CONCEPTION AND OPTIMIZATION OF MAN-POWERED PLANES

CYCLAIR

by E. Schoberl
Nurnberg, F.R. Germany

Presented at the XX OSTIV Congress, Benalla, Australia (1987)

Summary

The whole range of possible flying speeds has been investigated for man-powered aircraft of optimum design using the present state of technology. A minimum power requirement of under 200 watts is possible with extreme large planes which are very difficult to handle and to fly.

There is an optimum configuration at a flying speed of about 8.5 m/s. This plane with about 25 m wing span has a power requirement slightly below 200 watts (near the ground) with a glide ratio of 44 and can be flown by experienced light weight pilots. CYCLAIR can be built at a weight of slightly over 30 kg with the following design characteristics:

- fully sandwich covered wings with laminar flow airfoil;
- carbon fibre reinforced epoxi main spar in 4 sections designed for 3 times the static load;
- sandwich covered cabin with semi-supine pilot position;
- all-moving elevator;
- all-moving rudder with auxiliary rudder;
- rear propeller to protect the tail surfaces from avoidable turbulence.

This CYCLAIR plane is similar to the MIT designed MICHELOB LIGHT EAGLE which is larger, a little heavier and optimized for slower flying speed. With this MICHELOB LIGHT EAGLE, MIT will make the flight legend of Daedalus a reality in the near future.

This 110 km long flight from Crete to the Greek Mainland will be the climax and the preliminary end of man powered flight which will remain a privilege for few enthusiasts only because it requires both a high-grade technology and high-athletic effort of the pilot.

The prizes donated by Henry Kremer were worldwide a great incentive for the development of many human-powered aircraft. The precise design of high-strength ultralight construction is also necessary for planes with the lowest possible power requirement, like electric or solar powered planes or unmanned high altitude crafts for communication relays in the stratosphere.

1. General

The prizes donated by the British industrialist Henry Kremer were incentives for most of the man-powered aircraft (MPA) developed in the past 25 years.

The consequent application of high-strength light-weight materials, such as graphite-epoxy composites, and the progress made in aerodynamics, especially with laminar flow airfoils made it possible to design MPA with very low weight, and aerodynamically sophisticated design which led to the break-through and the great successes in the past decade.

Bryan Allen was the first who completed the one mile long figure of eight flight with Paul MacCready's Gossamer Condor in 1977, and crossed the English Channel in 1979 with the Gossamer Albatross, setting two incomparable milestones in history of aviation.

The Kremer World Speed Competition demanded a flight over a 1500 m long triangular course to be completed within three minutes and allowed storage of the pilot's energy 10 minutes prior to take off. This prize was first won by an MIT-student group with their Monarch in May 1984. Four further prizes have been awarded for flights to improve the existing record by at least 5 percent. MacCready did this with the Bionic Bat in July and December 1984. Both MIT and MacCready used energy storage.

Also in 1984, a German amateur team, unsupported by any large wealthy sponsor, built their first man-powered aircraft, Musculair 1. Two weeks after completing the Musculair 1 they won the figure of eight Kremer prize for non-Americans with a speed almost twice as fast as MacCready's Gossamer Condor. Two months later they won the Kremer speed prize, in August 1984, by improving MacCready's speed of the Bionic Bat by 7 percent, without storage energy. To test the reserves of pilot and aircraft, they made the first man-powered passenger flight in history of aviation on October 1, 1984.

In 1985 this airplane was involved in a traffic accident on the road and was badly damaged. The team decided to build the Musculair 2, being an aircraft designed for high speed. Again, they won the Kremer speed prize and improved their world record from 35.7 km/h to 44.3 km/h.

To get an impression of the size and weight of the airplanes:

Musculair 1: span 22 m; empty weight 28 kg

Musculair 2: span 19.5 m, empty weight 25 kg

This paper deals mainly with experiences gained by the Musculair projects, and with possible developments corresponding to the present state of the art, as well.

2. General considerations of plane conceptions

Although many pioneers achieved their great successes with canard-type planes (Wright brothers, Focke, MacCready and latest Burt Rutan and Jeana Yeager with their Voyager in December 1986) this conception could, despite the stall safety, not achieve general successes, mainly because of the following four disadvantages:

- the unavoidable side-faces of the fuselage located far in front of the center of gravity make yaw control difficult. Sometimes power consuming swept-back main wing design is necessary;
- the lift of the canard wing is generated with too much induced drag because of its low aspect ratio;
- the main wing often does not operate at the best glide ratio or minimum sinking velocity, as its angle of attack cannot be arranged as much as that of the canard wing;
- the canard wing affects the field of vision.

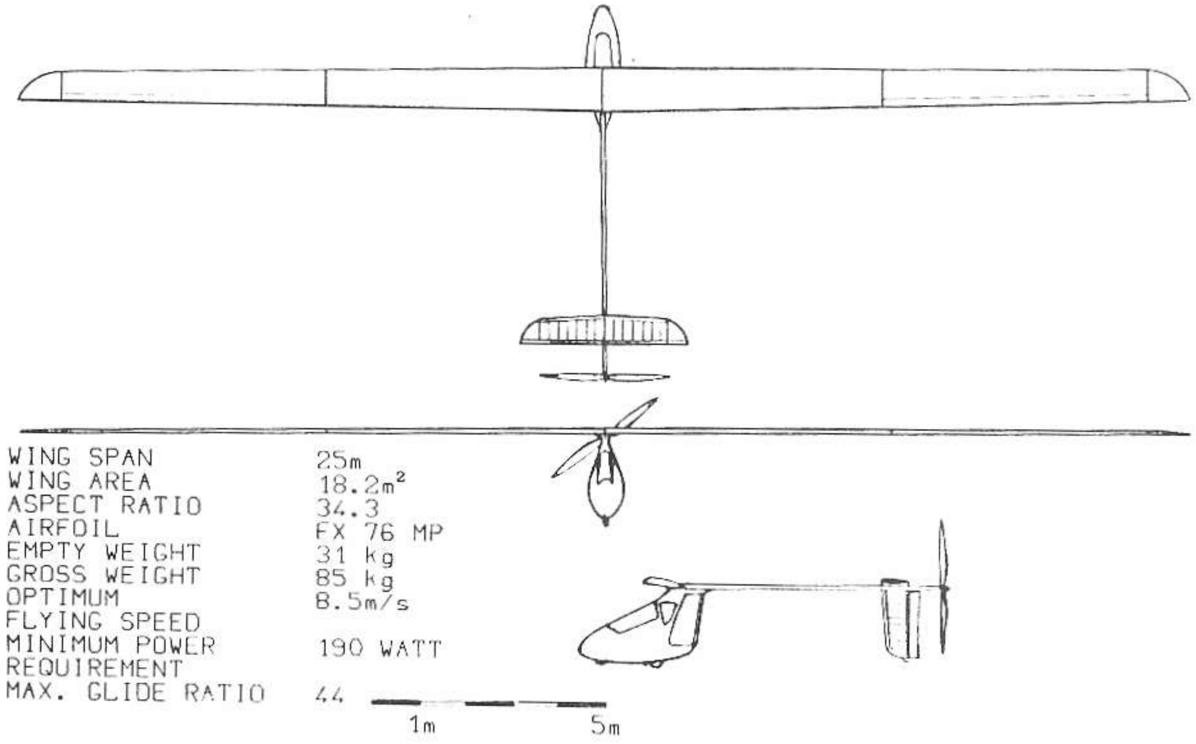
Conventional high-wing monoplanes with faired cabin and all-moving rudders have proved to be the best for light-weight, efficient safe and simple controllable MPA's.

With the increased knowledge of the precise design of high-strength microlight construction, designers will turn to cantilever structures that eliminate external wires. Rough estimations at the early design state of Musculair 1 clearly showed that the power absorbed by the increase of structural weight is more than outweighed by the lower drag of a cantilever design. The utilization of the ground effect, when using low-winged monoplanes, was generally overestimated.

Spring-centralized all-moving elevators and rudders turned out to be both light-weight and effective. Based on the analysis of test flights, the author thinks that an all-moving rudder with an auxiliary rudder is more favorable.

Front-, middle- and rear propeller positions have proved equivalent in successful MPA's, although middle-and rear-arrangements are aerodynamically better.

A favorable aircraft conception combining minimum power demand and good natured flying behaviour is the cantilevered high-winged monoplane Cyclair (Figure 1) with



WING SPAN	25m
WING AREA	$18.2m^2$
ASPECT RATIO	34.3
AIRFOIL	FX 76 MP
EMPTY WEIGHT	31 kg
GROSS WEIGHT	85 kg
OPTIMUM FLYING SPEED	8.5m/s
MINIMUM POWER REQUIREMENT	190 WATT
MAX. GLIDE RATIO	44

FIG. 1: **CYCLAIR**-MAN-POWERED PLANE DESIGNED FOR LONG DISTANCE FLIGHT

laminar flow airfoils, hanging faired cabin with the pilot in semirecumbent position, all-moving elevator, all-moving rudder with auxiliary rudder and pusher propeller.

Design considerations of this new design will now be discussed.

3. Optimization from long distance flight to speed flight

Based on the aforementioned considerations and aircraft weights that can be reached with advanced aerodynamical microlight design, a whole range of man-powered flight was investigated from long distance flight with minimum power requirement to short time speed flights.

Only the best laminar flow airfoils in the range of Reynolds numbers from 300,000 to 800,000 were considered, such as the FX 76 MP, designed by Prof. F.X. Worthmann especially for MPA in 1976.

The following main influences were taken into consideration when making the optimizations:

- aircraft dimensions and corresponding weights;
- ground-effect factor of 0.8 (flying altitude about 1/4 wing span);
- lift coefficient not over 1.1 in order to have enough stability and control reserves;
- Reynolds numbers not below 300,000 to avoid unexpected laminar bubble separation with hysteresis effects;
- minimum chord length at the wing of a low-speed long distance plane 0.7 m and of a speed plane 0.4 m.

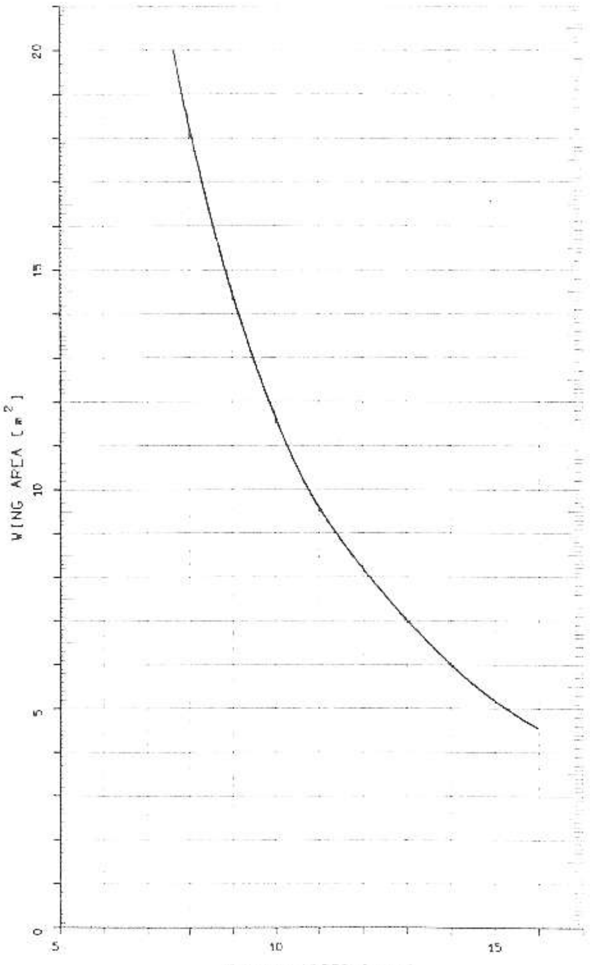


FIG.2 : WING AREA REQUIRED FOR C_L = 1.1

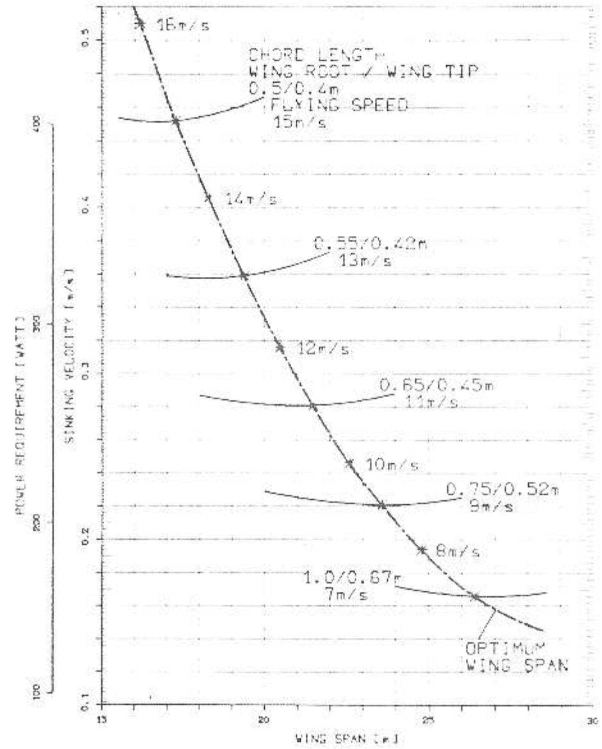


FIG.3 : MIN. SINKING VELOCITY AND POWER REQUIREMENT AND OPTIMUM WING CONFIGURATION OF MAN-POWERED PLANES

Figure 2 shows the rapid decrease in wing area with increasing flying speed. The optimum wing span and chord length of a trapezoidal wing with the corresponding sinking velocity and power requirement is given in Figure 3 for the whole flying speed range.

The most important results of the optimization are shown in the velocity polars (Figure 4). The minimum power requirements of MPA at the present state of art is slightly more than 150 watts (near the ground), achievable with a low-speed plane (about 6 m/s) of over 25 m wing span. The author is of the opinion that wing-spans larger than 25 m are not practical because there is little further reduction in power requirements, while the aircraft becomes hard to control because of the increased moment of inertia, even with extreme lightweight construction. In addition, the aircraft becomes quite sensitive to gusts.

A favorable wing has 25 m span (18 m² wing area), has a maximum glide ratio of 44, and a power requirement of only 190 watts. Such a wing can be satisfactorily handled and controlled by an experienced pilot.

This Cyclair-type of plane is capable of covering long distance flights, even against light headwinds, and does not react so sensitively to gusts because of the higher flying speed.

At a flight speed of more than 13 m/s a very high power is required with an airplane with smaller wing span. Even with

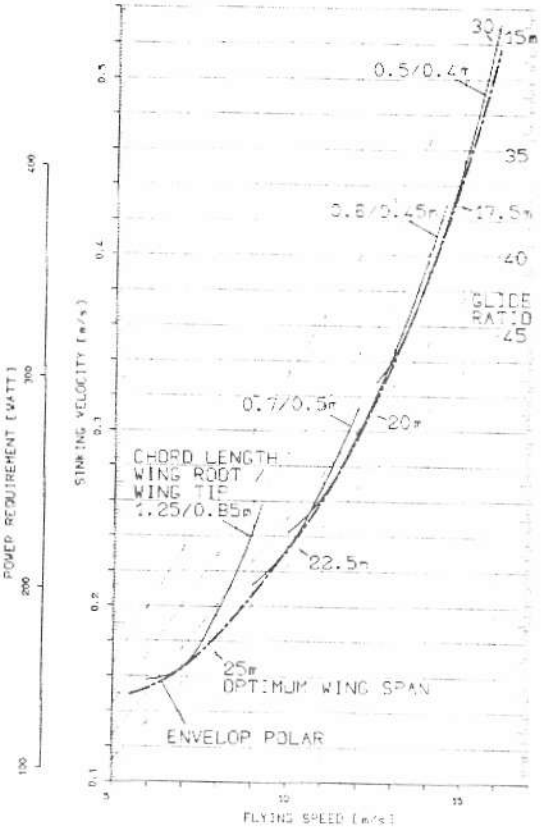


FIG.4 : VELOCITY POLAR OF MAN-POWERED PLANES WITH OPTIMUM WING CONFIGURATION

the high speed aircraft Musculair 2 showed that first class athletes are capable of flying such speeds for a few minutes only. With such an airplane it seems possible to fly the 1500 m speed course in about 100 seconds without energy storage; this means a flight speed of 54 km/h. A new speed record could be set with such an airplane.

4. Wing shape and structure

Though an elliptically shaped wing seems aerodynamically the best, a trapezoidal wing is preferred for design and aerodynamical reasons. A trapezoidal wing can be built more easily, of lower weight and more precisely, and the airfoil operates better at the wing tips because of the larger chord length and higher Reynolds numbers there.

The increase in induced drag near the ground is small when turning away from the ideal elliptical lift distribution. More important are well shaped and profiled wing tips. With the semicircular design of the wing tips the effective wing span is increased and hence the induced drag is slightly reduced.

To build a light-weight,strong wing, stiff in bending and torsion with the necessary accuracy required for the laminar flow airfoils, the application of carbon-fibre reinforced spar and foam/fiberglass sandwich covering is necessary (Figure 5). For aerodynamic reasons the sandwich has to cover at least the whole laminar area on the upper side and from the nose to the position of change in curvature of the lower side. In order to get the wing torsionally stiff enough, the nose covering and the spar must at least form a closed tube. Sandwich covering and carbon spar deform differently under load. On the Musculair 2 wings, too early boundary layer transition occurred just behind the spar on the upper side. This can be avoided with a slightly flexible spar-covering connection. The best solution seems to be a wing-structure as shown in Figure 5 with flexible aileron connection forming an integral part. These flexible connections have been tested successfully in gliders (Speed Astir) and model aircraft.

5. Elevator and rudder

All-moving elevators and rudders, mainly applied for weight reasons, have generally proved to be good. An all-moving vertical tail with auxiliary rudder seems to be better for lateral control. Airfoils with 9 to 10 percent thickness, like the NACA 0009 or the FX 100 MP, are favorable as they work well even at low Reynolds numbers (below 300,000). Although elliptical tail wings are aerodynamically better, trapezoidal ones are lighter and more easily built. When arranging the ele-

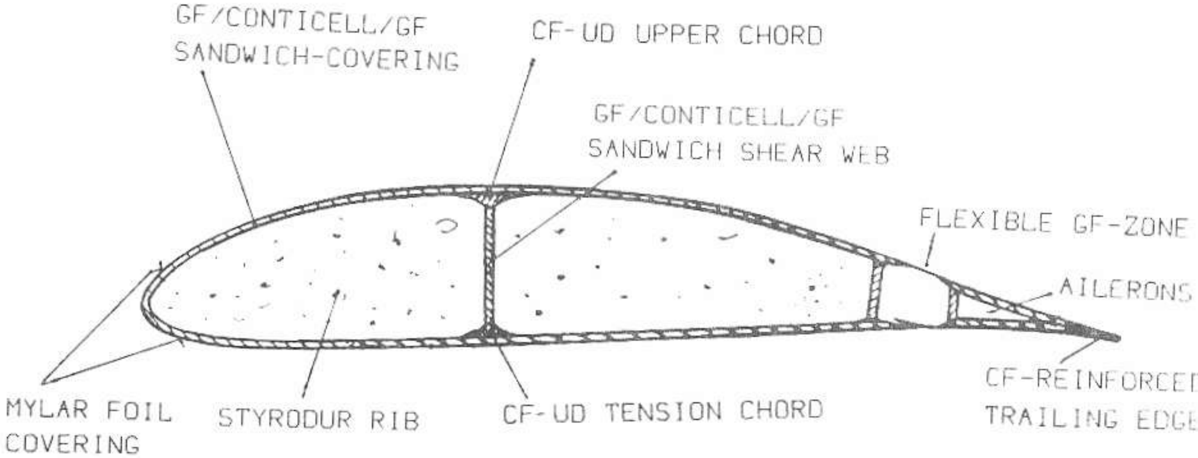


FIG.5 : WING STRUCTURE WITH WORTMANN AIRFOIL FX 76 MP 160

vator, great care has to be taken that at no flying position does it get into the downwash turbulence of the wing.

7. Drive and propulsion

Although a flapping wing can in theory be made quite efficient, the propeller is by far the most efficient means of propulsion. A maximum efficiency of 90 percent can only be reached in MPA with relatively large slowly running propellers designed for minimum induced losses. Larrabee's elegant method has to be mentioned here.

A large propeller adds weight and beyond a certain size the tips are likely to strike the ground when the aircraft is taking off or landing. Therefore, the diameter required for good efficiency (89 percent) and medium efficiency (85 percent) is given in Figure 6.

6. Fuselage

It was found that the pilot delivers about the same power output in a semi-recumbent position as in an upright position. For the recumbent position the cabin can be made smaller. The aerodynamic drag can be further reduced through the use of an extremely light fiberglass sandwich fairing at least in the front part which ensures a more accurate shape and surface finish. The supporting fuselage structure with the wing connections and the stabilizer strut in which the propeller shaft rotates are preferably made of carbon-fiber tubes.

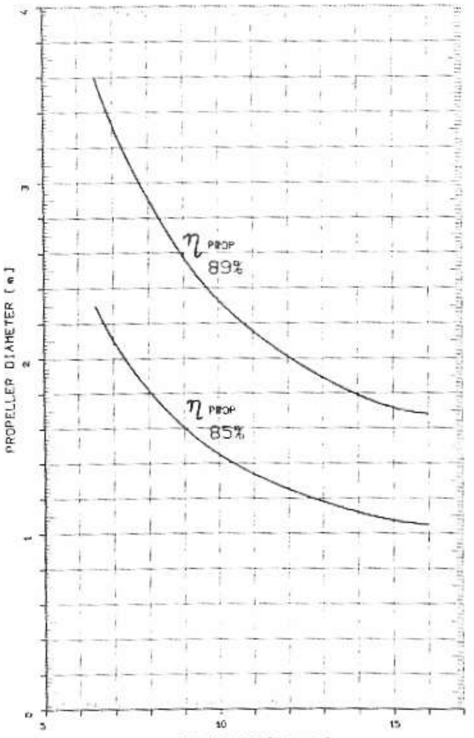


FIG.6 : PROPELLER DIAMETER REQUIRED FOR 85% AND 89% EFFICIENCY

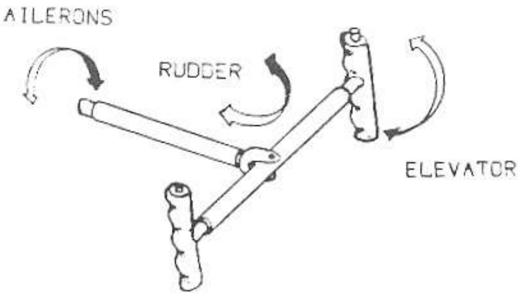


FIG.7 : THREE AXIS CONTROL STICK

The chain drive is a highly efficient, light weight and reliable one when carefully designed and built. In MPA-projects in Japan and Germany it was found that the pedal power output could be improved by about 5 percent through the use of an elliptical chainwheel.

In order to protect fuselage and wings from the accelerated and turbulent slipstream of the propeller, it was often arranged behind the wings (MacCready's Bionic Bat) or behind the tail wings (Rochelt's Musculair 1 and 2).

Although a long propeller shaft is necessary, a pusher propeller is advantageous, as the tail surfaces work more effectively in the accelerated air flow in front of a propeller, and the power demand of the MPA can be slightly reduced.

8. Controls

Most MPA designers have solved the control ergonomically in a very elegant manner. Because precise control with steering handlebars (Figure 7 — MIT design) is very important, the pilot must keep his/her body almost immobile above the hips to allow the controls to be handled sensitively, while cycling with high power output. When steering, the pilot has only to imagine, that he holds the wingtips with his hands and moving the controls will cause the plane to perform the desired maneuvers. Sideway tilting of the control bar operates the ailerons, rotation around the vertical axis acts upon the main rudder, and tilting the handgrips around the horizontal axis acts on the elevator. As the aerodynamic control forces are rather small, it is practical to install self-centering spring units.

For long-distance flights it is desirable to install an automatic control system to reduce the pilot's mental workload. Such an autopilot can improve the system performance by maintaining flight near minimum power requirement. MIT designed for their Daedalus project their Michelob Light Eagle an autopilot weighing only a few 100 gram, so the pilot can concentrate more on power performance and navigation.

9. Technological Outlook

The prizes donated by Henry Kremer were a great incentive for the realization of the dreams of human-powered flight and the flight with solar energy. MIT may be making the flight legend of Daedalus a reality in the near future. This will be the climax and preliminary end of man-powered flight which will remain a privilege of a few enthusiasts and universities only, because it requires both a highly sophisticated technology and high athletic and flying effort of the pilot.

The development of human-powered helicopters is, because of the high power requirements and the stability and control problems, very difficult. Nevertheless, Professor Akira Naito's team from Nihon University Tokyo did in fact succeed in getting their helicopter, A Day Fly, a few centimeters off the ground for a few seconds on December 6, 1985. As the power requirement for getting out of the ground effect is more than 2 kilowatts, it does not seem likely that a general breakthrough will be achieved in the near future.

The precise design of high-strength microlight construction developed for MPA in the past years did give impulses to the unusual aerodynamics at Reynolds numbers between those for model aircraft and gliders.

The technology developed will also benefit unmanned high-altitude aircraft powered with solar or hybrid energy, used, for example, for communication relays which can remain aloft in the stratosphere for weeks or months.