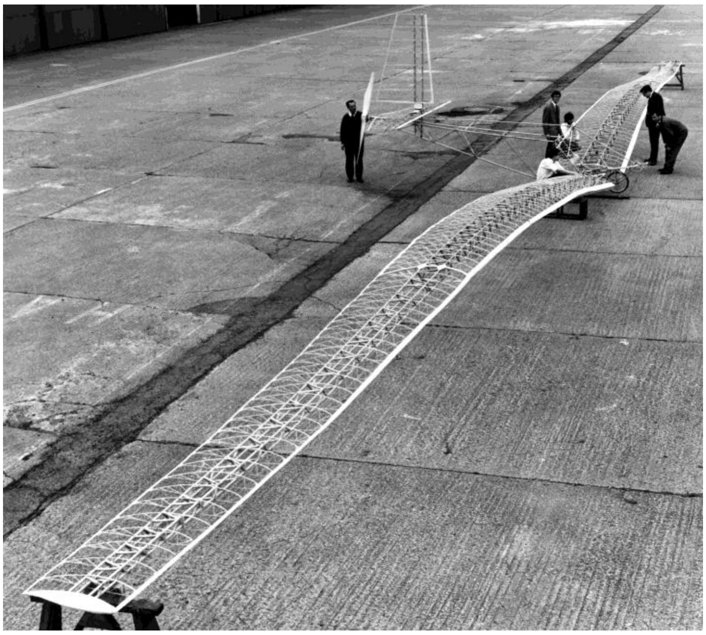


Figure 10

Top: Assembly of 'Toucan' by the Herts Pedal Aeronauts continues as this book is printed and will result in the largest, most sophisticated of all man-powered aircraft designs when completed for test during 1971.



British Aircraft Corporation

Figure 11-largest of all the single seat man-powered aircraft is the Weybridge machine unusual in having surfaces including wing halves movable as control surfaces. Basic fuselage structure and wing spar are metal tube. Below is the completed fuselage tail covered with Melinex film, nose cowl behind.

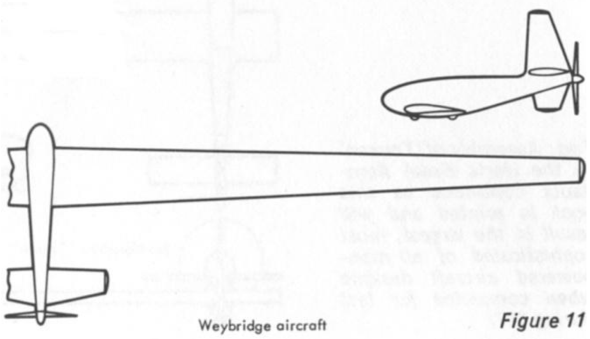
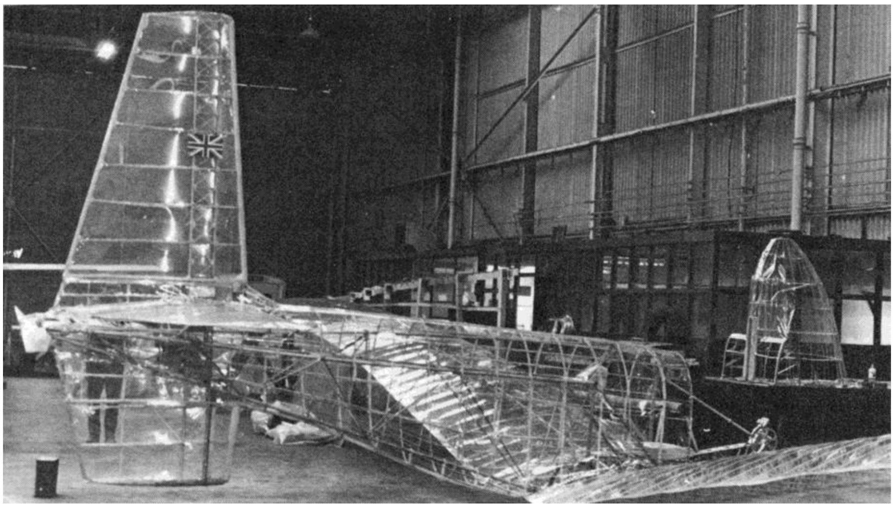


Figure 11



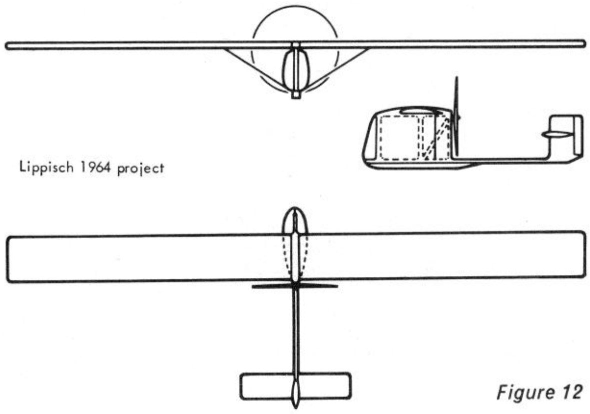


Figure 12

Table 1

Machines Built and Flown

	Haessler-Villinger "Mufli"	Bossi-Bonomi "Pedaliante	Southampton "SUMPAC"	Hatfield "Puffin I"	Hatfield "Puffin II"	Japanese "Linnet II"	Malliga aircraft
Span (ft)	44·3	55·8	80·0	84·0	93·0	73·0	65·0
Wing Area (ft^2)	104·0	230·0	300·0	330·0	390·0	280·0	–
Aspect ratio	18·8	13·4	21·3	21·4	22·0	19·0	–
Empty weight (lb)	81	215	128	118	140	99	113
Flying weight (lb)	246	358	269	267	290	225	239
Wing loading (lb/ft^2)	2·37	1.55	0.90	0.81	0.74	0.80	–

1.4 Kremer Competitions

There are two Kremer competitions[6] the £5000 and the £10,000 competition. The conditions of entry are the same for both competitions. Regarding the aircraft, it must be a heavier-than-air machine and must not incorporate any lighter-than-air gas devices. The aircraft should be powered and controlled by the same crew throughout the competition. No devices for storing energy or jettison of any part of the machine is permitted.

Other Projects

	South-end (2-seater)	Wood-ford	Lippisch 1964	C.A.S.I. Ottawa (2-seater)	H.P.A. "Toucan" (2-seater)	Wey-bridge Group
Span (ft)	90·0	78·8	50	90·0	123·0	120
Wing area (ft^2)	400·0	356·0	210·0	448·0	600·0	480·0
Aspect ratio	20.3	17.6	12.0	18.0	25.0	30.0
Empty weight (lb)	156	119	60	209	145	125
Flying weight (lb)	438	260	200	522	445	275
Wing loading (lb/ft^2)	1.1	0.73	0.95	1.16	0.74	0.57

On the ground one ground crew member is permitted to assist in stabilising the aircraft at the wing tip during take-off. The flights for the competition shall be made in still air, which for this purpose is defined as a wind not exceeding an even speed of 10 knots.

Detailed weight of four man-powered aircraft

Weight in lb	Haessler-Villinger	"SUMPAC"	"Puffin I"	"Puffin II"
Wing	43·1	79·4	65·0	85·0
Fuselage	23·5	20·0	26·4	26·4
Tail	8·8	2·6	4·0	6·2
Undercarriage	–	} 22·7	14·7	14·7
Drive	} 4.4			
Propeller		3·1	2·7	2·7
Misc. equipment	1·0	0·2	5·1	5·1
Empty weight	80·8	128·0	117·9	140·1
Pilot	145·0	141·0	150·0	150·0
Total weight	245·8*	269·0	267·9	290·1

* The total weight of the Haessler-*Villinger* aircraft also includes 20 lb, equal to the weight of a rubber bungee, carried in the nose of the machine at all times.

[6] There are currently [2015] 4 Kremer Competitions, see http://aerosociety.com/About-Us/specgroups/Human-Powered/Kremer

1.4.1. Kremer £5,000 Competition

Prizes of £2500, £1500, and £1000 respectively will be awarded to the first three entrants to fulfil the conditions. The entrant, designer and pilot must be citizens of the United Kingdom or the British Commonwealth, the aircraft being designed, built and flown within the British Commonwealth.

The course shall consist of two flights in opposite directions, each including three turns made around three markers spaced at $^1/_4$ mile intervals in a straight line, a typical course is shown in Figure 13. Both flights must be completed within a period of one hour. Minimum ground clearance will be 10 ft when passing the first and third markers on both flights.

1.4.2 Kremer £10,000 Competition

A prize of £10,000 will be awarded to an entrant from any part of the world who first fulfils the conditions. The course shall be a figure of eight, embracing two turning points, which shall not be less than $^1/_2$ mile apart. It must be ensured that the machine is in continuous flight over the entire course and must be flown clear of and outside each turning point. Ground clearance will be minimum of 10 ft at start and also at the finish, both of which are the same point half-way between the turning points. Between start and finish the ground clearance is unrestricted.

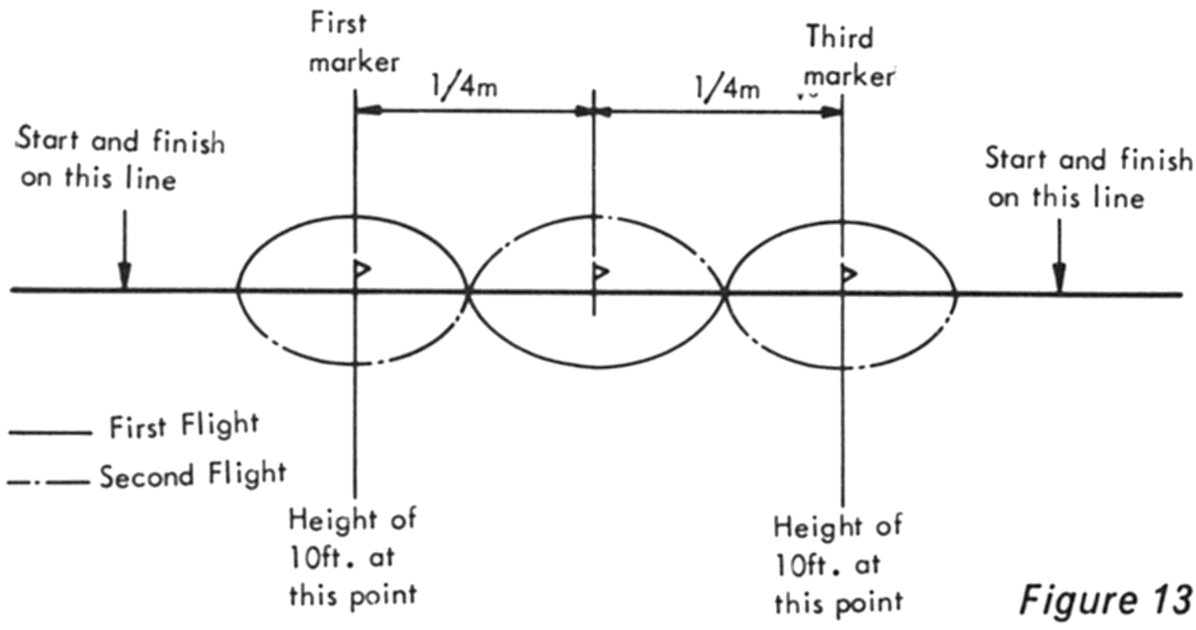


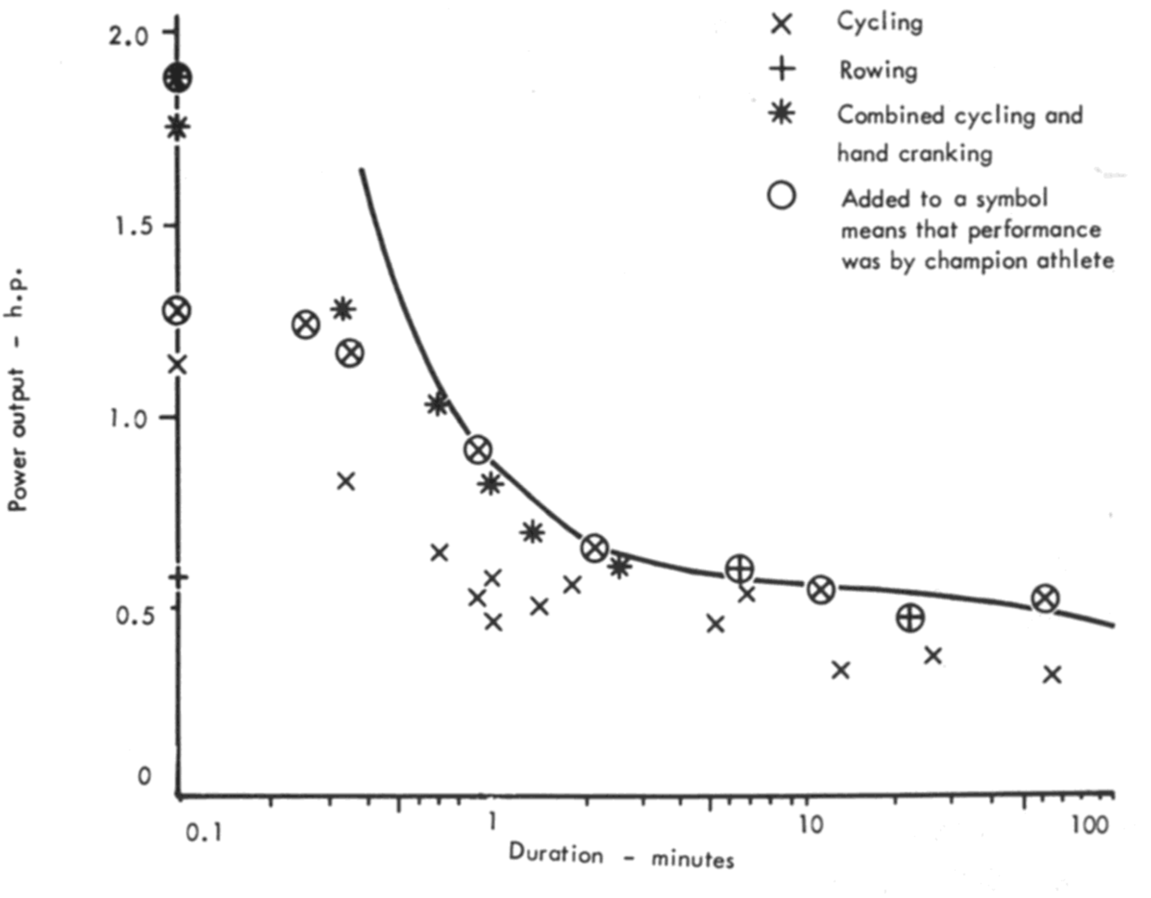
Figure 13

2. MAN POWER

BEFORE any design study can take place, information is required regarding the characteristics and capabilities of the motive power unit, in this case man. The pre-war attempts at man-powered flight suffered through inadequate data concerning man power. This data is now to hand since Wilkie[7] correlated existing information, the validity of which has since been confirmed by the SUMPAC and Puffin flight trials.

2.1 Steady power output

Man power comes from the chemical processes that take place within the body. Chemical energy results from the oxidation of food to form Carbon dioxide and water. The muscles transform the chemical into mechanical energy, with an efficiency, i.e. work output/chemical energy used, of 20 to 25% under favourable conditions.



Maximum power output plotted against total duration of the exercise

Figure 14

[7] Man as an Aero Engine, D. R. Wilkie, *Journal of the Royal Aeronautical Society*, August 1960.

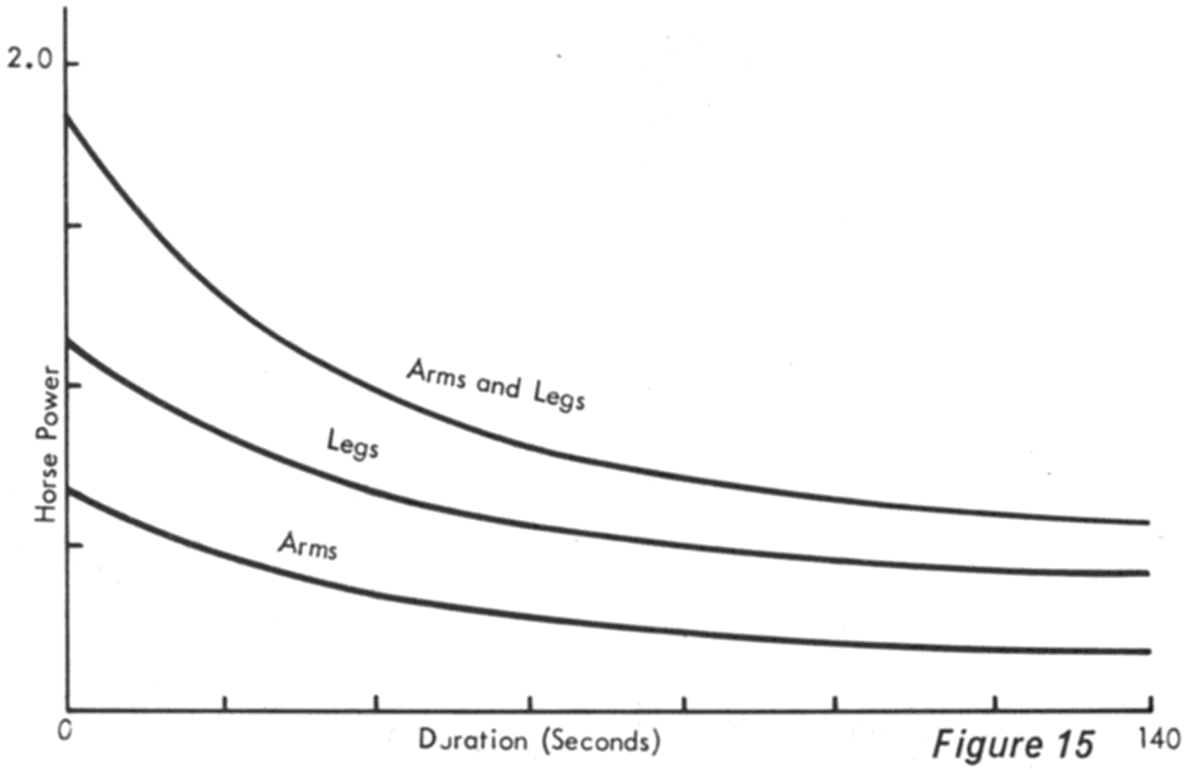


Figure 15

Steady power output depends on an adequate supply of oxygen that can be absorbed at the lungs and transported by the blood stream to the active muscles. The lungs and blood stream have a limited capacity so that a limit is set regarding the steady energy conversion. A fit young man can absorb up to 4 litres of oxygen per minute, the maximum absorption that has been recorded is 5.4 litres/minute by an Olympic athlete. Since a litre of oxygen yields about 0.1 h.p. of mechanical work under optimum conditions the steady power output must be limited to 0.4-0.54 horsepower, depending on whether we are considering fit ordinary men or champion athletes. These values are in good agreement with experimental results regarding mechanical power output, see Figures 14 and 15.

2.2. Additional energy sources

Although the steady power output is the result of oxidation, there is a further source of energy resulting from the hydrolysis of various compounds, such as the hydrolysis of glycogen to lactic acid.

The rate of these hydrolytic reactions is not limited by the supply of reactants from outside the muscle, although the total amount of energy available is limited by the amounts of such chemicals stored in the muscle.

Hence, in brief bouts of exercise, say 0.1-5 minutes between 2 and 0.5 h.p., may be released by hydrolysis.

This indicates the reason for power output greater than that deriving from the steady state, being recorded, see Figures 14 and 15. Of course, the stores of hydrolysable chemicals must be replenished after the exercise is over, the energy needed being obtained from additional oxidation.

2.3 Experimental data regarding man power

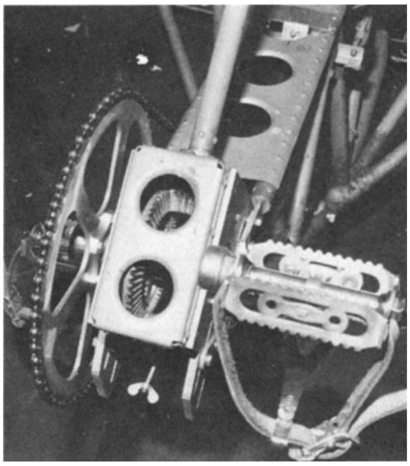
The data collected by Wilkie is presented in Figure 14 and presents the results from three different types of exercise that are pertinent to the man-powered aircraft problem:

2.3.1. Rowing

Rowing is, when using a sliding seat (see results in Figure 14), an effective method of producing external mechanical work provided that the duration is more than two or three minutes. For short bursts a high power output is necessary resulting in high frequency sliding and a disproportionate wastage of energy due to the required acceleration and deceleration of the system.

2.3.2. Pedal-cycling

Cycling is the most flexible means of man-power utilisation, hence its application in all man-powered aircraft to date. With cycling the full steady power production of the body can be developed. Under no-load conditions the maximum rate of pedalling is about 180 r.p.m. whereas the optimum for greatest efficiency is about 60 r.p.m.



Bevel gear transmission and chain drive for road wheel on the Weybridge machine.

2.3.3. Pedal-cycling with hand cranking

The total amount of energy available from hydrolytic reactions is limited by the initial size of the chemical stored in the active muscles. Therefore, maximum usage of hydrolytic energy sources can be made by using most muscles. It has been found that simultaneous cycling and hand-cranking yields about 50% more power than cycling alone but only for a short time. Ursinus, see Figure 15, found that the advantage is very small after 5 minutes when the power output becomes limited by the oxygen supply.

2.4. Application to man-powered aircraft

Pedal cycling has been the obvious choice for all existing projects and it is reassuring that both the “SUMPAC” and “Puffin” were piloted by ordinary cyclists, even if durations have been a maximum of two minutes.

As we have seen from the preceding sections power output is basically:

(I) Steady oxidative energy production of between 0·4 and 0·5 h.p. depending on the individual concerned.

(ii) Additional energy production by hydrolytic reactions.

The latter is required to aid take-off and climb to cruising altitude although for existing aircraft some of the cruising power is used for take-off and the flight durations have been reduced by earlier fatigue. The steady oxidative power is required for cruising and here it is interesting to note that “Puffin I” had a calculated cruise horse power of 0·38.

Discussion with John Wimpenny, who has piloted both “Puffin I” and “II”, indicates the need for a suitable ground rig to check the power available from the pilot and also allow him to train under precise conditions. Furthermore, tests by the Hatfield Group indicated that amongst ordinary cyclists only a few came within the required power production range and even those had power output levels that varied from day to day. To quote John Wimpenny some days he wondered why he had finished the flight when he did whereas on others he was glad when it was over.

To comply with the requirements for the Kremer £5000 competition, there certainly seems a case for considering the combination of hand cranking with pedal cycling both to aid take-off and also to get back up to 10 ft altitude at the end of each run. Finally if one is considering manpowered flight simply as a sport the use of a mechanical energy storage device is not ruled out, so that man power could be conserved for higher cruise horse-power outputs.

3. BASIC AERODYNAMICS

CERTAIN basic aerodynamic parameters have to be considered during the design of a man-powered aircraft and the designer must become conversant with these before attempting such an exercise. It is generally considered that the designer can only acquire the necessary knowledge through an intensive study of the subject, but such a point of view stems from a lack of insight into the design procedure. It must be emphasised that design is concerned with results, it is the process whereby an end product is created to comply with a need. To ensure that the end product is obtained in the most effective manner the designer is required to use not only his technical knowledge but also an intuitive-cum-creative approach to the problem. It is perhaps relevant to remember that the early aviators did not wait until the science of aerodynamics was sufficiently advanced to ensure success before designing and building their aircraft.

The case of man-powered aircraft design is in a somewhat analogous position at the present time. Fortunately sufficient aerodynamic knowledge is available because there are very few basic criteria that are actually essential to the design procedure. It is proposed to now introduce these various aspects of aerodynamics relevant to the design criteria, the approach being essentially straight-forward and non-theoretical. By trying to “picture” what actually happens in practice the reader obtains a better fundamental understanding of the subject, then if desired the theory can be studied in the realisation that it is simply a method of modelling the practical situation to provide numerical data for the design procedure. Those who wish to fill in the theoretical background of aerodynamics are referred to the bibliography.

A powered aircraft is subject to four essential forces; weight; lift-to overcome the weight and ensure that the aircraft can actually fly; drag resulting from the retarding forces imposed by the air through which the aircraft flies and thrust - the force provided by the motive power to overcome drag to a sufficient extent as to propel the aircraft forward.

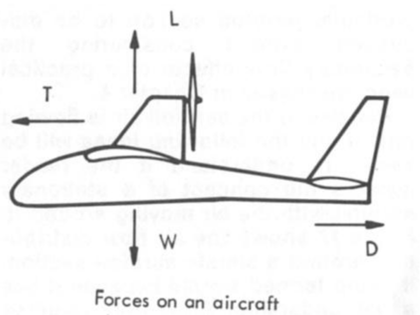


Figure 16

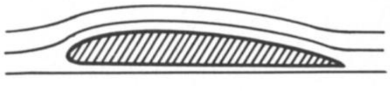


Figure 17

Gliders obviously do not have thrust but fly continuously in a dive, the slope of which must be sufficient to provide a forward component of the weight to enable the drag to be overcome. Lift equals the weight so that the gliding angle must depend on the L/D ratio. In fact it can be easily shown that if a glider is working at its optimum velocity and has an L/D ratio of 40 then the gliding angle is 1 in 40. However, if the nose of the glider is dropped even further the gliding angle increases but so does the air speed. A modern high performance sailplane having a good L/D ratio of the order of 40 would have a minimum sinking velocity of 2 ft/sec so that thermals providing upcurrents of a greater magnitude would enable the sailplane to gain altitude.

The bibliography contains some references on gliding which are considered to be of interest to the reader due to the close affinity between it and man-powered flight. Certainly the expertise gained in the field of gliding will be extremely useful when man-powered flight becomes more of a sport and extended flights are attempted.

3.1 Lift

An aerofoil is the term given to a wing of infinitely large span, so allowing the characteristics of a particular aerofoil section to be discussed without considering the secondary flow effects of a practical wing, discussed in Chapter 4.

Relative to the aerofoil air is flowing past it and the following ideas will be easier to understand if the reader accepts the concept of a stationary aerofoil with the air moving around it. Figure 17 shows the air flow distribution around a simple aerofoil section, it being termed simple because it has a flat underside. Continuity requires that the air flowing over the top of the aerofoil must have a higher velocity than that underneath. This higher velocity can only be obtained at the expense of some other feature of the air flow, namely a reduction in air pressure. This can be found from Bernoulli's equation, giving the change in pressure p = ρ/2 $(V^2 - v^2)$ where V and v are the mean and local flow velocities respectively. Proof of Bernoulli's equation is given in most text books on fluid mechanics or aerodynamics, being derived from consideration of the internal energy of the fluid and the motion resulting from that energy.

Figure 18 shows a typical pressure distribution around an aerofoil section. The large area of low pressure above the aerofoil is of particular interest as it is this that provides the upward lift force. From Figure 18 it is apparent that changes of aerofoil section shape or angle of incidence between the aerofoil and airflow must affect the pressure distribution and hence the magnitude of the lift. For the purpose of practical design calculation a "lift coefficient" is introduced to define these characteristics in numerical terms:

$$L = C_L \frac{\rho}{2} S V^2 \qquad (1)$$

Where L = lift (lb),

C_L = lift coefficient,

ρ = air density (0.0024 slugs/ft3),

S = wing area (ft^2),

and V = aircraft velocity (ft/sec)

The angle of incidence for the simple aerofoil section in Figure 17 is the angle between the flat underside of the section and the direction of the airflow. For more complex sections a datum line is defined for this purpose, normally the chord line which is a convenient reference being the straight line joining the centres of curvature of the leading and trailing edges.

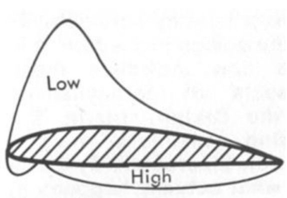


Figure 18

3.2. Profile drag

The profile drag is a characteristic of the aerofoil section and is different from induced drag, which is discussed in the next chapter, since the latter includes for secondary flow effects of a finite wing.

For design purposes the profile drag of a wing can be equated in a similar manner to the lift:

$$D_W = C_D \frac{\rho}{2} S V^2 \qquad (2)$$

where the relationship between equations (1) and (2) is clearly evident. D_w and C_D are the profile drag of the wing (lb) and the drag coefficient respectively. The drag coefficient is a function of the aerofoil section and angle of incidence, as also is the lift coefficient.

The profile drag, also sometimes referred to as the section drag, is a collective term for two types of resistance to motion:

(i) form drag,

and (ii) skin friction

Form drag is a resultant of the horizontal component of all forces acting on the aerofoil together with the additional pressure drag caused by the wake. Any object moving through a fluid causes the flow to first separate then rejoin after the object has passed. The rejoining of the separated flows is never perfect and a turbulent wake is formed which in the case of an aerofoil consists of a staggered arrangement of vortices being shed at the trailing edge. A streamlined shape leaves a smaller wake than blunt objects and Figure 19 shows the order of magnitude of the wake of an aerofoil section. An interesting comparison can be made with photographs of the wakes behind ships.

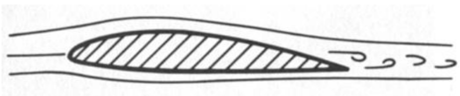


Figure 19

Skin friction is a factor that affects any fluid flowing past a surface, although its magnitude is dependent on the smoothness and cleanliness of the surface. The thin sub-layer of fluid adjacent to the surface attaches itself to the surface and remains stationary with respect to the surface. The next sub-layer is slowed down by the stationary fluid to a velocity well below that of the free-stream velocity. Each subsequent sub-layer further out from the surface increases in velocity until eventually the local fluid velocity equals that for the free stream, see Figure 20. The total region of fluid flow required for the velocity to change from the free stream velocity down to zero at the surface is termed the “boundary layer”. The depth of this layer depends on the properties of the fluid, namely its viscosity or resistance to shear, and the nature of the flow, whether laminar or turbulent. With a laminar boundary layer the fluid particles flow along streamlines at constant positions relative to the surface. With a turbulent boundary layer the particles move about in a random manner within the layer and the resulting surface friction drag is higher.

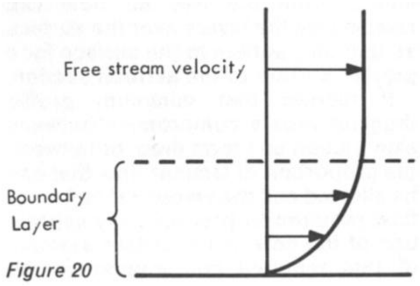
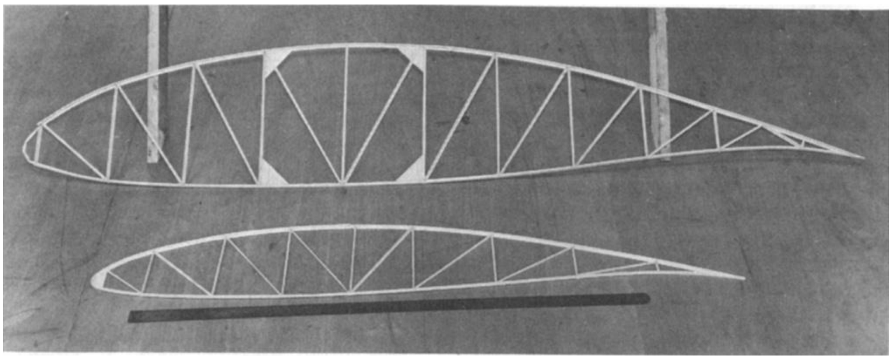


Figure 20

Considering flow over an aerofoil section the boundary layer starts from the front and builds up in thickness as the flow travels along the section. The boundary layer over the front of the section will be laminar but as the thickness increases the flow becomes unstable and transition takes place to a turbulent boundary layer. For low skin friction drag it is important for the laminar boundary layer to remain stable over as large a proportion of the aerofoil section surface as possible. However, on the other hand the wake is larger and therefore gives increased form drag than a turbulent boundary layer. This is because the particles in the turbulent boundary layer take energy from the free air flow and re-energise the layers near the surface so that they adhere to the surface for a greater portion of the aerofoil section.



Experimental rib structures for the Weybridge aircraft utilising Tee section booms and braces.

It follows that minimum profile drag requires a compromise between skin friction and form drag, or between the proportion of laminar flow that can be allowed and the amount of turbulent flow required to prevent early separation of the flow. An excellent example of this required compromise is the golf ball. The golf ball is dimpled to promote a turbulent boundary layer so minimising the size of the wake with a considerable reduction in form drag at the expense of a comparatively small increase in surface friction. In practice this allows the golf ball to travel further from a given shot, a feature that was noticed in the early days of the game when smooth balls were used, it being found that used rough balls were better than the new ones.

In the case of aerofoil sections chosen for man-powered aircraft, profile drag must be low requiring the correct compromise between the laminar and turbulent boundary layers. The Southampton group for example found it possible to maintain a laminar boundary layer for 60-70% of the chord over the top surface but only with absolute cleanliness and smoothness of the surface. In practice small influences generally prevent the laminar boundary layer being maintained for anything greater than 35% of the chord.

3.3. Stalling

As the angle of incidence of an aerofoil section increases the velocity of the air increases over the upper surface with a resulting improvement in the lift coefficient. However the pressure distribution over the upper surface changes, there being a large difference between the lower pressure area over the front of the section compared to the region behind. When this pressure gradient becomes too great the flow form breaks down. Figure 21 shows such a breakdown of the flow pattern which is due to separation of the flow from the surface. A simple analogy can be taken by considering the air climbing up a pressure hill which if too steep is insurmountable, the air flow then reserves its course down the hill and in reality separation of the flow takes place.

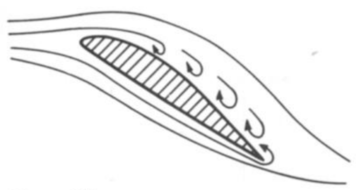


Figure 21

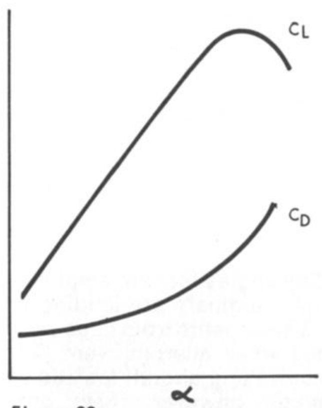


Figure 22

Increasing the angle of incidence increases the separated flow and so gives a loss in lift. The improvement in the lift coefficient gradually decreases until at some particular angle of incidence it reaches a maximum. As the separated flow increases there is an associated increase in the form drag. Variations of C_L and C_D against angle of incidence for a typical aerofoil section are shown in Figure 22. The point of maximum C_L is termed the stalling point. In practice an aircraft stalls if its air speed falls below the stalling speed. As the speed decreases the angle of incidence of the wing has to increase to provide the required lift and stalling occurs if it increases beyond the stalling point.

3.4. High lift devices

Improved lift can be obtained from an aerofoil section if the angle of incidence can be increased without separation occurring. This may be achieved to some extent by modification of the aerofoil section or by use of high lift devices such as slots and flaps. The discussion of methods for obtaining improved lift coefficients is relevant to man-powered aircraft since any such improvement results in a smaller and subsequently lighter aircraft.

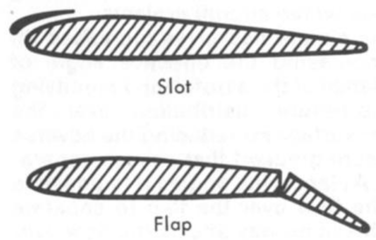


Figure 23

Simple forms of the slot and flap are shown in Figure 23. The slot is formed by an auxiliary aerofoil near the leading edge which gives a decrease in air velocity in that region. The rise in pressure undergone later by the boundary layer is therefore diminished and separation possibly prevented or at least postponed to a larger angle of incidence. Even if the flow separates over the upper surface of the auxiliary aerofoil, its wake is discharged into the main air flow where it cannot seriously affect the lift of the main aerofoil. However, the slot gives increased lift at the expense of increased profile drag and this has made it unaccepted for all the existing man-powered aircraft projects.

The simple flap gives increased lift by increasing the effective angle of incidence of the aerofoil and modifying the pressure distribution over the upper surface so reducing the adverse pressure gradient that causes separation. At large flap angles it is possible for the flow over the flap to separate but this in no way affects the flow over the main part of the aerofoil. Hence, the large flap angles that are employed when modern airliners are landing or taking off. The benefits from flaps were first noticed when ailerons were first used for controlling aircraft instead of wing-warping, however they only became of practical importance in the 1930's by which time a variety of different flap designs had evolved.

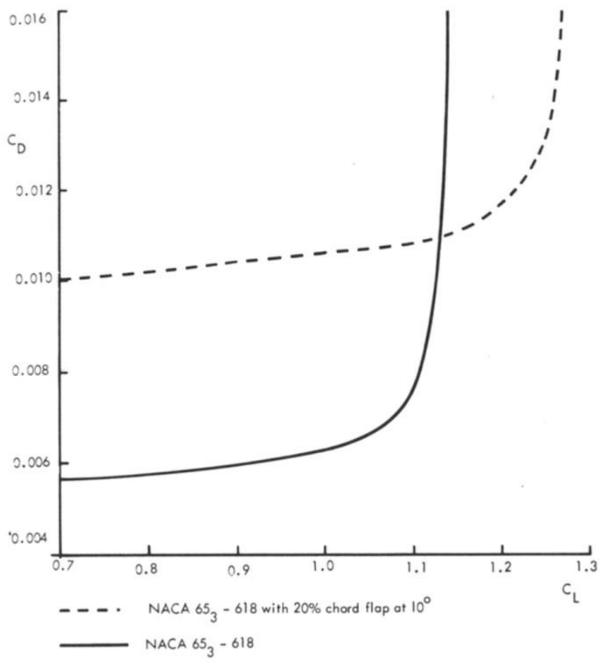


Figure 24

During the last war N.A.C.A.[8] tests on low-speed laminar-flow aerofoil sections suggested that considerable increases in lift coefficient could be achieved by utilising small flap angles, see Figure 24. However, no further development work has been devoted to this subject with regard

[8] National Advisory Committee for Aeronautics, U.S.A.

to its application to man-powered aircraft since comparable performances have been obtained by specially cambered aerofoil sections, which after all work on the same principle to a flapped aerofoil.

Other high lift devices work by direct modification of the boundary layer. Separation can be prevented if the boundary layer near the separation point is re-energised, i.e. taking the simple analogy of the flow climbing the pressure hill the importance of an energy input to the boundary layer is self evident. A natural form of re-energising occurs during the transition from a laminar to a turbulent boundary layer. Vortex generators provide an artificial means of causing this transition on increasing the turbulence of the boundary layer so that there is greater transfer of energy from the free air flow into the boundary layer. Generators proposed for powered aircraft consist of small vanes projecting from the wing surface set at an angle of incidence to the local flow direction. Aero modellers employ several types, (1) suspended elastic line ahead of the leading edge that oscillates during movement, (2) sawtooth inlay on upper leading edge to disrupt the flow, (3) spanwise thread superimposed at critical chord, and (4) spanwise wooden strips cemented in position to disrupt the boundary layer. Insufficient work has been done to check the possible applications of vortex generators, but it is anticipated that they only modify the performance of an aerofoil near the stalling point and that the increase of profile drag in this region would preclude their application to man-powered aircraft.

Direct control of the boundary layer by boundary layer suction is aerodynamically the most efficient high lift device but in practice the most complex as wing requires either a porous surface or suction slots with the associated pumping gear. It is the additional power required that will limit the possible development of boundary layer suction but ultimately it could prove that part of the available man-power be used for partial boundary layer control with a resulting overall gain. Certainly experiments could be rapidly implemented using small auxiliary power sources which whilst being outside the spirit of the Kremer Competition might greatly benefit the future of man-powered flight.

The subject of high lift devices cannot be left without some mention of sweptback wings, especially that of delta wing aircraft. Although not a high lift device by true definition, a look at an Avro Vulcan delta winged bomber during landing will indicate that large angles of attack are possible. without stalling. The air flow tries to follow a path perpendicular to the leading edge of the swept wing resulting in final flow towards the fuselage that stabilises the boundary layer and prevents separation. Unfortunately the Delta wing is generally considered to have poor low speed characteristics and may not be applicable to man-powered aircraft.

3.5. Aerofoil sections for man-powered aircraft

The choice of an aerofoil section for a man-powered aircraft depends on it having good lift characteristics for a low profile drag, the latter criterion being evident from the low power available to overcome the aircraft drag. Profile drag is not only a function of the shape of the section but also on the length of the chord and the free air stream velocity, since these determine the type of boundary layer over the aerofoil. An aerofoil section having a low profile drag if the boundary layer is mainly laminar could have a comparatively high drag if the boundary layer becomes turbulent over a large portion of the aerofoil.

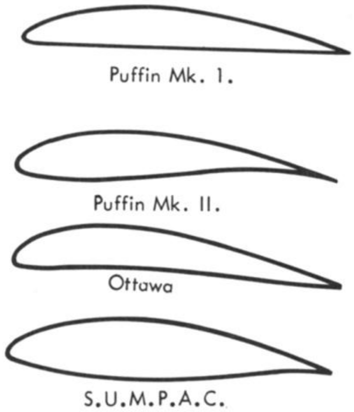


Figure 25

Since it is assumed that the designer of man-powered aircraft will not have testing facilities available to check his choice of aerofoil section, he must rely on available test data normally found using comparatively small models in wind tunnels. The problem that faces the designer is whether he can be sure that the data available is still relevant when applied to the full size aircraft. Or stated slightly differently, is there some factor that can be used to relate full size designs to test models so that aerodynamically their behaviour will be the same. This is a problem that exists in all fluid dynamics work and is solved by the introduction of a non-dimensional parameter termed the Reynolds number *(Re),* where:

$$R_e = \frac{\rho C V}{\mu} \qquad (3)$$

A study of equation (3) shows that the relevant properties of the air are taken into account by the density and viscosity terms, whilst the chord and velocity can also be equated. Hence, test results from a small aerofoil section obtained in a wind tunnel can be used for the full size aircraft provided that the chord x velocity are the same for both.

For example:

A man-powered aircraft design has a wing span of 70 ft, a flying speed of 20 m.p.h. and a model of $3\frac{1}{2}$ ft wing span has been built to test the aircraft behaviour. What velocity will be needed in the wind tunnel?

The model and full size aircraft can be related by the Reynolds number.

$Re_{model} = Re_{aircraft}$

However the air density and viscosity are the same for both so that the important relationship is:

$(C.V)_{model} = (C.V)_{aircraft}$

The ratio of the sizes is 20/1 so that according to the speed of the model it has to be 20 times greater than that of the aircraft, 400 m.p.h., to ensure that the characteristics found by testing are directly relevant to the full size aircraft.

This example clearly shows how few designers of man-powered aircraft will have suitable test facilities available to check their designs. However, this need not restrict any potential designer because the data presented in this book has been specially selected to overcome this difficulty and ensure that adequate information is available.

The above example also shows that a model working at low speeds has totally different flying characteristics to that of a full-size aircraft. This explains why aeromodels do not have exactly the same proportions as full-size aircraft. Aeromodels work within a Reynolds number range 1000 to 200,000 whilst aircraft work within a range from 5,000,000+. By comparison gliders work within a range up to 4,000,000.

Man-powered aircraft so far built have worked within the Reynolds number range 500,000 to 1,000,000, a range that can be termed unconventional by normal aeronautical standards. Unfortunately, the comparatively low values of Reynolds numbers means that man-powered aircraft are outside the mainstream of aeronautical research and development so that for the "Puffin I" and "SUMPAC" aircraft the designers had to rely on aerofoil sections developed for high performance gliders.

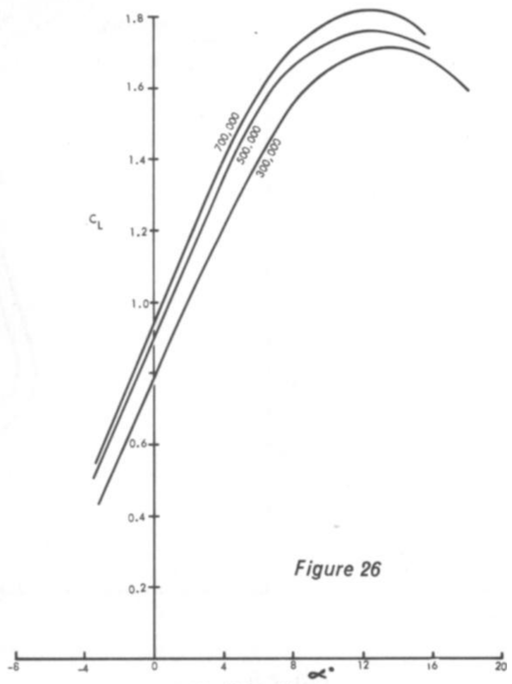
Figure 25 shows some of the aerofoil, sections used for existing man-powered aircraft, most having a fairly high camber to provide good lift coefficients, the exception being the Wortmann FX-05191 section which was especially developed for a low drag glider work. The FX-63137 section was specially developed for use with "Puffin II" by Dr. Wortmann and is the only such section to be so developed for man-powered aircraft for which comprehensive wind tunnel and "Puffin II" test data exists. Other aerofoil sections have been designed since but lack test data and even where estimated performance is quoted it gives promise of only small improvements compared to the FX-63137.

"Puffin II" worked at a mean Reynolds number of 625,000 and at this value the section working at its design incidence of 2° gives a lift coefficient and profile drag coefficient of 1·15 and 0·0092 respectively. Comparison with the design data for other projects is given in Table 2 and shows these values to be excellent.

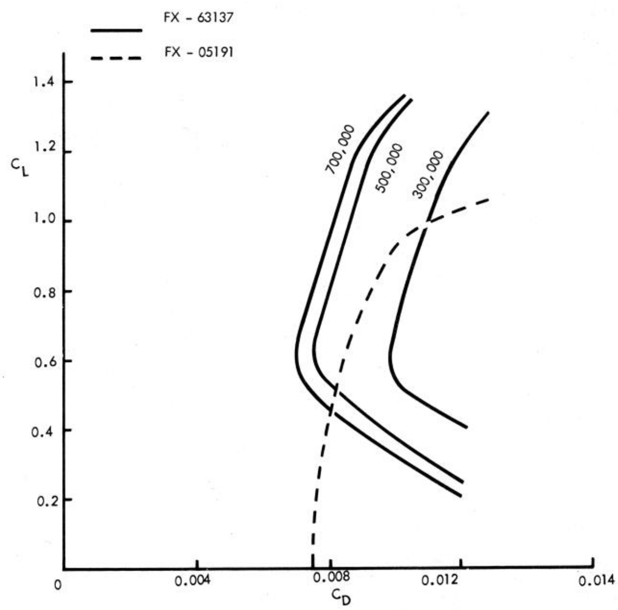
Table 2

Design data for Man-powered Aircraft

	"Puffin I"	"Puffin II"	Ottawa	Southampton
Mean *Re*	800,000	625,000	900,000	700,000
Design C_L	0·8	1·15	1·0	0·85
C_d	0·009	0·0092	0·011	0·0083
C_L/C_d	89	125	91	102



Lift coefficients for the FX - 63137 aerofoil section



Lift - drag curves for the FX - 63137 and FX - 05191 aerofoil sections

Figure 27

Figure 26 shows the variation of lift coefficient with angle of incidence and Figure 27 shows the lift-drag polars for the FX-63137 section for Reynolds numbers of 3, 5 and 700,000 respectively. For comparison the lift-drag polar of the FX-05191 section is included in Figure 27 for a Reynolds number value of 700,000. Judging from the plots in Figure 27 the profile drag of the FX-63137 is not expected to increase for Re values higher than 700,000. Co-ordinates of the Wortmann FX-63137 section are as follows.

FX-63137

	x/c	*y/c upper*	*y/c lower*		*x/c*	*y/c upper*	*y/c lower*
T.E.	0·99891	0·00082	0·00040	11	0·40243	0 12137	−0·00848
23	0·99034	0·00501	0·00373	10	0·33933	0 12128	−0·01460
22	0·97344	0·01189	0·00921	9	0·27891	0 11792	−0·01895
21	0·94848	0·02043	0·01514	8	0·22221	0·11122	−0·02161
20	0·91571	0·03018	0·02052	7	0·17037	0 10165	−0·02277
19	0·87590	0·04114	0·02479	6	0·12403	0·08961	−0·02256
18	0·82970	0·05323	0·02729	5	0·08422	0·07555	−0·02122
17	0·77773	0·06605	0·02745	4	0·05158	0·06005	−0·01887
16	0·72115	0·07927	0·02530	3	0·02650	0·04371	−0·01537
15	0·66074	0·09204	0·02098	2	0·00960	0·02740	−0·00995
14	0·59750	0·10331	0·01475	1	0·00102	0·01012	−0·00232
13	0·53274	0 11221	0·00716	LE.			
12	0·46733	0·11833	−0·00103				

4. AIRCRAFT AERODYNAMICS

CHOOSING an aerofoil section and the investigation of relevant data that is required for such a choice is just one aspect of the various aerodynamic considerations that are required for a complete aircraft. These other aspects of aerodynamics are now to be considered.

4.1. Aerodynamics of practical wings

The basis of the discussion of aerodynamics in the preceding chapter was the aerofoil, a wing of infinitely long span. By comparison, a practical wing is one that has a finite span.

From the discussion of lift formation in section 3.1 it will be noted that there is a low pressure area above the aerofoil section and a relatively high pressure area below it. With a practical wing these two regions must meet at the wing tip with the result that air flows from the higher pressure region over the wing tip into the lower pressure region above, see Figure 28.

The motion of the air at the wing tip causes a general drift along the upper surface of the wing towards the fuselage and an equivalent drift away from the fuselage under the wing. Where these secondary air movements meet the air flowing around the fuselage, the fact that they are travelling at right angles causes appreciable disturbances of the flow. It is vitally important that the junction of the wing and fuselage is smooth and streamlined so that these disturbances can be reduced to a minimum.

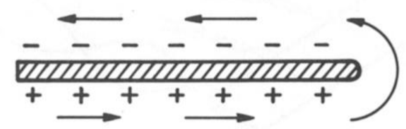


Figure 28

Flow of air at the wing tip takes air from below the wing into the low pressure region above, giving an increase in pressure and a resulting decrease in lift. (It must be remembered that the formation of lift is dependent on the low pressure area above the aerofoil section.) Therefore, there is some loss of lift and the general distribution of the lift is not uniform as might be supposed from the basic aerofoil considerations. Theoretically the three-dimensional behaviour of the airflow results in a lift distribution that is elliptical in shape. In practice the loss of lift tends to be more concentrated near the wing tip so that actual loss of lift is less than predicted by the theoretical elliptical distribution. Figure 29 shows typical lift distributions for the rectangular wing. Due to its concentration near the wing tips the loss of lift it can be ignored for aspect ratios greater than 10. Since configurations that have been and will be chosen for man-powered aircraft embody high aspect ratios the loss of lift has no practical significance and equation (1) is still valid.

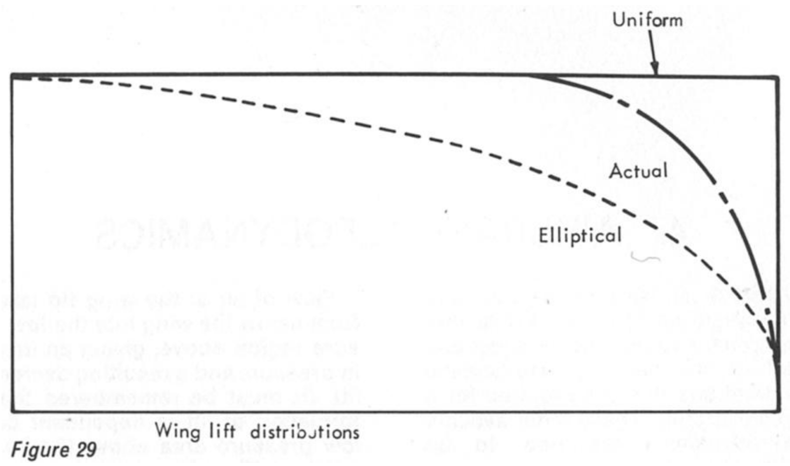


Figure 29

Tapered wings tend to have actual lift distributions that correspond very closely to the theoretical elliptical distribution and so were chosen for the SUMPAC and Puffin project.

4.2. Induced drag

The flow of air over the wing tip, as illustrated by Figure 28, causes a large vortex to form which trails behind the wing tip. Many text-books on aerodynamics give evidence of this wing tip vortex, showing photographs taken in wind tunnels of models with smoke flowing near the wing tips. Aircraft when flying in humid atmospheric conditions sometimes develop “vapour trails” at the wing tips and this is entirely due to the vortices that are formed.

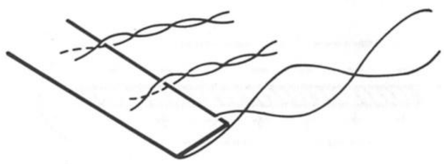
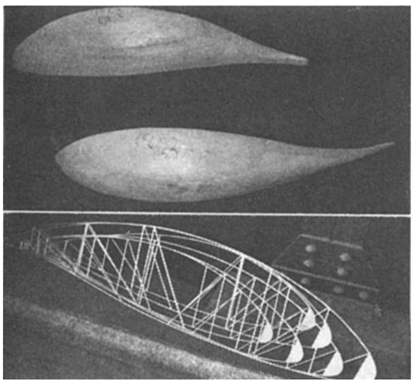


Figure 30

As well as the wing tip vortices the air drifts above and below the wing are in the opposite direction and on meeting at the trailing edge of the wing form further small vortices, see Figure 30. These small vortices tend to converge on the two larger tip vortices and roll into two vortex tubes, one on either side of fuselage, at a distance from the fuselage that is somewhat less than that of the wing tip.

It can be appreciated that the actual movement of air around a wing is quite complex. Furthermore these vortex tubes require energy for their formation and continuation. The energy can only come from the aircraft itself and takes the form of additional wing drag, being termed the “induced drag” since it is induced as a result of lift.

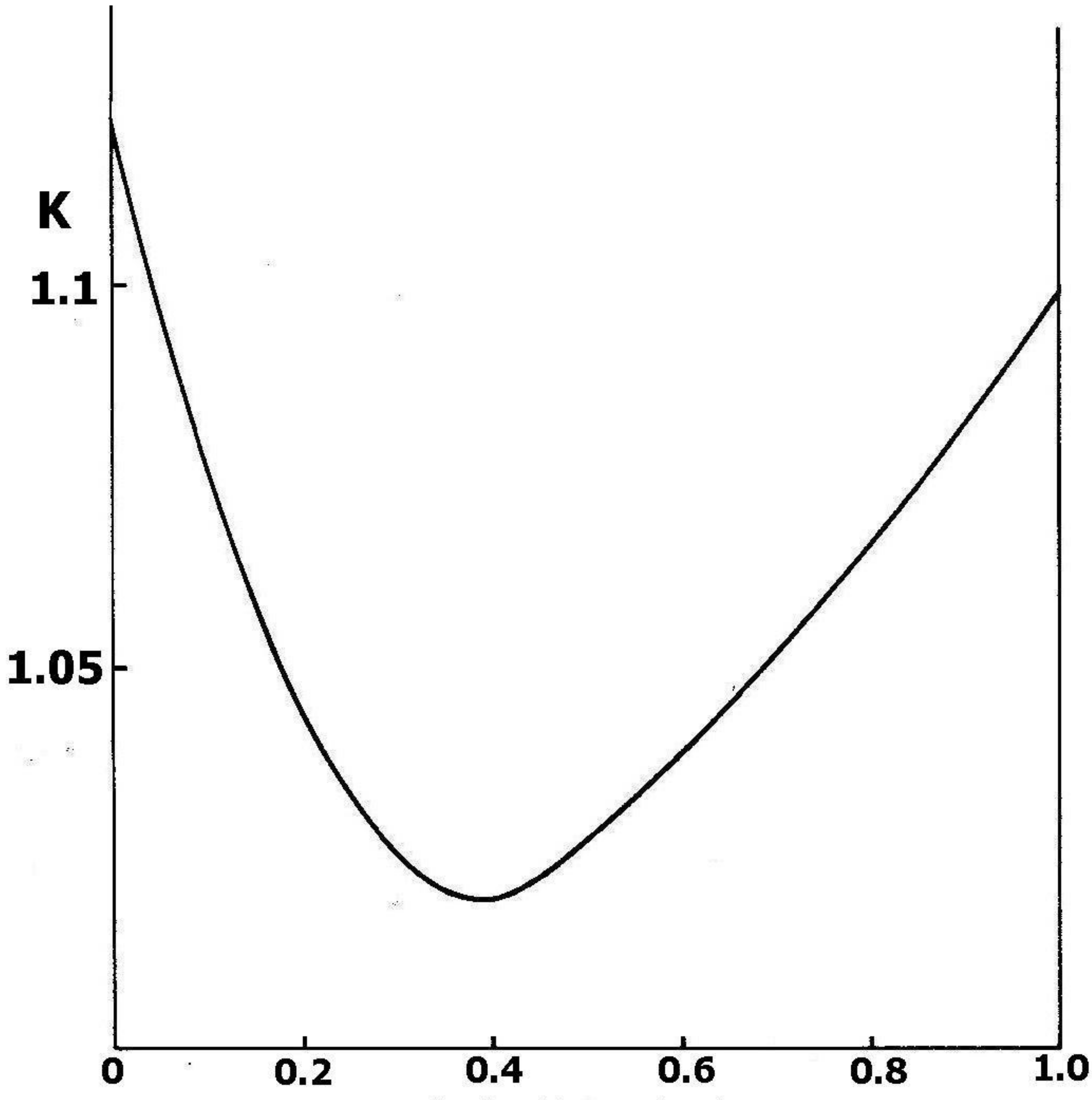
Above: The carved balsa lips of the Linnet MK 1, elegant in shape, following the aerofoil section N.A.C.A. 63_3-1218 and sectioned to reduce lip drag. Subsequent Linnet tips are less curved.



Bottom: Linnet MK 1 wing ribs illustrate lightweight structure and taper in section as well as thickness.

Referring to the elliptical lift distribution which, although not realised in practice with a rectangular wing plan-form, is theoretically that distribution resulting from a 3-dimensional air flow. A wing with an elliptical planform should have an elliptical lift distribution so that theory and practice coincide. This is found in practice and the secondary air flows which should cause elliptical distributions with other plan-forms are therefore minimised resulting in the vortices that are generated at the wing tip and trailing edge being reduced to a minimum.

Hence induced drag is a minimum with an elliptical wing. This indicates partly why this wing planform was used for the wartime Supermarine Spitfire fighter.



Variation of induced drag with wing geometry

Figure 31

From theory the induced drag coefficient C_D. for an elliptical wing is given by:

$$C_{D_i} = \frac{C_L{}^2}{\pi A} \quad (4)$$

where A is the aspect ratio, wing span/mean wing chord. Relevant textbooks on aerodynamics can be consulted to obtain the theoretical background to this equation. Nevertheless from the discussion earlier regarding induced drag being the result of lift production, the relevance of the C_L^2 can be appreciated. Furthermore, as the main part of the induced drag results from the vortices concentrated at the wing tips it becomes proportionally less for larger wing span, hence the inclusion of the aspect ratio in equation (4).

Although the elliptical wing planform represents the ideal, the associated construction is complex and in practice rectangular and straight tapered wings are used. It is possible to achieve an elliptical lift distribution from straight sided wings by varying the angle of attack along its length but this is complex and also wasteful of useful wing lifting area. For straight wing planforms with constant angle of attack, equation (4) needs to be modified to the form:

$$C_{D_i} = \frac{K' C_L{}^2}{\pi A} \quad (4a)$$

Variation of *K′* with configuration is shown in Figure 31. It will be seen that for most normal wing taper ratios *K′* is approximately equal to 1 so that equation (4) is still applicable. The inclusion of *K′* only becomes of relevance for rectangular or near rectangular wings.

From consideration of the mechanism of induced drag the reduction of C_D; for tapered as opposed to rectangular wing becomes obvious. Following a similar argument, the increase of *K′* for very sharply tapered wings as indicated in Figure 31 appears somewhat surprising. However, for such wings the tip vortex formation is not confined to the actual wing tip, but occupies a wing tip region extending some little way along the wing itself. This results in larger vortices being formed than otherwise and provides the explanation for the increase of *K′* for tip chord/root chord <0·4.

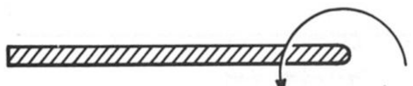


Figure 32

It may be possible to reduce induced drag by using wing tip plates to prevent the flow of air over the wing tips causing the tip vortices. Aeromodellers use this technique for model aircraft and a similar beneficial effect has been noted on fighters using wing tip tanks.

4.3. Ground effect

At the trailing edge of the wing the vortices that give rise to the induced drag, have a downward component which is termed the “downwash” of the wing. The downwash is illustrated by Figure 32. Only at rear of the trailing edge do the full vortex tubes develop. The downwash can be correlated to the lift distribution being greatest at the wing tips where there is most loss of lift.

Near the ground there is an interference effect on the wing, the down-wash is reflected from the ground as an “upwash” which combats and thereby reduces the formation of the wing trailing vortices. In other words there is a ground effect that reduces the induced drag.

Variation of induced drag near the ground is given by Figure 33 as a plot of *K* against the ratio wing height above ground/wing span. Since man-powered aircraft fly very close to the ground this effect is appreciable. In fact it would be true to say that man-powered flight would be virtually impossible without the help of the ground effect.

Before the last war this effect was investigated because at least one fatal crash of a heavily loaded plane had been attributed to it. This was due to the particular plane just having enough power to take off since the induced drag was reduced near the ground. It had insufficient power to overcome normal induced drag so could not gain altitude and eventually crashed into a near ground obstacle.

4.4. Biplanes

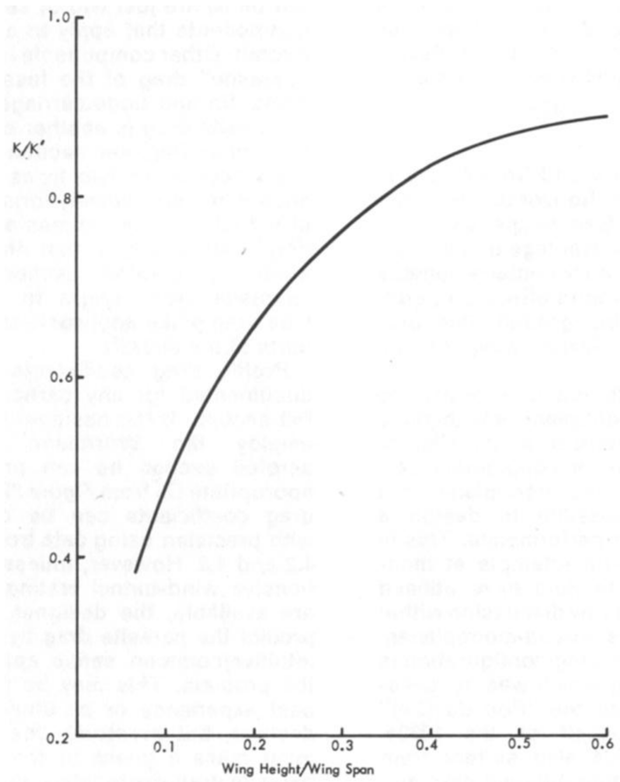
At first sight a biplane configuration appears to be very advantageous for man-powered aircraft. It is possible to gain twice the wing area for the same wing span as a monoplane or alternatively reduce the wing span to give the same wing area as the monoplane. Furthermore, a biplane having its two wings braced together has a stronger construction, hence its wide usage during the early days of aviation.

Unfortunately these advantages are off-set by two major aerodynamic factors, loss of lift and high induced drag!

With two wings set one above the other the air flow under the top wing interferes with the low pressure region over the bottom wing and thereby reduces the lift. This loss of lift can be reduced by staggering the wings but at the expense of more complex construction. The following correction factors are for an unstaggered biplane compared with a monoplane of the same wing area and lift coefficient:

Gap/Chord Ratio	*Correction Factor*
0·5	0·73
1·0	0·86
1·5	0·92

From this table the disadvantages of a small gap become apparent, if only the loss of lift is considered. The other aerodynamic disadvantage of a biplane is high induced drag.



Variation of induced drag with ground effect

Figure 33

Instead of two wing tips with associated vortex formation, as with the monoplane, the biplane has four wing tips so giving approximately twice the induced drag for the same wing span and chord. In practice the induced drag will not be quite as bad as that since the downwash from the top wing will be deflected by the bottom wing, just as the downwash from a monoplane is deflected by the ground. Hence the induced drag of the top wing is decreased in a similar manner to the monoplane due to ground effect and the total induced drag coefficient of a biplane having two wings of equal span is given by:

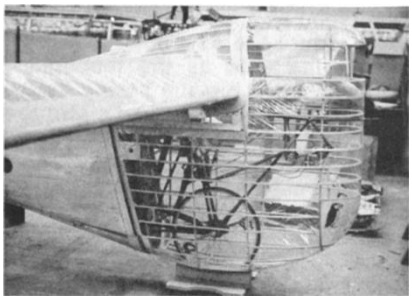
$$\frac{(1+K){C_L}^2}{\pi A}$$

where K can be found from Figure 33 except that the horizontal axis can now be read as Gap/wing span.

One other disadvantage of a biplane is that whereas a monoplane benefits greatly due to ground effect to operating close the ground, this only applies to the lower wing of the biplane

It is an interesting exercise to compare the monoplane and biplane and it will be found to be possible to design a biplane of comparable performance to the monoplane but certainly not possible to design a biplane of better performance. This is why all successful attempts at man-powered flight to date have utilised monoplanes and why discussion within this book centres around monoplanes.

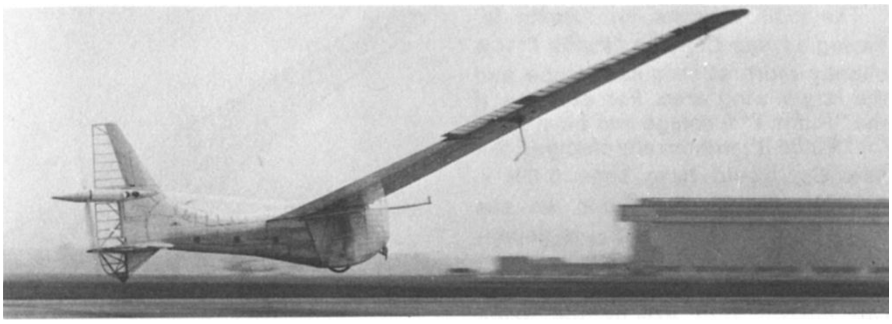
One other twin wing configuration is the tandem wing which was successfully employed on the “Pou du Ciel” (flying flea) aircraft of the 1930s. Unfortunately this also suffers from the problem of high induced drag and so has little practical relevance to man-powered flight.



4.5. Aircraft drag

The profile and induced drag of the wing have already been discussed, but these are just two of several drag components that apply to a complete aircraft. Other components include the “parasite” drag of the fuselage, tailplane, fin and undercarriage.

Parasite drag is another expression for profile drag, see section 3.2, since it also combines two types of resistance to motion; namely form drag and skin friction. The expression “profile drag” refers only to that drag appropriate to aerofoil sections whilst “parasite drag” refers to the same type drag when applicable to all other parts of the aircraft.



The wing to fuselage fairings and side profile of the nose were changes in the Puffin II, seen above; with the Puffin MK I airborne at Hatfield.

Table 3

Aircraft	C_D	C_{D_f}	Wing area (ft^2)
“Puffin I”	0·009	0·0040	330
“Puffin II”	0·0092	0·0031	390
Southampton	0·0083	0·0043	300

Profile drag coefficients are well documented for any particular aerofoil section. If the designer wishes to employ the Wortmann FX-63137 aerofoil section he can predict the appropriate C_D from Figure 27. Induced drag coefficients can be calculated with precision using data from section 4.2 and 4.3. However, unless comprehensive wind-tunnel testing facilities are available, the designer can only predict the parasite drag by using an intuitive/common sense approach to the problem. This may be helped by past experience or by studying past designs, but eventually the designer must make a guess at the expected parasite drag. Fortunately, the parasite drag is generally only a very small proportion of the total drag when compared to the profile and induced drags that any slight inaccuracies in its estimation make little difference to the complete aircraft drag figures. The Haessler-Villinger aircraft shown in Figure 3 is a typical example of this. By comparison with present day man-powered aircraft it is not considered a particularly “clean” design, yet it had the following drag breakdown for free air conditions:

Fuselage 8%

Pylon 2%

Parasite drag 18% { Tail surfaces 5%

Bracing wires 3%

Profile drag 34%

Induced drag 48%

For performance calculations the parasite drag is generally related to the total wing area as a parasite drag coefficient C_{D_f} the subscript *f* referring to the fuselage which is the major component of the parasite drag. The total aircraft drag can then be calculated by an extended version of equation (2):

$$D = \frac{\rho}{2} S V^2 (C_D + C_{D_f} + C_{D_i}) \qquad (5)$$

where D = total aircraft drag (lb)

S = wing area (ft^2)

V = aircraft velocity (ft/sec)

C_D = profile drag coefficient

C_{D_f} = parasite drag coefficient

and C_{D_i} = induced drag coefficient from equation (4a)

Some text-books add the profile and parasite drag coefficients and present the total value as an overall drag coefficient C_{D_o}. This is common practice in aeronautical design work but this convention will not be followed here to avoid any possible confusion.

Values for the parasite drag coefficient are presented in Table 3 for those post-war man-powered aircraft that have flown. These values will provide a basis for estimating the C_{D_f} of any proposed design and the success of the aircraft to which they applied gives reassurance regarding their validity.

The main reasons for "Puffin II" having a lower C_{D_f} than "Puffin I" is a slightly more streamlined shape and the larger wing area. For example, if the "Puffin I" fuselage had been used for "Puffin II" without any changes, the new C_{D_f} would have been 0·004 x 330/390 = 0·0033. From this we see that assumed value for C_{D_f} is dependent on wing area.

This becomes obvious if we have two aircraft with exactly the same fuselages and tail surfaces, if both are travelling at the same velocity both will have exactly the same value of parasite drag. Yet if the first aircraft had only half the wing area of the second, C_{D_f} for the first would be twice that for the second simply because of our notation whereby parasite drag =

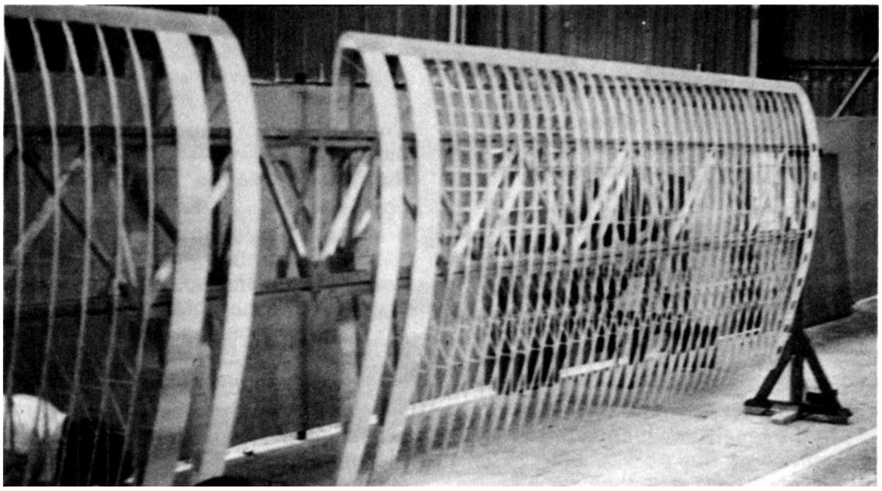
$\frac{\rho}{2} S V^2 C_{D_f}$ (from equation 5)

From previous remarks it will be appreciated that C_{D_f} is not absolutely critical. A 20% error in the estimation of the C_{D_f} will only make some 3 or 4% difference to the assumed total drag of the aircraft. Nevertheless, there is so little spare power when considering man-powered aircraft that the designer must ensure that parasite drag is reduced to a minimum providing that this does not increase weight or structural complexity. This normally means paying close attention to the fuselage shape, and in this respect the following rules are good ones to follow:

(i) The fuselage must be streamlined in at least one direction, to minimise wake formation and the associated form drag;

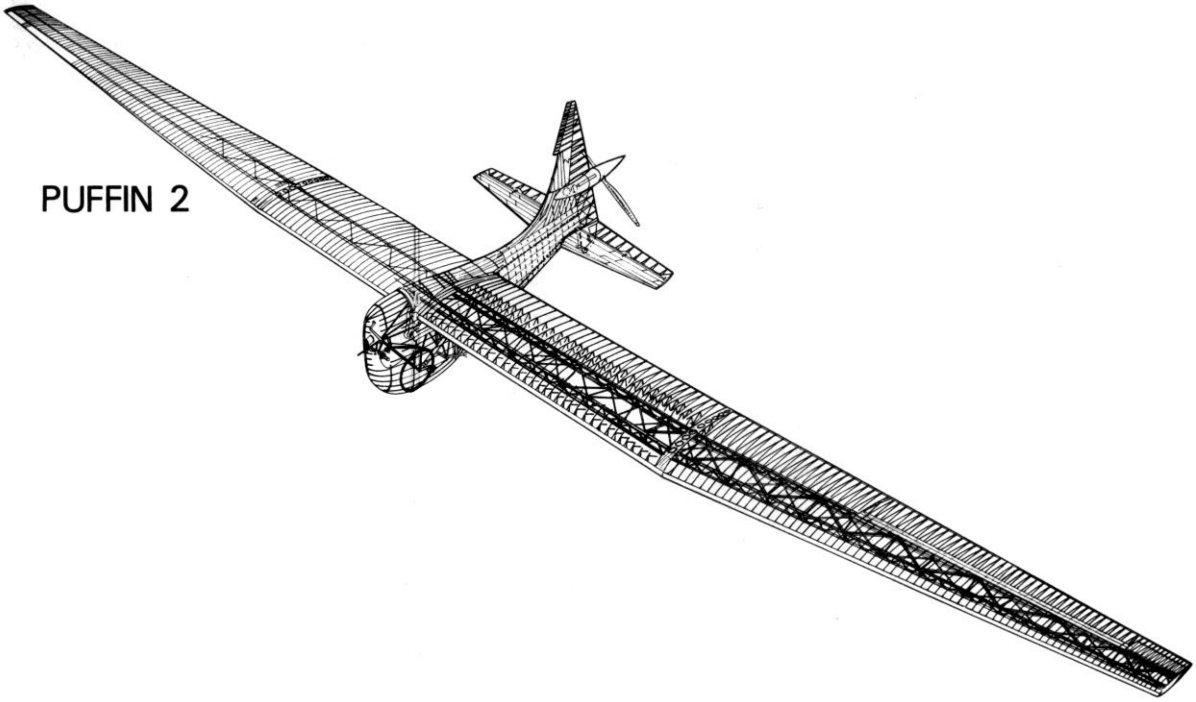
(ii) Streamline the pilot cockpit! It is obviously easier to build a simple open cockpit but all designs of man-powered aircraft except the Malliga machine have covered cockpits to minimise pilot drag. No figures are available to check the reduction in drag resulting from this and it would be interesting to see if any loss of power results to the restriction of the pilots breathing in a covered cockpit; and

(iii) Ensure that most of the fuselage is out of the propeller slipstream since it is at a higher velocity than the general airflow and so generates more drag.



Above, the close rib spacing of the revised centre section on Puffin II, seen prior to assembly on the fuselage. Below, a profile of the Puffin II tail showing the enlarged rudder, and removal of horn balance on the elevators.

Following these rules the Puffin design of fuselage is good and this is borne out by the comparatively low C_{D_f} values. Positioning the propeller at the tail ensures that the fuselage is unaffected by the slipstream and also tends to decrease the size of wake and the associated form drag. However, although aerodynamically ideal this propeller position does have mechanical drive/aircraft control problems which need to be considered when designing an aircraft.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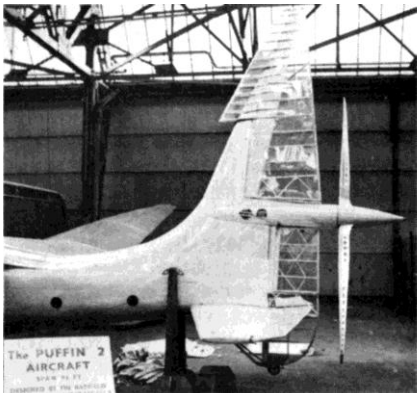

The PUFFIN 2
AIRCRAFT

5. AIRCRAFT PERFORMANCE

THE two previous chapters have introduced the basic aerodynamic parameters concerned first with the choice of aerofoil section and then with a complete aircraft. Only sufficient detail has been provided to enable the reader to appreciate the most relevant aspects of the subject.

However, aerodynamic data only becomes of direct use to aircraft design when it can be utilised to predict the performance of any particular aircraft configuration.

The following sections are presented on the basis that such an aircraft configuration has. been assumed. Namely that the aircraft weight *W,* wing span *l,* wing area *S,* aspect ratio *A* and the aerofoil characteristics C_L and C_D are known.

Now the weight must be supported by the lift so that from equation 1:

$$W = L = C_L \frac{\rho}{2} SV^2$$

hence the aircraft velocity can be predicted

$$V = \sqrt{\frac{W}{C_L \frac{\rho}{2} S}} \qquad (6)$$

Since the proposed aircraft design must have a particular fuselage configuration it will be possible to estimate the parasite drag coefficient, following the discussion in section 4.5. The total aircraft drag can then be predicted by equation 5:

$$D = \frac{\rho}{2} SV^2 (C_D + C_{D_f} + C_{D_i})$$

This new data regarding the proposed aircraft can now be utilised to predict the aircraft performance.

5.1. Steady level flight

Steady level flight, or cruising flight, is the simplest form of aircraft manoeuvre and as such provides a basis for judging whether the proposed aircraft is practical. If for example the power requirements of a proposed man-powered aircraft during cruise are greater than, or near the limit of, that available from the pilot then obviously the design is impractical since insufficient power is available for other necessary manoeuvres such as the take-off and climb to cruising height.

The thrust provided to propel the aircraft must equal the drag so that the power absorbed by the aircraft during steady level flight is:

$$\frac{DV}{550} \; h.p.$$

where *D* is the aircraft drag as predicted by equation 5. To a certain extent this oversimplifies the situation as it ignores any trimming movements of the controls that may be necessary to maintain the aircraft at the correct flying attitude. Any such movements of the controls will incur an extra drag penalty but as it is anticipated that the movements will be very small it can be assumed that the extra trim drag is negligible. This is a very convenient assumption as it is virtually impossible to calculate the trim drag component, nevertheless experience with “Puffin” and “SUMPAC” tends to indicate the validity of the assumption.

The power required to be provided by the pilot will be greater than that required by the aircraft due to the losses in the transmission and the propulsion. Hence, pilot power input can be written as:

$$P_{Cruise} = \frac{DV}{\eta 550} \tag{7}$$

where η is the combined transmission and propulsion efficiency.

Transmission and propulsive efficiencies will be discussed in detail In Chapter 7. Both “Puffin I” and “SUMPAC” were designed on an assumed η of 0·8 and so little development has taken place over the intervening period that this value is still a good basis for man-powered aircraft design.

5.1.2. Example

Find the cruising power to be provided by the pilot of a man-powered aircraft of 70 ft wing span and having a total weight of 245 lb. The aircraft employs the Wortman FX-63137 aerofoil section (as employed for “Puffin II”) and has a rectangular wing planform with an aspect ratio of 15. Assume that the aircraft flies at a steady clear height of 5 ft during cruising and that in this position the wing is a mean height of 10 ft above the ground. Finally the aircraft has a similar fuselage form to “SUMPAC” (see Figure 5).

Solving such a problem requires that the designer decide what information he already has and therefore what information he needs to find or guess.

Inspection of equations 5, 6 and 7 indicates that we know :

W = 245 lb (given) η = 0·8 (assumed) and we need to know:

C_L, S, V, C_D, C_{D_f} , and C_{D_i}

The given aerofoil section is the Wortmann FX-63137 for which the design CL = 1·15 (see Table 2) was used for “Puffin II”. This value will be used for the present example.

$$Wing\ Chord = \frac{Wingspan}{Aspect\ ratio} = \frac{70}{15} = 4.66\ ft$$

∴ S=70 x 4·66=327sq.ft Velocity V may now be calculated from equation 6:

$$V = \sqrt{\frac{W}{C_L \frac{\rho}{2} S}} = \sqrt{\frac{245}{1 \cdot 15 \frac{0 \cdot 0024}{2} 327}}$$

= 23·3 ft/sec

The profile drag coefficient C_D for the aerofoil section can be found from the curves in Figure 27.

Checking the Reynolds number,

Re= 6250. C. V = 6250.4·66.23·3 = 680,000.

∴ from Figure 27: CD= 0·0086

The parasite drag coefficient C_{D_f} for the fuselage can be predicted from that for “SUMPAC”, see Table 3:

C_{D_f} = 0·0043 x 300/327 = 0·0040 The induced drag coefficient C_{D_i} can be found from equation 4a:

$$C_{D_i} = \frac{K'{C_L}^2}{\pi A} = \frac{1 \cdot 1(1 \cdot 15)^2}{\pi 15} = 0 \cdot 0308$$

This will be reduced by ground effect. For a wing height of 10 ft and a span of 70 ft, K = O·57 (see Figure 32).

∴ C_{D_i} = 0·0308 x 0·57 = 0·0176 ∴ the total drag of the aircraft

$$= D = \frac{\rho}{2} S V^2 \left(C_D + C_{D_f} + C_{D_i}\right)$$

$$= \frac{0 \cdot 0024}{2} 327(23 \cdot 3)^2 \, [0 \cdot 0086 + 0 \cdot 0040 + 0 \cdot 0176] = 6 \cdot 42 \, lb$$

The cruising power

$$= \frac{DV}{\eta 550} = \frac{6 \cdot 42.23 \cdot 3}{0 \cdot 8.550}$$

= 0·34 h.p.

5.1.3. This example has been explained in full so that the working may be followed with the minimum of reference to the text. Judging the calculated power requirement in comparison with the output values of Figure 14, it should be well within the capabilities of an ordinary fit cyclist and so such an aircraft design is considered to be feasible.

The lift/drag ratio at cruise conditions would be 245/6·42 i.e. L/D = 35 which compares well with those for modern high performance sailplanes and those man-powered aircraft that have actually flown.

Breakdown of the drag is:

Parasite drag	14%
Profile drag	29%
Induced drag	57%

These values provide an interesting comparison with the equivalent values for the Haessler-Villinger “Mufli” quoted in section 4·5.

5.2. Climbing flight

5.2.1. During a climb part of the aircraft weight is acting against the aircraft in the direction of the drag. This component of the weight together with the drag must equal the thrust required, see Figure 34. If the angle of the climb is θ° then

$T_{(climb)} = D + W \sin(\theta)$

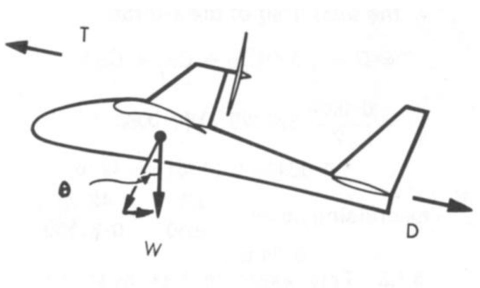


Figure 34

Since sin θ = θ (radians) for very small angles the power absorbed in a climb is given by:

$$P_{(Climb)} = \frac{V}{\eta 550}\left(D + \frac{L}{D}\theta\right)\ h.p. \qquad (8)$$

Or, as the lift must equal the weight, this can be expressed in the form:

$$P_{(climb)} = \frac{VD}{\eta 550}\left(1 + \frac{L}{D}\theta\right)\ h.p. \qquad (8a)$$

As most readers are no doubt more familiar with angles expressed in degrees rather than those expressed in radians, equation 8a can be further modified to much more convenient form:

$$P_{(Climb)} = P_{(Cruise)}\left(1 + \frac{L\theta°}{D\ 57{\cdot}3}\right) \qquad (9)$$

where θ° = climbing angle measured in degrees.

5.2.2. Example

Taking the aircraft design considered in section 5.1.2, find the power to be provided by the pilot when the aircraft climbs at an angle of 1°.

$P_{(cruise)}$ =0·34 h.p. and L/D=38 From equation 9:

$$P_{(Climb)} = 0 \cdot 34\left(1 + \frac{38}{57 \cdot 3}.1°\right) = 0 \cdot 566\ h.p.$$

A climb of 1° represents a slope of 1 in 57.

To climb to 5 ft clear height requires that the aircraft travels 57 x 5 = 255 ft.

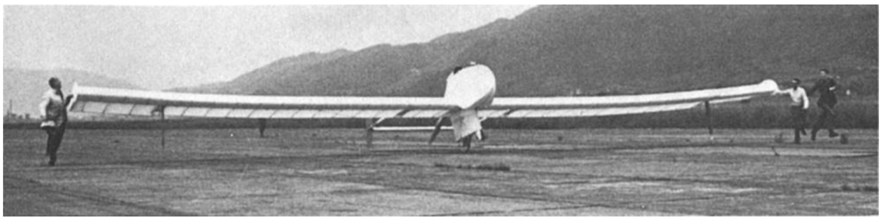
The time taken to climb to 5 ft would

be 285/V = $^{285}/_{23.3}$ = 12·2 seconds.

The power requirement of 0·566 h.p. for 12·2 seconds would appear to be within the capabilities of an ordinary fit cyclist, judging by the values presented in Figure 14.

5.3. Take-Off

5.3.1. In reality an aircraft takes-off, climbs to altitude then goes into steady level cruising flight. These manoeuvres have been discussed in the reverse order within this chapter so that the simplest forms of flight were discussed first.



First take-off by the Malliga aircraft in July 1967. The flight covered 150 yards at a height of 1-2 feet.

During take-off the designer not only has to consider the aerodynamic drag but also the rolling resistance of the undercarriage. At the start of the take-off run there will only be rolling resistance, as drag is a function of V^2 and this will be zero at this point. At the end of the take-off run all the weight of the aircraft will be supported by the lift, none of the weight will be resting on the undercarriage so that the rolling resistance will be zero and there will only be drag to overcome.

Rolling resistance is a function of the weight acting on the undercarriage and the coefficient of friction μ between the surface and the undercarriage. Typical values of μ are as follows:

Runway, concrete or tarmac	$\mu=0{\cdot}02$
Hard turf	$\mu=0{\cdot}04$
Average field, short grass	$\mu=0{\cdot}05$
Long grass	$\mu=0{\cdot}10$
Soft ground	$\mu=0{\cdot}10$ to $0{\cdot}30$

To minimise take-off power it is important that rolling resistance and therefore μ is a minimum. Needless to say, all man-powered aircraft that have taken-off under man-power have done so from well-maintained runways.

Rolling resistance obviously varies during the take-off due to the amount of aircraft weight that is supported by the lift varying with velocity.

Rolling resistance= $R = \mu(W-L)$ (10)

The power required for take-off is provided partly through the undercarriage. At the beginning of the run all the power is transmitted through the driving wheel whilst at the end of the take-off run all the power is transmitted through the propeller. The combined thrust from the wheel and propeller must be *greater* than the combined drag and rolling resistance at any particular point during the take-off run. This excess thrust is required to accelerate the aircraft along the runway otherwise the necessary speed for take-off will never be attained.

The excess thrust

$= T - (D + R)$

$$=T-[D+\mu(W-L)] \qquad (11)$$

The acceleration a at any particular point during the take-off run is given by:

$$a = \frac{g(T-[D+\mu(W-L)])}{W} \qquad (12)$$

where T = thrust provided by the drive wheel and propeller, lb;

W = aircraft weight, lb;

D = aircraft drag at the instance considered, lb;

L = aircraft lift at the instance considered, lb;

μ = coefficient of friction;

a= aircraft acceleration at the instance considered, ft/sec^2;

g = gravitational constant = 32·2 ft/sec^2.

Since the actual power provided by the pilot is a function of the thrust x velocity, the actual power required to move the aircraft will be low during the early part of the run due to the low velocities. It follows from this that the pilot can provide the greatest amount of excess power during the early part of the run so that accelerations will be greatest during this section.

Provided that the rolling resistance is not high the power requirements for take-off need not be greater than that for cruising flight. Aircraft drag will be lower than at cruising altitude due to the closer proximity to the ground with the associated reduction in induced drag.

5.3.2. Example

Take the aircraft described in section 5.1.2 and check the feasibility of take-off with the pilot power input being constant and equal to the aircraft cruising power of 0·34 h.p. Assume the drive and transmission efficiency as η = O·8. Furthermore, assume the take-off run to be along a runway with μ= 0·02.

There is no direct way of predicting the aircraft behaviour during take-off. The most convenient way is to take several points along the take-off run and check conditions at those points so that a graph of accelerations can be drawn. Cruising speed is 23·3 ft/sec so that a take-off speed of 24 ft/sec would be convenient to allow a small margin to start the aircraft into its initial climb. The take-off run can then be divided on a velocity basis, with the arbitrary points under consideration being 0, 4, 8, 12, 16, 20 and 24ft/sec respectively. At 0 ft/sec:

The power absorbed by the aircraft will be zero so that all 0·34 h.p. can be used for acceleration. This acceleration cannot be determined accurately as the “static” coefficient of friction is much greater than that for rolling, but nevertheless will be of a high order.

At4ft/sec:

$$D = \frac{\rho}{2} SV^2 \left(C_D + C_{D_f} + C_{D_i}\right)$$

from the previous example we know that S = 327 sq. ft

C_D= 0·0086

$$C_{D_f} = 0 \cdot 0040$$

The induced drag will be less due to the closer proximity to the ground. From Figure 33 K = 0·4

$$\therefore\ C_{D_i} = 0 \cdot 0308\ \times 0 \cdot 4 = 0 \cdot 0123$$

$$\therefore D = \frac{0 \cdot 0024}{2} 327(4)^2[0 \cdot 0086 + 0 \cdot 0040 + 0 \cdot 0123] = 0 \cdot 16\ lb$$

$$L = \frac{0 \cdot 0024}{2}.327.1 \cdot 15.(4)^2 = 7 \cdot 2\ lb$$

R = 0·02(245 - 7·2) = 4·76 lb

$$Thrust\ provided = T = \frac{P\eta 550}{V} = \frac{0 \cdot 34.0 \cdot 8.550}{4} = 37.4lb$$

$$\therefore Acceleration = a = \frac{32 \cdot 2\left(37 \cdot 4 - (0 \cdot 16 + 4 \cdot 76)\right)}{245} = \mathbf{4 \cdot 3}\ ft/sec^2$$

At 8 ft/sec:

$$D = \frac{0 \cdot 0024}{2}.327(8)^2[0 \cdot 0086 + 0 \cdot 0040 + 0 \cdot 0123] = 0.64lb$$

$$L = \frac{0 \cdot 0024}{2}.327.1 \cdot 15(8)^2 = 29lb$$

$$R = 0 \cdot 02(245 - 29) = 4.36lb$$

$$T = \frac{0 \cdot 34.0 \cdot 8.550}{8} = 18.7lb$$

$$a = \frac{32 \cdot 2\left(18 \cdot 7 - (0 \cdot 64 + 4 \cdot 36)\right)}{245}$$

= **1·8** ft/sec^2

Similar calculations can be repeated for velocities of 12, 16, 20 and 24 ft/sec.

At 12ft/sec:

D = 1·44 lb, L = 65·2 lb, R = 3·6 lb, T = 12·4 lb

∴ *a*= **0·97** ft/sec^2

At 16ft/sec:

D = 2·56 lb, L = 116 lb, R = 2·58 lb, T = 9·4 lb

∴ *a*= **0·56** ft/sec^2

At 20 ft/sec:

D = 4 lb, *L* = 181 lb, *R* = 1·28 lb, T=7·5 lb

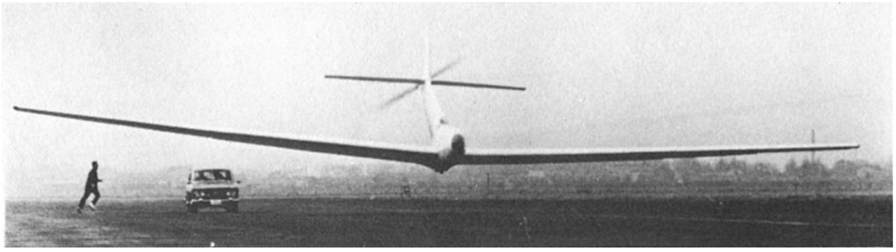
∴ *a*= 0·29ft/sec^2

At 24 ft/sec:

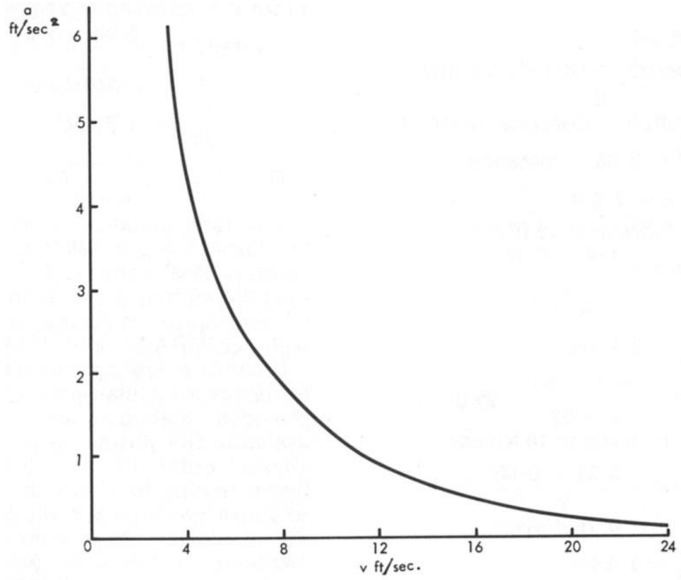
D = 5·76 lb *L* = 245 lb *R* = 0, T = 6·2 lb

T = 6·21b

∴ *a*= 0·2ft/sec^2



A plot of the variation in aircraft acceleration during the take-off run is given in Figure 35. However, acceleration is of little interest in itself but it enables the designer to find the length of the take-off run and the time taken. Unfortunately there are no equations for these but provided that the answers do not need to be absolutely accurate, a simple graphical solution can be used.



Variation of acceleration with velocity during take-off

Figure 35

From V = 0 to V = 4 ft/sec:

The acceleration is very high so assume that the time and distance taken to accelerate to 4 ft/sec are very short.

From V = 4 ft/sec to 8 ft/sec:

a= 4·3 ft/sec^2 at V = 4 ft/sec

a = 1·8 ft/sec^2 at V = 8 ft/sec

$$\therefore average\ a = \frac{4 \cdot 3 + 1 \cdot 8}{2}$$

= 3· 05 ft/sec^2

Change in velocity = acceleration × time taken

4 ft/sec= 3·05 ft/sec^2 x *t* sec

∴ t=1·31 secs

$$\frac{(Final\ velocity)^2 - (Initial\ velocity)^2}{2}$$

= acceleration x distance travelled

= 3·05 x distance

∴ Distance=**7·9**ft

From V = 8 ft/sec to 12 ft/sec:

$$Average\ a = \frac{1 \cdot 8 + 0 \cdot 97}{2}$$

= 1·38 ft/sec^2

$$t = \frac{4}{1 \cdot 38} = \mathbf{2 \cdot 9}\ sec$$

$$Distance = \frac{(12^2 - 8^2)}{2.1 \cdot 38} = \mathbf{29} ft$$

From V = 12 ft/sec to 16 ft/sec:

$$Average\ a = \frac{0 \cdot 97 + 0 \cdot 56}{2}$$

= 0·76 ft/sec^2

$$t = \frac{4}{0 \cdot 76} = \mathbf{5.3}\ sec$$

$$Distance = \frac{(16^2 - 12^2)}{2.0 \cdot 76} = \mathbf{74} ft$$

Take off by Linnet II in 1967. Pilot position had been changed from that of Linnet I. Tailplane is modified to an inverted section at this stage.

From V = 16 ft/sec to 20 ft/sec:

$$Average\ a = \frac{0 \cdot 56 - 0 \cdot 29}{2}$$

=0·42 ft/sec^2

$$t = \frac{4}{0 \cdot 42} = \mathbf{9 \cdot 5}\ sec$$

$$Distance = \frac{(20^2 - 16^2)}{2.0 \cdot 42} = \mathbf{171}\ ft$$

From V = 20 ft/sec to 24 ft/sec:

$$Average\ a = \frac{0 \cdot 29 - 0 \cdot 2}{2}$$

= 0·24 ft/sec^2

$$t = \frac{4}{0 \cdot 24} = \mathbf{16.7}\, sec$$

$$Distance = \frac{(24^2 - 20^2)}{2.0 \cdot 24} = \mathbf{367}\, ft$$

The total distance travelled during the take-off run is 649 ft and the time taken is **35·8** seconds. The values are realistic as they are of a similar order of magnitude to those experienced with "SUMPAC", and "Puffin I".

5.3.3. Conclusion

Considering the take-off performance of a man-powered aircraft, provided that a good run-way is available the power required is of a similar order to that for cruising flight. Hence, to check the feasibility of a man-powered aircraft design, it is not necessary to perform the calculations outlined in the previous section but simply to check the horsepower required for steady level flight. This greatly eases the designers' task as the calculations are comparatively straight forward and are outlined in some detail in section 5.1.2.

It is only necessary to study the take-off run in detail if the designer needs precise information regarding the length of run and the time taken. This would be particularly useful if the power requirements would be sufficiently high as to cause doubts regarding the anticipated success of the design. Also this information would be useful if the take-off surface had a limited length.

Judging from the list of surface coefficients it is obviously inadvisable to attempt take-offs from fields or grass surfaces due to the increased power requirement. Taking the example described in section 5.3.2, to achieve the same length of take-off run from a field with $\mu = 0·05$ (short grass) the horse-power absorbed would be 0·45 instead of 0·34, an increase of over 30%.

Under normal circumstances, i.e. good run-way surface of adequate size, the take-off is not a major difficulty with a man-powered aircraft. A more serious problem is the climb up to the cruising altitude after take-off. The example in section 5.3.2 indicated over 60% increase in the power absorbed during the climb compared to cruising conditions (or take-off).

This problem has led to the suggestion of gaining a higher speed on the ground than is necessary for take-off and using the excess speed to zoom to necessary altitude. The horse-power absorbed at the higher take-off speed would be greater than that for normal take-off, but not as great as that absorbed in a conventional climb. For example an increase of some 4 ft/sec in the take-off speed would, for the aircraft considered in section 5.3.2, require O·45 h.p. instead of O·34 h.p. However, this excess speed would enable the aircraft to zoom to 5 ft altitude. This technique has been employed with the "Puffin II" aircraft but it cannot be attempted until the pilot is thoroughly familiar with his aircraft and also has some instrument with which to judge aircraft speed.

Take off by Linnet III showing the increased dihedral, inverted section tail at negative position and wing tip assistants holding skids.

5.4. Turns

Turns are the most complex manoeuvres that have been attempted and are likely to be attempted by manpowered aircraft within the foreseeable future. Any more complex manoeuvre requires several hundred feet of altitude to be attempted safely, this order of altitude being incomparable with the present 5-10ft visualised for man-powered aircraft.

During turns the outer wing tip travels a greater distance than the inner one and so the velocity of the outer wing is greater than that of the inner. Even if there is no lateral control provided the aircraft will automatically bank because of the differences in wing lift due to the velocity differences. If lateral control is provided by means of ailerons or spoilers this bank will be provided by the pilot at the start of a turn.

There are four problems to consider during turns:

(i) the amount of bank required for a given turn;

(ii) the loss of lift associated with the banked wings;

(iii) the variations of lift and drag due to the differences of velocity of the outer and inner wings; and

(iv) the differences in induced drag due to the two wing tips being at different heights from the ground.

Taking the first problem, bank is necessary because with any object turning a corner there is a force tending to fling it outward. This force is generally termed the “centrifugal” force and is equal to

$$\frac{WV^2}{gr}$$

where *W* is the weight of the aircraft (lb)

V is the velocity of the aircraft (ft/sec)

g is gravitational constant 32·2 ft/sec^2

and r is the turning radius of the aircraft (ft)

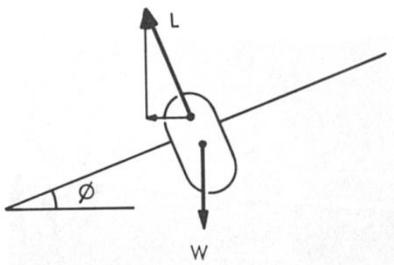


Figure 36

The “centrifugal” force must be combated by some other force otherwise the aircraft would continue to slide outwards in a turn, and the other force is the horizontal component of the lift provided by the bank of the aircraft and is illustrated in Figure 36. It follows

$$L\sin\psi = \frac{WV^2}{gr}$$

since L must equal *W* and sin $\psi \approx \psi$ (radians) for small angles, then

$$\frac{\psi^\circ}{57.3} = \frac{V^2}{gr} \tag{13}$$

The permissible angle of bank must be small for man-powered aircraft due to the close proximity to the ground, hence the assumption that sin $\psi = \psi$ is valid.

Since the wing is banked the whole of the lift is not acting vertically, only that vertical component L cos ψ. The total lift must be increased therefore so that $L \cos \psi = W$ and this increased lift can only be obtained by increasing the velocity V with a resulting rise in the power absorbed. Provided the angle of bank is small cos $\psi \approx 1$ and the resulting increases in velocity and power are negligible. Fortunately this is the case for man-powered aircraft.

As the aircraft turns the corner the outer wing is travelling at a higher velocity than the inner wing. For example an aircraft travelling round a corner with a radius four times that of the wing span, at a mean velocity of V ft/sec would have the outer wing tip travelling at a velocity 11% greater than V and the inner wing tip at 11% less than V. This causes a lift variation along the wing. If in level flight a uniform lift distribution is assumed, the lift distribution changes to that shown in Figure 37 whilst going round such a corner. The new lift distribution is approximately linear and what is lost on the inner wing is gained on the outer wing so that total lift remains approximately the same and no extra power is absorbed.

However, since the lift varies along the wing so will the profile drag. There will be greater profile drag on the outer wing compared to the inner. Furthermore, the induced drag will be greater on the outer wing than on the inner wing because the banked wing has the outer wing tip further from the ground. This combined increase in drag acting on the outer wing tends to swing the aircraft out of the turn unless the pilot provides sufficient force at the fin to counteract the increase drag.

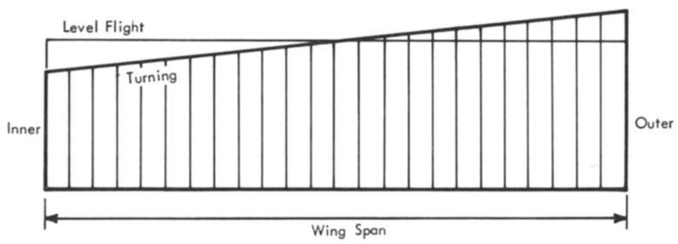
The problem of turns with man-powered aircraft is one of control rather than performance, since any required increase in power is negligible due to the small angles of bank. This small angle of bank poses another problem of control for the pilot since any errors could cause the lower wing tip to touch the ground. To judge the angle of bank involved consider the aircraft discussed in section 5.1.2.

Wing span = 70 ft, mean wing height= 10 ft, V = 23·3 ft/sec.

Supposing the aircraft goes round a turn of 280 ft radius, i.e. radius = 4 x wing span, the required angle of bank ψ can be found from equation 13

$$\psi = \frac{57 \cdot 3V^2}{gr} = \frac{57 \cdot 3(23.3)^2}{32 \cdot 2\ 280} = 3\,{}^1\!/_2{}^\circ$$

This means that the height of the inner wing tip is 8 ft whilst that of the outer wing tip is 12 ft.



Variation of lift distribution during a turn *Figure 37*

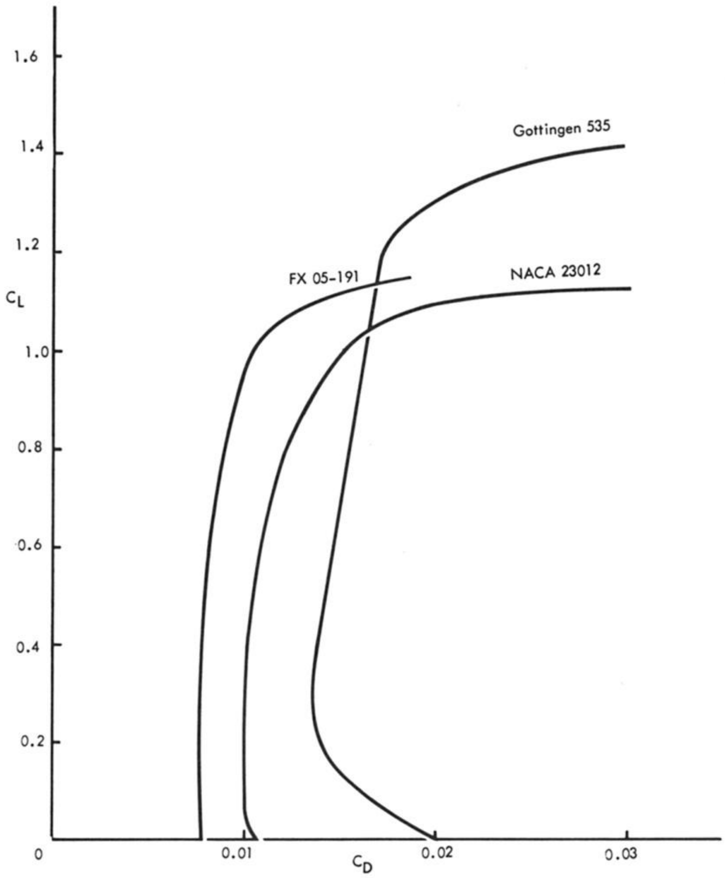
On this basis it would be possible to fly the aircraft around a 140 ft radius turn since the inner wing tip would still be 6 ft above the ground. However to drop the inner wing tip any lower would be dangerous since any sudden gust of wind or a change of wind direction whilst going round the turn, could cause the wing tip to move into contact with the ground.

Even with a 7° angle of bank, as would be the case for the 140 ft radius turn, the assumptions that cos $\psi \approx 1$ and sin $\psi \approx \psi$ (radius) are still valid as cos 7° = 0·993; sin 7° = 0·122 and 7° = 0·122 radians. However, the only designs in which such large angles of bank would be attempted would be those with a high wing configuration. If a low wing is employed to take advantage of the ground effect in reducing the induced drag then the angle of bank must be reduced and the pilots will need to control the aircraft more carefully.

5.5. Man-powered aircraft performance

Summarising the findings of the previous sections, the only performance problems that the designer need be concerned with are those of the climb and the cruising flight.

Fortunately the more complex problems of take-off and turning do not represent a performance problem. This has been clearly indicated by the examples presented in sections 5.3.2 and 5.4.



Lift-drag curves for three aerofoil sections

Figure 38

The designer can make a rapid and realistic check on the feasibility of the proposed design simply by calculating the cruising power, since both take-off and turns require power levels of a similar order. Climbing power is proportional to the cruising power, as indicated by equation 9, whilst their relative magnitudes can be judged from the example in section 5.2.2. In the extreme case when the pilot can produce sufficient power for steady level flight, but has only a small margin for climb, the design need not be considered impractical. This can only really be judged on the required purpose for which the aircraft has been designed, but the climb can either be performed with a smaller climbing angle or by zooming from the take-off using a loss in speed to gain height. Both these could be achieved by only using an extra small proportion of the cruising power, but the gain in height for such cases would only be comparatively small.

6. DESIGN STUDIES

A LIST of man-powered aircraft that have flown is given in Table 1, section 1.3. It is proposed to consider a few of these aircraft designs in greater detail from the point of view of both theoretical performance and that achieved in practice.

6.1. Haessler-Villinger Aircraft

Design data from Table 1 is:

Wing area	= 104 sq. Ft
Aspect ratio	= 18·8
Flying weight	= 246 lb

Haessler[9] presents further information:

Aerofoil section	= Gottingen 535
Sinking speed	= 17 ft/sec
Glide angle	= 1:24
Propulsive and Drive efficiency	= 82%

The forward velocity of the aircraft can be found if the sinking speed and glide angle are known:

V = 24 x 1·7 = 40·8ft/sec

From the discussion in the introduction to Chapter 3, the glide angle is related to the L/D ratio.

∴ L/D = 24

$$Total\ aircraft\ drag = D = \frac{245}{24}$$

= 10·25 lb

Power absorbed for steady level flight can be found by equation 7:

$$P = \frac{DV}{\eta 550} = \frac{10\cdot 25\ \times 40\cdot 8}{0\cdot 82\ \times 550} = 0\cdot 93\ h.p.$$

Although the longest flight recorded was 790 yards this included a short climb from a rubber bungee launch and then a final shallow glide at the end of the powered run. The length of the actual powered flight was 2000 ft, this being at a constant altitude of 10 ft. Time for this powered flight was quoted as 1 minute 12 sec and is presumably longer than the theoretical 49 seconds for such a flight due to a force 2 head wind.

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9 Man-powered flight in 1935-37 and today, H. Haessler, *Canadian Aeronautical Journal*, March 1961.

This power-duration value of 0·93 h.p. for 72 seconds is greater than the performance of a champion athlete (see Figure 14) and so is rather suspect. More so when it is considered that the pilot had to concentrate on controlling the aircraft whilst also providing the power.

Checking this power we can calculate the theoretical performance by assuming V = 40·8ft/sec. The validity of this assumption can be checked from the final calculated performance.

$$C_L = \frac{W}{\frac{\rho}{2}V^2S} = \frac{245}{0\cdot0012(40\cdot8)^2104} = 1\cdot18$$

From the lift-drag polar curve for the Gottingen 535 aerofoil section presented in Figure 38, C_D = 0·017.

Parasite drag coefficient is assumed as 0·009 from information presented by Haessler.

Induced drag coefficient =

$$\frac{K'C_L{}^2}{\pi A} = \frac{1\cdot1(1\cdot18)^2}{18\cdot8} = 0\cdot024$$

K' is equated to 1·1 since the wing planform is approximately rectangular.

$$\therefore Drag = \left(\frac{\rho}{2}SV^2(C_D + C_{D_f} + C_{D_i}\right)$$

$= 0\cdot0012.104(40\cdot8)^2(0\cdot017 + 0\cdot009 + 0\cdot0024)$

= 10·4 lb

This agrees well with the value of 10·25 lb presented above, but this value is for free air conditions. The ground effect has not been allowed for when calculating the induced drag coefficient.

For 10 ft altitude the new induced drag coefficient, from Figure 33, becomes:

0·75 x 0·024 = 0·018

∴ the new total drag value= 9·16 lb

∴ Power absorbed at 10 ft altitude =

$$\frac{9\cdot16 \times 40\cdot8}{0\cdot82 \times 550} = 0\cdot83\ h.p.$$

Hence the new maximum power duration value for the Haessler-Villinger aircraft of 0·83 h.p. for 72 seconds is plotted as point 1 on Figure 39 in which the earlier power curves of Wilkie (Figure 14) are plotted on a linear scale. The value is equivalent to that produced by a champion athlete. Neverthless, there is no further doubt as to the accuracy of this value following the above check. Furthermore it does not represent an out of the ordinary performance value for the Haessler-Villinger aircraft since over 15 flights were recorded with durations of over 1 minute.

6.2. Bossi-Bonomi Aircraft

Design data from Table 1 is:

Wing area = 230 sq.ft Aspect ratio= 13·4 Flying weight= 358 lb

Bossi[10] presents further information:

[10] A man has flown by his own power in 1937, E. Bossi, *Canadian Aeronautical Journal*, December 1960.

Aerofoil section-N.A.C.A. 23012 Speed-24 m.p.h. (37 ft/sec)

Following the discussion in Chapter 1 the most pertinent question regarding the Bossi-Bonomi performance is whether the machine could have taken-off under man-power alone. Bossi alleges that on one flight the aircraft took off under its own power and flew 300 ft before landing. This has been denied by other people connected with the project. It is therefore proposed to check the feasibility of such a feat through a theoretical performance study.

$$C_L = \frac{W}{\frac{\rho}{2}V^2 S} = \frac{358}{0 \cdot 0012(37)^2 230} = 0 \cdot 95$$

From the lift-drag polar curve for the N.A.C.A. 23012 aerofoil section presented in Figure 38, C_D= 0·0136.

Since the Bossi-Bonomi fuselage is a particularly clean design it is assumed to be equivalent to that for the "Puffin II" fuselage.

$$C_{D_f} = 0 \cdot 0031 \times \frac{390}{230} = 0 \cdot 0053$$

, allowing for differences in wing area.

Induced drag coefficient=

$$\frac{K' {C_L}^2}{\pi A} = \frac{1(0 \cdot 95)^2}{\pi \; 13 \cdot 4} = 0 \cdot 0214$$

K' is equated to 1 since the wing planform is approximately elliptical.

During take-off the wing height is 4 ft and the induced drag coefficient is reduced by ground effect to:

$$C_{D_i} = 0 \cdot 4 \times 0 \cdot 0214 = 0 \cdot 0083$$

$$\therefore Drag = \frac{\rho}{2} S V^2 \left(C_D + C_{D_f} + C_{D_i} \right)$$

= 0·0012 230 $(37)^2$ (0·0136 + 0·0053 + 0·0083)

= 10·7 lb

Propulsive and drive efficiency for the Bossi-Bonomi aircraft is quoted as 50% by Haessler. Unfortunately Bossi does not quote a value. However, for the take-off run the pedals were coupled by a single chain drive to the wheel so that for this condition drive efficiency would be of the order of 80%.

∴ Power required just at the point of take-off

$$= \frac{10 \cdot 7.37}{0 \cdot 8.550} = 0 \cdot 9 \; h.p.$$

From this value it would certainly appear feasible for a man to have produced this order of power output for sufficient time to have taken off.

Checking this power we can use the theoretical procedure outlined in section 5.3.2. Assume that the pilot delivers 1·0 h.p. during the take-off run then duration of the run along the ground can be calculated. The values presented below gives a summary of the calculations.

Velocity ft/sec	*Acceleration* ft/sec	*Time* seconds
7	5	
13	2·3	1·6
19	1·3	3·3
25	0·8	5·7
31	0·4	10·0
37	0·1	24·0
		44·6

Hence, it would have been possible the Bossi-Bonomi aircraft to have for taken off if the pilot output was 1·0 h. p. for 44·6 seconds.

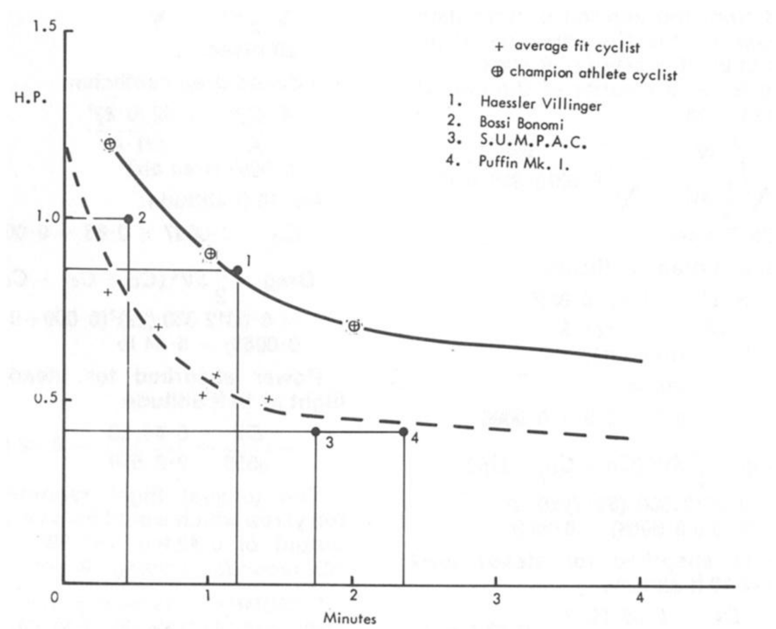


Figure 39 Power – duration performances achieved by non-powered aircraft

However, Bossi quotes that the aircraft flew for 300 ft after take-off. The duration would have been 300/37 = 8 seconds.

If we take the drive and propulsive efficiency of 50% quoted by Haessler the power would have been 1·44 h.p.

Equivalent duration value at 1 ·44 h.p.

$$1 \cdot 0\ h.p. = 8\ \times \frac{1 \cdot 44}{1 \cdot 00} = 11 \cdot 5\ sec$$

∴ the flight that Bossi describes could have been accomplished by the pilot expending 1·0 h.p. for 56 seconds.

This value is presented as point 2 on Figure 39 and is within the capabilities of a good cyclist.

It is concluded that it was entirely feasible for the Bossi-Bonomi aircraft to have taken-off using man-power only and that the account of the flight presented by Bossi is accepted.

6.3. SUMPAC

Design data from Table 1 is:

Wing area = 300 sq. ft

Aspect ratio = 21·3

Flying weight = 269 lb

Further details from Tables 2 and 3:

C_L = 0.85
C_D = 0.0083 } N.A.C.A. 65_3-818 section

C_{Df} = 0043

It is reported that the balsa wing structure was unstable and that buckling occurred. Therefore the profile drag would be greater than anticipated from the aerofoil section data. Because of this Co would be of the order of 0·010 instead of 0·0083.

The forward velocity of the aircraft can be found:

$$V = \sqrt{\frac{W}{\frac{\rho}{2}SV^2}} = \sqrt{\frac{269}{0 \cdot 0012.300.0 \cdot 85}}$$

= 29·7 ft/sec

Induced drag coefficient

$$= \frac{K'{C_L}^2}{\pi A} = \frac{1 \cdot 02(0 \cdot 85)^2}{\pi\ 21 \cdot 3}$$

= 0·011 (free air)

For 10 ft altitude:

$$C_{D_i} = 0 \cdot 011\ \times 0 \cdot 6 = 0 \cdot 0066$$

$$\therefore Drag = \frac{\rho}{2}SV^2\left(C_D + C_{D_f} + C_{D_i}\right)$$

= 0· 0012.300.$(39 \cdot 7)^2$(0·01+ 0·0043+0·0066) = 6·36 lb

Power absorbed for steady level flight at 10 ft altitude

$$= \frac{DV}{\eta 550} = \frac{6 \cdot 44.29}{0 \cdot 8.550} = 0 \cdot 42\ h.p.$$

The longest flight recorded was 650 yards which would involve a power output of 0·43 h.p. for 650 x 3/29·7 = 65 seconds. Add 40 seconds as a realistic value[11] for take-off and this flight represented 0·43 h.p. for 105 seconds, plotted as point 3 on Figure 39.

6.4. "Puffin I"

Design data from Table 1 is:

[11] "SUMPAC" take-off power requirement was theoretically O·55 h.p. for 30 seconds.

Wing area	= 330 sq. ft
Aspect ratio	= 21 · 4
Flying weight	= 267 lb

Further details from Tables 2 and 3:

C_L = 0·8 } FX-05191 section,

C_D = 0·009 } see Figure 25

C_{Df} = 0·004

The forward velocity of the aircraft:

$$V = \sqrt{\frac{W}{\frac{\rho}{2}SC_L}} = \sqrt{\frac{267}{0{\cdot}0012\ 330\ 0{\cdot}8}}$$

= 29 ft/sec

Induced drag coefficient

$$= \frac{K'{C_L}^2}{\pi A} = \frac{1 \cdot 02(0 \cdot 2)^2}{\pi\ 21 \cdot 4}$$

= 0·0097 (free air)

For 10 ft altitude:

$$C_{D_i} = 0 \cdot 0097\ \times 0 \cdot 65 = 0 \cdot 0063$$

= 0·0012 330 $(29)^2$(0·009 + 0·004 + 0·0063) = 6·44 lb

Power absorbed for steady level flight at 10 ft altitude

$$= \frac{DV}{\eta 550} = \frac{6 \cdot 44.29}{0 \cdot 8.550}$$

The longest flight recorded was 993 yards which would involve a power output of O·42 h.p. for 993 x 3/29 = 103 seconds. Adding 40 seconds for take-off power requirements and this flight represented 0·42 h.p. for 143 seconds, plotted as point 4 on Figure 39.

6.5. Summary

The four design studies above provide an excellent check on the theoretical design procedures laid down in the previous chapters. Whereas the usual design procedure works from assumed or known data to predict the aircraft performance, the above design studies have approached the problem form the opposite direction. Taking four aircraft whose performance is known it has been possible to check back and ensure that the required power and aerodynamic data agrees with that discussed earlier.

Agreement with the man-power output graphs in Chapter 2 is particularly good. Both pre-war man-powered aircraft indicate power outputs equivalent to that of a champion athlete for their best flights whereas “SUMPAC” and “Puffin I” have power outputs equivalent to an average fit cyclist. The reason for this is that the two later aircraft were larger than either the Haessler-Villinger or the Bossi

Bonomi aircraft and so were more difficult to control. Hence, the pilots were not chosen for optimum power output but for their expertise in handling the aircraft.

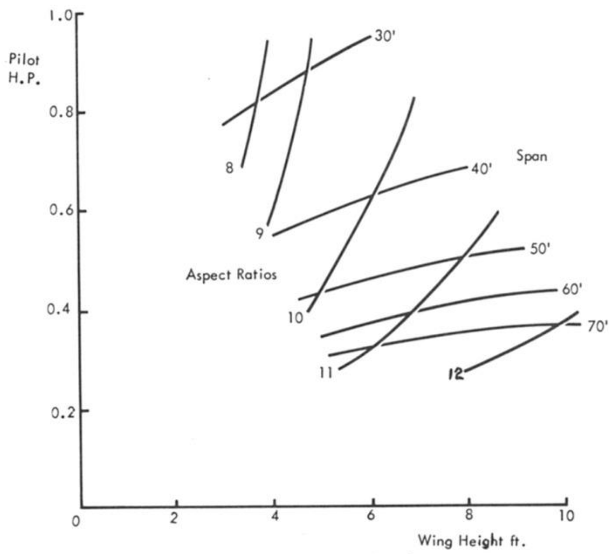


Figure 40 Power requirements for non-powered aircraft

Since the design data presented in the previous chapters has been shown to be realistic it is possible to apply it to man-powered aircraft design in order to predict general characteristics. Figure 40 shows a family of curves for a series of man-powered aircraft of different wing spans. The plot is of minimum pilot input power for a given wing span and height above the ground. For each point the power required was calculated for a range of aspect ratios and that giving minimum power is actually plotted in Figure 40. In practice it was found that power requirements increased rapidly for smaller aspect ratios but only slightly for larger aspect ratios.

The curves in Figure 40 are based on several assumptions, all of which appear to be realistic and which follow from data presented earlier:

(i) use of the Wortmann FX-63137 aerofoil section, with a design C_L of 1·15;

(ii) rectangular wing planform, with K'=1·1;

(iii) a weight/wing span relationship of $W = 190 +$ (wing span ft) so that a 40 ft wingspan aircraft would have a weight of 230 lb; and

(iv) a transmission/propulsive efficiency of 80%.

Several conclusions can be drawn from Figure 40 but these depend on the choice of possible man-power values. For this discussion it is considered that the pilot's power input will be equivalent to that of an average fit cyclist. To consider a greater power input is to exclude the majority of people from flying a man-powered aircraft. The maximum useful power will therefore be in the order of 0·5 h.p. for 60 seconds. Using this as a basis it appears that an aircraft of 40-50 ft span could be flown by an ordinary cyclist for short distances (200 yards) at clear heights of a few feet. Since such an aircraft would be easier to construct than any of the existing man-powered machines, and would certainly be more manageable both in the air and on the ground, it could be attempted by the home constructor or at most only require a few individuals to build it. Aircraft of 40-50 ft wing spans could provide a basis for man-powered flight as a sporting activity but this would depend on whether short hops would be sufficient motivation for such a sport.

It follows from Figure 40 that increasing the wing span gives decreasing return in terms of reduced power requirements. Hence, to minimise the power input sufficiently to attempt the Kremer prizes requires a larger wingspan than that employed for “Puffin II”, with all the associated problems of control and construction.

The Malliga aircraft has a 93 in dia. pusher propeller. Note thin tube spar, and the styrene fairing for the rear of fuselage nacelle.

7. DRIVE AND PROPULSION

CAREFUL design of the drive and propulsive system is required otherwise the already small power output of man could not be usefully employed to propel the aircraft. In previous chapters an efficiency of 80% has been assumed and this is attainable by any carefully designed system.

7.1. Drive mechanisms

The drive mechanism takes the man-power input through to the undercarriage wheel and propeller. Those aircraft that have flown have a cycling input and it is considered that this will be retained for future man-powered aircraft. Although rowing is a possible means of power input the drive mechanism for converting the reciprocating to a circular motion would be more complex than for cycling. Also there is the problem of providing controls that the pilot can manipulate whilst using his arms to propel the aircraft.

Cycling power input has the advantage of continuous development with respect to bicycles and the availability of lightweight and reasonably priced components. Weight is a very important criteria since power input depends on the overall weight of the aircraft. Some inefficiency can be accepted if it means reducing the weight of the drive and propulsion system. There is a direct comparison between efficiency and weight since with an aircraft weighing 250 lb, 2 lb is approximately equivalent to 1% of the power required. Weight and efficiency are obviously important but there is one other criteria that must not be neglected in the drive design, that of reliability.

Since the drive from the pedals to the undercarriage is well defined from bicycling experience, it is the drive from the pedals to the propulsion unit that requires careful consideration by the designer. Figure 41 shows drives used on the Haessler-Villinger, Bossi-Bonomi, SUMPAC and Puffin aircraft respectively. The Haessler-Villinger aircraft employed the simplest form of drive since it did not incorporate a driven undercarriage. It consisted of a twisted belt between two pulleys, one driven by the pedal cranks and the other driving the propeller. Haessler developed his own belt in order to minimise mechanical losses. He employed a woven flat belt with a special rubberised surface to eliminate slip and ensure better contact with the pulleys. The pulleys also had their metal surfaces covered with a layer of rubber to improve contact still further. Belts were changed every 6 flights due to stretch. Haessler assumed the system to have negligible losses which appear to be a fairly valid assumption when taking into account its simplicity and the level of performance demanded from the pilot compared with that actually achieved in practice.

At the other end of the scale the Bossi-Bonomi drive is the most complex employed in a man-powered aircraft to date, consisting of a chain drive to the main drive shaft which then drives the propeller shaft through bevel gears. In spite of its complexity a mechanical efficiency of 94% is quoted for this drive system which also appears to have been very reliable in operation. However, one disadvantage to the system was its high weight.

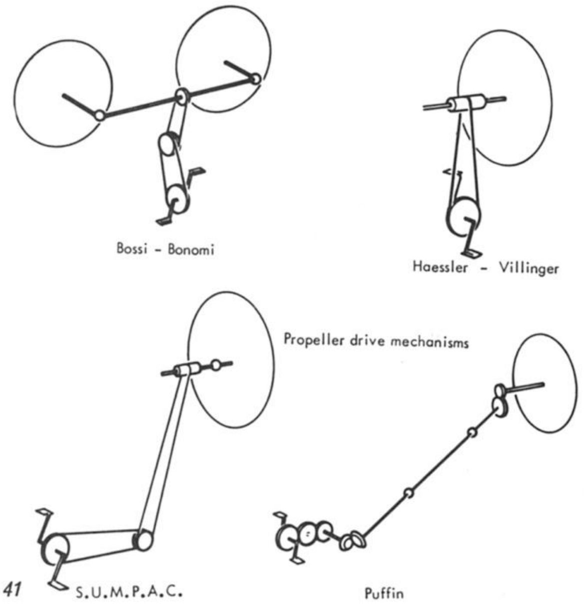


Figure 41

A more detailed diagram of the SUMPAC drive is given in Figure 67. It consists of a *3/32* in Renold chain to drive the main 27 in racing cycle type undercarriage wheel from the pedal cranks, and a twisted flat Steel belt to drive the propeller shaft from the wheel. This type of belt is unusual and unfortunately did not prove entirely satisfactory in practice. The belt was made of 0·008 in thick spring Steel joined by two rows of spot welds and then annealed in the region of the weld. To eliminate slip the belt was coated with a proprietary brand of "belt-stick". A flexible shaft drive was used to transmit the power to the propeller due to required change of angle between the belt and the propeller. Overall mechanical efficiency for the system was quoted as 95%.

The drive employed for the Puffin aircraft managed to eliminate the need for chains and belts by extensive use of gears. The designers were fortunate in their freedom to choose such a system as it resulted in a light weight highly efficient yet very reliable drive. This freedom of choice stemmed from the designers' association with the aircraft industry and the availability of necessary components or access to the machinery for manufacturing such components. It is anticipated that not all designers of man-powered aircraft will be able to get special gears manufactured so this limits their drive mechanisms to the use of chains and belts. Nevertheless a brief description of the Puffin drive is included as it is an example of good design and therefore worthy of study.

A 3:1 step-up gear box transmits the drive from the pedal cranks to the main 22 in diameter undercarriage wheel. On the same shaft as the wheel is a bevel gear unit, which turns the drive through 90° for transmission to the propeller at the rear of the aircraft. The power is transmitted through a light Magnesium alloy tube complete with two universal joints, one at each end to take up any eccentricities that may occur. A splined shaft at the end of the drive tube mated with a splined bore in the final drive bevel gear unit. This in turn was directly coupled to the propeller shaft. The splined shaft is an extra complexity but one necessary in this type of system to allow the withdrawal of the main drive wheel.

Similar systems to that employed for Puffin are envisaged for the Toucan and Weybridge projects. This similarity stems from all the designs having propellers mounted at the rear of the fuselage, although equivalent transmission systems could be evolved using chains and belt but with some increase in the overall weight of the drive and perhaps with some decrease in reliability. Further similarity extends to the fact that all three groups involved with these projects are connected with the aircraft industry.

The Ottawa project will employ a most unusual drive system, in fact the whole project incorporates many novel features. Referring to Figure 9 earlier the propulsion system incorporated two contra-rotating propellers located aft of the wing trailing edge. The two propeller system is not new, being employed for the Bossi-Bonomi aircraft, but is a break away from the present design trend of using a single propeller for simplicity and low weight. Two propellers were chosen to eliminate any asymmetry in the propulsion that might affect controllability of the aircraft and because the transmission need only be carried over short distances. The transmission system consists of a standard bicycle pedal and chain drive to the main undercarriage wheel axle from which two short drive shafts transmit power to the right and left propellers. The most notable part of the system from a design point of view is the method of changing the direction of the drive by means of four almost frictionless angular gearboxes. A prototype model of such a gearbox is shown in *Figure 42* and is shown to contain two back-to-back universal joints.

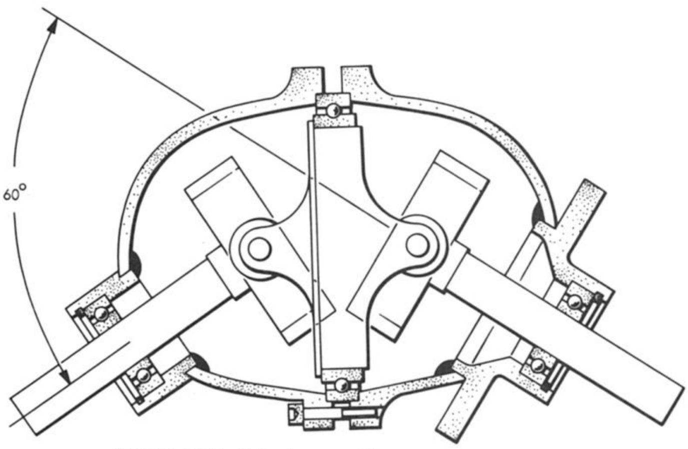
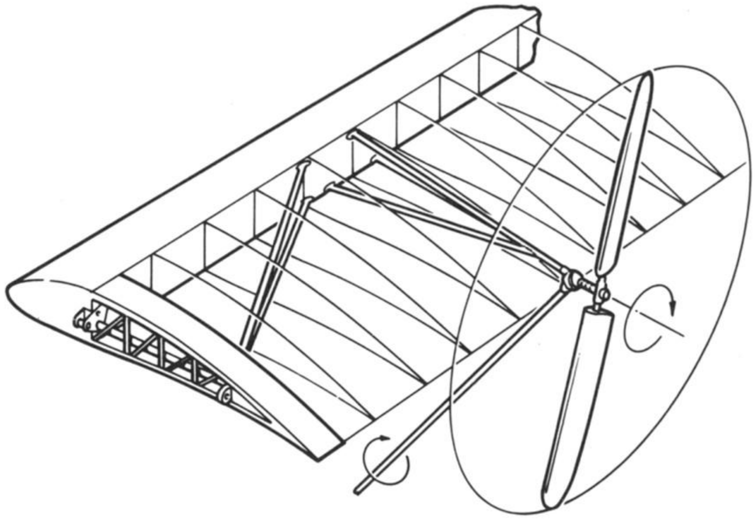


Figure 42 Proposed gearbox design for a propeller drive mechanism.



Propeller arrangement Ottawa aircraft

Figure 43

Figure 43 shows the drive and propeller arrangement in the right wing. A special ratchet arrangement in the propeller shaft protects the propeller from damage in case of an abrupt change of rotational speed, that might be caused by the main wheel contacting the runway at an incorrect peripheral speed. No details of mechanical efficiency of the transmission system are available but the complete system including propellers has been designed for a total weight of 21 lb.

7.2. Transmission Design

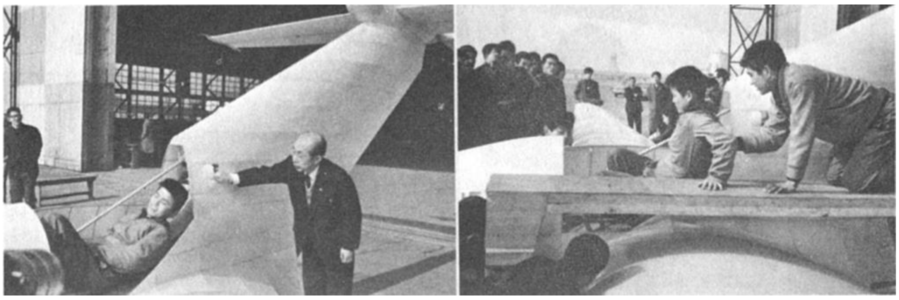
All existing and proposed designs employ one fixed ratio between the pedal cranks and the propeller/main undercarriage wheel, the ratio being so fixed that at a chosen take-off or flying speed the pilot is pedalling at 60 r.p.m. This particular pedalling speed is the optimum for greatest efficiency by the pilot, as discussed in Chapter 2 on "Man Power". Consider an aircraft with a take-off speed of 30 ft/sec and a main undercarriage wheel diameter of 27 inches, actual diameter 28 inches when including for the tyre:

Circumference of the wheel

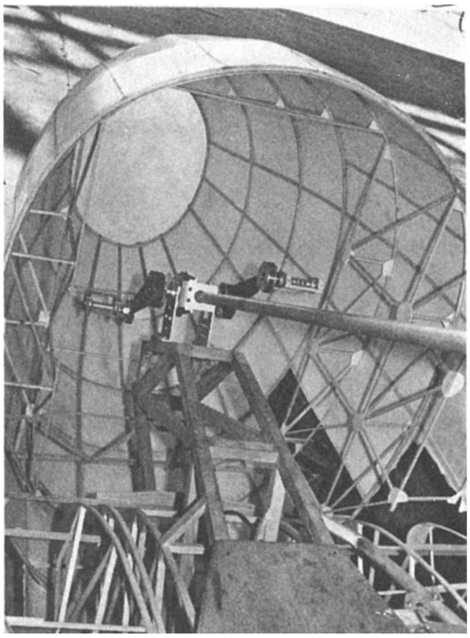
$$= \frac{28 \times \pi}{12} = 7 \cdot 33\, ft$$

∴the wheel must rotate 30/7·33 = 4·1 times per second.

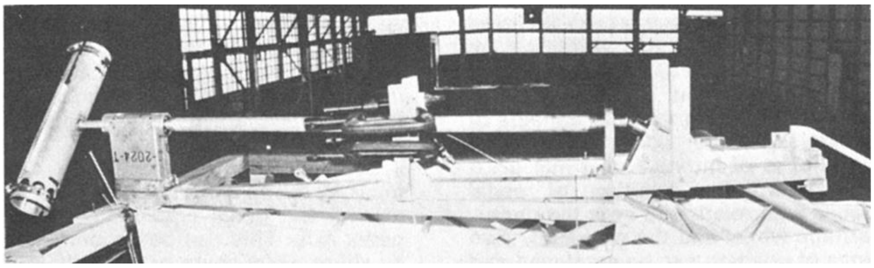
As the pilot input speed is 60 r.p.m., i.e. 1 revolution/second a step-up ratio of approximately 4:1 is required. If higher speeds are considered then a proportionally higher step-up ratio must be employed.



Above: Professor Hidemasa Kimura of Nihon University, responsible for the design of Linnet, and the first 'silting' of the pilot in Linnet I *at Tokyo. Above right is the overwing support trestle for pilot access. Below is an interior view of the drive on Linnet I with propeller shaft driven by bevel gears. Controls had yet to be added. The arrangement is similar to that adopted by the Weybridge machine.*



Below: on Linnet I, the prop shaft from the pedal driven bevel gears in the nose inclined up and rearwards to a horizontal shaft with universal joint, ball race supported and subsequently covered by large bullet fairing.



A fixed ratio proves satisfactory in practice because unlike the varying power input required to operate a bicycle over a wide range of road gradients the pilot of a man-powered aircraft is operating at more-or-less constant speed throughout the period when he is required to deliver maximum power. Some slight help could result from the use of varying gear ratios during the early stages of the take-off run but at the expense of a more complex system, some increase in weight and increased mechanical losses. Oxford University have tested a 3-speed bicycle hub gear and found that at maximum power input from the cyclist the mechanical efficiencies recorded were:

Bottom-gear	94%
Middle-gear	96%
Top-gear	99%

The low efficiency with the lower gears makes the use of a variable speed transmission system unattractive especially as any losses incurred in such a device are additional to mechanical losses found in other parts of the system.

John Wimpenny demonstrates the cycling position of Puffin pilot. See also page 24.

Before going on to other aspects of transmission the riding position of the pilot is of interest as it has great bearing on the position of pedal cranks with relation to both the undercarriage wheel and the propeller. Two types of position can be employed and these can be defined in the following terms:

(i) *Reclining* position and
(ii) *Cycling* position

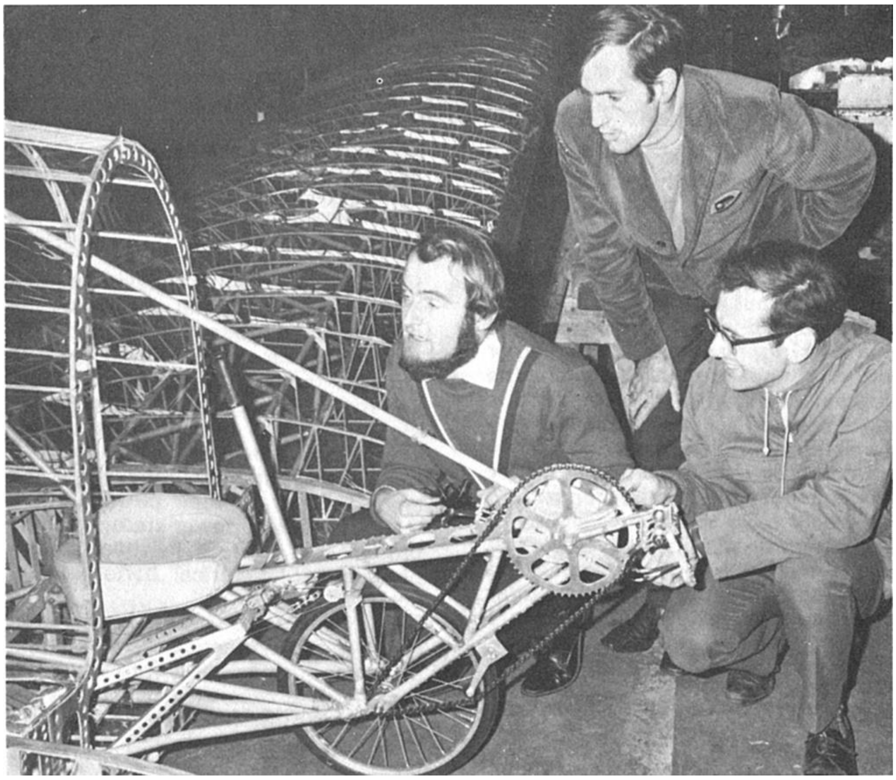
The reclining or semi-reclining positions as employed for the SUMPAC, Bossi-Bonomi and Haessler-Villinger aircraft allows the pilot to operate in a seating position and press against the back of the seat when operating the pedals. This has the advantage of leaving the pilot's hands free to operate the controls. On the other hand the cycling position allows a simpler support framework for the pilot's seat but requires that the pilot be strapped in to leave his arms free to operate the controls. The cycling position was employed for Puffin and proved very satisfactory. In practice the designer has a free choice of riding position and this must ultimately rest on which is the simplest form to build into the fuselage. Work at Southampton University indicated that there is no significant difference in the power a pilot can produce when operating from either position.

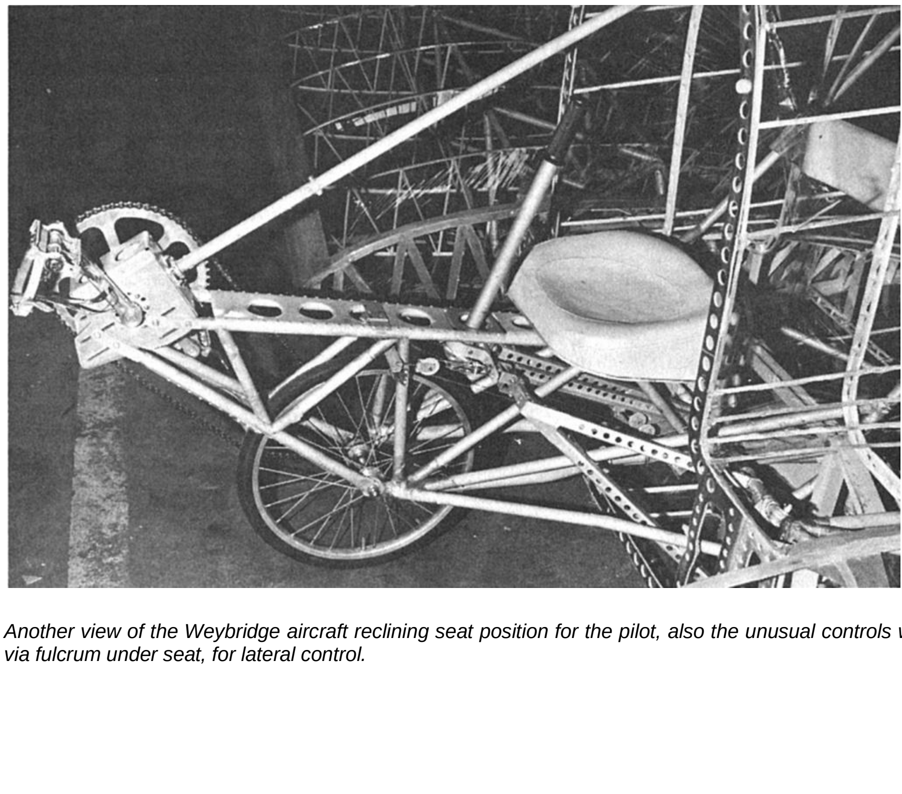
Transmission design depends on the layout of the proposed aircraft and the workshop facilities available. The following generalised comments are presented as an aid to design, for more specific help the layouts used in the previous aircraft can be studied. Mechanical losses must be kept to a minimum so that wherever shafts or gears require to run in bearings it is wise to use ball or roller bearings. These can be bought over the counter in a wide range of sizes and indeed ball bearings are used extensively in bicycles.

Somewhere in the system the drive must be turned through 90° from the axis of the pedal cranks to the propeller axis. This can be accomplished by either bevel gears or a twisted belt/ chain. Much thought has been given to the twisted belt or chain, the previous Section 7.1 discussed the solution used by the group at Southampton University. Dr. Lippisch has expressed the view that a conventional chain drive can be twisted through 90° and makes a simple yet highly efficient transmission system, but that this only works if the distance between the two sprocket wheels is about 3 ft. He proposed using this system with his 1964 man-powered aircraft, see Figure 12.

Many other forms of twistable belt or chain have been suggested ranging from nylon rope to the type of bead link chain used for wash-basin plugs.

Chris Lovell, the pilot (left), Keith Sherwin (the author-centre) and Phil Green of Weybridge discuss the Reclining position and drive before first tests in December 1970.





Another view of the Weybridge aircraft reclining seat position for the pilot, also the unusual controls which can pivot entire wing panels via fulcrum under seat, for lateral control.

These suggestions are now redundant as in recent years positive drive belts have come into widespread use. This type of belt has gear-like teeth on the inner surface that mate with suitably geared pulleys and so combine the advantage of both belts and chains, and was used by the London group for the revision of the SUMPAC drive. A typical modern application of such a belt is the replacement of a timing chain in a car engine. Although this application is more highly loaded than that for a man-powered aircraft transmission, positive drive belts and the necessary pulleys can be bought over the counter in a wide variety of sizes.

One mechanism that has been proposed for man-powered aircraft application but has not as yet been employed, consists of two cranked shafts at right angles to each other with a connecting rod between, the diagram in Figure 44 illustrates this more clearly. This is essentially a very simple light weight yet reliable system if it could be made to work. In theory it is not possible as the connecting rod would have to change slightly in length during each stroke. Nevertheless one such system has been made to work by incorporating a rubber buffer in the rod which allows the necessary changes in length to take place. An efficiency of 97·5% was claimed for this system.

7.3. Power storage

Although the Kremer competitions prevent the use of power storage devices for the aircraft attempting the courses, this does not restrict their application for man-powered flight in general. Indeed for general sporting and training activities the use of power storage would be of considerable advantage providing such devices were of comparatively light weight and small volume for their power output. Various types of power storage can be thought of: rotating flywheels, compressed air, electrical batteries and springs.

The first three on closer examination prove to be impractical as the actual device or the machinery for converting the energy proves extremely heavy for the power output achieved. One form of spring system that does appear to be worthy of consideration is the use of rubber which when stretched can store the required energy. Rubber motors are widely employed for model aircraft but it is not suggested that a similar system employing rubber strips extending the length of the fuselage and directly coupled to the propeller be used for man-powered aircraft purposes. Such a system is not impractical but can be improved upon be other methods of stretching the rubber.

One device that was proposed but has not actually been used, nevertheless looks very promising, is based on the use of heavy gauge vulcanised rubber thread of high elasticity. This type of rubber can give up to 900% elongation when stretched and the proposed device stretches the rubber around the periphery of a cylindrical drum. A diagram of the power storage device which is patented by the College of Aeronautics, Cranfield is given in Figure 45. The rubber is attached to the output end on the left-hand side of Figure 45 and is then wrapped around the cylinder. With the output shaft locked the cylinder can be rotated by a hand crank or directly from the pedals. For this particular device the input is geared down by a 7:1 ratio. To release the power the cylinder is locked and the power transmitted to the propeller by unlocking the output end. For the output end a geared step up ratio of 18: 1 ratio is proposed. Power to propel say SUMPAC for 3 minutes could be obtained by the use of this device with 2 strips of rubber each having $^{5}/_{8}$ in square cross-section and being 15 ft long (un-extended). Maximum duration would require 45 windings round a 1 ft diameter drum.

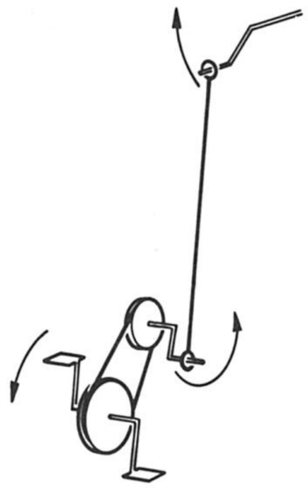


Figure 44

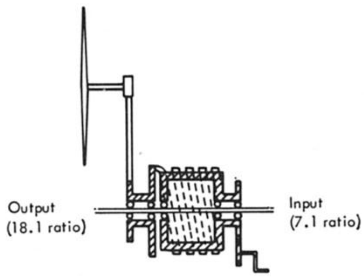
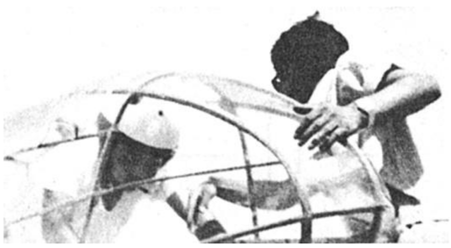
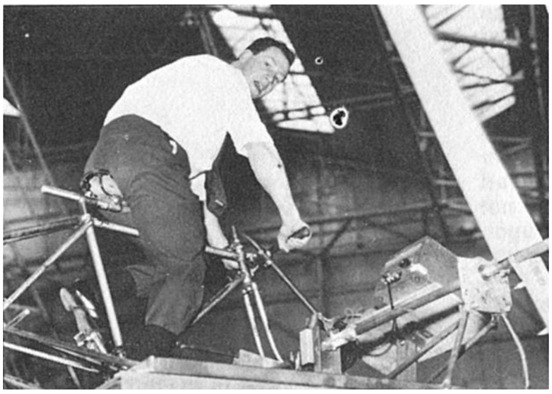


Figure 45

Greater durations would require shorter, thicker lengths of rubber in turn necessitating higher gear ratios on both the input and output sides. The mechanical efficiency and weight of such a device are unknown but it is anticipated that both could be maintained within acceptable limits by correct design. Even if this or any equivalent design increased the weight of the aircraft by say 10% the required increase in power required to propel it is only 15% and so possibly acceptable. The mechanical efficiency of the particular device described could be improved by constructing the surface of the drum as a series of small diameter rollers.

Pilot in Japanese SM-OX is in the cycling position, here being enclosed by transparent fairing.





Most man-powered Aircraft projects have a pilot test rig to assess the energy required and to check the drive mechanism. This is the unit made for training Puffin pilots at Hatfield, registering developed Horse Power as the cyclist drives the propeller.

7.4. Propulsion considerations

In terms of conventional man-powered aircraft and within the discussion of this chapter the only suitable form of propulsion in the air is the propeller. Flapping wing machines have and are being researched as a suitable form of man-powered aircraft but discussion regarding these will be reserved to Chapter 11.

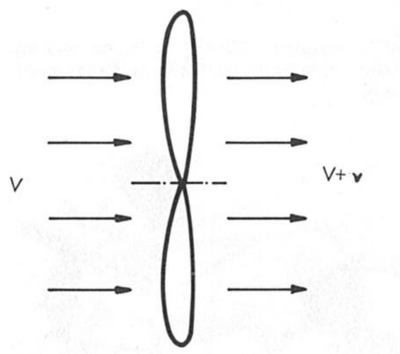


Figure 46

The propeller works by taking in air at the front and forcing it out at the back at a higher velocity. In so doing the propeller is simply providing evidence of Newton's law of mechanics that states "every action has an equal and opposite reaction". The thrust is dependent on the mass of air involved and its change of velocity across the propeller. In the case of propellers, one has a high mass of air and a small change in velocity whereas a jet engine of equivalent thrust has a comparatively high change in velocity but low mass of air.

If a propeller is working on an aircraft with a velocity of V and the actual change of velocity across the propeller is v then the air enters the propeller with velocity V and leaves with velocity $V + v$, as shown in Figure 46. The efficiency of the propeller defined as the ratio of the useful work to the total work is defined as:

$$\eta = \frac{V}{V+v} \qquad (14)$$

This is sometimes termed the Froude efficiency or the ideal efficiency. In very simple terms, if we think of the useful output of work from the propeller this is evident by it propelling the aircraft along at a velocity of V. To obtain this the propeller then has to accelerate still air to a velocity of $V + v$. Hence V is a measure of the useful work output and $V + v$ a measure of the input power, resulting in equation 14.

The ideal efficiency of a propeller is never fully realised in practice because it only considers the behaviour of the axial flow of air across the propeller. Additional sources of lost power exist, these including:

(a) drag of the propeller blades;

(b) the energy imparted to the rotation of the airflow; and

(c) the periodicity of the flow and the loss of thrust towards the blade tips.

The most important of these additional effects is usually the drag of the propeller blades which can be taken into account by the blade element theory.

7.5. Propeller geometry

The propeller consists of blades rotating at right angles to the direction of flight. These blades act in a similar way to aerofoils and produce lift. It is the lift component that provides the thrust from the propeller blades. To provide good lift properties the blades must be shaped to a suitable aerofoil section. Careful consideration of the aerofoil section is necessary because not only does the lift depend on it but also the drag of the propeller blades which as mentioned above is an additional cause of propeller inefficiency. The same considerations discussed earlier in Chapter 3 in connection with the wing aerofoil section also applies to a large extent to the propeller aerofoil section. However there is one important difference; the Reynolds number at which the propeller blades of a man-powered aircraft works is very low, a maximum of 250,000, so that the air flow tends to be laminar over most of the surface. Because of this, although strictly speaking it only applies to propellers for man-powered aircraft, a simple aerofoil section provides adequate performance and is very much easier to construct.

All propellers used for man-powered aircraft have employed the 9% thick Clark Y section shown in Figure 47. Performance curves for this section are shown in Figure 48 for a typical propeller. The curve of C_D include for the induced drag so that these curves cannot be compared directly with a wing aerofoil section where only the profile drag is considered. Performance using this section is very satisfactory as evidenced by "SUMPAC" with a propeller efficiency of 88% and "Puffin I" with 89%.

In a general way a propeller can employ any number of blades and for powered aircraft 2, 3 and 4 bladed propellers have been widely employed. For the particular application to man-powered aircraft only 2 bladed propellers have been used for the very good reasons of lightness and simplicity of construction. There is a case, at least in theory, for trying 3 bladed or even 4 bladed propellers but the slight gain in efficiency does not really outweigh the disadvantages. For the purpose of the present discussion only 2 bladed propellers will be considered. The reader is referred to Wickens[12] if he wishes to obtain more detailed information regarding the effect of differing numbers of blades.

9% thick Clark Y section

Figure 47

One major parameter to consider whilst still maintaining a simple geometric approach to the problem is that of "pitch", the angle at which the blade is set so that it can operate correctly. Using a very simple analogy a particular point on the propeller blade must advance through the air by executing a helix in a similar way to a corkscrew advancing through a cork, see Figure 49. The steeper the angle of the helix the quicker it will advance. It will be appreciated that the propeller must be designed so that each part of the blade advances the same amount for each revolution. If we take a point a at the tip of the blade, say of diameter *D,* for each revolution it will turn through a distance πD. Now take a point *b* half way along the blade, the distance it travels through is $\pi D/2$. However, both points must advance the same amount so that the pitch of *b* must be twice as great as that of *a,* this being simply illustrated in Figure 50. This means that the pitch of the blade varies. The blade pitch or the amount of advance per revolution is so important that it is correlated by a special parameter termed the "Rate of advance" *J* where:

$$J = \frac{V}{nD} \qquad (15)$$

$V =$ aircraft velocity (ft/sec);

[12] Aspects of efficient propeller selection with particular reference to man-powered aircraft, R. H. Wickens, *Canadian Aeronautical Journal*, November 1961.

n = rotational speed of the propeller (revs/sec); and

D = propeller diameter (ft)

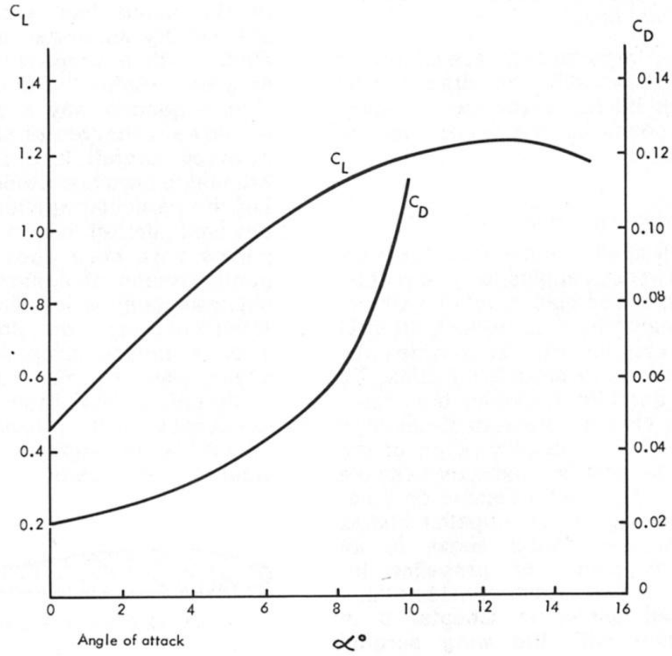


Figure 48 Performance curves for the 9% Clark Y aerofoil section

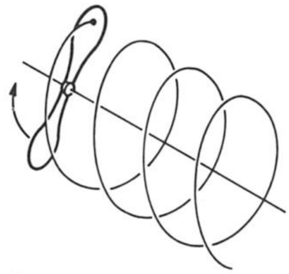


Figure 49

Propeller efficiency varies with J and for a two-bladed propeller optimum performance is obtained with J ≈ 1·0. Propellers for “Puffin I” and “SUMPAC” had J values of 1·0 and 0·8 respectively this is the range of operating rates of advance anticipated for man-powered aircraft.

7.6. Propeller blade theory

The following section presents a simple introduction to the blade element theory some knowledge of which is essential for propeller design work. Only sufficient of the theory will be discussed to allow the reader to appreciate the relevant features of blade design and also to be in a position to actually design if necessary. For a deeper study of the subject the reader is referred to the specialist book presented in the bibliography.

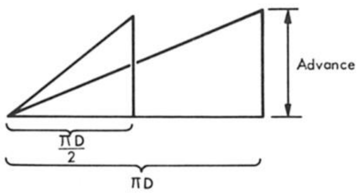
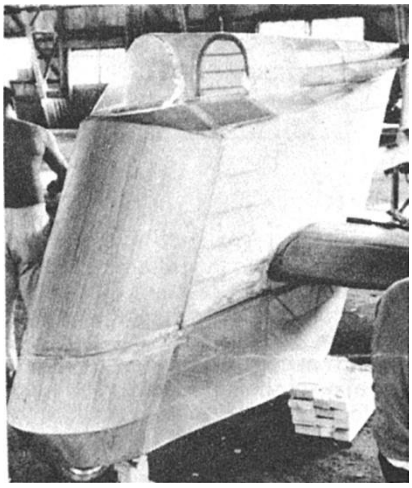
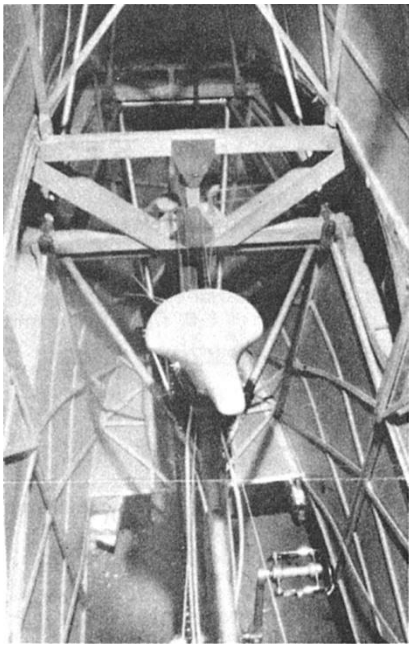


Figure 50



Pilot nacelle on the Eiji Nakamura aircraft uses two wheel cycling position and propeller drive by shafts from base.



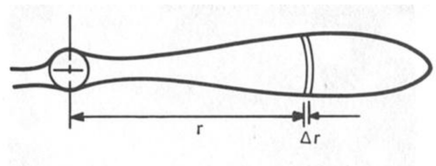


Figure 51

An element is defined as a thin section of the blade at an arbitrary radius *r* and having a thickness Δ*r* where Δ*r* is small compared with the radius. Figure 51 illustrates what is meant by this. The chord of the element chosen is *c.* We can now consider what happens to the airflow approaching the blade element. Taking a section across the element, as shown in Figure 52, indicates that the blade velocity at that element is $2\pi rn$ and that at right angles to this air is moving a velocity *V* due to the aircraft flying at that speed. Combining these two velocities the blade element observes the air approaching it at velocity V_R and at an angle ϕ to the direction of rotation, where

$$\tan\phi = \frac{V}{2\pi rn} \tag{16}$$

This angle is a function of J and this more formal approach ties in with the descriptive discussion presented earlier in section 7.5. Hence, relative to the blade element the airflow has a velocity V_R and an angle of approach of θ. To provide lift the element must have a positive angle of attack α to this airflow, so that the actual blade element angle must be θ + α degrees to the angle of rotation.

For example consider a propeller of 8 ft diameter, *J* of 1·0, C_L of 0·8 when using a 9% thick CLARK Y section and used for an aircraft flying at 30 ft/sec. Find the blade element angle at a radius of 3 ft from the centre.

$$J = \frac{V}{nD} \therefore n = \frac{30}{1 \cdot 8} = 3 \cdot 75\, rev/sec$$

Referring to Figure 52 the rotational speed at 3 ft radius

= 2πrn = 2π3.3·75 = 70·8ft/sec

V = 30ft/sec so that from equation (16)

$$\tan\phi = \frac{V}{2\pi rn} = \frac{30}{70 \cdot 8} = 0 \cdot 424$$

∴ ϕ = 23°

Referring to Figure 48, to provide a C_L of 0·8

α= $3^1/_2$°

∴ the blade element angle for a radius of 3 ft

= ϕ + α = $26^1/_2{}^0$

This provides a method by which the angle of any element along the propeller blade can be calculated. It is quite sufficient to calculate to within the nearest $^1/_2$° of angle because it is not possible to actually construct a propeller blade to a greater accuracy.

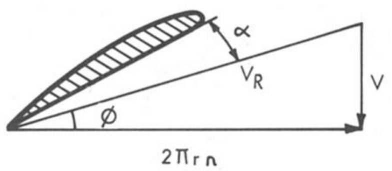


Figure 52

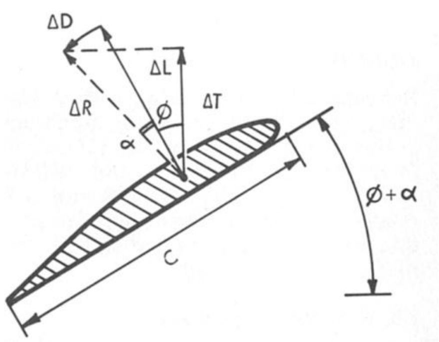
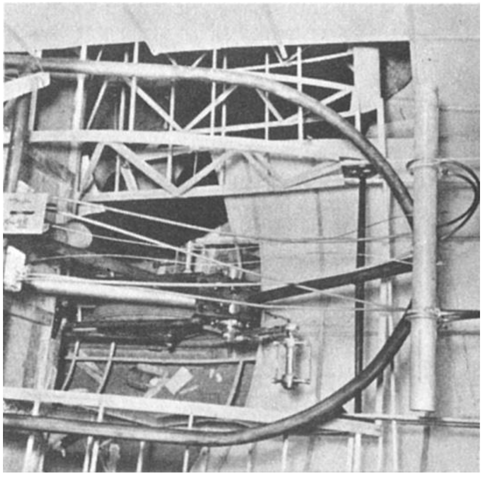


Figure 53



Looking down into Linnet III cockpit the cycling position, control bar, metal tube frame and cable controls are evident.

Having found the blade angle at any particular radius the only other data the designer wants is the chord C. An appropriate simple theory can be evolved by referring to Figure 53. It shows the element which we earlier defined at being of width *Δr.* The element is operating at angle of $\phi + \alpha$ and producing lift and drag. Since these are small parts of the complete lift and drag produced by the whole blade it is convenient to define them as ΔL and ΔD respectively. Combining the lift and drag components the resultant force acting on the element is ΔR. It is the forward component of ΔR that provides the thrust ΔT from the element. Providing that angle γ is small, say one or two degrees, then it is possible to say that the magnitude of ΔR and ΔL are equal although both are operating in slightly different directions. Then we can express the thrust in terms of the lift:

$$\Delta T = \cos(\phi + \gamma) \qquad (17)$$

If there was no drag then the whole of the lift component could be used for the thrust. But with drag being present part of that drag is acting against the lift and so reduces the thrust accordingly. This in formal symbols is what equation (17) expresses. Angle γ is a measure of the drag with relation to the lift, the larger the drag the larger γ and the smaller the thrust. Therefore γ is a measure of inefficiency and introduces into the theory the effect of drag which was not present for the ideal efficiency discussion, equation (14).

The lift from the element can be equated by

$$\Delta L = \frac{\rho}{2}.C_L.(Element\ area).{V_R}^2$$

where the units are specified for equation (1).

From Figure 52 we see that

$$V_R = \frac{V}{\sin\phi}$$

and by definition the element area is Δr x C

$$\therefore\ \Delta L = \frac{\rho}{2}.C_L.\Delta r.C\left(\frac{V}{\sin\phi}\right)^2 \qquad (18)$$

We now have an equation which when combined with equation (17) above gives:

$$\frac{\Delta T}{\Delta r} = \frac{\rho}{2}.C_L.C.\left(\frac{V}{\sin\phi}\right)^2.\cos(\phi + \gamma) \qquad (19)$$

Providing that we can express ΔT/Δr as some value we now have an equation that will enable us to calculate the chord C.

Ideally the velocity $V + v$ leaving should be constant right across the blade and this can only be achieved if the thrust grading ΔT/Δr has a constant slope across the propeller blade. The meaning of this can be seen from the solid line in Figure 54 where the thrust grading varies from zero at the centre to some finite value at the blade tip and between the two the thrust grading is defined by a straight line joining them. When used in association with the equation (19) the values found from this theoretical thrust grading could enable the chord at any particular element of the propeller blade to be calculated. However, this approach would not be completely realistic as in practice the thrust grading will not follow a straight line. At the tip of the blade there will be some loss of lift just as there is some loss of lift at the tip of a wing, a phenomena described in section 4.1.

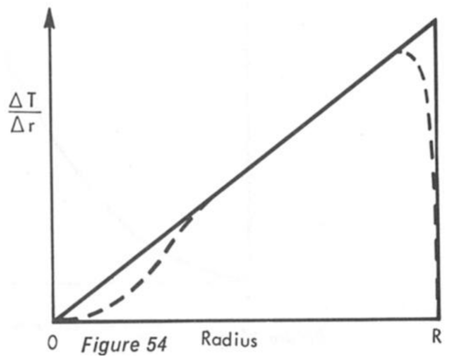


Figure 54

Following the considerations of actual behaviour there will be a flow of air over the blade tip giving rise to tip vortices and so causing induced drag. However the induced drag has already been included for in the curves presented for the CLARK Y section in Figure 48.

The strength of a propeller blade must be adequate for it to operate correctly. This means thickening the sections near the centre of the blade which in turn causes the practical performance of the blade to vary from the ideal. Variation of the thrust grading compared to the ideal is indicated by the dotted lines in Figure 54. An actual thrust grading curve for the particular propeller used with "Puffin I" is shown in Figure 55. The curve is presented as a plot of $\Delta T/\Delta r$ in terms of the ratio of total blade thrust T to blade radius R, against the element radius r in terms of the blade radius R. In other words the thrust grading and radius are presented in a general non-dimensional form so that the relevant numerical values can be applied to any particular propeller size or thrust. Although strictly the curve in Figure 55 is only valid for j = 1·0 the numerical values of ΔT/Δr derived from it when used with equation (19) will enable realistic sizes of blade chord to be calculated for man-powered aircraft applications.

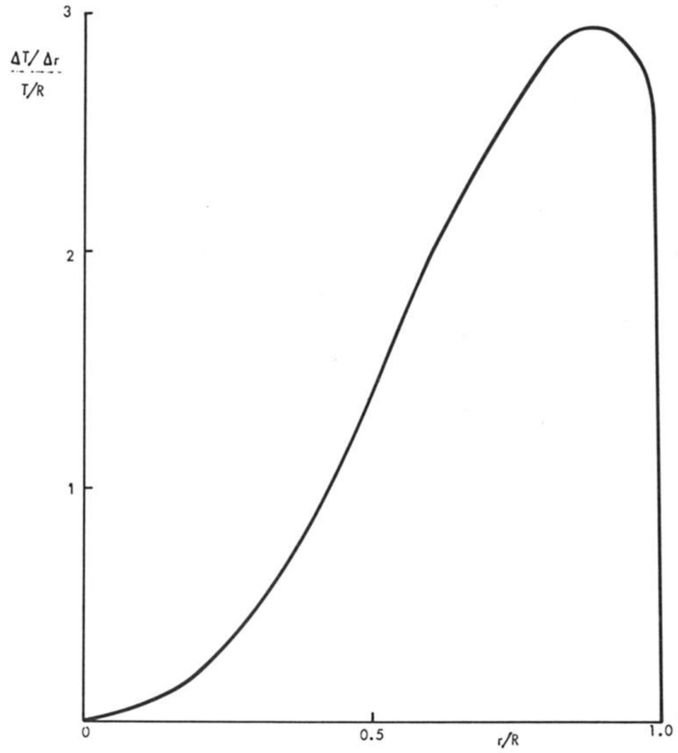


Figure 55 Generalised thrust grading variation with propeller radius

For example consider a propeller of 8 ft diameter, J of 1·0, C_L of 0·8, aircraft speed of 30 ft/sec and a total propeller thrust of 7 lb. Find the blade chord at a radius of 3 ft from the centre assuming the use of the 9% thick CLARK Y section.

From the previous example in this section:

ϕ = 23°

Referring to *Figure 48* at C_L= 0·8, C_D= 0·032

∴ tan γ = 2° 18'

Now the thrust for one blade is 3·5 lb so that

T/R = 3·5/4 = 0·875

From Figure 55 at r/R = $^3/_4$ = 0·75

$$\frac{\Delta T}{\Delta r} = \frac{T}{r} \times 2\cdot 65 = 2\cdot 32\ lb/ft$$

Using this value with equation (19):

$$\frac{\Delta R}{\Delta r} = \frac{\rho}{2} C_L C \left(\frac{V}{\sin\phi}\right)^2 \cos(\phi + \gamma)$$

we obtain:

$$2 \cdot 32 = \frac{0 \cdot 0024}{2}\, 0 \cdot 8\, C \left(\frac{30}{\sin 23°}\right)^2 \times \cos(26°\, 18')$$

2·32 = 0·0012.0·8. C. 5900.0·8965

∴ C = 0·456 ft

The blade chord at radius of 3 ft = 5·47 inches.

This provides a simple yet effective method by which the chord of any propeller blade element can be calculated.

7.7. Propeller efficiency

Propeller blade element theory outlined above provides a ready method of designing a blade by the use of equations (16) and (19) with empirical data from Figures 48 and 55. The whole design procedure as outlined hinges on the provision of a realistic thrust grading curve based upon previous propeller designs and their performance in practice. We know for instance that the propeller used for "Puffin I" and on which the curve in Figure 55 is based gave an efficiency of 89% under test. This is very reassuring when extending the use of Figure 55 to the design of other propellers but does not tell the designer precisely that his efficiency is going to be with a diameter and a *J* value different to those used for "Puffin I".

Rear view of Linnet II shows incredibly light propeller structure.

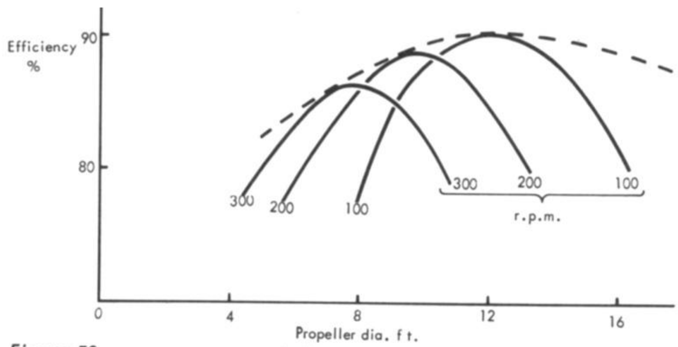


Figure 56 Variation of efficiency with propeller diameter

It is possible to extend the blade element theory in order to find the efficiency for each element. Briefly the efficiency is a measure of the thrust produced for the power absorbed by the propeller and this can be subdivided to equate the increments of thrust and power for each element. The increment of thrust is defined by ΔT in Figure 53 and defined as:

$$\Delta T = \frac{\rho}{2} C_L\, \Delta r\, C V_R^{\,2} \cos(\phi + \gamma)$$

similarly the power absorbed by each element is dependent on its radius and increment of torque, the latter being the horizontal component associated with ΔT so that ΔP, the power increment can be defined as

$$\Delta P = (2\pi . n . r) \times \frac{\rho}{2} C_L \Delta r C V_R^{\,2} \times \sin(\phi + \gamma)$$

Efficiency for each element η =

$$\frac{\Delta T.V}{\Delta P} = \frac{V}{2.\pi.n.r\ \tan(\phi + \gamma)} \qquad (20)$$

It is possible to use equation (20) to find the total efficiency for the complete propeller blade by summing the efficiencies for each element. This can best be explained by means of an example:

Consider the propeller described in the previous examples having a diameter of 8 ft, J of 1 ·0 and V of 30 ft/sec. From the previous example we know:

n = 3· 75 revs/sec, γ = 2° 18′

and that at a radius of 3 ft: ϕ = 23° and C = 0·456 ft.

Now the efficiency at a radius of 3 ft can be found using equation (20):

$$\eta = \frac{30}{2\pi.3\cdot 75.3\ \tan(24°\ 9')} = 0\cdot 945$$

i.e. 94·5%

Extending the theory to other elements of the blade we obtain the following results as in Table 'A'.

Table 'A'	radius (ft)	0·33	1 ·0	1 ·67	2·33	3·0	3·67
	φ°	75° 18'	52°	37° 18'	28° 36'	23°	19° 6'
	C (ft)	0·243	0·335	0·473	0·540	0·456	0·386
	η	0·842	0·915	0·920	0·915	0·895	0·880

Table 'B'	radius	0·33	1·0	1·67	2·33	3·0	3·67	Total
	C (ft)	0·243	0·335	0·473	0·540	0·456	0·386	2·433
	η × C	0·205	0·307	0·435	0·494	0·408	0·340	2·189

Overall efficiency = 2·189/2·189 = 0·90 i.e. 90%

The efficiency of each element is effective over an area of the blade that is proportional to the blade chord. It is therefore possible to ascertain the total blade efficiency by summing the product *η* x *C* for each element and then dividing by the sum of the chords (refer to Table 'B' on next page).

It is not necessary to take a larger number of elements as the value obtained by this method is adequate for our purposes. It is possible using this technique to compare two different types of propeller or alternatively to modify a blade shape and note the effect on performance.

This theoretical value of efficiency is obtained by taking propeller drag into account, but there are other small losses and the actual efficiency will probably be of the order of 88% instead of 90%. A comprehensive study of propellers suitable for man-powered aircraft has been made and the variation of diameter with maximum efficiency is given in Figure 56. The dotted line shows the envelope for a series of curves and from this it is possible to estimate a suitable rotational speed and the maximum attainable efficiency for a particular diameter. Although Figure 56 was based on a theoretical study the results are in good agreement with efficiencies obtained in practice; as seen in comparisons below:

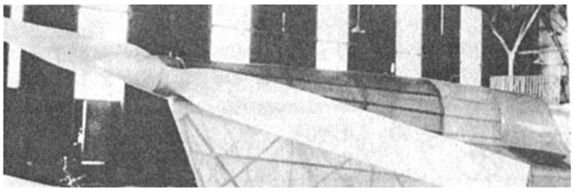
Figure 56 indicates a propeller with a diameter of 11 ft as being the most efficient, but in practice smaller diameters are used to save weight.

7.8. Propeller Construction

The blade element theory discussed in sub-section 7.6 provides a means of designing the propeller blade in terms of the 9% thick CLARK Y section. It would obviously be impractical to use this section throughout the length of the blade otherwise the strength near the centre would be inadequate. A thickening of the blade towards the centre is therefore necessary and to illustrate the amount that has proved satisfactory in practice, Figure 57 presents a drawing of the Puffin propeller blade. This blade retains a 9% thick section throughout most of its length, changing to a 10% thick section at a radius of 2 ft, i.e. r/R = 0·45; thereafter varying continuously to $14^1/_2$% thickness at 1·33 ft radius, i.e. *r/R* = 0·39; and $18^1/_2$% thickness at 0·67ft radius, i.e. r/R=0·15.

	Diameter (ft)	n (r.p.m)	J	η
Haessler-Villinger	4.9	600	0.83	82%
"Puffin I"	9.0	330	1.00	88%
"SUMPAC"	8.0	280	0.80	88%

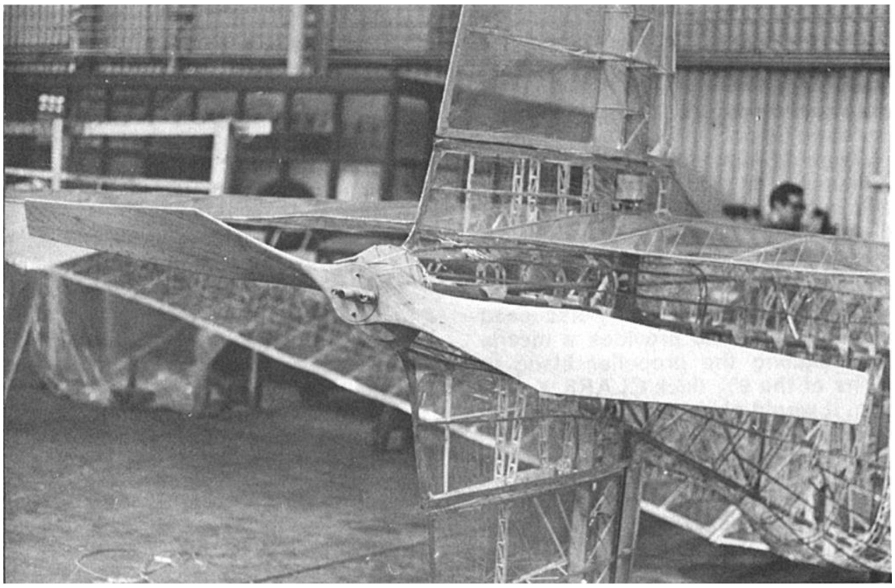
The centre of the propeller is normally housed in a streamlined spinner otherwise there would be considerable increase of both aircraft and propeller drag due to disturbed airflow in this region. Furthermore it is useful if the propeller is constructed as two separate blades clamped in position at the centre. If a suitable clamping device is used this arrangement allows the blades to be removed for transportation and the pitch of the blades to be adjusted for optimum performance. In this case the spinner must be removable and serves as a housing for the clamping device.

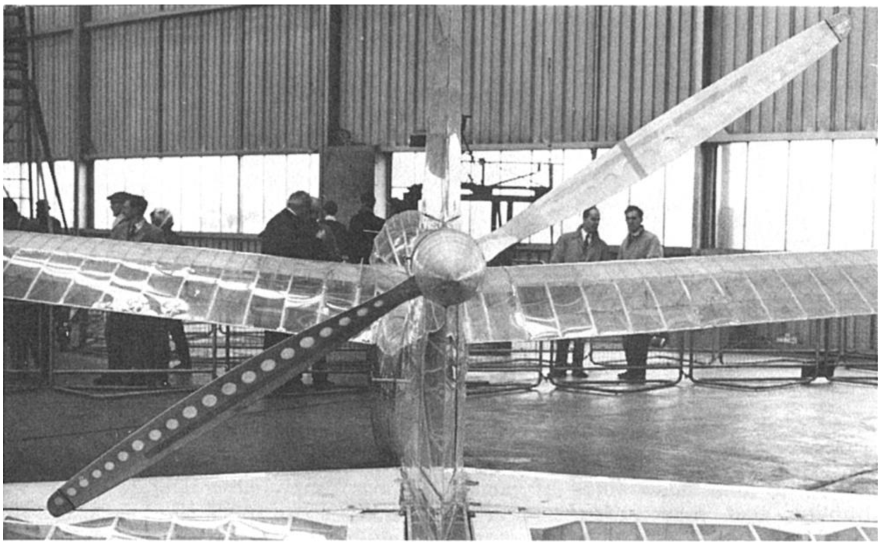


Left, the rigid, high aspect ratio propeller made by Eiji Nakamura. Below, the Weybridge aircraft propeller, and the adjustable pitch propeller of Puffin I and II, with lightening holes in balsa blades.

Provision for adjusting the pitch of the propeller is most useful, because of errors that inevitably creep into the construction of both the propeller and aircraft may require it to operate away from the theoretically assumed conditions. The propeller blades should be set to their designed position and then adjustments must be made on a "trial and error" basis during flight trials. Too fine a pitch means a sudden speeding up of pedal rate after just taking off whilst too coarse a pitch will prevent the aircraft reaching its take-off run. Obviously it would help considerably if one has access to a propeller testing rig but this is written on the basis that most designers of man-powered aircraft do not have such facilities. On the other hand the Weybridge aircraft uses a fixed pitch solid propeller simply because the designers considered variable pitch to be an added variation that could cause trouble. They rated reliability to be more important than optimum efficiency.

Both Puffin and SUMPAC propellers were tested in wind tunnels before flight testing. The Puffin propeller achieved its designed efficiency without modification but the SUMPAC propeller initially only achieved 75% efficiency as against its designed 89%. Subsequent investigation of the airflow over the propeller indicated that laminar flow conditions prevailed over a large proportion of the surface causing excessive form drag and therefore too high a profile drag. The drag was reduced by gluing a serrated paper strip to the upper surface of the blade at a position (0·2 x chord) back from the leading edge. This propagated a turbulent flow which reduced the form drag at the expense of some increase on skin friction yet giving an overall improvement in profile drag. The effect of this was a dramatic increase of efficiency from 75% to 88% only 1% below the theoretical.





This is the only example of a turbulator being used for propeller blades. All other man-powered aircraft have operated successfully without such devices. The Hatfield group did some experiments with transition strips on the propeller blades but found them unnecessary. Without the use of a propeller testing rig it is considered that quantitative experiments regarding the application of transition strips are impractical. The designer must err towards previous experience and assume that his propeller does not need them. However some indication of the actual airflow behaviour can be gained by coating part of the surface of the blade with a quick drying paint then operating the propeller under flight conditions. If the airflow was laminar when the paint dried the surface will be smooth but if the airflow had separated the surface will be rippled. On the basis of this experiment the designer will then be able to judge whether a transition strip would be of benefit or not.

With regard to actual construction of the propeller there are no standard techniques, the only guide that may be given is to quote the methods used on Puffin and SUMPAC. The Puffin propeller employed layers of balsa sheet cemented together, giving the appearance of a solid balsa construction, and strengthened with plywood strips on the top and bottom of the blade. Lightening holes were cut in the balsa and the whole blade covered with "Melinex" plastic sheet. The SUMPAC propeller on the other hand employed a centre light alloy tube running the whole length of the blade. Plywood ribs were attached to the tube at regular intervals, approximately 3 inches, and the spaces between filled with balsa. One modification to this latter form of construction that may prove effective would be to use expanded polystyrene instead of balsa to minimise the total propeller weight.

The Spinner on the Puffin prop hub is retained by rubber bands and removes easily for access to the blade clamps for any adjustment of propeller pitch. Note the added cuffs at the blade root.

Finally it has been suggested that a propeller would be more effective if operating in a shroud or duct. Certainly in theory a gain of some 25% in thrust over a propeller operating in the open and absorbing the same power is possible. This is due to the reduction of blade tip losses and the better pressure distribution of the flow in the duct. However, in practice these advantages would probably be off-set by the increase in weight and the profile drag of the duct itself. When the McEvoy aircraft is reconstructed it should provide answers to these problems.

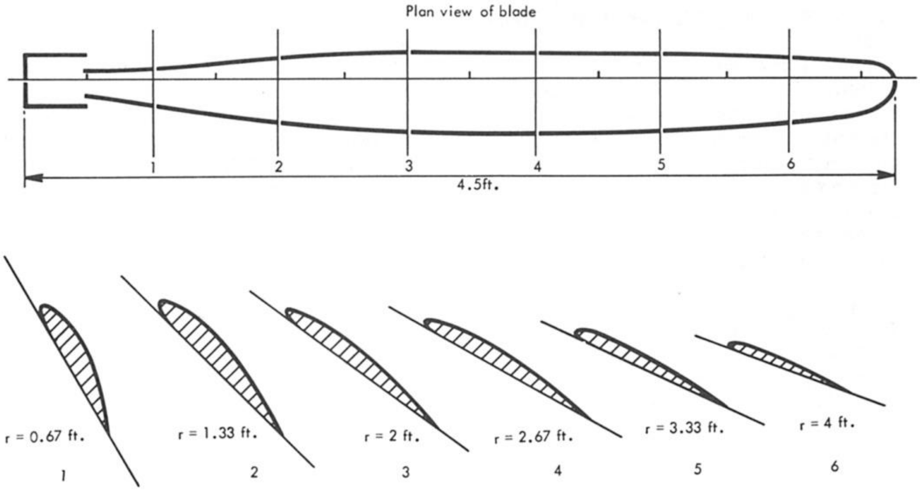


Figure 57 Propeller blade design for Puffin Mk.I.

8. MATERIALS AND CONSTRUCTION

MATERIALS for use in the construction of man-powered aircraft fall into one of two categories: materials used for the aircraft structure and covering materials. The main consideration within this chapter is the choice of materials for the main aircraft structure. Materials are chosen for their strength, stiffness and weight characteristics, close attention particularly being paid to the latter. Although the largest proportion of the aircraft weight will probably be the pilot, it is still important to minimise overall weight by careful structural design and correct choice of materials.

Since most man-powered aircraft will probably be built by individuals or groups working at home, this places further constraints on the choice of materials, namely economic and manufacturing limitations. Both Puffin and SUMPAC were largely constructed of spruce and balsa, materials that comply with the constraints set by home construction whilst providing adequate structural properties. Such materials are in fact “naturals” for aeromodellers and this is mentioned because it is anticipated that many people interested in the designing and construction of man-powered aircraft will probably have had previous aeromodelling experience.

Turning to covering materials the Haessler-Villinger machine employed silk but this has since been superceded for such purposes by nylon. Parachute nylon was chosen for SUMPAC because of its lightness and strength. Originally two coats of ordinary glider dope were used to tighten the nylon giving a weight of 2 oz/sq. yard but due to the slackening effect achieved in a damp atmosphere a further two coats of dope had to be applied. Although doped nylon adds to the strength of the structure it imposes a severe weight problem. It was originally intended that “Puffin I” should be covered with Japanese tissue and doped, a covering since used for the Malliga machine. Weight of tissue and a thin coat of dope were assumed to be $^{3}/_{4}$ oz/sq. yard. “Melinex”[13] plastic sheeting at $^{1}/_{2}$ oz/sq. yard was employed for Puffin giving a lighter covering, although one that adds little to the strength of the structure. This type of covering can be tightened by running a warm iron over it and this process has to be repeated at frequent intervals to keep the covering taut. Melinex is to be used for all the other man-powered aircraft projects at present under construction and although it may not always be the automatic choice its many excellent properties including minimisation of the surface friction due to the smooth surface finish, make it a very attractive proposition.

8.1. *Strength of materials*

Before comparing the various materials the strength and stiffness factors by which they are judged must be defined. Strength is the measure of the load a material will withstand for a given cross-sectional area and is given the symbol f and units of lb/sq. in. The strength of a material varies depending on whether it is in tension or compression.

Strength alone is insufficient to judge the characteristics of a material because it may have the required strength but in supporting the load may deflect considerably. In the case of an aircraft large structural deflections would result in a loss of the correct aerodynamic shape. Hence, strength is only of use if the resulting deflections are of an acceptable magnitude, in other words that the

[13] Was an I.C.I. trade name when the book was originally published, now a Du Pont trade name.

structure is adequately stiff. Stiffness is a measure of the load applied over a given cross-sectional area compared to the resulting deflection in terms of the original length. Young's modulus E is normally used to define stiffness:

$$E = \frac{Stress}{Strain} = \frac{W/_A}{x/_l} \left({}^{lb}/_{sq.in} \right)$$

where W = load applied (lb)

A = cross-sectional area over which the load is applied (sq.in)

x = deflection (in)

and l = original length (in)

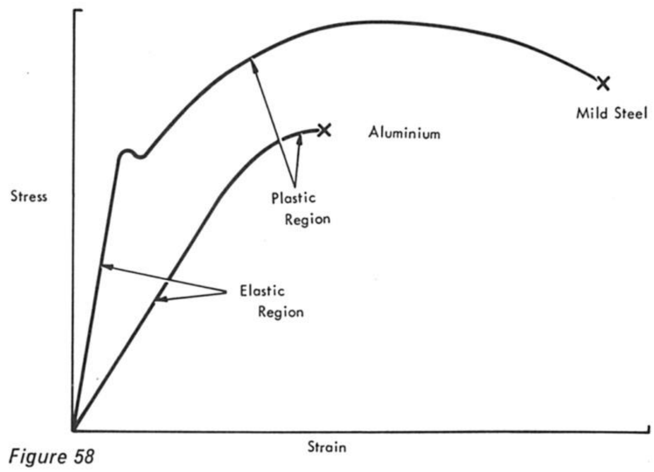


Figure 58

Young's modulus is also termed the modulus of elasticity because it only applies within the elastic region of the materials behaviour. A structural material deflects in two modes, first elastically and then if the applied stress becomes great enough it continues to deflect plastically. Figure 58 shows stress/strain curves, a more precise way of defining load/deflection properties, for two metals: mild Steel and Aluminium. Although both have different characteristics they both show the elastic and plastic regions. Within the elastic region the deflection is proportional to the applied load and when the load is removed the material returns to its original size. Within the plastic region the deflection is not proportional to the load and even when the load is removed the material remains deformed. Also within the plastic region materials experience a type of deformation known as "creep" where the deflection continues with time when the load is held steady.

It is important then to operate within the elastic region otherwise large permanent deformations of the structure result. However, although this is the ideal it is not always possible to achieve this state. With mild Steel there is a dramatic change from the elastic to the plastic region so that the designer can define exactly the limits of elasticity within which he requires the material to operate. Materials such as Aluminium and wood have a very gradual change from the elastic to the plastic region, so to utilise the strength properties of the material effectively some plastic deformation must be tolerated. The allowable strength for such materials is termed the Proof strength, and is defined as a certain ratio of the maximum stress the material is just capable of withstanding, in the case of man-powered aircraft a ratio of $^2/_3$ proves satisfactory for materials that have been used in practice.

Both curves in Figure 58 are taken to a typical breaking point which in the case of Aluminium and similar materials represents the maximum strength. This maximum stress point is defined as the ultimate tensile strength f_t. Materials subjected to compressive loading can also fail but not in this case due to breaking but to crushing. Maximum stress for this mode of failure occurs at the ultimate compressive strength f_c. Ultimate strength values are those on which the design is actually based, not directly of course, but when used in association with a suitable proof stress/maximum stress ratio such as the $^2/_3$ mentioned above.

Table 4

Material	d lb/in³	E lb/in²	E/d x10⁶	f_t lb/in² x10³	F_t/d x 10⁵	f_C lb/in² x 10³	f_c/d x 10⁵
Steel	0·28	29	1·03	190	6·8	198	7·16
Aluminum alloy	0·10	10	1·00	67	6·7	56	5·6
Magnesium alloy	0·066	6·5	0·98	40	6·0	28	4·2
Spruce, Sitka	0·016	1·3	0·81	9·4	5·9	4·7	2·9
Pine, white	0·015	1·1	0·73	7·6	5·1	4·0	2·7
Balsa	0·005	0·48	0·90	2·5	5·0	1·4	2·7
Carbon fibre	0·058	24	4·2	130	22·4	126	21·7
Glass fibre	0·074	7	0.95	110	14·9	39	5·2
Expanded polystyrene	0·0006	0·0008	0.013	0·022	0·37	0·015	0·25

8.2. Properties of materials

Table 4 presents a list of materials, together with their relevant strengths and stiffness values, that are considered to be of direct interest for man-powered aircraft application. Symbols used in Table 4 are d-material density; E-Young's modulus; f_t, and f_c, the ultimate tensile and compressive strength respectively.

Table 4 does not represent a completely comprehensive range of materials since such metals as Titanium and Beryllium have not been included for the reasons that they are not easily obtainable, are expensive and pose special manufacturing problems.

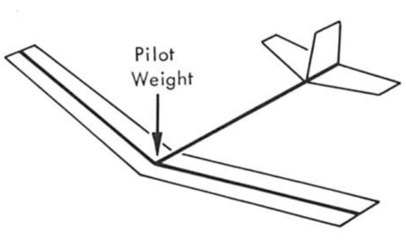


Figure 59

Properties quoted are for the Aluminium and Magnesium alloys that can be bought over the counter.

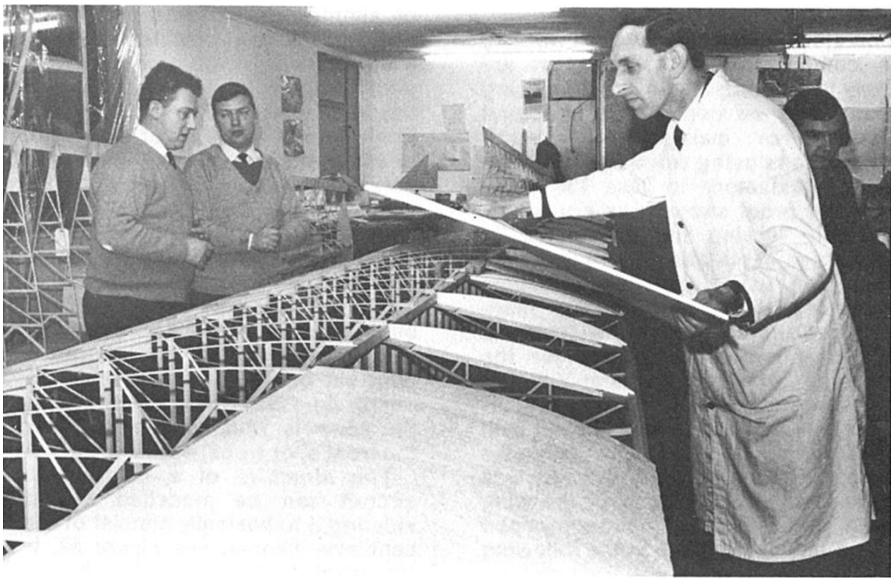
Properties quoted for the spruce and pine are those that apply at a 15% moisture level within the wood. All wood contains moisture due to its cellular nature both "free" in the cells and absorbed in the cell walls. The 15% level largely represents moisture absorbed in the cell walls and is the level that well seasoned wood can maintain in average temperature conditions. Varying the moisture level from this value affects the volume and strength of the wood. Checks can be carried out to ascertain the moisture level of a sample of wood by baking it in oven and comparing its weight before and after. Such checks are carried out where wood is to be used for structures that must comply with exacting requirements.

The properties presented for balsa wood apply also at 15% moisture level and to the particular density quoted. Both strength and stiffness values tend to vary in direct proportion to the density of balsa wood. The particular density quoted is a typical value since balsa wood with a density .anywhere between 0·003 and 0·008 lb/in^3 can be easily obtainable. Moisture levels within balsa wood tend to be stable providing that a large surface area is not used. "Puffin II" used small section balsa strips in the construction of the wing ribs and these gave satisfactory service for over 3 years. On the other hand "Puffin I" wing had most of its surface sheeted in balsa which proved unstable due to varying atmospheric conditions. At times the balsa dried out too much and the moisture level had to be increased to an acceptable level by steaming the outside surface by means of a kettle. The low moisture level was indicated by an accompanying shrinkage of the wood. However, it is feasible to build large balsa structures satisfactorily, for example the de Havilland Mosquito was largely constructed using balsa wood, but the wood has to be sealed and this imposes a weight penalty for man-powered aircraft applications.

Carbon fibre and Glass fibre are really misnomers because what is meant by these, at least within the context of this book, are Carbon fibre composites and Glass fibre composites. Composites are a term given to fibres within an epoxy resin matrix. Most people have seen glass-fibre composites as applied to the construction or repair of car bodies so there is no need to elaborate on this description. The strength and stiffness of fibre composites depends on how the fibres are arranged and in what direction the load is applied. Properties presented in Table 4 for Carbon and Glass fibre composites are valid for a 50% volume of fibre in the composites with all the fibres parallel and the loads applied along the fibres. Strengths are a maximum under these conditions so that if the use of other configurations is anticipated it is probably wise to obtain more detailed information from the supplier. For other glass-fibre composites it is impractical to quote any general values of properties due to the wide range of fibre forms available commercially.

Information on Carbon fibre composites is limited but that presented in Table 4 clearly indicates the improved strengths and stiffness it has over other materials when compared on a density basis. The use of Carbon fibre composites has been well published recently with regard to the fan blades in turbo-jet engines. Also there has been some limited use on racing cars but as yet there has been no general break through regarding the widespread use of Carbon fibre composites. Until this happens their high cost prohibits general use for man-powered aircraft. Nevertheless data on Carbon-fibre composites has been included in Table 4 for general comparative purposes.

The properties for expanded polystyrene are those applicable to the particular density quoted. A wide range of densities are available with 0·0004 lb/in^3 as a lower limit and 0·0012 lb/in^3 as a practical upper limit. Strengths and stiffness vary directly with the density but since these are so much lower than the other materials quoted, expanded polystyrene will largely be employed for secondary structures where low weight is of paramount importance. Therefore minimum density will be the criteria by which expanded polystyrene is chosen.



Leading edge section of Toucan is sheathed in expanded polystyrene supported by sub ribs of the same material. Application, and results of test sections have proved extremely successful.

The final choice of materials of construction does not only depend on the type of comparison made in Table 4 but also on structural considerations that will be discussed later. For example, Steel is indicated to be a good structural material in Table 4 but when actually applied to a man-powered aircraft design the required thickness to withstand the comparatively low loads involved may prove so small that it needs extra supports to prevent it buckling. This is just one example to show whilst a direct material strength and density comparison is useful it does have limitations, in the same way that the use of metals proved impractical for SUMPAC and spruce was used for the primary structure instead.

Properties quoted in Table 4 are not exact as all materials vary from sample to sample. Data presented in Table 4 are mean values so that if one tests several samples 50% are likely to have properties below those quoted. The designers' problem is to choose a strength value so that only a small proportion of samples have values lower than it. It is impractical to find a sufficiently low value so that all samples have values greater than it, so the designer normally accepts a value at which he is sure 95% of all samples will have a strength greater than this. It is termed the "95% confidence limit" and is included for in the $^{2}/_{3}$ ratio mentioned earlier that must be applied to the ultimate strength to obtain the proof strength value.

A study of Table 4 indicates that most materials are weaker in compression than in tension, taking three typical materials:

Aluminium alloy	f_c/f_t = 0·835
Sitka spruce	f_c/f_t = 0·50
Balsa	f_c/f_t = O·56

Therefore structural members working in compression are those that are likely to fail first, all other things being equal, and so control the structural design. For man-powered aircraft applications using wood or Aluminium it is satisfactory to take the compressive proof strength as $^{2}/_{3}$ x f_c.

Before leaving the discussion of properties of materials there may be a case for using plywood in some instances when considering man-powered aircraft. Certainly widespread use of plywood was made for the fuselage of the Haessler-Villinger machine but instead of using a standard type, special cedar plywood with a thickness of 0·024 in to minimise weight. Standard birch plywood was used in the construction of the wing span of "SUMPAC", such plywood being readily available in the following two grades:

Thick-ness	Wt (lb/in^2)	E × 10^6	f_s	f_t
0·032	0·135	1·78	2770	9160
0·064	0·258	1·71	2470	7880

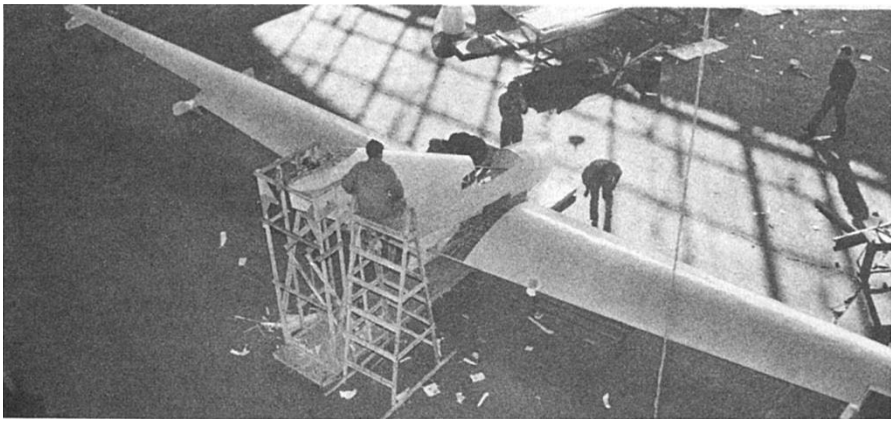
Values for f_t and E are as defined before, fs is the shear stress since plywood does not actually fail in compression but by shearing and buckling, therefore quoting values of f_c has little value. Properties of plywood vary depending on whether loaded parallel to or at right angles to the face grain direction. The data presented above is for loading parallel to the face grain in the case of the tensile strength and normal to the face grain in the case of the shear strength.

8.3. Overall structural considerations

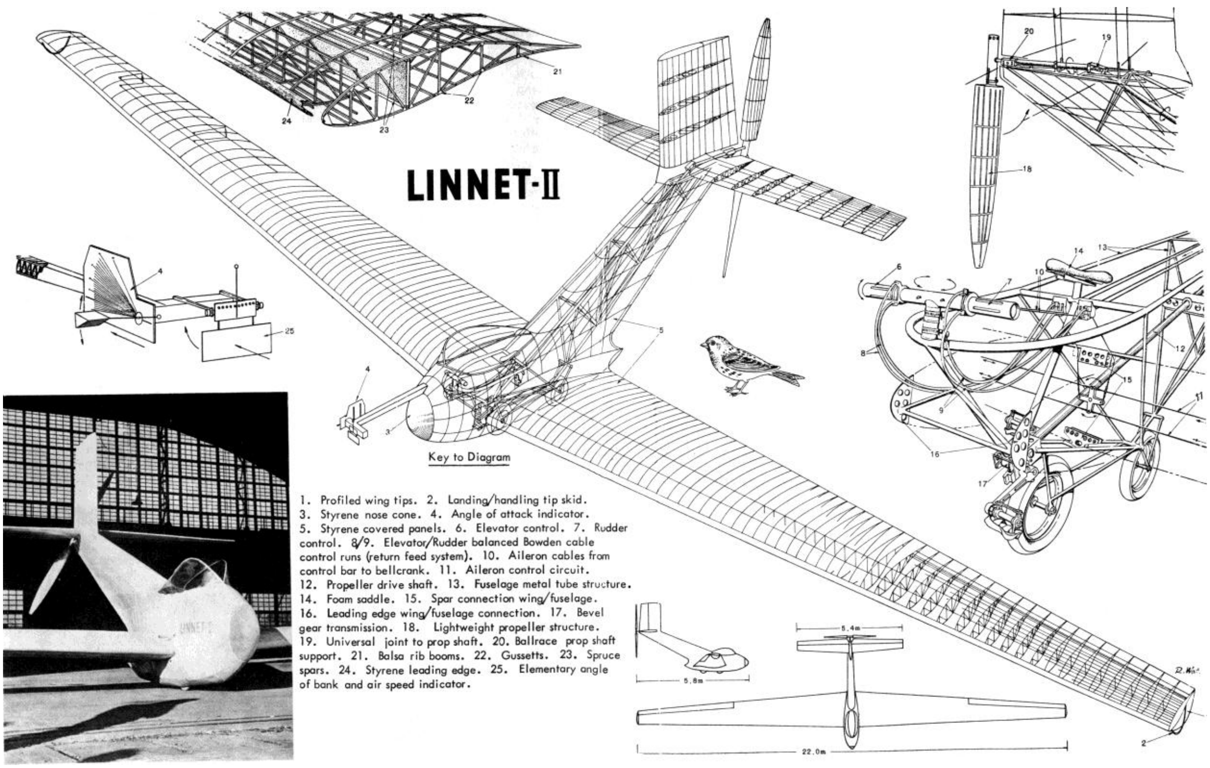
A complete aircraft is a complex structure and this is still valid when considering man-powered aircraft. It is not possible to analyse the aircraft structure as it stands, but rather to model the existing structure in terms of simpler components that can be analysed. A man-powered aircraft as a structure basically consists of the pilot support frame, the wings and the rear fuselage with these three firmly joined together at some point or within a small region. This is particularly important since the main weight to be carried is that of the pilot, the pilot support frame must be directly coupled to the wing primary structure to directly transmit forces. The interconnection between the pilot support frame and the wing structure was carried to the extent that the pilot sat between the two main wing spars on "SUMPAC" and operated the controls with his hands through the front spar webs, see Figure 67.

The structure of a man-powered aircraft can be modelled by considering it to basically consist of three cantilever beams, see Figure 59, two representing the left and right hand primary wing structures and the third representing the rear fuselage structure. This idealisation will allow us to lay down simple rules so that the sizes of the basic members of the wing structure can be calculated based on the material properties given in the previous section. However, before looking at structures in more detail it is necessary to consider whether they should just be designed to operate at cruising conditions when the materials are operating at their correct proof strength, or whether they should be overdesigned to allow for excess loads to be applied to the aircraft. Stated like this it must be evident that the aircraft structures must be overdesigned, the question being to what extent because if the structures are made too strong they also become too heavy and if too weak then failure can occur.

The proportion by which the actual strength of the aircraft structure is greater than that required to simply operate in level flight at cruising conditions, is termed the "load-factor" n. The value assigned the load-factor for a particular aircraft depends on its purpose and to assess this both the required manoeuvres and the atmospheric gusts that may be encountered must be considered. A typical modern high performance glider, for instance, has a maximum positive load-factor of +5 but such aircraft comply with stringent loading requirements. At the opposite end of the scale British civil airworthiness requirements specify a negative load-factor of -1 which is equivalent to inverted flight. Since man-powered aircraft fly very close to the ground and have limited manoeuvring capabilities of which inverted flight is certainly not one, it is adequate at the present time to employ a maximum *n* of +2 and a lower value of -0·5.



Linnet Mk. 1 being assembled in a hangar by students of Nihon University Tokyo. The short moment arm of the rear fuselage and high aspect ratio of the wings are evident as well as the requirement for precise assembly jigs to cope with the size of structure.



To consider the manoeuvring load factors that apply let us take an example of a man-powered aircraft with a wing loading of say 1·0 lb/sq.ft, i.e. total aircraft weight/wing area, employing the Wortmann FX-63137 aerofoil section with a design C_L of 1·15 and a stalling C_L of 1·8.

Cruise velocity =

$$V = \sqrt{\frac{W}{\frac{\rho}{2} C_L S}} = \sqrt{\frac{1 \cdot 0}{0 \cdot 0012.1 \cdot 15}}$$

= 26·8 ft/sec

This is the condition that corresponds to a load factor of + 1 and at this condition the minimum flying velocity is the stalling speed:

$$V_S = \sqrt{\frac{1 \cdot 0}{0 \cdot 0012.1 \cdot 8}} = 21.6\ ft/sec$$

where 21·6 ft/sec is the minimum velocity that is practicable at a load factor of + 1.

Referring to Figure 60 it is possible to construct a manoeuvring envelope or *V-n* diagram, a diagram within which possible manoeuvres of the aircraft can be defined. If a manoeuvre is attempted that falls outside the diagram structural damage to the aircraft may occur. Increasing the load-factor to +2 it is possible to increase the stalling velocity to 21·6 x √2 = 30·6 ft/sec at this value. The stalling velocities that are equivalent to particular load-factors define the stalling line representing one boundary, the upper left hand boundary to the diagram.

If the aircraft dives it is possible for the speed to increase well above cruising velocity; the question is what maximum design speed do we allow and what is the load-factor at that point. It is considered that a maximum altitude of say 20 ft be placed on the operation of man-powered aircraft, this being unobtainable by man-power alone but if gained by help from convection up-currents would be a suitable safe maximum within present-day restrictions. If the aircraft dived from 20 ft and if the whole of its potential energy was converted to kinetic energy the resulting maximum diving velocity would be given by:

$V_D^2 = V_C^2 + 2\ g\ h$

$= (26 \cdot 8)^2 + 2.32.20$

= 44·8 ft/sec

This velocity represents the right hand boundary of the manoeuvring envelope as shown in Figure 60 and to find the positive load-factor that applies at this velocity it is necessary to consider the ultimate strength of the structure. Maximum positive load factor is +2 which gives proof stresses in the structure under cruising conditions, i.e. V_C= 26·8 ft/sec, so that at the maximum diving velocity the required load factor would be equivalent to the ultimate loading (1·5 x proof loading). The load factor at V_D is given by:

$$1 \cdot 5\ \times 2\ \times \left(\frac{26 \cdot 8}{44 \cdot 8}\right)^2 = 1 \cdot 08$$

which is considered to be satisfactory. If the load factor at V_D had been below 1·0 then the assumed maximum diving velocity would be too great.

The negative section of the envelope is fairly arbitrary as it is unlikely that negative load-factors will be reached by manoeuvres alone. Stalling speeds for negative load-factors are higher than for the same positive load-factor because wing sections have lower maximum C_L values when working inverted.

The manoeuvring envelope shown in Figure 60 is well suited to man-powered aircraft operation since it covers adequately all possible manoeuvres yet gives a structure that is sufficiently strong for the aircraft to operate near the ground in winds of up to force 3 in strength. If in the future man-powered aircraft are required to operate in thermals at heights over 20 ft above the ground the load-factors would have to be increased, but at the expense of increasing weight.

Structural proof strength requirements are defined by the case of a positive load-factor of 2·0 at the cruising velocity V_C.

8.4. Design of wing spars

The primary structure of a man-powered aircraft wing can be modelled by two cantilever beams. A cantilever beam is one that is fixed and supported at one end only. In the case of a man-powered aircraft the support is the main unit joining the wings to the fuselage. The most stringent requirement regarding the structural design of a man-powered aircraft is the primary structure of the wing and this can be modelled by cantilever beams with one of two different types of loading, either uniformly loaded or with uniformly varying loads. Figure 61 illustrates the difference between the two, the uniformly distributed load (a) representing the lift on a wing of rectangular plan form, whilst the uniformly varying load represents the lift on a wing of uniformly tapering plan form.

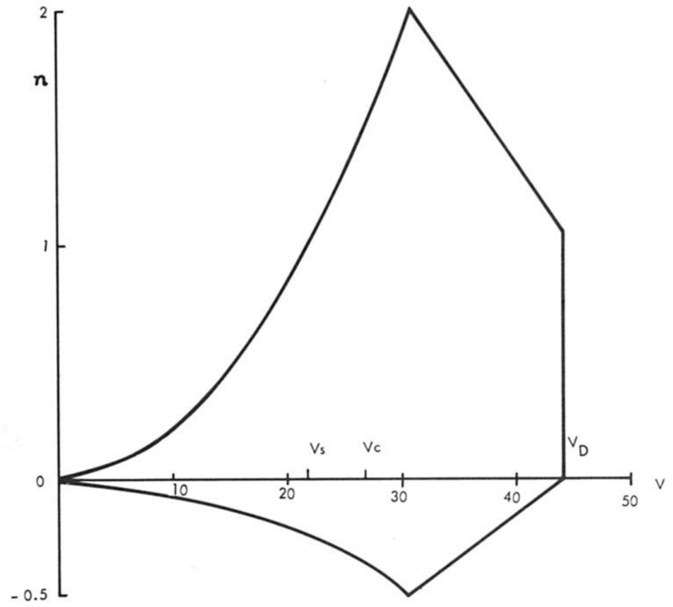


Figure 60 Typical non-powered aircraft manoeuvring envelope

Strength requirements of the wing primary structure depend not only on the length and loading of the beam, but also its cross-sectional shape defined by z its “section modules” with units of in^3. Figure 62 shows two typical symmetrical sections that are of practical interest for man-powered aircraft:

(i) “I” section beam, suitable for wing spars having good bending properties but if only one is used it allows the wing to twist under aerodynamic loads. Where two spars are used and are braced together to take torsional loading, it results in a very rigid structure, this type of structure being employed for “SUMPAC”, “Puffin II”, Weybridge and H.P.A. “Toucan” projects.

(ii) Box beam, having good bending properties and some resistance to twisting. Used for the Japanese “Linnet” aircraft with spruce flanges and balsa wood webs. Very much simpler to construct than the structure mentioned above employing two spars.

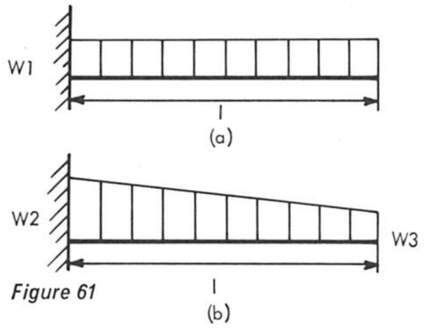


Figure 61

There is another possibility, that of using a stressed skin around the nose of the wing but in practice this has proved unsatisfactory since balsa construction is too unstable whilst other materials tend to be too heavy.

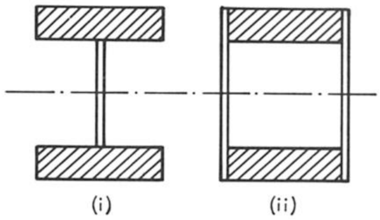


Figure 62

The bending stiffness of both the "I" section and box section beam is concentrated in the top and bottom flanges. Under normal loading the top flange is compressed whilst the bottom one is in tension. Since the compressive strength is less than the tensile strength it is the load on the top flange that controls the design. It is convenient to make both flanges the same size and this certainly simplifies the design procedure. If the vertical webs are very thin compared to the flange thickness and both flanges are of the same size then the section modulus for both types of structure can be approximated by:

z = 2 x flange cross-sectional area x distance from centre line to bottom of flange.

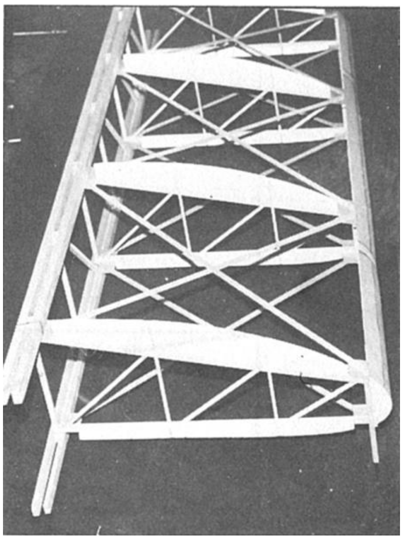
The maximum compressive stress in a cantilever beam can be calculated from the following equations:

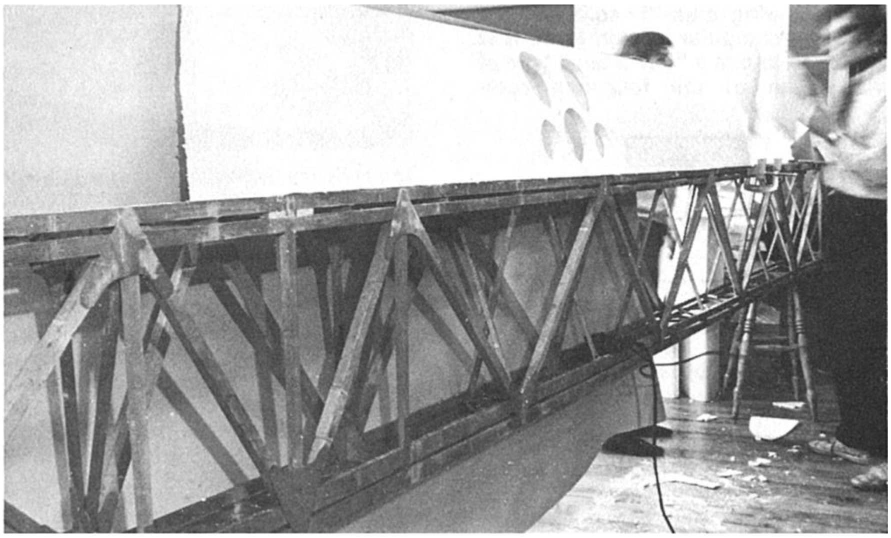
(a) Beam uniformly distributed load of W_1 lb/in:

$$f = \frac{W_1 l^2}{2z} \qquad (21)$$

(b) Beam with load uniformly varying from W_2 (lb) at the root to W_3 (lb) at the tip:

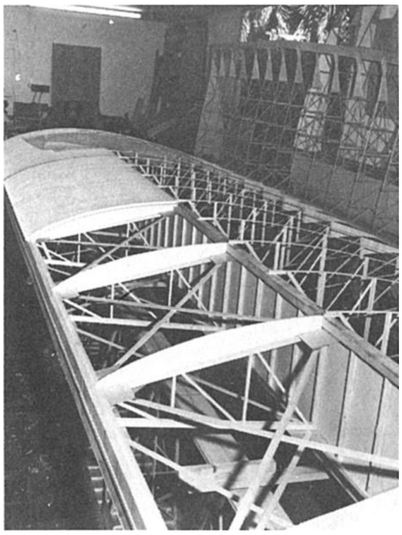
$$f = \frac{(W_2 - W_3) l^2}{6z} + \frac{W_3 l^2}{2z} \qquad (22)$$





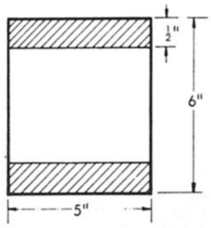
Above: Puffin main spar unit being incorporated into Liverpuffin wing.

Below left: test section of Toucan wing showing I spar and below, the final development with vertical braces and ply web plus sturdy L.E.



When considering the structural design of a wing spar the loading not only comes from the lift but also the weight of the wing itself, the weight opposing the lift. Typical weights of wings for existing aircraft are given in Figure 63. Although there is some scatter most of the wing weight/span values fall within the shaded area shown. The highest value represents the Bossi-Bonomi machine which was built with a high load factor to comply with the pre-war Italian air worthiness requirements, whilst the lowest value represents the Japanese "Linnet" so both are exceptions to the general design trend.

Application of the above formulae to a wing span problem can best be explained through a typical example. Consider the aircraft discussed in Chapter 5, 70 ft wing span, total weight of 245 lb, wing area 327 sq.ft and the wing is rectangular in plan form. It is proposed to use a "box beam" type of wing span of the following root section:



Would this spar be suitable if the top and bottom flanges are constructed of spruce?

The first point to check is whether there is sufficient depth of aerofoil section to accommodate this span. This particular wing has a chord of 327/70 = 4·66ft. Since the aerofoil section is the Wortmann FX-63137 with a thickness/chord ratio of 13·7% the maximum thickness is 0·64 ft = 7·7 in so there is adequate space to accommodate the proposed span.

To work out the loading on the wings, the total lift load at V_c = 245 lb. From Figure 63 a typical wing weight of 70 (lb) can be assumed.

load on wings=245-70=175 lb at V_C

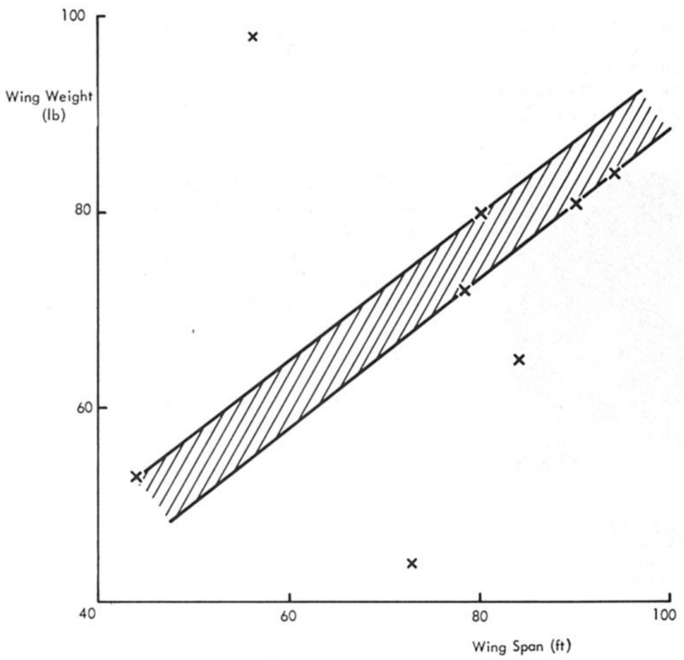
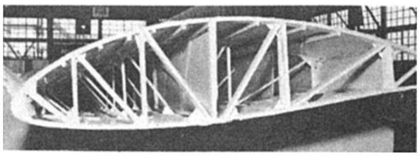


Figure 63 Variation of wing weight with span for man-powered aircraft.

The load factor is 2 so the total design load on the wing is 350 lb.



Linnet II wing section showing structure with span-wise longerons.

Considering the spar to be a uniformly loaded cantilever beam, due to the rectangular plan-form, of length 420 in with a uniformly distributed load of 350/840 = 0·42 lb/in. From equation (21):

$$f = \frac{W_1 l^2}{2z} = \frac{0 \cdot 42(420)^2}{2z} = \frac{37{,}000}{z}$$

Now z = 2 x flange area x

distance from centre line to flange

= 2 x $2^1/_2$ x $2^1/_2$ = $12^1/_2$ in^3

$$maximum\ stress\ f = \frac{37{,}000}{12.5}$$

= 2960 lb/in^2

From Table 4 the ultimate compressive strength for spruce is 4700 lb/in^2 so the proof strength is $^2/_3$ x 4700 = 3140 lb/in^2

Hence the spar as proposed is adequately strong having a margin of

$$\frac{3140}{2960} = 6\%$$

This margin could either be maintained as an additional safety margin or the span flanges could be cut down by 6% in order to save weight. The final choice depends on the purpose for which the aircraft is intended and therefore how critical weight is.

If the spar was retained at the same cross-section along the length of the wing the total weight of the flanges alone would be:

4 x 420 x $2^1/_2$ x 0·016 = 67·2 lb

which nearly represents the total wing weight assumed for this aircraft. This weight is obviously too great and it could be reduced in practice by tapering the flanges from the given thickness at the root where the maximum load occurs to say, $^1/_{16}$in thickness at the wing tips.

Deflection will be fairly large at the wing tip with this type of construction, of the order of 3 ft, but providing the strength requirements are complied with it can be an advantage because it increases the effective dihedral angle of the wing so improving lateral stability of the aircraft.

8.5. Wing construction

The example given in the previous section indicates the procedure by which the wing spar structural performance can be checked. However, with regard to the actual construction of such a spar two further points must be considered namely:

(a) the construction of the webs; and

(b) the positioning of the spar in the wing.

A suitable material for the construction of thin webs is plywood and the particular spar under discussion would have adequate shear strength with webs of 0·032 in thick plywood. This can be checked because the direct shear load on the spar at the root is equal to the load between the root and the wing tip, i.e. 175 lb. With two webs 6 in high and 0·032 in thick the total cross-sectional area = 0·384 sq. in.

$$\therefore shear\ stress = \frac{175}{0 \cdot 384}$$

= 455 lb/sq. in

which is well below the shear strength of 2770 lb/sq.in quoted for this type of plywood.

Although two 0·032 in thick plywood should give adequate strength there would be a tendency for them to buckle in practice. This can be overcome by vertical supports, say of balsa wood, positioned at approximately 9 in intervals as shown in Figure 64.

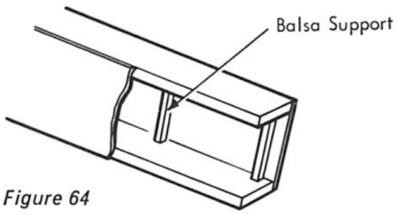
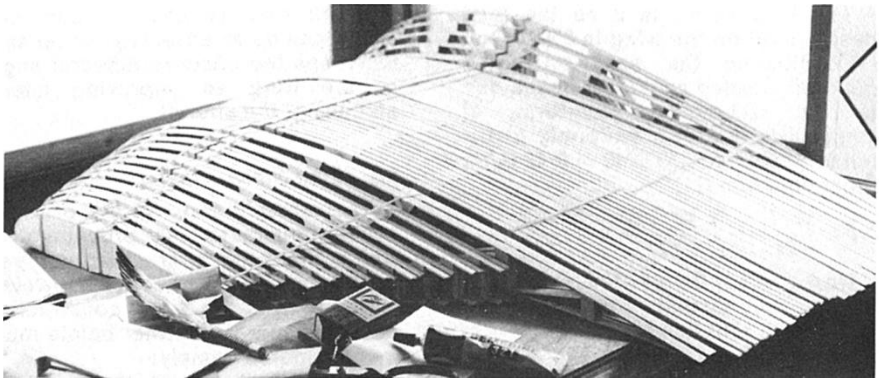
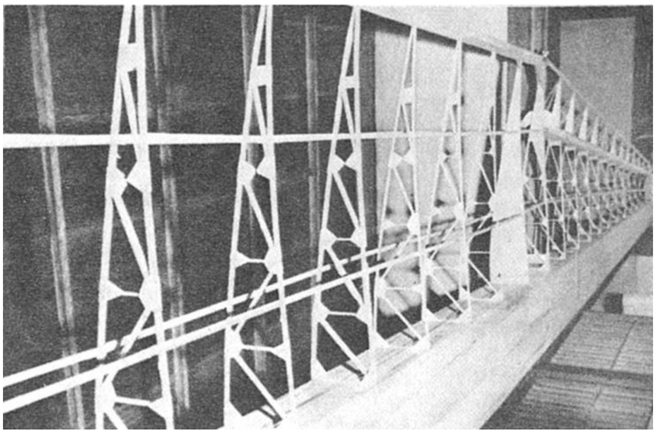


Figure 64



Positioning of the spar in the wing must be such that twisting of the wing is minimised under aerodynamic loading. Generally the pressure on an aerofoil tends to act about a centre of pressure at approximately $^{1}/_{3}$rd chord back from the leading edge and to minimise twisting of the wing this is the point at which to place the spar. Figure 65 shows the box spar in position in the Wortmann FX-63137 section.

Figure 66 shows a twin spar type of wing primary structure, this being the one used for "Puffin II" but typical of the type used for other aircraft. The important thing to notice is the torsion bracing between the two spars to minimise twisting of the wing. Balsa strips are generally used for this purpose.



Top: collection of wing ribs, and at left, the assembled wing of the Nakamura man-powered aircraft illustrate use of a Leading Edge box spar arrangement.

Spruce is a most suitable material for the wing spar flanges, not only can it be easily used without the need for elaborate manufacturing equipment but also the sections used are sufficiently large so as not to buckle under working conditions. Comparing values of f_C and f_C/d for spruce and Aluminium we find that:

	f_C	f_C/d
spruce	4,700	2·9
Aluminium	56,000	5·6

On this basis Aluminium would appear to be far superior but consider the span example in the last section. Each spruce flange size was 5 in x $^1/_2$in at the root. To maintain the same strength the flange size using Aluminium would need to be 5 in x 0·042 in at the root. It would be impossible to reduce this thickness any further along the length of the span and even at this thickness additional supports would be needed to prevent it buckling. Furthermore the nearest standard size of available material would be 18 gauge (0·048 in thick) so that all together the Aluminium would come out very much heavier than the spruce with this type of construction, whilst Carbon fibre composites are far too costly. Recently thin Aluminium tubing has been used for the primary wing structure of the Weybridge aircraft. The type of structure is the twin spar type with 4 tubular webs and thin (10 thou. thick) tubular bracing.

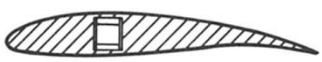
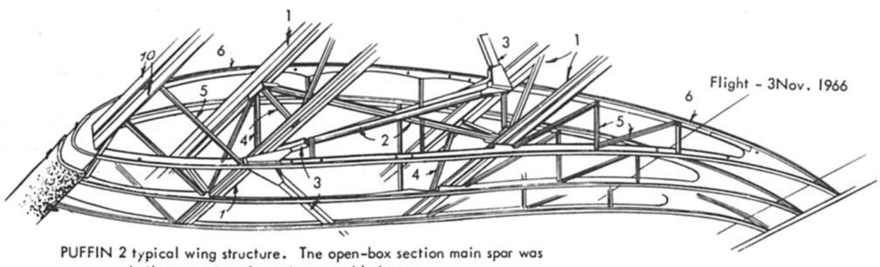


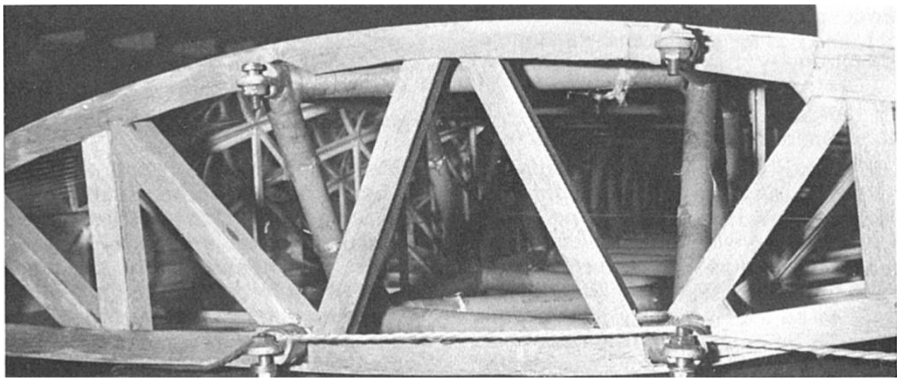
Figure 65



PUFFIN 2 typical wing structure. The open-box section main spar was built as a unit before wing assembly began.

1. Spruce main-spar box
2. Balsa cross-bracing every fifth hole
3. Horizontal balsa cross-bracing
4. Vertical bracing between upper and inner spar boom (Spruce inboard, balsa outboard)
5. Balsa rib bracing
6. T – section balsa ribs

Figure 66



Combination of metal tube wing spars and balsa ribs for the Weybridge machine is in part influenced by use of articulated wing panels for lateral control. This is a semi span transport break joint.

One other material that does show promise for use in wing spars is glass fibre composite. This is widely used in glider construction and allows sufficient flexibility in manufacture for the wing spar cross-section to be maintained at its optimum along its length. One possibility for the man-powered aircraft application is a basic box structure of expanded polystyrene wrapped around the outside with glass fibre and coated with epoxy resin bonding material. However, more research is required at the present time before this can become a standard form of construction.

Design of the wing secondary structure must be such that it is sufficiently stiff to maintain the correct aerodynamic shape yet have minimum weight. Figure 66 shows the girder type of balsa ribs used on “Puffin II”. A similar type of rib construction was used for “SUMPAC” based upon the use of $^{1}/_{4}$ in x $^{1}/_{8}$ in balsa bracing strips. This type of construction is satisfactory but is laborious to make and requires storage in a fairly well controlled atmosphere; if too damp the structure can warp. It is only considered to be necessary when weight is of paramount importance. Where some weight can be added in order to provide a more robust structure or to reduce construction time then sheet ribs of either plywood or balsa may be used. Both would need capping with balsa strip to prevent damage occurring to the covering material. Positioning of the ribs is a compromise between aerodynamic efficiency on the one hand and constructional time and weight on the other. “Puffin II” used ribs at $4^{1}/_{2}$ in centres whilst “SUMPAC” used ribs at 9 in centres without any apparent loss of aerodynamic efficiency.

Recently expanded polystyrene has been considered for the secondary structure of wings. It has the advantage of being easily shaped with hot-wire cutters and being of very low density. Its application to a man-powered aircraft will be discussed more fully in Chapter 10 with regard to “Liverpuffin”.

8.6. Fuselage construction

Stiffness is the most important aspect of the fuselage design because it supports the rudder and elevator control surfaces and too great a deflection under aerodynamic loads would prevent these fulfilling their correct function. The fuselage construction on “SUMPAC” was a spruce framework braced with wires, shown in Figure 67. A framework of this nature provides the most effective form of construction for conventional fuselage shapes. More recently Steel and Aluminium tubes have been employed for this type of framework, due to their improved stiffness characteristics, (E/d) given in Table 4, on the Japanese “Linnet” and Weybridge projects.

Thin Aluminium tubes are to be employed for the fuselage of the C.A.S.I. Ottawa project, and to minimise weight wall thickness of 0·016 to 0·020 in are envisaged. Welding and bolting are impractical for such thin tubes and a special laced joint has been developed by Professor Czerwinski[14] to overcome these problems, see Figure 68. The tubes are cemented together with epoxy resin then laced with fibre-glass cords and finally saturated with low viscosity epoxy resin. Joints of this type have been used extensively on the Weybridge aircraft and can provide strengths as great as that of the parent Aluminium tube and have the advantage of being versatile, whilst not requiring any special tooling. Before considering the use of such a type of joint in practice one would need to examine whether the weight penalty of simpler bolted joints would be acceptable, also test specimens would need to be tried before finalising the design.

The fuselage for Puffin was of monocoque construction where all the loads are carried in the skin. This was a most sophisticated design using sheet balsa for the skin. Construction was complex but unfortunately it did not survive the crash of "Puffin II" in 1969.

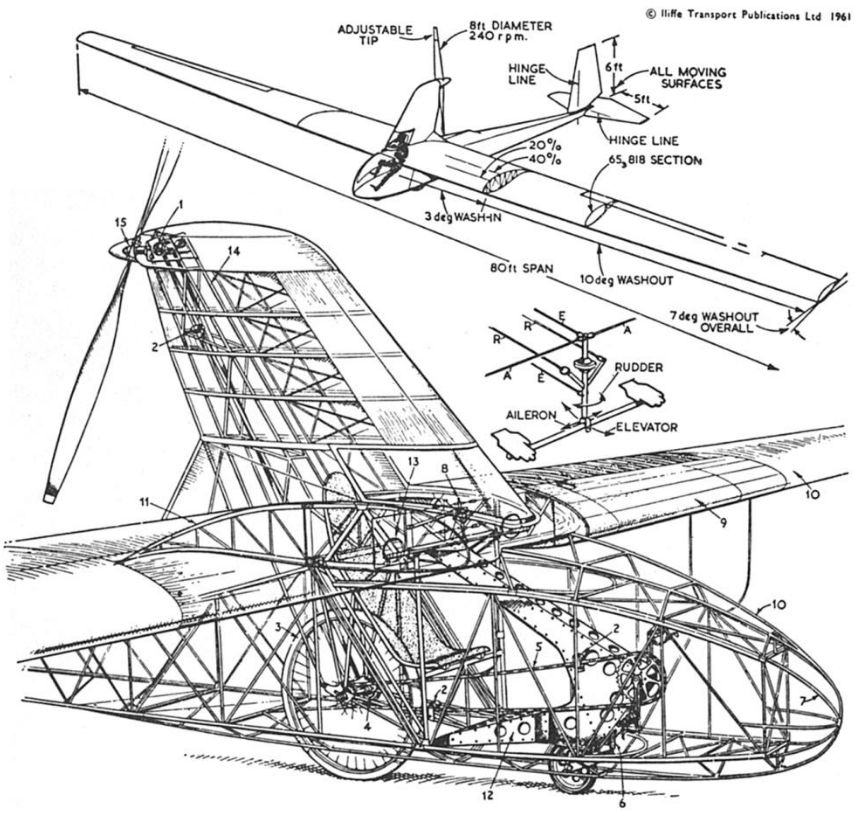


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Figure 67

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[14] Structural trends in the development of man-powered aircraft, W. Czerwinski, *Journal of the Royal Aeronautical Society*, January 1967.

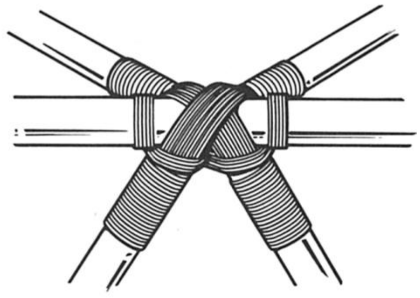
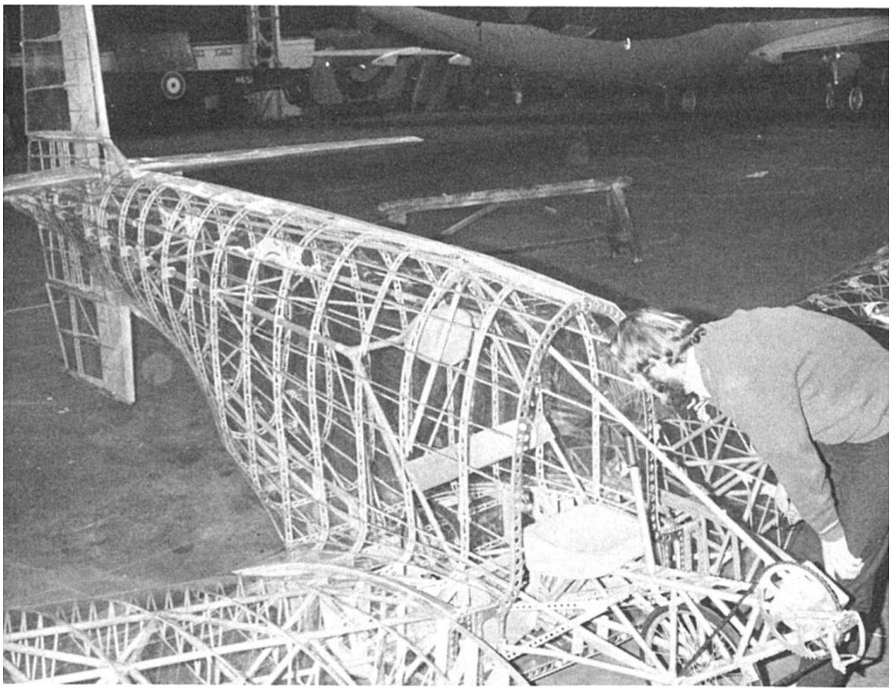


Figure 68

Earlier discussion regarding overall aircraft drag indicates that the fuselage drag will only be a small proportion of the total drag. It is therefore worth considering a fuselage design aimed at constructional simplicity rather than aerodynamic refinement, the “pod and boom” type of construction. The pilot is housed in the “pod” and the tail surfaces are carried on a “boom”. The “boom” for such a fuselage represents the major part of the structure and this can be simply solved by using a standard Aluminium tube or possibly a wooden box construction. Chapter 10 discusses the “pod” and “boom” type of fuselage in more detail.

The fuselage frames for the Weybridge machine are made up of braced and laminated booms to form an external streamline shape for the basic metal tubular fuselage structure. Melinex covering, applied here, is completely transparent.



9. AIRCRAFT CONTROL

THE function of aircraft controls is to allow the pilot to execute any desired manoeuvre with the aircraft. Obviously with man-powered aircraft the manoeuvres will be limited for various reasons:

(i) limited altitude;

(ii) limited attention that the pilot can give to manoeuvring the aircraft whilst also powering it;

(iii) the limited load factors that the structure is designed to withstand; and

(iv) limited additional power available for actually executing manoeuvres.

Manoeuvrability depends not only on the controls provided but also the "inherent" stability of the aircraft. Stability determines how an aircraft will react if gusts or other external forces move an aircraft away from its prescribed position. "Inherent" stability concerns the response of the aircraft to such forces when the controls are fixed and the aircraft responds of its own accord.

Controllability of an aircraft depends to some extent on the inherent stability. A totally stable aircraft would always fly straight and level, so would not be controllable. On the other hand fighter aircraft must be manoeuvrable so stability is reduced to a minimum. Therefore between the two is a compromise that is acceptable for man-powered aircraft.

9.1. Inherent stability

Aircraft stability is a large subject but it will only be considered to the extent that it can provide useful answers for the designer regarding the sizes of tail surfaces and the wing dihedral angle. This is the angle which the wing is inclined to the horizontal and is defined as β.

Figure 69 defines the three axes, longitudinal, lateral and vertical about which the aircraft is free to move; the motions being:

rolling-about the longitudinal axis

yawing-about the vertical axis, and

pitching-about the lateral axis.

These motions take place about the centre of gravity of the aircraft so that the position of the centre of gravity is important. For man-powered aircraft, having limited manoeuvrability, a satisfactory ruling is that the aircraft centre of gravity should be directly under the centre of lift of the wing at $^{1}/_{3}$ chord. Pilot weight can be moved to give this correct CG position.

One other motion that the aircraft can execute is the side-slip, this being discussed below during the section on "lateral stability".

Longitudinal stability is the basic requirement for an aircraft to fly since it defines the required tailplane. Consider an aircraft flying along and a gust causes the nose to tilt upwards, shown in Figure 70. The wing angle of incidence at position *(b)* is greater than for position (a) so that it produces more lift. If the wing was on its own it would tend to carry on increasing angle of incidence until it stalled and its behaviour became unstable.

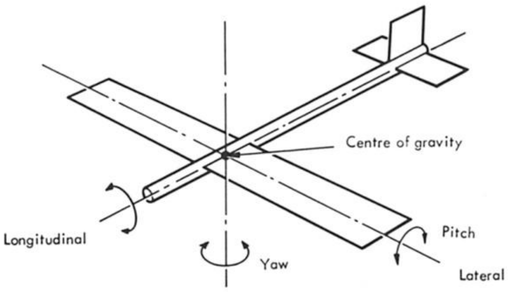


Figure 69

However, referring to Figure 70 as the wing angle of incidence increases the tailplane meets the airstream at a positive angle of incidence. Lift is generated by the tailplane, bringing the tail up and restoring the correct flying attitude of the aircraft.

Longitudinal stability requires that the tailplane area and distance from the centre of gravity are sufficiently large for the forces on the tail to overcome the out of balance forces on the wing. Assuming a symmetrical aerofoil section for the tailplane a general empirical ruling that is suitable for man-powered aircraft is:

$$area\ of\ tailplane = \frac{0{\cdot}2.S.C}{l} \qquad (23)$$

where S = wing area (sq.ft)

C = wing mean chord (ft)

l = distance from the aircraft CG to centre of the tailplane (ft)

The area of the tailplane found in this way also includes the area of the elevation, the area of which can vary from 30% to 100% of the tailplane area. When the elevators represent the total tailplane area this is the case of an all-flying tail.

Figure 70

Although the equation (23) provides a ruling for longitudinal stability it gives no indication of the aircraft behaviour that will result in between the aircraft being disturbed and it settling back to its old flying attitude. Two types of aircraft longitudinal motion can occur pitching and/or phugoid motion defined in Figure 71. Pitching is an oscillation of the aircraft about its correct flight path and generally each oscillation occurs within a short period below 3 seconds. Should it prove troublesome in practice the size of the tailplane or the distance from the wing must be increased to combat it.

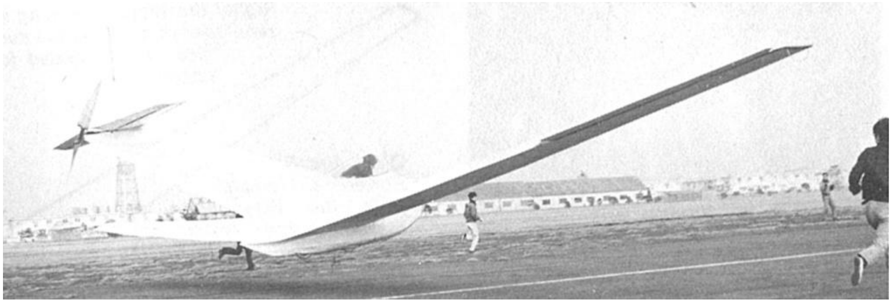
Phugoid motion is an oscillation in height at a fixed angle of incidence relative to the flight path. It is produced when the pitching oscillation does not die out rapidly and the pilot overcorrects. It results in a velocity variation the highest velocity being at the bottom of each oscillation with the lowest velocity at the top. The time taken for oscillation is given by:

$$t = \frac{4 \cdot 4.V}{g}$$

where *t* is in seconds, V is the true airspeed in ft/sec, and g = 32·2 ft/sec^2. For most aircraft the time for each oscillation is so large that the pilot can exercise the necessary corrective action. However, for man-powered aircraft the airspeed is sufficiently low for t to be of a similar order as that for the pitching motion. Phugoid motion may be troublesome and was experienced with both

SUMPAC and Puffin. Experience with Puffin indicated that if the pilot attempted to fly the aircraft by judging it's correct attitude against the horizon the phugoid oscillation occurred, but it did not occur when the aircraft was flown on the basis of constant speed.

Below: Linnet II at the critical stage of lift-off at Chofu airport Tokyo in 1967. The Aileron shows need for correction of the left bank. Elevators are deflected up, later the Linnet appears to have been fitted with an inverted aerofoil tailplane section.



Although longitudinal stability is largely controlled by the tailplane, the fuselage and the position of the propeller also have some effect. The fuselage itself acts like an aerofoil section in the direction of flight and produces lift which opposes the action of the tailplane. Therefore the fuselage has a destabilising effect. Propellers tend to act like additional lifting surfaces so that a tractor propeller works in the opposite direction to the tailplane tending to destabilise the aircraft whilst a pusher propeller has a stabilising effect.

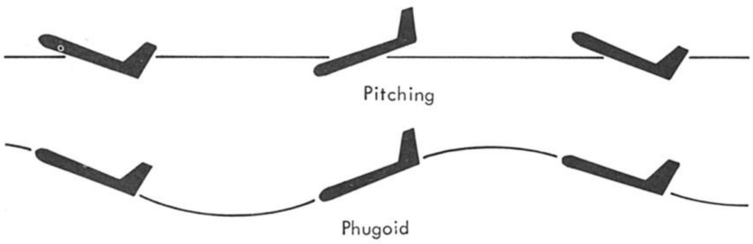
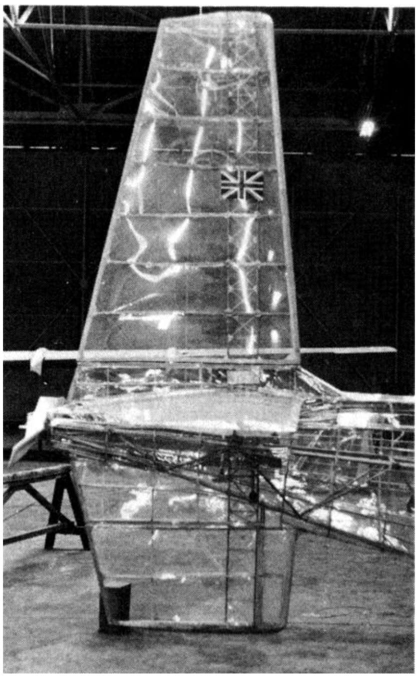


Figure 71

The foregoing discussion on longitudinal stability concerns the conventional tailplane set at the rear of the wing. However, it is possible to have a canard arrangement where a foreplane is set in front of the wing. This is a more complex problem than the conventional tailplane because stability can only be maintained if the change of C_L with the angle of incidence is less than for the main wing. If a gust forces the nose up then the increase of lift must be greater for the main wing than for the foreplane. One advantage of the canard arrangement for a man-powered aircraft is that it provides a surface in front of the pilot from which he may judge the flying attitude of the aircraft with reference to the horizon.

Before leaving the topic of longitudinal stability one other practical aspect is that of considering a flying wing aircraft. Stability is usually maintained by sweeping back the wings in this case so that the part of the wing with the elevators attached is operating well to the rear of the main lifting section of the wing, in a similar way to a normal tailplane.



Of all the Man-Powered aircraft projects the Weybridge machine control system is the most adventurous. All the surfaces are moveable except for the small fixed area at top and front of lower fin (above).

Lateral stability is a collective term for two types, “weathercock” and “spiral” stability. Weathercock stability is as its name implies that characteristic that enables the aircraft to follow a straight course just as a weathercock will point the wind direction in a stable manner. Another term for weathercock stability is “directional” stability. It is dependent on the side area of the aircraft. The fuselage alone is normally unstable and vertical tail surfaces, i.e. fin and rudder, must be provided. The basic mechanism of weathercock stability is similar to that for longitudinal stability and is dependent on the fin size and distance from the aircraft CG defined by n_V, the yawing moment due to sideslip:

$$n_V = \left(\frac{S_F l}{Sb}\right)\alpha \qquad (24)$$

where S_F= fin area (sq.ft)

l = distance from the aircraft CG to the centre of the fin (ft)

S = wing area (sq.ft) *b* = wing span (ft)

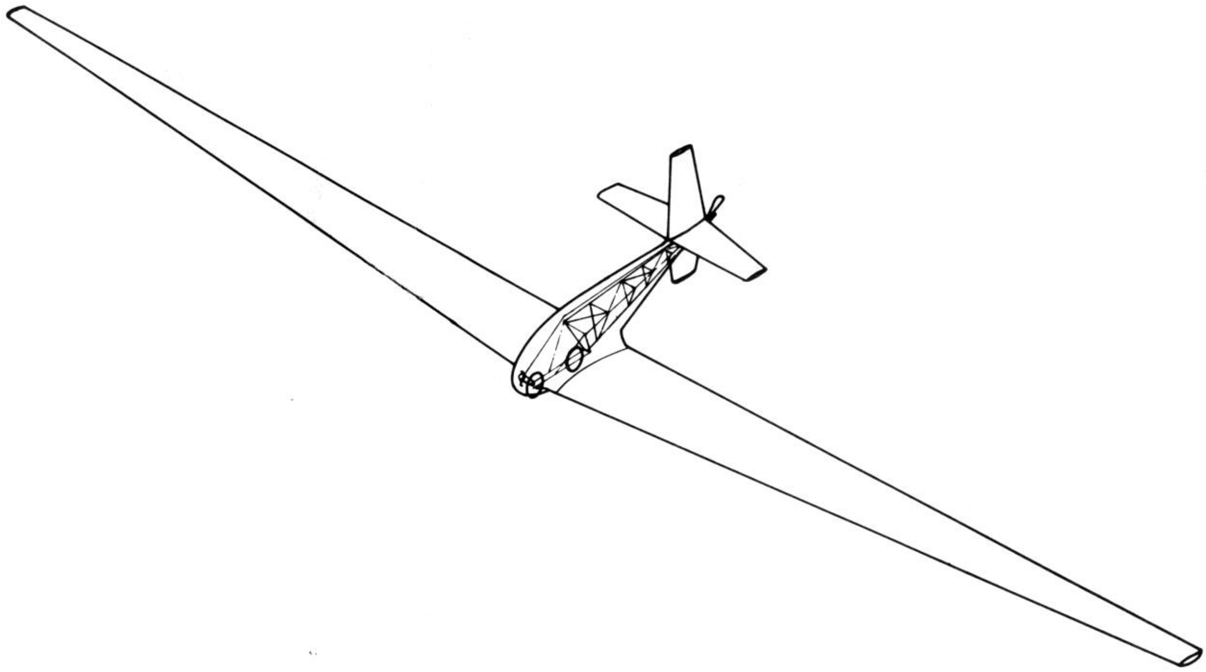
and a = changes of lift coefficient with changing angle of incidence,

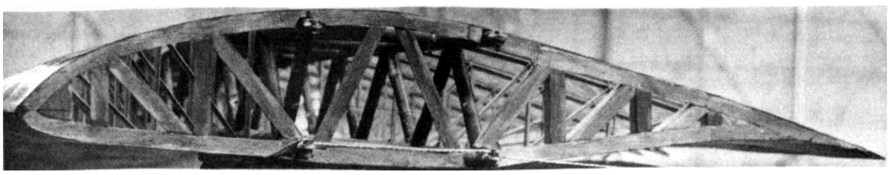
= 0·1/deg for the Wortmann FX-63137 aerofoil section.

Assuming a symmetrical aerofoil section for the fin a general empirical ruling that is suitable for man-powered aircraft and has also been proved by experience with gliders is that n_v should not be less than 0·0007, i.e.

$n_v \geq 0{\cdot}0007$

This gives a ruling by which the size of the fin can be found and is a basic requirement whether a rudder is incorporated on the aircraft or not. At least one man-powered aircraft, H.P.A. “Toucan”, is being designed without a rudder.





Above: the Weybridge wing at semi-span joint, the entire surface can be rotated for lateral control.

Problems arise if the fin is made too large (n_v much larger than 0·0007) as it increases the tendency of an aircraft to become spirally unstable. Spiral instability is where an aircraft, if disturbed begins a shallow turning dive which continues to tighten-up until, if it continues far enough, the aircraft goes into a spiral dive or spin. The larger the fin the more the aircraft is forced round into a tighter turn. With the aircraft in such a position the wings are banked so that the lift is also forcing the aircraft into a tighter turn. It is virtually impossible to maintain spiral stability at the high lift coefficients used for present day man-powered aircraft, but providing that the rate of tightening-up is low the pilot can correct for it.

Spiral stability can be improved by increasing the dihedral angle of the wing. The effect of dihedral is important during the side-slip of an aircraft which results when it is banked, either intentionally or due to some external force, simply because there is a component of the lift in the horizontal direction. As the aircraft side-slips and providing it has dihedral the air meets the lower wing at a high effective angle of incidence than the higher wing, see Figure 72, so increasing lift on the lower wing which provides a righting motion.

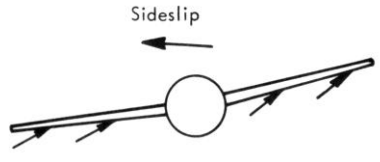


Figure 72

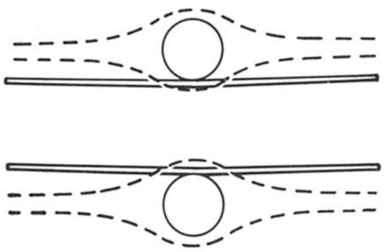


Figure 73

Dihedral also has an effect on Dutch Roll which is a combination of both rolling and yawing, deriving its name from the ice-skating on the canals of Holland. It consists of a roll and yaw in one direction which is over-corrected with the aircraft overshooting to roll and yaw in the other direction. This need not be troublesome providing the amount of motion is not excessive. Large directional stability and smaller dihedral tends to damp it out but in the case of a man-powered aircraft the dihedral angle must be a compromise between spiral instability and Dutch Roll requirements. Assuming that dihedral is constant along the length of the span, then the lateral behaviour is defined by l_v, a non-dimensional measure of the rolling moment due to sideslip.

$$l_v = {}^1/_4\beta\alpha \quad (25)$$

where β = dihedral angle (degrees)

and α = changes of lift coefficient

with changing angle of incidence

= 0·1/deg for the Wortmann FX-63137 aerofoil section.

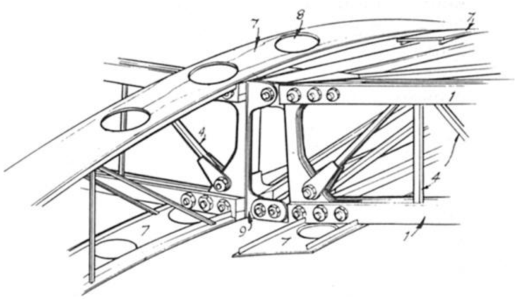
This is an approximation which is suitable for design purposes. No hard or fast rules have been developed but for a high wing man-powered aircraft a suitable ruling is that

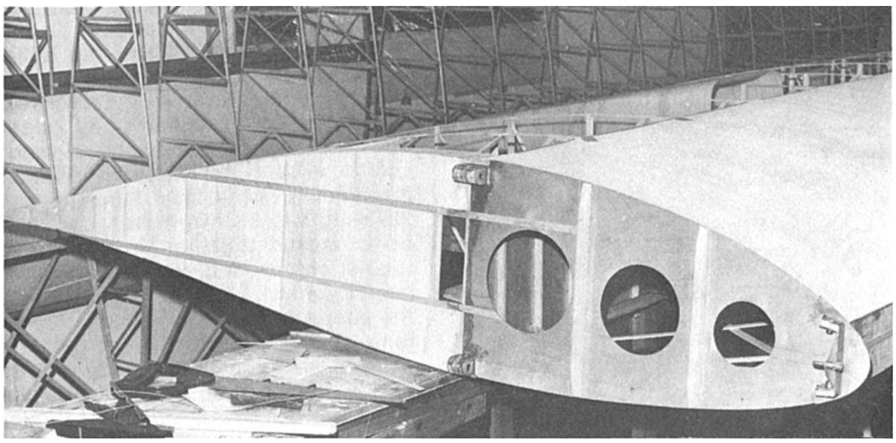
l_v= -0·12

Using this as a starting point the actual dihedral angle can possibly be modified on the actual aircraft to provide more acceptable handling conditions. The position of the wing is important in connection with the dihedral angle because during sideslip the airflow round the fuselage increases the effective dihedral angle of a high wing and decreases the effective dihedral angle of a low wing, illustrated in Figure 73. This is why a low wing aircraft requires a greater dihedral angle than a high. Typical values of dihedral angles chosen for man-powered aircraft have been 5° for “SUMPAC” and 11° for “Puffin II”. Although the two appear to be un-related the dihedral angle for “Puffin II” only applied over the two outer wing sections and where only part of the wing is used in this manner, dihedral angles have to be increased accordingly.

The position of the wing has some effect on lateral stability since the position of the aircraft centre of gravity in relation to the wings depends on it. If the centre of gravity is below the wing it has a righting effect on a banked aircraft. Therefore it follows that a high wing configuration improves the lateral stability. It is also found that sweep back enhances the dihedral effect during a side-slip.

Lateral stability of a man-powered aircraft is made more complex than that of conventional aircraft by having to bank near the ground where the effect is to reduce the induced drag on the lower wing and increase it on the higher wing. If the bank is associated with a turn the result of the ground effect is to reduce the amount of turn actually achieved or if the rudder power is insufficient, possible to turn in the opposite direction.



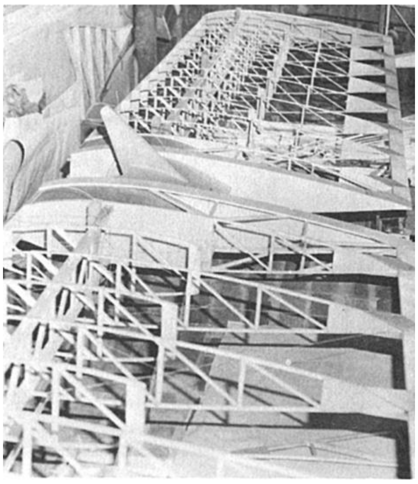


Transport break at semi-span on Toucan has provision for the dihedral adjustment about the chord line indicated by the pickup at the leading edge here, and with variable links at the two spar joint lugs on the plywood and sheet balsa faced end rib.

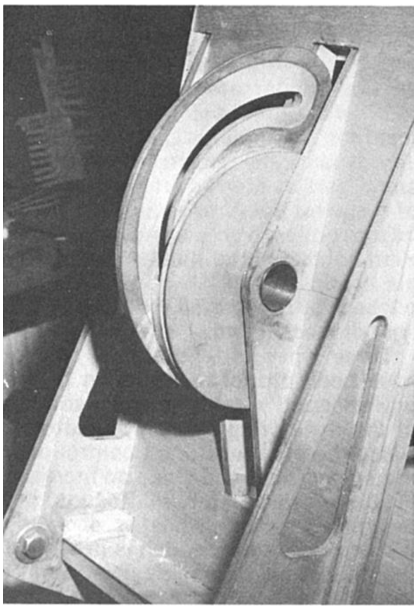
9.2. Controls

Three controls are generally required, directional, longitudinal and lateral. The directional control is the most basic because turning is the simplest form of manoeuvre that is performed by a controlled aircraft. Normally this is achieved by the use of a rudder but where wing spans are large it is found that the rudder can be ineffective due to the ground effect mentioned above. This was found to be the case with “Puffin II” .and tip spoilers were used so that the drag on the lower wing could be increased by the pilot to overcome the reduction in induced drag. The H.P.A. “Toucan” having a much larger wing span is dispensing with the use of a rudder, although the fin is being retained to give direction stability, and relying altogether on the use of tip spoilers for directional control.

For more conventional man-powered aircraft having wing spans below say 85 ft, the use of rudder only is entirely satisfactory providing that it represents a large proportion of the total fin area. This is not only to give sufficient rudder to overcome the induced drag effect but also to provide effective leverage at the low velocities experienced. "SUMPAC" was designed with an all-flying vertical tail surface so that rudder area represented the total fin area. A basic design requirement for the rudder is that it should be aerodynamically balanced by having some part of the rudder area forward of the pivot point, to reduce the loads on the rudder structure and its support. Pilot control of the rudder must be by his hands, and this is usually accomplished by a pivoted horizontal bar type of mechanism.



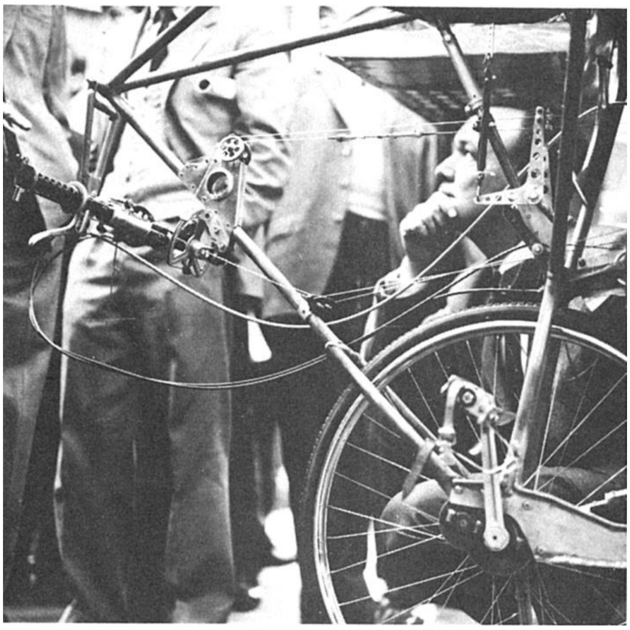
The one piece all-moving elevator of Toucan (above) is actuated via the projecting horn through a cam control (below) giving a positive trim rather than proportional feedback. to the control-column.



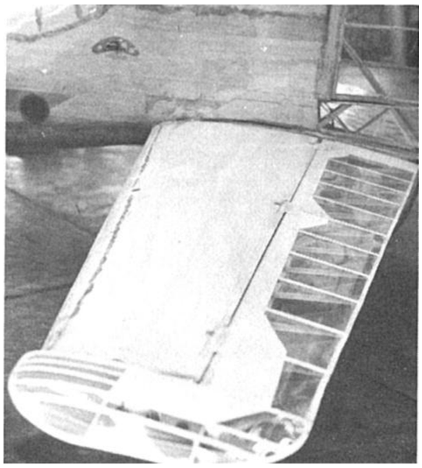
Three types of longitudinal control have been proposed, variation of the power input, elevators and variation of the main wing angle of incidence. Since the pilot has direct control over the power input and since an increase in the power input will cause the machine to climb whilst a decrease will cause it to descend, it is proposed that this could be an effective form of longitudinal control. However, two possible problems exist, that of trimming the aircraft correctly in the first place for take-off and the initial flight, and the chance of the aircraft stalling when power was decreased. Of the other proposals all man-powered aircraft have used elevator control except the Haessler-Villinger machine. It had a fixed tailplane and the wing was in two halves, each half being moved together to give longitudinal control and separately to give lateral control. Haessler[15] reports that the lateral control was satisfactory as long as the aircraft did not get into extreme position because there was then a danger of unsymmetrical stalls occurring. However, longitudinal control was not satisfactory because it caused over-controlled takeoffs, too steep a climb with resultant loss of speed, and insufficient sensitivity of control for landings. Later the machine was modified to a normal tailplane and elevator arrangement with much better results.

[15] Man-powered flight in 1935-37 and to-day, H. Haessler, *Canadian Aeronautical Journal* March 1961

It is likely that most man-powered aircraft will utilise elevators, control of which can either be by a stick moved in the longitudinal direction to which the rudder bar can be attached, as for SUMPAC; or a twist grip which is actually incorporated in the rudder control bar, as used for Puffin.

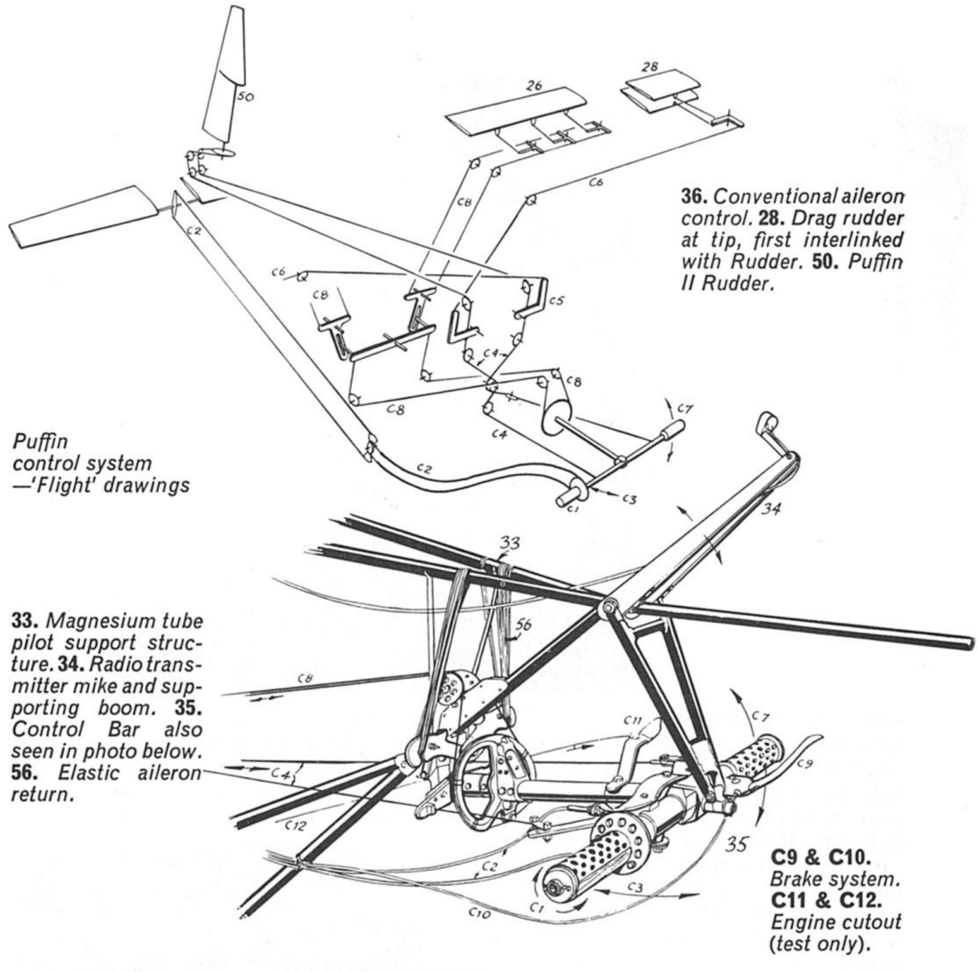


Right: The road wheel and forward frame of Puffin II with the cable operated controls from the horizontal bar suspended at the forefront of the fuselage. Below right is the Puffin I tail unit showing the original horn balance for the comparatively narrow chord elevators. The balance was not used on Puffin II.



Lateral control is the more complex type of control to decide on simply because the lateral motions are more complex than those in the longitudinal direction. There may be a case for not using lateral controls but relying on a large dihedral angle to maintain lateral stability. Although this would limit manoeuvrability it would benefit the pilot considerably by reducing the amount of attention he had to give to controlling the aircraft. It would also cut down on the drag that is normally experienced with lateral controls. The arguments for and against the elimination of lateral controls are not clear-cut, but they are all based on the assumption that the aircraft is already in the air. However, during the take-off run it would be more difficult to maintain the required course and also to counteract the effect of side gusts without lateral control. Only actual experience will provide the answer and it is reassuring, that model aircraft fly without any form of lateral control, but it may be dangerous to extrapolate experience in this manner. If lateral control can be dispensed with it allows the pilot more freedom so that he could also possibly use his hands for increasing the power in put to the propeller by hand cranking. Vine used both feet and hands for powering his machine, controlling the rudder by one twist grip, the elevators by another and the ailerons by cords attached to his shoulders.

Lateral controls are of three possible types, ailerons, spoilers and variation of wing half incidences. The latter has been discussed above in connection with the Haessler-Villinger machine and is being used for the Weybridge project. Ailerons are the usual form of control and this is usually chosen because of the better response compared to spoilers. Ailerons can either be of the conventional longitudinal type or the transverse wing tip type as used on the Malliga machine. This latter form do not incur the large drag penalties that the longitudinal type do in practice. Furthermore spoilers are worthy of consideration because they are very much simpler to construct and operate. Spoilers can be operated by levers on the rudder bar in a similar manner to brake levers on the handlebar of a bicycle and this would have the advantage of taking a well tried and accepted form of bicycle control into the man-powered aircraft field.

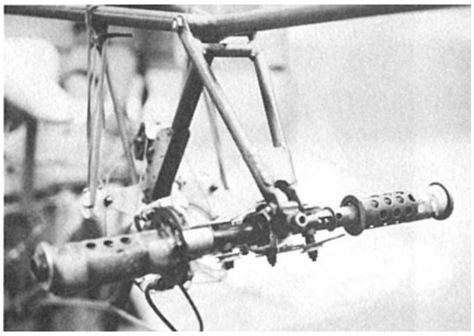


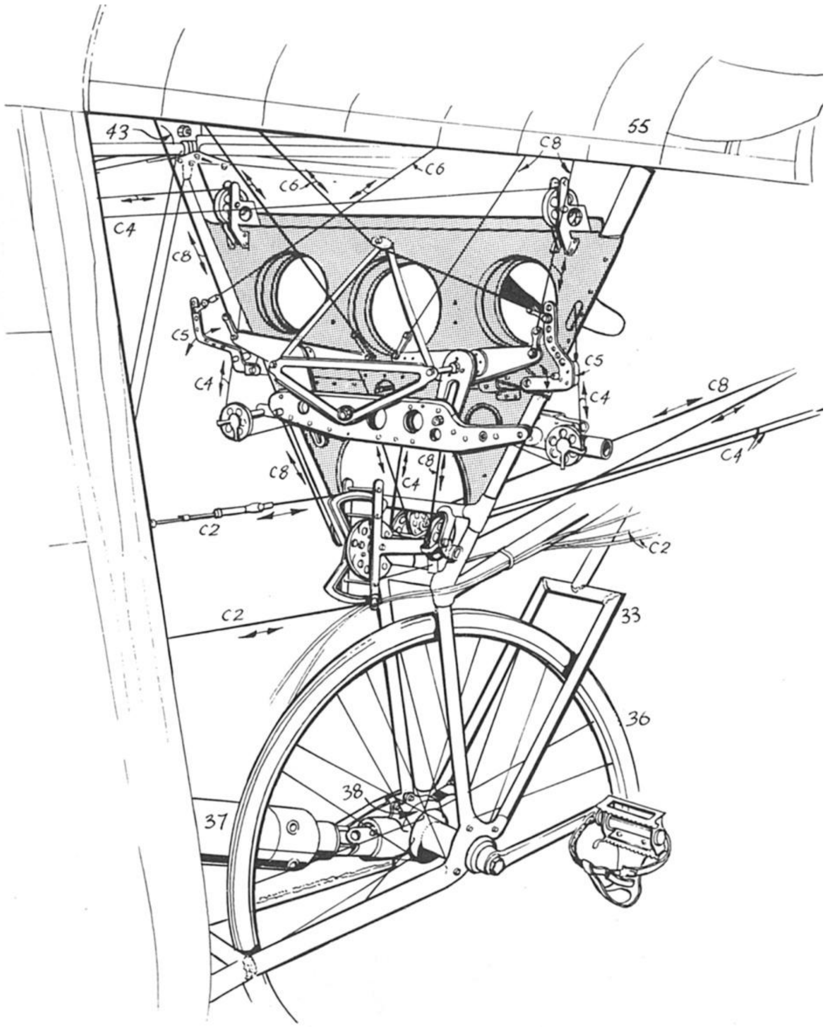
36. *Conventional aileron control.* **28.** *Drag rudder at tip, first interlinked with Rudder.* **50.** *Puffin II Rudder.*

Puffin control system —'Flight' drawings

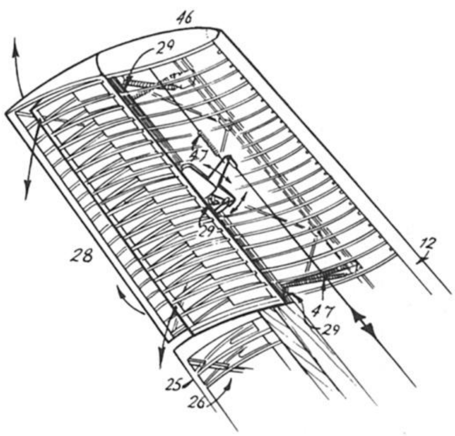
33. *Magnesium tube pilot support structure.* **34.** *Radio transmitter mike and supporting boom.* **35.** *Control Bar also seen in photo below.* **56.** *Elastic aileron return.*

C9 & C10. *Brake system.* **C11 & C12.** *Engine cutout (test only).*





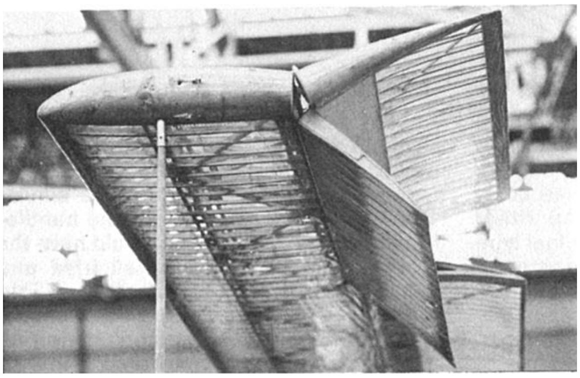
It is important when considering all aspects of man-powered aircraft behaviour and control to utilise experience from other similar activities rather than simply accept existing conventional aircraft knowledge.



12. *Sorboprene leading edge covering. 25. 3/32 in Balsa trailing edge.* ***26.*** *Normal ailerons.* ***28.*** *Drag rudders.* ***29.*** *Hinges.* ***46.*** *Balsa tip.* ***47.*** *Return spring.*

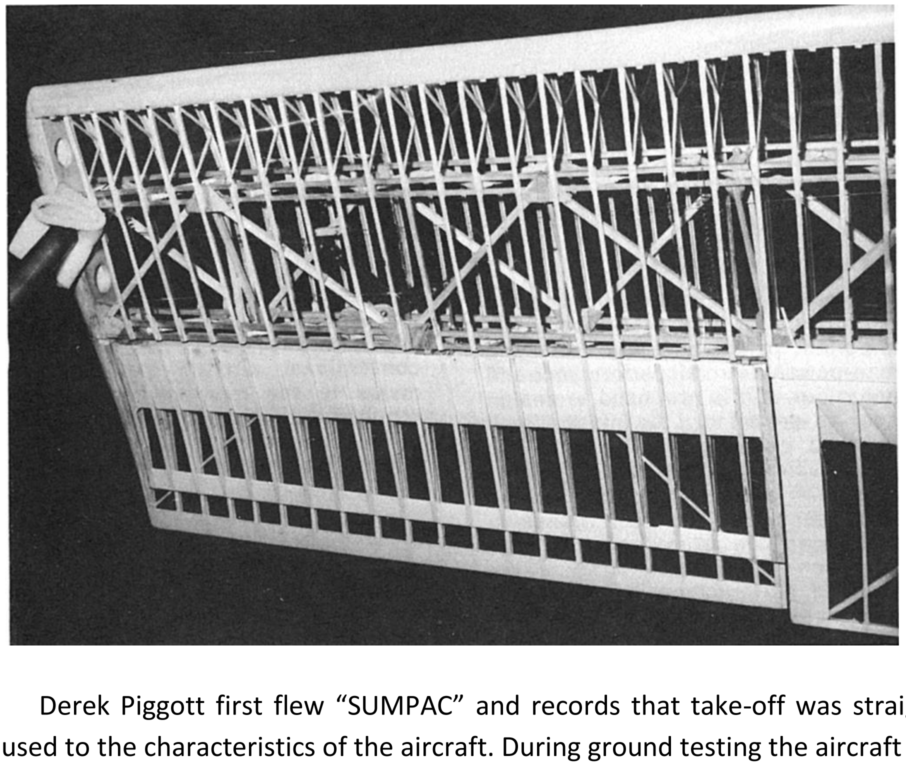
9.3. Flying

The flying characteristics of existing man-powered aircraft are totally different to those for conventional aircraft or gliders due to the low air speed, low wing loadings and large wing spans. If in the future emphasis changes from aiming at the Kremer prizes to man-powered flight as a sport it is possible to consider machines of 40-50 ft wing span with improved flying characteristics. However, this can be gained only at the expense of increased power input so that the designer must choose how far he can go towards improved manoeuvrability without making the project too impractical. Man-powered aircraft will never handle as well as other aircraft but manoeuvrability can be improved to a generally acceptable level providing that flights are restricted to calm conditions.



The Puffin II drag rudder used at the wing tips to improve control. At first this was coupled with rudder but was later disconnected. Above the panels are in the open position. below, closed, also revealing close rib spacing.

Existing man-powered aircraft have only been flown either very early in the morning or at near dusk conditions at night to ensure that the air was relatively still. “Puffin II” could not be flown in winds greater than 3 or 4 knots, whereas “SUMPAC”, with its smaller wing span, could be flown in light winds of 5 to 8 knots. Indeed “SUMPAC” was reported to have flown successfully in cross-wind conditions.



Derek Piggott first flew “SUMPAC” and records that take-off was straightforward once he was used to the characteristics of the aircraft. During ground testing the aircraft developed a tendency to swing severely off the runway as patches of wheel slip were experienced when observers saw daylight under the wheel. After experiencing this several times the first flight came when instead of slowing down after the slip occurred the pilot continued to increase the pedalling rate and climbed away at a nose high altitude; overcorrecting for this caused the aircraft to dive to land back on the runway. Derek Piggott described the take-off as “Cycling on patches of ice”. The tendency to swing continued and many of the early flights ended in “ground-loops”, when a wing tip touched the ground and the aircraft spun round on that tip.

Subsequent investigation showed that the early flights of “SUMPAC” were at a near stalled condition and that the propeller speed was too low or alternatively the propeller pitch was too fine for the aircraft speed. Trouble was experienced throughout the initial testing of “SUMPAC” due to matching the propeller setting to the ground speed especially if flying in light winds, partly due to the lack of any speed indication for the pilot and also possibly due to transmission belt slip.

A simple speed indication of the vane type, a type widely employed for aeromodelling purposes, was used for Puffin on an arm extending out from the nose of the aircraft. This arm provided a reference point from which the pilot could judge the longitudinal attitude of the aircraft. Quick reference to speed indication was provided by a coloured scale rather than a calibrated scale. Three colours were used, red for stalling speed, yellow for cruising speed, and green for above cruising speed. A further point regarding Puffin was that the transmission did not slip so that the take-off difficulties experienced with “SUMPAC” were not encountered. Later development of “SUMPAC” included a positive drive belt which eliminated many of the earlier faults.

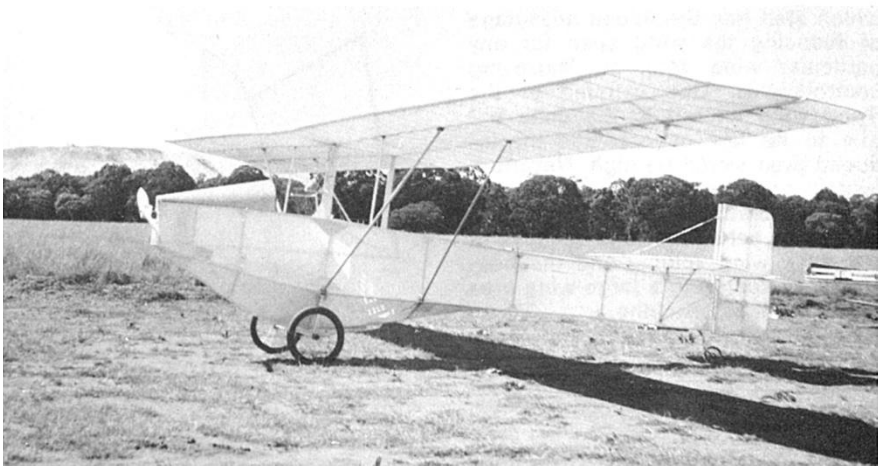
10. AIRCRAFT DESIGN

10.1. Aircraft configuration

THE preceding chapters provide the information for an appreciation of the important parameters that determine man-powered aircraft performance and behaviour. If it is proposed to design such an aircraft then the information if followed correctly will eliminate the risk of failure. However, the success of an aircraft will depend on the level of performance the designer wishes to attain and the overall aircraft configuration that is envisaged. If the required performance is compatible with that for an attempt at the Kremer Prize then the chances of success are considerably reduced compared with a less ambitious performance requirement. However, since the constructional problems of a smaller aircraft are reduced compared to those of aircraft aimed at the Kremer Prize it is anticipated that the enthusiast who designs and constructs his own aircraft will aim at a maximum flight of say 200-300 yards. This would mean a total power durations of under a minute with power requirements of 0·45-0·5 h.p. and a wing span in the region of 50 ft. The reader is referred back to Figures 39 and 40 to check this reasoning.

Having been guided to a particular aircraft size through the performance requirements, the designer must then choose the type of aircraft configuration. Whether monoplane or biplane, type of fuselage, propeller position, whether conventional, canard or tailless. There is a wide variation of possible choices but the reasoning behind the SUMPAC configuration, that it should be similar to that of a glider because this was the type of conventional aircraft that approximates to the man-powered aircraft requirements most closely, was based on a practical and common sense approach that is still valid to-day.

The biplane has no real advantage over the monoplane due to its increased induced drag outweighing its other merits and this also applies to a tandem wing layout. Therefore the reduced constructional work on a monoplane makes it an automatic choice. However, even with a monoplane one has the choice of high- or low-wing configuration. The high wing has better stability characteristics than a low-wing configuration but the latter reduces the induced drag by working nearer the ground. One other factor is that the high wing is less likely to touch the ground during manoeuvres with the aircraft banked. A high wing configuration has much to commend it but perhaps a better compromise is a mid-wing or shoulder wing layout providing that structure is suitable and this invariably means having a non-detachable wing. Malliga compromised by building his aircraft as a low wing machine but mounting the undercarriage below so that the wing was still well above the ground.



Strictly conventional in its configuration, the Vine machine from Krugersdorp, Republic of S. Africa.

Position of the propeller must either be in a pusher position at the rear of the main fuselage or alternatively mounted on a pylon above the fuselage. These minimise drag by ensuring that no major part of the aircraft is in the relatively high speed airflow leaving the propeller. If the propeller can be incorporated on the fuselage this is better than carrying the extra weight of a special pylon, but the latter may be the only effective solution for some designs in order to simplify the propeller drive system.

All man-powered aircraft projects to-date have had conventional tailplanes and fins at the stabilising surfaces. There is a case for considering the canard (tail first) configuration because a lifting fore-plane can be employed which provides a useful proportion of the total aircraft lift enabling the wing area to be reduced. However the correct design of such a foreplane requires a deeper study of stability than that presented in Chapter 9. The basic requirement for stability is that the change of C_L with α for the fore plane should be less than for the main plane and this can be maintained by using the same aerofoil section for both but working the fore plane at a higher angle of incidence, see Figure 74. When a high C_L is employed the induced drag of the foreplane must be maintained within acceptable limits by using a high aspect ratio.

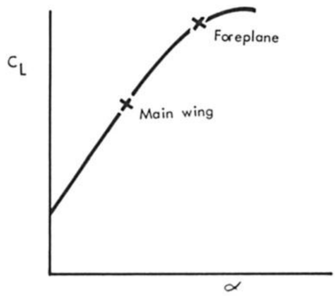


Figure 74

There is also a case for considering a flying wing aircraft because of the weight saved by the elimination of tail surfaces and the fuselage extension to carry them. Here again the designer would need a deeper knowledge of aircraft stability than that already presented to ensure complete success. The basic requirement for longitudinal stability is sweepback which also has the added advantage of reducing the wing span for any particular wing area, so improving controllability. One extreme of the flying wing aircraft is the delta but due to its low aspect ratio the induced drag would be high. Nevertheless the delta configuration has several attractive features namely, minimisation of the actual fuselage because of the large wing volume and the possibility of achieving a large wing area from a compact machine.

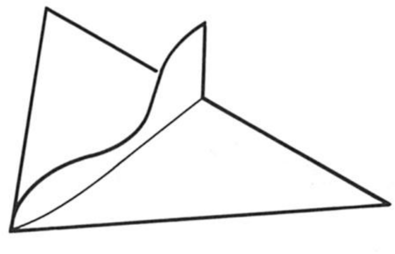


Figure 75

To ascertain whether the delta configuration has any practical possibilities for man-powered aircraft let us consider the simple configuration shown in Figure 75. With a wing span of 35 ft and a total length of 17 $^{1}/_{2}$ ft, the wing area would be 306 sq.ft. Aspect Ratio = $^{35}/_{8.75}$ = 4

Highly cambered aerofoil section of the Wortmann FX-63137 type would be unsuitable for this configuration. However, the Wortmann FX-05191 section used for "Puffin I" having a flat under surface and a reflex trailing edge would be ideal. C_L for the aerofoil section would be 0·8. Assuming a total weight of 220 lb we can now ascertain the performance.

From equation (6)

$$V = \sqrt{\frac{W}{C_L \frac{\rho}{2} S}} = \sqrt{\frac{220}{0 \cdot 8.0 \cdot 0012.306}}$$

= 27·4 ft/sec

The mean chord would be 8·75 ft so that from equation (3) the mean Reynolds number can be found:

$$Re = \frac{\rho . C . V}{\mu} = 6250.8 \cdot 75.27 \cdot 4$$

= 1,500,000

This value is high for a man-powered aircraft and would ensure that the profile drag would be lower than for "Puffin I". Figure 76 presents lift/ drag polar curves for the FX-05191 section for Reynolds numbers of 1,500,000 and 700,000. From this a suitable working value of C_D would be 0·0075. Since the wing represents nearly the whole of the aircraft a suitable value for the overall profile and parasite drag coefficient C_{D_f} is 0·008.

Now the induced drag coefficient=

$$\frac{K' {C_L}^2}{\pi . A} = \frac{1 \cdot 12 . (0.8)^2}{\pi . 4} = 0.057$$

K' is equated to 1·12 since the wing planform is assumed to taper to a point, see Figure 30.

$$\therefore Drag = \frac{\rho}{2} . S . V^2 . \left(C_{D_o} + C_D\right)$$

= 0·0012.306.$(27.4)^2$ x (0.008 + 0.057) = 18lb

The ground effect has not been allowed for when calculating the induced drag coefficient. For 5 ft altitude the new induced drag coefficient becomes:

0·58 x 0·057 = 0·033

$$\therefore the\ new\ total\ drag\ value = 11lb$$

$$\therefore Power\ absorbed\ at\ 5\ ft\ altitude = \frac{11 \times 27 \cdot 4}{0 \cdot 8 \times 550} = 0 \cdot 69\ h.p.$$

It is therefore possible to think in terms of short, say 100 yard, flights with such a machine at 5 ft altitude assuming that the pilot has the reserve of energy to climb to this altitude.

If the delta configuration shown in Figure 75 was modified so that instead of one central fin there were two fins on the wing tips this would have two benefits:

(i) the tip to root chord ratio would change with a resulting improvement of K' and

(ii) the wing tip fins would act as barriers to the formation of the wing tip vortices with some reduction of the induced drag.

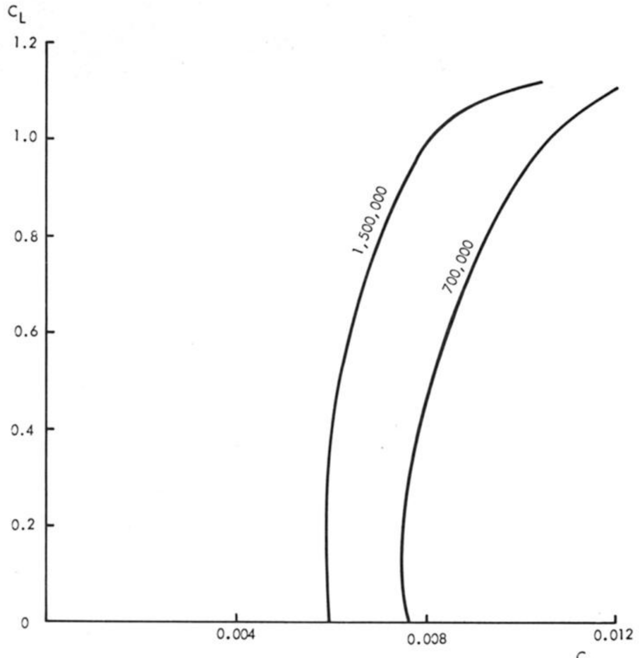
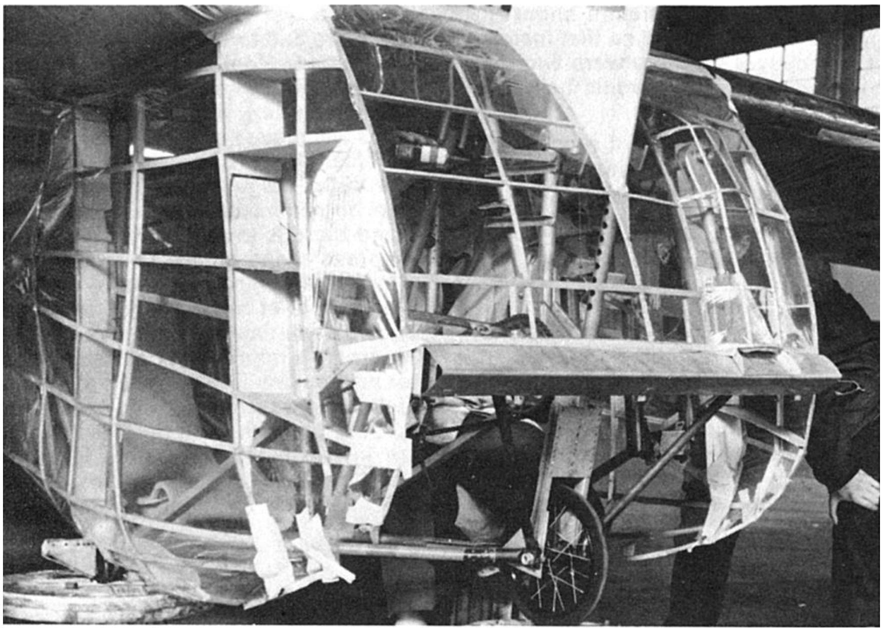


Figure 76

Lift – drag curves for the FX – 05191 aerofoil section

Using this new type of configuration the Delta wing does seem a practical possibility for man-powered aircraft that are going to operate at only low altitudes for sporting purposes. The main advantage with such a configuration is that it can lend itself to very simple straightforward construction yet would provide a stiff structure due to the small span.



Side by side sealing in the reclining position was chosen for the Southend two-man machine resulting in a blunt, broad nose.

Whatever configuration is actually chosen it is inevitable that when trying something new, some small modifications will prove necessary after ground and flight trials. By careful designing at the initial stages these modifications can be minimised later. On the other hand there is probably more incentive to press ahead rapidly so that at least one has a complete machine that will be capable of short “hops” and then spend more time modifying afterwards in order to improve performance and/ or manoeuvrability. The example of the delta wing was included above because not only does the author think that it is an interesting and feasible idea but also because it proves there is still ample scope for original designs at the present, pioneering, stage of man-powered flight. At the very least the designer will have enough information on hand to check through the feasibility of his design from a performance point of view.

10.2. The case for 2-seater aircraft

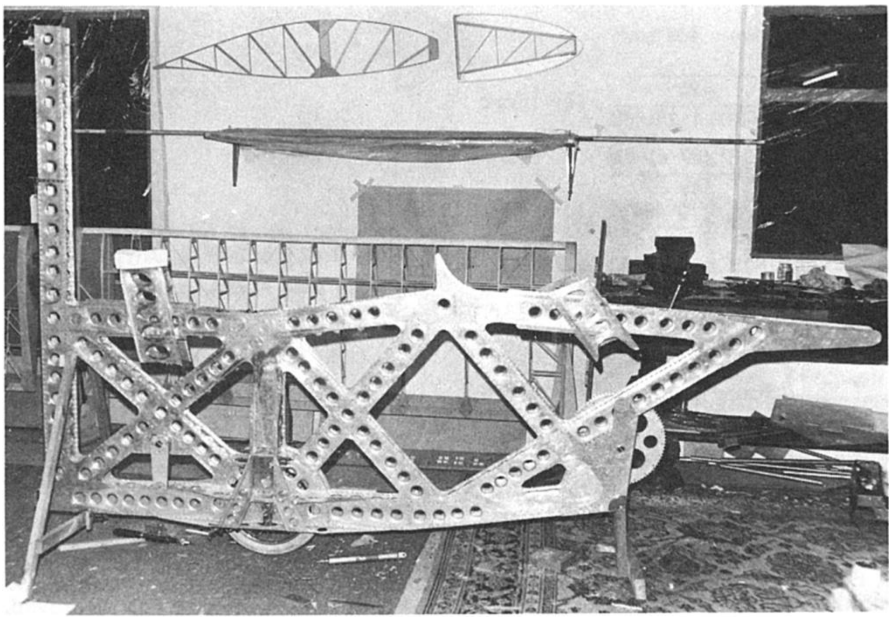
Throughout the remainder of the book man-powered aircraft are discussed on the basis of being single-seater machines. These are easier and cheaper to construct than multi-seater machines and at the present state of the art, man-powered flight is very much an individualistic activity. However, there is a case for 2-seater aircraft as evidenced by three projects: Southend, Ottawa and H.P.A. “Toucan”; so that a general discussion of man-powered flight would be incomplete without presenting this case.

The three projects above were all designed with a direct attempt at the Kremer Prize as a basis. It was argued that any man-powered aircraft designed for such a direct attempt would have a large wing span with high aspect ratio and low wing loading. Flying ability required for such a machine would be very high indeed and that single-seater aircraft suffered by no pilot combining the required flying ability with being a first class athlete. The 2-seater machines were designed to provide a compromise solution, one of the crew being an expert pilot with good cycling ability and the other a cyclist of professional standard to provide above average power output.

In practice, the case for 2-seater aircraft is not as clear-cut as this. In the first instance construction of such an aircraft takes longer and is more complex than for a single seat aircraft. Therefore one needs a larger or more dedicated group working on the project. For the same average power requirements, 2-seater machines are larger than the equivalent single-seater machines, which not only increases still further the problems of actually flying them, but also places further limitations on the atmospheric conditions in which they can be flown.

Looking at man-powered flight at the present time, unless one is attempting for the Kremer Prize then there is no valid reason for designing a 2-seater aircraft. However, in the future when man-powered flight has developed as a sport, there will certainly be a need for 2-seater training aircraft for training new pilots, but such aircraft will no doubt have a much lower performance capability than the present day 2-seater projects in order to be more compact and robust.

Tandem seating in the Toucan called for a special riveted frame of remarkable light weight for its size. This is the principal structure with pick-up points for wing and rear fuselage. (Note use of small wheel).



Two man machine

The following study is based on the assumptions:

(i) use of the Wortmann FX-63137 aerofoil section, with a design C_L of 1·15;

(ii) rectangular wing plan form, with K = 1·1;

(iii) weight/span span relationship of W = 350 + wing span (ft);

(iv) a transmission/propulsive efficiency of 80%; and

(v) a wing height of 10 ft.

Except for (iii) and (v) listed above the other assumptions are the same as those used for the single man aircraft summarised in Figure 40.

Calculations

70 ft span-weight = 420 lb

AR= 10.

Wing area = 490 sq.ft

$$V = \sqrt{\frac{420}{0 \cdot 0012.1 \cdot 15.490}} = 25\ ft/sec$$

$$Power = \frac{0 \cdot 0012.(25)^3 490}{440} \times \left[0 \cdot 0125 + \frac{0 \cdot 464}{10}.0 \cdot 57\right]$$

= 0·81 h.p. i.e. 0·405 per pilot

AR= 12

Wing area = 408 sq.ft

$$v = \sqrt{\frac{420}{0 \cdot 0012.1 \cdot 15.408} = 27.4\ ft/sec}$$

$$Power = \frac{0 \cdot 0012.(27 \cdot 4)^3}{440} \times \left[0 \cdot 013 + \frac{0 \cdot 464}{12}.0 \cdot 57\right]$$

= 0·80 h.p. i.e. 0·400 per pilot

AR= 15

Wing area = 326 sq.ft

$$v = \sqrt{\frac{420}{0 \cdot 0012.1 \cdot 15.326}} = 30.7\ ft/sec$$

$$Power = \frac{0 \cdot 0012.(30 \cdot 7)^3 326}{440} \times \left[0 \cdot 0143 + \frac{0 \cdot 464}{15}.0 \cdot 57\right]$$

= 0·82 h.p. i.e. 0·41 per pilot

∴ For 70 ft span-minimum pilot power input ≈ O·4 h.p.

One man machine

The assumptions are as for Figure 40 except that wing height= 10 ft

Calculations

70 ft span-weight = 260 lb AR = 12

Wing area = 408 sq.ft

$$V = \sqrt{\frac{260}{0 \cdot 0012.1 \cdot 15.480}} = 22\ ft/sec$$

$$Power = \frac{0 \cdot 0012.(22)^3}{440} \times [0 \cdot 013 + 0 \cdot 022]$$

= 0·415 h.p.

Equivalent power for AR= 15 comes out to 0·42 h.p. and for AR = 10

Wing area = 490 sq.ft

$$V = \sqrt{\frac{260}{0 \cdot 0012.1 \cdot 15.490}} = 20\ ft/sec$$

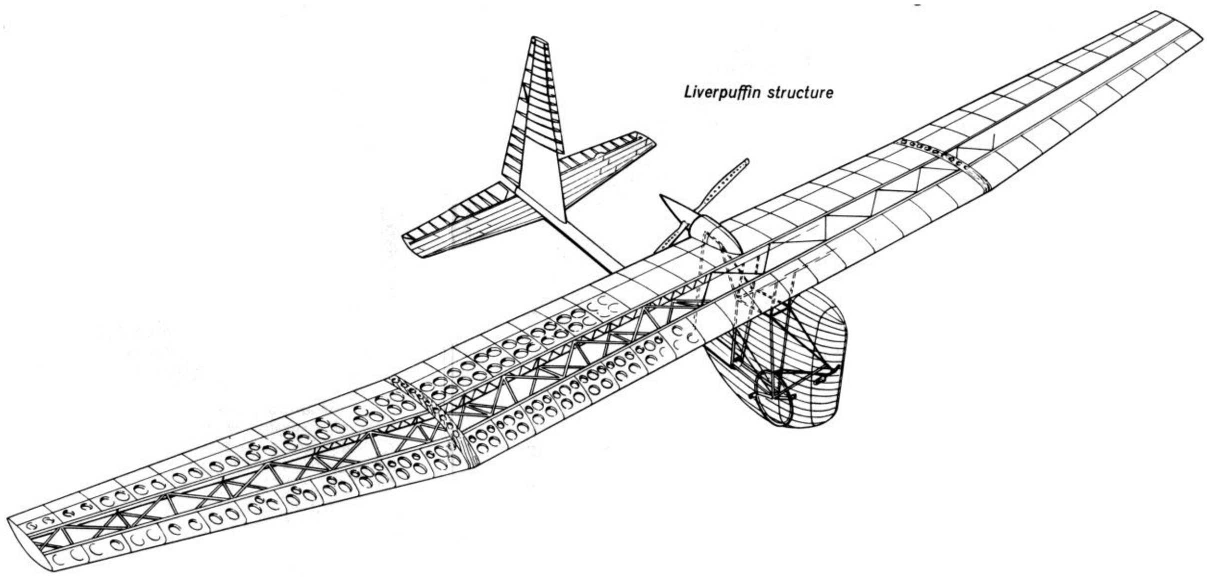
$$Power = \frac{0 \cdot 0012.(20)^3 490}{440} \times [0 \cdot 0125 + 0 \cdot 0265]$$

Minimum power ≈ 0·410 h.p.

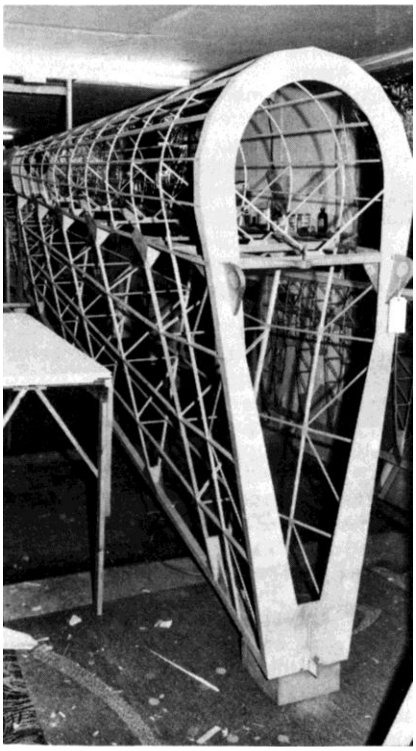
Conclusion

The case for two as opposed to one-man machines is not disproved. Comparing on a span basis, as opposite, there is very little in it-just a slight margin in favour of two man machines 0·4 h.p. as opposed to 0·410 h.p.; $2^1/_2$% difference. Therefore the case for and against two man machines rests largely on practical considerations and so the previous arguments still stand.

The assumed weights appear to be realistic although the 2-man could be slightly optimistic.



There could be no greater contrast than in the rear fuselage sections of the single seat liverpuffin (above) and the two seat Toucan (below).



10.3. Design of "Liverpuffin"

It is perhaps instructive at this stage to briefly run through some of the design considerations that were used in formulating the design of "Liverpuffin", but before doing so it is necessary to give the background to the project.

This project is part of the undergraduate course in engineering design at Liverpool University. Design can be considered to be that aspect of engineering that is concerned with results, the result normally being a piece of hardware, and it can only be taught satisfactorily if the students meet real design situations. This is done by teaching design through projects in which the theoretical knowledge can be applied to practical problems. Design and construction of a man-powered aircraft was chosen as a major design project for the reasons that:

(i) It is of a similar order of complexity to projects found in industry.

(ii) Although the theoretical design can be carried out at a sophisticated level, the actual machine can be built by undergraduates using simple tools and equipment.

(iii) Unlike many other equivalent projects there are no standard solutions to the problem of designing a man-powered aircraft. It is therefore possible to make a worthwhile contribution within this field of study and in fact students can only achieve satisfactory solutions by using their initiative.

Having decided on the man-powered aircraft project, the Hatfield group offered to give the remains of the crashed "Puffin II". These were received in September 1969. Because the aims and configuration were eventually changed from those of "Puffin II" the name was modified to "Liverpuffin".

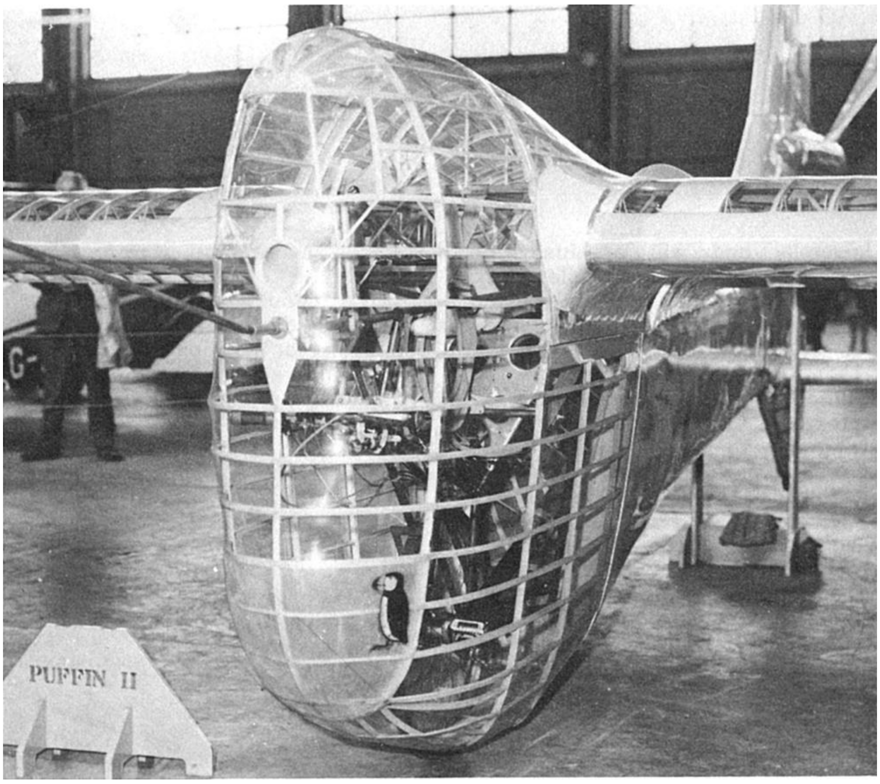
The Puffin remains consisted of "the wing" with the primary structure in sound condition but nearly all the balsa ribs smashed, the main pilot support frame, the propeller, rudder tailplane. The latter two items had some damage but were easily repairable. Nothing remained of the fuselage.

First steps in any design project is to sift through a background of information and use this as a basis for determining the aims of the project. In this case the primary aim must be the required performance level of the aircraft, whether to build a machine capable of attempting the Kremer prize or one that is just capable of flying, being the two extremes of possible performance. The background information for this particular project was from papers published in the various journals, a study of the Puffin remains and discussions with members of the Southampton and Hatfield groups. Knowledge of the Malliga project was only obtained after the aims and configuration had been formulated and this is specifically mentioned since the two projects are very similar yet evolved independently.

All the members of the group involved in the project were very conscious of the history of the Puffin project. Here was an aircraft on which a great deal of time had been spent in creating an advanced design with a sophisticated construction yet it had not attempted the Kremer competition. This was largely due to the machine being difficult to control and so only being trusted to experienced pilots whose power output was below that of a champion athlete. The major problem was the climb back up to 10 ft altitude required at the end of the runs for the Kremer prizes. From equation (9):

$$P_{(climb)} = P_{(Cruise)}\left(1 + \frac{L}{D}\frac{\theta}{57.3}\right)$$

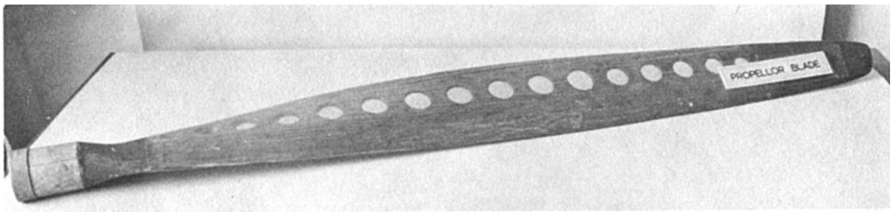
so that with an L/D ratio of 33, which is what "Puffin II" attained when operating near the ground, a 1° climbing angle means that the climbing power would be nearly twice the cruising power and it would need to be maintained for some 15 seconds in order to regain the 10 ft altitude.



Prior to its ultimate crash in collision with airfield equipment, Puffin II had been developed up to a state of aerodynamic cleanliness few other Man-Powered aircraft could hope to match. Note the symbol on the front cowling, and the wing fairings.

It was therefore decided, with much regret on the students' part, that to build a machine for a direct attempt at the Kremer prize would be impractical at the present state-of-the-art of manpowered flight. However it must be emphasised that this only applies to the “direct” approach to the competition where the pilot is expected to provide all the necessary energy for the flight. There is a possible “indirect” approach where, if machines can be made sufficiently small and manageable, it can be flown on hot sunny days and take advantage of convection up-currents to gain height.

With this at the back of their minds, the group decided that the aims for “Liverpuffin” would be to build a machine which would be easy to construct; robust; manageable both on the ground and in the air; transportable and capable of taking off and making flights to 100 to 300 yards at a 3-5ft altitude with a wide range of possible pilots at the controls. Transportability is a most important criteria because unlike the Hatfield group where Puffin was built and flown on the same site, “Liverpuffin” is being built in the University and will eventually be flown at an airfield some 8 miles away. Therefore it must be capable of being transported in several sections as was “SUMPAC”.



Using a similar wing arrangement as “Puffin II” it was decided that the aircraft would have a wingspan of 65 ft, giving a wing area of 318 sq.ft. The aerofoil would be the Wortmann FX-63137 used for “Puffin II” with C_L= 1·15 and C_D= 0·009. A total weight of 280 lb was assumed as it provided sufficient margin to increase constructional weight in order to improve robustness and would also accommodate pilots of up to 155 lb in weight.

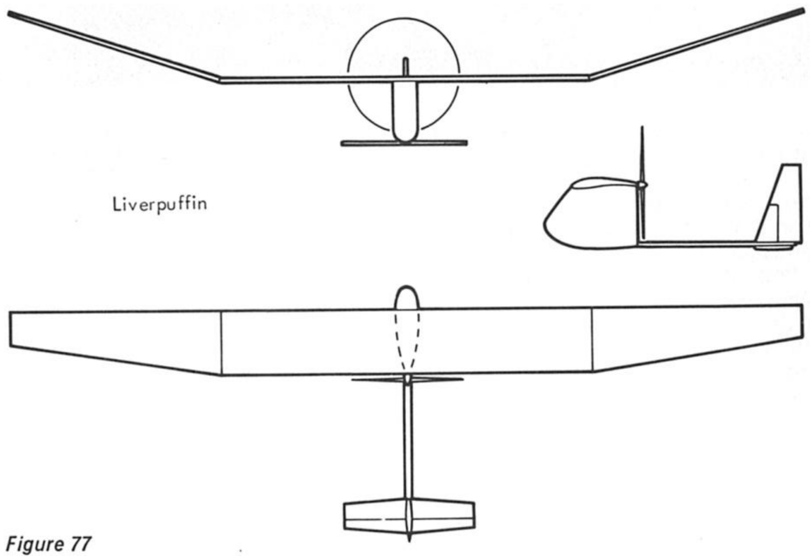


Figure 77

The general arrangement of the proposed design is shown in Figure 77. Reasons for the choice of this particular configuration will be presented after discussion of the performance.

From equation (6):

$$V = \sqrt{\frac{W}{\frac{\rho}{2}.C_L.S}} = \sqrt{\frac{280}{0 \cdot 0012.1 \cdot 15.318}}$$

= 25·3 ft/sec

Parasite drag coefficient is assumed to be equivalent to that for "Puffin II", so

$$C_{D_f} = 0 \cdot 0031 \times \frac{390}{318} = 0 \cdot 0038$$

Say 0·004

∴ Overall profile and parasite drag coefficient: C_{D_o} = 0·013

Induced drag coefficient with the aircraft at 4 ft altitude, i.e. wing tips 14 ft above the ground:

$$C_{D_i} = \frac{K.C_L{}^2}{\pi.A}$$

Aspect ratio= 13·3, $^K/_{K'}$ = 0·67 (from Figure 33) and K' = 1 ·03 (from Figure 31).

$$\therefore\ C_{D_i} = \frac{0 \cdot 69(1 \cdot 15)^2}{\pi.13 \cdot 3}$$

= 0· 0012. 318. $(25 \cdot 3)^2$ x (0·013 + 0·022)

= 8·55 lb

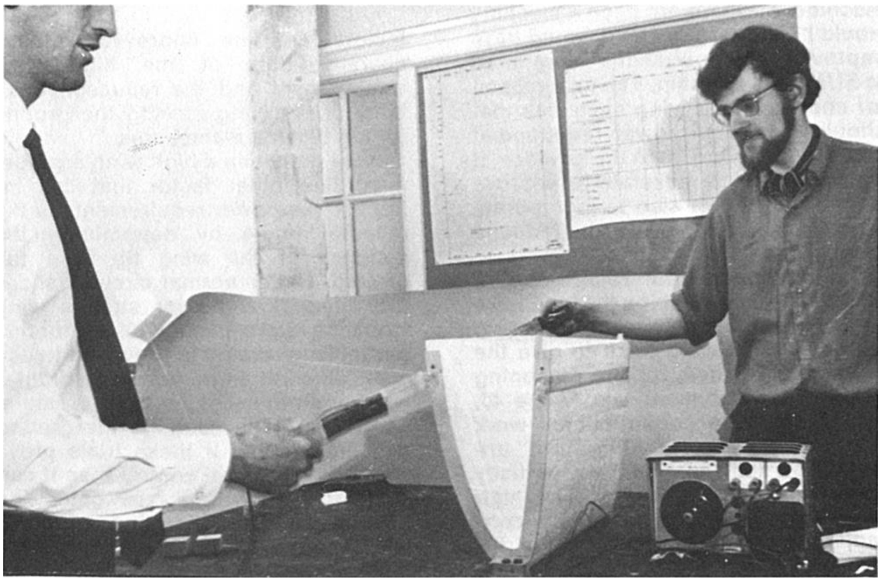
Assuming a propulsive and drive efficiency of 80% the cruising horsepower at 4 ft altitude becomes:

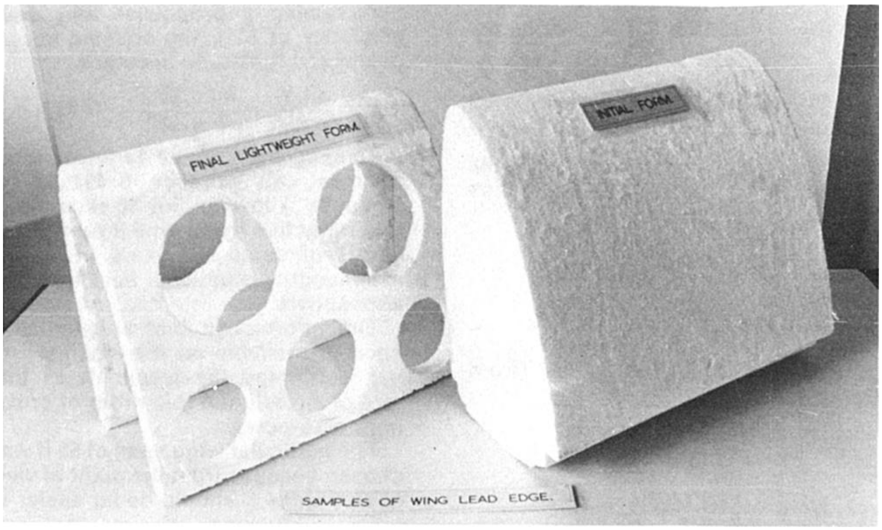
$$P = \frac{D.V}{\eta.550} = \frac{8 \cdot 55.25 \cdot 3}{0 \cdot 8.550} = 0 \cdot 49\ h.p.$$

Judging from Figure 14 an ordinary fit man can produce 0·49 h.p. for 1 minute. Allowing only 30 seconds of this for actual flying time it represents flights of some 250 yards in length, assuming no additional help from the atmosphere.

The information that subsequently became available on the Malliga project confirmed the feasibility of this size of aircraft and this order of cruising horse-power.

Above, the Puffin propeller blade as to be used in Liverpuffin. Below, the author (left) makes a test cut in expanded polystyrene for the wing leading edge section.





The particular wing span of 65 ft was chosen because from the point of view of size alone it should be far easier to control than either SUMPAC or Puffin. Any further reduction in wing span would so increase the cruising horsepower that it greatly reduces the number of people who could pilot the machine. Furthermore such a machine would be more robust and would have improved transportability compared to SUMPAC or Puffin. The final reason for choosing 65ft wing span was that should the horsepower requirement prove a little too high in practice it would always be possible to improve on the weight and also to incorporate wing tip plates to reduce the induced drag.

By designing “from square-one” a completely new machine it would have been possible to devise on low wing aircraft of 50 ft wing span to give the same performance, for the reasoning behind this statement see Figure 40, but to minimise constructional work many of the parts from “Puffin II” are to be utilised and this partially determined the high wing. The high wing arrangement is also very convenient for detaching the wings for storage and transportation. Additional factors are the improved stability characteristics of the high wing arrangement and the reduced possibility of the wing striking the ground during banked manoeuvres.

Having chosen a high wing arrangement one other factor that can influence the power requirements is the dihedral angle by determining the distance of the wing tip from the ground. Under normal circumstances the dihedral angle for such a wing would be approximately 10° but for this particular aircraft it is proposed to use a 20° dihedral angle for the two outer wing units because no form of lateral control is to be used for the ground and flight trials. If these trials prove the need for lateral control then it can be incorporated at a later date. The question of elimination of any form of lateral controls depends on the following arguments:

(a) it is possible to turn on the use of rudder alone;

(b) if a wing tip dips due to a gust there is a side slip action that tends to right the aircraft; and

(c) induced drag on the dipped wing tip is reduced tending to turn the aircraft round the higher wing tip with a corresponding increase of lift on the lower wing which will tend to right it.

These arguments are based on the aircraft being in a position to be able to manoeuvre freely. The argument for the incorporation of lateral controls is that during take-off the aircraft is not free to manoeuvre. However, experience with "Liverpuffin" should give some very useful feed-back of information regarding these points. The advantages of eliminating lateral controls are that it greatly simplifies the pilot's control problem and this is very important for a training aircraft, which is what "Liverpuffin" really is, and it simplifies the construction of the wing. Should some form of lateral control prove necessary after ground/flight trials it is proposed to incorporate spoilers on the upper surface of the centre wing section.

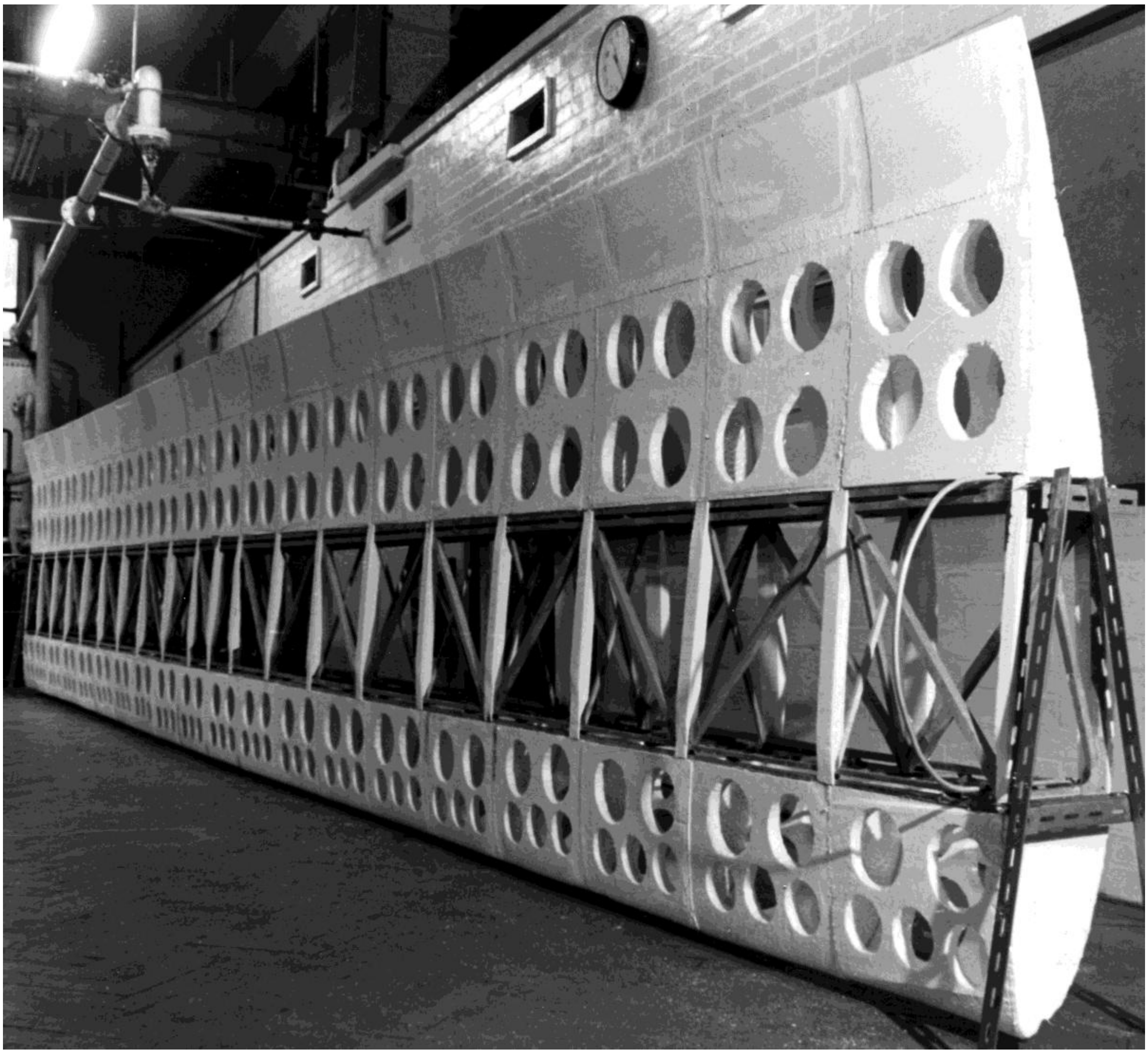
Choice of dihedral angle depends on providing enough inherent lateral stability but if too large it reduces the controllability of the aircraft, which then just wallows in flight. This would be acceptable to a certain extent with man-powered aircraft where manoeuvrability is going to be limited anyway. However, although a 20° angle has been provisionally chosen the final angle can only be decided after flight trials.

Turning to the general configuration of "Liverpuffin" the choice of the "pod and boom" fuselage is an excellent example of a simple functional design. It provides for a pusher propeller position yet minimises the distance of the drive from the pedals to the propeller. The only part of the aircraft in the slip stream of the propeller is the fin and although some small drag penalty must be paid for this the rudder will itself operate more effectively in a faster airstream. A fuselage must provide maximum moment-arm for the control surface and this the "boom" achieves without an elaborate structural design. Furthermore a fuselage has a basically de-stabilising effect which a boom, being the smallest type of fuselage, will not have.

Pod and boom type fuselages are likely to be widely applied to future man-powered aircraft. In principle there is no difference between single boom or twin boom layouts. The single boom was chosen for "Liverpuffin" because it is easier for transporting. On the other hand the twin boom arrangement allows more freedom in the positioning of the propeller and drive, and is also lighter overall.

10.4. Construction of "Liverpuffin"

A study of the remains of the Puffin wings convinced the Liverpool group of the excellent workmanship and the many man-hours that had gone into constructing the strip balsa ribs. However, the fact that very few remained intact confirmed the view that such a form of construction would be unsuitable for an undergraduate project. Searching for an alternative form of constructing the secondary wing structure it was realised that due to its low density, expanded polystyrene was an attractive material choice. After a study of all suitable forms of construction an expanded polystyrene shell with lightening holes and stiffened with thin expanded polystyrene ribs at 18 in spacing was eventually chosen. Construction is simplified because the Expanded Polystyrene can be formed using a low voltage (6-12 v) hot wire cutter whilst the lightening holes can be formed using a template and a soldering iron with a long bit.



Centre panel of Liverpuffin wing viewed from the underside.

Parts that are being retained from “Puffin II” are:

(i) Wing primary structure with a reduction in wing span.

(ii) Propeller.

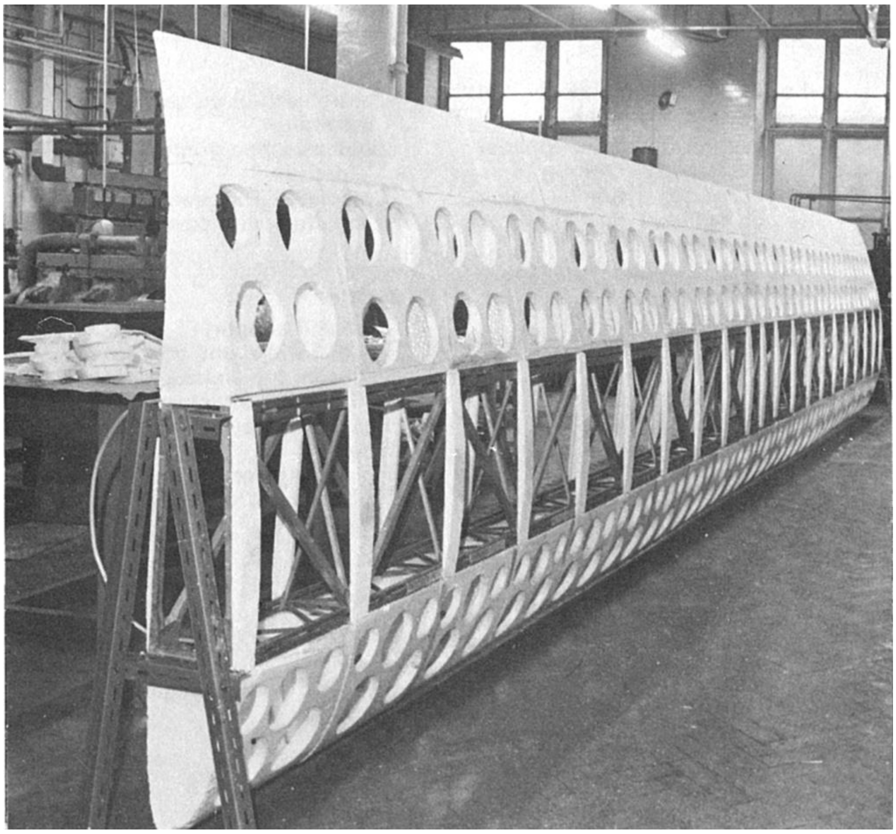
(iii) Part of the fin and rudder.

(iv) Tailplane with the span reduced to 11 ft because of the increased moment arm compared to “Puffin II”.

(v) Pilot support frame.

The primary structure of the fuselage “pod” is shown in Figure 78 and consists of i in 0/diameter x 18 gauge Aluminium alloy tubing bolted together and attached to the existing

Puffin Magnesium alloy pilot support frame. This form of construction was chosen so that the students could make it without resorting to any additional workshop equipment other than a few hand tools. Anyone contemplating a similar structure having the opportunity to use welded or Aluminium brazed joints would be well advised to incorporate them for a more rigid structure. Nevertheless, if care is taken to ensure an interference fit for the bolts, bolted joints are highly satisfactory especially if the joints are further strengthened with epoxy resin glue. The boom is a 4 in 0/diameter x 18 gauge Aluminium alloy tube and although the boom is quite heavy in this form, some 10 lb, it was chosen for simplicity of construction and because it is a standard size of tube that can be bought ex-stock. Furthermore the criteria for stiffness was considered to be very important because the control of "Liverpuffin" relies on effective rudder operation so that any large deflection at this point would detract from the operation of the rudder.



Top surface of Liverpuffin centre panel emphasises use of plastics.

Checking the deflection of the boom under a typical rudder operating load of say 10 lb, the boom can be considered to be a cantilever beam with a point load of 10 lb at the end operating at 10 ft distance from the support. Deflection for such a beam is given by:

$$Deflection = \frac{w.l^3}{3.E.I}$$

where w = point load (lb)

l = effective length of the beam (ins)

E = Young's modulus for the material (lb/sq.in)

and I = second moment of area for the cross-section =

$\pi . r^3 t$ for a tubular beam of radius r (in) and wall thickness t (in)

Now for the size of boom tube chosen:

$I = \pi.(2)^3.0{\cdot}048 = 1{\cdot}2\ (in^4)$

also E = 10 x 106 lb/sq.in for Aluminium alloy

$$\therefore Deflection = \frac{10.(120)^3}{3.10.10^6.1 \cdot 2}$$

= 0·48 in (say $^1/_2$in)

This deflection was considered to be acceptable and in fact a tube size of 3 in 0/diameter x 18 gauge would have been acceptable but it was decided to err on the side of minimum deflection because the weight was acceptable within the total weight allowed for “Liverpuffin”.

The weight breakdown for the complete aircraft is as follows:

Wing	lb
Centre section primary structure	31·0
2 outer section primary structure	15·0
Complete E.P.S. secondary structure with covering	28·0
	74·0
Fuselage	
Seat and support	8·5
Pedals, wheel and gearbox	6·1
Propeller transmission system	8·0
Pod primary structure	6·0
Pod secondary structure	4·0
Boom	10·0
Fin and rudder	2·5
Tailplane and elevator	5·0
Propeller	2·7
	52·8
Pilot	155·0
Total weight	281 ·8

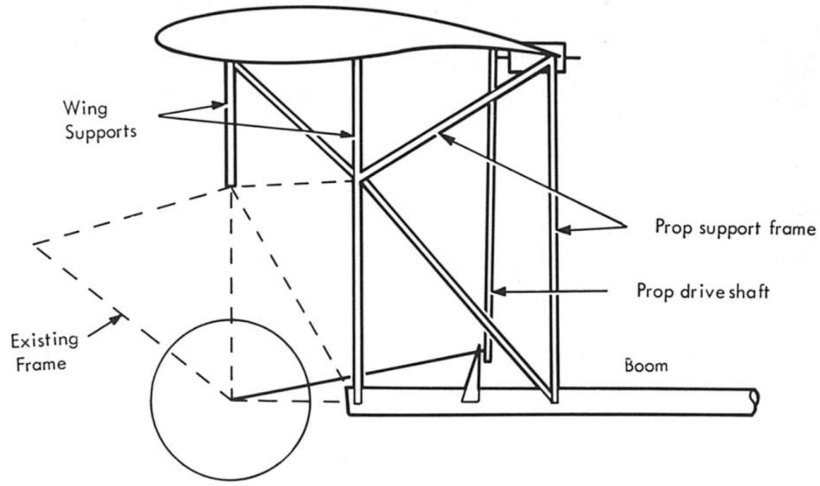
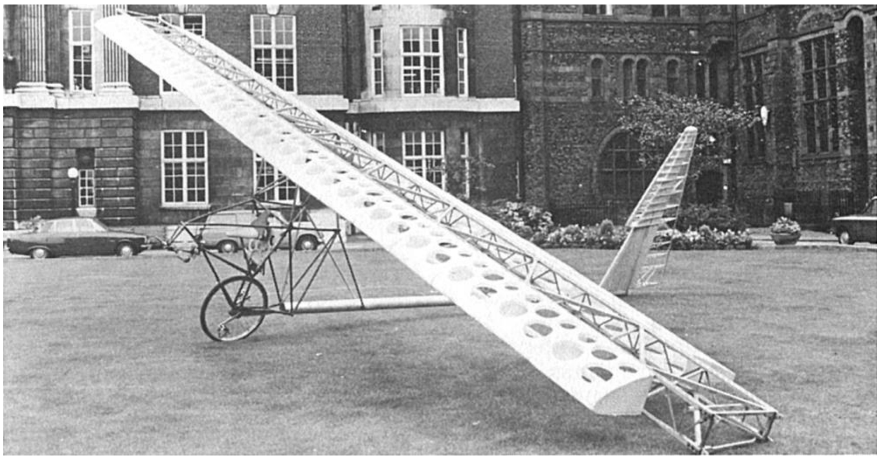
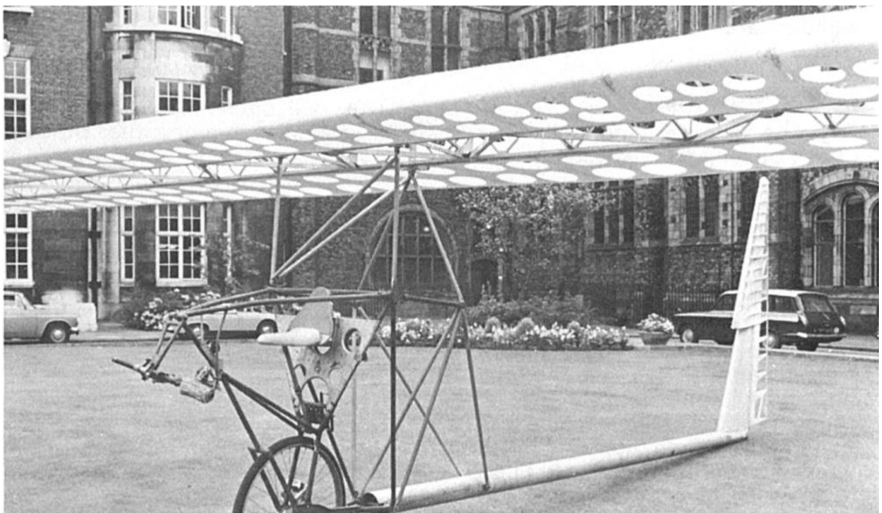


Figure 78



This weight is the one used for working out the required cruising horsepower. In practice it is anticipated that the weight can be increased by 20lb before the success of the project became doubtful



Posed in the august surroundings of Liverpool University, Liverpuffin basic structure with rear fuselage boom is seen here. A belt and shaft drive is used to drive the propeller and the road wheel.

11. UNCONVENTIONAL AIRCRAFT

THE preceding chapters concern fixed wing aircraft which within the man-powered flight context can be considered to be conventional. However, many attempts at man-powered flight have involved helicopter or flapping wing designs and within the context of the present chapter these are the types of unconventional aircraft referred to. At first sight the choice of helicopter or flapping wing design appears to be basically sound because power is limited and therefore it is sensible to consider using it in the most effective way by driving the lifting surfaces directly. Unfortunately very little success has been achieved in practice because the design of such machines is not as straightforward as for fixed wing aircraft.

11.1. Helicopter design

Only one man-powered helicopter has been observed to lift itself off the ground, the Bailey Cyclopter. This was a two man machine employing a rotor based on that used for the Benson Gyrocopter but with a thinner aerofoil section and increased chord. Rotor diameter was 20 ft and there was a step-up gearing ratio of 1·75:1 from the pedals to the rotor. Empty weight was 104 lb and with two men the total weight was approximately 400 lb. Directional control of the machine was by tilting the complete rotor disc in the required direction of travel, although flight trials never progressed to the stage of using this. Observers considered that it just lifted from the floor while being demonstrated at the R.A.F. Handicrafts Exhibition 1962.

The main reason for considering a helicopter instead of a fixed wing aircraft is that it gives promise of being more compact and more simple to construct since all the work is in the rotor because there is no need for an elaborate fuselage. It is comparatively easy to check the feasibility of a man-powered helicopter project by checking on the power absorbed in hovering flight.

Basically a helicopter comprises a rotor set horizontally so that the thrust equals the weight of the machine. Although helicopter designs with more than one rotor have been considered, the present discussion will only consider the one rotor configuration otherwise the helicopter looses its basic advantage of simplicity.

The helicopter rotor has similar characteristics to a propeller although a satisfactory design of rotor blade is one that has a rectangular planform with a constant blade angle throughout its length. The lift coefficient will be a constant for this type of blade and the thrust is given by:

$$T = \frac{\rho}{6} n.c.R.(V_T)^2.C_L \qquad (26)$$

where T = thrust (lb),

$\rho =$ air density (0·0024 slugs/ft3) ,

$n =$ number of rotor blades, $c =$ blade chord (ft),

$R =$ rotor radius (ft),

V_T = rotor tip velocity (ft/sec) = 2. π x revs/sec x R,

C_L= lift coefficient.

Cpl. Technician Ronald Hacking (left) from Luton, and Cpl. Technician Nicholas Hockenhull from Southampton, demonstrate Warrant. Officer Spencer Bailey's "Cyclopter".

This is an equivalent relationship for rotor craft to the lift equation (1) for fixed wing aircraft.

Now the power absorbed by producing this thrust is theoretically equal to T.U./550 where *U* is the induced velocity that the rotor produces in the vertical direction. From simple momentum considerations:

$$U = \sqrt{\frac{T}{2.\pi.R^2.\rho}}$$

We are now in a position to formulate the equation for a rotor producing thrust, that is the equivalent to the case of a helicopter hovering. However, there will be some tip losses of the rotor blades and a factor of 1·25 is normally assumed for the hovering efficiency.

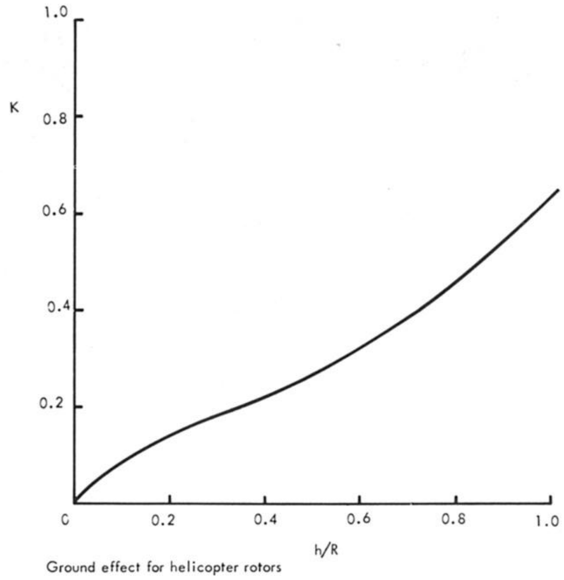


Figure 79

As the rotor of a man-powered helicopter will be working near the ground the downward airstream will be reflected by the ground and this will help support the helicopter. Just as the ground effect reduced the induced drag for a fixed wing aircraft so too does it reduce the induced power requirements of a helicopter rotor. Figure 79 presents a variation of *K* the ground effect factor against rotor height, plotted in a non-dimensional form as height *h* as a proportion of the rotor radius *R.*

The power required by the rotor to allow hovering flight is given by

$$\frac{1\cdot 25.K.T}{550}\sqrt{\frac{\mathrm{T}}{2.\pi.\mathrm{R}^2.\rho}}$$

However, this only applies to an ideal rotor because real rotors absorb additional power in overcoming the drag incurred in moving the rotor through the air. Power absorbed in drag can be approximated for the man-powered application by the equation:

$$\frac{\rho}{8}.n.c.R(V_T)^3C_D = 0\cdot 75.T.V_T.{}^{C_D}/_{C_L}$$

where C_D is the overall rotor drag coefficient, combining both the profile and the induced drag terms.

The total hovering power that must be provided by the pilot of a man-powered helicopter, assuming a transmission efficiency of 96%, is given by:

$$P_{(Hover)} = \frac{1\cdot 3.K.T}{550}\sqrt{\frac{T}{2.\pi.R^2.\rho}} + \frac{0\cdot 78.T.V_T}{550} + \frac{0\cdot 78.T.V_T}{550}\,{}^{C_D}/_{C_L} \qquad (27)$$

A study of equation (27) indicates the importance of minimising the thrust T, or in other words the weight of the helicopter, and the rotor tip velocity V_T. On the other hand the values of rotor radius R and lift/drag ratio C_L/C_D should be as high as possible. The requirements of low V_T and high *R* values are conflicting so that the final design will represent a suitable compromise between these two.

Taking a typical example of a man-powered helicopter with a total weight of 220 lb, hovering with the rotor blade height 4 ft from the ground. Both the weight and the rotor height assumed here are considered to be the minimum that it is possible to achieve in practice. Assume the use of a highly efficient cambered aerofoil section for the rotor of the Wortmann FX-63137 type with a working C_L of 1·15 and an equivalent combined profile and induced drag coefficient C_D of 0·018. For a two bladed rotor of 20 ft radius having rectangular blades of 2 ft chord, the rotor tip velocity can be found from equation (26):

$$T = \frac{\rho}{6}.n.c.R.(V_T)^2.C_L$$

$$\therefore\ V_T = \sqrt{\frac{6.T}{\rho.n.c.R.C_L}}$$

$$= \sqrt{\frac{6.220}{0{\cdot}0025.2.2.20.1{\cdot}15}}$$

= 76 ft/sec

The height to rotor radius ratio = 4/20 = 0·20 so that K = 0·14 from Figure 79.

From equation (27) the hovering power is given by:

$$P_{(hover)} = \frac{1\cdot 3.K.T}{550}\sqrt{\frac{T}{2.\pi.R^2}} + \frac{0\cdot 78.T.V_T}{550}{}^{C_D}/_{C_L}$$

$$= \frac{1{\cdot}3.0{\cdot}14.220}{550} \times \sqrt{\frac{220}{2.\pi.20^2.0{\cdot}0025}} + \frac{0{\cdot}78.220.76}{550}\frac{0{\cdot}018}{1{\cdot}15}$$

= 0·44 + 0·37 = 0·81 h.p.

Judging by this example it is feasible to build a simple helicopter with a two-bladed rotor of 40 ft diameter that will hover for a few seconds. To ensure that the rotor height of 4 ft would still allow the helicopter to hover a few inches above the ground the fuselage height must be reduced to the order of $2^1/_2$ to 3 ft which means a reclining position for the pilot.

It has been suggested that most benefit from the ground effect could be gained by having the rotor beneath the pilot. Providing that a suitable lightweight support frame can be designed for such a configuration there is the major practical problem of the rotor striking the ground. Taking this into account, a rotor height of 4 ft does appear to be the minimum that is practicable with a man-powered helicopter.

Pursuing the feasibility study of a man-powered helicopter in hovering flight a range of rotor radii and chords have been considered for a given total weight of 220 lb and a rotor hovering height of 4 ft. Variation of the chord and radius causes a variation in the induced drag of the rotors, this has been taken into account within this feasibility study. Use of two-bladed rotors and the Wortmann FX-63137 aerofoil section has been assumed.

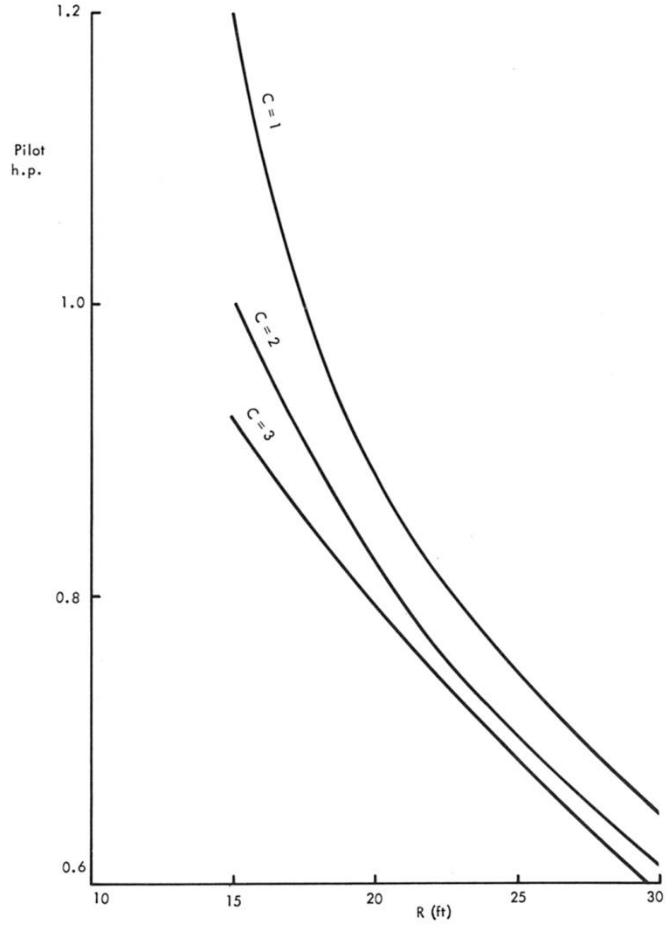


Figure 80 Variation of power with helicopter rotor radius

Bob Wilson with his family of five girls and three boys produced a helicopter (rotor not filled here) with no less than 13 wheels and 36 gears. He works for the Michelin Co. which accounts for all the tyres: but no news of successful flight has been announced.

Figure 80 shows the required power input for various rotor radii and chords. Although the graphs are probably not entirely correct, because a constant weight of 220 lb has been assumed whereas in practice the weight will vary with the radius, it nevertheless clearly indicates the need for large sized rotors before man-powered helicopters become feasible.

The high power values shown in Figure 80 is why so many of the small man-powered helicopters that have been built have been so unsuccessful. In view of this exercise and its small rotor radius it is surprising that the Bailey Cyclopter even managed to lift itself at all.

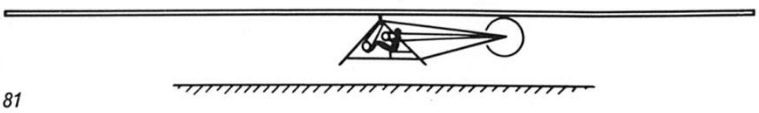


Figure 81

Following from this study the smallest man-powered helicopter that it is possible to fly is one with a two bladed rotor of 25 ft radius and a chord of 2 ft, or alternatively a four-bladed rotor of 25 ft radius with a chord of 1 ft. Such a machine would require 0·7 h.p. for a hovering flight with the rotor at 4 ft height, equivalent to a clear height of 1 ft. Figure 81 shows the approximate proportions of such a machine. A tail propeller of 2 ft diameter would be required to maintain the machine in its correct position, otherwise the torque of the main rotor would tend to turn the fuselage around. Figure 81 shows the general proportions of such a machine. It is anticipated that the tail propeller would absorb approximately 10% of the power for the main so that an additional hand-cranked drive directly coupled to the propeller would provide this additional power.

Position of the pilot and the final centre of gravity position would be critical, otherwise the rotor would tilt. However, if the pilot could change his position this could be used to provide a crude form of directional control since the helicopter would travel in the direction of the tilt.

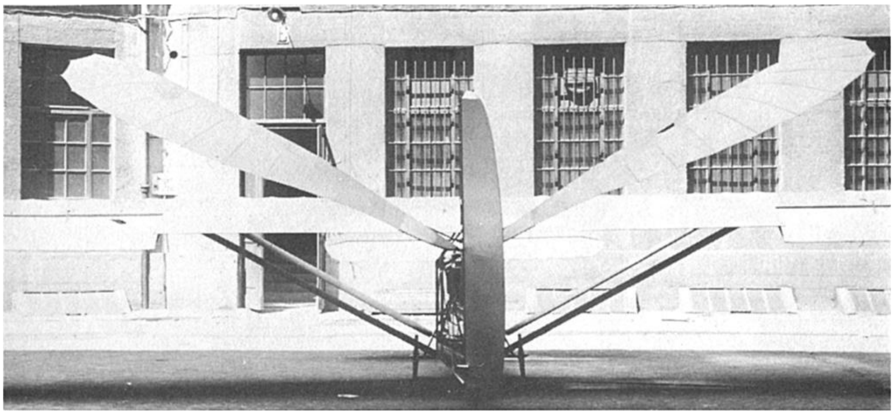
Horizontal motion of a helicopter is more complex than hovering flight because the rotors behave differently during each revolution. If we consider a helicopter moving forward then the rotor blade that is also moving forward will meet the airstream at a higher velocity than that moving back. To equalise lift the two blades should be set at different angles of incidence, and in reality helicopters have flapping hinges that allow the blades to take up the correct positions. With our simple machine it would be impractical to use anything other than fixed rigid blades so that the unequal lift may prove a problem.

At low forward velocities of the order of 4 ft/sec the power absorbed is less than for hovering flight. This is because the rotor disc tends to behave like a solid surface and provides some of the lift necessary to support the weight so reducing the amount of thrust required from the rotor. However, at higher velocities this gain is more than off-set by the increase in machine and rotor drag.

For the simple helicopter given in Figure 81 the angle of incidence of the rotor will be that of the aerofoil section to give the necessary lift and drag values. To simplify construction the rotor blades need only be of single spar construction, and to reduce the weight to a minimum a load factor of 1 would be satisfactory, especially as a man-powered helicopter is unlikely to fly with clear heights greater than 1-2 ft. Deflection of the rotor blades under loading conditions is no problem because the rotation of the blades and the resulting centrifugal forces will tend to oppose it.

11.2. Flapping wing aircraft

Flapping wings could prove to be a most efficient form of practical aircraft lifting/propulsion system because unlike the conventional aircraft with a fixed wing and propeller the flapping wing combines the two and so eliminates the additional losses and drag of the propeller. (Also for reasons given later the profile drag of the main wing is reduced.) Although at first sight very simple the flapping wing design is in reality far more complex than either the fixed wing aircraft or the helicopter. More research is required before even the basic flapping motions can be fully defined and then a considerable amount of time and effort will be needed to evolve the necessary design rules to enable practical machines to be made.

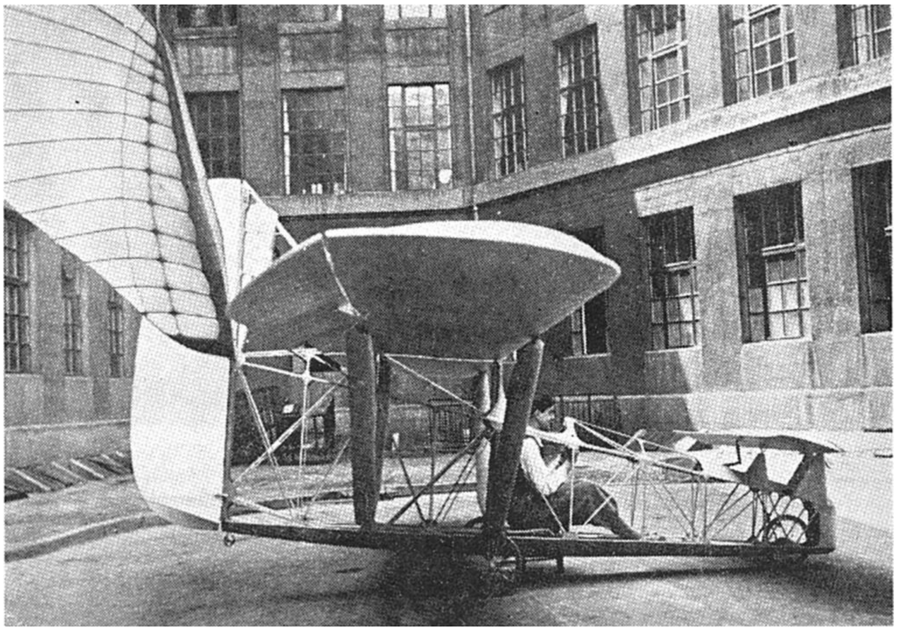


Constructed by Dr. Martin Sultan before obliged to abandon Germany to settle in Palestine, this unique man-powered canard featured flapping wing propulsion, see other views below.

Flapping wing aircraft are very much a thing of the future. All previous attempts apart from the Lippisch ornithopter have been unsuccessful and the best that was achieved with the Lippisch machine was an extended glide. Once the design problems have been solved for flapping wing systems they will not only be of value to man-powered but more especially to the smaller conventionally powered aircraft where the quieter propulsion and short take-off characteristics will be very advantageous in the crowded airspace of the future. The quieter propulsion will stem from the elimination of propellers or jets and the chance of burying the power unit inside the fuselage.

To appreciate the technical problems that surround the design of flapping wing aircraft it is necessary to study the behaviour of such with regard to insect and bird flight. Insects and birds use different modes of flapping but it is instructive to consider them both.

Insect wings consist of a leading edge rigid spar with a trailing flexible diaphragm attached to it. Lift and propulsion are achieved by a very rapid vertical oscillation of the wings with the diaphragm taking up different angles of incidence along the span in order to balance out the lift, propulsive force and drag development. Further lift balancing is achieved by insects using two pairs of wings. One of the most sophisticated of the insect systems is that of the dragonfly where independent muscle control of each pair of wings and also the wing diaphragm appears to be used, otherwise its full hovering and flight manoeuvrability could not be obtained. However, this manoeuvrability is gained at the expense of the wings being maintained in a fixed lateral position unlike other insects where the wings fold into the body.



Full sized and model ornithopters have attempted to copy the insect motion since it represents the simplest flapping mode. Success has been limited because the insect wing behaviour relies on very high frequency flapping which is impractical with larger devices.

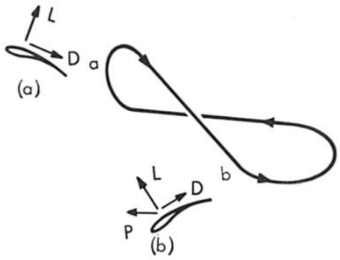


Figure 82

Bird wings are totally unlike those of insects for this very reason. Birds are larger and heavier and are unable to use the very high frequency flapping mode of insects. Wings that have evolved for birds utilise a rigid spar (bone) supporting an aerofoil section and it is from this form of construction that the first practical wings were developed. Lift and propulsion is achieved by executing a figure-of-eight motion of the wing in a transverse direction. A typical figure-of-eight motion is illustrated in Figure 82 and this can be considered to be the 1st mode of oscillation of the bird wings. At point a on the cycle the aerofoil section shown produces both lift and drag whilst at b it is producing both lift and propulsion. Throughout much of the figure-of-eight the wing will be producing some forward propulsive force but it is inevitable that this will be lost at certain parts of the cycle. This is also true of the lift component.

Certain small birds such as the humming bird rely entirely on this first mode of operation and balance the lift and propulsion by high-speed flapping, not of the same order of frequency used by insects, but high speed by bird standards. For the larger birds this is impractical and lift/propulsion are balanced by a second mode oscillation of the wing. Unlike the first mode which is in the transverse direction, the second mode takes place longitudinally along the wing.

Figure 83 illustrates what is meant by this second mode operation of the wing. At position 1 the wing is curved with the tip at the bottom of its down stroke whilst the centre of the wing is at the top of the upstroke. At position 2 the wing has reached the limit of movement in the opposite direction with the centre of the wing now down and the wing tip now up. At position 3 the wing has returned to the original position.

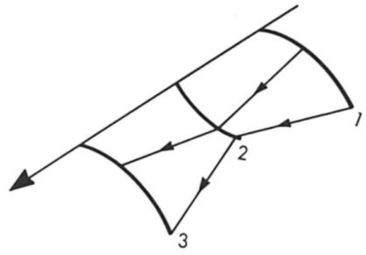
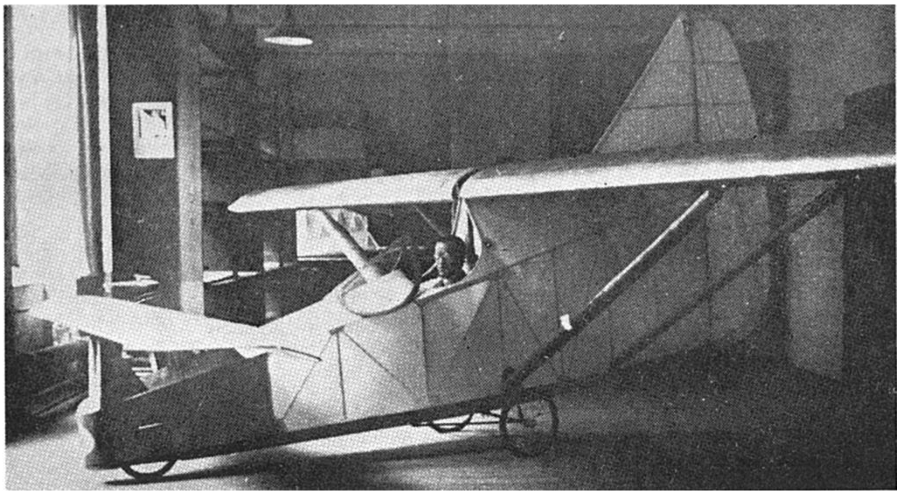
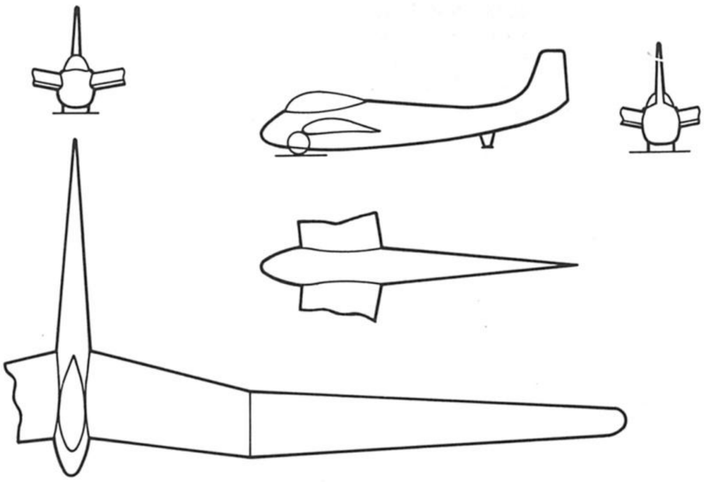


Figure 83

This second mode of operation allows different sections of the wing to operate at different parts of the figure-of-eight first mode operation, so balancing lift and propulsion. However, as portrayed in *Figure 83* the second mode movements are idealised and in practice birds compromise by working the wing longitudinally in two segments, which approximates as closely to the ideal motion as the rigid spars (bones) allow. A study of gulls in flight shows that there is some vertical movement of the body during each stroke of the wings, indicating that with its two-segment wing the lift balance is not perfect. A proposed man-powered ornithopter design employing this type of operation is shown in Figure 84.



With surfaces covered the Sultan Canard was ready to fly for the Ursinus prize until abandoned for political reasons.



Proposed ornithopter design

Figure 84

As well as the first and second mode operation of the wings in order to provide the necessary lift and propulsion, birds can move the wings independently in order to control their flight. For example, a turn can be executed by increasing the propulsive forces on one wing tip relative to the other. There is no need to elaborate on this theme as a study of birds in flight will clearly indicate the very wide range of control they have, which is one of the basic reasons for their excellent manoeuvrability.

A bird represents a highly sophisticated flying machine, with a level of complexity that man-made machines cannot hope to achieve at the present time. The first stage in the design and construction of a flapping wing aircraft must be to incorporate the first and second mode operations of the wing in order to produce the necessary lift and propulsion, relying on conventional control surfaces for aircraft manoeuvre control. It is necessary to incorporate the second mode motion of the wing at an early stage not only to ensure a smooth flight path but also to reduce the stress levels in the main spars and therefore the weight of the wings.

John Elliott the leader of the Farnborough Man-Powered Ornithopter Group has developed a theory relating to the balanced lift second mode operation of flapping and in fact was the first person to fully define the longitudinal motion of this type. His research has now progressed to the stage of testing model segmented wings which behave in a similar way to those of birds. From this work it is hoped that an 8 ft wing span model may be flying using a 3-segment type of flapping wing.

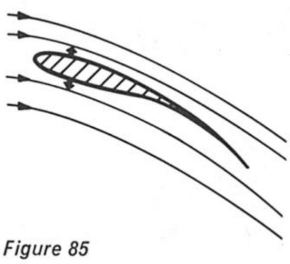
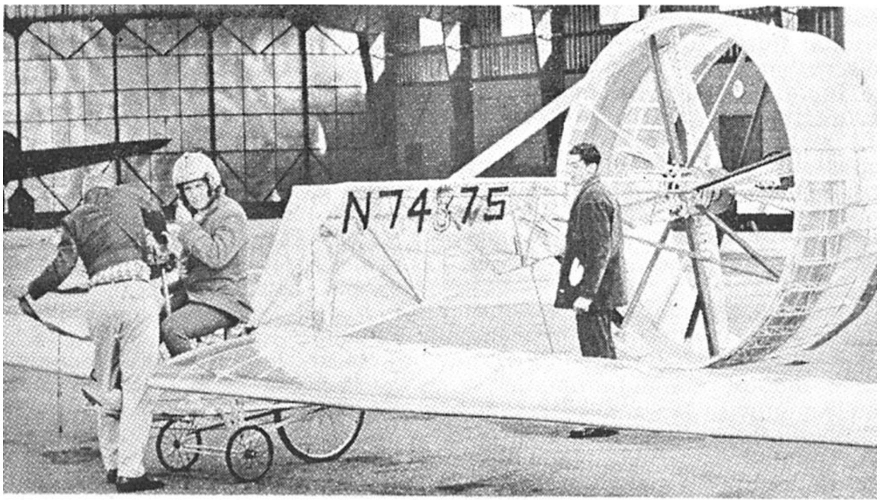
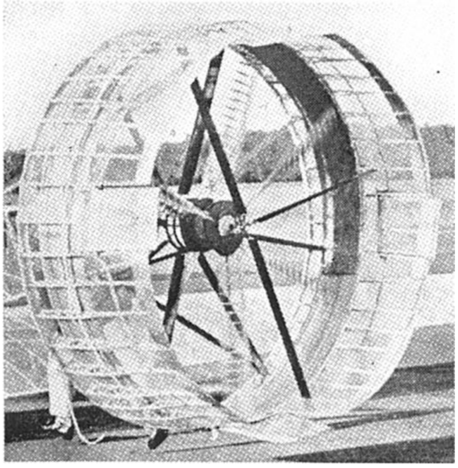
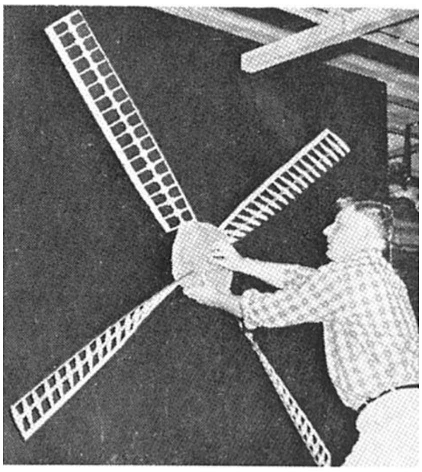


Figure 85

If flight models prove successful there is still a long way to go before the flapping wing research can be applied to man-powered aircraft. To minimise power it is necessary that the wings should oscillate at their natural frequency. Returning to the discussion of insects, a dragonfly for instance resonates its wings before take-off probably for this very reason. To design the necessary resonant structure for a full-sized aircraft requires a comprehensive knowledge of its aero-elastic properties and this is further complicated by the superimposed first and second mode oscillations.







Mylar covered circular propeller shroud which also provides tail surfaces on the McAvoy MPA-1 made in the U.S.A. show small rudders and elevator trimmers in action. Above, James M. McAvoy displays the frame of his 84 in ,diameter, 4-blade, propeller designed to operate at 240 rpm, driven by torque tube from bicycle type drive. At top, prior to an accident which curtailed flight tests, the completed machine displays its unconventional approach. The 54 ft machine has since been taken over by the pilot, Robert W. Ritchie at Georgia Tech.

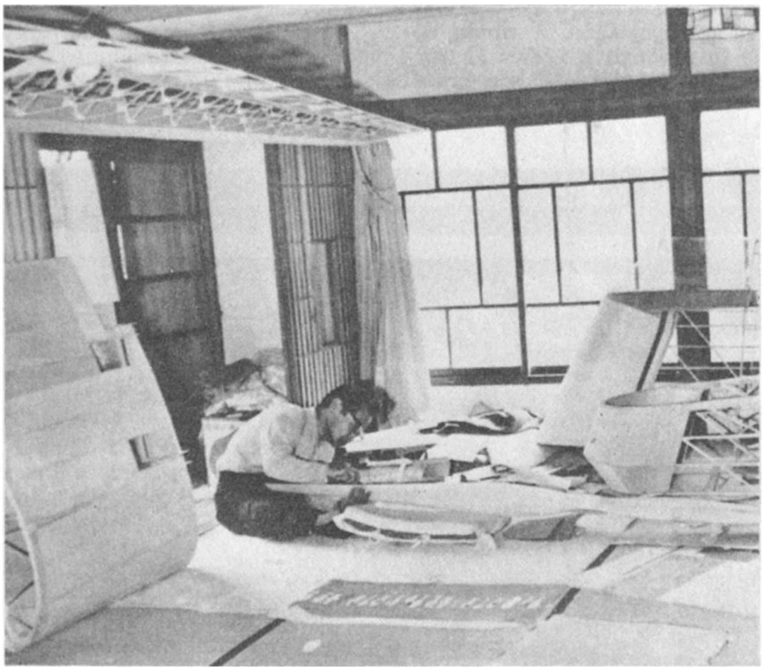
An additional effect that has been noted during the wind tunnel testing of flapping wings by John Elliott, is the elimination of flow separation at the trailing edge of the aerofoil section. Consider the aerofoil section shown in Figure 85, under normal operating conditions there would be separation of the flow over the top surface resulting in a wake behind the section. Separation occurs when the energy level of the flow is too low to maintain the adverse pressure gradient at the surface. In the case of the flapping wing energy is obviously being transmitted directly into the flow and separation is prevented. Figure 85 shows typical streamlines as noted from actual wind tunnel tests on flapping wings.

Flow of the type shown in Figure 85 greatly reduces the profile drag of the aerofoil section by eliminating the form drag component. In this respect flapping wings have a similar effect to boundary layer control devices and blown flaps. This is a particularly useful outcome of the flapping wing research since it may be possible to incorporate this on fixed wing aircraft by having a small mechanical input to resonate the wing and so reduce profile drag.

50 year old Wally Smith of Mordiallac, Australia, in his man-powered helicopter, tested at Fishermans Bend, but so far unsuccessful.

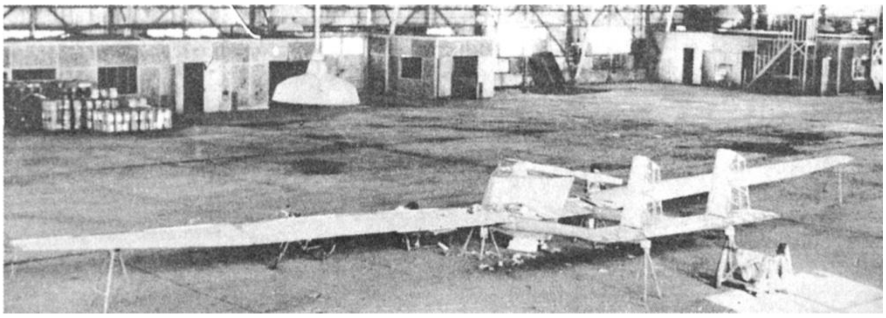
12. MAN-POWERED FLIGHT

IN the post-war era the Kremer competition gave the initial incentive for the design and construction of man-powered aircraft. This incentive is no longer the primary consideration in choosing to build a man-powered aircraft because, although there are large wing span machines like the Weybridge and H.P.A. “Toucan” projects being built with the Kremer prize in view, there are more recent projects such as the “Malliga” aircraft and “Liverpuffin” with more limited performance objectives. The development of these machines is of very great value to the future of man-powered flight since they point the way to small compact machines that can be built by enthusiasts or by small groups of people in their spare time. Furthermore, the cost of such machines would be below £100, and in fact, if the cost was of primary importance, it would be feasible to produce a flyable aircraft for approximately £50. These costs are of a similar order to those involved in other equivalent activities and would be far less than say that spent on a model aircraft equipped with full house proportional radio control.

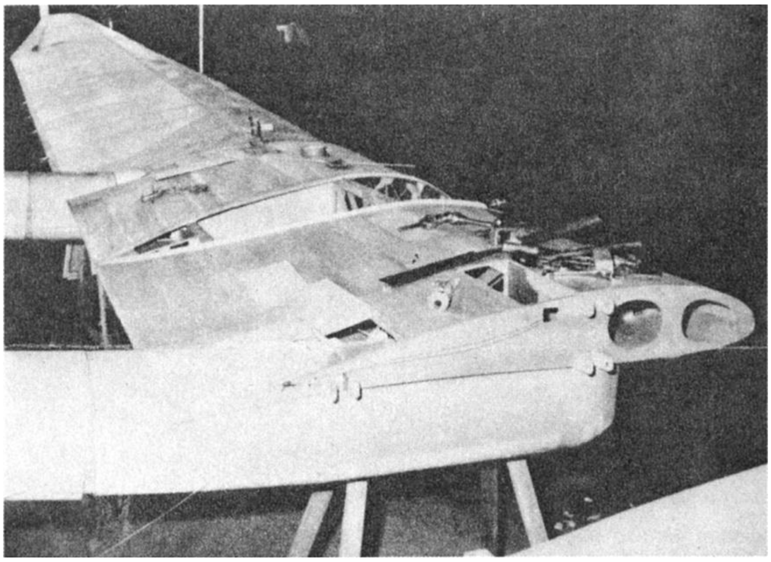


Eiji Nakamura working single handed on his 69 ft span MP-X-6 machine prior to completion in 1969. Airframe weight was 132 lbs. First tests were unsuccessful due to structural failure.

It is therefore possible for the enthusiast to design and build a suitable aircraft at reasonable cost. Once this has been accepted and such machines have been built then there is a basis for man-powered flight as a sport, and as a sport it then has a very bright future. To refer back to the introductory chapter, it would have been difficult to assess the potentiality of gliding as a sport if only viewed from its beginnings. In a similar way we are still at the pioneering stage of man-powered flight and one cannot accurately predict its future. However, as other forms of sports flying become too costly or restricted by the ever increasing rules necessary to preserve air safety, man-powered flight will become more attractive as a legitimate branch of aviation.



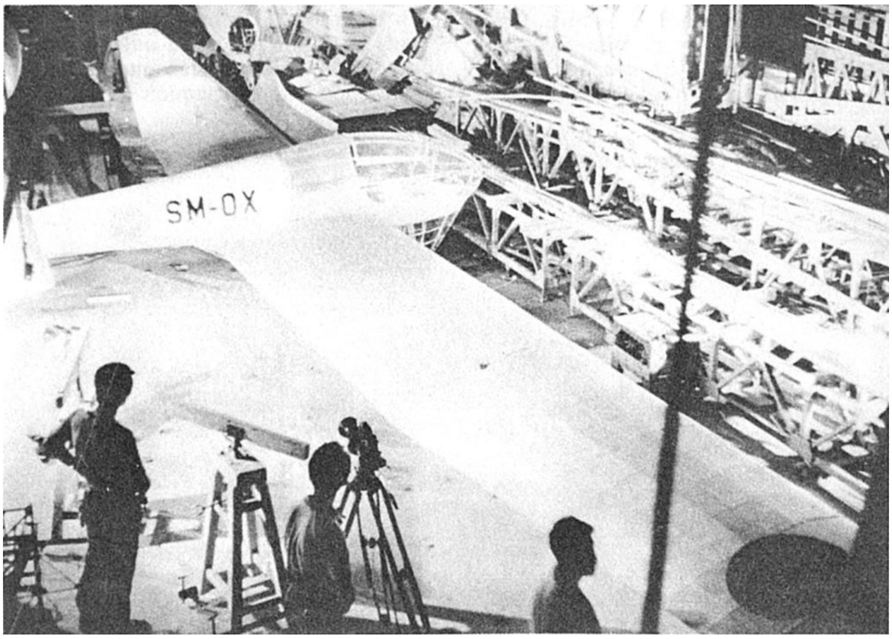
Above, assembly of the Nakamura man-powered machine in a Tokyo hangar in 1969 reveals the short twin boom fuselage (19 ft 8 in overall length) and the high aspect ratio of the 69 ft wings. Area is 226 sq ft and the aerofoil section is Gottingen 532; see below for transport joints including area where propulsion nacelle fits on to wing centre section.

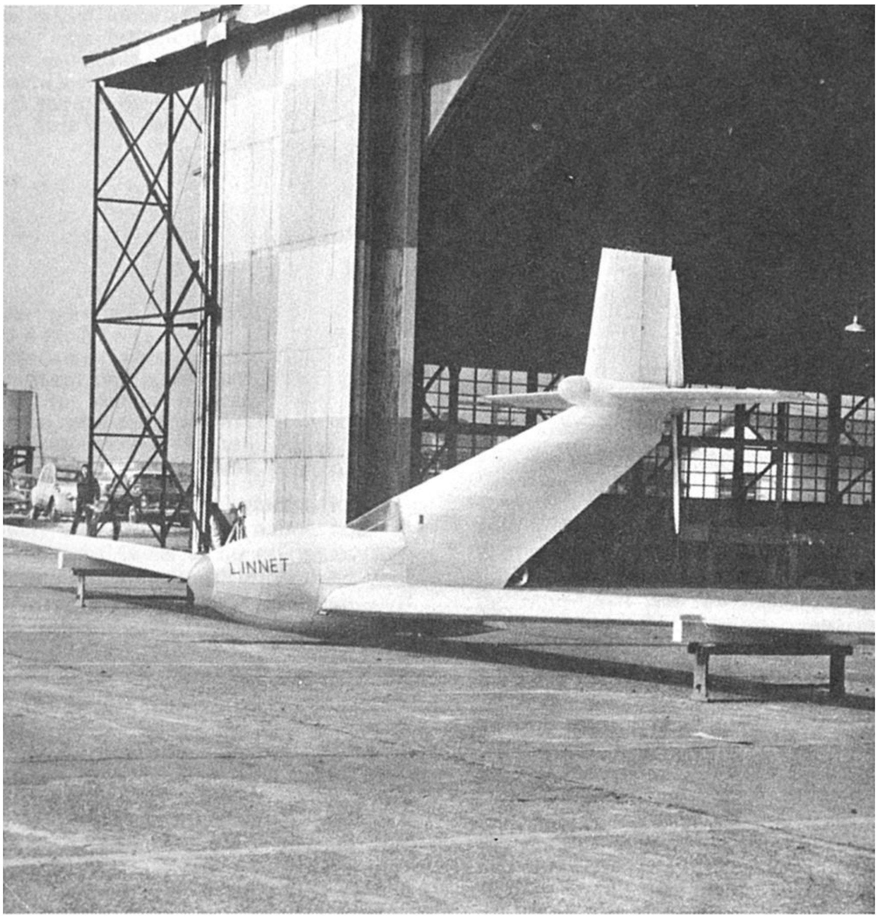


Not only does man-powered flight appeal to those interested in aviation but it could provide an outlet for keen cyclists who find to-day's crowded roads more and more restrictive. One particular advantage of man-powered flight as a sport is its silence, whilst limited performance capabilities require operation in the ground effect region which ensures safety of the pilot.

Kenichi Maeda's SM-OX, made with the assistance of a Gliding Club over $3^1/_2$ years, first flew for 50 ft at 6 ft height on August 24th 1969.

First assembly of the Maeda SM-OX shows the constant chord centre panel and tapered tips of this machine designed by a 22 year old.





Roll out of the Linnet Mark I which made its first flight on February 26th 1966 after basic study and construction dating back to April 1963. Wing section was NACA 63_3-1218, aspect ratio 18·5. Empty weight 105 lbs. It cruised at 6 ft altitude, airspeed 17 m.p.h. Covering was Balsa on wing leading edge, otherwise styrene sheet.

It must be remembered that it is only over the past decade that true man-powered flight has been realised. With the present interest in this activity it is entirely feasible that developments over the next decade could be even more rapid. It is therefore necessary to plan for its potentiality as a sport. The first requirement is a runway and in this respect it is suggested that many of the deserted war-time airfields could be utilised for such purposes, but if left for too long could be irrepairable.

Once man-powered flight becomes established as a sport it could itself provide a direct incentive to aircraft design and development through club and national competitions. One can ultimately envisage its acceptance as an athletic event in the Olympic Games.

Although competition itself provides an incentive for improvement, this can only partly be achieved unless fundamental research is also undertaken in low speed aerodynamics or possibly into new types of structures. Such work would be ideally suited to the institutions of higher education, universities and polytechnics, where relevant work could be accomplished within a comparatively short time scale and on a limited budget.

It must be remembered that many of the recent advances in glider design stemmed from research carried out in academic institutions in Germany. The availability of the FX-63137 aerofoil section for man-powered aircraft also stemmed from the same source.

Looking at the question more broadly, as the aircraft industry becomes more involved with a few highly sophisticated aircraft projects it becomes increasingly more difficult for the academic establishments to stimulate interest in actual practical aircraft design problems. Man-powered aircraft projects could provide valuable design experience not only of direct relevance to the aircraft industry but in providing engineers generally with an appreciation of aircraft design problems which could be capitalised on if at some future date the industry needed to expand.

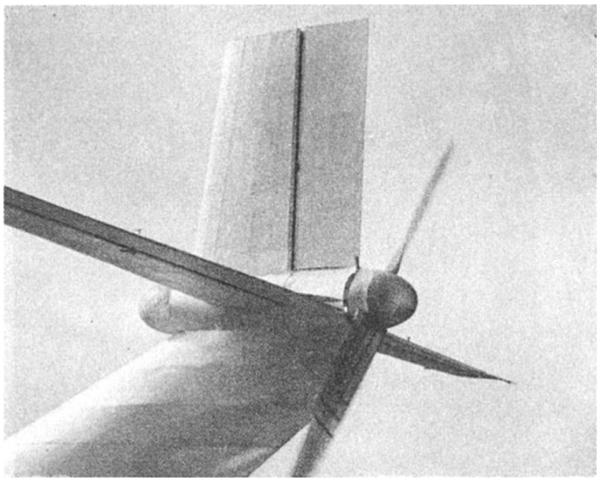
Performance of sporting man-powered aircraft could be extended by:

(a) using athletes as pilots;

(b) combined hand cranking and foot pedalling; and

(c) utilising low altitude convection up-currents.

The former would be the obvious requirement for competition at national level. Combined hand cranking and foot pedalling by an ordinary fit man provides power levels equal to those of athletes for durations under 3 minutes. However, when using both hands and feet there is a problem of controlling the aircraft. If experience with “Liverpuffin” proves the feasibility of control by rudder and elevator only it would then be possible to incorporate a hand-cranking device in man-powered aircraft that could be moved in two directions to manipulate these controls. However, if a form of lateral control proves necessary then it becomes more difficult to control whilst also hand cranking. One possible method of incorporating this would be to use radio control for the lateral control surfaces operated by push button on the hand-cranking device.



Above, the acorn fairing on Linnet I filled after first flights to streamline the layshaft arrangement which picked up drive from the pilot's pedals and shaft via bevels.

If low altitude convection up-currents can be utilised this would be the most promising technique for helping man-powered flight to develop as a sport since durations would not then depend on athletic prowess. The criteria for a person participating would simply be his or her ability to take-off.

Low altitude convection up-currents must in no way be confused with the thermals used for extending the performance of gliders because these only develop fully above about 300 ft altitude, whereas with man-powered flight we are thinking in terms of altitudes of 20 or possibly 30 ft maximum, at least within the early stages of development. A further point is that gliders are highly manoeuvrable in order to circle within thermals and gain most benefit from the rising air. Man-powered aircraft are limited in manoeuvrability and this to some respect will limit the extent to which convection currents can be utilised.

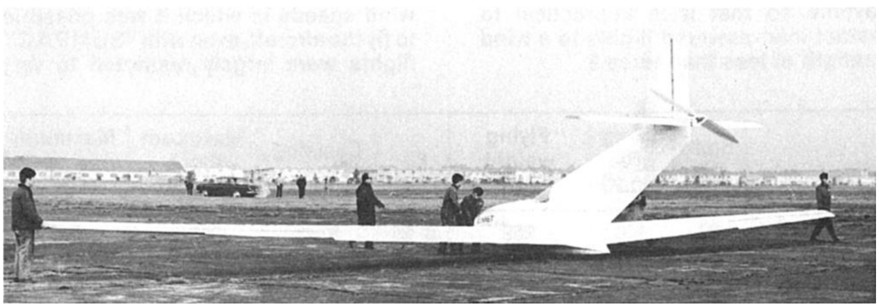
Unfortunately information is limited on convection currents in the near ground region up to 20-30 ft because they have little practical significance for other forms of aviation. We have all seen warm air rising from a hot surface on a sunny day but tests are required to establish the usefulness of this rising air. Up-currents rising at a minimum velocity of 1 ft/sec would be adequate for man-powered aircraft purposes, and theoretically it is possible to achieve this order of magnitude at a height of 10 ft above a runway with only 2°F difference in temperature between the runway and the surrounding grass. However, if warm air rises from a certain region it must be replenished from air descending in an adjacent region so that probably with warm air rising from a runway there will be down draughts over the grass at either side. This means that the span of the man-powered aircraft must be less than the width of the runway in order to take full advantage of the maximum upward velocities that should be found at the centre of a runway.

Up-currents develop when the surface temperature of one region is higher than that of the surrounding regions. Increases in surface temperature depend on the amount of sunshine together with the dampness of the surface, or its covering, and its reflection factor. Moisture in the ground, or in the grass/crop over it, evaporates and this evaporation tends to reduce the surface temperature. The reflection of solar radiation also has considerable bearing on the surface temperature, typical values for the amount of solar radiation wasted by reflection from different types of surface are as follows:

Type of surface	*solar radiation wasted*
	%
Cereal crops	3-15
Damp sand	10
Dry sand	18
Bare ground	10-20
Grass fields	14-37
Dry ploughed fields	20-25

It is difficult to provide hard-and-fast rules regarding development of up-currents, but this information does indicate that their development will be more certain above bare ground or stretches of tar macadam/concrete rather than over grass or crops.

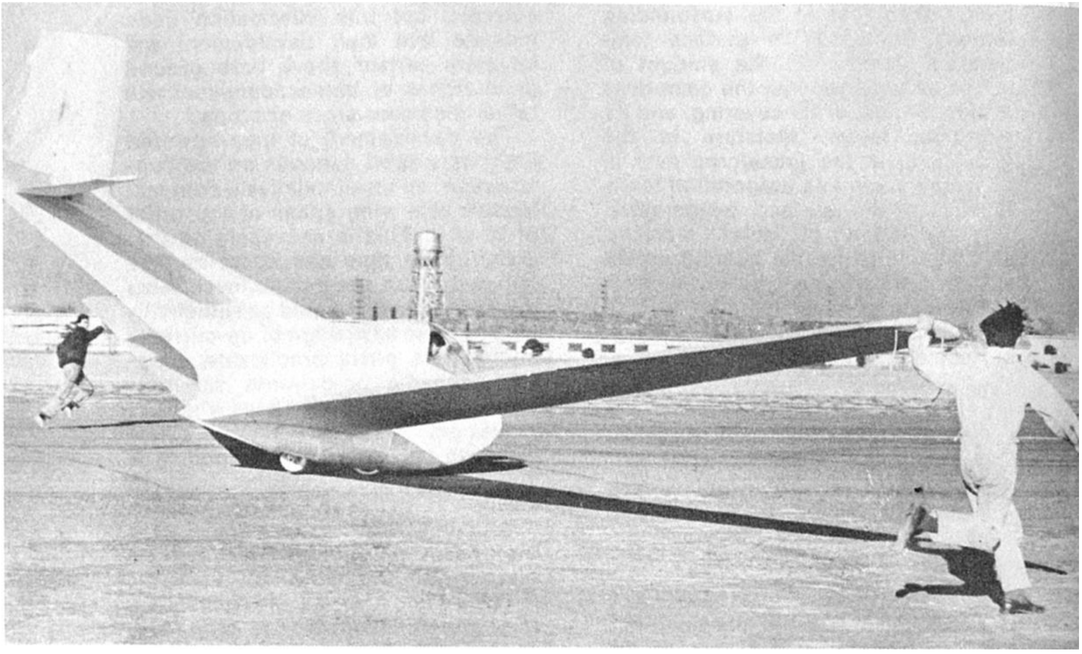
Below, preparing the Linnet for a first flight with cuffs fitted to the propeller blade roots. Note the comparative rigidity of the 72ft 3in span wing which had 3 degrees dihedral angle.



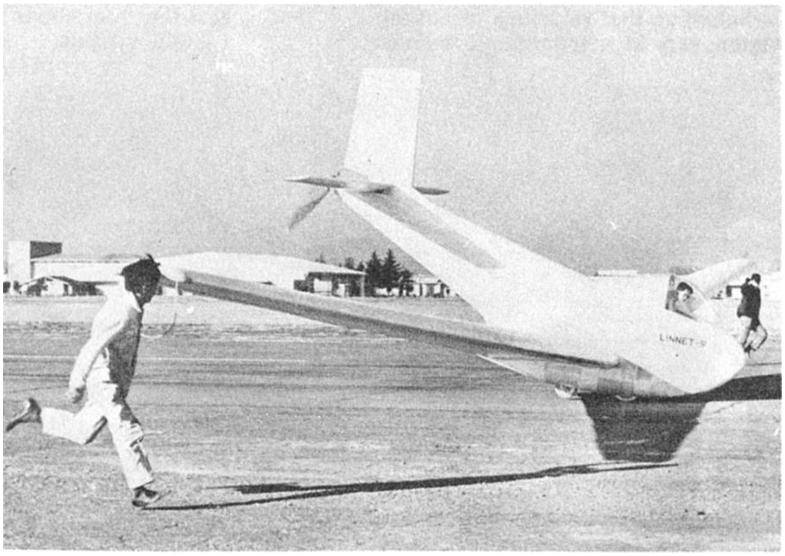
The development of man-powered flight as a sport depends on the construction of small relatively-compact aircraft with wing spans of the order of 50-65 ft. This is necessary so that construction time and costs can be reduced to an acceptable level. Also this size of aircraft would be sufficiently small to take advantage of up-currents should this prove practicable. However, suitable up-currents can only develop on warm sunny days when the movement of the air will itself cause winds to occur near the ground. It is considered at this stage that flights in a wind strength of force 3 would be an acceptable requirement which also fits in with the structural load-factors discussed in Chapter 8.

The Beaufort wind scale from which the force numbers arise is defined by the following classification:

Beaufort No.	Wind speed at 33 ft (m.p.h.)	Wind description	Noticeable effects
0	<1	Calm	Smoke rises vertically
1	1-3	Light	Smoke drifts
2	4-7	Light	Leaves rustle
3	8-12	Light	Leaves in motion
4	13-18	Moderate	Small branches in motion



These two views of Linnet Ill at take-off represent a significant advance in man-powered flight. No evidence has been produced to show that the wheels are driven. Take-off is said to be in 80 metres at prop. r.p.m. of 200. Each photo shows assistants at the tips of the cantilever wings. Tailplane was changed to all flying type, aerofoils altered from that of Linnet II, dihedral doubled to 6 degrees and fixed tabs used instead of ailerons. The tailplane is of inverted NACA 4412 section, wings are NACA 8418 tapering to 8415 at the tips.



Typical statistics for wind strengths in England are:

Annual frequency of winds

force 1 or less 10%

Annual frequency of winds

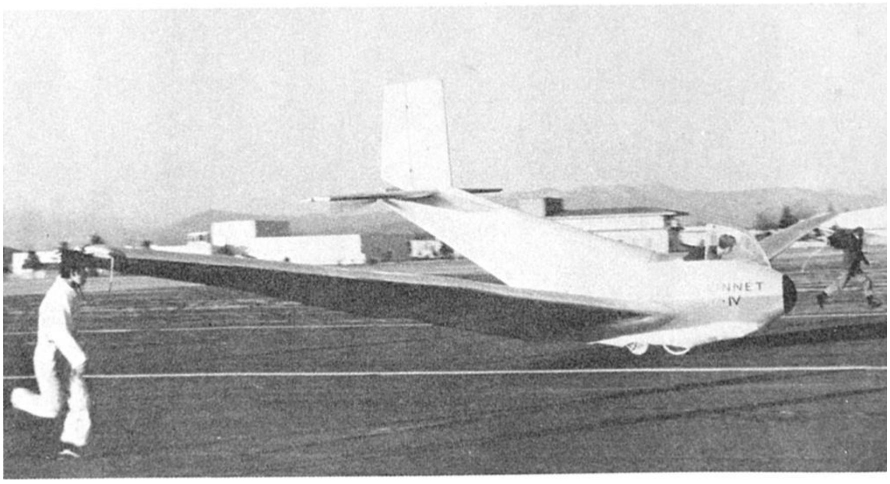
force 2 or less 30%

These percentages are for both day and night hours combined and it must be borne in mind that light winds are more frequent at night than in the daytime so that it is impractical to restrict man-powered flights to a wind strength of less than force 3.

	Span (ft)	Wing area (sq.ft)	Flying weight (lb)	C_L	Cruising h.p.	Maximum flight (yards)	Maximum wind speed (knots)
"SUMPAC"	80	300	269	0·85	0·43	650	5-7
"Puffin I"	84	330	250	0·8	0·42	993	5
"Puffin II"	93	390	290	1·15	0·30	1200+	2-3

The capability of an aircraft to fly in certain wind conditions depends on its wing span and wing loading. In the case of a man-powered aircraft the smaller the span the higher will be the wing loading and the higher the wind speed in which it is capable of flying. This is clearly indicated by the following comparison below of the three British machines to have flown. Although these were the maximum wind speeds in which it was possible to fly the aircraft, even with "SUMPAC" flights were largely restricted to very early in the morning or late at night.

Based on previous experience it should be possible to handle a man-powered aircraft of 50-65 ft wing span with a wind strength of force 3. It must be remembered that this requirement which is of the utmost importance to man-powered flight as a sport has only been attainable through the developments of a highly efficient aerofoil section capable of combining a high lift coefficient, i.e. C_L= 1·15, with low profile drag. If in the future more improvements in lift coefficients can be made through fundamental research in academic establishments, then even smaller wing spans can be considered and man-powered flight can be developed even further.



Increase of wingspan to 78 ft 9 in and incorporation of wash-out on the tapered NACA 8418 section wing is an immediately noticeable feature of Linnet MK. IV, first flown in March 1971. Empty weight of 119 lbs and use of symmetrical tailplane section are further changes of this progressively developed design by Nihon University students under Professor Hidemasa Kimura as above.

Flying man-powered aircraft in windy conditions will itself create some new problems. Unlike other forms of aviation, altitudes will be very low and certainly well within the earth's surface boundary layer. This is the region of the atmosphere where the wind velocity changes from zero at the actual surface to the free airstream velocity. The boundary layer roughly extends to 100-200 ft altitude depending on the wind speed and type of surface. It can be assumed to be fully turbulent so that velocities within this region vary in a logarithmic manner according to the relationship:

$$V_X \propto log\left(\frac{X}{X_0}\right)$$

where Vx = mean air speed at height X and X_0 = the roughness length of the surface.

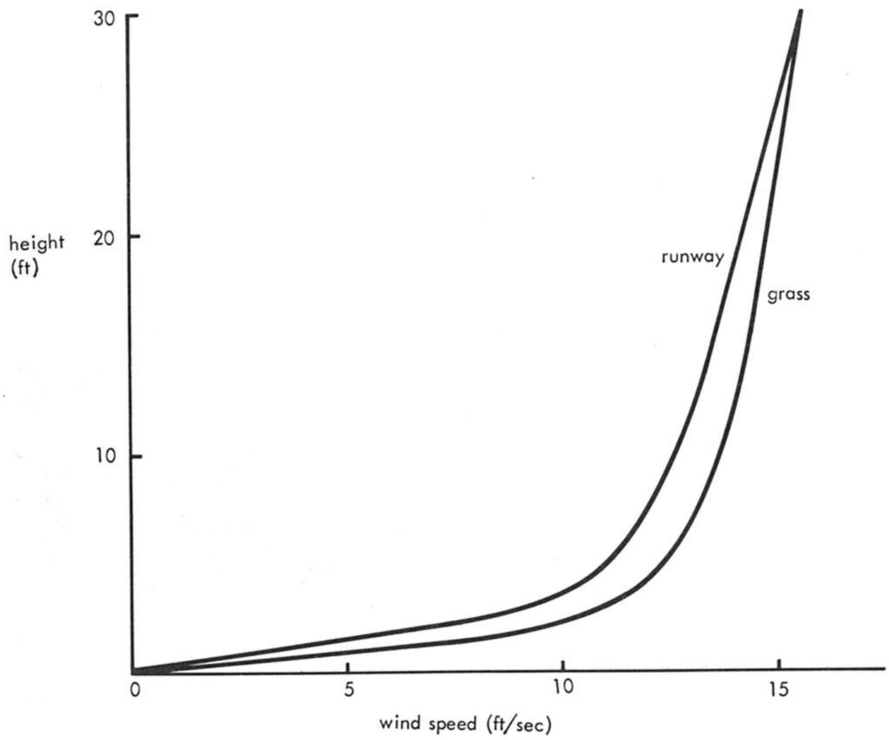
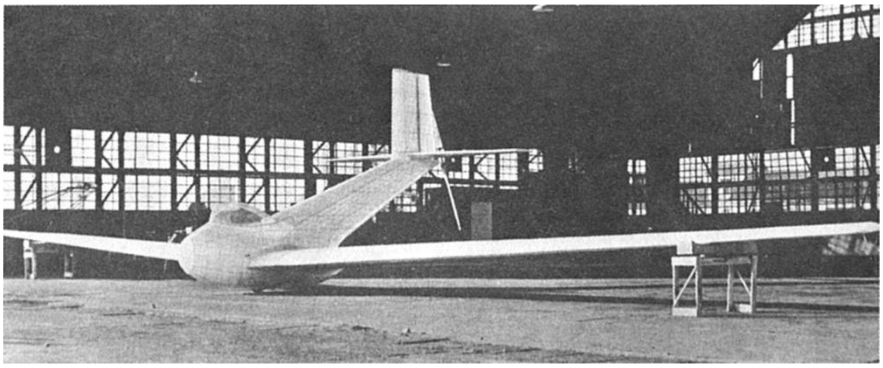


Figure 86

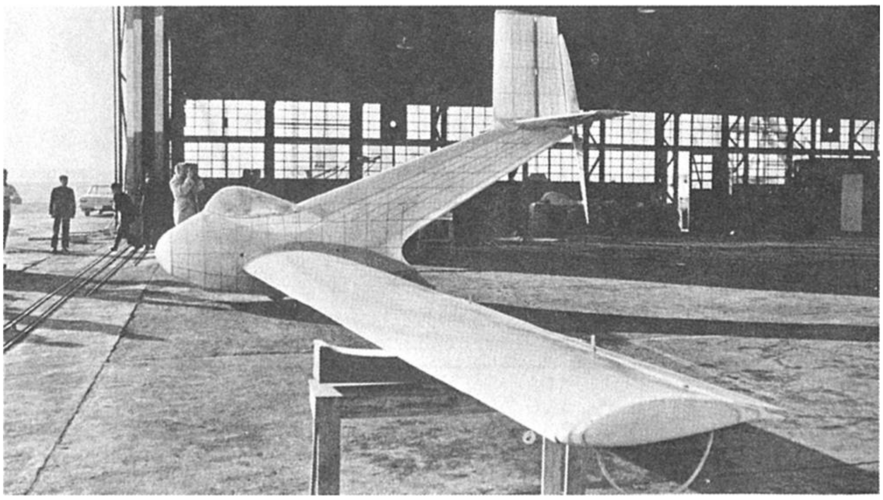
Variation of wind speed near the ground

Figure 86 shows two wind profiles near the ground for two surfaces, a runway and also for grass of 21/2 - 3 inches depth, since X_0 the roughness length will vary with the types of surface. It has been assumed that the wind strength is force 3 with a wind speed of 12 m.p.h. at 33 ft, implying an approximate speed of 16 ft/sec at 30 ft height.

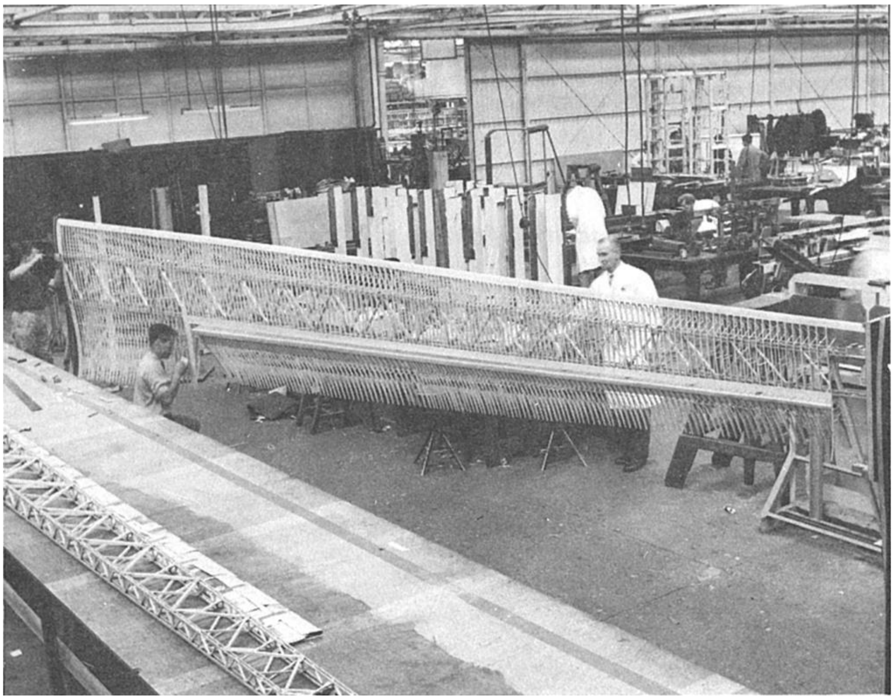


The Linnet Mk. 2 ready for flight test in February 1969, when it was successfully flown by pilot S. Sato. Each wing has 57 ribs.

NACA 63_3-1218 wing section of Linnet II was the same as that for the first version. Span 72 ft 3in, Flying weight approximately 220 lbs.



Several problems would be encountered when flying a man-powered aircraft in such wind profiles. Assume that a man-powered aircraft has a wing height of 5 ft during take-off and that its cruising speed was 30 ft/sec. From Figure 86, at 5 ft above the runway the wind speed would be 11 ft/sec so that the aircraft would only need to attain a rolling speed of 19 ft/sec along the runway to take-off. However, at this speed the rotational speed of the propeller would only be 19/30 of its correct speed to sustain the necessary thrust. In practice the pilot would need to take-off then rapidly increase his rate of pedalling before stalling or alternatively keep the aircraft on the runway until a correct rolling speed of 30 ft/sec was achieved. This latter course of action would have the advantage of allowing the aircraft to zoom to a height of several feet by converting the excess kinetic energy into potential energy. However, it would incur a high drag penalty because at a rolling speed of 30 ft/sec the relative airspeed would be 41 ft/sec.



Complexity of Puffin II wing assembly with its multiple close spaced ribs is clear in this view of the port lip panel in its jig. The Starboard panel mainspar box can be seen on the bench in the foreground. Note the large aileron area. At this stage the lip drag rudder is omitted.

Once in the air there would be the problem of manoeuvring the aircraft. Even when flying into wind, variations of roughly 1 ft/sec in wind speed could be encountered over different surfaces. Consider an extreme case of an aircraft flying at 10 ft altitude half over the grass and half over the runway. If the relative cruising speed was 30 ft/sec a 7% variation lift of one wing relative to the other would be experienced. Finally, consider a landing into wind, the aircraft is going to move from a higher into a lower velocity airstream as it nears the ground. In order to maintain correct lift and prevent stalling the actual speed of the aircraft must be increased by increasing its diving angle.

It will be apparent from the foregoing remarks that, although the design of man-powered aircraft is well defined, there is a great deal that we have yet to learn regarding man-powered flight. This can only be gained by experience and it is probably this aspect of man-powered flight that represents its greatest fascination.

CONVERSION FACTORS

Distances and Areas

1 inch	= 2·54 cm
1 foot	= 0·305 metres
1 mile	= 1·609 km
1 sq.ft	= 0·093 sq.m

Weights and Wing loadings

1lb	= 0·4546kg
1 lb/sq.ft	= 4·88 kg/sq.m

Velocities

1knot	= 1·151m.p.h.
1 m.p.h.	= 1·467 ft/sec
1 km.p.h.	= 0·911 ft/sec

Miscellaneous

1 radian	= 57·3°
g (at London)	= 32·2 ft/sec^2
π	= 3·142 ≈ 22/7

"It's a pity, we could have dispensed with the radio if there had been just one volunteer."

American Aircraft Modeler

SIGNIFICANT DATES IN THE HISTORY OF MAN-POWERED FLIGHT

c. 1500	Leonardo da Vinci made a study of man-powered flight.
1852-3	Sir George Cayley designed and built a man-carrying glider.
1896-1902	Sir Frederick Handley Page and Major Moore experimented with a flapping wing.
1929	Alexander Lippisch built a man-powered ornithopter. The machine made a few short flapping flights, but did not take off under man power.
1933	Oskar Ursinus, Editor of *Flugsport,* arranged the offer of 500 marks for the first 1 km flight around two pylons 400 m apart. The prize was not won, but Haessler and Villinger (see below) won a consolation prize. Their longest flight was 790 yd.
1936-37	Systematic tests on the power that man could produce were done by Ursinus in his Muskelflug Institut and the results were published in *Flugsport.*
1935-38	Helmut Haessler and Franz Villinger, two young engineers from Junkers, flew their machine “Mufli”, at Frankfurt. Many significant flights were made, but in all. cases the machine was launched by bungee, and did not take off under its own power.
1936-7	A prize similar to the German one was offered in Italy. Enea Bossi and Vittorio Bonomi built and flew their machine, the “Pedaliante”. This was, in general, shock-cord launched; it is alleged, but not confirmed, that some flights actually took off under man power alone.
1939-45	Both the Haessler-Villinger and the Bossi-Bonomi machines were destroyed during the war.
January 1957	Formation of a Committee of enthusiasts in the United Kingdom to clarify the problems of man-powered flight.
April 1959	The Committee became the Man-Powered Aircraft Group of the Royal Aeronautical Society.
November 1959	Mr. Henry Kremer, an industrialist, offered £5000 for a figure-of-eight flight by a man-powered aircraft, under conditions laid down by the Royal Aeronautical Society and the Royal Aero Club.
June 1960	The Royal Aeronautical Society announced the existence of a fund to help promising subjects.
9th November 1961	First flight of the Southampton University machine “SUMPAC”.
16th November 1961	First flight of the Hatfield Club’s machine “Puffin”.
May 1962	Special prize of £50 awarded by the Aeronautical Society to Mr. J. C. Wimpenny, of the Hatfield Club, for a straight flight of half a mile.
April 1963	Hatfield machine, “Puffin I”, damaged during landing.
August 1965	First flights of Hatfield Club’s “Puffin II”.
February 1966	First flights of Japanese “Linnet” machine.
February 1967	First flights of Japanese “Linnet Mk. II” achieving flight of 45 ft.
March 1967	Kremer Competition made international and prize increased to £10,000; announcement of a simplified course, initially open only to Commonwealth entrants, with a total prize money of £5,000.
April 1969	Design study of “Linnet Mk. III” started.
August 1969	First flight of Japanese “SM-OX” machine. Achieving flight of 100 ft.
September 1969	Adoption of “Puffin” remains; creation of “Liverpuffin” at the University of Liverpool.
March 1970	First flight of Japanese “Linnet Mk. III”.
December 1970	First assembly and taxi test of Weybridge machine at Wisley.
March 1971	First flight of Japanese “Linnet Mk. IV”.

BIBLIOGRAPHY

THE following books are recommended for those readers who wish to make a deeper study of various topics discussed earlier.

Gliding

The Story of Gliding, by A. and L. Welch, published by John Murray.

New Soaring Pilot, by A. and L. Welch and F. Irving, published by John Murray.

Meteorology for Glider Pilots, by C. E. Wallington, published by John Murray.

Gliding, by Derek Piggott, published by A. & C. Black.

Aerodynamics

Aerodynamics, by N. A. V. Piercy, published by English Universities Press.

Aerodynamics of the Airplane, by C. B. Milliken, published by John Wiley.

The Element of Aerofoil and Airscrew Theory, by H. Glauert, published by Cambridge University Press.

Shape and Flow, by A.H. Shapiro, published by Heinemann.

Propellers

Theory of Propellers, by T. Theodorsen, published by McGraw-Hill.

Stability and Control

An Introduction to the Longitudinal Sudie Stability of Low Speed Aircraft, by F. Irving, published by Pergamon Press.

The Principles of the Control and Stability of Aircraft, by W. J. Duncan, published by Cambridge University Press.

Airplane Performance, Stability and Control, by C. D. Perkins and R. E. Hage, published by John Wiley.

Helicopters

Aerodynamics of V/STOL Flight, by B. S. McCormick, published by Academic Press.

Aerodynamics of the Helicopter, by A. Gesson and G. C. Myers, published by Macmillan.

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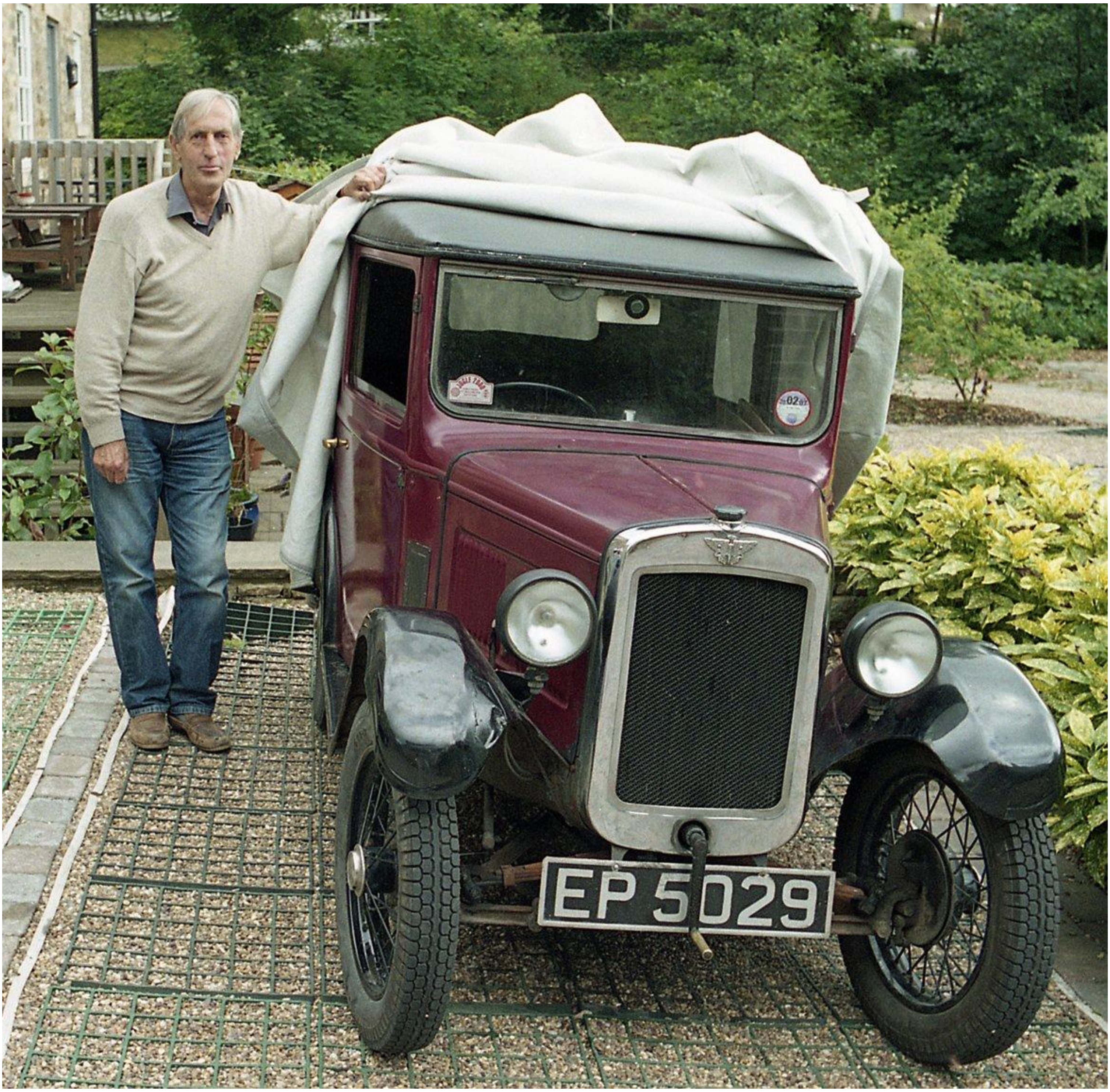

Dr Keith Sherwin standing beside his much loved Austin 7 Photo: Fred To