AERODYNAMICS OF FLIGHT AT SPEEDS UNDER 5m/s

by

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1. Introduction

The Gossamer Condor, with its flight speed of less than 5 m/s, operated in a relatively unexplored flight realm. Here we explore various aspects of its aerodynamic characteristics, particularly those aspects which during the vehicle development program were investigated with advanced analysis techniques: stability and control, and airfoil design. The focus is always on the Gossamer Condor (in its final form or in earlier versions), but the discussion will provide some insight about certain phenomena, which will be encountered with other extremely slow flying aircraft. A brief history of the Gossamer Condor development has already been published (MacCready 1978) which includes a treatment of power required this paper omits that aerodynamic subject.

Appendix A gives details on computer simulation of the flight dynamics of the configuration which made the Kremer Prize flight. It was prepared by Henry Jex, utilizing program and computer courtesy of Systems Technology Inc.

2. A Perspective

An underlying philosophy of the design of the Gossamer Condor was the vehicle should be made so large and light that there would be a substantial margin of Dower to handle any problems which might arise. Power required for an airplane of a fixed shape varies as (weight)^3/2 and (span)^-1; thus if you keep weight low while increasing span you can produce a vehicle which can fly with any arbitrarily low power value. We had no preconceived idea of how stability and control would be handled just the faith that they could be handled effectively if there was a, reasonable power margin. It turned out this faith was justified. The solutions yielding a satisfactory design were fairly simple, although finding them was not. Coping with the stability and control phenomena required assimilating clues from flight tests on many different vehicle configurations, from model tests in air and water and from computer analyses. The configuration still empirical, based on the clues and some intuition. Subsequent numerical analyses presented here in Appendix A substantiated the conclusion from flight tests that the configuration handled stability and control satisfactorily. The challenge of achieving stability and control came especially from the scale of things (so large, so light).

A scale factor of special importance in assessing vehicle dynamics is mass which ratios the mass of the vehicle to the mass of a cube of air could enclose the vehicle. Table I gives this relative mass for representative devices.

Table 1 relative Mass of Flight Systems

Vehicle	Relative Mass
Commercial Jet (Boeing 707)	0.86
Bird (Sea Eagle, Haliasetus Albuilla)	0.24
Sailplane (Standard Cirrus)	0.077
Dragonfly Aeschna Cyanea)	0.0033
Human powered aircraft (Gossamer Condor)	0.0031

The Table shows the Gossamer Condor is in the lightweight flying insect range, several orders of magnitude removed from the range of normal aircraft for which a background of aeronautical tradition and insight has been built up over the years. The same fundamental equations still determine vehicle dynamics 'but designers' experience is of less value than normal. (in some ways it can even be of negative value) and flight tests with model or full scale vehicles of proper relative mass are of greet value. Since model tests on the dragonfly scale are difficult, it was logical to do model tests with a normal size (~ 1m span) model in water. So that the low relative mass ratio could be approximated.

While we should not give the impression that the Gossamer Condor was designed according to some random cut and try technique it is certainly true that much of design was "roughed out" and then proven in the ultimate medium flight. A deliberate effort was made to avoid "overkill" in design or many standard aerodynamic calculation's which could in principal have been made with some precision were executed in greatly simplified form, on the that provided the performance was approximately in the desired range, flight performance would be satisfactory. It is fair to say that in this area the collective experience of the design team and of many experts who gave advice proved an invaluable aid. This approach then permitted us to focus or what appeared to be the more difficult aerodynamic problems, which discussed in this paper and here we used an amalgam of methods, experience, observation and test. We do not suggest that this is necessarily suitable for design of other types of vehicles, although we believe that, in all cases, detailed design analysis is necessary only if it meets the criteria that the results of analysis are of sufficient importance to merit the effort.

3. Philosophy of Controllability VS stability

the starting concept was to ignore stability and figure that controllability was all that was needed. The flight speed was very slow (under 5 m/s and initially as low as 3 m/s), and certainly damping would be high because of the vehicle proportions, and so if controllability were satisfactory the pilot could easily react quickly enough to put, the vehicle into any desired attitude as it turned out the final vehicle seemed to be near neutral stability around all axes and hence the pilot’s control task was not difficult. Any mental or physical effort for control decreases significantly the power the Pilot has left to propel the aircraft. Thus we found that it was essential to have control forces light. This dictated the use of ailerons on the canard (stabilizer) to cause the surface to roll, rather than using the pilots power directly to roll the surface directly via wires. These ailerons took very little force to manipulate - Just an easy wrist twist but they added to the sluggishness of control; the canard first had to roll, powered by the slow moving oncoming wind, and then it could give yawing moment.

4. Illuminating the challenge

The first vehicle had a 29m (95 loot) span (96' was intended, being pieces of 12' tubing, but the hanger at Mohave airport could not accept 96') and a 3.7m (12 foot) chord, see Figure l. Structural problems left the airfoil so misshapen that the drag, was high. Nevertheless, by a sequence of many changes, the airplane was able to make a 2 1/2 minute flight. From the very first, pitch control proved to be adequate. This had already been indicated by tests on two 2.5m span models and a 27m span full scale “model” which the crew could run with and control in pitch without a pilot on board. As the flights moved toward exceeding a minute, for the first time we began looking hard at the problems of lateral stability and control. It was obvious the vehicle was not stable laterally. This was not surprising since there were no vertical surfaces of any sort, just the horizontal wing and horizontal canard. In flight the Gossamer Condor would slide off to one side or the other and contact the ground. We introduced the tilting (rolling) stabilizer in configurations which permitted it to be controlled by the pilot or automatically by tabs which sensed the amount of yaw of the vehicle. We tried ailerons of the wing tips, fixed and movable vertical surfaces the of the wing 3/4 of the way out, and used several kinds of spoilers on the top surface near the tips. We also tried adding vertical area above the by filling the space between the king post and the rearmost wire mylar sheet.

The tests with all these configurations were not encouraging. In fact it seemed that addition of and manipulation of the various surfaces had very little effect on the subsequent motion of the aircraft. One significant clue did start emerging, although somewhat unclearly. The rapid raising of a spoiler (0.6m high, 2m long) near one tip would momentarily cause a small, sharp yaw reaction, but keeping it extended would not produce much further effect. Also, once the spoiler was up the pilot could then not keep the vehicle flying level; more power was needed. These phenomena were somewhat obscured by the fact that more propulsion power was also required when the turbulence was stronger. Finally, on one day when we were doing crude tow tests, dragging the aircraft behind a car with an observer reading force with a spring scale, we began correlating drag with spoiler control motions. The main interpretation of all these clues was that the drag added, impulsively, bar the spoilers was obviously high, affecting a large circulation, and yet big events happening out near a tip had little effect on roll.

When one pushed the vehicle into the air, the amount of force required was surprisingly large, and the pilot-engine could not keep the plane aloft for more then a few seconds. There seemed to be an effect of “getting on the step”, when the thrust required would be much less. The 40 second flight on December 26th, 1976 (Figure 1) was the first really sustained flight. Evidently it got to the right speed and stayed there, without acceleration and putting energy into the starting vortex which arises during acceleration. The 2-1/2 minute flight a month later was powered by a strong, championship-level cyclist. It was made in very quiet air, involved only one operation of a spoiler for direction control.

The likely importance of “apparent mass” (the resistance to vehicle acceleration caused by the coupling to the air) became evident when we did the calculation showing that the roll inertia of the wing was increased by an order of magnitude by the apparent mass. Eventually rolling the wing would require large roll forces and be expensive as regards energy.

5. Redesign

A first cut at calculating, controllability factors by means of a computer model showed one striking; effect that a large lift change on one wing would have very little direct effect on roll. The limited modelling did not suggest how to improve the situation, but one approach was evident. Decrease the chord at the tips. This cuts down apparent mass effects there as a function of the

square of the chord, and also cuts down roll damping in direct proportion to the chord. This design change decreased wing area and hence increased the flight speed. Me speed increase required more attention be given to cutting the parasite drag coefficient, which meant putting a streamline housing around the pilot area. The only other major redesign factor was adopting a 2 surface airfoil. This served two vital functions: a) it permitted the use of an airfoil which was much less critical to angle of attack changes from turbulence than the original rather sharp-edged single surface airfoil (the drag bucket was broadened), and b) it permitted a single spar to be located near the center of pressure, facilitating and lightening the structure, while letting this spar be completely out of the airstream. The low pitching moment coefficient of the double surface airfoil was an added bonus.

The resulting second-generation vehicle, built at Shafter Airport, went through many tests and design stages. However, there was really little difference, beyond airfoil thickness and structure, between the final config configuration which made the Kremer Prize flight August 1977 (Figures 2 & 3) and the very first configuration flown at Shafter Airport on March 15, 1977. There were some important control changes. We tried varying center of gravity positions (i.e., varying loads on the canard), and varying methods of effecting the roll of the canard. We experimented briefly with a vertical fin on the canard and then with a rudder positioned on a frame far behind the propeller, and finally we provided a wing twisting capability.

During the redesign stage in February 1977, clues for the design came from the above computer analyses, from tests on various configurations of the Mohave vehicle, from short glide tests with a 2.5 m balsa and tissue paper model and a 1m span balsa sheet model, under water tests with a 1 m span balsa sheet model, and the computer analyses. The water tests were especially helpful. They were performed so as to get a “feel” for phenomena when apparent mass effects would dominate (when the relative mass ratio eras very small). As one hushed the model through the water and felt the force it was evident that coordinated turns were feasible with low drag, but that accelerations involving yaw without roll or roll without yaw created large drag The tests provided encouragement that a vehicle could be “gentled” but not “horsed” around a turn. The “gentling” involved motion around an axis perpendicular to the wing surface, i.e. tilted slightly back from the vertical. Certainly at zero speed such motion involved the least apparent mass for a rotation. In ordinary flight the situation was the same, providing: in effect a decisive yaw-roll coupling coincidence with turning with little additional power.

In summary, there was an expectation but no computational assurance that the new Shafter Airport configuration would turn without large turning force being required, and that a rolling canard would have more effectiveness on the new vehicle than on the old. There was no real information about how to effect coordinated turns. The tests with the new vehicle at Shafter Airport showed the rolling canard to be very effective in producing well coordinated (draw-roll) direction changes of some 200, but it was not satisfactory for handling greater direction changes. By the time the Gossamer Condor made its last flight late in 1977, the situation with respect to controllability was that the vehicle worked well, there was some appreciation for the reasons underlying the good control and stability characteristics, but there was no complete understanding. The development was based on clues derived from many areas, with a very strong

emphasis on flight tests with various vehicle shapes and controls. The computer modeling of vehicle dynamics had served its purpose but was hastily done and not evaluated completely. The more complete modeling presented in Appendix A. is more informative - and in general agreement with the flight observations.

The vehicle was still a quiet air performer. It was occasionally operated in winds as high as 3.5 m/s flying only straight into the wind; turns were not attempted at wind speeds exceeding 1.5 or 2 m/s. As convective conditions began in mid morning the control was just able to permit safe flight, but ground handling became unsafe since a 1.5 m/s cross or tail wind could readily damage the plane on the ground.

6. Some Analytical Design features

Only three aspects of the design were derived with the aid of detailed analysis; the airfoil section, the propeller design and the lateral dynamic stability.

Initially it was hoped that a single surface airfoil, with a finite nose radius formed by the main spar tube, would be satisfactory. This appeared to perform tolerably at design attitude but had a very limited low drag range with angle of attack. A number of different rigid leading edge fairings were examined, analysed on a computer and tested in flight. An example of some of the many airfoils investigated is shown in figure 4. It will be observed that small leading edge changes, imperceptible in the figure, have substantially reduced the leading edge pressure peak. Flight tests verified the higher lift coefficient obtainable with the leading edge more carefully shaped. In this design process a simple quasi-linear computer airfoil design program, providing a rapid turnaround with direct plots of airfoil shape and pressure distribution proved very useful. It was possible to iteratively change the airfoil at the computer console; and, with experience, one could develop half a dozen airfoils in an hour, each aimed at correcting some undesirable feature of the previous one.

It was finally decided that a normal finite thickness airfoil would be required for the Shafter version of the Gossamer Condor. The requirements of the airfoil were that its design CL should be about 1.0, and that it should have a low drag at design attitude, with a reasonably wide low drag range; that the pitching moment should be smaller than -0.04, and that the CLmax should be about 1.5. Very important other requirements were that it should be easy to build, that there should not be extreme curvatures (particularly concave which would not be achievable with the flexible covering, and that the performance should tolerate imprecise construction and billowing of the covering. A further feature which was felt to be desirable in the layout and construction of the airfoil was that most of the lower surface should be flat. It was found essential to have some nose camber to suppress pressure peaks in that vicinity, so the final design was contrived to be flat from 100/6 chord aft. The airfoil used on the Gossamer Condor was the Lissaman 7669 (Figure 5). The two-dimensional characteristics of the airfoil have never been determined, but flight observations with tufts indicated that flow was fully attached at cruise lift coefficient. When the same airfoil was employed on a later airplane, the Gossamer Albatross, with much more accurate and rigid surfaces, the cruise lift coefficient was found to be 20-30% higher, and the section drag coefficient considerably lower than on Gossamer Condor. A slightly different airfoil, differing primarily in being 13.5% thick instead of 11% thick, was tried in flight on the Gossamer Condor and found to have much higher profile drag.

The same 11% airfoil was used on the canard, and on the propeller. The propeller design philosophy was to use the simplest geometry compatible with good performance, which predicated a constant chord blade with the appropriate twist. A number of twist distributions were examined on the AeroVironment propeller design computer programs, and the performance for a range of advance ratios was examined, to select a propeller design which appeared to have the most desirable performance over the operational range. Here, as with the airfoil considerable effort was spent in iterating through design variable and computer performance plots with the final design being selected as one which showed an acceptable wide range of good performance. Testing of the propeller was done on the aircraft, in the air. No measures of the propeller performance are available, but estimates of the aircraft drag and pilot power output suggest it is in excess of 75%. Two different propellers were tested on the Gossamer Condor both of 3.8m diameter with one of 40cm chord and one of 30cm chord. Pitch was adjusted by twisting the blades on a shaft, to give the pilot a pedaling rate near 90 rpm at cruising speed. Both propellers appeared to have comparable performance. It is believed that the location of the propeller directly aft of the wing and fuselage was very helpful in that these flying surfaces produced a rectifying or guidvane effect, straightening the inflow to the propeller.

7. Final Comments and Conclusions

(1) For an aircraft which flew extremely slowly (<5 m/s) and hence has low relative mass (vehicle mass v. mass of the air to which it couples), there is so little background experience that standard intuition is a poor guide to vehicle dynamics. Thus it is beneficial to treat the problem using computer simulation based on fundamental concepts - particularly for lateral stability and controllability.

(2) Computer analysis was also a valuable tool for selecting and design of specialized aerodynamic features involved in the airfoil and propeller.

(3) Flight tests showed that the less the CL of the canard, the less the pitch stability. There was always adequate pitch controllability. With the large ditch damping of the vehicle, the pilot response time was comfort ably faster. Than any pitching motions and so pitch stability was not critical. With the canard lightly loaded, say operating at a CL 0.3, in turbulence the pilot would have to be correcting for pitch rather often, which was a slight distraction Paid probably harmful to efficient flit both aerodynamically and as regards pilot power potential. Of course the higher the loading on the canard, she stronger the yawing torque as the canard was rolled. A satisfactory compromise operation of the canard was Cl ~ 0.6, which gave the potential of a wide Cl range for control, adequate loading for yaw control, and satisfactory total stability.

(4) Model tests at low relative mass in water suggest that a wing with large apparent mass influences rotates most July in its own plane. This couples yaw and roll in a manner which opens up practical mechanisms for effecting turns. The complete computer analysis of the Gossamer Condor dynamics is consistent with this particular coupled motion, as are the full scale flight tests. A manifestation of this apparent mass phenomenon is that large up or down forces put out on the wings by the ground crew would have very little effect on roll. Small backward or forward forces near the tips, however, would have a large and immediate effect on roll.

(5) Coordinated turns, at radii down to about 200', would be initiated and continued by wing warping, with the canard roll used for trim. The wing with wash-in would be on the inside of the turn, just opposite to the case of initiating a turn in a normal airplane with strong yaw stability.

(6) The final configuration had controllability completely satisfactory for the purpose for which the vehicle was developed. Evidently the amount and location of the vertical fuselage area was just what was needed to provide the sort of yaw-roll coupling which made the “rolling stabilizer twisting wing” system yield coordinated turns. It is worth noting here that the “rolling stabilizer twisting wing” concept is not new; soaring birds have been using it for one hundred million years. Incidentally, the power requirements during turns seemed to increase more than expected, say about 20% for a 75m radius.

(7) The computer simulation of lateral and longitudinal stability/controlability given in Appendix A gives insight into why the vehicle dynamics of the Gossamer Condor were satisfactory.

(8) The designers might like to take credit for creating every successful solution to

flight dynamics problems, but they appreciate the large role played by luck in the design process. For example, the size and positioning of the vertical area turned out to be a good choice. However, the choice was forced on the design by 1) the need for the pilot to be close to the center of gravity since he dominates the vehicle mass, 2) the need for him to be enclosed in order to decrease parasite drag (which might not have been required if the tip chord had remained large and the flight speed low, but lateral control dictated a narrow tip chord) and 3) the need for the fuselage to be deep to provide a low support point for the flying wires.

(9) The vehicle dynamics analysis of Appendix A is ix A is illuminating but also shows that a more careful evaluation would be justified, one which explores many configurations and control variations.

Reference

MacCready, P.B., 1978, Flight on 0.33 Horsepower: Gossamer Condor. AIAA Preprint

Reproduced from: "Man-Powered Flight the Channel Crossing and the Future." Proceedings of the Third Man-powered Aircraft Group Symposium at the Royal Aeronautical Society, London, 6th February 1979.

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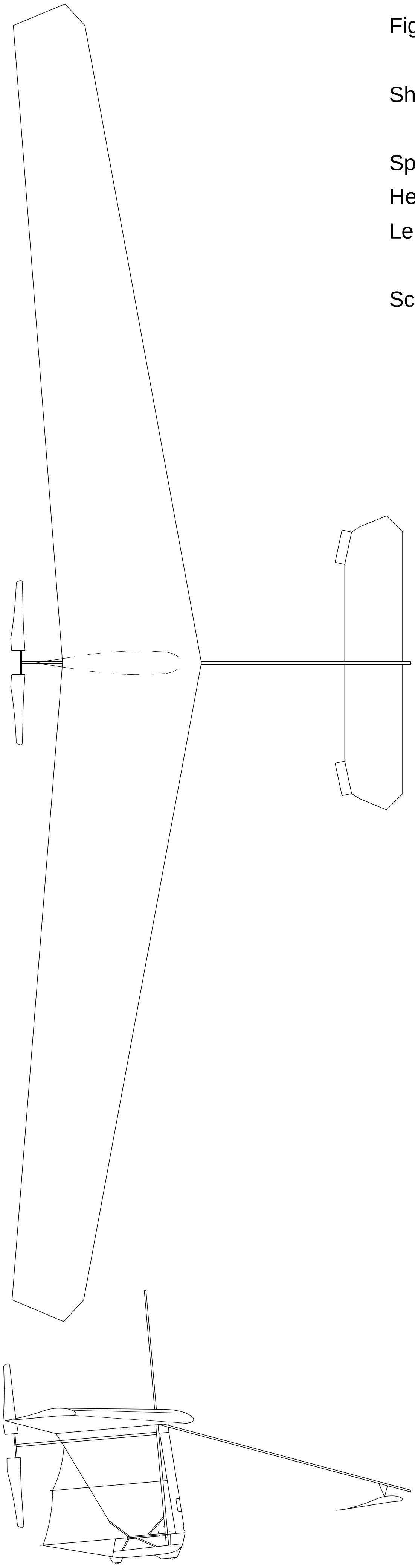


Figure 3. Three view drawing of final Shafter configuration.

Shown in flying position. No wires shown.

Span 96'
Height 19'6"
Length 30'

Scale 1:125

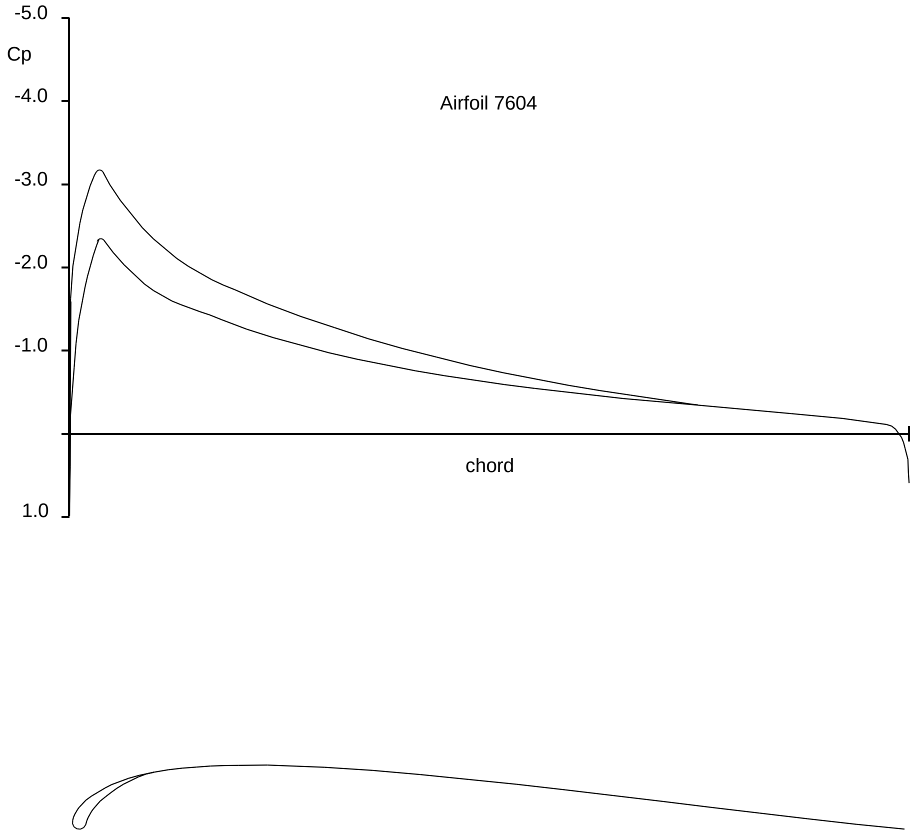
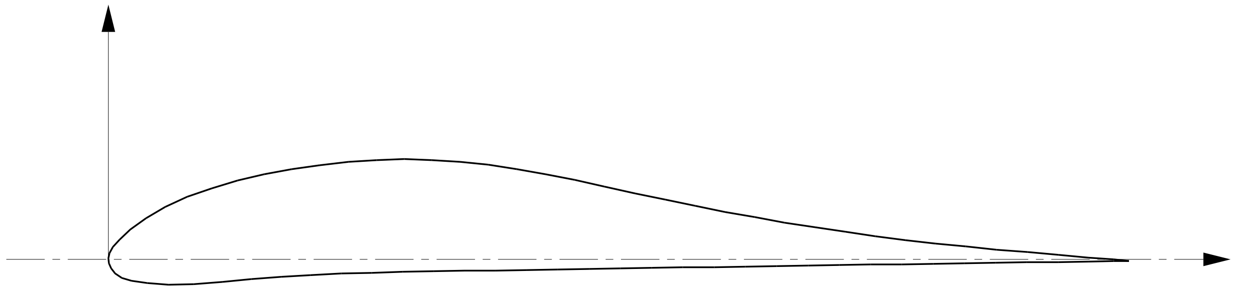


Figure 4. As shown airfoil and pressure distribution.



All Values in Percent Chord

x	upper surface	lower surface
0	0	0
1.25	2.25	-1.64
2.5	3.34	-2.01
5.0	4.96	-2.30
7.5	6.15	-2.30
10	7.06	-2.16
15	8.40	-1.70
20	9.26	-1.38
30	9.92	-1.06
40	8.97	-0.91
50	6.96	-0.75
60	4.86	-0.60
70	3.16	-0.45
80	1.81	-0.30
90	0.84	-0.16
95	0.41	-0.08
100	0	0

Nose radius 1.84, center of nose circle (1.84, 0.14)
Trailing edge angle from chord line
Upper surface 4.50, Lower surface -0.90

Figure 5. as shown 7669 airfoil.