Man-Powered Flight: Achievements to Date with a New Suggestion

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Man's desire to fly is as old as humanity, but his many attempts to do so succeeded only sixty five years ago with the advent of mechanical power. However, mechanical power did not eliminate man's desire to fly on his own power; interested professionals as well as dedicated individuals have continued working on this problem for the past sixty years. Their efforts have recently begun to bear fruit. A summary review of these efforts is presented, together with some conceptual and technical developments which have led to the first noteworthy successes of man-powered flight. Since these successes rely, among other things, on wings with extraordinary aspect ratios, a point may soon be reached where the corresponding wing spans will become intolerable. The application of a particular wing configuration is suggested to alleviate this dilemma.

ON June 28, 1968, the British magazine *PUNCH* published an illustration of a man-powered aircraft in flight ostensibly being demonstrated to a group of officials, a high-ranking military man among them. The latter's comment: "Absolutely useless . . . its payload is less than the smallest bomb we've got." This illustration well explains one of the reasons why man-powered flight has never received significant support from the Aeronautical industry. Similar reasons are given by many members of General Aviation, except for a minority of enthusiasts willing to pedal to become airborne but whose financial possibilities are generally too limited for the relatively substantial expenditures required to produce a man-powered aircraft possessing satisfactory flying qualities—as defined later in this article.

Today it is relatively easy to design and to build a well-flying airplane, adequately powered by a still too expensive, but reliable engine. Techniques are known, data are available and, in general, the state-of-the-art is such that design emphasis is placed on refinements, efficiency, and cost. Matters are very different with a man-powered aircraft (MPA), whose design requires a special variety of aerodynamic optimization and, above all, utmost ingenuity in structural concepts so as to satisfy the most difficult condition: an incredibly low T.O. weight[1] compatible with structural integrity. With the present state-of-the-art, the MPA constitutes a technically challenging goal, whose elusiveness is moving a number of professionals, and an even greater number of not-so-professional hopefuls, to try to reach it.

One can go back to Greek mythology and start with the legend of Daedalus and Icarus; the latter, as the legend goes, flew too close to the sun and met his death by drowning in the Aegean Sea when the wax, holding together his wings' feathers, melted and the wings disintegrated. Leonardo da Vinci (1452–1519) took a more scientific approach to flying before starting to design his flying machine; he studied the flight of birds (Sul Voli Degli Uccelli, 1505) and concluded that the only way for man to fly would be to imitate the birds as closely as possible. Considering that the aerodynamic, structural, and materials knowledge for the problem at hand was almost nil at da Vinci's time, it is no surprise that his machine was doomed to failure.

With the appearance of Joukowski's wing theory at the turn of the century and Prandtl's general aerodynamic theory, more basic knowledge became available to interested researchers who, in the twenties and thirties, again started investigating the possibilities of man-powered flight. In France attempts were made in the early twenties to fit bicycles with wings, making it possible to achieve jumps of noteworthy distances.[2] Jumps followed by an extended glide are not, however, what one might call "real flying," and further attempts with this approach were soon abandoned since the goal of a sustained horizontal flight at constant speed appeared hopelessly unattainable.

In Italy in the mid-thirties, Bonomi and Bossi produced an interesting two-propeller machine (Fig. 1) with which the pilot was able to take off using stored energy and to extend significantly his glide by pedaling[3]; but the machine suffered from overweight and could hardly sustain a true horizontal flight. In Germany at about the same time (1936) Haessler and Villinger designed and built a single seater with pusher propeller (Fig. 2) and flew, after assisted takeoff, some seven hundred meters at about three meters above the ground.[4]

These and similar attempts led a group of German experts to the conclusion that a systematic approach should be taken first to analyse and to define the basic MPA problems before attempting to find their solutions. Since the crucial problem of an MPA is the very limited power of man, it was immediately obvious that the first problem to be investigated

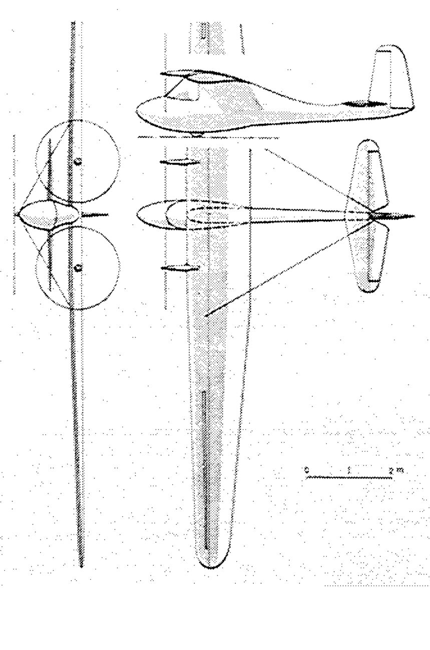

Fig. 1 Three-view of the Bossi-Bonomi MPA.

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was what is, in fact, the power that a man can produce; under what conditions, for how long? What is the man's optimum posture in the aircraft? What is the most efficient method for transmitting the man's effort into a rotating shaft? Or should it be rotating? Comprehensive tests were conducted in Germany by the Muskelflug Institut and the results widely publicized by the German aviation promoter O. Ursinus, in his aeronautical review *Flugsport*.[5] In the same period, Schulze and Stiasny wrote a detailed and well-illustrated book on the general subject of flight under muscular power.[6] World War II brought further development of man-powered aircraft temporarily to an end.

The trend of aircraft development of the postwar period was generally toward the higher scale of Reynolds numbers, requiring more power to achieve higher speeds. General Aviation wanted better rates of climb, higher maneuverability, faster cruising speeds, more comfort, and also demanding more power. Amongst the diminishing class of aircraft still flying in the range of moderate Reynolds numbers are the sailplanes. Designed and built by experts, they incorporate up-to-date aerodynamic refinements and design sophistication[7–9] and yield performances fully recognized by the Fédération Aéronautigue Internationale.

Using the results of meticulous and exhaustive studies of wings, performed for many years primarily in the USA by NACA,[10] it appeared in the late forties that the MPA did not have much chance of success; either the available manpower was too low† for the minimum attainable weight, or the aircraft's maximum tolerable weight for such a limited power appeared unattainable—less than 50 kg empty, including everything except the pilot.

Not much chance does not mean, however, no chance at all, especially for those who consider that such a skill-demanding and long-standing engineering problem should not be left unchallanged until definitely proven unsurmountable—or until resolved. In the mid-fifties a few prominent British engineers were rekindling interest in the ultra-light, extra-efficient small aircraft.[11] By the late fifties several studies were published in scientific and technical journals, related to the fundamental engineering aspects of man-powered flight[12–15] as well as the use of man as an aero engine.[16] These studies pointed toward the conclusion that additional theoretical effort, especially in the field of wing sections at low Reynolds numbers, and much engineering ingenuity would have to be expanded to make man-powered flight a reality; also, that such flight is definitely not an impossible task.

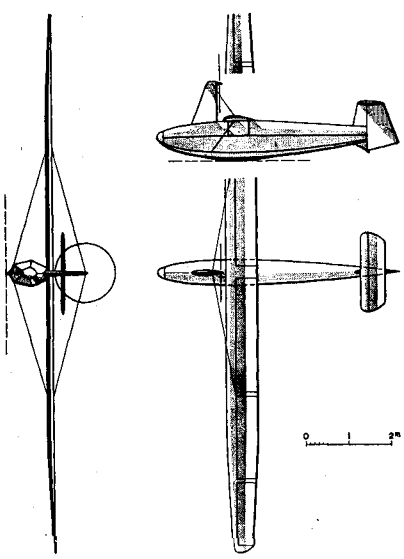


Fig. 2 Three-view of the Haessler-Villinger MPA.

† In the order of ¾ of a horsepower, decaying rapidly with fatigue and leveling off at 30–40% of one horsepower.

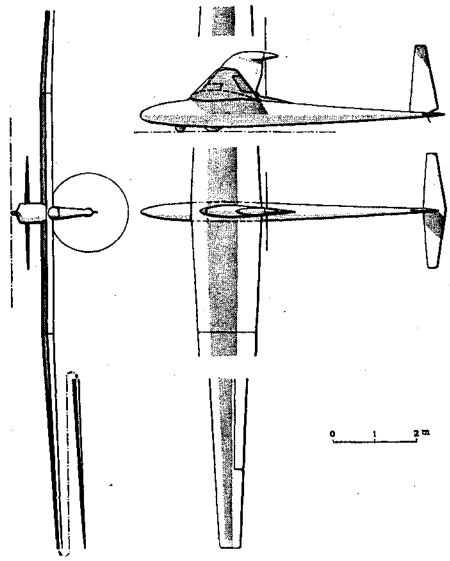


Fig. 3 Three-view of the Southampton MPA.

As a result of this conclusion a study group was organized in England in 1957, for the purpose of looking further into the problems related to the MPA, and for providing moral and technical support to interested individuals anxious to take an active part in such an endeavor. The study group soon became part of the British Royal Aeronautical Society, which found it worthwhile to make several grants availiable in support of promising design groups qualified for building and testing a man-powered aircraft. Among the first to be known for their activity are the University of Southampton Group,[17] working on a single seater with pusher propeller located on a pylon above the wing (Fig. 3); the Hatfield Man-Powered Aircraft Club, organized by engineers of the former DeHavilland Aircraft Company working on a single seater with pusher propeller located at the aft end of the fuselage (Fig. 4); the Southend Group, working on a two seater with tractor propeller located on a pylon above the nose of the fuselage. Various setbacks forced the latter group to extend schedules and postpone first flight attempts. The Southampton and the Hatfield groups, on the other hand, flew their aircraft within a week of each other (November 9 and November 16, 1961), proving without any doubt that flight by manpower alone is possible without the assistance of stored energy, as attested by the certificate issued to the Southampton Group in February 1964, by the Royal Aeronautical Society (Fig. 5). Other groups were organized in England

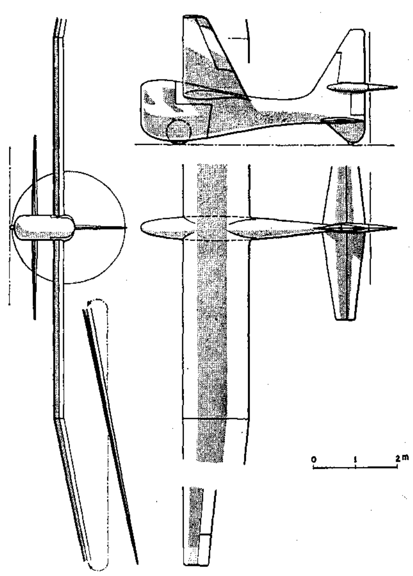
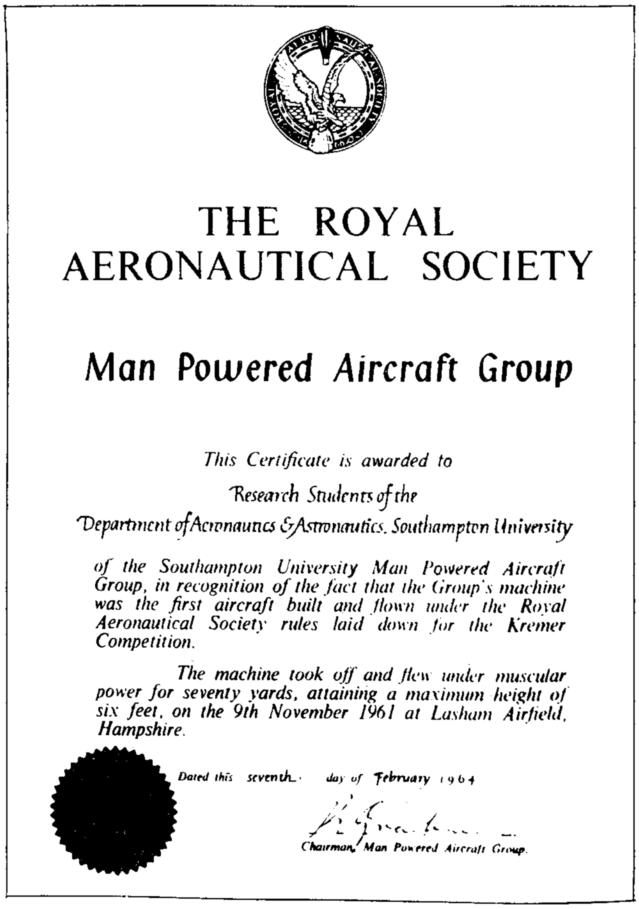


Fig. 4 Three-view of the Hatfield MPA.



THE ROYAL AERONAUTICAL SOCIETY

Man Powered Aircraft Group

This Certificate is awarded to

Research Students of the Department of Aeronautics & Astronautics, Southampton University

of the Southampton University Man Powered Aircraft Group, in recognition of the fact that the Group's machine was the first aircraft built and flown under the Royal Aeronautical Society rules laid down for the Kremer Competition.

The machine took off and flew under muscular power for seventy yards, attaining a maximum height of six feet, on the 9th November 1961 at Lasham Airfield, Hampshire.

Dated this seventh day of February 1964

Chairman, Man Powered Aircraft Group.

Fig. 5 Royal Aeronautical Society certificate to the Southampton group for first flight with manpower.

soon thereafter investigating propeller-driven aircraft (the Weybridge Group, for example), as well as rotorcraft; some of this work was also sponsored by the Royal Aeronautical Society.

The greatest boost to the movement was a £5,000 prize offered in 1959 by the British industrialist H. Kremer, to be awarded to the individuals responsible for the first flight of a man-powered aircraft that would perform a figure eight at least three meters above the ground, without any form of takeoff assistance—man-produced stored energy not allowed either. The prize was also restricted to subjects of the British Commonwealth.

Although the first entirely man-powered flight was accomplished by the Southampton Group, the longest straight-line flight (over 900 m) was made by the Hatfield machine.[18] The latter sustained rather extensive damage to the wing in 1963 when attempting a turn and is being rebuilt, as the Mark 2, with a new airfoil especially designed for this type of aircraft.[19] It is appropriate to mention here that new airfoils have been developed during the past ten years for aircraft flying at low Reynolds numbers—for example, the F. X. Wortmann series[20]—which is superior to the NACA series for this particular application.

In other countries, too, groups were organized to work on the problem of man-powered aircraft; in Canada, under the sponsorship of the Canadian Aeronautical Society; in France, students of the Ecole Nationale Supérieure de l'Aéronautique, under the guidance of M. Pain, have approached the problem in an ingenuous manner, different from the general trend taken in England and elsewhere. Although their machine has not flown yet (Fig. 6 shows a photograph of a model), some of the basic novelties are worth mentioning; it is a canard configuration, chosen for the fact that all surfaces are lifting as compared to an aft-tail configuration where the stabilizer has a stabilizing role only. It is also a semi-biplane configuration with moderate aspect ratios and a large interplane distance. This requires a struts-and-wire-bracing construction, but a trade-off study showed that the added drag was more than compensated for by the lightness of the aircraft and its sturdiness (for effect of drag/lightness ratio, see Ref. 1). The structural material is magnesium in tubes and sheets, with Mylar covering. The large (3-m diam) slow-rotating propeller, with variable pitch, is driven by the pilot through an extra-light, variable-inertia, no torque system of high-speed rotating disks that always generate a certain amount of stored energy. This special system was developed by O. Durouchoux and patented in the USA in 1965. Credit for the whole concept of this MPA is due to Gabriel Voisin, the well-known aircraft designer of the early days of aviation. Although the concept does not meet the Kremer-prize competition requirements because of the variable-inertia system, it is worth watching for its flight-test results.

In Japan, a group of students at the University of Tokyo designed, built, and flew an MPA (Fig. 7) under the guidance of H. Kimura, professor at the University and designer of the Japanese Zero Fighter of W. W. II[21]; in Australia and—our preference for more power and the relative ease of affording it notwithstanding—even in the USA, A. Lippisch started a project while with Collins Radio at Cedar Rapids, Iowa. A group was organized at the Georgia Institute of Technology, producing an interesting single seater with two coaxial pusher propellers counter rotating in an aft-located shroud, that acted as stabilizer. The very low wing of the machine could have taken good advantage of ground effect were it not for a wind blast that damaged the machine on the ground (1963); this writer's personal contacts indicate that there is activity in this field in other well-known universities and colleges—there are certainly groups or individuals who quietly work but consider that their accomplishments are not ready yet for publication.

What about the Kremer prize? In February 1966, Kremer doubled it to £10,000 and made it open internationally,[22] which underlines the fact that the problem is a real braintwister requiring meticulous tradeoff considerations and painstaking effort. As yet the prize is still open: nobody has won it.

Technical Considerations

A glance at the plan views of the various man-powered aircraft reveals the fact that wing spans b and wing aspect ratios b^2/S have been growing steadily and reaching almost incredibly high values, while wings' specific weights W_w/S have remained unbelievably low (Fig. 8). Following Prandtl's theory, the wing drag for an angle of attack α is given by $C_{D_{wing}} = C_{Do} + C_{Di}$, where the induced drag i $C_{Di} = C_L^2/\pi A$, C_{Do} the basic wing profile drag, C_L th corresponding lift coefficient, and A the effective aspect ratio. Since C_{Do} is a function of the wing section, a section

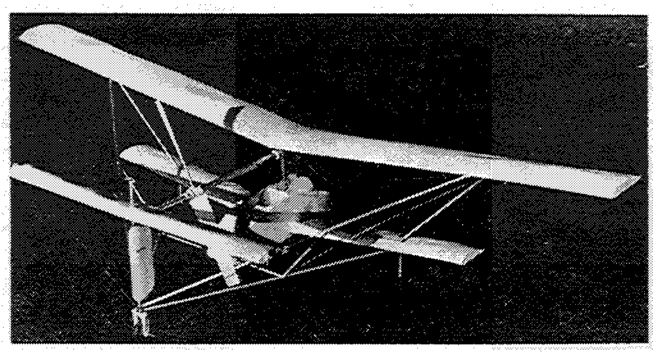


Fig. 6 Photograph of the G. Voisin MPA.

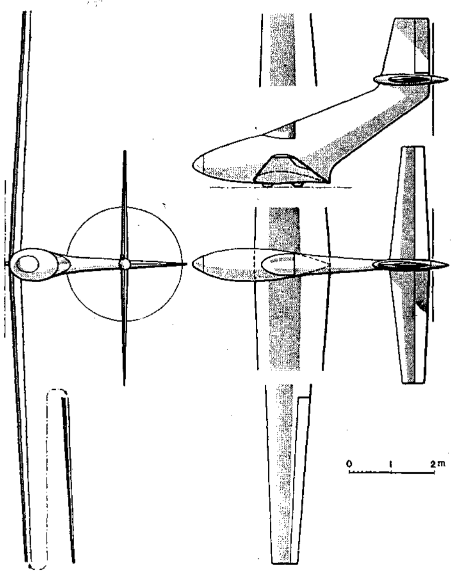


Fig. 7 Three-view of the Nihon MPA.

of minimum C_{D_o} should be chosen while maintaining adequate lift, i.e., a section with the highest values of C_L/C_D for best glide angle or, in case of the MPA, the highest value of C_L^3/C_D^2 for minimum power. Since C_{D_i}, the second term of $C_{D_{wing}}$, is inversely proportional to the aspect ratio, it is no surprise that wings of higher and higher aspect ratio are being designed to reduce this term as much as other considerations permit. A cross-over point is reached when wing span is so enormous that wing weight and flexibility become prohibitive; the optimum tradeoff mus tbe thoroughly established before settling on a final design.

It appears to this writer, however, that such an extremely high aspect-ratio wing with its awesome span is a two-sided sword; on one hand it reduces the induced drag—therefore the total aircraft drag—to values that make man-powered flight possible, while on the other hand it makes it exceedingly difficult to bank the aircraft and to negotiate a turn (or two turns, as required by the Kremer-prize rules) within a limited field and/or time (fatigue) without the imminent danger of hitting the ground with a wing tip in the event of even a very light gust.

A very thought-provoking study of the flight of birds by C. Cone Jr.,[23] establishes the fact that there are two basic types of soaring birds; those with high aspect-ratio wings (albatross, seagull, etc.) and those whose wings appear to

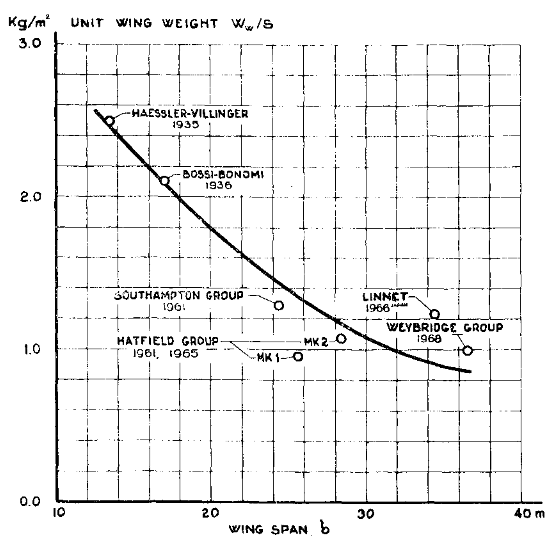


Fig. 8 Trend of specific wing weight vs wing span.

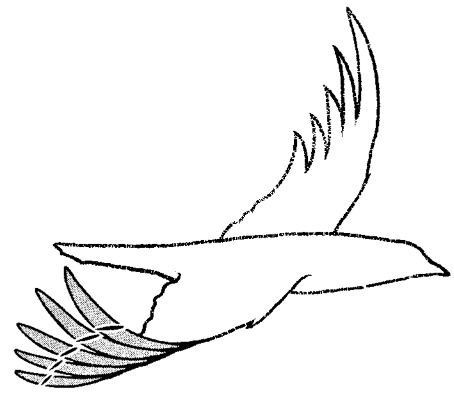


Fig. 9 Bird's wings in soaring flight.

have a very modest aspect ratio (vultures, hawks, etc.). Yet both types are good soarers, making one wonder if birds of the latter type do not use some ingenious technical device known to birds but not known to man (until C. Cone discovered it) which makes the geometrically low-aspect-ratio wing behave as if it had a high aspect ratio. Cone's studies, confirmed by wind-tunnel tests, show that the ingenious technical device is embodied in the bird's flexible wing-tip feathers that, under varying air loads, bend upward and assume a staggered multiplane configuration during soaring flight,[24] thus, greatly reducing the induced wing-tip drag (Fig. 9).

Man's cleverness notwithstanding, he is not skillful enough to reproduce the infinitely variable adjustability of birds' wings and, compared to birds, man-made machines may look graceful but still remain rather crude and stiff, or flexible the wrong way and at the wrong time. There is no doubt, however, that the search will continue as long as the problem remains unresolved; the French approach, for example, of reducing induced drag by installing multiple wing-tip slots[25] is a practical way of imitating the spread feathers of the birds' wing tips.

Another approach to the problem of wing-drag reduction can be found in a study performed in France at the Institut Aérotechnigue de St. Cyr by Nénadovitch,[26] working under Toussaint, on numerous biplane configurations by varying the wings' stagger and their interplane distance. His studies show that for a given airfoil there is an optimum configuration of interplane distance and corresponding stagger, such that the polar curve of the cellular wing displays the unexpected property of having lower drag and higher lift than the equivalent monoplane for all flight angles. In other words: if the inclination of an isolated wing-section's resultant force with respect to the air stream is taken as a reference, the resultant force of the combined wing sections leans forward of the reference for all practical angles. Figure 10 is a reproduction of the results published in Ref. 26, based

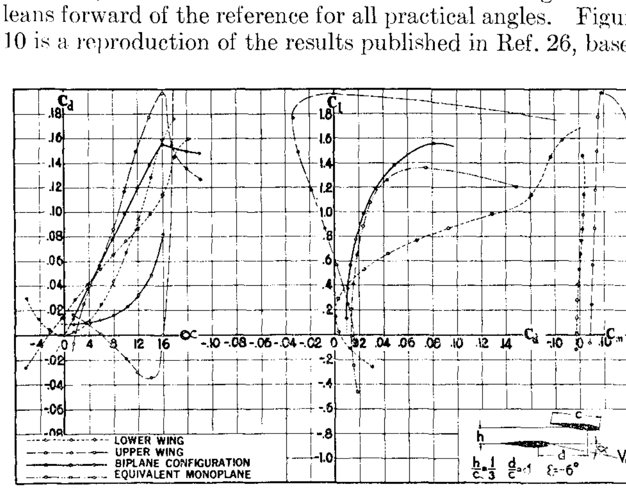


Fig. 10 Polar curves of special biplane configuration.

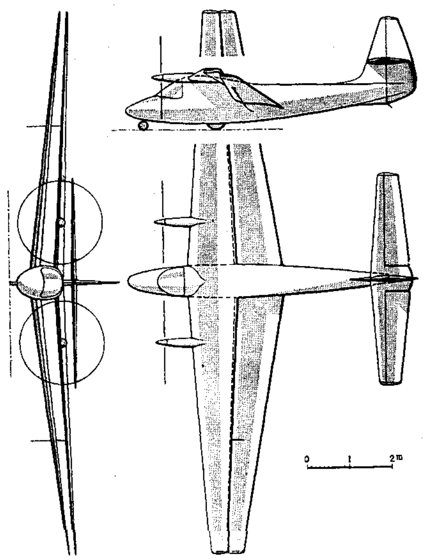


Fig. 11 Three-view of suggested MPA.

on tests performed with a 12% thick symmetrical Joukowski airfoil and at a Reynolds number of 550,000.

This again may be just what the birds' wing tips do—and do it probably several times over since there are several plus-one staggered wing-tip feathers. Similarity is very noticeable between the wing-sections' configuration shown on Fig. 10 and the tip-feather arrangement of Fig. 9. Such a configuration then, reduces C_{D_0} while still leaving the possibility of reducing C_{Di} by Cone's method (wing tips bent upward[27]) or by the previously mentioned French method of multiple wing-tip slots: it appears possible then, to design with a lower aspect ratio—and therefore a smaller wing span—a cellular wing as good as a monoplane with extremely high aspect ratio. Following this concept may make it easier to build a man-powered aircraft maneuverable enough to negotiate turns without having the wing tip scraping the runway, thereby increasing the chances of meeting the Kremer prize requirements.

An aircraft conceived along these lines may look as shown on Fig. 11. Although smoothness of airflow around the wings would dictate pusher propellers, weight and C.G. considerations bias the choice in favor of large diameter, slow- and counter-rotating propellers located far ahead of the wing's leading edge.

Whatever the new concepts, a very detailed aerodynamic analysis and tradeoff study is essential before starting any construction. New ideas in structural design must be considered and developed[28] so that the appallingly low weight allowance not be exceeded, and a search for novel solutions to power transmission must be undertaken for two critical reasons; to reduce both power losses and weight increases. The advice to designers by W. B. Stout, the renowned U.S. aircraft designer, "Simplicate and add lightness," can be nowhere better applied. Wind-tunnel tests and even free-flight tests are desirable to confirm results of theoretical studies. The former have to be done in a low-turbulence wind tunnel and at low Reynolds numbers (500,000–800,000), whereas the free-flight model should satisfy the required scaling effects: linear scale λ, weight scale λ^3, power scale $\lambda^{7/2}$. Scaling factors may be derived from the Navier-Stokes equations developed into the Reynolds law for wind-tunnel tests and the Froude law for free-flight tests.[29,30] Since in the latter case the Reynolds law cannot be satisfied, only a partial similitude is achieved. Nevertheless a wealth of information can be obtained from such tests. Primarily, a correct mass distribution can be assessed. Flight characteristics can be studied at the same time with the proviso that some modification be made to the model's wing section: a sharper leading edge, reducing the airfoil section's sensitivity to Reynolds number changes; or the addition of a leading-edge trip wire, to prevent the abrupt laminar separation over the wing oftentimes so disappointing with models flying at very low Reynolds numbers (about 50,000). One wants the model—the same as with the full-size aircraft—to stay in the air as long as possible with a minimum of power or, in other words, to fly with the smallest sinking velocity. Since the sinking velocity $V_S = [(W/S)\cdot(\rho/2)\cdot(C_D^2/C_L^3)]^{1/2}$ with W/S = wing loading, and the effect of Reynolds number on C_D^2/C_L^3 cannot be completely eliminated, one can use the model's wing loading, reduced by λ, to keep the model sinking velocity comparable to that of the full-size aircraft. Additional data on flying-model characteristics can be found in a comprehensive study of flying-model aerodynamics written by F. W. Schmitz, with an introduction by L. Prandtl.[31]

Conclusion

The answer to the question "Can man fly on his own power?" is yes, as attested by Fig. 5. The answer to the question "What for?" depends to a great extent on the state of mind of the person asking the question, objective or subjective. Objectively speaking, the MPA is now in its earliest stages and a great deal of development has to go into it before claims can be made of its having any direct practical usefulness. But the mere fact of studying the problem, designing the aircraft, building and flight-testing it can be of outstanding value to broaden the knowledge, sharpen the thinking and develop the skill of those willing to engage with the problem. By definition, the successful and useful MPA must be of ultra-light construction, represent a highly efficient aerodynamic design, display an exceptionally sound structural concept, and the design as a whole must satisfy regular Civil Aeronautics Board (CAB) requirements for soaring aircraft. Under these conditions the feeblest thermal shell, as defined by C. Cone,[23] should be able to pick up the MPA and lift it to an altitude sufficient for soaring.

Since soaring is an accepted and recognized way of flying, the MPA would have bridged, therefore, the gap between its apparent uselessness of today and the accepted vistas so familiar to sailplane pilots, while at the same time placing at the pilot's disposal the possibility of some additional lift so frequently wished for during cross-country flights.‡ Design skills and new manufacturing techniques developed while creating a useful man-powered aircraft are bound to find their way into General Aviation resulting in lighter, less expensive and more efficient airplanes, requiring a minimum of power to deliver superior performance. Such results as these should be sufficient answer to the objective question "What for?" in addition to the reason of research for research's sake.

Subjectively speaking—parallel to the mountain climber's "because it is there" answer—one could say that designing, building, and flying an MPA is a forbidding problem and, although proved feasible, not completely surmounted thus far (to wit: the still open Kremer prize). If one asks then of what use the MPA can be, let it be remembered that a year after the Wright Brothers flew, a prominent scientist of that time (1904) witnessed one of the flights and commented: "Very interesting, but what's the use?"

By the year 1912, when the airplane's speed, altitude, and range had progressed to a point where the scientific com-

‡ Thoughts on taking off with manpower and of continuing to fly as a glider were discussed by L. Welch in the *Journal of the Royal Aeronautical Society* of December 1961, under the title "Gliding and Man-Powered Flight." Similar ideas were developed most recently by B. Shenstone in a major paper presenting today's knowledge on Unconventional Flight, published in the *Journal of the Royal Aeronautical Society* in August 1968.

munity detected a genuine utility for airplanes, prognoses began to be made on their future capabilities. "One thing is sure, however," commented another prominent scientist of that time, "because of the square-cube law the airplane will never be able to carry more than four to five people."§

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