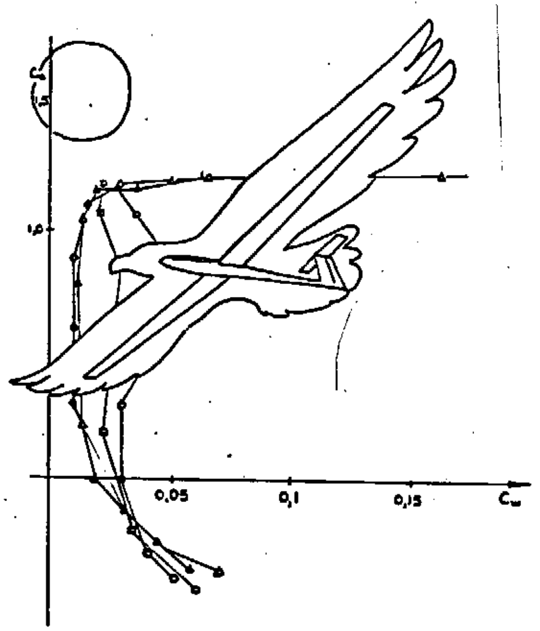
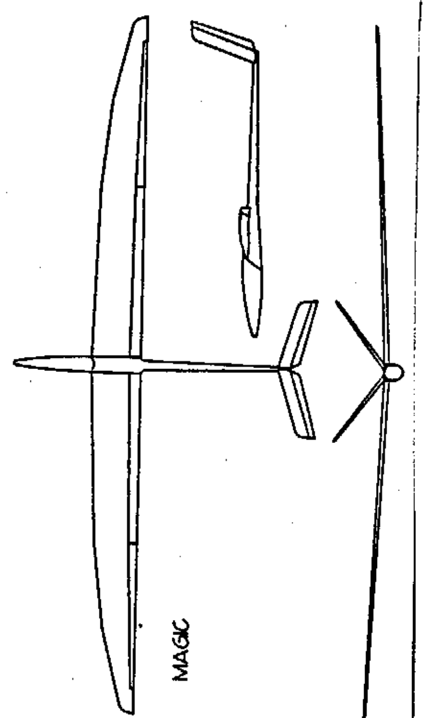
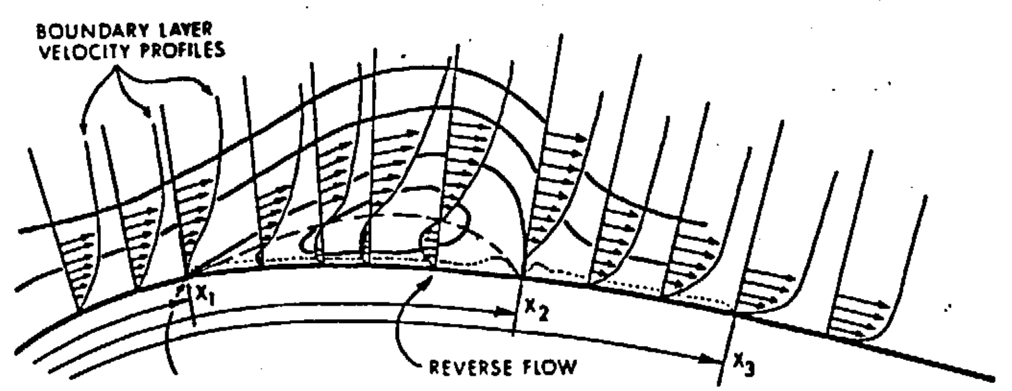
Soar Tech







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for

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SOARTECH NUMBER NINE

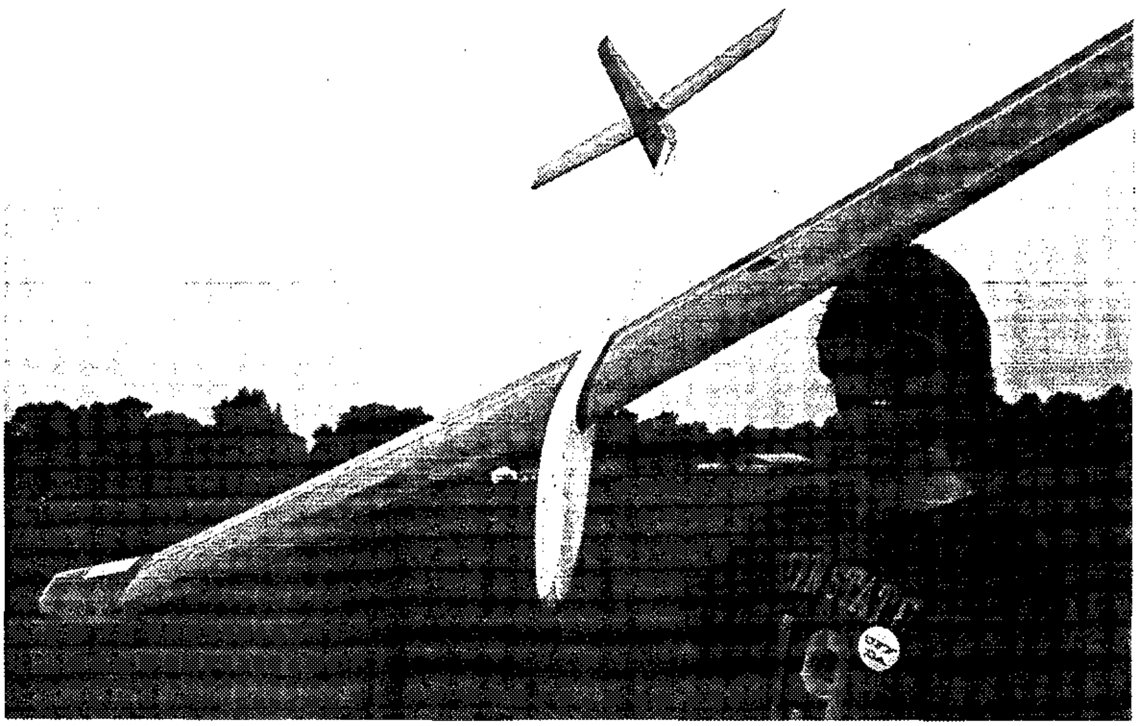
This issue has been slow in coming. "Airfoils at Low Speeds" by Selig, Dinovan, and Fraser was a real challenge to publish and distribute; and its continuing popularity has been far greater than anyone expected. It also aroused significant interest in and demand for all of the other issues of Soartech. This has kept us very busy for far longer than we expected, so issue number nine has been waiting in the wings for quite a while. The authors of the papers have been very patient and understanding too. Some of these were written quite some time ago, and some to come in the next issues have been in my hands too long as well. I am, however, confident that my entry into retired life, and reorganization of the production process will allow me to prepare and publish the next few issues in fairly rapid succession.

CONTENTS OF THIS ISSUE:

ABOUT THE COVERS

The montage on the front cover begins with the original SOARTECH logo designed by Steve McLellon in 1982. It became the cover for SOARTECH number one and is on the letterhead stationery that we use. Below is a magnified and exaggerated boundary layer flow schematic for a laminar bubble which is one of the most significant factors in RC sailplane airfoil performance. Finally, there is a three view of Frank Weston's "Magic" which, by its name, reminds us that for all the science we seek, there is still a bit of the black arts alive in RC sailplane design.

The rear cover reproduces a figure used by full scale sailplane design guru John McMasters. It illustrated a talk he gave at a NASA sponsored conference in 1979. Although model sailplanes aren't included in the domains illustrated, we can see quickly where they fit. Gives and interesting perspective doesn't it. Mr. McMasters also used a similar illustration based upon Reynolds Number. I've included it in another part of this edition. They capture attention in a way that tickles the imagination.



Michael Selig at the LSF RC Soaring Nationals in 1992. Michael's new design is his standard class "Opus?". Michael used a new and unpublished airfoil for this very light weight aircraft. He also showed us that soaring performance is more than just theory.

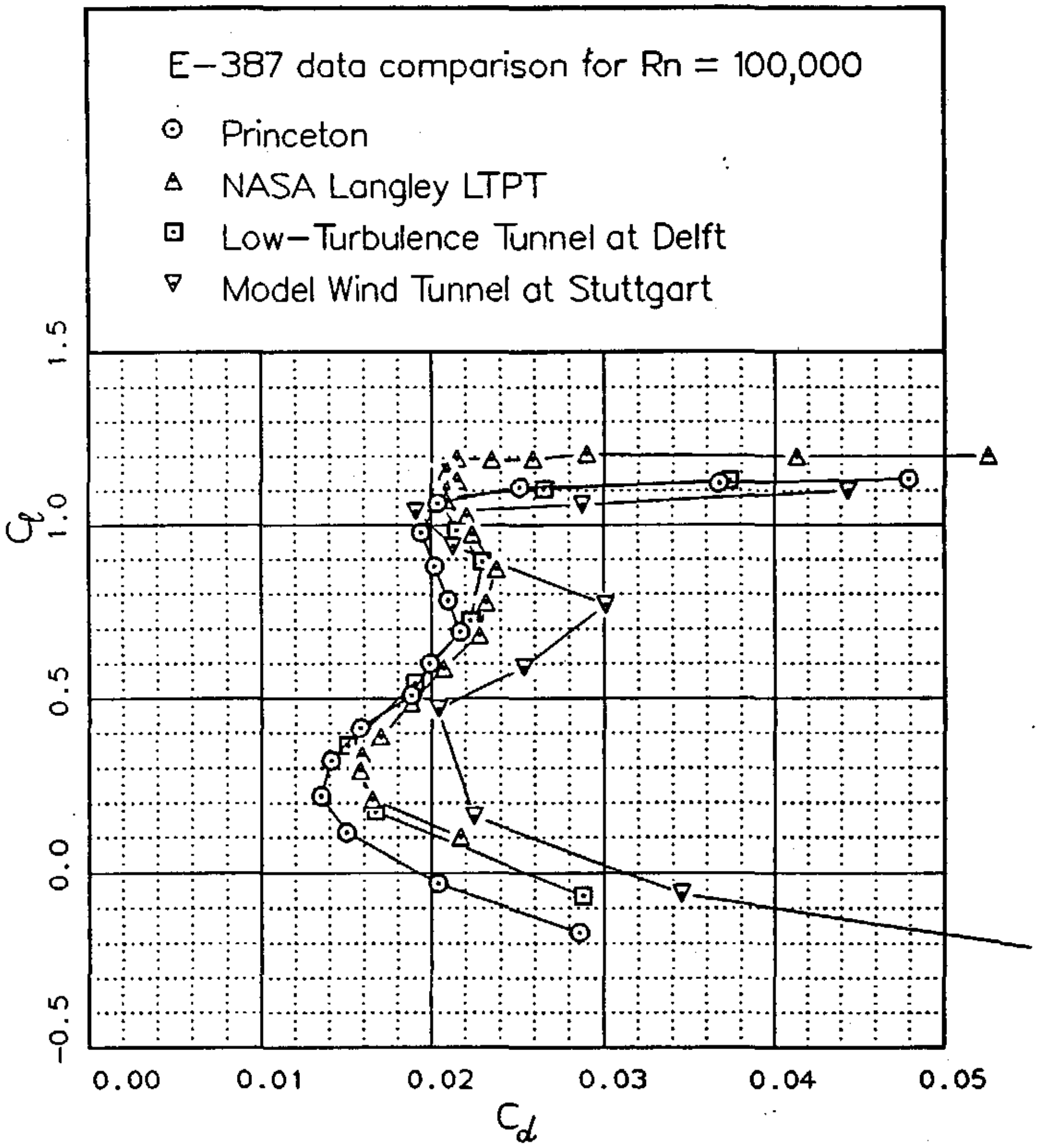
THE USE OF WIND TUNNEL DATA

When I saw this paper, I wondered what could be better to follow the publication of the Princeton wind-tunnel data of Soartech Number 8, than this detailed exposition of how such data can be used. Martin Simons prepared this work for a conference titled "Aerodynamics at Low Reynolds Numbers". This was an international affair which was sponsored by the Royal Aeronautical Society, and held in London in October of 1986.

Although this paper was presented before the Princeton work was published, its applicability is perhaps enhanced by the addition of such a large body of consistent data to the modest amount and questionable reliability of what we had available when it was prepared. I am including it in this edition of Soartech with the permission (and encouragement) of the author. When it was included in the proceedings of the London conference, it contained an extensive Appendix of representative wind tunnel data from what was available at the time.

In the interest of conserving space, I have omitted Appendix two from this publication. The data of Soartech 8 is itself a suitable appendix, and much of the remainder is already contained in Martin Simons excellent book "Model Aircraft Aerodynamics" which is published by Argus Books in England and is available from Zenith Aviation Books in the USA. The text also mentions an Appendix three - which is missing from the London paper also. Mr. Simons states that it compares wind tunnel data with theoretical data generated by the Epper-Sommers program. This type of data is also well represented in earlier editions of Soartech, and in Mr. Simons' book.

One of the clear points of this paper is that effective performance analysis that leads to high performance sailplane design must begin with an extensive breakdown and analysis of the mission of the aircraft. Other articles by Mr. Simons and Mr. Saxer in earlier issues of Soartech also demonstrate this key principle (which is essential to all aircraft design efforts). I remember discovering that a naive entrepreneur once asked the notable psychic Edgar Cayce to describe, in his trance state, the "perfect flying machine". The response was very tortuous and cryptic; but in-depth study of the text of his answer, revealed that the description was of a BIRD! A bit of humerous psychic irony! If you set down the mission tasks for a Bluejay, you'll see that it is just about perfect for its mission; *BUT* - you wouldn't want to use that same mission analysis for your sailplane would you?


E-387 data comparison for Rn = 100,000
Princeton
NASA Langley LTPT
Low-Turbulence Tunnel at Delft
Model Wind Tunnel at Stuttgart
C_l
1.5
1.0
0.5
0.0
-0.5
0.00
0.01
0.02
0.03
0.04
0.05
C_d

The use of wind tunnel data in the design of radio controlled contest model sailplanes

By Martin Simons

Introduction

The aerodynamic design of any aircraft is conditioned by the kind of flying it will be required to do. World Championships in the F.A.I. category for radio controlled sailplanes (classed F3B in the official rules) are multi-task contests. A Championship consists of five or more rounds, in each of which the competitor flies three times to perform different tasks. The three tasks are:

(A) Duration. The pilot aims for a 6 minute flight, timed from the moment of release from the towline, with a spot landing. Points are lost if the flight time is either less than or more than 6 minutes and if the landing is more than 1 metre from the marked point. A nine minute 'working time' is allowed for completion of the task, giving the pilot some small choice as to the right moment for launching and the opportunity of trying twice or more if the first attempt fails.

(B) Distance. Two parallel lines are marked on the ground 150 metres apart. Within a working time of eight minutes, as many laps as possible of the 150 metre course so marked, are flown within four minutes, the sailplane being observed to cross the appropriate line at the end of each lap. Distances are measured to the nearest quarter lap, subject to some other simple rules. The sailplane may be launched as soon as the working time begins and may explore the air for thermal lift before crossing the start line. The model may land and be re-launched but once the start line has been crossed the task must be completed within four minutes and still within the eight minute working time.

(C) Speed. The same 150 metre course is used as for distance. The sailplane must complete four laps in the shortest possible time, the flight being completed within 5 minutes of working time. Failure to complete four laps results in zero score.

The various allocations of 'working time' have been found necessary to enable a fair number of rounds to be flown with a large entry, within a week or ten days of varying weather. The organisation and timing officials can cope with no more than five or six gliders in the air at one time, and only two for the speed task. The working time system also allows a rough equalisation of aerial conditions during each 'heat' of the championships.

Launching by electric winch is now usual, with certain restrictions on the size of motor and energy storage devices, and on the length, elasticity and breaking strength of the line. A good launch, depending to some extent on the wind strength, will usually take the glider to an altitude considerably better than 150 metres above the ground, with excess velocity which the pilot may convert to more altitude by climbing very steeply after dropping the towline. Models have to be very strong if they are not to break up during the last stages of the launch, when the winch is often giving full power and the monofilament line is at full stretch. The launching rules are still under review and will almost certainly be changed again to prevent contests being decided solely by the ingenuity of winch engineers.

No instruments or devices such as variometers, capable of signalling from the model to the pilot on the ground, are permitted.

The rules for both the speed and distance tasks have been changed in recent times. The effect of the most recent changes has been to put more emphasis on pilot skill and the aerodynamic qualities of the sailplane and less on the winch. In task (A), an expert contest pilot will expect to achieve six minutes, give or take a few seconds, and land on or very near to the one-metre spot, quite consistently, so scoring close to the maximum possible number of points every time this task is flown. Thermal upcurrents will be used if there are any but a good model, handled well, can achieve six minutes without thermals if the launch gives the requisite initial altitude. If downcurrents are encountered, an experienced pilot will usually be able to find the corresponding upcurrents to extend the flight, if necessary, or may make a quick decision to land and re-launch. It is important to have a model with a low minimum rate of sink and a small turning radius for using the very small and narrow thermals that occur close to the ground but as with full-sized soaring, these qualities must be accompanied by the ability to fly fairly fast with a flat glide ratio, to get out of sinking air into better conditions. Everything then depends on an accurate spot landing. For this, powerful airbrakes or drag flaps are essential. As a contest task, Task (A) is barely achieving its objective, discrimination between the most skilful pilots. In one typical round of the 1985 World Championships, held at Waikerie in South Australia in fairly cool and gusty weather, 18 of the forty-two competitors achieved flights within ten seconds of the six minutes and 14 were within two metres of the spot.

The distance task, (B), is much more difficult. Until this year, there was a maximum allowed distance of twelve laps. This almost reduced the task to a nonsense; 28 pilots (66%) achieved the maximum score in the same example round at Waikerie. For this reason the task has now been made open-ended but the four minute time limit assumes great significance. The problem is more complicated than that of the final glide in a full-sized sailplane race. The task is a series of glides in opposite directions connected by 180 degree turns at the end of each lap. It is not good enough to fly the model through the course at or near to its theoretical best glide ratio, because the time may run out with the glider still high in the air. A flat glide ratio is most necessary but this must be achieved at a high velocity. There is usually some wind, which requires changes in the airspeed depending on whether the sailplane is going against the breeze, which requires a faster trim, or going with it, which requires a lower airspeed. Turning too steeply at the ends of the laps causes a sharp increase of vortex-induced drag with a loss of speed and height, but shallow turns are wasteful of time and distance. If lift is found during the task the pilot may use it by a form of 'dolphin' soaring, but cannot afford to wander about in search of thermals. The task is relatively new, but upwards of twenty laps seem to be quite attainable. To achieve thirty it would, with current types of aircraft, be essential to gain height in a thermal before starting, and then fly the task at fairly high speed throughout, taking eight seconds for each lap, i.e., about 68 km/h.

The speed task (C) has, until now, been the most important of the three. The higher Championships placings have often been decided by this task alone. Times about twenty seconds for the four laps are necessary to achieve a good score, and occasional 17 sec. times have been reported. At Waikerie, in

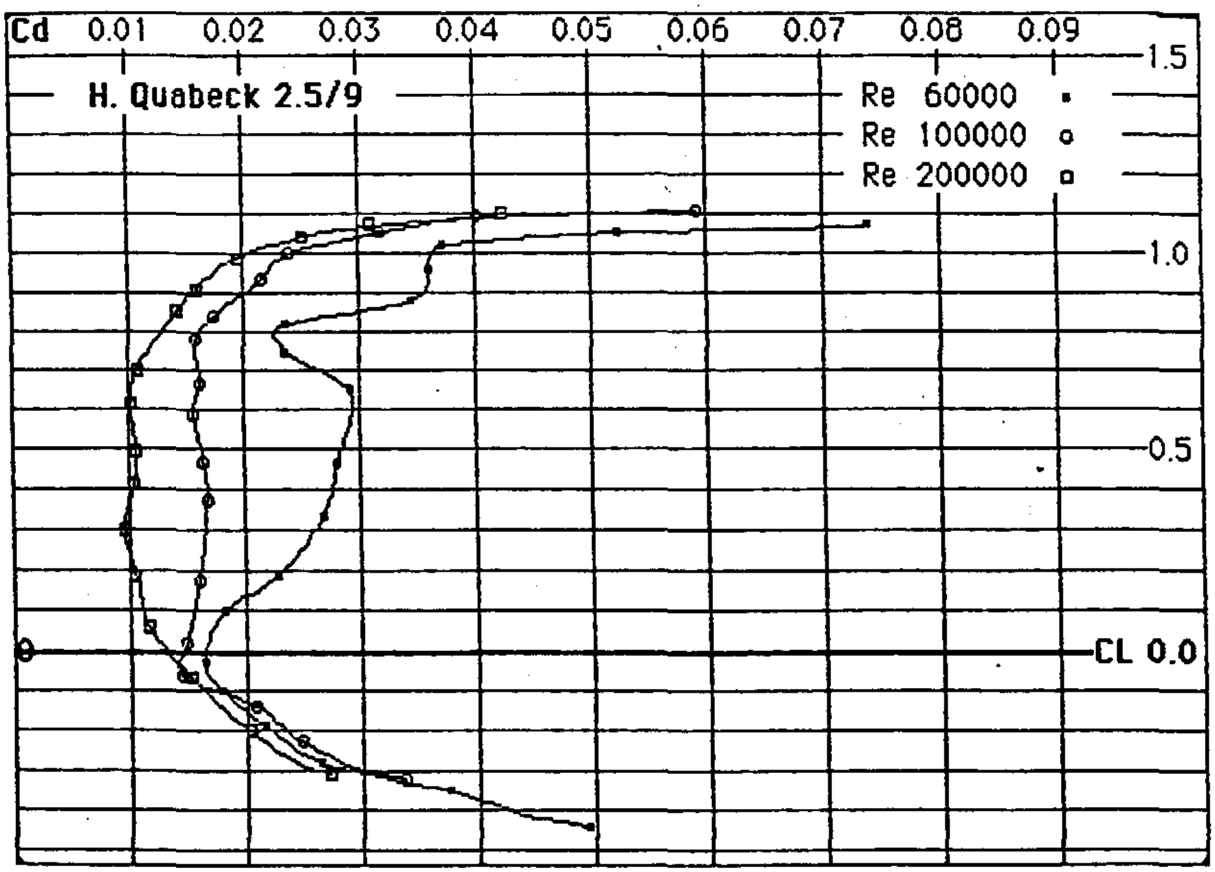


FIGURE 1. Wind tunnel test results on the HQ 2.5/9 aerofoil.
[From Althaus]

the example round, the winning time was 18.9 seconds. A pilot who achieved 19.7 seconds placed second and scored 40 points fewer. One second was thus worth 50 points. These times represent average velocities, relative to the ground, of over 30 metres per second or 110 km/h. Since this includes three 180 degree high speed turns it is clear that the maximum speeds in the straight segments of the flight are higher. Judgment of the turns is crucially important. Aerodynamically the requirement is for very low profile and parasitic drag. Flutter of control surfaces and pilot-induced oscillations are serious problems.

Typical Sailplane Dimensions

The sailplanes are restricted by the rules to a maximum of 1.5 square metres total lifting surface area.[1] The maximum allowable mass is 5 kg and the area loading must be between 1.2 and 7.5 kg/sq metre. The gliders may carry ballast up to one or other of these maxima (whichever is reached first), but may not jettison ballast in flight. Lead or steel weights are carried in tubes inside the wings, when required.

Currently, F3B class models are usually slightly under 3 metres' span with aspect ratios between 10 and 15. A few aircraft of larger span have been

[1] The area is assumed to be projected onto the plane in which lie the X and Y axes of the aircraft. The area so projected includes wing and tailplane and any auxiliary lifting devices. The aircraft may use variable geometry devices providing these can be operated by remote control in flight. That is, the contestant may not change any major component, such as the entire wing, during a championship. Repairs to damaged components are permitted. Pilots may use two models, but both must be registered and scrutinised prior to the opening of the championship and in one contest round the pilot must use the same model for all tasks unless the aircraft is irreperably damaged. Conformity with the rules must be demonstrated with extensible flaps or telescopic wings both fully deployed and retracted. At least one F3B sailplane with telescopic wings has flown successfully, the Tele F, built by the current World Champion, Ralf Decker.

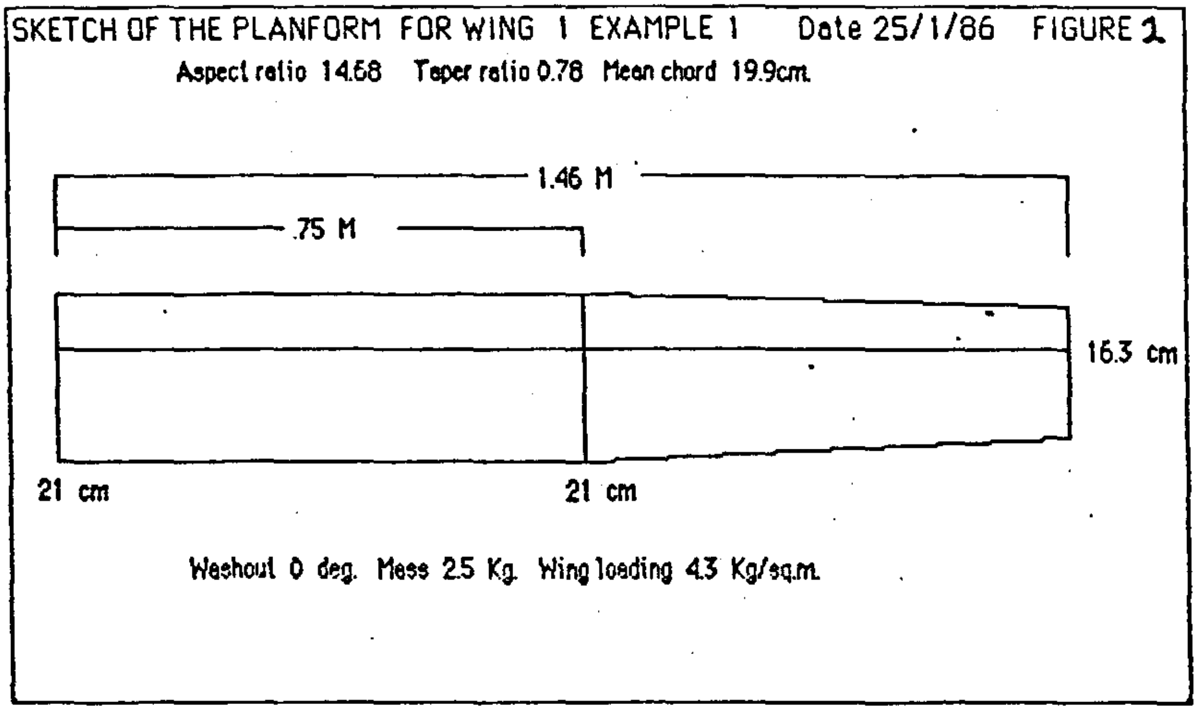


TABLE 1
EXAMPLE 1 SAILPLANE WING DESIGN EXERCISE

Eppler 193 - Althaus Vol 1 pp 63 & 68

Span: 2.92 metres Aspect ratio: 14.68
Mass: 2.5 Kilogrammes Weight: 24.51 . Newtons
Wing area: .58 sq m Wing loading: 4.30 kg/sq.m
Root chord: 21 cm. Tip chord: 16.38 cm.
Chord at taper break: 21 cm
Standard mean chord: 19.89 . cm.
Aerodynamic mean chord: 20 cm
Taper break: 0.759 metres from centre line
Washout: 0 degrees Taper ratio .78
Slope of lift curve in radians 4.51

GEOMETRICAL CHARACTERISTICS OF EXAMPLE WING

2y/b	Chord, m.	Co/C	Sin θ	Incidence
0.0000	0.210	1.0000	1.0000	0.00
0.1564	0.210	1.0000	0.9877	0.00
0.3090	0.210	1.0000	0.9511	0.00
0.4540	0.210	1.0000	0.8910	0.00
0.5878	0.203	1.0321	0.8090	0.00
0.7071	0.192	1.0938	0.7071	0.00
0.8090	0.182	1.1527	0.5878	0.00
0.8910	0.174	1.2049	0.4540	0.00
0.9511	0.169	1.2462	0.3090	0.00
0.9877	0.165	1.2728	0.1564	0.00

TABLE 2 PERFORMANCE CALCULATIONS

Velocity, m/sec: 26.25 Mean Reynolds number: 357474
Root angle of attack 1.572

Cl	Chord	Re number	Profile Cd	Local angle
0.11	0.210	377404	0.01124	1.57
0.11	0.210	377404	0.01124	1.57
0.11	0.210	377404	0.01124	1.56
0.11	0.210	377404	0.01124	1.53
0.10	0.203	365667	0.01125	1.49
0.10	0.192	345030	0.01158	1.46
0.09	0.182	327405	0.01172	1.39
0.08	0.174	313225	0.01181	1.26
0.07	0.169	302840	0.01184	1.02
0.04	0.165	296504	0.01145	0.66

Mean Lift Coefficient = 0.10

Profile drag coefficient 0.0114
Induced drag coefficient 0.00023
Efficiency 0.961 K factor = 1.041

V = 26.25 L/D = 8.6 Sink = 3.041

Velocity, m/sec: 18.56 Mean Reynolds number: 252772
Root angle of attack 3.144

Cl	Chord	Re number	Profile Cd	Local angle
0.22	0.210	266865	0.01043	3.14
0.22	0.210	266865	0.01043	3.15
0.22	0.210	266865	0.01043	3.13
0.21	0.210	266865	0.01025	3.05
0.20	0.203	258565	0.01023	2.98
0.20	0.192	243973	0.01061	2.91
0.19	0.182	231510	0.01085	2.77
0.17	0.174	221484	0.01083	2.51
0.13	0.169	214140	0.01385	2.05
0.07	0.165	209660	0.01262	1.31

Mean Lift Coefficient = 0.20

Profile drag coefficient 0.0106
Induced drag coefficient 0.00090
Efficiency 0.961 K factor = 1.041

V = 18.56 L/D = 17.4 Sink = 1.070

Table 2 contd.

Velocity, m/sec: 8.30 Mean Reynolds number: 113043
Root angle of attack 15.721

Cl	Chord	Re number	Profile Cd	Local angle
1.09	0.210	119345	0.02062	15.72
1.09	0.210	119345	0.02062	15.73
1.08	0.210	119345	0.02055	15.64
1.05	0.210	119345	0.01950	15.26
1.02	0.203	115634	0.03117	14.90
1.00	0.192	109108	0.03355	14.56
0.94	0.182	103534	0.03430	13.86
0.84	0.174	99050	0.03280	12.57
0.65	0.169	95766	0.03212	10.24
0.37	0.165	93763	0.02542	6.57

Mean Lift Coefficient = 1.00

Profile drag coefficient 0.0256
Induced drag coefficient 0.02256
Efficiency 0.961 K factor = 1.041

V = 8.30 L/D = 20.7 Sink = 0.400

Velocity, m/sec: 7.92 Mean Reynolds number: 107782
Root angle of attack 17.293

Cl	Chord	Re number	Profile Cd	Local angle
Stalled				
Stalled				
Stalled				
Stalled				
1.12	0.203	110252	0.02189	16.39
1.09	0.192	104030	0.02215	16.01
1.03	0.182	98716	0.02164	15.24
0.92	0.174	94441	0.03880	13.83
0.72	0.169	91309	0.03663	11.26
0.40	0.165	89399	0.02747	7.23

Mean Lift Coefficient = 1.10

Profile drag coefficient 0.0668
Induced drag coefficient 0.02730
Efficiency 0.961 K factor = 1.041

V = 7.92 L/D = 11.7 Sink = 0.677

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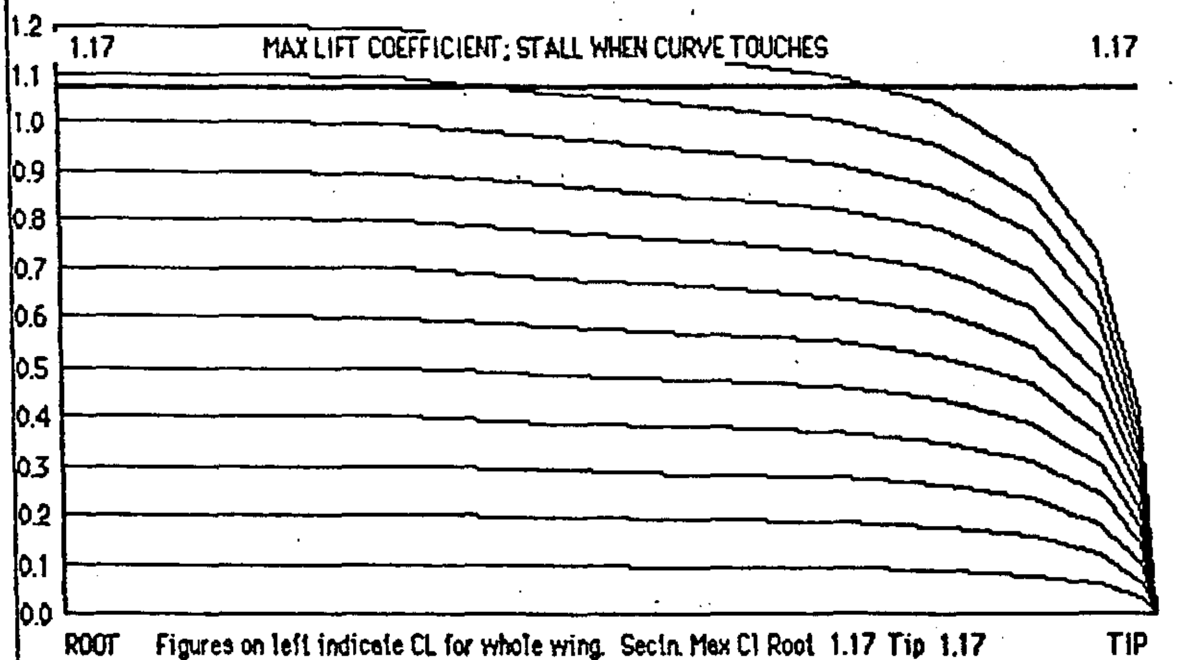
used, up to 3.6 metres, but the direction reversals at the ends of the speed and distance laps are of great importance and the rate of roll into and out of turns is likely to be slower on larger span aircraft even if they would perform a little better in the straight glides. Half rolling the model inverted and diving through the turns is a technique used with good effect by some pilots. This, too, requires a very rapid rate of roll and tends to keep the span down.

Large amounts of ballast, to bring the total mass in flight up to the maximum of 5 kg, have been tried but experience shows that more time is lost in the resulting large-radius turns, than is gained by the heavier wing loading on the straight. Flaps are often used as landing aids but also to increase wing camber during the launch and duration flying and, coupled with elevators, to assist the high speed turns. If flaps are not used for landing, air brakes or spoilers are required.

A fairly typical maximum wing loading for a modern F3B sailplane in the speed task is 5.5 kg/sq m. and with the ballast removed this would fall to about 3.5 kg/sq m. At the 1985 World Championships (where the author was one of the official scrutineers), the average mass of 84 sailplanes (42 competitors) measured without ballast before the contest was 2.47 kg. The lightest model scaled 1.62 kg and flew the speed tasks at just over 2 kg. (placed 27th. over-all). The greatest wing span was 3.12 metres, reached by two of the German models (which placed 7th and 8th). Four or five models were under 2.5 m span, two of the American group flying these with relatively thick aerofoils and heavily ballasted for the speed task. These were specifically designed to be launched at very great speed by an

FIGURE 3 SPANWISE VARIATION OF LIFT COEFFICIENT



Figures on left indicate CL for whole wing. Secln. Max Cl Root 1.17 Tip 1.17

extremely powerful winch and did not do very well under new launching rules introduced shortly before the contest.

The 1985 Championship winner, flown by Ralf Decker, was 2.8 metres' span, with aspect ratio 12.6, a straight-tapered wing with taper ratio 0.8, with full-span 'flaperons' and airbrakes. The mass without ballast was 2.46 kg. The aerofoil section was the HQ 2.5/9 (2.5% camber, 9% thickness) tapering to 2.5/8% at the tip. The wing, as on several other models, was of glass-fibre reinforced plastic construction, laid up in female moulds in the manner of full-sized sailplanes. The surface form and finish were of very high standards. It probably goes without saying that modellers now are using carbon and even boron fibres to reinforce highly stressed areas of both wings and fuselage and there is a move towards sandwich wing skins.

Wind Tunnel Data

To produce a sailplane capable of doing well in all three tasks, and also structurally strong enough to take a fast winch launch from the (still quite powerful) motors permitted, is very difficult. One of the most important decisions is the choice of aerofoil section. At their highest speeds, with wing chords less than 25 centimetres, the average Reynolds numbers reached by F3B sailplane wings are somewhat less than half a million, outside the range of most modern wind tunnel test data. In the low speed phases of flight, the mean wing Re number commonly falls to less than

PERFORMANCE POLAR FOR WING NUMBER 1, EXAMPLE 1

Eppler 193 Wing loading = 4.30 kg/sq.m.
Span = 2.92 metres. Aspect ratio = 14.68
Root Chord = 21.00 cm. Mid Chord =21.00 cm. Taper ratio = 0.78

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	3.041	8.632
18.56	1.070	17.355
15.16	0.698	21.722
13.13	0.545	24.068
11.74	0.456	25.735
10.72	0.392 *	27.325 *
9.92	0.438	22.646
9.28	0.431	21.553
8.75	0.438	19.986
8.30	0.400 *	20.742
7.92	0.677	11.694
7.58	0.738	10.263

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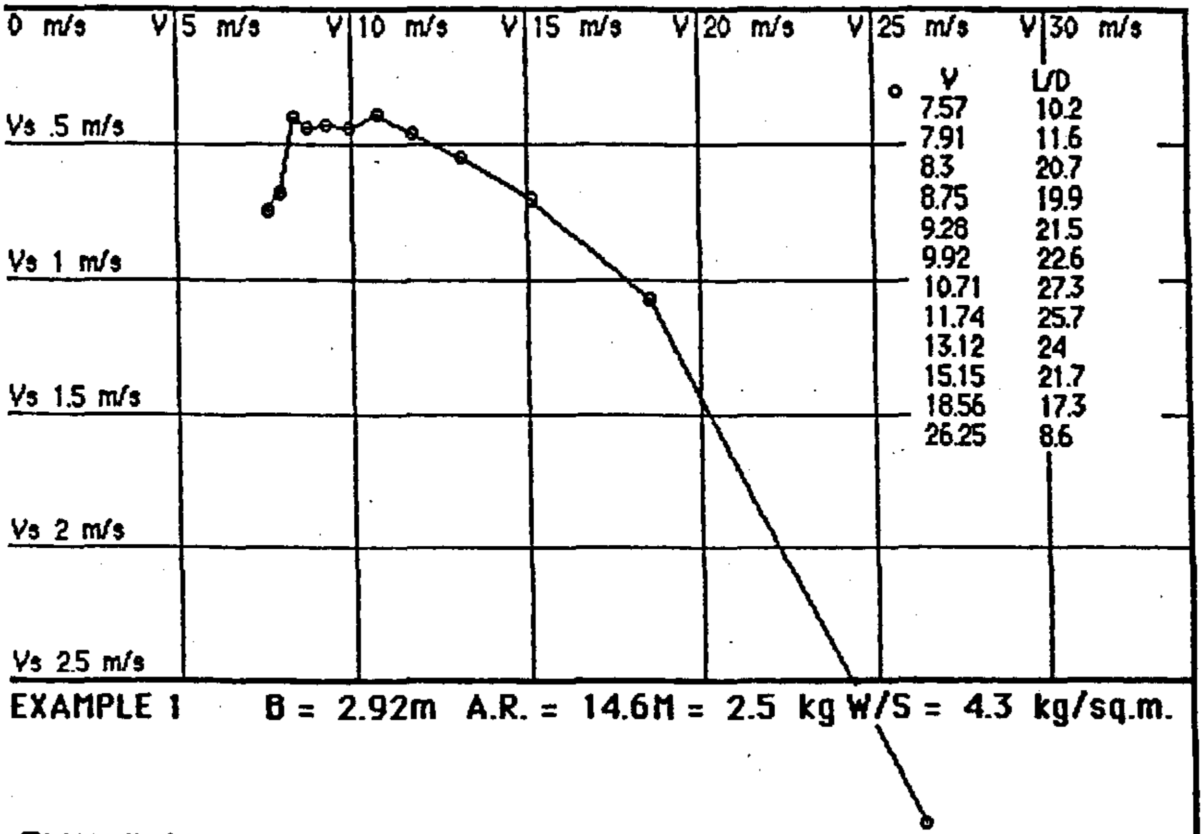

EXAMPLE 1 B = 2.92m A.R. = 14.6M = 2.5 kg W/S = 4.3 kg/sq.m.

FIGURE 4

120000 and if taper in planform is used, the local Re may be well under 100000 towards the tips.

The low Re wind tunnel results described in N.A.C.A. Report 586, produced in the U.S.A. in the late nineteen thirties, and the very extensive work done elsewhere in earlier times, was of little value to modellers because the wind tunnels used had high turbulence factors. For the designer of full-scale aircraft the problem used to be to estimate the effect of scaling up the data from the small wind tunnel model to the large wing at flying speeds. A degree of small scale airstream turbulence in the tunnel actually produced results in the wing boundary layer closer to the full-scale condition than a smooth airstream would have done. For work at very low Re numbers, the condition of the boundary layer is of critical importance and corrections for tunnel turbulence cannot be made in the usual ways. There is no way of adapting low turbulence tunnel test data at high Re, to model scales. It is apparent from such low Re wind tunnel tests as have been done, that the theoretical methods used by Drs. Wortmann and Eppler and others who have followed their lead, do not produce very accurate results below Re about 250000.[2]

Until 1977 aeromodellers in search of information about aerofoils were forced to rely on some very old and limited information from the pre-1940 researches of F. W. Schmitz at Cologne.[3] Schmitz's results and some others

[2] Some test results at three low Re numbers on the Eppler 387 aerofoil, from the Delft Low Speed Laboratory, are compared in Appendix 1 with the theoretical predictions of the Eppler program. The author is indebted to Dan Somers of NASA (Langley) for this material.

[3] F.W. Schmitz, Aerodynamic des Flugmodells, Carl D. Lange Verlag, 1942, reprinted 1953 & 1976. Available in English translation from the British (Patent Office) Library by M. Flint, as RTP Translations 2460, 2204, 2442, 2457.

4 PERFORMANCE POLAR FOR WING NUMBER 2 EXAMPLE 1

H. Quabeck 2.5/9 Wing loading = 4.30 kg/sq.m.
Span = 2.92 metres. Aspect ratio = 14.68
Root Chord = 21.00 cm. Mid Chord =21.00 cm. Taper ratio = 0.78

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	2.598	10.104
18.56	1.067	17.400
15.16	0.663	22.859
13.13	0.526	24.964
11.74	0.456	25.773
10.72	0.398	26.930 *
9.92	0.377	26.317
9.28	0.357 *	25.980
8.75	0.369	23.714
8.30	0.405	20.505
7.92	0.746	10.617

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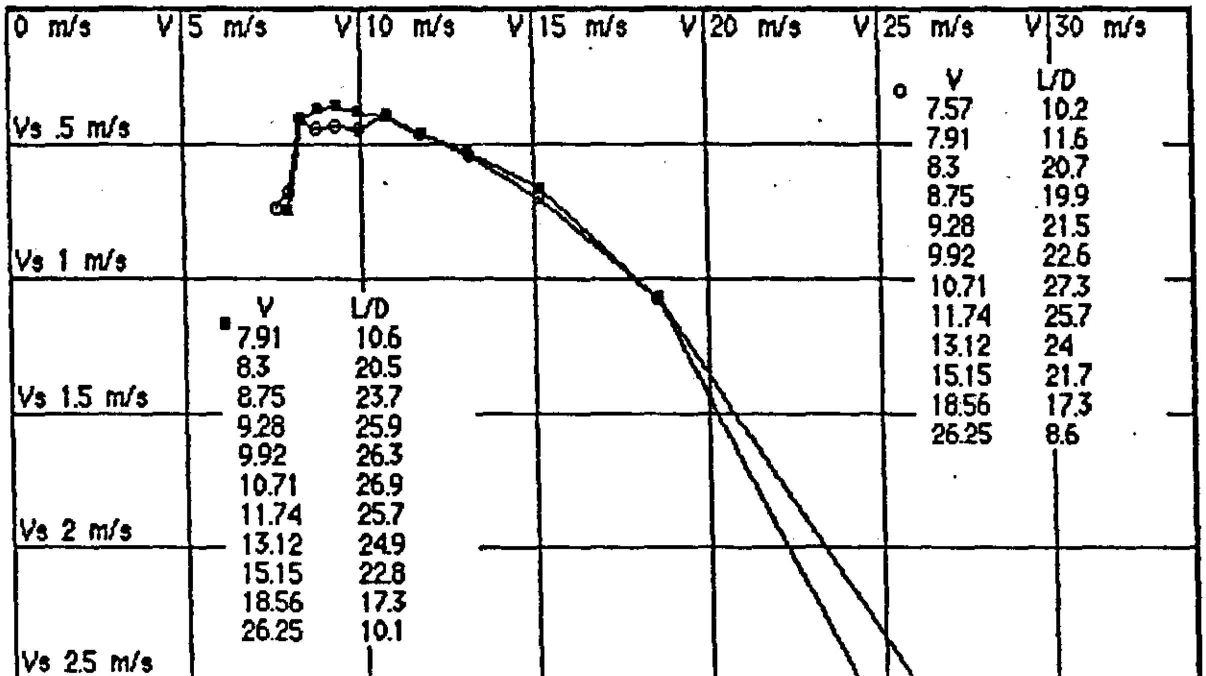

EXAMPLE 1 o B = 2.92m A.R. = 14.6M = 2.5 kg W/S = 4.3 kg/sq.m.
(E 193)

▪ B = 2.92m A.R. = 14.6M = 2.5 kg W/S = 4.3 kg/sq.m.
(HQ 2.5/9)

FIGURE 5

from Krämer, Muessman, Wortmann and Pfeninnger were collected together and included in an appendix to the book Model Aircraft Aerodynamics written in 1974.[4] Lnenicka and Horeni in Czechoslovakia published some test data on a few aerofoils in 1977 but details of the apparatus are not known.[5] There has been further work more recently at Delft and Notre Dame Universities but modellers have not found it easy to gain access to these results.

In 1980 Dieter Althaus published wind tunnel test results at low Reynolds numbers on a number of aerofoils, and followed this with a further publication in 1985.[6] The tests were done in the small, low turbulence wind tunnel at Stuttgart University, the work being undertaken mostly by student members of the AKAMODELL group under Dr Althaus' supervision. The tunnel is of a simple open return or Eiffel type with a test section 0.8 metres long and of rectangular cross section, 0.37 by 0.6 m. Drag measurements are by traversing wake rake. The turbulence factor reported is 0.8 x 10^{-3}. (The present author visited Stuttgart briefly in 1983 to see the tunnel and inspect some of the test-pieces used in it.) Dr Althaus' publications represent the largest collection so far of data on aerofoils relevant to radio controlled sailplanes of the F3B type. The methods used to construct the test pieces were straightforward and it is not impossible for aeromodellers to reproduce wing profiles equal to those used by the test group. Some confirmation of this comes from results for a segment of an actual model sailplane wing, carried out by H. J. Schmidt, a former student at Stuttgart,

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4 M. Simons, Model Aircraft Aerodynamics, 1978, reprinted 1983, Argus Books.

5 B. Horení & J. Lnenicka, Letecké Modelárství a Aerodynamika, 1978, Nase Vojsko, Prague. Some of these results are included here in Appendix 2.

6 D. Althaus, Profilpolaren für den Modellflug, Band 1 1980, Band 2 1985, Neckar Verlag, Villingen.

5 PERFORMANCE POLAR FOR WING NUMBER 3 EXAMPLE 1

H. Quabeck 1.5/9 Wing loading = 4.30 kg/sq.m.
Span = 2.92 metres. Aspect ratio = 14.68
Root Chord = 21.00 cm. Mid Chord =21.00 cm. Taper ratio = 0.78

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	2.182	12.028
18.56	0.938	19.784
15.16	0.605	25.069
13.13	0.501	26.215
11.74	0.428	27.404
10.72	0.387	27.682 *
9.92	0.374 *	26.535
9.28	0.394	23.579
8.75	0.447	19.576
8.30	0.796	10.431

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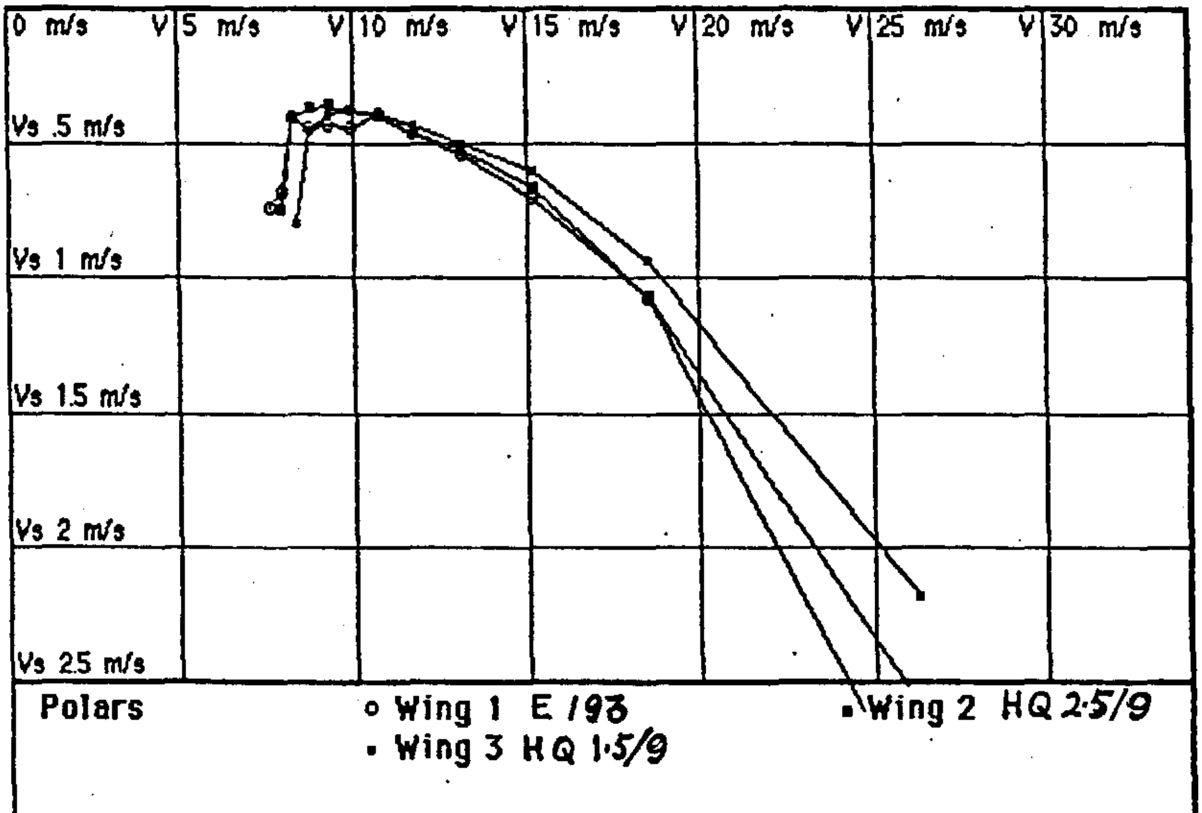


FIGURE 6

which correlate very well with the earlier tests done on the specially made wind tunnel test piece for the same aerofoil.[7]

The difficulties of measuring aerofoil characteristics in small tunnels at very low speeds, have been described by Mueller, Jansen and Batill, with results at least for some aerofoils that differ from those at Stuttgart.[8] There remains, therefore, a good deal of doubt about the applicability of the available test results to models. As far as aeromodellers are concerned, the only recourse is to the best information available and this, even now, is not very much. For all that, the Stuttgart test work represents an important step forward.

Objectives of the present study

Data now being available for a number of suitable aerofoils, it becomes worthwhile to investigate mathematically the effects of changing the aerofoil section and varying some other important parameters, such as the wing aspect ratio and taper of contest sailplanes. The designer needs to know whether it pays to use a profile with very small camber, for the sake of the speed task, or whether such a profile will spoil the low-speed performance of the aircraft so much that it ruins the duration and distance task flying. The benefits of high aspect ratio, tapered, wings for full-sized sailplanes are well known, but with models there is a danger that the very low Reynolds numbers consequent on reducing the chord may cause

[7] Hans Julius Schmidt, private communication, 30th December 1985. See Appendix 3.

[8] T. J. Mueller & S. M. Batill, Experimental Studies of Separation on a Two-Dimensional Airfoil at Low Reynolds Numbers, AIAA Journal Vol 20, No. 4, pp 457 - 463, April 1982; and T. J. Mueller & B. J. Jansen, Aerodynamic Measurements at Low Reynolds Numbers, Proceedings of the 12th Aerodynamic Testing Conference, Williamsburg, Va, March 21 - 24, 1982, AIAA - 82 - 0598.

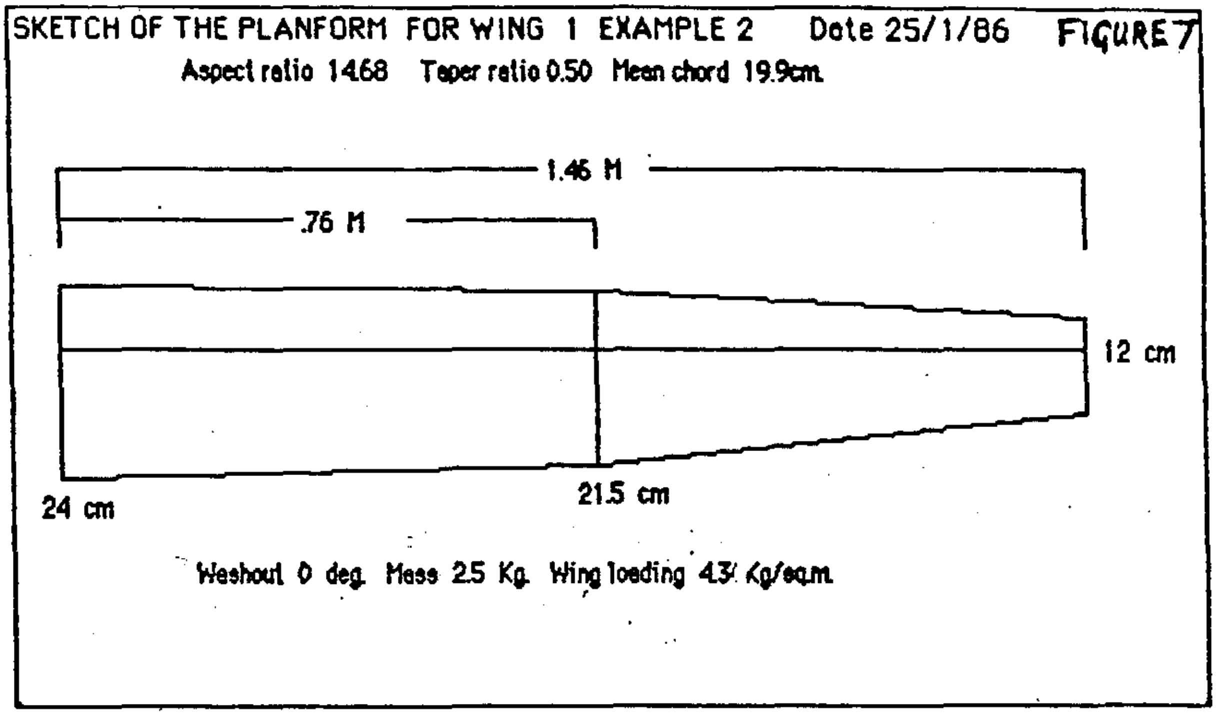


TABLE 6
EXAMPLE 2 SAILPLANE WING DESIGN EXERCISE

M. Quabeck 1.5/9 Althaus Vol 2 p 64

Span: 2.92 metres Aspect ratio: 14.68
Mass: 2.5 Kilogrammes Weight: 24.516 Newtons
Wing area: .58 sq m Wing loading: 4.30 kg/sq.m
Root chord: 24 cm. Tip chord: 12 cm.
Chord at taper break: 21.5 cm
Standard mean chord: 19.89 cm.
Aerodynamic mean chord: 22.77 cm
Taper break: 0.76 metres from centre line
Washout: 0 degrees Taper ratio .5
Slope of lift curve in radians 5.189

GEOMETRICAL CHARACTERISTICS OF EXAMPLE WING

2y/b	Chord, m.	Co/C	Sin 0	Incidence
0.0000	0.240	1.0000	1.0000	0.00
0.1564	0.233	1.0321	0.9877	0.00
0.3090	0.225	1.0655	0.9511	0.00
0.4540	0.218	1.0993	0.8910	0.00
0.5878	0.202	1.1870	0.8090	0.00
0.7071	0.178	1.3453	0.7071	0.00
0.8090	0.158	1.5183	0.5878	0.00
0.8910	0.142	1.6934	0.4540	0.00
0.9511	0.130	1.8496	0.3090	0.00
0.9877	0.122	1.9599	0.1564	0.00

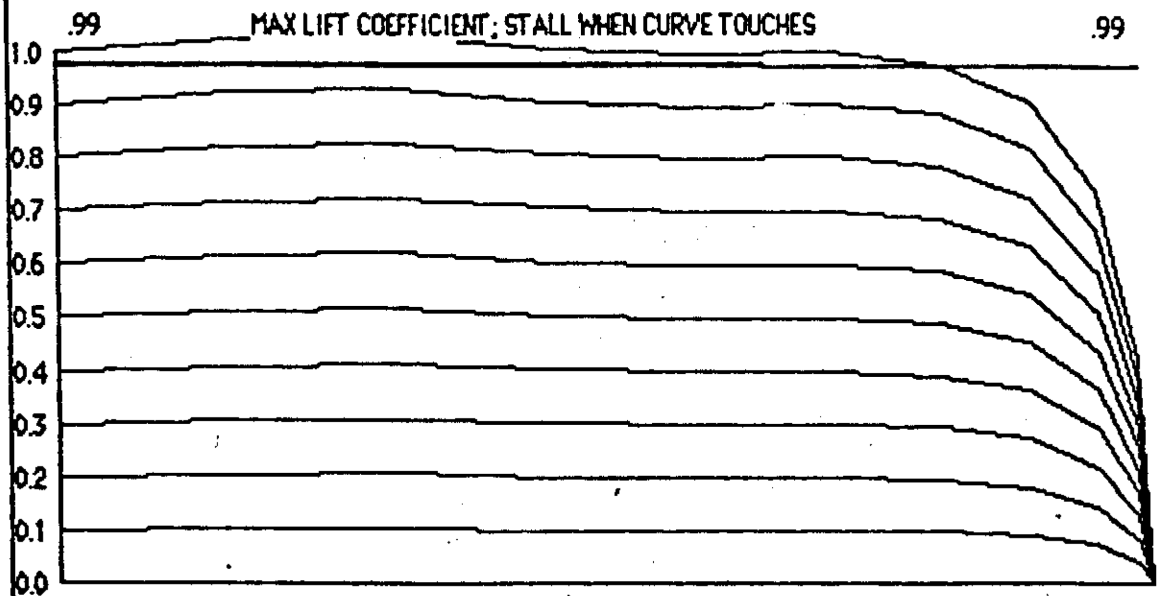
premature flow separation, high drag and even dangerous tip stalling on a tapered wing. It is also of interest to study the effect of simple camber-changing flaps, which seem to offer the advantages of both high and low cambered wing profiles.

The present study applies only to sailplane performance in straight flight. A full analysis of the design problem would require a great deal of attention to the behaviour of the models in turns at various speeds and angles of bank to determine the best strategy and configuration for the crucially important direction changes at the end of each lap. Nothing of this kind has been attempted here. Much remains to be done on launching technique also.

Methods

Estimation of the performance of a complete sailplane is a very complex matter, but useful results may be obtained if it is assumed that a good wing design will always be better than a bad one, so long as the rest of the aircraft, fuselage, tail unit, etc., are roughly similar. In what follows, therefore, no attention at all is given to the fuselage and other parasitic items. The calculations and curves plotted refer only to the wing. It hardly needs to be said that addition of fuselage and tail drag, interference effects etc., must reduce the performance at all flight speeds and the glide ratios, sinking rates etc., for a real model aircraft will be inferior to those emerging from the calculations below. If nothing else, this should sound a cautionary note for model aircraft designers who have made some exaggerated claims on behalf of their products. The best glide ratio achieved

FIGURE 8 SPANWISE VARIATION OF LIFT COEFFICIENT



Figures on left indicate CL for whole wing. Secln. Max Cl Root .99 Tip .99

TABLE 7 PERFORMANCE POLAR FOR WING NUMBER 1 EXAMPLE 2

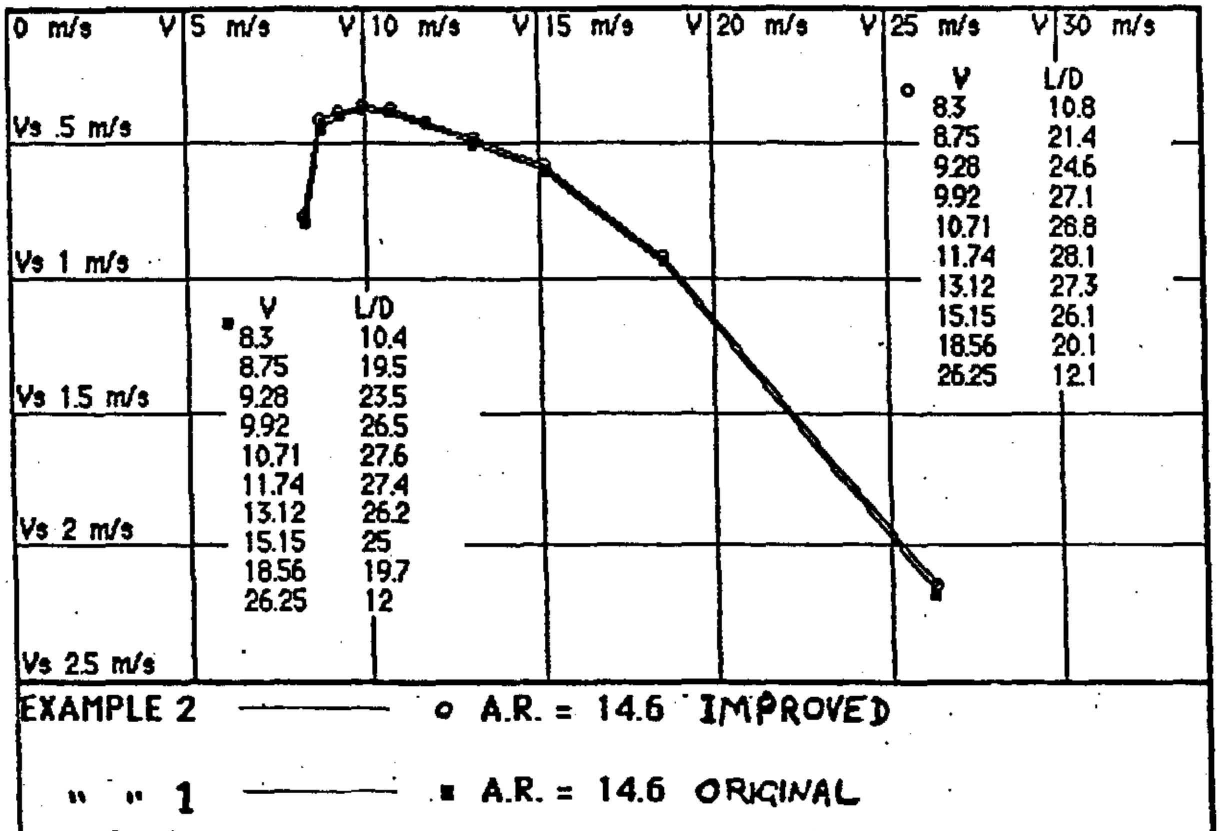
H. Quabeck 1.5/9 . Wing loading = 4.30 Kg/sq.m.
Span = 2.92 metres. Aspect ratio = 14.68
Root Chord = 24.00 cm. Mid Chord =21.50 cm. Taper ratio = 0.5

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	2.155	12.184
18.56	0.919	20.198
15.16	0.581	26.106
13.13	0.479	27.376
11.74	0.418	28.116
10.72	0.371	28.870 *
9.92	0.366 *	27.140
9.28	0.376	24.661
8.75	0.407	21.482
8.30	0.767	10.821

****

by any of the wings described below is only a fraction over 30:1, and this turns out not to be the most suitable for the F3B contest.

To estimate with some precision how the performance of a wing is affected by its planform, it is not good enough to base the calculations on a notional mean Reynolds number as has often been done in the past. The Re number changes as the speed changes, so at the very least a separate calculation should be done for a number of different flight velocities. For models, this is particularly important because the wings operate in a Reynolds number regime where the profile drag coefficients increase quite rapidly as the flight speed falls off. An example is shown in Figure 1, which is a re-plotting of results from Althaus. The aerofoil in this case is one of those specially designed by Helmut Quabeck, using the Eppler program, for contest sailplanes. It was used by Decker for his 1985 winning aircraft. At Re 200000 this profile exhibits a fairly well defined low drag range or 'bucket' with a section drag coefficient (Cd) of slightly more than 0.01 over a lift coefficient range (Cl) from 0.19 to 0.6. The minimum Cd according to the Stuttgart tests is 0.0095 at Cl = 0.3. At Re 100000 the increase in profile drag is quite marked, Cd averaging about 0.016, more than 60% higher though the width of the 'bucket' is somewhat greater, extending from Cl = -0.06 to 0.8, with the minimum Cd = 0.0144. At the lowest Re number tested, 60000, the profile is obviously on the point of general flow separation at the higher lift coefficients. More detailed investigation would doubtless reveal separation bubbles on this aerofoil behaving in ways which are now fairly well known.


0 m/s V 5 m/s V 10 m/s V 15 m/s V 20 m/s V 25 m/s V 30 m/s
Vs .5 m/s
Vs 1 m/s
Vs 1.5 m/s
Vs 2 m/s
Vs 2.5 m/s
o V L/D
8.3 10.8
8.75 21.4
9.28 24.6
9.92 27.1
10.71 28.8
11.74 28.1
13.12 27.3
15.15 26.1
18.56 20.1
26.25 12.1
▪ V L/D
8.3 10.4
8.75 19.5
9.28 23.5
9.92 26.5
10.71 27.6
11.74 27.4
13.12 26.2
15.15 25
18.56 19.7
26.25 12
EXAMPLE 2 o A.R. = 14.6 IMPROVED
" " 1 ▪ A.R. = 14.6 ORIGINAL
FIGURE 9

To use data of this kind in performance calculations requires interpolation between, and sometimes extrapolation beyond, the wind tunnel curves to find values appropriate to a particular wing Re number in flight. Even at one flight speed, if the wing is tapered, further interpolation is required across the span. In the calculations that follow, a simple method of interpolation devised originally by Nick Goodhart for the 'Sigma' full-sized sailplane project, has been used. The details have been published elsewhere.[9]

In estimating the vortex-induced drag of tapered wings, a common method is to multiply the usual equation for CD_i by a factor, K, which allows for the departure of the planform from the ideal elliptical form. This has not been found satisfactory for the present work and since a micro computer was available the more elaborate Lotz method was adopted. This is based on lifting line theory, requiring an estimation of the spanwise distribution of circulation expressed as a Fourier series.[10] This, on the assumption that the slope of the lift curve of the wing is essentially rectilinear and that there is no appreciable sweep-back or forward, allows the spanwise lift loading required to yield a give wing lift coefficient to be estimated. The local or section lift coefficient at each of ten standard spanwise stations is discovered. From this an indication of any dangerous tip stalling condition can be obtained and at the same time by interpolating separately for each

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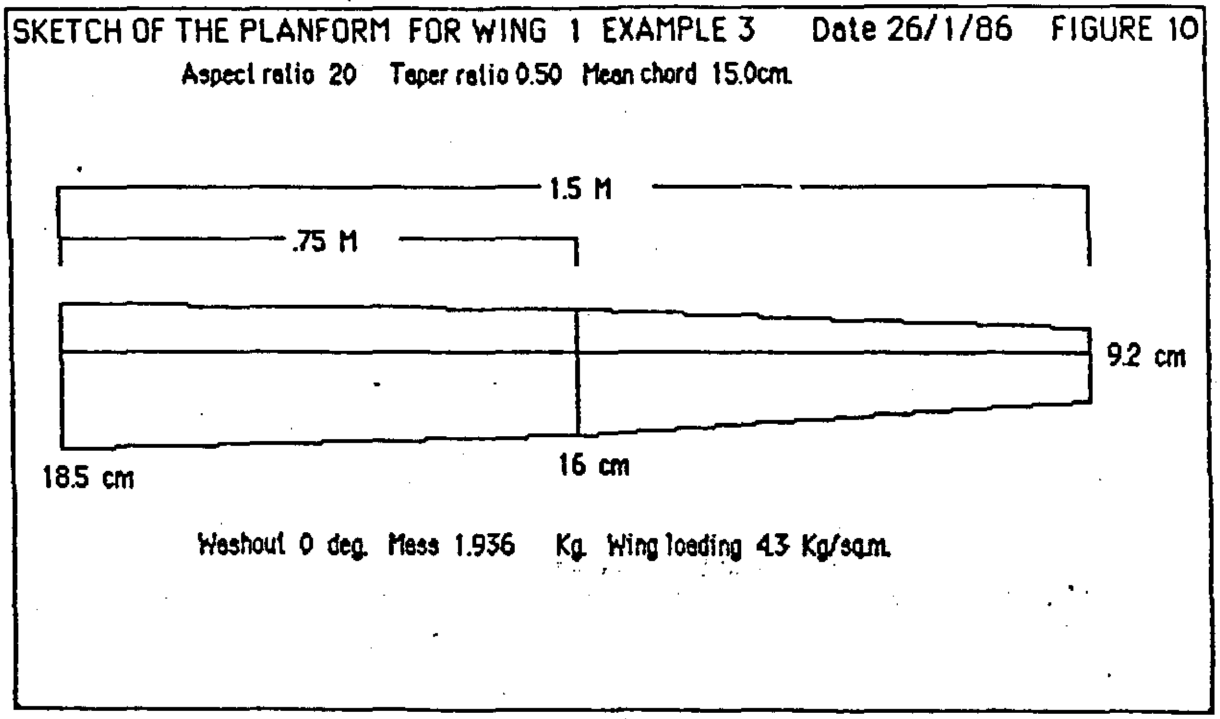
[9] M. Simons, Using a hand-held programmable calculator in estimations of model sailplane performance, in SOARTECH 1, 1982, obtainable from H. Stokely, 1504 Horsehoe Circle, Virginia beach, VA 23451, U.S.A. The author is grateful to Nick Goodhart for permission granted, some years ago, to use the Sigma program and adapt it for models. Except for the interpolation method, the work reported here is not otherwise based on the Sigma program.

[10] The method is outlined in several standard texts, including Abbott & Von Doenhoff, Theory of Wing Sections, Dover 1959, pp 9 - 27. The particular procedure followed here comes from Introduction to Aeronautics, by C.F.Toms, 1947, Griffin & Co., pp 282 - 295. This, with its charts and stencils, lends itself well to straightforward computer programming. There is, however, a printing error in one of the worked examples in this source.



SKETCH OF THE PLANFORM FOR WING 1 EXAMPLE 3 Date 26/1/86 FIGURE 10
Aspect ratio 20 Taper ratio 0.50 Mean chord 15.0cm.
Weshout 0 deg. Mess 1.936 Kg. Wing loading 4.3 Kg/sq.m.

TABLE 8 PERFORMANCE POLAR FOR WING NUMBER 1 EXAMPLE 3

H. Quabeck 1.5/9 Wing loading = 4.30 Kg/sq.m.
Span = 3.00 metres. Aspect ratio = 20
Root Chord = 18.56 cm. Mid Chord =16.08 cm. Taper ratio = 0.5

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	2.463	10.657
18.56	1.073	17.308
15.16	0.641	23.640
13.13	0.508	25.859
11.74	0.416	28.198
10.72	0.374	28.641 *
9.92	0.353 *	28.130
9.28	0.370	25.080
8.75	0.391	22.402
8.30	0.826	10.051

****

spanwise station and its local Re number, the local profile drag coefficient is found. The performance polar is then obtained by spanwise integration of both the profile and vortex-induced drag for each mean lift coefficient.

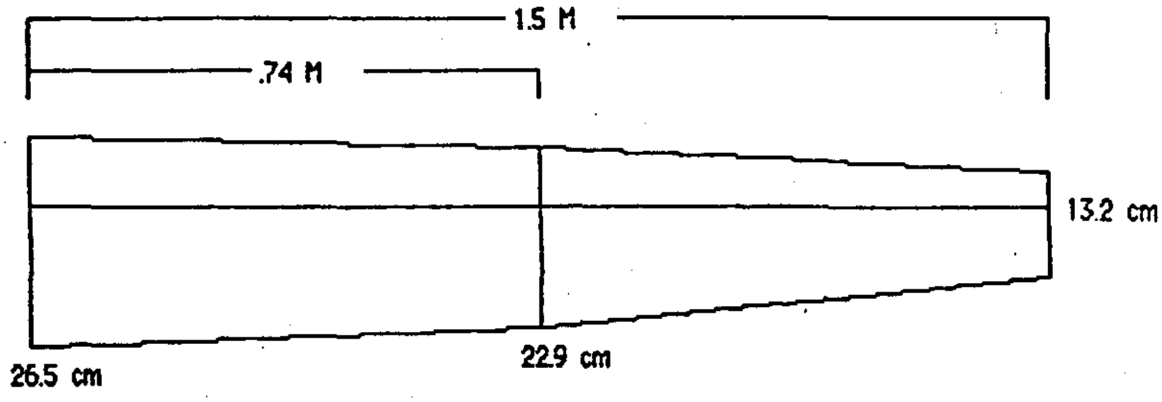
The computer program[11] first calls up wind tunnel data held on disc file, for the chosen aerofoil. The widely separated test points are joined by a spline curve. The program then calls for details of the wing: span, aspect ratio, taper ratio, wing chord at root and at one other point, washout in degrees and spanwise extent of washout (a proportion of the wing which is free of twist may be stated). The assumed total mass of the aircraft is also required. The wing planform is then sketched as in Figure 2 and the wing dimensions are printed as in Table 1.

The program then goes through the Fourier series procedure from CL (whole wing) = 0.1 up to and slightly beyond the stall, in steps thus: 0.1, 0.2, 0.3....0.9....to stall. Typical extracts from the output are shown in Table 2. The flight velocity depends on the value of CL and the mass. The angle of attack at the wing root is found from the average lift curve slope taken from the tunnel test figures. For each of the ten usual spanwise stations, the local or section lift coefficient Cl is given, the Re number at that point is found, the corresponding profile drag (Cd) is interpolated (or extrapolated) from the wind tunnel data, and the local angle of attack is found. The total drag is then summed and the lift/drag ratio and sinking speed worked out. When the procedure is complete, a diagram such as that shown in Figure 3 is plotted, enabling the designer to assess the likelihood of tip stalling. After this, the performance polar is printed out (Table 3) and

[11] Apple Macintosh, program written in Microsoft Basic version 2.

SKETCH OF THE PLANFORM FOR WING 2 EXAMPLE 3 Date 26/1/86 FIGURE 11

Aspect ratio 14 Taper ratio 0.50 Mean chord 21.4cm.



Washout 0 deg. Mass 2.767 Kg. Wing loading 4.3 Kg/sq.m.

TABLE 9 PERFORMANCE POLAR FOR WING NUMBER 2 EXAMPLE 3

H. Quabeck 1.5/9 Wing loading = 4.30 Kg/sq.m.
Span = 3.00 metres. Aspect ratio = 14
Root Chord = 26.52 cm. Mid Chord =22.97 cm. Taper ratio = 0.50

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	2.081	12.616
18.56	0.891	20.826
15.16	0.575	26.351
13.13	0.468	28.022
11.74	0.415	28.306
10.72	0.370	28.952 *
9.92	0.366 *	27.143
9.28	0.385	24.134
8.75	0.409	21.401
8.30	0.890	9.323

****

plotted as in Figure 4. The program may be run through several times to allow easy comparison of superimposed polar curves.

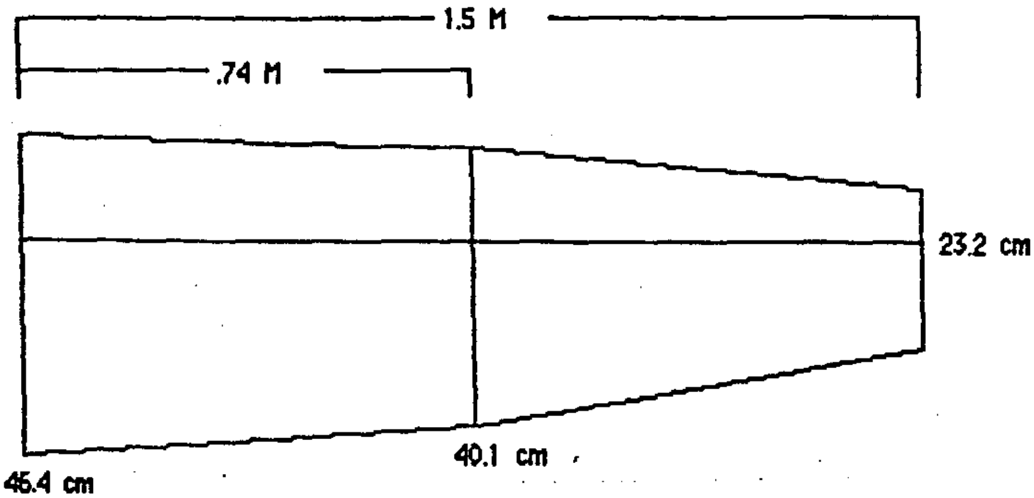
Results

The sketch in Figure 2 represents the wing of a sailplane called Marjali used from 1981 to 1985 by several members of the Australian International Team. It was developed over several years from early in1981, following the publication of a three-part article, by the present author, in The Australian Radio Control Modeller magazine. Most of the development work was done by Stefan Smith, a former member of the team, and a kit for this design has been successfully marketed in Australia. The assumed mass for the present calculations was 2.5 kg, though the model can be built down to 2.2 kg. without very much difficulty and, of course, may be ballasted to considerably more than this. A 16mm (5/8th inch) diameter steel rod joins the wings and carries the bending loads through the fuselage. To ballast the model, this short wing joiner is replaced by a longer rod of the same material, extending over half the total span. Lead ballast may be added too, if required. The aerofoil section used was the Eppler 193, which is 3.5 % cambered with a thickness of 10.2%. In 1981 this was considered by many competitors to be the best available aerofoil for these models. The author's recommendation for a section with much less, or even zero, camber, with flaps, was not followed. With very moderate taper and aspect ratio less than 15, the wing is fairly representative of the F3B type of a few years ago.

As Figure 3 shows, such a wing is very safe at the stall, being very little different in this respect from a rectangular wing. Washout is generally not

SKETCH OF THE PLANFORM FOR WING 3 EXAMPLE 3 Date 26/1/86 FIGURE 12

Aspect ratio 8 Taper ratio 0.50 Mean chord 37.5cm.



Washout 0 deg. Mass 4.842 Kg. Wing loading 4.3 Kg/sq.m.

TABLE 10 PERFORMANCE POLAR FOR WING NUMBER 3 EXAMPLE 3

H. Quabeck 1.5/9 Wing loading = 4.30 Kg/sq.m.
Span = 3.00 metres. Aspect ratio = 8
Root Chord = 46.41 cm. Mid Chord =40.19 cm. Taper ratio = 0.5

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	1.640	16.010
18.56	0.766	24.218
15.16	0.537	28.226 *
13.13	0.479	27.420
11.74	0.449	26.140
10.72	0.426 *	25.134
9.92	0.439	22.581
9.28	0.458	20.258
8.75	0.495	17.690
8.30	0.991	8.376

****

used for F3B sailplanes. If washout is used, at high speeds the outer parts of the wing are forced to operate at negative angles of attack, with consequent increases in drag and slower times in the speed task as a result.

The polar (Table 3 and Figure 4), is of considerable interest. It has been noticed in practice that aircraft with the Eppler 193 and its slightly less cambered stable-mate, E 205 (not, so far, tested in the wind tunnel), show little variation of sinking speed over a range of flight speeds. Up to a certain point, increases of forward speed do not produce any noticeable effect on the rate of descent and, accordingly, there is a marked improvement in glide ratio, quite noticeable in flight when the trim is moved slightly forward. Pilots sometimes say that the sailplane 'gets up on the step' in the way small power boats do. As the figures show, at 10.7 m/sec flight speed, the rate of sink of this wing is actually fractionally less than the rather sharp peak at V = 8.3 m/sec, near the stall. The glide ratio, about 27:1, is at its best also at the higher speed. The cause is not very hard to find. At Re about 100000, which corresponds to the mean wing Re just above the stall (Table 2), the wind tunnel results show characteristics associated with the formation of separation bubbles on the wing. It is not that the wing 'gets up' onto a step at higher speeds, but rather, it is brought off an even higher step, at low speeds. The top of the polar curve is flattened or 'dished' by the separation bubble. If this could be removed without affecting the faster parts of the polar, there would be a

TABLE 11. PERFORMANCE POLAR FOR WING NUMBER 1 EXAMPLE 3

H. Quabeck 1.5/9 . Wing loading = 5.56 Kg/sq.m.
Span = 3.00 metres. Aspect ratio = 20
Root Chord = 18.56 cm. Mid Chord =16.08 cm. Taper ratio = 0.5

Velocity Metres/Sec	Sink M/sec	L/D Ratio
29.82	2.626	11.357
21.09	1.121	18.811
17.22	0.682	25.255
14.91	0.545	27.385
13.34	0.455	29.295
12.18	0.403	30.189 *
11.27	0.386 *	29.210
10.54	0.404	26.087
9.94	0.428	23.211
9.43	0.942	10.015

****

TABLE 12 PERFORMANCE POLAR FOR WING NUMBER 2 EXAMPLE 3

H. Quabeck 1.5/9 Wing loading = 3.89 Kg/sq.m.
Span = 3.00 metres. Aspect ratio = 14
Root Chord = 26.52 cm. Mid Chord =22.97 cm. Taper ratio = 0.5

Velocity Metres/Sec	Sink M/sec	L/D Ratio
24.95	2.027	12.309
17.64	0.869	20.294
14.41	0.558	25.800
12.48	0.454	27.469
11.16	0.399	27.937
10.19	0.357	28.533 *
9.43	0.352 *	26.810
8.82	0.371	23.769
8.32	0.393	21.174
7.89	0.845	9.336

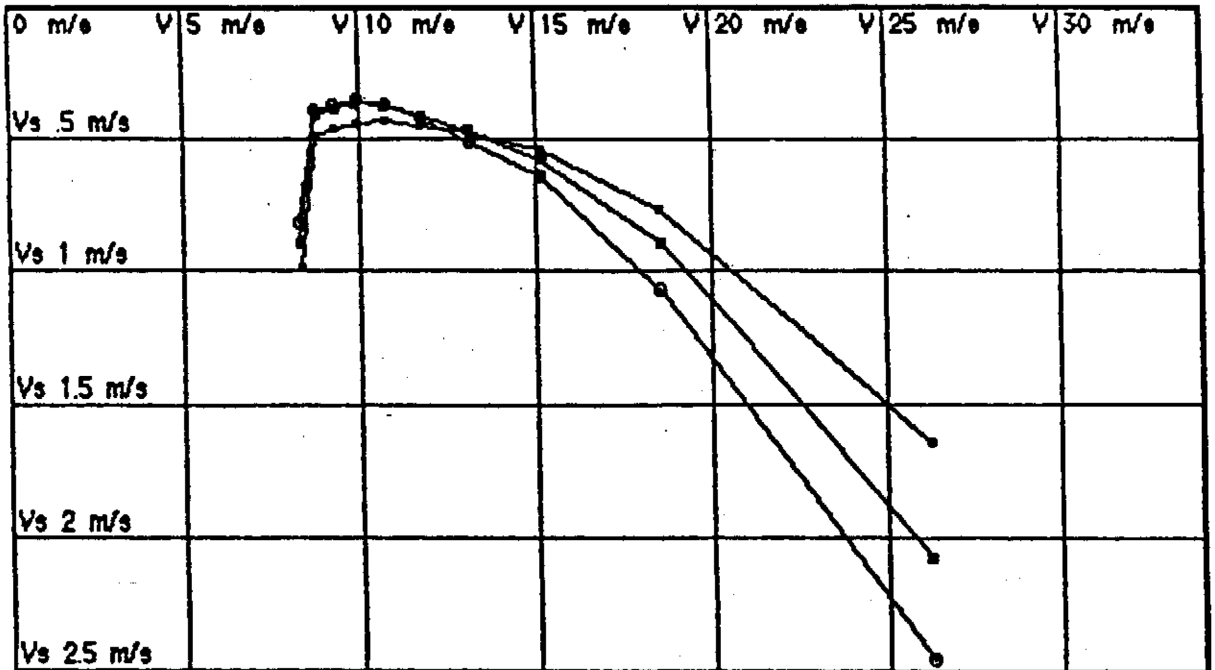
****

reduction in the minimum rate of sink, the 'step' effect would disappear and the all-round performance would be better.[12]

In Table 4 and Figure 5, the polar of a wing of identical planform but using the aerofoil preferred by Decker (Quabeck 2.5/9, 2.5% cambered and 9% thick, see Fig. 1) is shown. The wing loading is the same, to enable a direct aerodynamic comparison. The result is exactly what would have been hoped for. Although there is practically no difference in stalling speed, or in the glide ratio at 18.56 m/sec airspeed, the flat top of the polar has been filled out and a 9% improvement in rate of sink (0.35 as against .39 m/sec) is achieved at a speed safely above the stall. Generally it has been supposed that aerofoils of larger camber produce lower rates of minimum sink. This can apply only if the aerofoil does not develop separation bubbles at high angles of attack. It would be interesting to have wind tunnel results on a 3.5% cambered version of the Quabeck profile, for direct comparison with the Eppler section, but these are not available.

In a descent in still air, a saving in rate of sink of about 4 cm per second in a six minute duration task, represents 14.4 metres in terms of altitude. This is not altogether negligible but the small gain in rate of sink is not likely to matter very much if the sailplane has a good launch to start with and if the pilot finds even a small amount of thermal lift. It should be remembered that the figures of Tables 3 & 4 relate to the wing only.

[12] It is worth noting that irregularities of a somewhat similar kind, though much less obvious, have been noted in flight testing of some full-sized sailplanes, some of which exhibit almost two different polars at low speeds, or at least some local 'dishing' of the polar. The LS 3 test data published by Johnson, for example, shows this in a marked degree. Attention to sealing of the flap roots of this aircraft reduced the effect, but the cause, local bubble separation, is probably similar to that on the Marjali. See: R. H. Johnson, The Johnson Flight Tests, Soaring Society of America, 1980.



Polars
EXAMPLE 3

FIGURE 13

Of more importance to the competitor, the Quabeck aerofoil shows a worthwhile advantage at all flight speeds above 20 m/sec, this advantage becoming greater still as the airspeed rises towards that required for the speed task. It seems fair to say that the choice of aerofoil for the winning aircraft in 1985, was a good one.

In Table 5 and Figure 6, the effect of using a 1.5% cambered Quabeck profile is assessed (HQ 1.5/9, thickness is again 9%). The stalling speed is higher because, at the low Re end of the scale, this aerofoil has a lower Cl max of about 1.0 as compared with 1.1 for the 2.5% cambered version. Even so, the minimum rate of sink is still better than the E 193, and only slightly worse than the 2.5% cambered wing. Again, the difference, about 2 cm per second, is not likely to worry the experienced pilot who needs only a turn or two in thermal lift, to make up such a deficiency. More significantly, the high speed end of the polar shows a very considerable gain for all airspeeds above 10 m/sec. This is without ballast. If ballast were added, the sailplane with this wing profile would do better still against its more cambered rivals, even if they, too, were ballasted to the same wing loading.

Taper effects

The almost rectangular planform of the Marjali is, in standard theory, less efficient than a more nearly elliptical wing would be. It is also difficult to make a wing with a thickness of only 1.9 cm at the root (for the HQ 9% thick profile) sufficiently strong to withstand the winch launching loads. Accordingly, for both aerodynamic and structural reasons, a more strongly

TABLE 13 PERFORMANCE POLAR FOR WING NUMBER 3 EXAMPLE 3

H. Quabeck 1.5/9 Wing loading = 2.22 Kg/sq.m.
Span = 3.00 metres. Aspect ratio = 8
Root Chord = 46.41 cm. Mid Chord =40.19 cm. Taper ratio = 0.5

Velocity Metres/Sec	Sink M/sec	L/D Ratio
18.86	1.376	13.704
13.34	0.631	21.153
10.89	0.432	25.192 *
9.43	0.378	24.921
8.44	0.351	24.055
7.70	0.328 *	23.461
7.13	0.335	21.281
6.67	0.349	19.082
6.29	0.377	16.696
5.96	0.717	8.325

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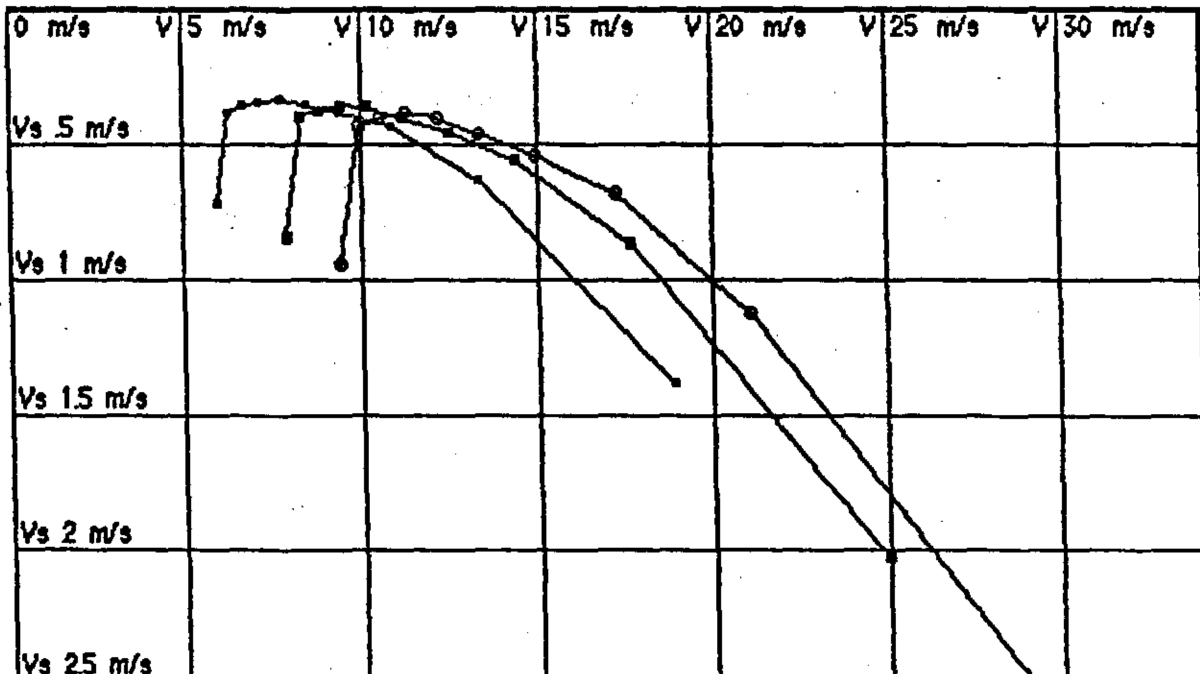


Polars ○ Wing 1 A = 20 ▪ Wing 2 A = 14
EXAMPLE 3 ▪ Wing 3 A = 8

M = 2.5 kg

FIGURE 14

tapered wing might be preferred. Such a wing is sketched in Figure 7; the detailed dimensions are given in Table 6. The HQ 1.5/9 profile is retained. The taper ratio is 0.5 (tip chord half the root chord) and the outer half of the wing is more tapered than the inner half. Figure 8 shows that such a planform should not give any trouble in handling at low speeds. Although the stall begins at about a quarter of the way out along the wing, the tips remain unstalled.

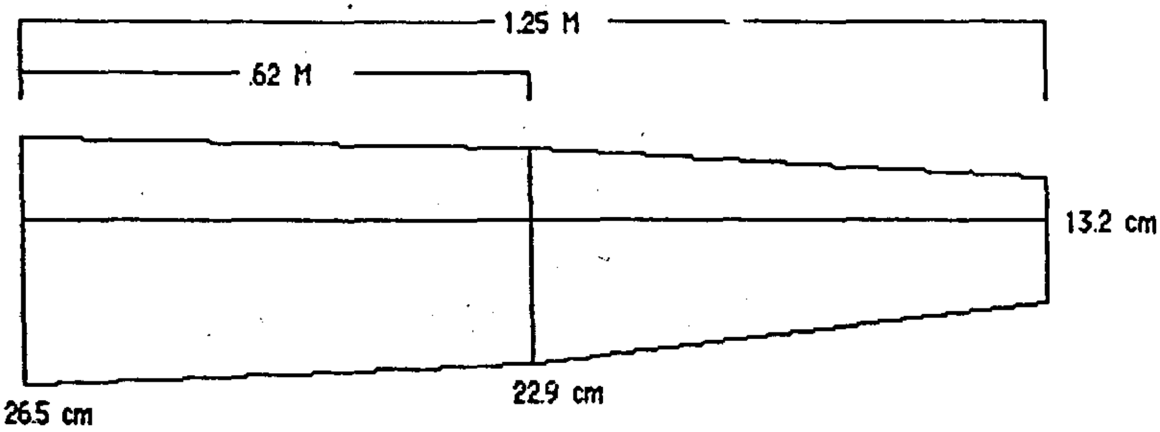
Table 7 shows the performance polar and in Figure 9 the improved and original wings are compared directly by plotting. The difference is very slight and would be undetectable in practice, although the more nearly elliptical wing has a one-point improvement in best glide ratio and about 1 cm/sec improvement in minimum sink rate (0.366 m/sec vs 0.374 m/sec). Justification of the more tapered wing on aerodynamic grounds is hardly possible but a wing root 2.3 cm thick is much easier to cope with structurally than one of 1.9 cm., and for this reason alone is to be preferred.

Aspect ratio effects

Tables 8 to 10 and Figures 10 to 12, move the study on to a different topic, that of the best aspect ratio. It is assumed that the HQ 1.5/9 aerofoil is retained and that the same type of taper proportions are used as in Figure 7, but the span is slightly increased to 3 metres for convenience. Wing loading is held constant at 4.3 kg/sq m. In Figure 10, the obvious difficulty of building a strong wing with root chord only 1.6 cm thick, is ignored. A maximum aspect ratio of 20 is chosen for the comparison because other calculations show that, even in terms of sinking speed, there is no

SKETCH OF THE PLANFORM FOR WING 2 EXAMPLE 4 Date 27/1/86 FIGURE 15

Aspect ratio 11.666. Taper ratio 0.50 Mean chord 21.4cm.



Washout 0 deg. Mass 2.3. . Kg. Wing loading 4.3. Kg/sq.m.

TABLE 14 PERFORMANCE POLAR FOR WING NUMBER .

H. Quabeck 1.5/9 Plain Wing loading = 4.30 kg/sq.m.
Span = 2.50 metres. Aspect ratio = 11.66..
Root Chord = 26.52 cm. Mid Chord =22.97 cm. Taper ratio = 0.5. .

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	2.093	12.542
18.56	0.909	20.431
15.16	0.597	25.405
13.13	0.494	26.571
11.74	0.443	26.515
10.72	0.400	26.767
9.92	0.398 *	24.908 *
9.28	0.415	22.362
8.75	0.446	19.636
8.30	0.929	8.935

****

advantage whatsoever in trying to exceed this figure for an F3B sailplane of about 3 metres span. At values of A > 20, Reynolds numbers fall to such an extent that slow speed performance does not improve further.

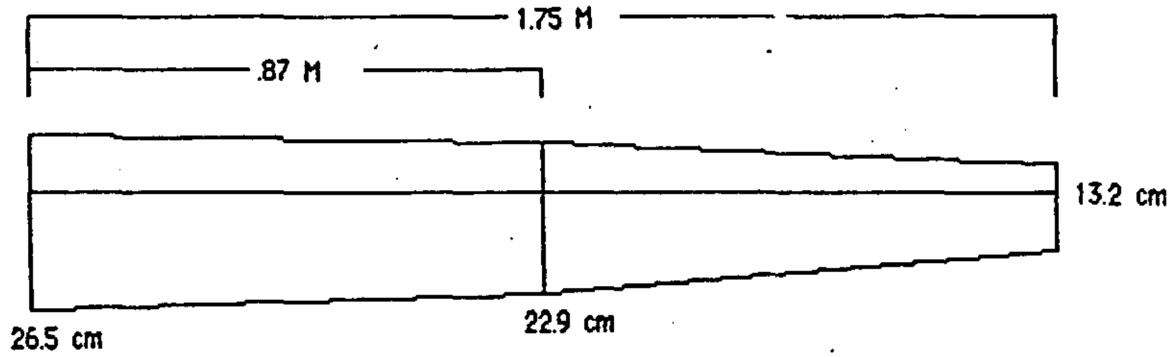
As Figure 13 shows, a low aspect ratio of only 8 gives a very considerable advantage to the sailplane at high speeds, if the wing loading is the same. There is a loss of low speed, soaring ability, but referring back again to Table 3, in fact this is not very serious. Compared with the original Marjali, which soars well enough for Task (A) in all but the weakest lift, the difference is 3.4 cm/sec at the same wing loading (but not, of course, anything like the same total mass). The A = 8 wing achieves its best glide ratio of 28 at the very respectable airspeed of 15 m/sec (54 km/h).

Results of very similar kind have appeared before and aeromodellers have found them difficult to believe.[13] Nobody, so far, seems to have built an F3B sailplane with such a configuration. The point that should be appreciated is that, if the wing loading is held constant, as in this case, the low aspect ratio sailplane becomes very heavy because it has a large wing area. So long as aerodynamic drag is in proportion, the main determinant of speed in a straight glide of a given angle is the total mass of the aircraft. A 'lead sled'

[13] See, e.g., M. Simons, The two-metre sailplane, in Soartech 3, 1984, obtainable from H. Stokely, (address above). The author's own 'Martinet' and the 'Searcher 2M' sailplane by Mark Kummerow built to test the theory, have demonstrated its essential accuracy but the appearance of these (rather unfashionable) model sailplanes seems to have coincided with demise of the 2 metre contest class. It should also be noted that studies of full-sized 15 metre span sailplane performance by Frank Irving, published in the OSTIV section of Swiss Aero Revue 5 & 6, 1972 and in his paper presented to the AIAA/MIT Symposium on Low Speed and Motorless Flight in 1972, indicated very much the same relationships. If the span of the sailplane is restricted to some figure by class rules, or by other factors, and if weak lift soaring ability is not critically important, the low aspect ratio, heavily ballasted, sailplane is superior. The present author in an article in Australian Gliding Yearbook, using the Sigma program, demonstrated the same points. The trouble is, a tractor would be required to move such an aircraft on the ground, and a very powerful tug aircraft to launch it.

SKETCH OF THE PLANFORM FOR WING 4 EXAMPLE 4 Date 27/1/86 FIGURE 16

Aspect ratio 16.333 Taper ratio 0.50 Mean chord 21.4cm.



Washout 0 deg. Mass 3.228 Kg. Wing loading 4.3 Kg/sq.m.

TABLE 15 PERFORMANCE POLAR FOR WING NUMBER

H. Quabeck 1.5/9 Plain Wing loading = 4.30 kg/sq.m.
Span = 3.50 metres. Aspect ratio = 16.333
Root Chord = 26.52 cm. Mid Chord =22.97 cm. Taper ratio = 0.5.

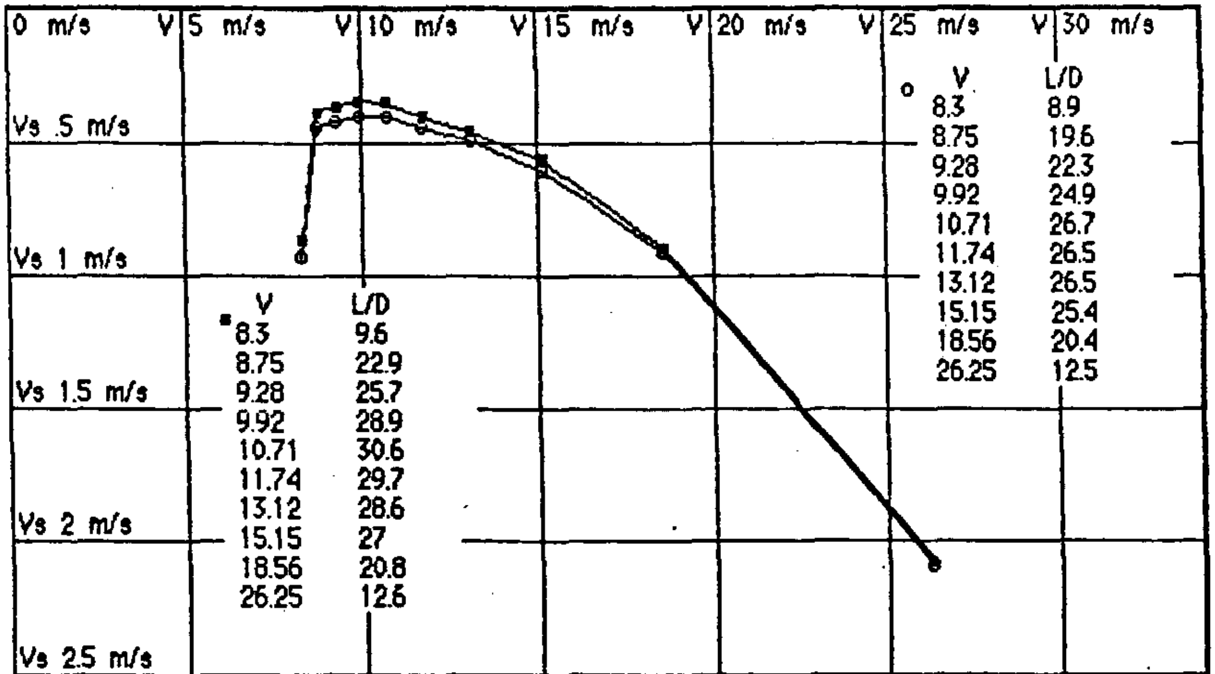
Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	2.072	12.669
18.56	0.891	20.833
15.16	0.560	27.089
13.13	0.459	28.612
11.74	0.395	29.708
10.72	0.349	30.683 *
9.92	0.342 *	28.985
9.28	0.361	25.735
8.75	0.381	22.962
8.30	0.863	9.623

****

on a slippery slope, will slide faster than a light one on the same slope, if the coefficient of drag is comparable. This is why full-sized sailplanes carry ballast, but while they need to slow down and turn in thermals, they do not, as a rule, have to make repeated 180 degree reversals of direction while maintaining their very high forward velocities. To achieve the performance shown in straight gliding flight, the A = 8 wing of Figure 13 & Table 10, must carry <u>4.8 kg total mass</u>. This approaches the maximum FAI limit of 5 kg. On the other hand, the A = 20 sailplane would have to be built down to <u>less than 2 kg</u>, to achieve the same wing loading. It would fly much slower down the same glide path.

In the speed task, the heavy, low aspect ratio model would probably prove very difficult to manage. It would require a very powerful winch, probably outside the allowed limits of motor power and line strength, to launch it to a height comparable with the lighter aircraft. It would undoubtedly fly very fast in the straight portions of the task, but would use a lot of space in the turns, so probably sacrificing much, or all, its advantages.

Yet more remains to be said. In Figure 14, and Tables 11 to 13, the three of Figures 10 - 12, are compared at the same total mass of 2.5 kg, which is a reasonable figure. It is now evident that the low aspect ratio wing is markedly superior at low speeds, because of its low wing loading, while the high aspect ratio example, now at a higher loading, does better in fast flight. The low aspect ratio aircraft could be flown at its lightest for the duration task, and would be ballasted to some degree for the other tasks, in which its advantages would again be discovered. In such a capacious wing, of course, there would be ample space for strong, light spars and plenty of



EXAMPLE 4 ∘B = 2.50m A.R. = 11.6M = 2.3 kg W/S = 4.3 kg/sq.m.

▪B = 3.50m A.R. = 16.3M = 3.22 k W/S = 4.3 kg/sq.m.

FIGURE 17

ballast but the sailplane need not be ballasted right up to the F.A.I. limit. It is safe to conclude that the low aspect ratio sailplane is more adaptable to the very different conditions imposed by the three-task type of championship. It can carry large amounts of ballast, but may be built very lightly and so be capable of soaring without ballast in very weak lift. It remains to be found out, by experience and perhaps by future calculations, how much ballast the low aspect ratio sailplane can afford to carry before losing in the turns everything it gains in the straights.

Span effects

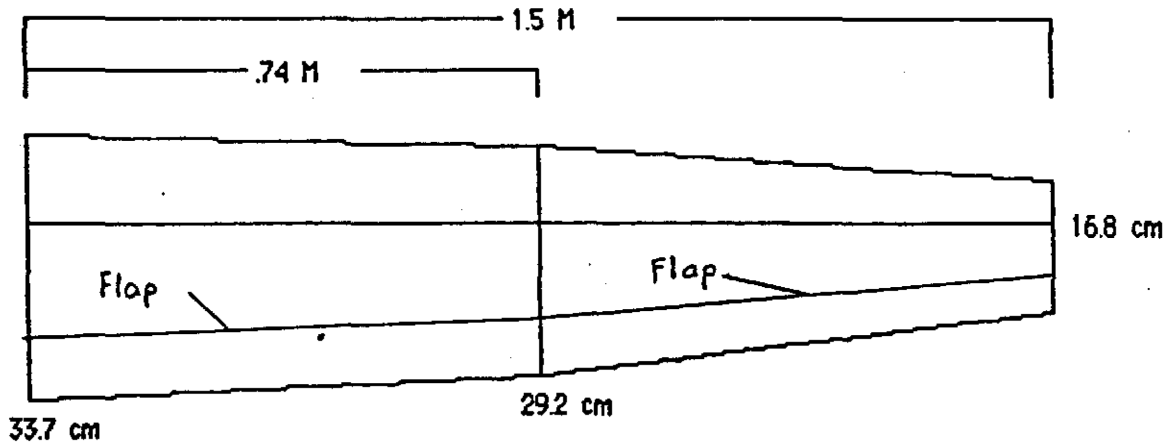
Figures 15 - 17 and Tables 14 & 15 show the effect of varying the wing span while retaining the same wing area. The aspect ratio varies from 11.66 for a span of 2.5 m, to 16.33 for the 3.5 m span, wing loading being held constant again at 4.3 kg/sq m. The improvement at low speeds with the larger span, although quite noticeable, is not worth worrying about so long as the maximum duration allowed is only six minutes. Clearly, there is practically no advantage in extending the span of the F3B model beyond the present typical figure of about 3 metres. The larger span shows no real gain at all at high speeds but the best glide figure of 30.6 :1 for the 3.5 metre span wing is at least worth remarking.

Flaps

For the sake of completeness, Figures 18 & 19 and Tables 16 & 17 are included to show how simple camber changing flaps may affect things. The example planform in this case has an aspect ratio of 11, which is probably a good compromise for a new design to put the low aspect ratio theory to

SKETCH OF THE PLANFORM FOR WING 1 EXAMPLE 5 Date 27/1/86 FIGURE 18

Aspect ratio 11 Taper ratio 0.50 Mean chord 27.3cm.



Washout 0 deg. Mass 3.521682 Kg. Wing loading 4.30Kg/sq.m.

TABLE 16 PERFORMANCE POLAR FOR WING NUMBER 1

H. Quabeck 1.5/9 Flap +5 Wing loading = 4.3 Kg/sq.m.
Span = 3.00 metres. Aspect ratio = 11
Root Chord = 33.75 cm. Mid Chord =29.25 cm. Taper ratio = 0.5

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	3.047	8.616
18.56	1.213	15.303
15.16	0.873	17.353
13.13	0.634	20.715
11.74	0.557	21.073
10.72	0.450	23.819
9.92	0.394	25.190 *
9.28	0.375 *	24.756
8.75	0.390	22.453
8.30	0.410	20.231
7.92	0.654	12.101

****

something of a practical test. Several models at Waikerie had A.R.s about this figure. It is important to note that for flaps on any sailplane wing to be an aid to performance, they must extend across the whole span, i.e., the ailerons must move together with the flaps. If this is not done, the vortices forming at the outer ends of the flaps usually increase the drag so much that there is no net benefit from the flaps at all. In fact, with this kind of aerofoil section and contest, flaps are probably of value only as landing and perhaps launching aids.

The HQ 1.5/9 aerofoil is only 1.5% cambered. Flaps in the reflexed position, calculations show, actually spoil the glide polar at high speeds. They are of more use in soaring but it has already been argued that for a six minute flight, small improvements of minimum sinking rate are hardly necessary. Figure 19 shows that the flaps do give a small improvement at the low speed end of the velocity scale, reducing the stalling speed and the minimum rate of sink but it is hard to imagine any occasion when this would really make a difference to a sailplane in a championship under the present rules.

Conclusion

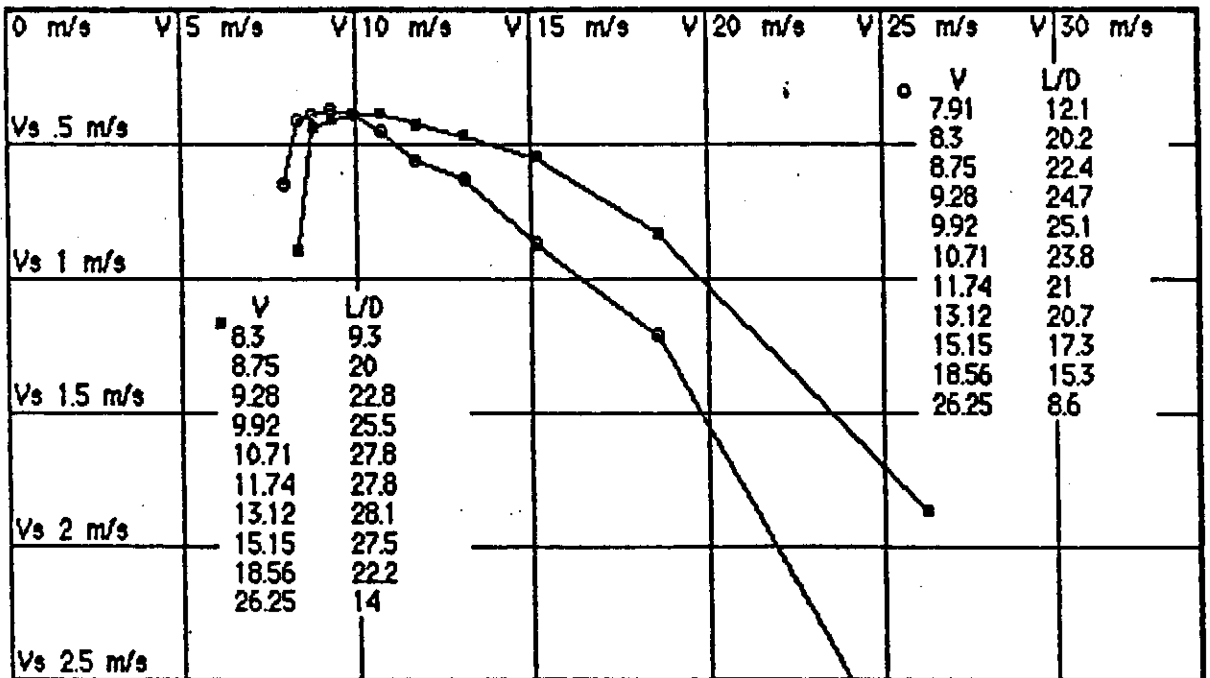
When all theoretical work is done, the points emerging most clearly are that in the present type of F3B multi-task contest, after pilot skill, the power of the initial launch is decisive. The sailplane needs to be reasonably efficient and above all strong. If two experienced contestants are equal in skill, the one getting the highest and fastest launch will win the championship. If the launching rules are changed in some way so that sheer energy input at the beginning of each flight becomes less important, it seems to the present

17 PERFORMANCE POLAR FOR WING NUMBER 2

H. Quabeck 1.5/9 Wing loading = 4.30 Kg/sq.m.
Span = 3.00 metres. Aspect ratio = 11
Root Chord = 33.75 cm. Mid Chord =29.25 cm. Taper ratio = 0.5

Velocity Metres/Sec	Sink M/sec	L/D Ratio
26.25	1.868	14.057
18.56	0.833	22.286
15.16	0.550	27.565
13.13	0.466	28.160 *
11.74	0.422	27.843
10.72	0.385 *	27.824
9.92	0.389	25.516
9.28	0.405	22.889
8.75	0.436	20.058
8.30	0.892	9.305

****



EXAMPLE 5 ∘ B = 3.00m A.R. = 11 M = 3.52 kg Flap +5°

▪ B = 3.00m A.R. = 11 M = 3.52 kg Flap 0°

FIGURE 19

writer that a more interesting sport would result. Too much emphasis has been placed upon sheer speed. The steering of rather heavy projectiles down steep glide slopes at 130 km/h, even with turns to be negotiated, has a rather limited appeal.

It seems necessary to extend the duration task to make this a better discriminator of soaring ability. A nine minute working time could be retained or extended to ten or twelve minutes with little difficulty for contest administration. Within this time 'slot', a duration of 8 minutes could be flown, with the usual allowance for preparation before launching. Genuine soaring would then be necessary on almost all occasions.

Perhaps in the long run, the most interesting kind of contest for radio controlled sailplanes would involve distance flying or racing over extended closed circuit courses. Given some changes to the rules along these lines, aerodynamic analysis will again suggest appropriate directions for development.

Appendix 1

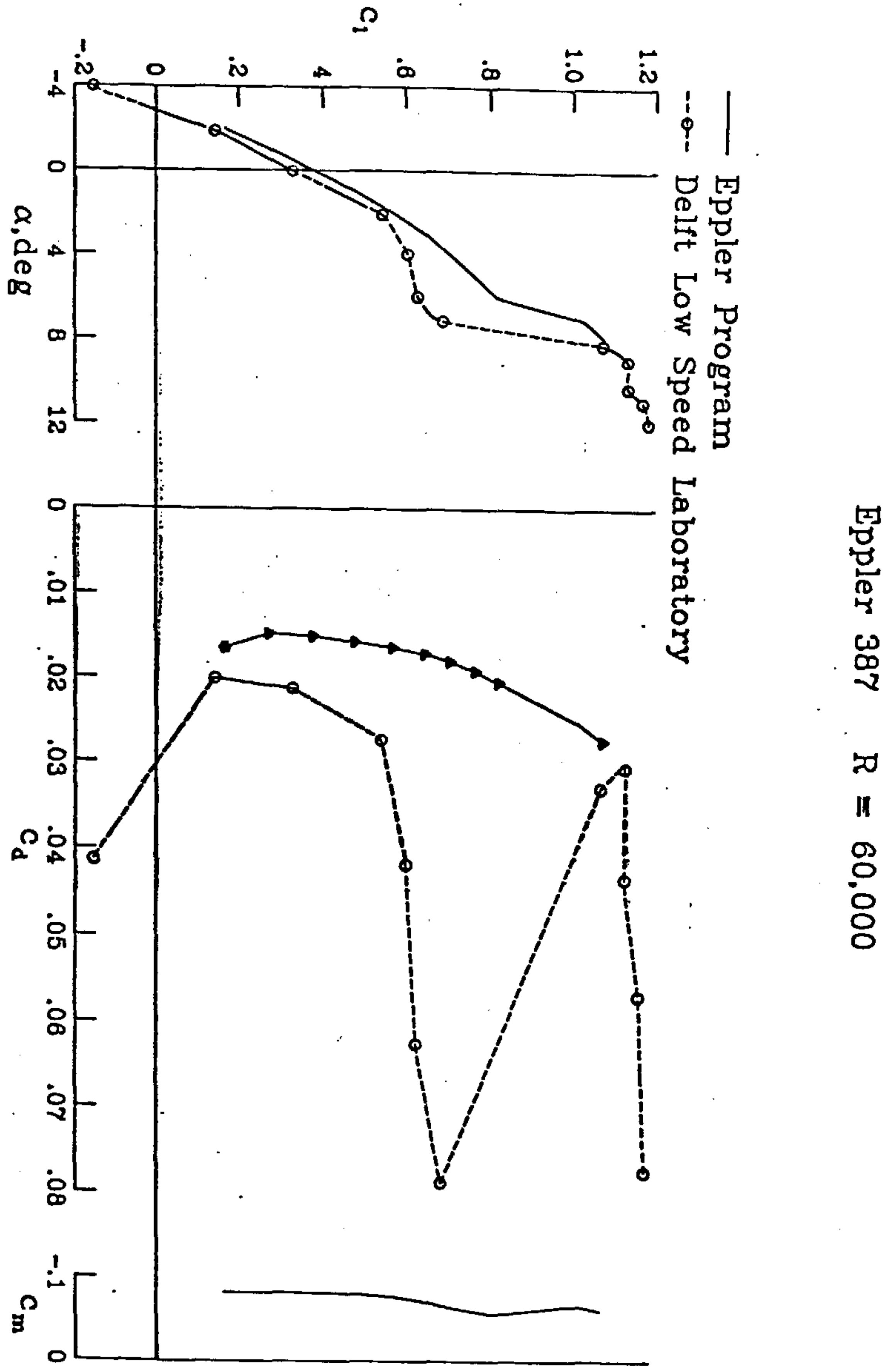
Comparison of theory and experiment

for the Eppler 387 Aérofoil

at Re numbers 60000,100000 and 20000.

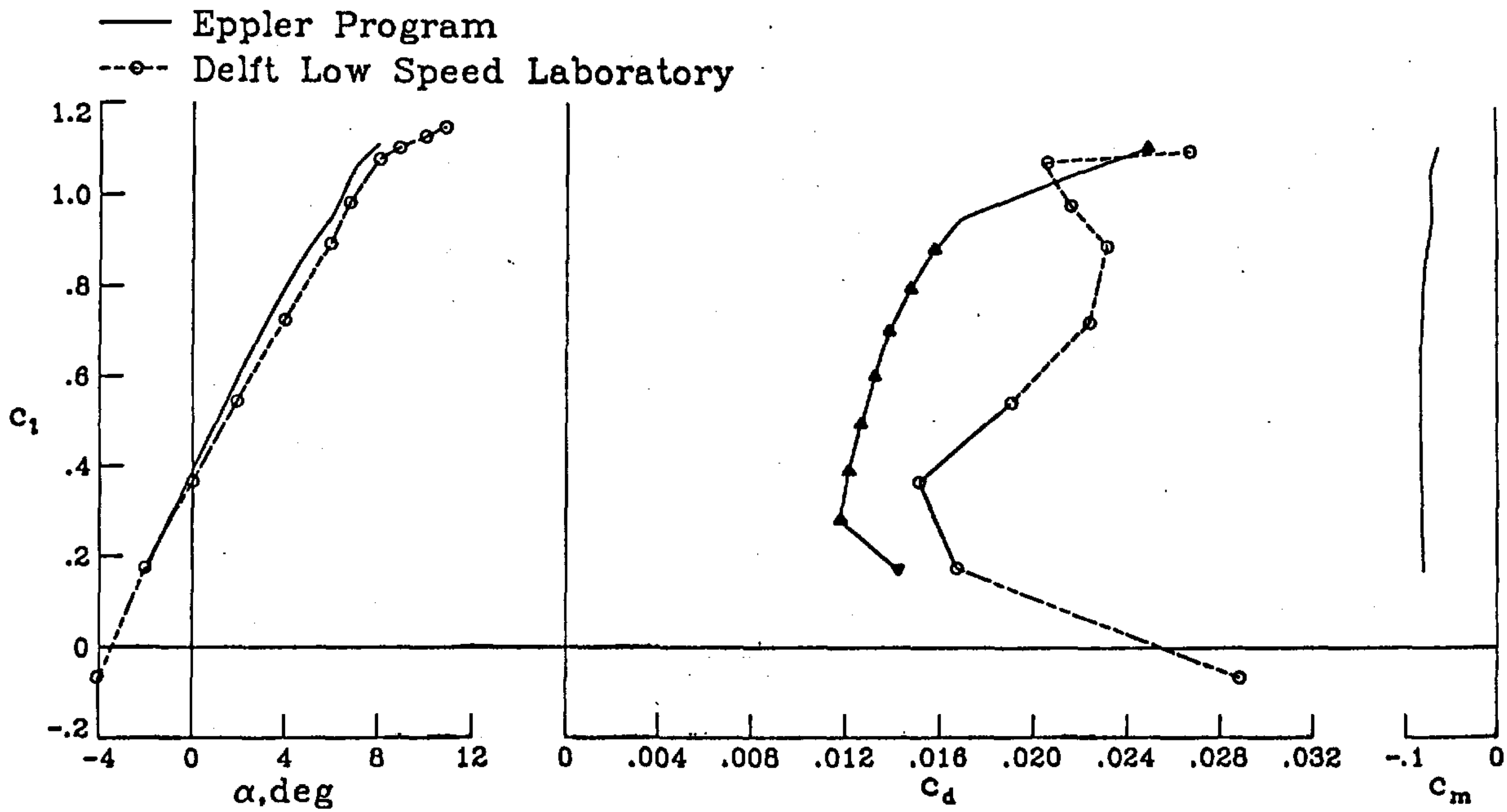
(Supplied by Dan Somers, NASA, Langley).

Measurements by the Delft Low Speed Laboratory.

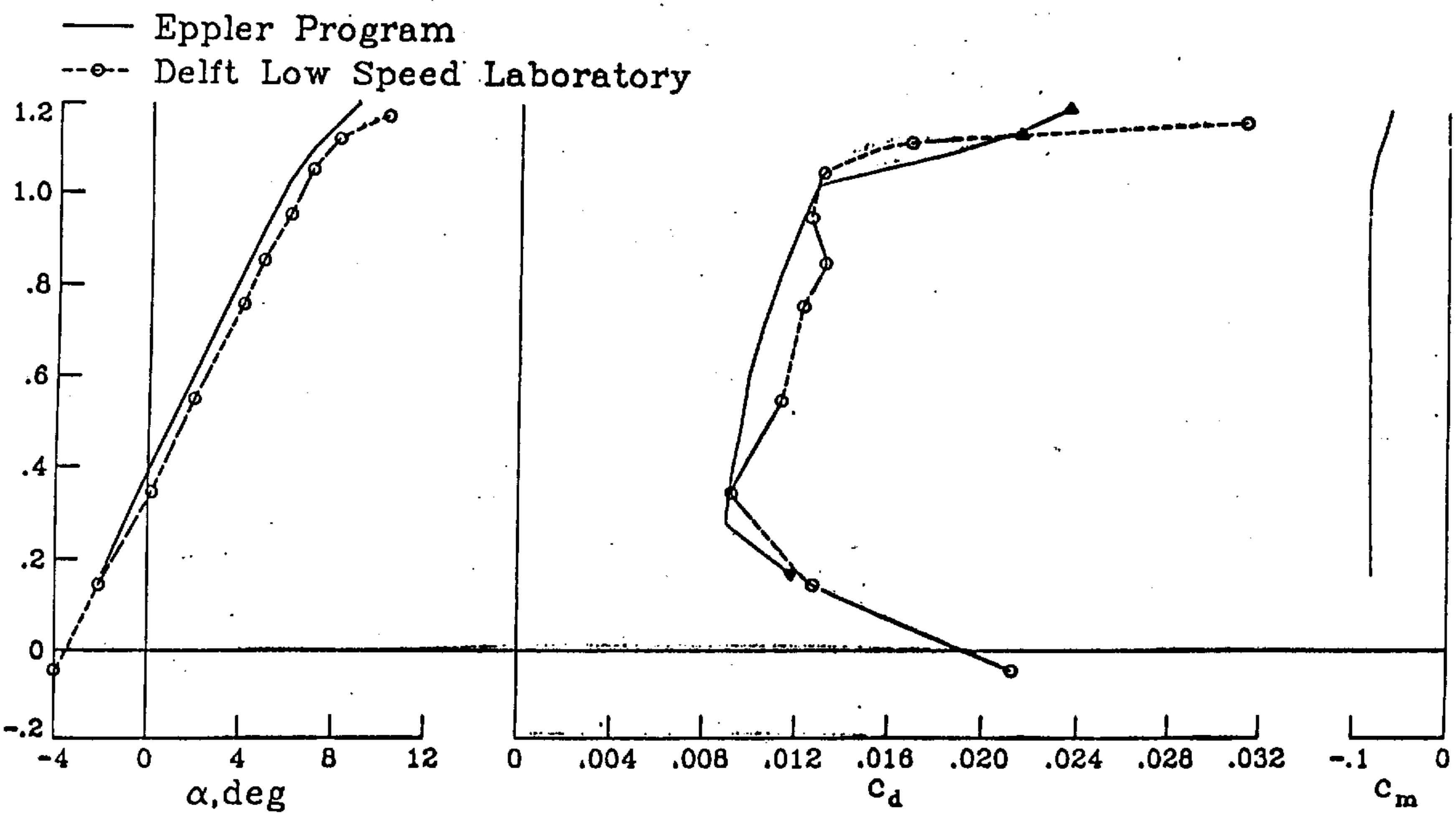

Eppler 387 R = 60,000
Eppler Program
Delft Low Speed Laboratory
C_l
-.2
0
.2
.4
.6
.8
1.0
1.2
-4
0
4
8
12
α,deg
0
.01
.02
.03
.04
.05
.06
.07
.08
C_d
-.1
0
C_m

COMPARISON OF THEORY AND EXPERIMENT

Eppler 387   R = 100,000



Eppler 387   R = 200,000

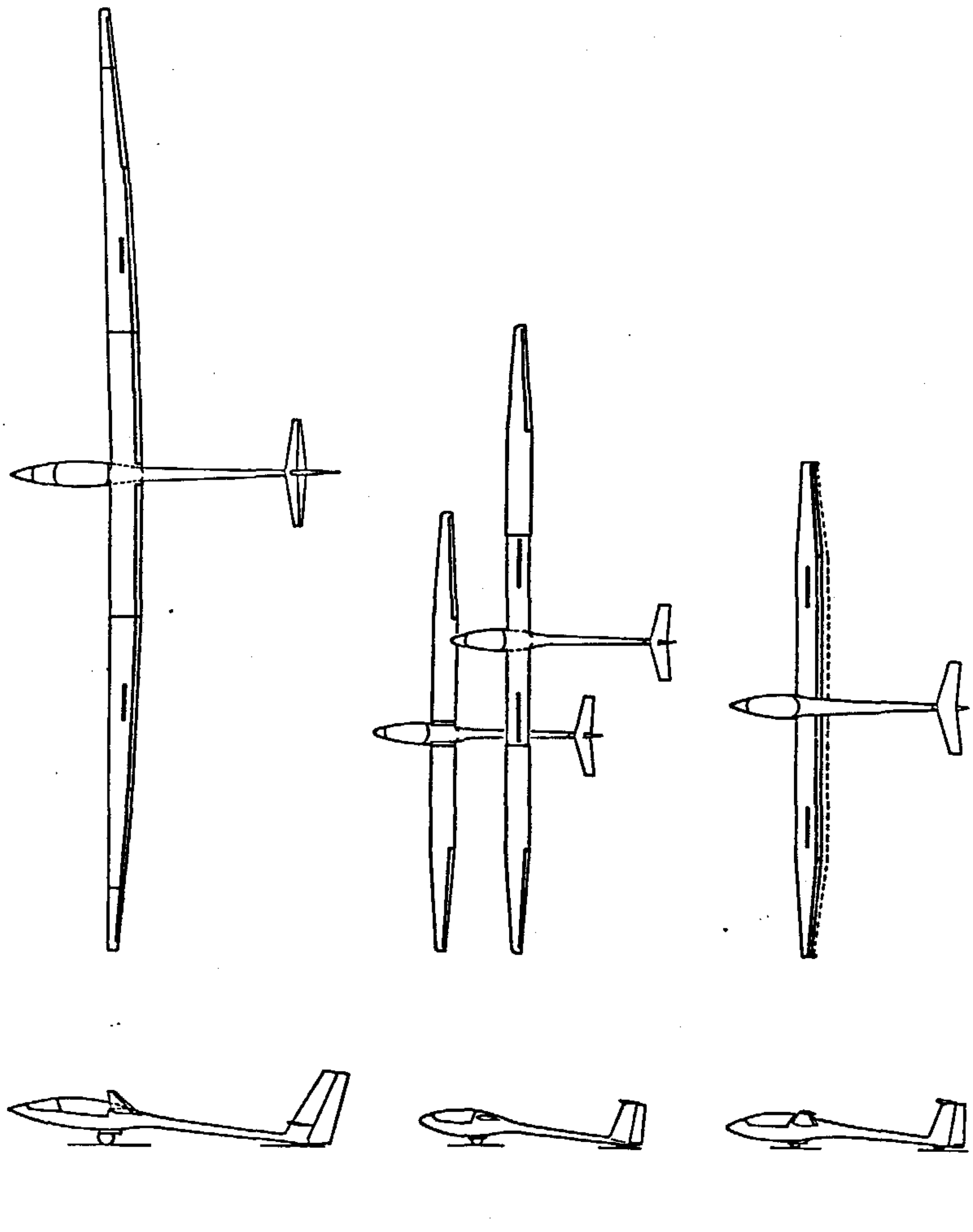


STATIC LONGITUDINAL STABILITY

Much of what we do in engineering today is geared to computer analysis. Model designers and builders are not always equipped with computers, or even if they have one, often don't have the programs necessary to do various analyses. For these individuals, Ferdi Gale' comes to the rescue with a purely graphical method for analyzing the various parameters that determine static longitudinal stability - or - "where to put the balance point", and "how well will it handle".

Written in textbook style completeness, this article will provide more than a tool for stability analysis. Those who pursue it in its entirety will gain insight into the entire subject as well as a technique for its computation.

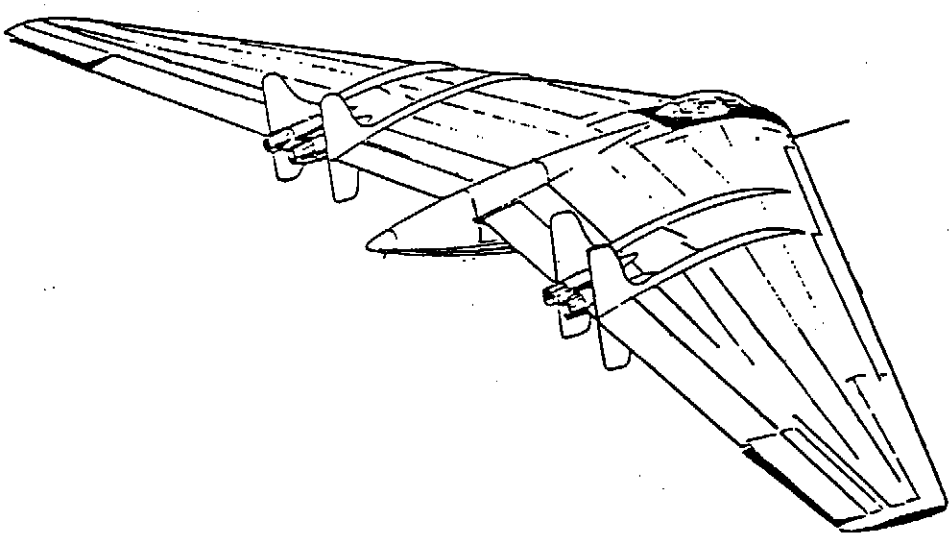
Ferdi is a senior model builder - flyer - designer (as well as a degreed engineer) from Italy who has published much on the whole range of model flight. His excellent English language books on the aerodynamics of RC sailplanes and flying wings are available from B^2 Streamlines, P.O. Box 976, Olalla, WA 98359-0976 U.S.A..

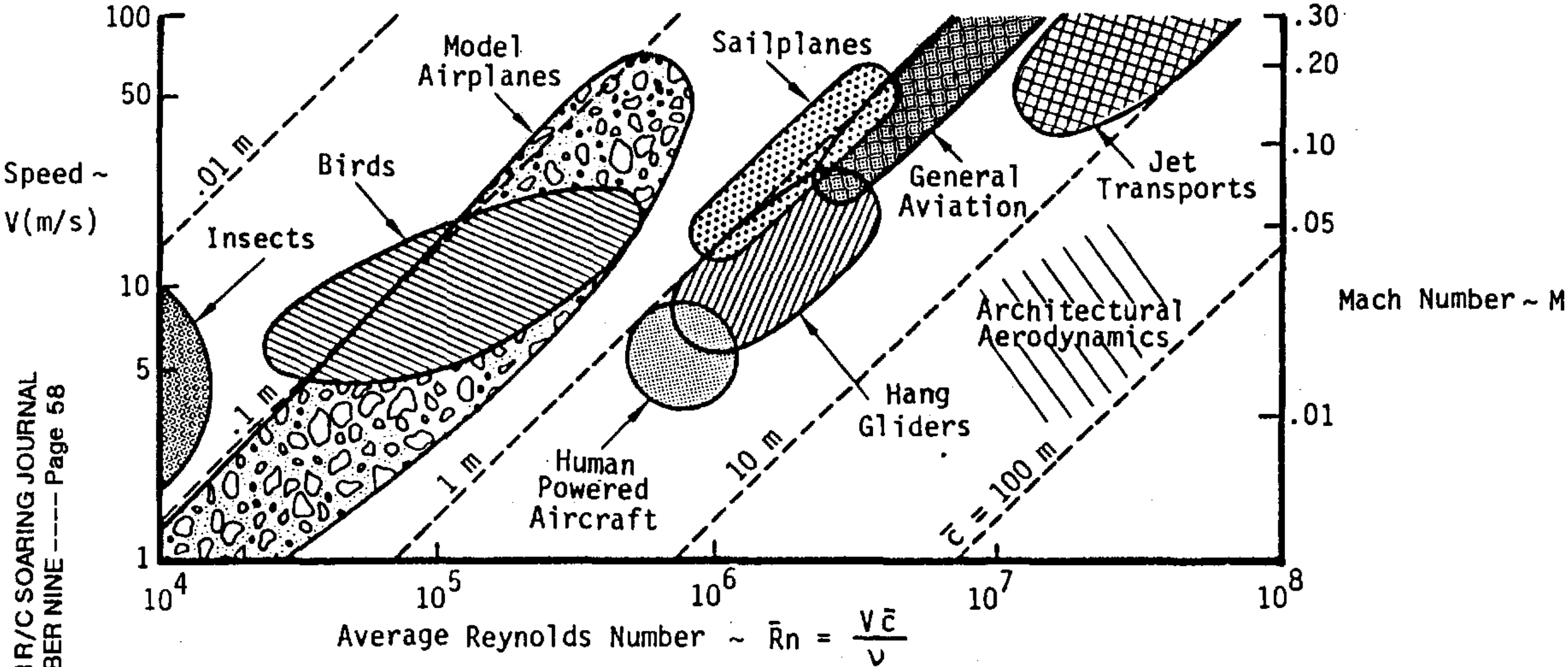


STATIC LONGITUDINAL STABILITY WITH THE "CROCCO" METHOD

Ferdinando (Ferdi) Galé,
(Associazione Aeromodellisti Milanesi,
Milan, Italy)

May 1992





Speed ~ V(m/s)
100
50
10
5
1
.01 m
.1 m
1 m
10 m
$\bar{c}$ = 100 m
Model Airplanes
Birds
Insects
Sailplanes
General Aviation
Jet Transports
Human Powered Aircraft
Hang Gliders
Architectural Aerodynamics
.30
.20
.10
.05
.01
Mach Number ~ M
10^4
10^5
10^6
10^7
10^8
Average Reynolds Number ~ $\bar{R}n = \frac{V\bar{c}}{\nu}$

In order to fly correctly, any aerodyne (that is, any flying machine depending on dynamic lift, such as aeroplanes, sailplanes, helicopters, autogiros, gliders, ultralights) must possess a certain static longitudinal stability : otherwise the flight - as it is commonly meant - is not possible.

In order to avoid misinterpretations, it must be stated that the static longitudinal stability (briefly, SLS), is exactly comparable to that one defined "stick fixed stability" on "full size" aeroplanes.

On the latter ones, in order to verify how self-righting the aerodyne is, the stick is pushed forward, about half way, until the nose is well downwards, then it is pulled back to its initial position, watching carefully ther behaviour of the craft.

Said maneuvre is repeated, always starting from a stabilized horizontal speed, pulling the stick backwards half way, and then pushing it to its original position , where it is firmly kept. If the aeroplane is statically stable, after some oscillations (because of the inertia), it goes back to its original attitude.

Exactly the same evaluation can be made with radioguided sailplanes, caring that the maneuvre starts when the flight is perfectly horizontal.

If the sailplane does not stabilise quickly, the centre of gravity may not be correctly placed in respect to the aerodynamic center of the complete craft, (too much advanced, too much in the rear), or the stabilator is too small, or its incidence is not adequate, or the lever arm between wing and stabilator is too short or too long.

Summarising, SLS concerns only the initial phase of the displacement while the dynamic longitudinal stability (briefly, DLS) involves the subsequent phases of the flight ; as far as radioguided sailplanes are concerned, SLS describes the behaviour with the stick in neutral position; DLS, on the contrary, concerns the behaviour of the sailplane when the stick is moved, in order to execute maneuvres, then taken back to neutral.

By convention, the definitions of SLS and of DLS can be summarised as follows : (FIG. 1) :

SLS (initial)	OSCILLATION (phugoid)	DLS (subsequent)
(1) Stable	Simple leveling	Very stable
(2) Stable	Damped	Stable
(3) Stable	Continuous	Neutral
(4) Unstable	Simple divergence	Unstable
(5) Neutral	None	Neutral
(6) Stable	Divergence	Unstable

Conditions (1), (2), (3) and (6) are statically stable, because they tend to go back to level flight, although conditions (3) and (6) will never make it. The time between an oscillation and the following one may range from few seconds to 60 seconds for aeroplanes, and the damping of the phugoid, it it happens, is completed in two or three full oscillations.

It may happen that an aerodyne is so stable and slow in recovering, that the damping is performed in one cycle only, or in an half cycle, but in a very long time, up to 60 seconds.

A similar behaviour is found, among flying models, in some radioguided sailplanes, which have derived from free flight gliders, usually characterised by a long and slim tubular fuselage.

If an aeroplane requires five cycle to complete the damping of the phugoid, it is classified as little stable, even if the damping time is much shorter than the above mentioned example.

It may also happen that the oscillations of an aeroplane are damped in such a long time, as to not be considered dangerous, or difficult to control.

Conditions (1) and (2) are recommendable for flying models (both free flight and radioguided), with damping times ranging from 3 to 6 seconds; in other words, without spoiling the maneuvrability, the oscillations, in addition to a small amplitude, must be dampened in a very short time, thus approaching the condition (1), for all practical purposes.

In any aeroplane of conventional design, the longitudinal stabilisation (static and dynamic) is achieved by means of the the so called longitudinal dihedral, (or decalage, as it was defined during the early days of aviation). In practice, the horizontal stabilizer has always a lower incidence than the wing. It may happen that in certain fast and/or aerobatic sailplanes, wing and stabilator have the same incidence, (usually 0°- 0°) ; in this case there is no geometrical longitudinale dihedral

as such, but the effective angle of attack of the stabilator is always lower than the geometric one, because of the wing downwash.

As a rule, the following assumptions are made in the study of the static longitudinal stability of sailplanes (both "full size" and radioguided):

1) - The sailplane is flying on a straight path at constant speed;

2) - The glide angle is very small (that is the flight is almost horizontal), so that one can reasonably assume that the lift is equal to the weight;

3) - The structure of the sailplane is extremely rigid (that is, no flexing or twisting of any kind may a happen);

4) - The air, in which the sailplane is flying, is incompressible, so that all the aerodynamic coefficients depend only upon the geometric configuration of the craft (wing, fuselage, empennages);

5) - Variations of the aerodynamic coefficients, caused by variations of the REYNOLDS number, Re, are disregarded.

By assuming, in first instance, that lift and weight are both applied on the centre of gravity, the condition of static longitudinal stability is verified when all the three following conditions are realised :

1) - The weight, W, is equal to the lift, L;

2) - The thrust is equal to the drag ;

3) - The overall moment (about the centre of gravity), Mg, of all the forces acting the sailplane , is nil. (FIG. 2)

In these considerations, L is the overall lift of the sailplane (wing, fuselage, stabilator), and not only the wing lift.

Having assumed that the sailplane is flying at constant speed, the above mentioned conditions are nothing else than the application of NEWTON's first law, that is :

$$L = W \qquad (1)$$

$$Mg = 0 \qquad (2)$$

where :

L = overall lift of the sailplane;

W = total weight of the sailplane;

Mg = algebric summation of all the moments about the centre of gravity, CG.

If these equations are divided, respectively by $1/2 \cdot \rho \cdot V^2 S$ and by $1/2 \cdot \rho \cdot V^2 \cdot S \cdot \bar{c}$, their coefficients are obtained :

$$CL = \frac{L}{\frac{1}{2} \cdot \rho \cdot V^2 \cdot S} = \frac{W}{\frac{1}{2} \cdot \rho \cdot V^2 \cdot S} \qquad (3)$$

$$CMg = \frac{Mg}{\frac{1}{2} \cdot \rho \cdot V^2 \cdot S \cdot \bar{c}} = 0 \qquad (4)$$

where :

CL = lift coefficient of the complete sailplane;

CMg= moment coefficient (about the centre of gravity) of the complete sailplane.

Generally speaking, for every sailplane there is only one CL value (marked with A in FIG. 3) for which CMg is equal to zero : by varying CL, also the value of CMg changes. It may have two series of values when the incidence is changed : a positive one (destabilizing) and a negative one (stabilizing).

The line I of the above mentioned FIG. 3 is typical of a stable sailplane : if CL (that is the incidence $\alpha°$) is increased from the value A, at which the conditions (3) and (4) are verified, to the value B, CMg gets the value B-C (negative).

On the contrary, the line II typifies an unstable glider; when CL is increased from the value A to the value B, CMg has a positive value (B-C').

From a practical point of view, when a stable sailplane is hit by a gust, the resulting increase of incidence is follewed by a speed reduction, so that the condition (1) remains valid; additionally the increment of CMg has a negative sign, and tends to lower the sailplane nose, thus stabilising its trajectory.

These elementary considerations must be elaborated further, since the longitudinal stability is very important; in order to do this, the sailplane is referred to two perpendicular axes, X-X and Z-Z. The axis X-X is the flight direction (straight and horizontal) : usually it coincides (but not necessarily) with the fuselage reference line.

The axis Z-Z, perpendicualr to X-X, passes through the leading edge of the average aerodynamic chord, $\bar{c}$, which represents the whole wing at all effects; the aerodynamic centre (focus) of the wing is conventionally located at 25% $\bar{c}$ (from the nose). FIG. 4 shows the positions of the centre of gravity and of the focus.

The fact that, for certain airfoils, the aerodynamic centre is not exactly located at .25 $\bar{c}$ does not invalidate the following reasonings, as indicated in the vast bibliography listed at the end of this book.

One should note that the isolated wing appears to be unstable, since the centre of gravity is behind the focus; in respect to the latter, the longitudinal coordinate of the centre of gravity, CG (measured on the X-X axis) is thus equal to Xg - Xa.

In order to perfectly understand the problem of the static longitu=dinal stability, an additional theoretical step must be made : the sum of all the moments acting on the centre of gravity (directly and indirectly) must be equal to zero, so that the overall moment about the centre of gravity, Mg is nil (equation 2). With the notations of FIG. 5, this means :

$$Mg = Lw \cdot [Xg - Xa] + [Dw \cdot Zg] + Mow + Mf - [Lt \cdot ltg] \qquad (5)$$

where :

Lw = wing lift;

Dw = wing drag;

Lt = stabilator lift;

Mow = wing moment about the leading edge of c (nose-up);

Mf = pulling-up moment due to fuselage;

Xg - Xa = lift lever arm about the centre of gravity;

Zg = wing drag lever arm about the centre of gravity;

ltg = stabilator lift lever arm about the centre of gravity.

It has been mentioned, in previous chapters, that forces and moments can be expressed by means of their adimensional coefficients; that is :

$$Lw = CLw \cdot S \cdot q \qquad (6)$$

$$Dw = CDw \cdot S \cdot q \qquad (7)$$

$$Mow = CMow \cdot S \cdot q \cdot \bar{c} \qquad (8)$$

$$Mf = CMf \cdot S \cdot q \cdot \bar{c} \qquad (9)$$

$$Lt = CLt \cdot st \cdot q \qquad (10)$$

where :

S = wing area;

q = dynamic pressure = $1/2 \cdot \rho \cdot V^2$;

$\bar{c}$ = average wing chord;

By dividing the equation (5) by the quantity $S \cdot q \cdot \bar{c}$ the equation of equilibrium is obtained, in terms of adimensional coefficients :

$$Mg/S \cdot q \cdot \bar{c} = CMg = CLw \cdot \left[\frac{Xg - Xa}{\bar{c}}\right] + CDw \cdot \left[\frac{Zg}{\bar{c}}\right] + + CMow + CMf - CLt \left[\frac{st}{S} \cdot \frac{ltg}{\bar{c}}\right] = 0 \qquad (11)$$

The equation (11) shows that the static longitudinal stability (SLS) depends upon a variety of factors, which are worthwhile to examine separately from each other.

As it has been said, the condition of SLS simply requires that, for a given variation of the angle of attack,$\alpha°$, a correspondent pitching moment Mg is produced, which tends to quickly bring back the sailplane to its initial angle of attack.

Having assumed, by convention, that the nose-up pitching moments are positive, the stability condition is expressed by the following simple relations :

$$Mg/\alpha w < 0 \qquad (12)$$

$$CMg/\alpha w < 0 \qquad (13)$$

The latter is in terms of adimensional coefficients.

If reference is made (as usually) to the wing lift coefficient,CLw, instead of the angle of attack,$\alpha w°$, the stability relation becomes

$$CMg/CLw < 0 \qquad (14)$$

since

$$CLw = aw \cdot \alpha° w \qquad (15)$$

where, as already mentioned,

aw = wing lift vs. incidence slope ; such a curve is practically a straight line for almost all airfoils, up to $\alpha = 15°$ approximately;

$\alpha° w$ = wing incidence.

It is worth noting, that, strictly from a matemathical point of view, the numerical value of the ratio CMg/CLw (negative) is the static margin, which will be dealt with later on.

High mathematics (derivatives, integrals, etc.) are required for a detailed analytical examination of the equation (11); having assumed that written for the average aeromodeller, who is not supposed to be familiar with that knowledge, only some practical considerations will be made.

Wing contribution - The wing contributes to the static longitudinal stability with two terms : the first one, CLw·[Xg - Xa]/ $\overline{c}$ is named "lift term", as it is -by immediate intuition - strictly dependent upon the wing generated lift and its lever arm about the centre of gravity, CG.

In other words, the more lifting is the wing, the stronger must be the stabilizing action of the horizontal plane.

The second term, CDw [Zg/$\overline{c}$], called "drag term" can be neglected, for all considerations regarding SLS only when the value Zg (positive or negative) is very small (that is from -0.05·$\overline{c}$ to 0.10·$\overline{c}$).

Seldom the drag term has to be considered for radioguided sailplanes, quite differently from other types of flying models with parasol or fin mounted wing. The influence of the drag term becomes relevant when the tail volume coefficient, TVC, is very small.

Both terms (lift and drag) are destabilizing and must be compensated for by the action of the stabilator.

In this respect, a consideration is necessary, which is not of immediate perception : aeromodellers are sometimes inclined to believe that a fin mounted wing makes the craft more stable. In reality, exactly the contrary is true : the higher the wing is mounted above the centre of gravity, the greater is its negative effect on the SLS.

A high wing (that is a large value of Zg) is desirable for other reasons (lateral stability, drag, interference, etc.).

The rational design of a sailplane is a compromise of different contrasting requirements, as mentioned in the preface ; the wing is just the first example.

Fuselage contribution - If the fuselage were a rotational solid body, perfectly streamlined, with its generating line parallel to the flight direction X-X, it would produce only drag, with its relative moment about the centre of gravity, CG, if this is not placed on X-X (as it is usually).

In reality all fuselages deviate from this ideal configuration, specially those derived from "full size" designs, which have a sort of pod in the front part, where the pilot is located.

It has been demonstrated theoretically, and verified with wind tunnel tests, that every fuselage generates drag (very high) and lift (definitely marginal), in a way which can be grossly compared to an airfoil : typically the curve of the resulting fuselage moment coefficient,CMf (versus the fuselage incidence α°f) is almost a straight line up to about 15°.

In other words, the fuselage has a moment, Mf, and its relative coefficient, CMf, which varies, as the wing, with the incidence.

Usually, the angle of zero lift of a fuselage, is positive in respect with the angle of zero moment (FIG. 6); the variation of CMf (versus the angle α°f) is positive for all fuselages of conventional design.

Therefore the fuselage contribution is highly destabilizing.

The practical effect, as shown in FIG. 7, is that the aerodynamic centre (focus) of the wing plus fuselage combination (usually called SLT = sailplane less tail) is further displaced towards the nose of the craft.

In order to achieve SLS conditions, it is necessary that the focus of the complete sailplane, FC is brought behind the centre of gravity, CG, with its abscissa equal to Xc.

The distance between the centre of gravity, CG, and the aerodynamic centre of the complete sailplane, FC, is - by definition - the static margin.

Such a distance is equal to Xc - Xg.

The static margin is commonly designated SM.

When the centre of gravity, CG, and the aerodynamic centre, FC, coincide, the point is called neutral point, NP. In most technical literature the term neutral point is used for the complete aerodyne, while the term aerodynamic centre (or focus) is adopted for the various parts (wing,empen= nages).

Stabilator contribution - The stabilator must generate a moment, Mt , having intensity and sign such as to nullify (ad exceed) all the moments acting on the centre of gravity, insofar described. Such a moment is the product of the stabilator lift, Lt, by its lever arm about the centre of gravity, ltg (Mt = Lt • ltg). By doing this, the focus FC is made to move behind the centre of gravity, CG (or to coincide with it).

From a conceptual point of view, the reasoning is rather simple: the wing is unstable, because of the lift; the fuselage increases such an intability.

The stabilator has the duty to put the things in order.

The stabilator - as already said - is just a small wing, with its induced drag and tip vortices; being placed behind the wing, it operates in its turbulent wake, which is deviated downwards (downwash). As a consequence, the effective angle of attack of the stabilator is larger than its geometric incidence (which is a positive factor for the SLS).

The last term of equation (11)can be split in to parts : the former, CLt, is the lift coefficient of the stabilator, the latter

$$\frac{st \cdot ltg}{S \cdot \bar{c}} = TVC \qquad (16)$$

is defined tail volume coefficient, TVC, which often used to give a rough and insuffcient indication of the SLS.

Such a volumetric ratio has nothing to do with volumes as such: it has got this name because each one of the two expressions, st•ltg and S•$\bar{c}$ is the product of an area by a linear measure, and therefore, from a dimensional point of view, it is a volume. The ratio of these expressions is just a pure number ; TVC ranges from 0.3 to 0.7 for radioguided sailplanes.

Since it is based only on geometric parameters of the sailplane and not on aerodynamic characteristics , the tail volume coefficient, TVC, is only a useful indication, but ,alone, it is insufficient to exactly define the conditions of SLS. Sailplanes having an identical TVC value, but totally different airfoils (wing and tail) exhibit completely different SLS qualities.

By inserting the value lts in the equation (. 11) in lieu of ltg (See FIG. 7) the resulting numerical value, TVC', is defined modified tail volume coefficient, and is commonly used in detailed analysis of the SLS.

The sketch of FIG. 7 shows also the lever arm A, which is the

distance between the application point of ther tail lift and the reference axis Z-Z (which is coincidente with the leading edge of $\bar{c}$).

Such a value, A, is used with the method developed by prof. Arturo Crocco, in order to determine the aerodynamic centre (focus) of the complete sailplane, as it will be described later on.

As a result of the fuselage contribution, the lift curve of the complete sailplane (versus the angle of attack $\alpha°$) always differs from the lift curve of the isolated wing, aw, by a quantity F, that is :

$$a = aw - F \qquad (17)$$

The quantity F , positive, depends only upon the overall characteristics of the sailplane, according to the relation :

$$F = \frac{at}{aw} \cdot \frac{st}{S} \cdot \left[1 - \frac{\varepsilon°}{\alpha°w}\right] \qquad (18)$$

where :

at = lift vs. incidence slope of the stabilator,

aw = lift vs. incidence slope of the wing,

st = stabilator area,

S = wing area,

$\varepsilon°$ = downwash angle,

$\alpha w°$ = wing incidence.

The effect of the quantity F (which is often neglected) becomes important when the the stabilator has a large area, or an high aspect ratio,AR.

Disregrading the drag term, already discussed, as well as elaborate mathematical calculations, the equilibrium equation (11) becomes :

$$CMg = CMo + \left[\frac{Xg - Xs}{\bar{c}}\right] \cdot CLw + \qquad (19)$$
$$- \frac{TVC'}{1+F} \cdot \left[\frac{at}{aw} \cdot \left(1 + \frac{\varepsilon}{\alpha w}\right) \cdot CLw - at \cdot (iw - it)\right] = 0$$

in which, in addition to well knwon terms, there are also :

X's = distance between the leading edge of c and the aerodynamic centre of the sailplane less tail, SLT (this focus is marked Fs);

iw = angle between the reference line X-X and the wing zero lift incidence;

it = stabilator incidence in respect with the X-X reference line.

The results of the above mentioned elaborations can be synthetised in a diagram with three lines, of which FIG. 8 is a qualitative example: from it it can be clearly seen that the wing plus fuselage combination,CMs, is defintely unstable; the horizontal plane (CMt) has a strong stabilising action, so that the complete sailplane (CMg) is absolutely stable.

SLS calculations, if made on rigorous bases, are complicated and time consuming ; the preceding notes give an idea of the complexity of the problem, if one wants to tackle it from the scientific point of view, but are totally impractical for the common aeromodelling activity.

Fortunately, as far as radioguided gliders are concerned, remarkable conceptual simplifications can be introduced for practical applications, and establish, already in the design phase, the conditions of SLS as well as the position of the centre of gravity, CG, and of the aerodynamic centre, FC, of the complete sailplane.

When an already realised (designed and built) sailplane does not appear to be trimmed, the only two quick remedies are :

1) - Alter slightly the longitudinal dihedral (usually by adjusting the incidence of the stabilator);
2) - Add (or reduce) ballast in the nose, in order to vary the centre of gravity.

   The second method, highly preferrable, is almost universally used : the ballast used to trim a rationally designed and built sailplane does not reach 8% or 10% of the total weight.

If the ballast required for a correct trim exceed 10% of the total weight, the entire design must be reviewed and amended.

An excessive amount of ballast in the nose deteriorates (that is : increases) the inertia moments about the centre of gravity,thus spoiling the maneuvrability.

It is definitely preferrable to increase the strength (and the weight) of the structures (particularly of those which are more loaded), instead of adding ballast.

In order to achieve this goal, the correct determination of the static margin (previously described) must be made already on the drawing board and not " a posteriori ", by adding ballast in order to move the centre of gravity.

The method devised, several decades ago, by the Italian aviation pioneer, prof. Arturo Crocco, is very apt to reach this goal : it involves only very simple arithmetics and graphics, allowing one to quickly assess the position of the aerodynamic centre of the complete sailplane, FC, thus having to add a little ballast only (so that the centre of gravity is ahead of it).

In other words, once the position of FC is known, it easy to establish its distance from the centre of gravity, such a distance being equal to the static margin, which is deemed necessary.

Additionally, the CROCCO method establishes, quickly, the moment coefficient of the complete sailplane, one of the few valid criteria for comparing the SLS of different contructions.

As it has already been mentioned, the aerodynamic centre (focus) of every airfoil is a point which does not change when the incidence changes : the moment coefficient about the focus remains unchanged as long as the aw curve does not deviate much from a straight line. Practically, this happens up to about 15°, that is much above the usual values of working incidences.

Additionally, the moment coefficient about the aerodynamic centre does not depend upon the aspect ratio, AR.

Inasmuch as the stabilator has its own focus (like the wing) and is rigidly connected to the wing by means of a fuselage (thus completing the aerodyne), it is of immediate intuition that there must be a focus of the copmlete sailplane, with its relevant moment coefficient.

According to the teachings of prof. CROCCO, the moment coefficient of the complete sailplane is given by the relation

$$CMoc = CMow + 4 \cdot \left[\frac{st}{S} \cdot \frac{A}{\bar{c}} \right] \cdot CMot \qquad (20)$$

where :

CMoc = moment coefficient, about the leading edge of $\bar{c}$, of the complete craft

CMot = moment coefficient, about the leading edge of $\bar{c}t$, of the stabilator;

st = stabilator area ;

S = wing area;

$\bar{c}$ = wing average chord ;

A = lever arm between the leading edge of $\bar{c}$ and the focus of the stabilator, Ft;

CMow = wing moment coefficient about the leading edge of $\bar{c}$.

The mathematical derivation of the equation (20) is appended; in this equation, all the moments are referred to the leading edge of $\bar{c}$. Therefore, also the lever arm A is measured from said leading edge. See FIG. 7.

The term [st/S • A/c], which appears in formula (20) is similar to the term [st/S• ltg/c] of the relation (16), already defined as tail volume coeffcient, TVC.

The following value is usually indicated as

$$TVC'' = st \cdot A / S \cdot \bar{c} \qquad (21)$$

which is the tail volume coefficient, which appears in the relation (20).

As it appears in FIG. 7 TVC" is greater than TVC and TVC', that is

$$TVC'' > TVC' > TVC \qquad (22)$$

because of the length of the respecti e lever arms A, lts, ltg.

Several decades ago, starting from the equation (20), prof. CROCCO developed a very simple arithmetical and graphical method, which allows the quick determination of the following data :

a) - position of the focus of the complete sailplane;

b) - the range of the centre of gravity, CG;

c) - the value of CMoc, the moment coefficient of the complete aerodyne.

Additionally, when the wing angle of attack is varied (still keeping the same longitudinal dihedral, k) the new values of the three data a) b) c) are quickly determined with a graphical method.

The inherent simplicity of the CROCCO method explains the favour that it enjoyed between WW I and WW II, when the CROCCO's textbooks were translated in several foreign languages; the preliminary trimming of any aerodyne, still on the drawing board, is very easy with this method.

Ideally, the CROCCO's graph should be determined by means of wind tunnel tests : since this is not possible for us aeromodellers, a calculation should be performed, which - fortunately - is very simple.

Assuming that the SLS of a typical sailplane (radioguided) has to be assessed, the following procedure is adopted :

1) - Pin down the geometric characteristics, that is (for instance)

b = 3.30 m
c = 0.16 m
S = 0.528 m
st = 0.08 m
A = 0.64 m (A = 4 c) (See FIG. 7)

2) - Calculate TVC" with the relation (21), that is

$TVC'' = [st/S] \cdot [A/\bar{c}] = [0.08 / 0.528] \cdot [0.64/0.16] = 0.606$

3) - Select airfoils and incidences for the wing and the stabilator, for instance :

wing : Wortmann FX 63-137 at +2°
stabilator : NACA 0009 at 0°

It goes without saying, that the incidences are referred to the flight line and not to the fuselage reference line (which might also be non parallel to the flight line).

In our example, the longitudinal dihedral (that is the incidence difference between the wing and the stabilator) is equal to k = -2°. Conventionally, the sign - indicates that the incidence of the stabilator is always lower than the wing incidence; it should be noted that the same value of longitudinal dihedral is obtained also with other incidence combinations, for instance :

Wing	0°	1°	1.5°	3°	4°
Stabilator	-2°	-1°	-0.5°	1°	2°

4) - Prepare a tabulation with some data of the selected airfoils, extracting them from tabulations and graphs issued by wind tunnel laboratories. (TABULATION 7.1).
The compilation of this tabulation may become a little elaborate, when modern, computer derived (laminar ?) airfoils are used.
As matter of fact, quite differently from the common practice of some decades ago :
- the data are never supplied in tabulated form,
- the polar graphs do not have the value of the relevant angles of attack,
- the graphs are printed, usually, on a very small scale.

In this case, it is advisable to enlarge the diagrams by means of any photostatic system, extract the data of interest, and draw - on a large scale - a graph similar to the example of FIG . 9.
Needless to say, one must select data derived at REYNOLDS number, Re, as close as possible to the value foreseen for our glider.

Reports from wind tunnel labs, usually show the moment coefficient about the quarter chord, CMq. This must be converted into the value CMo, which is used in the CROCCO method, by means of the relation

$$CM_o = CMq - 0.25 \cdot CL \qquad (17)$$

5) - Prepare , on a large sheet of paper (about cm 40 by 40 or larger) a reticule as shown in FIG. 10. Millimeter paper or, at least paper with very small squares is preferrable, since, as with any graphical system, the precision gets greater if scales and spacings are large.

CL and CM values, to be shown on the two axes (X-X and Y-Y), can be taken in any scale, provided their ratio is equal to one.

It is a convenient habit, with the CROCCO system, to draw a scale rib on the right top of the reticule; this rib represents the wing average chord $\overline{c}$, with its percentage subdivisions. It will be seen hereinafter, that several segments will end on this chord, thus determining the positions of the centre of gravity and of the aerodynamic centre, FC.

6) - Draw the line of CMow, as a function of the corresponding CL values, having care to indicate also the respective angles of attack . To do this, the data of the above mentioned tabulation are used.
For most airfoils which are used in aeromodelling, the resulting curve is a straight line, or,at least, a line which is"almost" a straight line for all practical purposes (Line I). What really counts, is that this curve is a straight line or similar to a straight line in the range of commonly used incidences, that is up to about 4° : seldom both the wing incidence and the longitudinal dihedral exceed this value.

7) - Starting from the origin O, draw two segments parallel to the x-x axis and to the y-y axis, which are proportional respectively to A and to $\overline{c}$ thus forming a rectangle, having A and $\overline{c}$ as sides. Any scale ratio is adequate, provided it is the same for A and for $\overline{c}$.

8) - From the origin O, draw the diagonal O-P of the just formed rectangle : such a diagonal is the base isocline line, which will help in future steps.

9) - Using the formula (.20), calculate the value of CMoc for a relative decalage (that is for a longitudinal dihedral) k = -2°, using two different pairs of CMo values (wing and stabilator), having a differen difference of two degrees; for instance :

	wing	tail
a)	+1°	-1°
	CMow = 0.317	CMot = -0.023
b)	+3°	+1°
	CMow = 0.358	CMot = +0.023

The following is obtained :

a) CMoc = 0.317 + 4 [-0.023] 0.606 =
= 0.317 - 0.0557 = 0.261

b) CMoc = 0.358 + 4 [+0.023] 0.606 =
= 0.358 + 0.0557 = 0.414

10) - Identify, on the line I, the point marked +1° (incidence at which the value CMow= 0.317 of case a) has been found) and draw a parallel to the base isocline, passing through this point. (Line II).
Identify, on the horizontal axis x-x the point corresponding to the value CMoc= 0.261 (just calculated under a) and draw,through it , a vertical line which cutsthe parallel line just traced.Let's indicate with H the intersection point.

11) - Identify, on the line I , the point marked +3 (incidence at which the value CMow= 0.358 of case b) has been found) and draw a parallel to the base isocline, passing through this point. (Line III).
Identify, on the horizontal axis x-x the point corresponding to the value CMoc= 0.414 (just calculated under b) and draw, through it, a vertical line which cuts the parallel line just traced. Let's indicate the intersection point with K.

12) - Draw a straight line which passes through H and K : this is the curve of the moment coefficient of the complete sailplane (Line IV).
If this line crosses the horizontal axis x-x to the left of the origin O (where the moment coefficients have a negative sign) the glider is inherently stable. On the contrary, if Line IV crosses the x-x axis to the right of the origin O, the craft is definitely unstable; for all practical purposes the glider is also unstable, if Line IV passes through the origin O.
In our example the line H-K (Line IV) crosses the x-x axis in a point

corresponding to to CM = -0.25, which is the value CMoc of the complete sailplane for CL = 0 ; it is a rather significant index of the static longitudinal stability (SLS).

A simple trick can be used, in order to trace the line CMoc [H - K] : let's calculate a value of CMoc with a tailplane incidence equal to 0° (That is with CMot = 0).

In our example, (k = - 2°), we get :

c) CMow = 0.34 CMot = 0

CMoc = 0.34 + 4·(0.606)·0 = 0.34

Now, let's draw the line V (parallel to the base isocline line) and passing through the point + 2° on the line I (CMow of the isolated wing).

A vertical line from the point CMoc = 0.34 (read on the abscissa axis) crosses the line V at point X.

Such a point is a point of the CMoc line [k = - 2°].

All vertical lines are not drawn entirely, for sake of simplicity: only their points of intersection with the parallel line to the base isocline are of interest.

13) - In order to find the aerodynamic centre (focus) of the complete sailplane, let's identify the point corresponding to the selected wing incidence (that is 2°) on the Line I (Moment coefficient of the isolated wing, CMow).
Then draw a straight line through this point, always parallel to the base isocline line (Line V).
The intersection of Line V and of Line IV [CMoc for k = -2°] determines the point X.
Let's draw a line connecting the origin O and the point X (Line VI): this line determines the position of the aerodynamic centre (focus) of the complete sailplane, FC, on the reference chord, $\overline{c}$.
In our example, such a distance turns out to be equal to 0.52$\overline{c}$.

When the tailplane is set at 0° (neutral), the focus, FC, coincides with the Centre of Pressure, CP ; under these conditions, this point is called Neutral Point; NP, (See FIG. 7), inasmuch as, in theory, the sailplane is balanced when the Centre of Gravity, CG, is located at this point. [FC $\equiv$ NP $\equiv$ CP $\equiv$ CG].

In practice, a certain (even small) static margin, SM, is required, because of the fuselage (that is certain distance between FC and CG).

14) - The most advanced (theoretical) position of the centre of gravity, CG, is obtained by tracing a straight line through the origin O, which is parallel to the line of the moment coefficient of the isolated wing, CMow (that is, by tracing through the origin a parallel to Line I).
This new line (Line VII) determines, on the reference chord, $\overline{c}$, the point CG1; the distance between CG1 and FC is the maximum static margin which is theoretically possible.
This position of the centre of gravity, CG1, is approached in slope soaring, when ballast is added in the nose in order to cope with the increased wind speed (and the trimming for calm air is abandoned).
By doing so, the centre of gravity is brought more forward, thus increasing the static margin ; since flight speed is increased, maneuverabilty is improved, although at the expense of efficiency, inasmuch as, under these conditions, the sailplane is flying at an angle of incidence smaller than the original one.

15) - The rearmost position of the centre of gravity, CG2, is found by tracing a straight line (Line VIII) through the origin O, and parallel to the line CMoc[k = -2°] moment coefficient of the complete sailplane(Line (Line IV).
This extremely backwards position of the centre of gravity, CG2 is approached to by some free flight models with lifting tail; however it is never convenient for radioguided sailplanes.
In our example, the positions CG1 and CG2 correspond respectively to 0.25$\overline{c}$ and to 0.93$\overline{c}$.

The CROCCO's graph, determined with tha above mentioned procedure, is crowded with lines and might be confusing.

It is a good habit to draw a "clean" version of it, (for instance by means of a photocopy), in which only the following lines appear :

- line I (CMow vs. CL of the wing alone);
- line IV (CMoc of the complete sailplane);
- all lines parallel to the isocline line.

Such a graph is quite suitable to draw some practical considerations, namely(FIG. 10 - B) :

1) - When the wing is set at 2° incidence, and the tailplane is set at 0°, the complete sailplane has a CL value of 0.66 (Line V);
2) - With the wing set at 3° (Line III), the CL of the complete sailplane is about 0.75, while the isolated wing has CL = 0.73 (approximately). The difference, CL (= 0.75 - 0.73 = + 0.02 is given by the horizontal stabilizer, which is set at + 1° (since k = - 2°).
3) - During slope soaring, as already anticipated, the sailplane flies at a lower incidence, than the original one (hence with a lower CL value). For instance, for a wing incidence α = 0°, let's draw another parallel to the isocline line (Line IX), thus determining the point Z. A line drawn from the origin and passing through the point Z, will determine the new position of the focus of the complete sailplane,FC, (on the reference chord $\bar{c}$, at 0.36 $\bar{c}$, in our example).
The centre of gravity must be placed at this point, or slighly ahead of it, as it will be seen later on.
In this case, the wing alone exhibits a CL value of 0.49, while for the complete glider the value CL = 0.462 is found.
The difference between these two values is negative (CL = 0.462 - 0.49 = - 0.028), because the tailplane is set at - 2° degrees, thus giving a negative lift (since k = - 2°).
Under these conditions, the sailplane is flying with a "raised" tail.

It appear, from all the above, that one of the great advantages of the CROCCO method, is the quick determination of the focus FC, of the complete sailplane, when the wing incidence is changed, and the longitudinal dihedral, k, is left unchanged.

Within certain limits, the static longitudinal stability, SLS, improves when the static margin, SM, increases ; this statement, apparently, contradicts the common suggestion to place the centre of gravity on the aerodynamic centre, FC, but it not really so.

As a matter of fact, it has been assumed, for the CROCCO method, that the fuselage had no physical dimensions, being an ideal mean to connect wing and stabilator : in reality, the fuselage is highly destabilizing, and pushes even more towards the nose the aerodynamic centre of the sailplane less tail (SLT), Fs. (FIG. 7).

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By adding the stabilator the focus is brought into the FC position; the CROCCO system, as a matter of fact, determines FC, ignoring the destabilizing effect of the fuselage. As a consequence, the centre of gravity position, CG, must be adjusted, in order to obtain the necessary static margin, SM.

Typically, in "full size" sailplanes, the position of the centre of gravity, CG is located between the 20% and the 40% of the wing average chord, c with a static margin ranging from $0.34\cdot\bar{c}$ and $0.14\cdot\bar{c}$.

In radioguided sailplanes the lower limit of the static margin, SM, has been found just below $0.10\cdot\bar{c}$ ($0.08\cdot\bar{c}$ being considered the ultimate value for aerobatic gliders).

Also the static margin is a kind of measure of the static longitudinal stability, like the value CMoc, determined with the CROCCO method.

Since both are based not only on the geometry of the aerodyne (lever arms and incidences) but also on the aerodynamic characteristics of the airfoils selected for the wing and the stabilator, their dependability is definitely superior to empirical methods, widely spread among us aeromodellers, which are based only on lever arm lengths and/or on the tail volume coefficient, TVC. (Sometimes, the reciprocal value 1/TVC is taken as SLS index).

The CROCCO method, which many Italian aeromodellers are using since decades, takes longer for the description than for the execution, which is usually performed in twenty minutes.

By using a simple program in BASIC, the execution time is reduced to that necessary to input the data.

For us aeromodellers, who deal with applied aerodynamics at an amateurial level ["Absit iniuria verbis"], the CROCCO graph is a kind of .... Phytagorean tabulation. It allows us to know the moment coefficient of the complete sailplane in the very early stage of the design, thus having the possibility to make all necessary changes even before laying the sketches on the drawing board.

If the sailplane turns out to be inherently stable, as indicated under paragraph 12) of this chapter, by knowing the position of the focus FC and the entity of the static margin, which we intend to adopt (usually ranging from $0.08\cdot\bar{c}$ to $0.20\cdot\bar{c}$) the correct position of the centre of gravity, CG, can be established already in the design phase.

The various pieces of "pay load" (servos, battery, receiver and ancillaries) can thus be placed in such a way as to minimise the addition of ballast.

Theory and experience have confirmed that, for any given combination of wing, stabilator and tail volume coefficient, TVC", there is an optimum longitudinal dihedral, k, which ensures the highest static longitudinal stability. Above and below this value (usually ranging from 1° to 4°) the sailplane shows lower SLS, especially in turbulent air.

A peculiar feature of the CROCCO graph is to allow the immediate determination of the position of FC, when the wing incidence is changed, and the longitudinal dihedral is kept unchanged.

In the example of FIG. 10 the wing is set at 3° and the stabilator at 1°; where would FC end up to be, if the wing was set at +1° and the stabilator at -1° (thus keeping the same relative dacalage k = - 2°) ?

Just draw a line, parallel to the base isocline line, through the point on the CMow line (Line I) which correspond to the new wing incidence, that is +1°, in our case.

The intersection of this new parallel line with the CMoc [k = - 2°] line (Line IV), determines a new X point (in our example it coincides with the point H).

Now we have only to repeat the procedure outlined at paragraph 13) : the new position of the aerodynamic centre(focus), FC, on the reference chord, $\overline{c}$, is determined by a straight line (Line IX) passing through the origin O and the new X point (H in our example).

Assuming to have set the centre of gravity in CG1, the new focus, FC FC' is closer to it than FC, and the static margin, SM, is thus reduced (as logically expected).

If also the longitudinal dihedral, k, is changed, then a new CROCCO graph must be drawn.

As a rule, in all calculations related to the static longitudinal stability, SLS, the following factors are disregarded : the effect of the wing downwash, the angle of induced incidence, any fuselage contribution.

As a matter of fact, all these factors vary substantially according to the speed (that is according to CL) : fortunately, at least as far as flying models of conventional design are concerned, they compensate each other.

The detailed analysis of the dynamic longitudinal stability (DLS), although possible,is beyond the scope of this elementary text, because it would have to depend upon higher mathematics as well as on the concept of the moment of inertia (and related, complicated calculations).

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APPENDIX

The CROCCO graph, mentioned in this article, is based upon equation (20), which is derivated from the main relations.

The *incidence* of the stabilator is always lower than that one of the wing, because of the *longitudinal dihedral k* : see FIG. 1, where :

αw - wing incidence

αt - stabilator incidence

$\bar{c}$ - wing average chord

$\bar{c}t$ - stabilator average chord

A - lever arm

k - longitudinal dihedral

The following moments are found, *about the leading edge*

$$Mow = Lw \cdot m \qquad (1)$$

$$Mot = Lt \cdot A \qquad (2)$$

These moments have opposite signs : Mow is *pitching down* (*in respect with the trailing edge*), .while Mot is *pulling up*.

The total moment (*about the leading edge of c*), Moc, is just the algebric summation of them, that is

$$Moc = Mow + Mot \qquad (3)$$

$$Moc = Mow + Lt \cdot A \qquad (4)$$

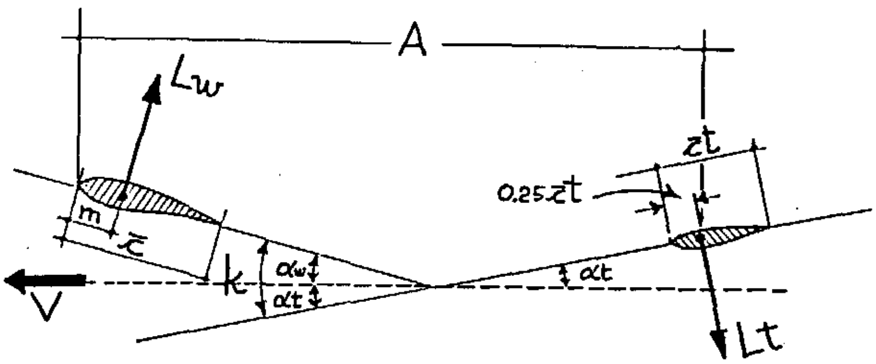


FIG. 1

By calculating the values of these two expressions, the following is obtained

$$CM_{oc}\cdot\frac{\rho}{2}\cdot S\cdot V^2\cdot\bar{z} = \left[CM_{ow}\cdot\frac{\rho}{2}\cdot S\cdot V^2\cdot\bar{z}\right]+\left[CLt\cdot st\cdot\frac{\rho}{2}\cdot V^2\cdot A\right] \qquad (5)$$

$$CLt\cdot 0{,}25\ \bar{z}t = CM_ot\cdot\bar{z}t \qquad (6)$$

$$CLt = CM_ot\cdot\bar{z}t\,/\,0{,}25\bar{z}t = \frac{CM_ot}{0.25\cdot\bar{z}L} \qquad (7)$$

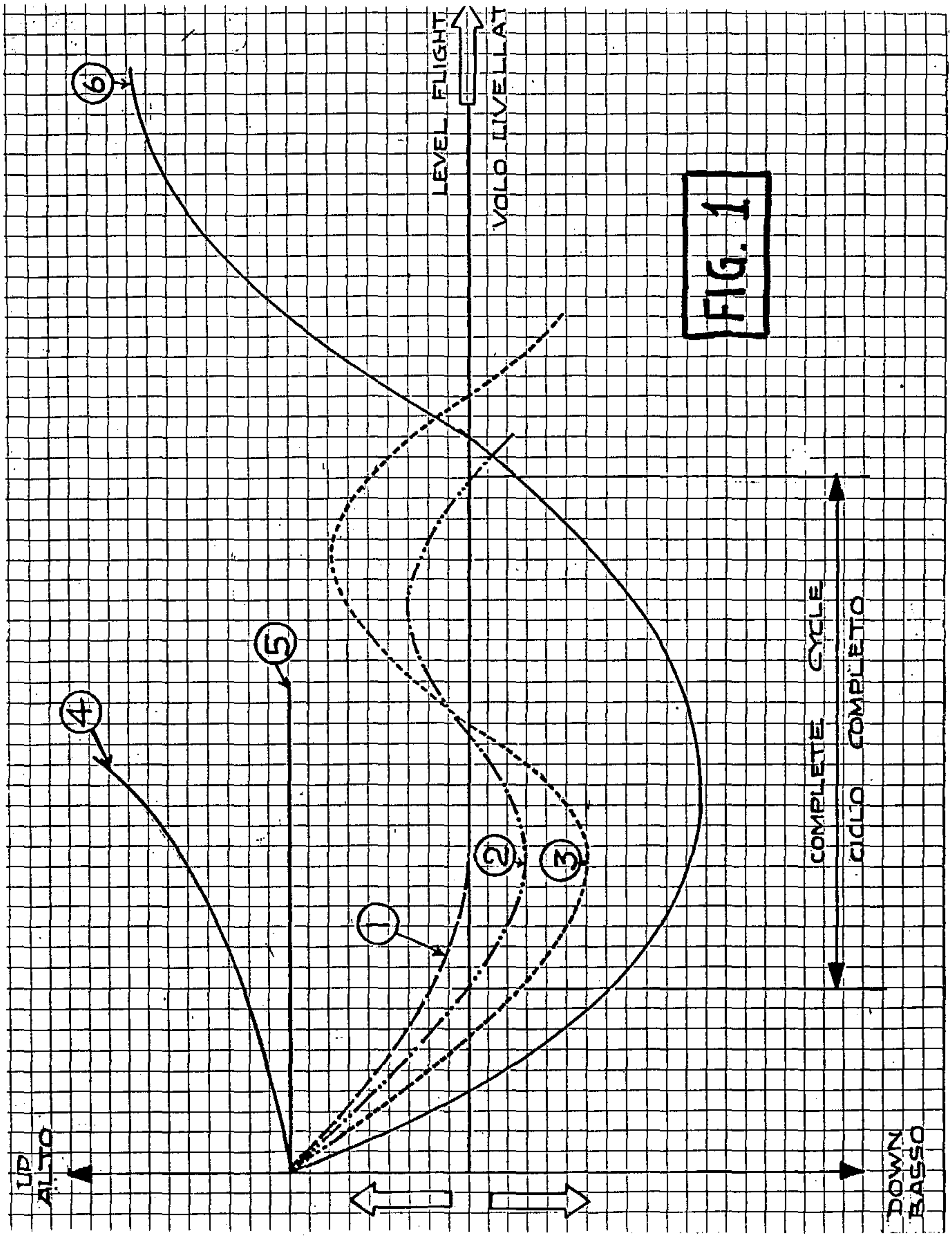
$$CM_{oc}\cdot\frac{\rho}{2}\cdot S\cdot V^2\cdot\bar{z} = \left[CM_{ow}\cdot\frac{\rho}{2}\cdot S\cdot V^2\cdot\bar{z}\right]+\left[\frac{CM_ot}{0{,}25\,\bar{z}t}\cdot st\cdot\frac{\rho}{2}\cdot V^2\cdot A\right] =$$

$$= \left[CM_{ow}\cdot\frac{\rho}{2}\cdot S\cdot V^2\cdot\bar{z}\right]+\left[4\cdot CM_ot\cdot st\cdot\frac{\rho}{2}\cdot V^2\cdot A\right] \qquad (8)$$

$$CM_{oc} = \frac{CM_{ow}\cdot\frac{\rho}{2}\cdot S\cdot V^2\cdot\bar{z}}{\frac{\rho}{2}\cdot S\cdot V^2\cdot\bar{z}} + \frac{4\cdot CM_ot\cdot st\cdot\frac{\rho}{2}\cdot V^2\cdot A}{\frac{\rho}{2}\cdot S\cdot V^2\cdot\bar{z}} =$$

$$= CM_{ow} + 4\cdot CM_ot + \left[\frac{st\cdot A}{S\cdot\bar{z}}\right] \qquad (9)$$

The formula (20) allows one to verify quickly whether the sailplane is stable (Moc must have a *negative value*), before starting a detailed design work, provided the sailplane has been geometrically defined and airfoils and related incidences have been selected for the wing and the stabilator as well.


LEVEL FLIGHT
VOLO LIVELLAT
UP
ALTO
DOWN
BASSO
COMPLETE CYCLE
CICLO COMPLETO
1
2
3
4
5
6
FIG. 1

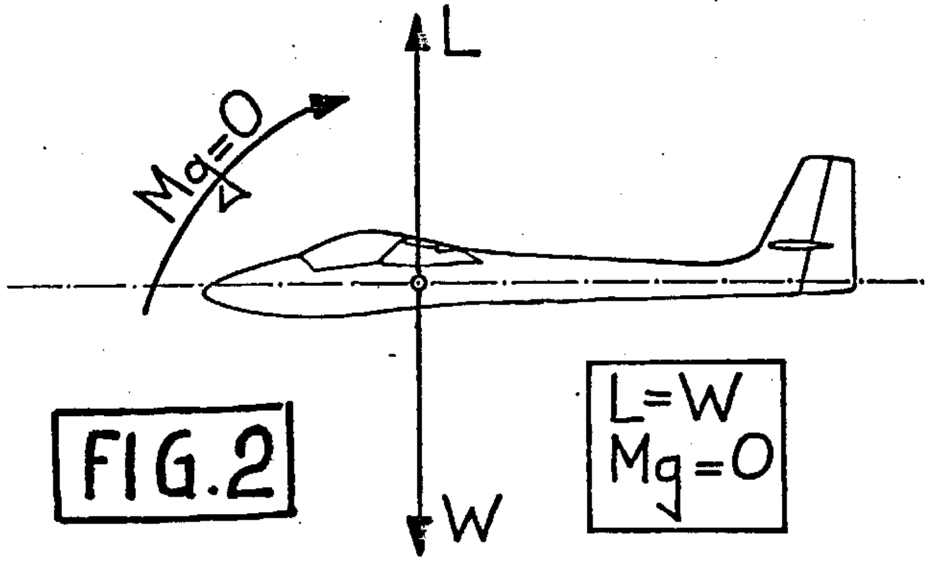


FIG.2

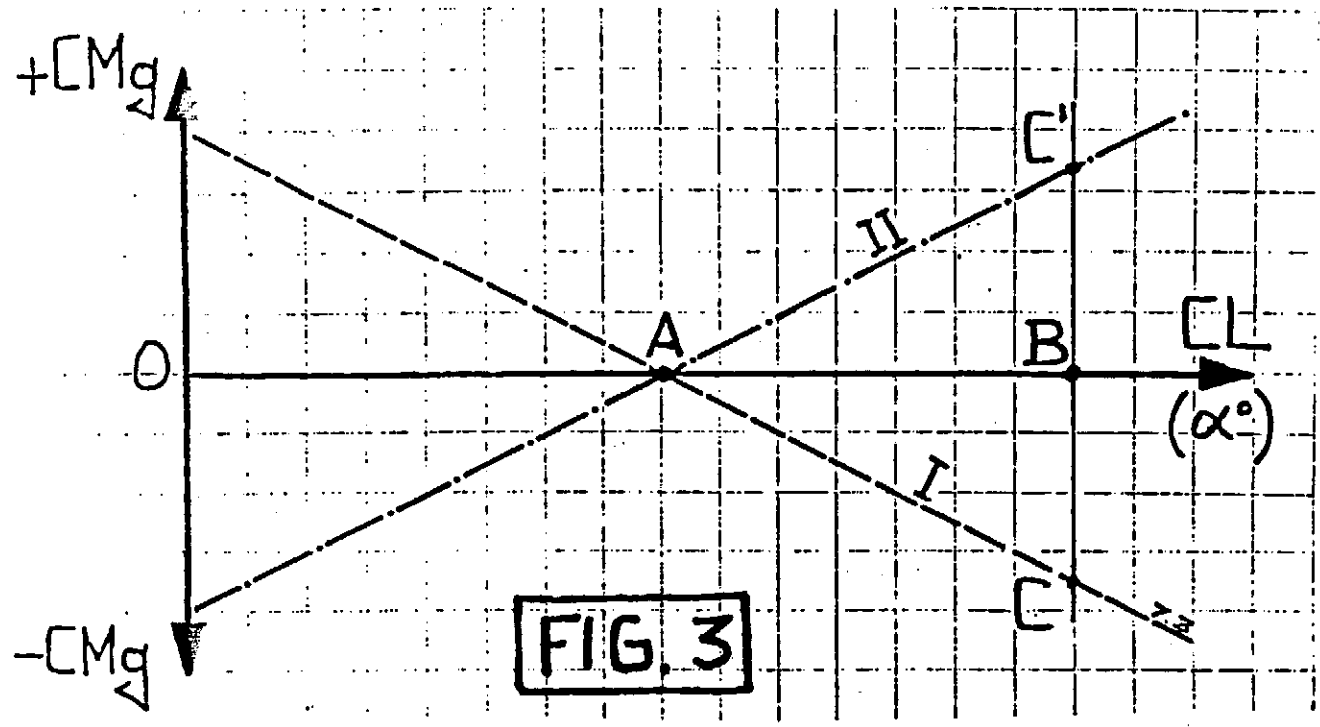


FIG.3

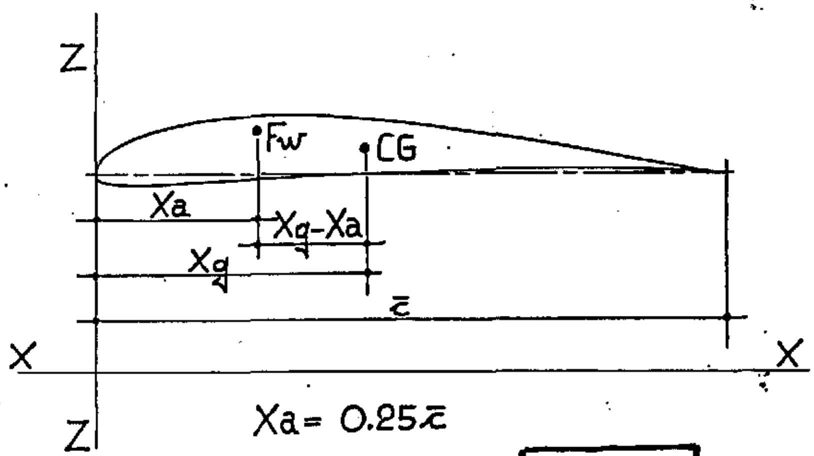


FIG.4

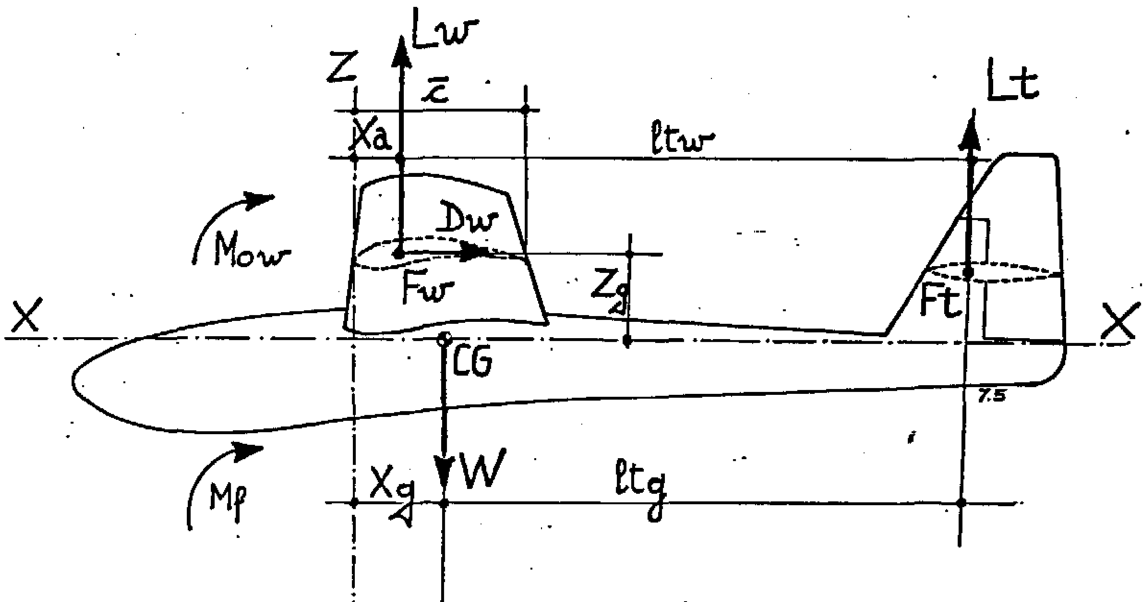


FIG.5

$$\boxed{M_g = L_w(X_g - X_a) + D_w \cdot Z_g + M_{ow} + M_f - (L_t \cdot l_{tg})}$$

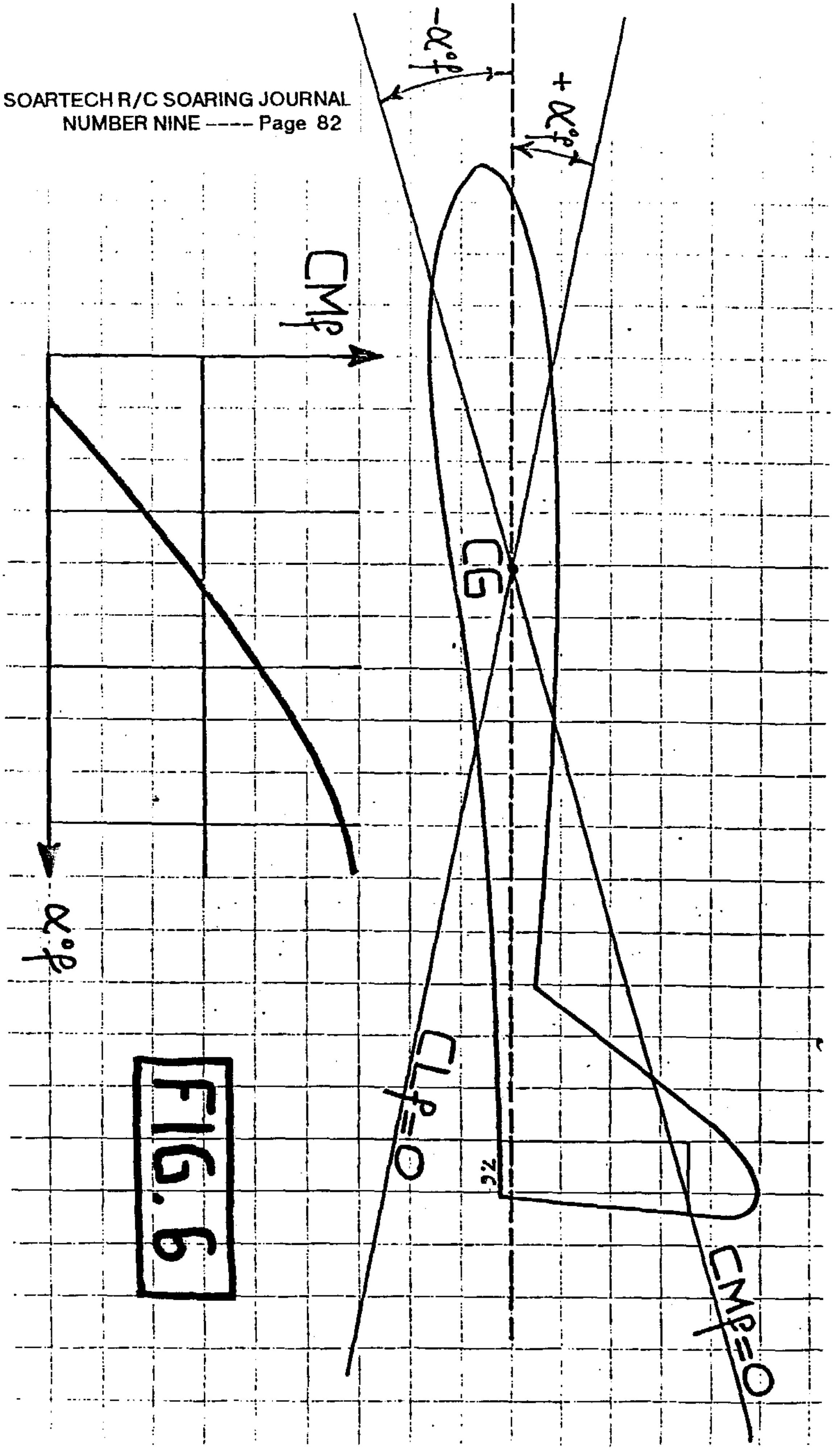


FIG. 6

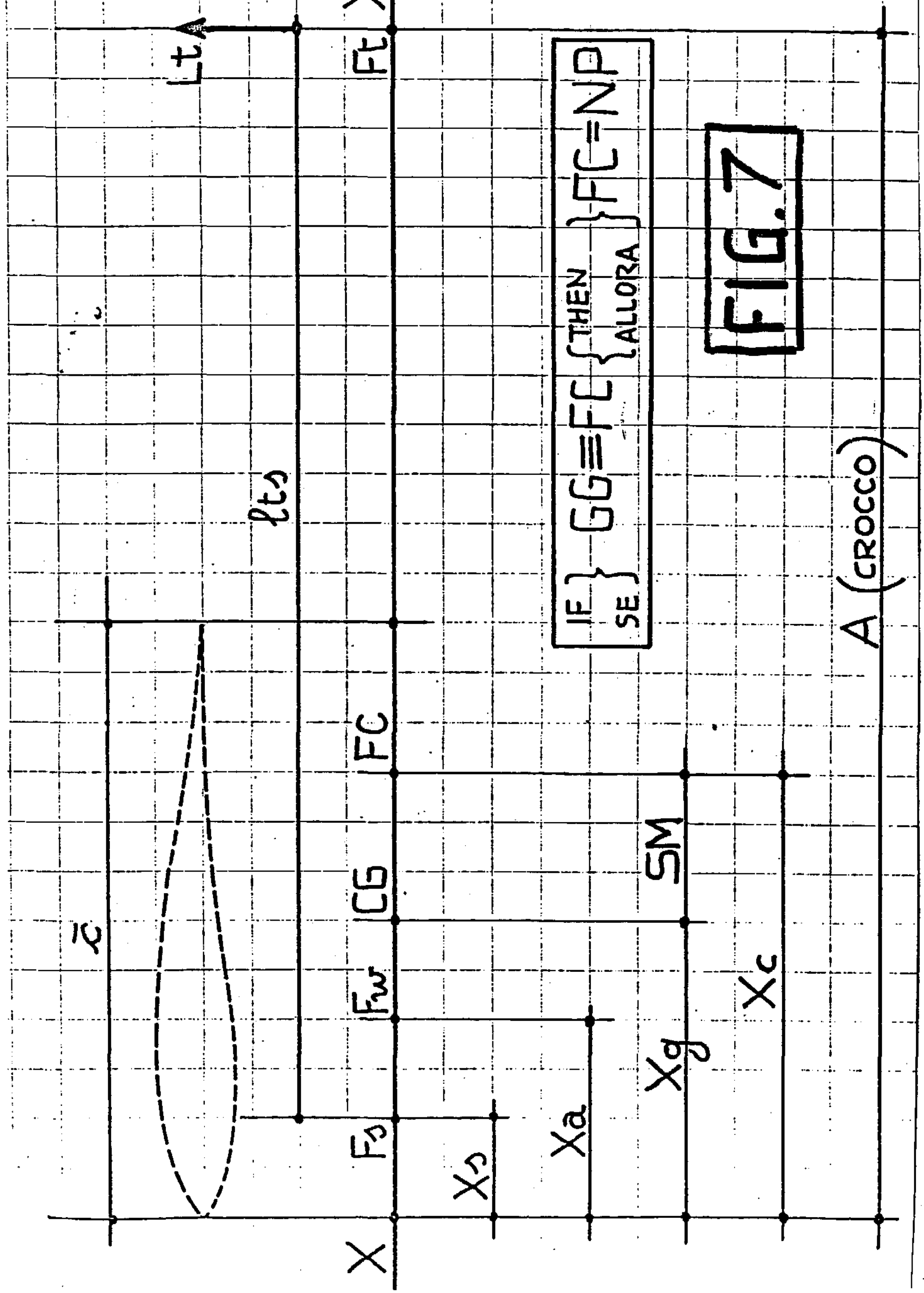

X
Lt
Ft
lts
c̄
FC
CG
Fw
Fs
Xs
Xa
Xg
SM
Xc
X
IF / SE } CG≡FC { THEN / ALLORA } FC=NP
A (CROCCO)

FIG.7

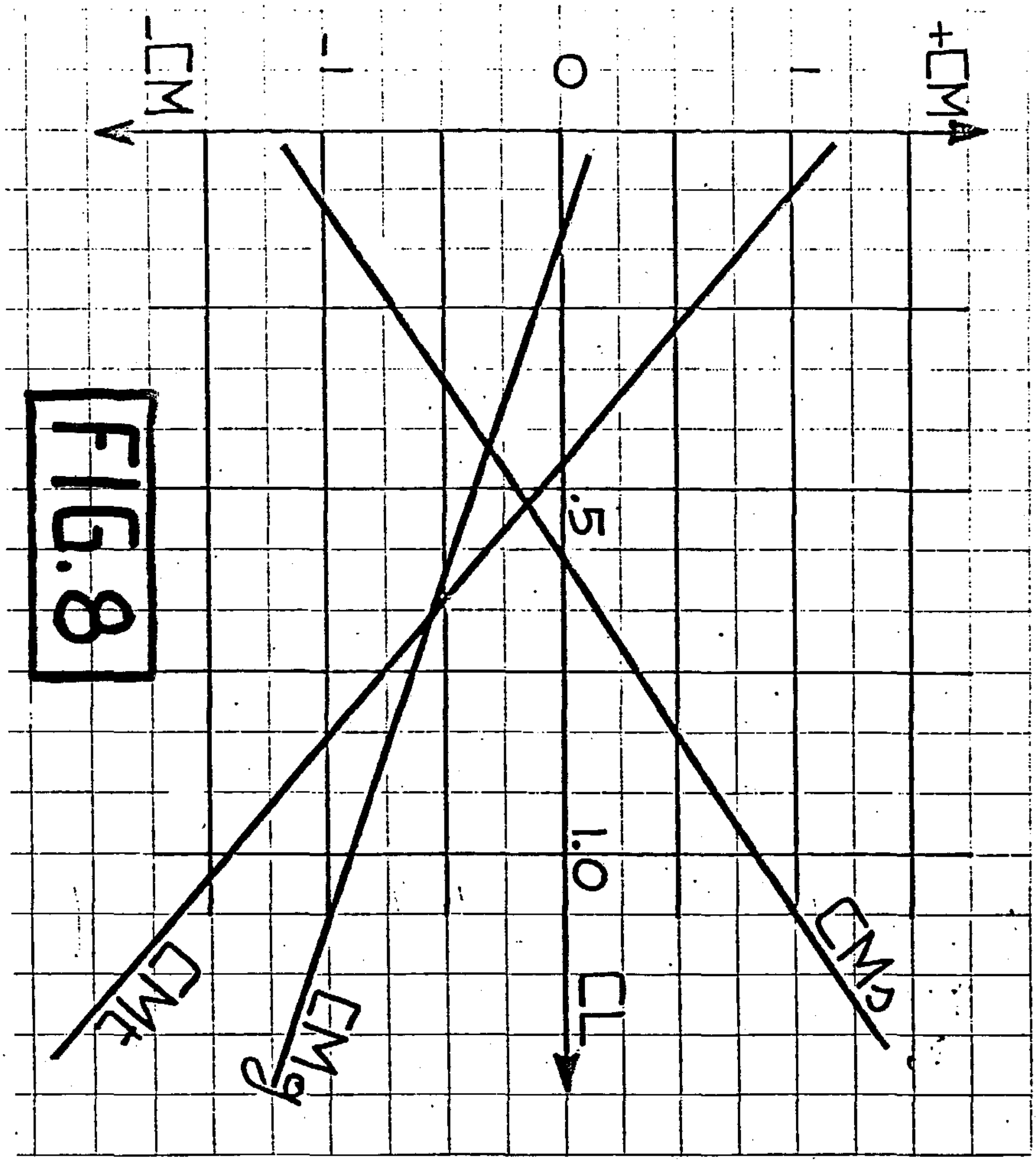
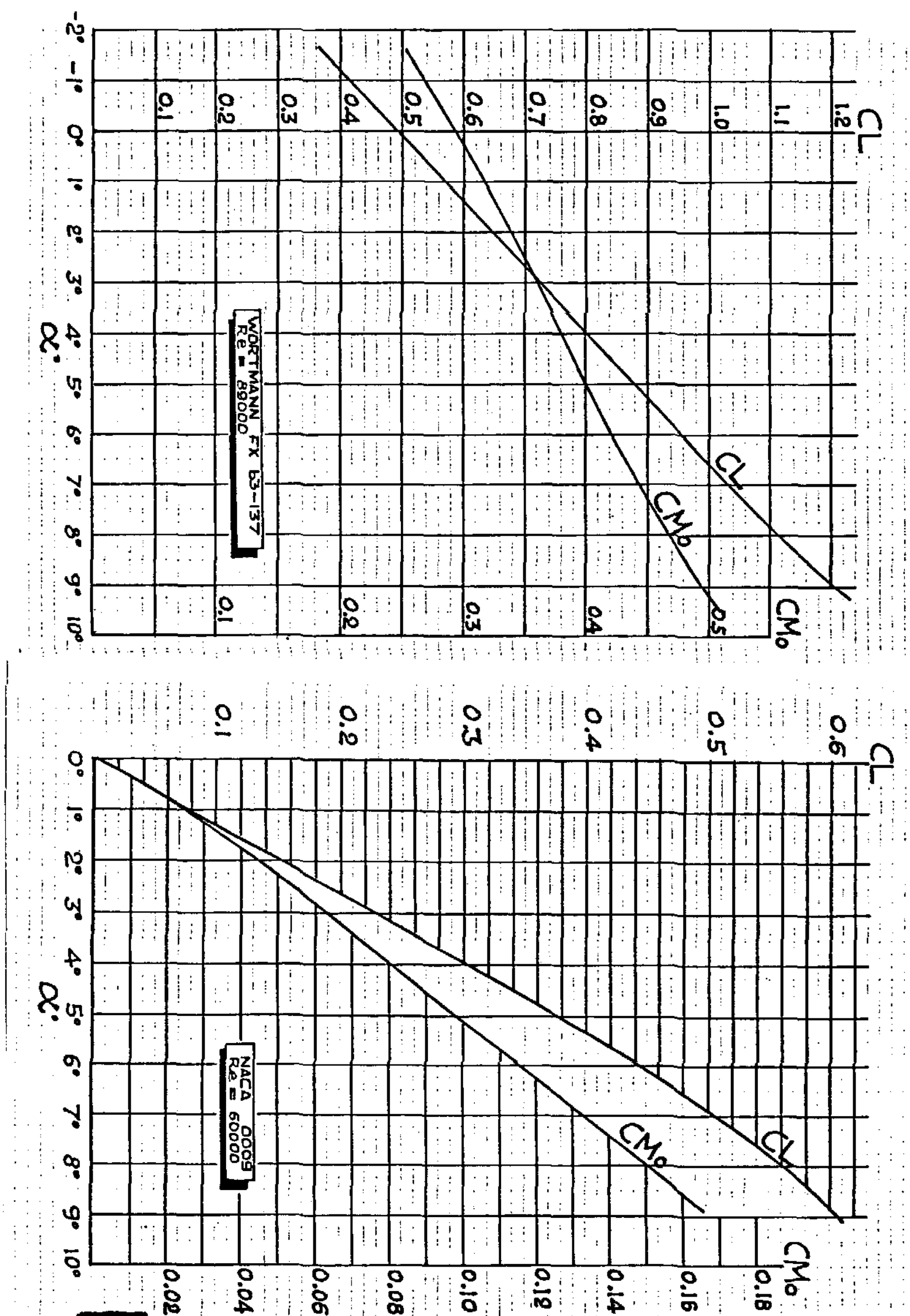


FIG. 8



CL
CMo
CL
CMo
WORTMANN FX 63-137
Re = 89000
-2° -1° 0° 1° 2° 3° 4° 5° 6° 7° 8° 9° 10°
α°
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2
0.1 0.2 0.3 0.4 0.5
CL
CMo
CL
CMo
NACA 0009
Re = 60000
0° 1° 2° 3° 4° 5° 6° 7° 8° 9° 10°
α°
0.1 0.2 0.3 0.4 0.5 0.6
0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18

FIG. 9

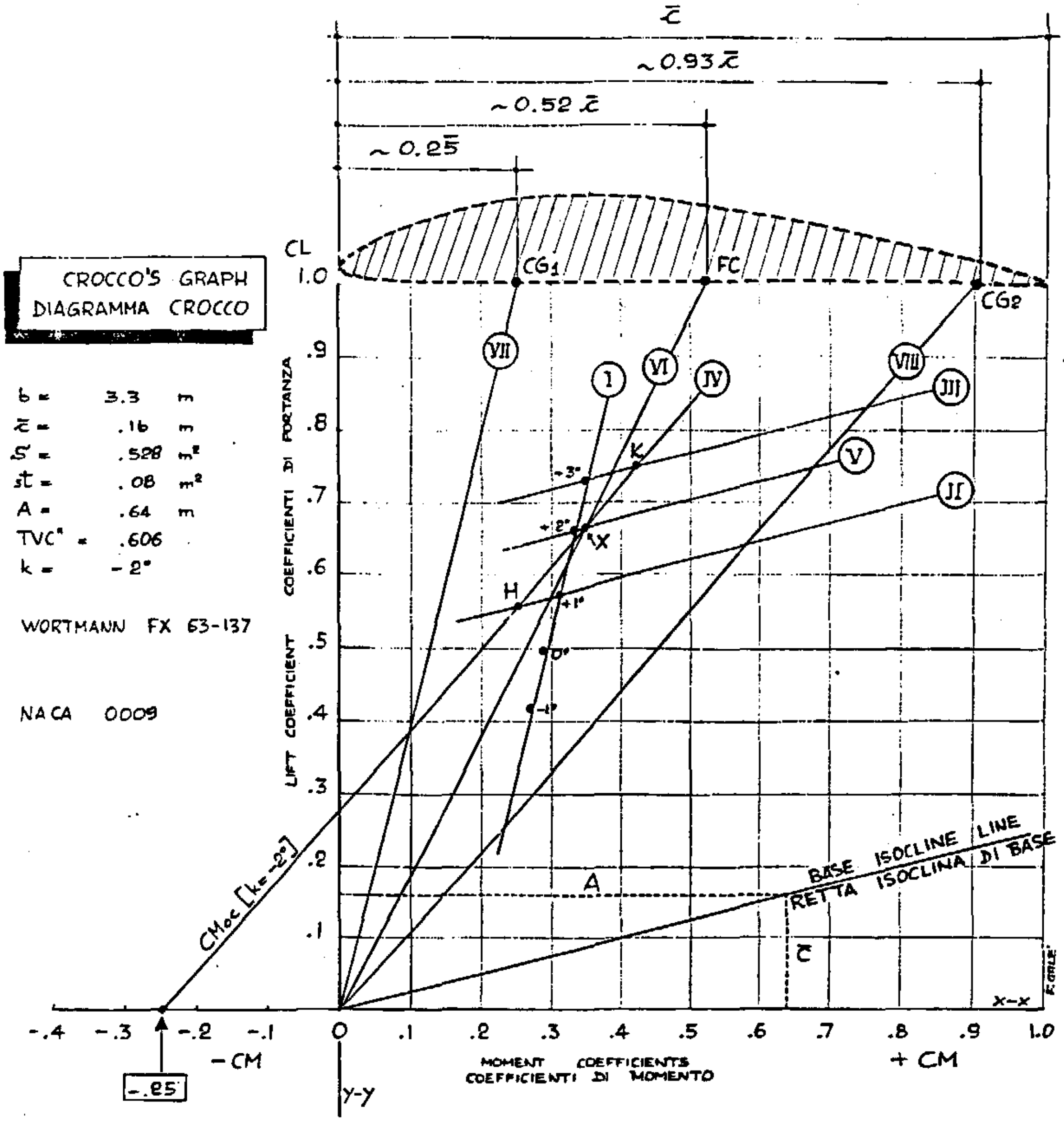
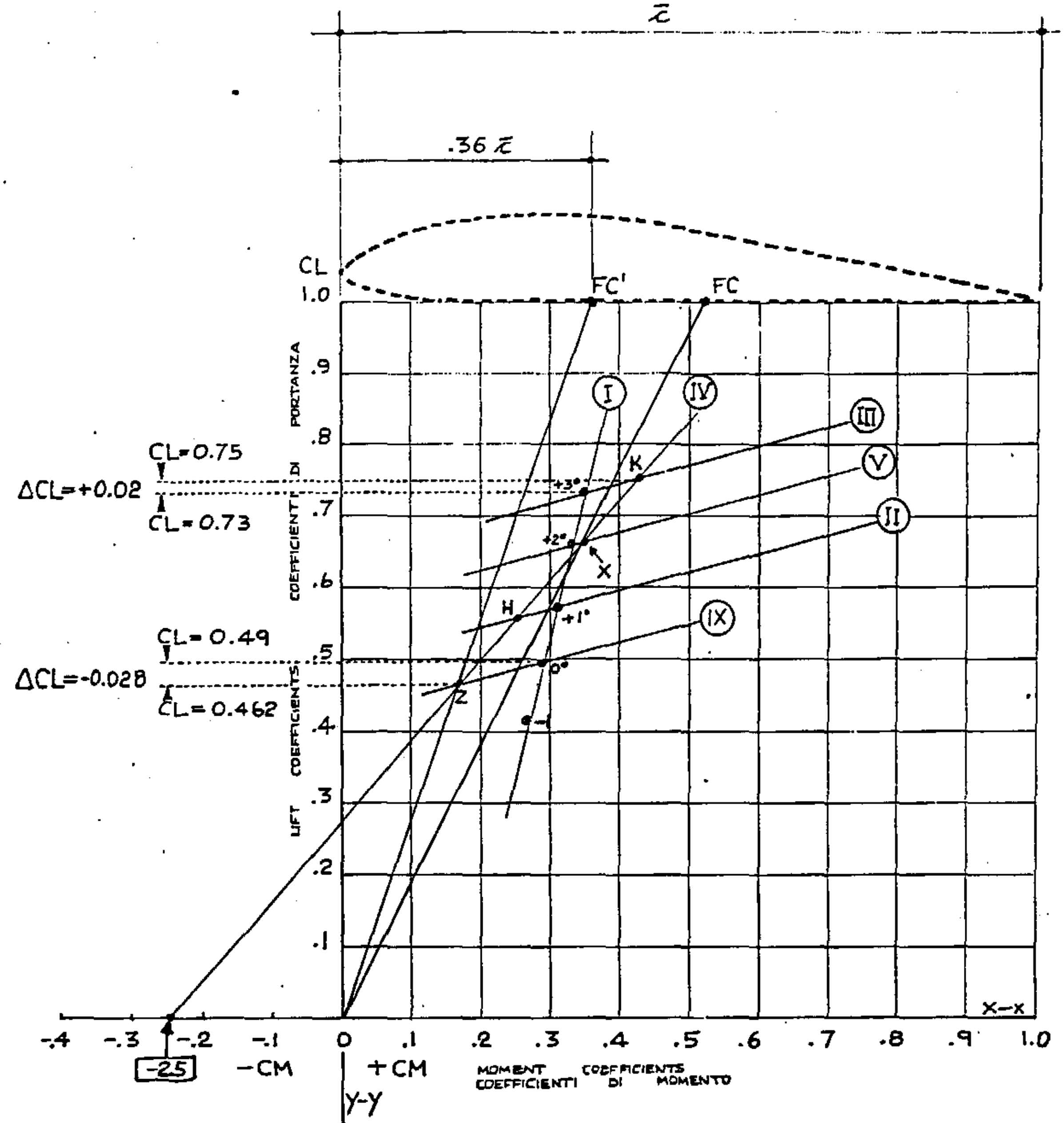

CROCCO'S GRAPH
DIAGRAMMA CROCCO
b = 3.3 m
c̄ = .16 m
S = .528 m²
st = .08 m²
A = .64 m
TVC° = .606
k = -2°
WORTMANN FX 63-137
NACA 0009
~0.93 c̄
~0.52 c̄
~0.25
CL
CG1
FC
CG2
LIFT COEFFICIENT COEFFICIENTI DI PORTANZA
MOMENT COEFFICIENTS
COEFFICIENTI DI MOMENTO
-CM
+CM
BASE ISOCLINE LINE
RETTA ISOCLINA DI BASE
CMoc [k=-2°]
-.25
Y-Y
X-X

FIG. 10-A



c̄
.36 c̄
CL
1.0
FC'
FC
.9
.8
.7
.6
.5
.4
.3
.2
.1
I
IV
III
V
II
IX
K
X
H
Z
+3°
+2°
+1°
0°
-1
CL=0.75
ΔCL=+0.02
CL=0.73
CL=0.49
ΔCL=-0.028
CL=0.462
LIFT COEFFICIENTS COEFFICIENTI DI PORTANZA
-.4
-.3
-.2
-.1
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
X-X
-25
-CM
+CM
Y-Y
MOMENT COEFFICIENTS
COEFFICIENTI DI MOMENTO

FIG. 10-B

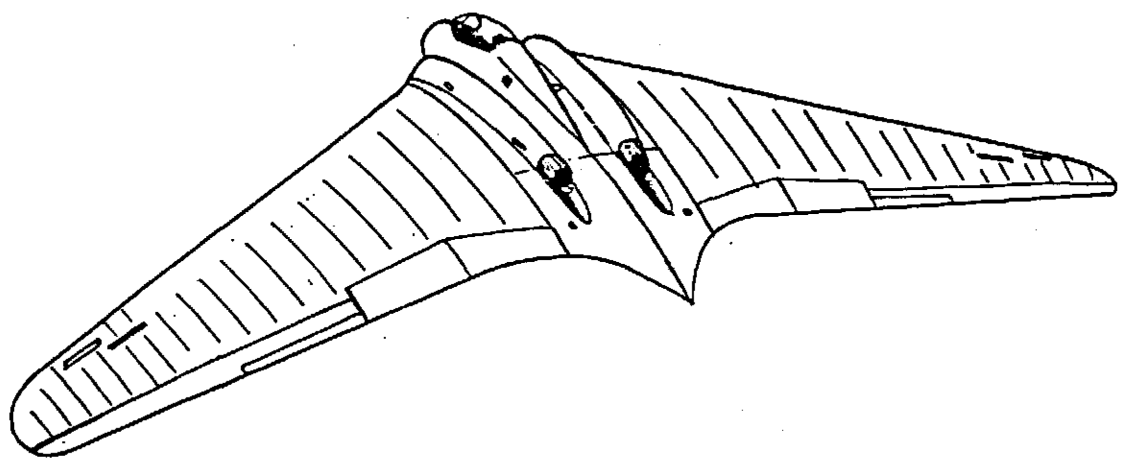
TABULATION / TABELLA 1

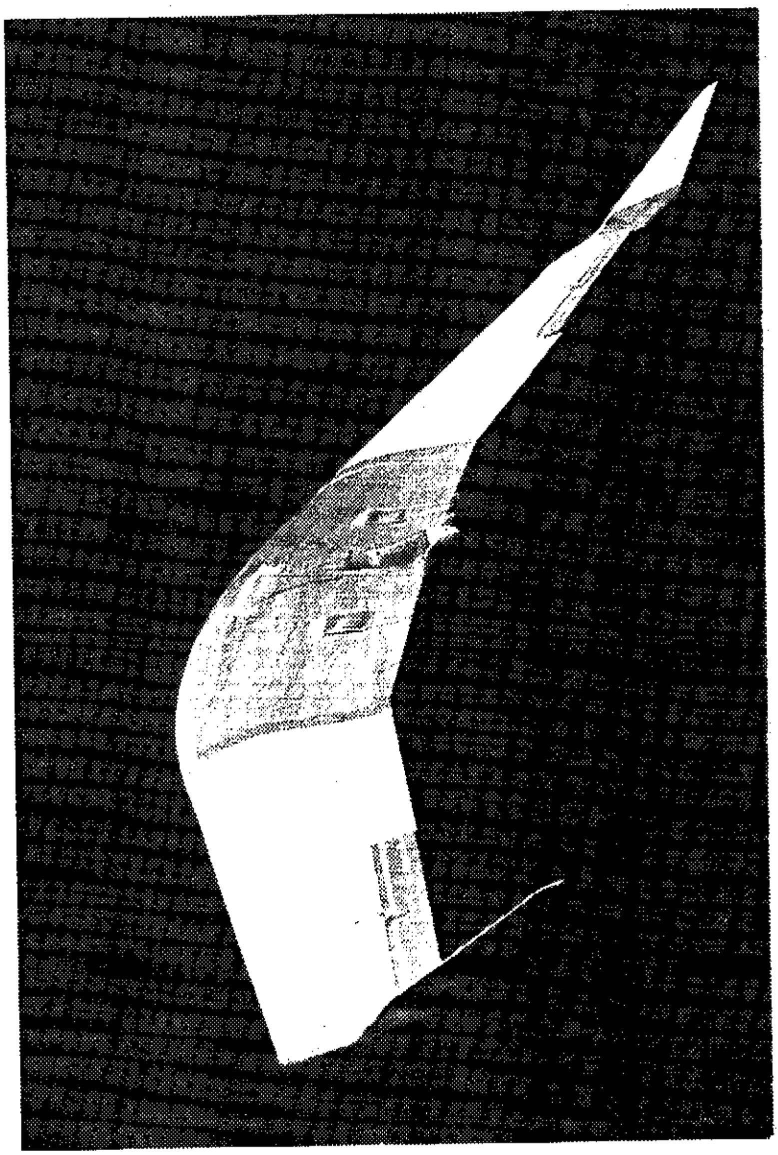
$\alpha°$	FX 63-137		NACA 0009	
	CL	CMo	CL	CMo
−1°	0.418	0.267	−0.078	−0.023
1°	0.569	0.317	0.078	0.023
3°	0.708	0.358	0.23	0.063
5°	0.88	0.4	0.36	0.098
7°	1.03	0.443	0.51	0.138
9°	1.202	0.494	0.61	0.166
	Re=~89000		Re=60000	

FLYING WINGS: do we Love them or Hate them?

Most model flyers are either fascinated with flying wings, or they find them totally uninteresting. For those of you in the latter group, I offer no apologies, and I heartily recommend that you read this paper by Noel Falconer regardless.

Mr. Falconer undertook a massive task in developing a flying wing platform for a very difficult mission, and learned much from the experience. Whether or not you intend to design, build, or fly a flying wing, the process that he details for us is both instructive and fascinating; and has application to all aircraft types.





FEAR THE FLYING WING!

Noel Falconer

The first question you have to answer about wings is *why*? And your reason for leaving the well-developed conventional needs to be compelling!

For flying wings are a compendium of aerodynamic problems. Yes, they're performers - but they resemble the little girl with the curly hair: "when she was nice she was very, very nice, but when she was bad she was *horrid!*"

This isn't confined to models. I'm privileged to know Eric Brown, who is one of the all-time great test pilots. Eric doesn't scare easily. His party trick was to land a jet fighter wheels-up, deliberately and without damage - he demonstrated this some forty times - and he taught himself to fly the first helicopter to reach Britain from its Cockpit Manual. Yet here are some extracts from his autobiography: "The plane" (the Messerschmitt 163B) "was generally very unstable and had to be firmly controlled all the time." (Nonetheless - in a glide! - "I dived to 438 mph.")

"The GAL/56, a new tailless, swept-wing glider ... had the most incredible stalling characteristics. When you eased the nose up to slow the speed down, the plane suddenly took charge and continued to rear up until it was in a tail slide. Even pushing the stick right forward to the dash made no difference. Then suddenly the stick movement would take effect and you would be pitched forward to fall almost vertically."

The De Havilland 108 Swallow tailless had already claimed Geoffrey de Havilland, and was to kill two intended successors to Eric as Head of Experimental Flying at Farnborough. (None of these aircraft had ejector seats.) "This was a tricky aeroplane that had to be handled very carefully ... I had got myself into an inverted spin ... The spin was very flat ... I recovered."

This wasn't unusual. Hortens crashed in Germany, and Northrops in America - Edwards AFB, the major US experimental field, is named for Captain Glen Edwards, who died testing the giant YB-49 flying wing jet bomber in 1948.

The textbooks agree. In his classic "Synthesis of Subsonic Airplane Design" Torenbeek warns: "... the flying and operational characteristics are troublemakers". Our own Martin Simons opines: "Only a very low aspect ratio or genuine delta wing with symmetrical aerofoil, because of its docility and large range of operating angles of attack, has something to commend it for high speed flight".

Flying wings *bite*. They can be semi-civilized but not tamed. My Merlin-S flew some 150 times. It was the fourth aircraft in this line, and there were several rebuilds as well as the three previous write-offs. I always piloted it with a finger on the parachute switch, and I absolutely *never* turned low and slow and tight. Still it caught me - a loop off the line and a spin off the loop, when I was tired and my responses were fractionally below par. Pilot error. Conventionals may forgive it. Wings don't.

More, they bite without warning. A sorted-out wing behaves reasonably normally most of the time. Deceptively! Many characteristics are familiar because two underlying factors have changed with opposing effects. Jack Northrop: "The combination of low static stability in pitch ... and low moment of inertia in pitch results in periods of oscillation for all-wing aeroplanes that are comparable to those of conventional types". Only we're close to the stability boundary, vulnerable to gusts or mishandling, and that low inertia means they can react like a striking snake.

Scribe this on your soul - or, be assured, your wings will do it for you, as mine did for me.

Your experience is invalid and your instincts untrustworthy.

One last warning. There is a fundamental contradiction between efficiency and dynamic stability that is particularly stark in wings. What removes the energy from oscillations is, mostly and usually, drag - and we have precious little. The cleaner we are, the narrower the path we must walk.

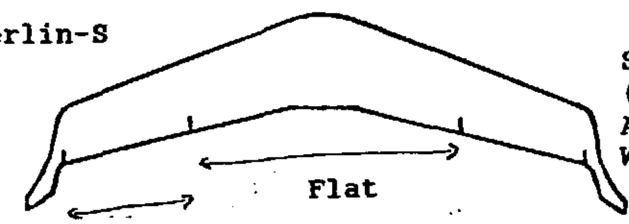
So, why bother?

For a fixed wing area, a flying wing has the absolute-lowest drag of any type of aircraft. It is likely to be superior in lift-to-drag ratio - glide angle - and is competitive in power factor, alias minimum-sink-rate.

The qualification is often important. Our machines have a poor maximum lift coefficient, and may need more area to keep landing speeds within bounds. Where this applies, as in fighters and airliners, it can swing the balance back to the conventional. (Incidentally, it does *not* apply to long-range bombers, which land light. The preference for the B-36 over the B-49 was arguably the most disgraceful abuse ever of the West's defence-provision system. Ironically, the B-49 is the lineal ancestor of the closely-similar STEALTH bomber that is now being developed. We could have had it in 1949.)

Allied with this aerodynamic performance is great structural efficiency. Loads can be spread along the wing, near the lift that supports them, and are well distributed to survive the stresses in a crash. This is dominant in my case - I fly big electrics, with several pounds of batteries, and am totally convinced that the flying wing is the correct configuration for electric-assisted sailplanes. (The Merlin-S - Figure 1 - was the glider I used as a test vehicle for the powered Merlins, shown in Figure 2. These have identical outer panels but a wider centre-section, with a pusher electric motor.)

Figure 1 - Merlin-S



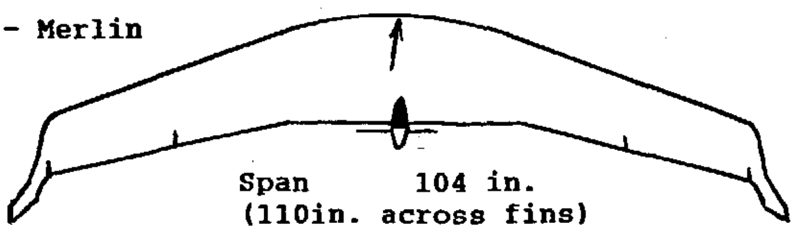
Span 77.5
(84 in. across fins)
Area 800 sqin.
Weight 3lb. 6oz.

8in. Tip Chord
12in. Chord at inner end of wing panel.

Airfoil is NACA 63015 on zero pitching moment line, cambered for Cl=0.4 in center section and Cl=0.0 at tip. (NB - bad choice)

Figure 2 - Merlin

Arc of Circle



Span 104 in.
(110in. across fins)
Area 1170 sqin.
Weight 8.5-11lbs.

Wing panels built as with Merlin-S but with 35 in. instead of 9 in. Centre-Section.
Scale = 1mm = 1"

Merlin-S was not laminarized - I had enough problems without this! - but was easily the fastest sailplane on our field, with a glide angle that, despite its two-metre span, matched the open class machines. Sink rate was lousy, though, and it was hard to fly - this wasn't all aerodynamic, either, without a fuselage it was difficult to judge its attitude, half a mile away.

Let's look at the projected Merlin-S2, which differs only in employing the Eppler E-374 section. I'm using the data from the MTB book, at the appropriate RN for each C_l, with 10% added to this for the tip sailfins and interference, and induced drag based on an effective aspect ratio of 7.6. Weight, adjusted for a mean bank angle of 15°, is 3½ pounds. At C_l 0.1, speed 73 fps or 50 mph, C_d is .0093. $(C_l/C_d)_{max}$ is 22.8 at C_l 0.38, and $(C_l^{1.5}/C_d)_{max}$ is 16.8 at C_l 0.76 - this may not be attainable in practice but the power factor $(C_l^{1.5}/C_d)$ is still 16.4 at C_l 0.60.

I compare this with a conventional using the Eppler E-174, except that I'm predicating a flap to extend its high-performance range; this section is cambered and unsuitable for flying wings. 30% rather than 10% is added, because there is a fuselage and tailplane, but the rest is the same. At C_l 0.1, C_d is .0103. $(C_l/C_d)_{max}$ is 21.1 at C_l 0.44, and $(C_l^{1.5}/C_d)_{max}$ is 16.3 at C_l 0.81. However, C_{lmax} is 1.05, and that putative flap could raise this to the 1.4 of the heavily-cambered E-385, while the wing is limited to 0.85. (This isn't strictly true: you can put flaps on (swept-back) wings, and correct the pitch-down with the elevons; but these must be much more powerful, and even so the effect is limited. Add in their vulnerability - there's no fuselage to keep them clear of the ground - and they're just not worth the bother.)

Both sets of figures are surprisingly good, but it's the comparison that interests us here, and this seems fair. Recognizing the limits of accuracy, the wing is faster, it glides flatter rather than steeper, it stays up about as well - provided you can fly it precisely enough! - and lands hotter. Then there's the structural efficiency above, and something not yet mentioned, operational convenience. My birds are one-piece, they ride on roof-racks, unprotected except for the sailfins, or even inside, so you can launch and pack-up enormously quickly.

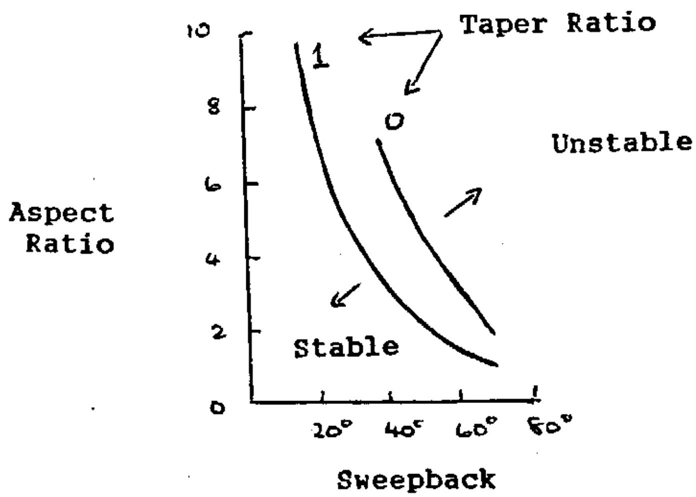
Right, you've judged the advantages outweigh the disbenefits, or you just think wings are pretty, or you're a masochist. What sort of wing?

Why listen to a clown when the king has spoken? Jack Northrop (yes, *that* Northrop) said: "If we add to the (swept-forward) aerofoil a protuding fuselage and an unusually large vertical tail surface, we ... have incorporated virtually all the elements of drag found in the conventional aircraft and have not accomplished our intent of improving efficiency. ... (A plank) offers the serious disadvantage that suitable distribution of weight ... is difficult and ... a large volume of space within the wing unusable. ... The swept-back arrangement seems to offer the best configuration ... It can be balanced ... utilising almost all available volume ... It seems to fly satisfactorily."

Initially, my Merlins embodied 11.6° sweepback (measured at the quarter-chord line, of the outer panels only). This was raised to 18.4°, primarily to increase the internal volume ahead of the CG and thus the useable space. (I'm pretty crowded, with 16 or 20 C- or D-cells, a Speed Controller and an UNGER, a big PCM Rx, parachute plus release servo, and space provision for the Direct Angle-of-Attack Command (DAAC) system, of which more later, plus a payload - I'm planning to fly cameras.)

Unwillingly: sweep is a blessing with a price. Figure 3 shows the stable region, where pitch-up at the stall does not occur. High aspect ratios, though essential for efficiency, are bad news when combined with even modest sweepback. (Taper ratio is tip chord divided by root chord; tip fins make this larger, effectively, while washout decreases it. I correct the simple taper ratio *at my 15° - 20° sweepback and with my sailfins* by multiplying it by (1 - (washout in degrees, divided by 50)) - without complete justification, but it gives sensible results. You need a bigger divisor at higher angles of sweep, and vice versa, and a smaller without tip fins. Remember that there is section as well as geometric washout, so if the aerofoil changes along the span the washout is the difference between the zero-lift angles.)

Figure 3



This is due to spanwise flow, which is aggravated by sweepback. It occurs even without this, as Figure 4 shows. You can see that a taper ratio of 0.4 gives a nice even lift coefficient, shading off at the tip so this doesn't stall, and this is in fact optimal for induced drag. Figure 5 indicates how this changes with sweep.

Figure 4

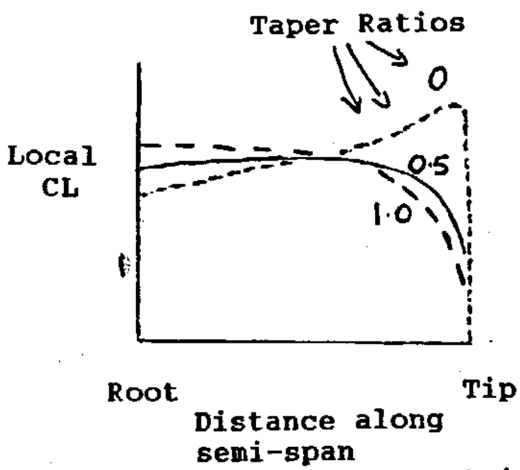
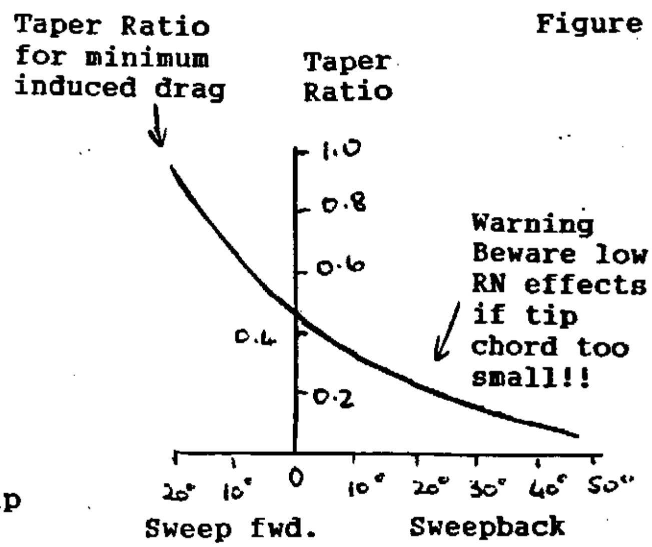


Figure 5



Remember to correct geometric taper ratio for washout!

Here we encounter one of the delights that makes flying wings an adrenaline high. Weathercock stability is low in theory and lower in practice. What there is comes from drag pulling back the wingtips.

Imagine you have a 4-metre wing with 20° sweepback, yawed 5°. The forward wing is then swept 15°, so has an effective semi-span of 2cos15°; the rear one 25°, and 2cos25°; 1.93 versus 1.81 metres. Great. Induced drag has 6½% more leverage on the forward wing, to twist it back to zero yaw.

Only ... induced drag is inversely related to semi-span *squared.*

This reverses the effect. The force decreases more than its lever-arm increases so the moment, too, decreases - and becomes destabilizing. Profile drag always helps, but not always enough. If you push a true flying wing too far you may - as I *have* - see your model snap-yaw through 180°. You *must* have fin area, or some equivalent to this.

This has the best leverage at the tips. Only there's more. *Lots* more.

Figure 6 shows the pitching moments of a plain swept-back wing as the C_l rises. Because of the strong tip vortex, the tip never stalls completely, so the wing stays stable. Add end-plates, or sailfins, and you run into the reversal at high lift in Figure 7, that produces a vicious pitch-up.

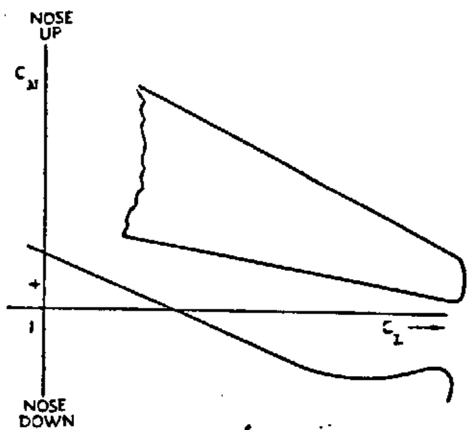


Fig. 6
Pitching characteristics at high lift of a plain swept-back wing.

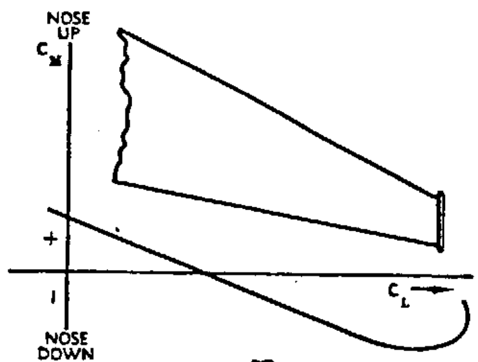


Fig. 7
Pitching characteristics at high lift of a swept-back wing with end plates.

So fit a centre fin on a boom?

This doesn't work either, not perfectly. Sweepback acts like dihedral. *Like*, not *as*. Think of a symmetrical sweptback wing, flying inverted. It stll has positive "dihedral": the effect depends upon the lift, both in direction and magnitude. Consequently, so should the fin area balancing it.

Don't under-rate the importance of this. Damping in yaw hardly exists, so a Dutch Roll of considerable amplitude (and long period) can build up. This matters because it confuses you about what other devilment your bird is about. And on the obverse side, I fitted extra fins to a Merlin, in an attempt to improve control in gusty conditions. It exhibited extreme spiral divergence, doubling its roll angle in 1-2 seconds.

I was half-expecting the problem. Not so its speed! Usually we don't bother about spiral instability in R/C models, it builds up so slowly that it's easy to correct. But the fundamental characteristics are different in a wing and - even when they're self-compensating otherwise - can hand out lethal surprises in peripheral areas like this.

My sailfins - Figure 8 - seem to be an answer. They're complex, though, and you have to understand them to use them effectively.

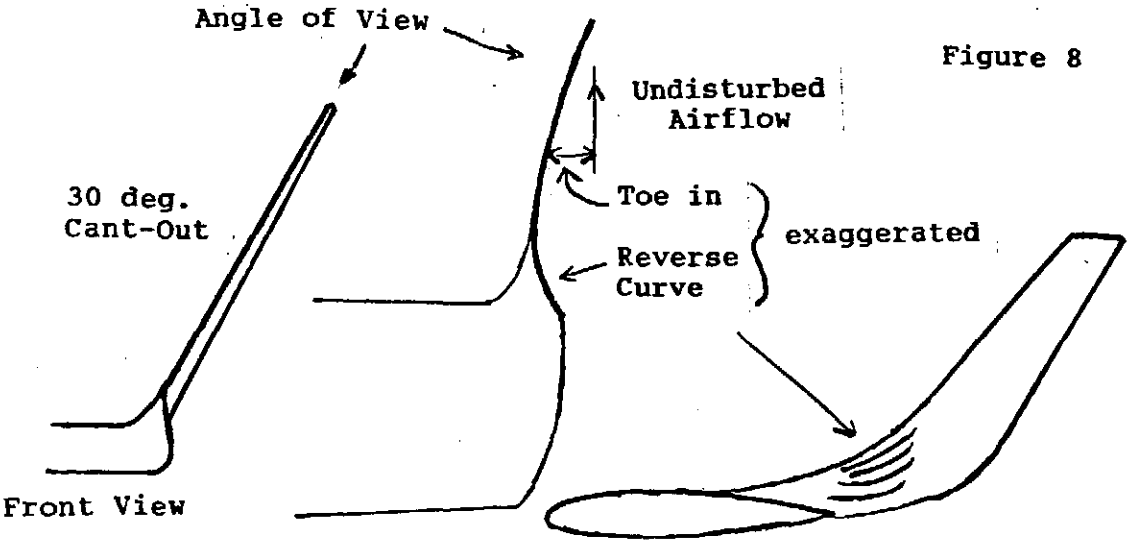


Figure 8

At the front there's a reverse-curved section that straightens the tip flow and extracts energy from it. It's quite small - Spillman showed that the vortex is strongly channelled, with all its power close to the tip, within a few percent of the chord-length there - and is followed by the main fin, which is slightly toed-in.

Suppose that there's 4° toe-in, and 10° yaw. Then the rear sailfin is at 6° angle-of-attack, and the forward one at 14° - where it has higher drag, pulling it back. This is an invaluable non-linearity, that makes the fin area much more powerful at high yaw angles, exactly when you need it.

We're not finished. Recall that increased dihedral-effect at high lift. The sailfins are canted outwards about 30° (the inexactitude is because they're semi-flexibly mounted, rigid ones are eternally being broken during ground handling) and near the stall the toe-in is increased by geometrical interaction, augmenting this effect.

Neat, eh? Except that all this works because they're at the tip - and the better it works, the more dangerous that site becomes.

Am I making too much of this?

I calculated precisely where the Merlin-S should balance if there were no extra tip-loading, allowing for sweep, taper, washout and section change. Of course I wanted a safe initial location, so I started with a centre-section C_l of 0.7 - stall is around 0.9 - and accepted the resulting mean C_l of 0.45. With zero control deflection, the indicated CG position was 6.47" ahead of the centre-section trailing-edge.

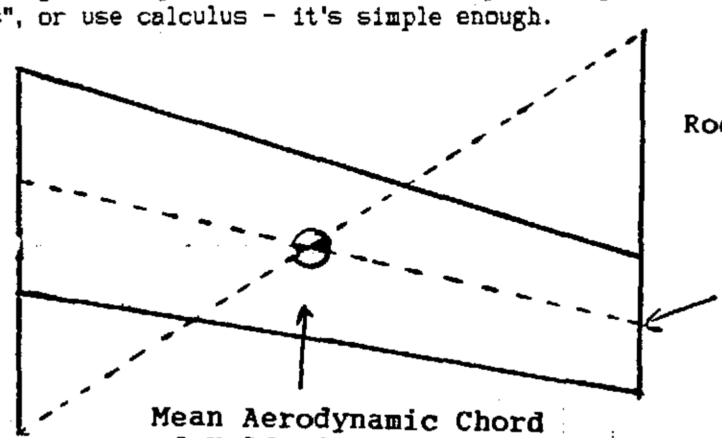
It ploughed in from hand-launches. Initial flights were still severely nose-heavy at 5.9"; the condition above was reached only at 5.2", *12½% of mean chord aft of the calculated balance-point.* And it was flown over 30 times at 4.95", 15% aft!

The one factor omitted was the tip-loading. I worked out the lift and moment if there had been no washout, neither geometric nor aerodynamic, and was able to quantify this effect. It was a startling 6°! No, I didn't believe it either - not until I'd arrived at the same answer by a couple of different routes. My 8½° washout, 4½° from wing twist and 4° from section change, was more than two-thirds gone.

There's a consequence and a conclusion. The first is that washout is much less damaging than I at least had believed; the other is that this is a very powerful factor indeed, so much so as to be central in the combination of stability and performance in wings. I'm persisting with my sailfins, at least until I move to electric twins and can control yaw with differential power, but I now know how dangerous they are - and I'm sweating!

Currently I'm designing for a CG some 7% of the mean chord (wing area divided by wingspan) ahead of the aerodynamic centre. Then I add easily-removable ballast to pull it 3% further forward for the early flights. This is reduced progressively but above all *slowly*. Incidentally, do *calculate* the aerodynamic centre - I've had frights because an apparently-obvious ac wasn't where it seemed to be. Figure 9 shows how for a plain-tapered wing; Martin Simons gives a procedure for more complex shapes in "Model Aircraft Aerodynamics", or use calculus - it's simple enough.

Figure 9



When a Merlin stalls straight, it mushes. In a turn or pull-up, it snaps into a spin. Recovery is stick central and forward, then back almost but not quite immediately. The sailfins stop the yaw without rudder assistance - which is handy because most Merlins don't have rudders. Height loss is about a hundred feet. If the ground doesn't get in the way.

I've referred to the parachute. This was easily the most important fitment on the Merlin-S, which was built to explore the nasties that had wrecked several powered birds. It was a man's handkerchief, spring ejected for fast deployment, with a two-point suspension to avoid candling; and it worked like a dream, de-spinning the aircraft but allowing glide control when out.

I recommend you include one - and use it as the drag brake, which keeps you familiar with the switch position, as well as ensuring that it's working. Parachutes are far and away the best sort of drag brakes for wings anyhow, normal airbrakes induce pitching effects that are hard to counteract, and if you fit top-and bottom units to avoid this - and finding the right balance isn't easy - the lower one is seriously vulnerable. Be careful that the cords are the same length, and attach them to the trailing edge.

Be careful about something else, too - something you've never bothered about in a conventional. *Lateral* balance. Because weathercock stability is low anyhow there's nothing to keep a model straight before it picks up speed on the line. If the CG is offset from the towhook, and the wind is calm, an irrecoverable yaw can develop all too easily. Otherwise tows start low and fast and go to only moderate height, though even Merlin-S uses an open-class bungee. You must allow the line to pull a Merlin from you *and not throw it*, with lots of up or up-trim that must come out *before* release.

Control is by elevons, with electronic mixing and servos immediately ahead of the surfaces. This last *matters*. Mechanical mixing can be made to work, but the linkages to it introduce slack and friction and inertia that I find unacceptable. Electronic mixers can be mated to some Txs and all Rxs; if you prefer not to employ them, I'd use a pitch and a roll servo in each half-wing, connected directly to an elevator inboard and an aileron outboard. Or you could have a thin, lightly-constructed elevon, that will twist, with the pitch horn at the inboard end and the roll horn at the tip - on top, of course, to avoid landing damage. (Are you beginning to suspect that I've cleaned off the bottom of a wing a time or three? If so, you're right.)

The snag with electronic mixing is that you either lose servo movement or encounter control interaction at extreme stick positions - which you use mostly in emergencies, when you least want complications. If the servos are at full throw in pitch when you inject a roll command, one can't go any further, while the other comes off the stops. So you lose some "up", and have only half the roll you were expecting. It's a pain.

Aggravating this is a highly similar aerodynamic effect. The airflow can seperate ahead of the elevon, and not reattach. Worse, there's hysteresis - when this occurs it persists, to far below the conditions where it began.

One response is to leave a gap, so that there's air bleeding through to re-energize the boundary layer - Paul Channon does this, very successfully. I prefer to attack the overall problem, with a rearward CG reducing the movement that is necessary, and meticulous gap sealing to make the merest twitch effective. (Notice that this renders slop intolerable.) Increasing the elevon chord can help the aerodynamics - it allows the airflow more distance to reattach - but this loads and consequently slows the servos, so again I avoid it. My hinges - Figure 10 - are unusual, they're simply strips of glass fibre, that bend on a large radius, plus a rigid sealing-strip on the other (top) surface. Incredibly, all this works.

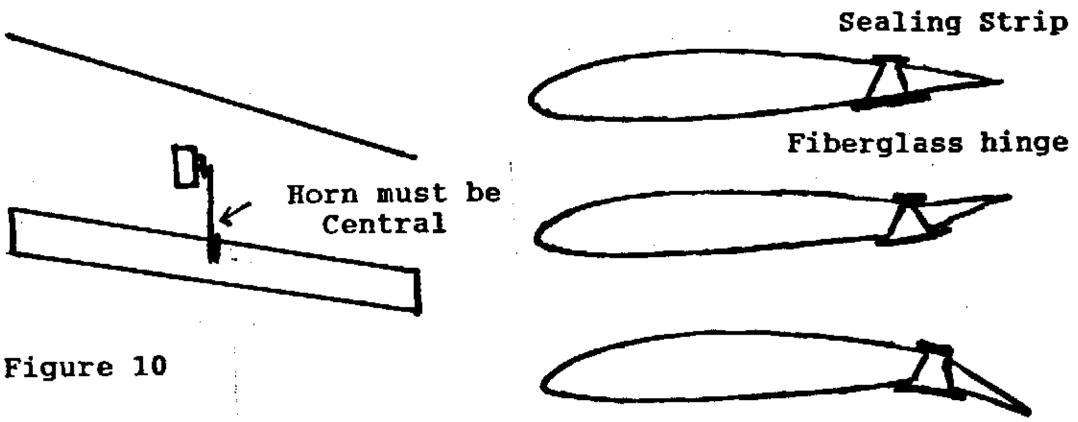


Figure 10

Piloting a wing smoothly is quite a trick. The low inertia in pitch causes a "bobble": after an "elevator" input the wing overshoots the new stable position, to a markedly greater extent than does a conventional, then swings below it and perhaps over again before settling down - Figure 11; this also occurs in rough air. A palliative is to move the stick only very slowly fore and aft - which takes self-discipline when roll control is normal. And there's the phugoid, the cycling between potential and kinetic energy, that is marked in wings - for the usual reason, it's damped by drag and the drag of a wing is low. It can be confused with the bobble; and it's best stopped by a quick but tiny injection of "up" at the top of the oscillation. *Quick*. This doesn't make it easier to control *slow* in pitch otherwise.

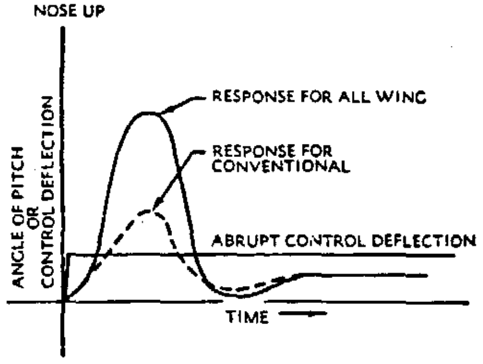


Fig. 11
Response of all-wing and conventional aeroplanes to elevator control.

I can pilot a Merlin, I can even do this reasonably reliably in favourable conditions when I'm not experimenting. Only I'm such an old hand that I qualify for vintage events - me, not my models. And *still* I can't fly it automatically enough to operate, say, an on-board camera, I need my whole attention for the aircraft.

This is the reason for DAAC, the Direct Angle-of-Attack Command system, shown in Figure 12. It's a vane that aligns with the airflow, ahead of and a little way above the leading-edge of the centresection, and activates a Hall Effect sensor; the signal from this goes through a rate gyro - a standard helicopter unit - that inserts feed-forward, so that the output indicates the relative airflow half a second hence; and this is compared with the angle-of-attack demand arriving through the pitch channel, after which discrepancies are converted into servo commands. Parts are working, but not together, not yet. I'm hopeful that this will ease the piloting task - it certainly looks as if it'll solve one major problem, judging the angle-of-attack of these very short aircraft at a distance.

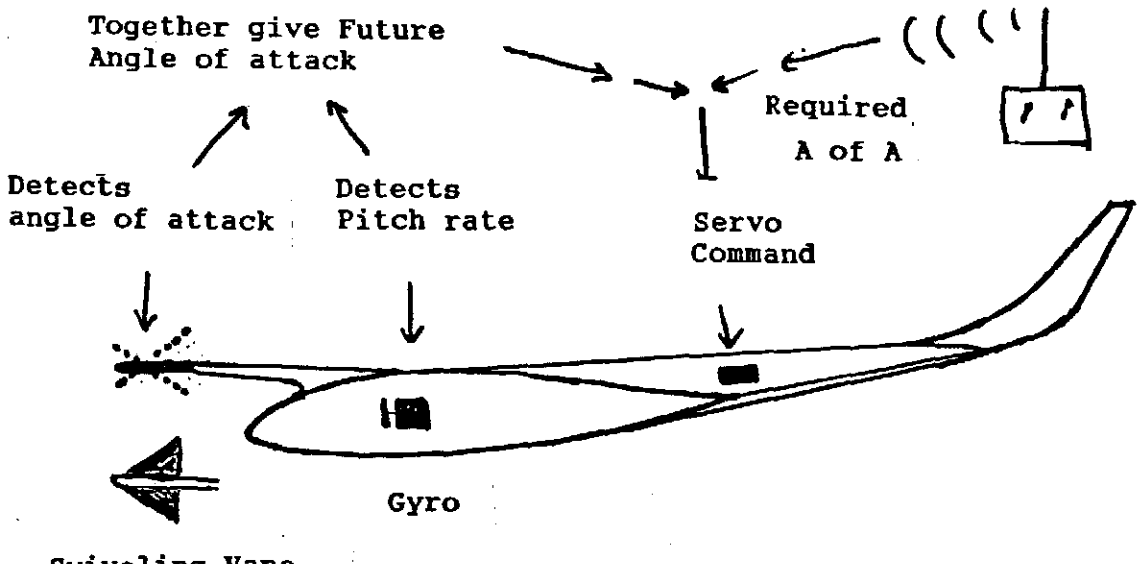
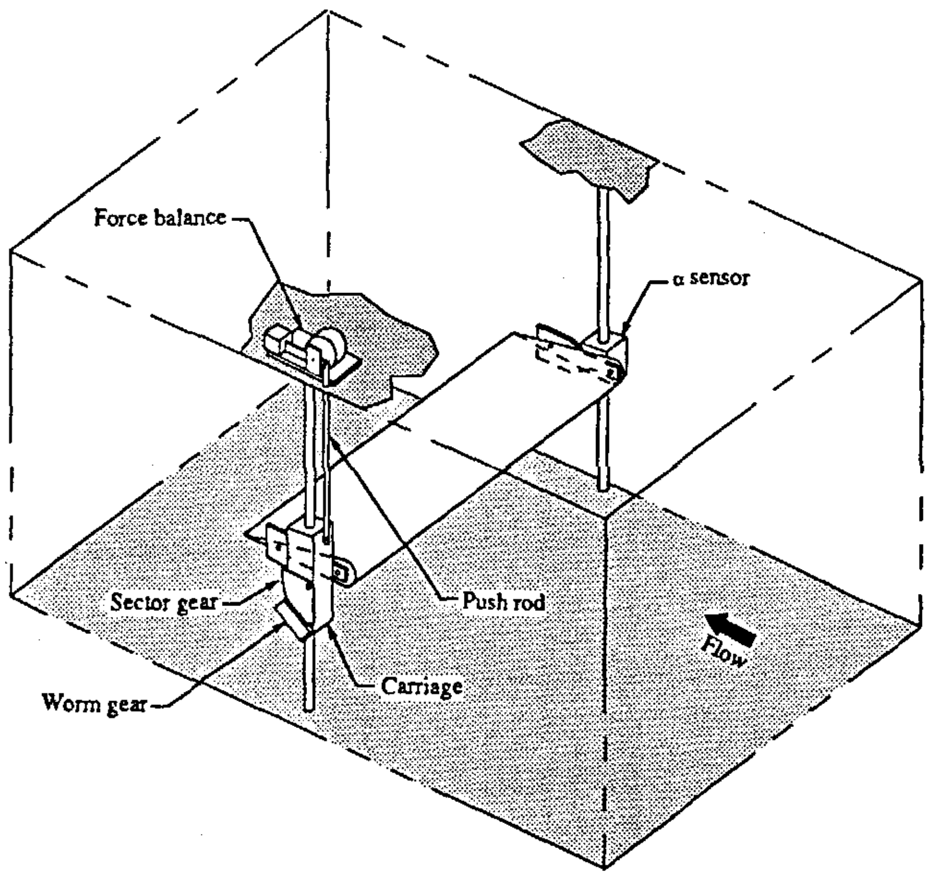


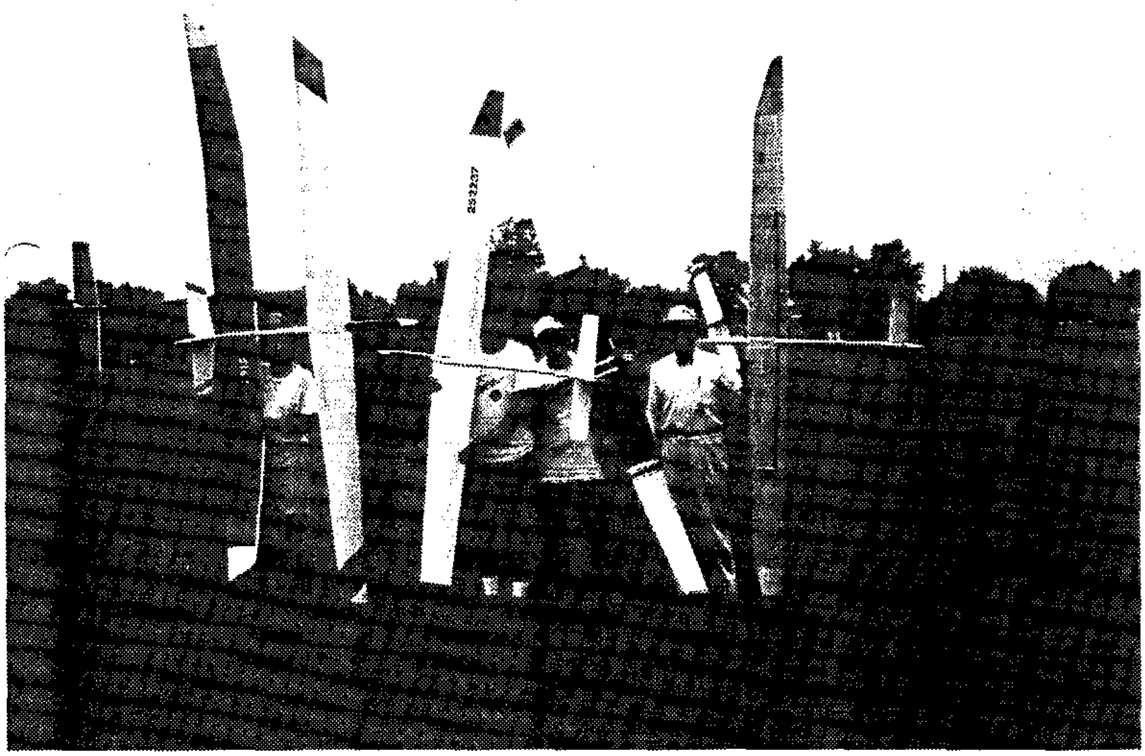
Figure 12

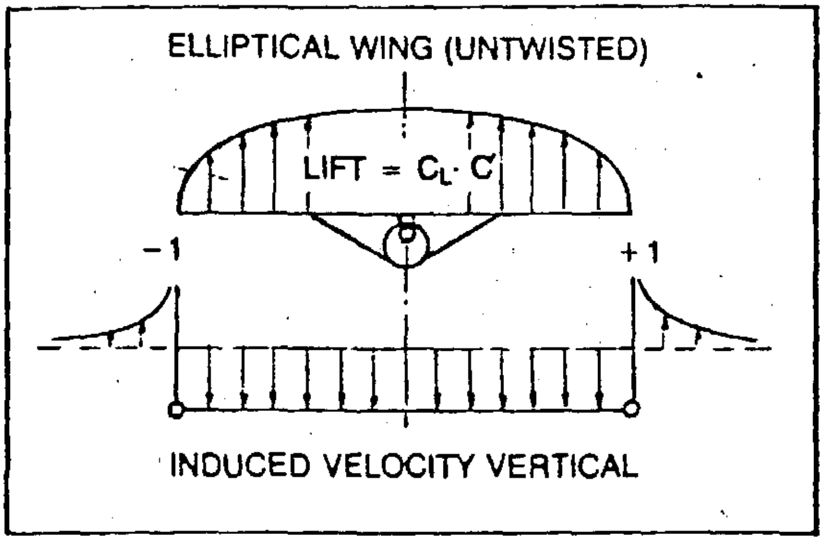
Don't be put off. Try a wing. At the least, you won't be bored!

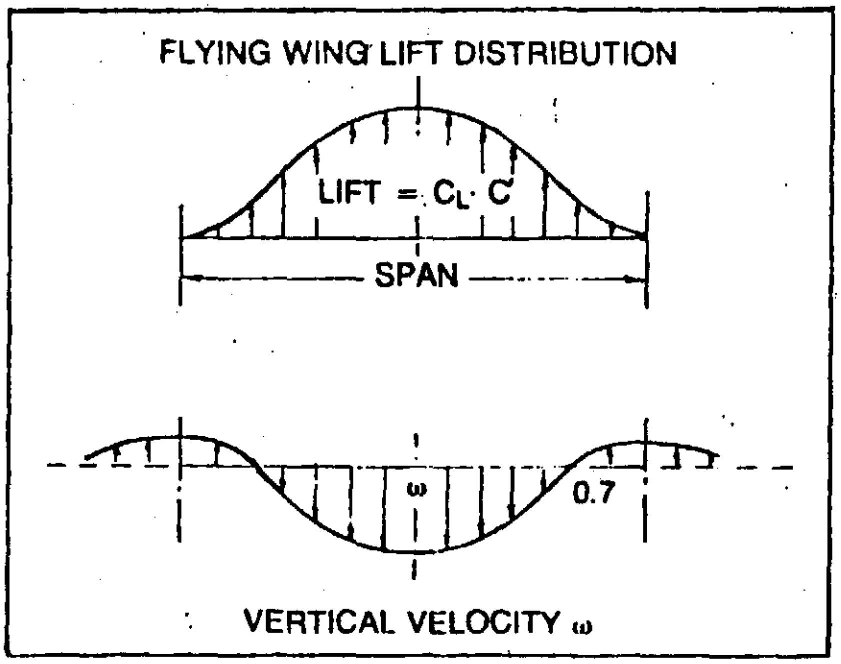

Force balance
α sensor
Sector gear
Push rod
Flow
Worm gear
Carriage

WING LOAD DISTRIBUTION CALCULATIONS

In his paper on performance analysis, Martin Simons has a lot to say about the effects of the distribution of lift forces along the span of the wing. In this paper, Max Chernoff gives us the basic mathematical relationships that allow the calculation of lift distribution. Since it uses lifting line theory, this analysis is good only for straight wings. Max hasn't quit though. I asked him some time ago to see if he could work up the means to analyze wings that are not straight. Some such method is necessary to do performance analysis of flying wings and to calculate the effects of the crescent type planforms that we are using today.




ELLIPTICAL WING (UNTWISTED)
LIFT = $C_L \cdot C$
−1
+1
INDUCED VELOCITY VERTICAL


FLYING WING LIFT DISTRIBUTION
LIFT = $C_L \cdot C$
SPAN
ω
0.7
VERTICAL VELOCITY ω

on wing load computation

Max Chernoff July 1992

In the application of lifting line analysis, a line of vortices on the quarter chord is assumed to represent the wing which are designated as the circulation. For subsonic conditions and moderate to high aspect ratios resulting air load distributions are adequate with the exception of effects of tip vortices which generally act to reduce drag than to have a great effect on the air load distribution. Input data consists of primary geometric data, Reynolds number, total air load and density of air under average conditions. From this are derived the total lift coefficient and velocity based upon spanwise variation in circulation.

Equations for analysis are as follows:

$$V = \frac{Re}{6360 x C_{ave}}$$

where V = velocity in fps
Re = Reynolds number
C_{ave} = average chord in feet

L = weight(lbs) x load factor

where load factor = 1 for level flight
load factor = 3 for strength analysis

$$C_L = \frac{8xL}{\rho x V^2 x A x \pi}$$

where C_L = lift coefficient
A = area in square feet
ρ = density
= .002378lbs.ft.$^{-4}$sec.^{2}

$$L = \rho V \int_{-s}^{s} K dy$$

where s = semi-span coordinate dimension
K = circulation

$$D = \rho \int_{-s}^{s} wK dy$$

where D = induced drag
and w = downwash at 3/4 chord

For analysis purposes, the symmetric loading model is to be considered here. Utilizing a lifting load program, various configurations were analyzed considering the following variations:

1. taper ratio
2. flap deflection
3. washout variation
4. washin variation
5. airfoil variation along semi-span

with the result that in all cases *spanwise variation in circulation closely approximated an elliptical form. Hence a variation in lift being described as elliptical is suitable for prediction of* *loads and variation in shear and bending moment.* The resulting expressions would then be in closed form not requiring numerical integration.

It follows that:

$$K = K_0\sqrt{1-\left(\frac{y}{s}\right)^2}$$

where K_0 = circulation at mid-span

from which:

$$L = \rho V K_0 \int_{-s}^{s}\sqrt{1-\left(\frac{y}{s}\right)^2}\,dy = \rho V K_0 \pi \frac{s}{2}$$

$$\text{and } K_0 = \frac{2L}{\rho V \pi s} = \frac{C_L V A}{\pi s}$$

and the induced drag finally is:

$$D_I = \int_{-s}^{s} \rho \frac{K_0}{4s} K_0 \sqrt{1-\left(\frac{y}{s}\right)^2}\,dy$$

$$= \frac{\pi}{8}\rho K_0^2 = C_{DI}\frac{\rho}{2}V^2 A$$

where C_{DI} = *induced drag coefficient*

From equation for K_0 :

$$C_{DI} = \frac{C_L^2}{\pi AR}$$

where $AR = \text{aspect ratio} = \frac{4s^2}{A}$

If the plan form is elliptical, the local C_L is constant since the chord varies in the same way as predicted by the plan form. In that case the local profile drag coefficient would also be constant over the span. The coefficient, C_{DP}, would then be derivable from airfoil data. In any case the value of the profile drag coefficient based upon the total lift coefficient if it is in the mid range of the curves. The total drag would then be the summation of both effects as follows:

$$DRAG = \left(C_{DI} + C_{DP}\right)\frac{\rho}{2}V^2 A$$

For local shear and bending moment values, integration from a lower bound of a reference station to the tip is now done. Using a change in variables:

$$z = y/s$$

and using the derived expression for K_0 , the shear value is :

$$S = C_L\left(\frac{\rho V^2}{\pi} A\right)\int_{z_0}^{1}\sqrt{1-z^2}\,dz$$

Evaluating the integral and using the arctan function instead of the arcsin function which exists in all computer languages, the shear value in lbs, S , is:

$$S = C_L \frac{\rho V^2 A}{2\pi}\left[\frac{\pi}{2} - \frac{y_0}{s}\sqrt{1-\left(\frac{y_0}{s}\right)^2} + \arctan\left(\frac{\frac{y_0}{s}}{\sqrt{1-\left(\frac{y_0}{s}\right)^2}}\right)\right]$$

Similarily for the bending moment using the same change in variable:

$$M = C_L\left(\frac{\rho V^2}{2\pi}As\right)\int_{z_0}^{1} z\sqrt{1-z^2}\,dz$$

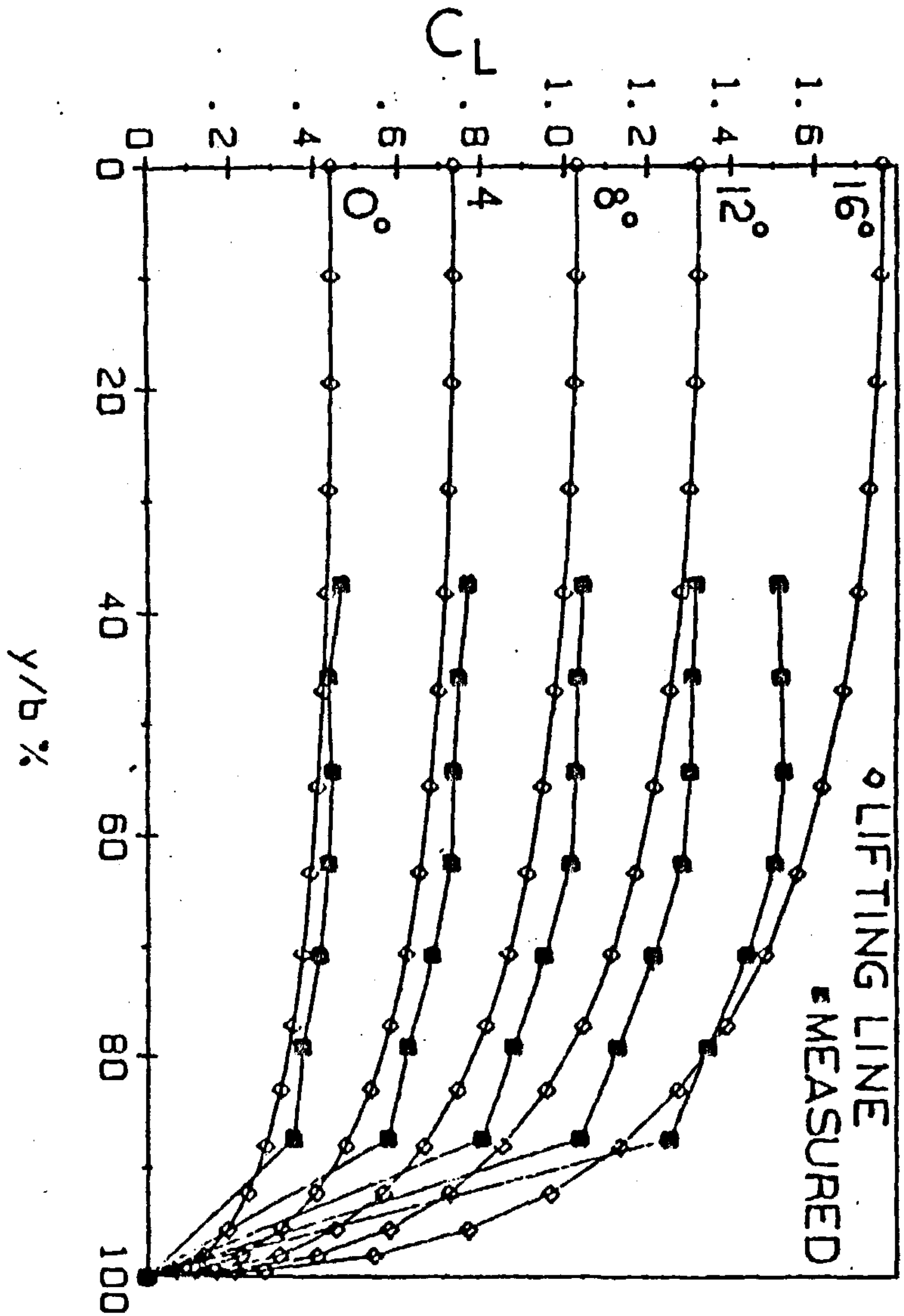
The integral is evaluated by parts and for the specified range, the bending moment in ft.lbs. , M , is as follows:

$$M = C_L\left(\frac{\rho V^2}{2\pi}As\right)\left[-\frac{\pi}{4} + \left(1-z_0\right)\sqrt{1-z_0^2} + \left(z_0+\frac{1}{2}\right)\arctan\left(\frac{z_0}{\sqrt{1-z_0^2}}\right)\right], \quad z = \frac{y}{s}$$

The mean chord location then can be determined by dividing the root moment by the semi span value.

References used are :

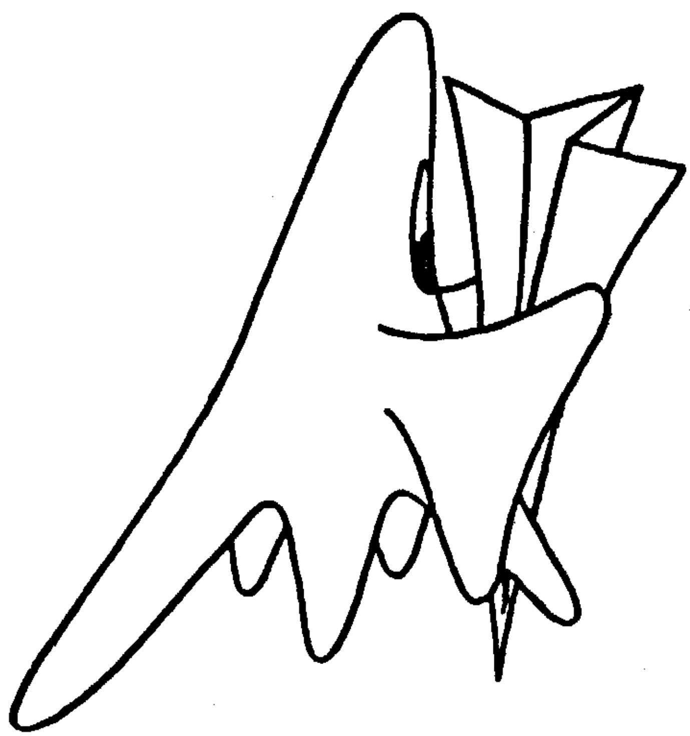
1. "Aerodynamics for Engineering Students", E.L.Houghton and N.B.Carruthers, Edward Hutton(Publishers) Ltd., Third Edition, 1982
2. "A Computer Program for Lifting Line Analysis for Symmetric Air Load Distribution", Max Chernoff, 1989

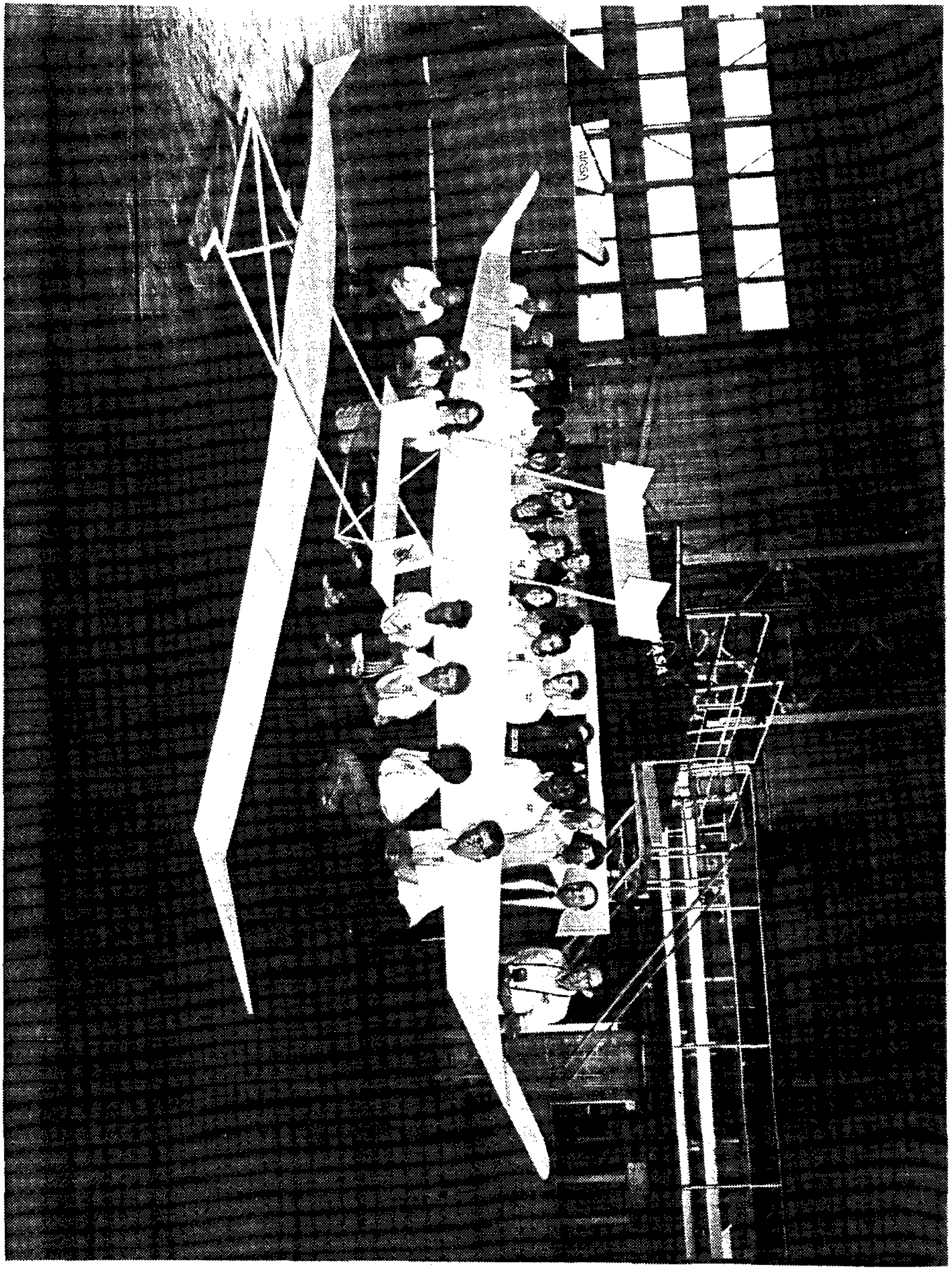

C_L
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
16°
12°
8°
4
0°
0
20
40
60
80
100
y/b %
LIFTING LINE
MEASURED

PAPER AIRPLANES

Basic aerodynamic principles underlie the flight and performance of all aircraft. The development of human flight began with models and their use in aerodynamic testing continues today. Paper airplanes are not, however, generally viewed as research tools. Hewitt Phillips, who before his retirement was head of Flight Dynamics at the NASA Langley Research Center, began his career with observations of the flight of paper airplanes.

It's fascinating that a man whose career has taken his imagination and creativity to the moon and planets can trace the origin of his interest to the flight of small models (an interest that he retains to this day). Hewitt is a well known and highly respected model designer, builder, and record setter; as well as a widely recognized research scientist. His observations are unique and provide a glimpse into the simplicity, elegance, and power of human observation and analysis.





4. The World Record Paper Airplanes with the students, teachers, and advisors.

WHAT CAN BE LEARNED FROM PAPER AIRPLANES?

by

Hewitt Phillips

Recently, model airplane publications, newspapers, and aviation technical publications have given much publicity to The World's Largest Paper Airplane. This project was intended to interest young people in science and technology. Whether it succeeded in this objective may not be known for some years in the future, but it did succeed in breaking the record for the world's largest paper airplane as listed in the Guinness Book of Records. Technical advisors on the project were Bill Reed, Jim Penland, Dick Whitcomb, and the author of this article, all NASA retirees and all former or active model airplane builders. (Dick Whitcomb informed me that he had beaten me in the New England Championship outdoor meet in Boston in 1933. I didn't know him at the time because he came from out of town to compete.)

The technical aspects of the paper airplane project will be discussed in more detail subsequently. Paper airplanes have never received a great deal of attention from model airplane builders. Participating in this project made me realize, however, that paper airplanes have the potential to illustrate and teach many technical points involved both in modeling and in full-scale aviation.

My first attempts at model airplane building, as far as I can recollect, were paper airplanes made to look like Lindbergh's airplane. I was 9 or 10 years old at the time. These models had a span of about 5 inches. A sketch of my recollection of them is shown in figure 1. Our family used to go for a month's vacation each year at an old hotel at Long Beach, near Gloucester, Mass. On rainy or foggy days, I would fly these models in the big living room of the hotel. They flew fine, but one thing I found out was that when I warped the wing to make them turn, they always turned in the opposite direction from what they were supposed to. Of course, Lindbergh's airplane had a pretty small vertical tail, but it wasn't until many years later that I learned about the effects of adverse yaw, directional stability, etc.

Years later still, in 1956, the Bell X-2 airplane, flying at supersonic speed over Edwards Air Force Base in California, rolled against the ailerons, got into a divergent maneuver, and crashed. The designers had incorporated a device to lock out the rudder at supersonic speeds because a trailing-edge control is pretty ineffective under those conditions, and the twist in the vertical tail caused by a rudder deflection would have given reversed control. The designers didn't properly consider the aeroelastic effects on the sweptback vertical tail itself, however. These effects reduced the stabilizing effect of the vertical tail to the extent that the airplane approached a condition of directional instability. As a result, the adverse yaw of the ailerons took over and caused the airplane to roll the wrong way, just like my paper model.

On fine days, I flew my paper models from the boardwalk and attempted to get them to soar in the updrafts. They invariably turned around and headed inland. Anyone who has tried slope soaring with a radio-controlled glider along a dune or cliff has noticed this same effect, which is powerful enough that a large amount of control is required to overcome it. When hang gliders were first used, quite a few of them crashed when flying alongside a dune or cliff because they had insufficient lateral control produced by shifting the pilot's body. Modern hang gliders are designed with a "keel pocket" or similar device to cause the wing to twist when the pilot's weight is shifted laterally, thereby increasing the lateral control available.

When my paper gliders momentarily hovered in front of the boardwalk, I observed the rapid climb in the updrafts. I wished I had some way to control them. My wish was fulfilled with the development of radio control, so that I can now keep my gliders headed into the wind. I haven't been able to do it yet with paper gliders, but I have done slope soaring with models as small as a wooden hand-launched glider.

To most schoolboys, of course, paper airplanes mean paper darts of delta planform folded from a single sheet of paper. These models fly well except for a rather common tendency to oscillate in roll. Aeronautical engineers, in years prior to WW II, frowned on these designs because of their poor aerodynamic efficiency, but during the war it was discovered that this planform had very much less drag at supersonic speeds than a more conventional unswept wing. Quite a few airplanes, such as the Convair F-102, for example, were made with Delta wings, but the Dutch-roll tendency was a serious problem. As a result, yaw and roll dampers were developed to damp out these oscillations. Perhaps this problem was recognized without consideration of paper airplanes, but the schoolboy's models nevertheless predicted it quite accurately. The schoolkids can now take pride in having outguessed the aeronautical engineers on what was an efficient aerodynamic configuration.

My early experiments with paper airplanes are just another example of how the youth of America were enthused with aviation following

Lindbergh's flight. Nowadays, however, very few young people spontaneously take up model airplane building. The start of the project to build the world's largest paper airplane came when officials of NASA and of the new aerospace museum in Hampton, VA, the Virginia Air and Space Center, were discussing possible exhibits to illustrate the principles of aerodynamics. One suggestion was to use a large paper airplane, of the delta-wing variety, about ten feet long, suspended above a console with explanatory material about aerodynamics. Later, Dr. Ferdinand W. Grosveld, then chairman of the Hampton Roads Section of the American Institute of Aeronautics and Astronautics (AIAA), heard about the idea and conceived a project in which students would be motivated to take an interest in science and engineering by attempting to break a world record. He looked in the Guinness Book of Records and found one category in which it appeared feasible to break the existing record. This category, The World's Largest Paper Airplane, specified that the record would be awarded to the model with the largest wing span, made entirely of paper, glue, and adhesive tape, that would fly at least 50 feet when launched from a 10-foot high platform. The record at that time was a span of 10 feet, but was increased to 16 feet, 4 inches during the course of the project by the students of Pendleton Heights High School, Indiana.

The story of how the Hampton, Va. school systems became interested and how four or more seniors were assigned to the project from each of the four Hampton High Schools has been told in so many modeling publications that it seems unnecessary to repeat it here. (see references 1-4). The point I would like to emphasize is that the specifications for this airplane posed an entirely impractical and arbitrary problem; what mathematicians would call an academic problem. The performance requirements were so low that even a non-aerodynamic shape (the proverbial brick) could have been thrown 50 feet from a ten-foot high platform, yet the fact that the record was based on wing span required a high-aspect ratio wing that had the potential for an excellent glide ratio. Such an academic problem is an excellent educational tool. Preconceived ideas as to what the glider should look like must be discarded, and consideration must be given to many factors not mentioned in the specifications. This process is exactly what the designer faces when designing a vehicle for a new task or a new flight regime that has not been previously explored.

Despite my experience with many small paper airplanes, I had very little idea what problems would be encountered in building a really large paper airplane. In order to get some experience, I built a three-foot span model, made of discarded copying-machine paper, using tubular spars, paper ribs, and paper covering on the top and bottom of the wing (figure 2). The construction was similar to that of a conventional model airplane of balsa and tissue. It was difficult and time-consuming to build, but it did glide, rather poorly, after a high-start launch. The weight was 5.6 ounces, about twice what would have been expected for a conventional balsa wood model. This model was kept secret from the students, because I didn't want to influence their thinking.

The model did influence our thinking about weight, however. If the model had been scaled up geometrically to a 25 foot span, say, the weight, going up as the cube of the scale, would have been 202 pounds, obviously too heavy for a hand launch. The conclusion was that all dimensions of the model except the wing span, such as the wing chord, fuselage length, tail size, etc., should be kept as small as possible. Also, the advantage of tapering the wing and the wing spars was recognized. I made some paper tubes for wing spars by wrapping paper on the sections of a 12 foot tapered fiberglass pole that I use for retrieving models. It was demonstrated that a 12 foot tapered paper tube of this type, weighing only five ounces, when held at its large end, would readily support its own weight with a safety factor of two or three.

Though these spars were too flimsy for the actual wing, this was the first indication that a really large model could be built without excessive weight. Later, many tests were made of different types of paper and glue, and the tubes were tested to destruction to determine which were most satisfactory. The students learned quite a lot about research techniques and about structures, but, I fear, not much about aerodynamics, because of the low requirement for aerodynamic efficiency.

A picture showing the design of the completed models is given in figure 3. Rolling paper tubes proved to be a simple procedure involving teamwork of the students. As a result, the entire framework was made from rolled paper tubes, using two to four layers of paper of thickness similar to that used in manilla folders, and glued together with spray cement or Titebond cement. The spray cement had the advantage that the tubes were ready for use immediately after completion, but the Titebond, when dry, resulted in a stiffer spar.

As the project neared completion, it was decided that the record trials would be made before a large crowd of people in the NASA flight research hangar at Langley Field. As a result, two complete gliders were built in case of damage to one of them. The first model was built with spray cement, the second one with Titebond. Figure 4 shows the bending of the wing of the first model under its own weight. The second model was about twice as stiff. The bending did not influence the flight characteristics, however. In flight, the weight on each spanwise section is approximately balanced by the lift on that section, so the wing bends up in flight much less than it bends down when held overhead in the launch position. The twin-boom fuselage arrangement, suggested by the students, also helps to spread the load spanwise as well as adding to the torsional rigidity of the structure.

Two factors considered important in the design of the models were ease of construction and transportability. The tubes were used for both ribs and spars, resulting in a flat airfoil that was covered just on top, like an indoor model. This technique allowed the students to do a neat job despite their lack of modeling experience. The paper tubes allowed the wing to be made in six-foot sections with plug-in joints between the sections. The wing had four six-foot sections, giving a basic span of 24 feet. Then, each glider had a removable four-foot center section that could be inserted to extend the span to 28 feet. When the gliders were assembled, strips of the covering paper were attached with scotch tape to cover the gaps between the sections.

As pointed out previously, aerodynamic efficiency was not a consideration in setting the record. It was desired to have a flat enough glide to allow a safe landing, but too flat a glide was considered undesirable because the flight from a ten-foot platform would exceed the space available in the hangar.

A final lesson learned by the students, as many aeronautical engineers have found to their dismay, was that the gliders came out considerably heavier than predicted. Fairly careful estimates of the weight of the paper in the spars and covering indicated a total weight of about five pounds. The actual weight of the completed 24 foot glider was 8 pounds and that of the 28 foot glider was 9.5 pounds. No doubt most of the difference is accounted for by the weight of glue, several bottles of which were used in the construction. Gussets, reinforcements, etc. probably accounted for the rest. The final weights, however, were well within the capabilities of the students to lift and launch the gliders.

The record attempt was made on March 25, 1992. The record was immediately broken by the 24 foot model with a flight of 101 feet, 9 inches. The record was then broken by the 28 foot model. Finally, small tip extensions, which might be called "span enhancers", were added to give a span of 30 feet, 6 inches. The model in this configuration made a glide of 114 feet, 9 inches. Considering the platform height and the height of the student launching the model, the initial height was probably about 15 feet, corresponding to a glide ratio of 7.6 to 1. The flight distance turned out to be just about right, considering that the hangar floor had been cleared for a distance of 150 feet.

The two gliders are now removed from further testing, one being displayed in the Virginia Air and Space Center in Hampton, Va. and the other in the Hampton School Department headquarters. It is interesting to speculate, however, on what might be done with these models. With small modifications, an efficient airfoil could be installed on the wing, which should produce a much flatter glide. A category exists in the Guinness Book of Records for the World's Largest Radio-Controlled Glider. The current (1992) record is a wingspan of 32 feet 6 inches. The paper glider could take this record also with the addition of radio-operated controls and some further enhancement of the wing span. Perhaps a better plan, however, would be to leave this record for the R/C glider enthusiasts.

References:

1. Grosveld, Ferdinand.- The "White Pelican" project. AIAA Student Journal,Vol.30, No.2, Summer 1992, pp 6-10.

2. Phillips, Hewitt. - The World's Largest Paper Airplane. Free Flight, the National Free Flight Society Digest, Vol. XXVI, No. 6, June/July, 1992.

3. World Record Paper Airplane: Model Aviation, Vol 18, No. 8, Aug. 1992, pg 24.

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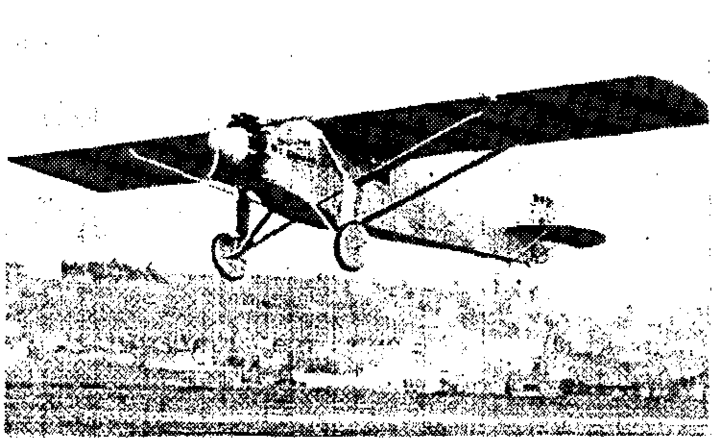
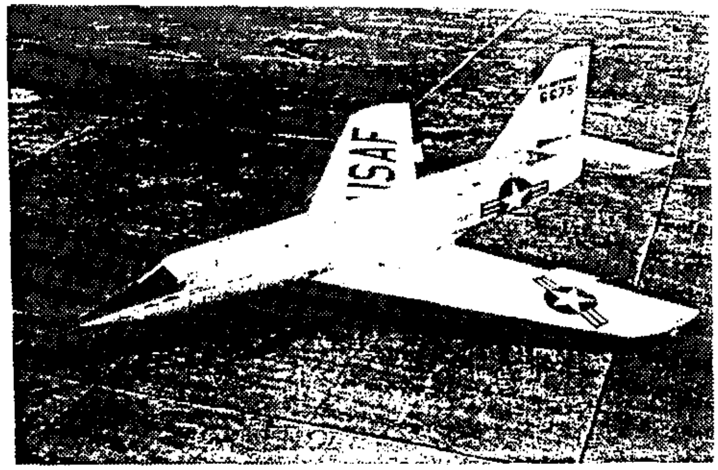
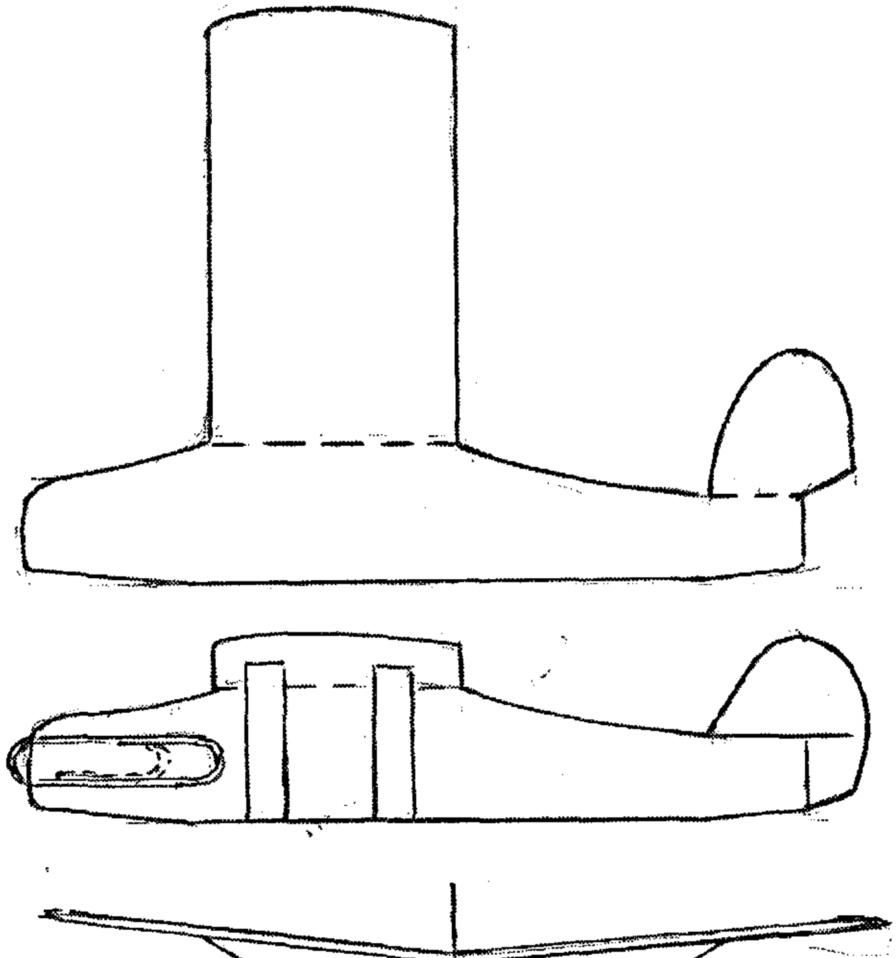
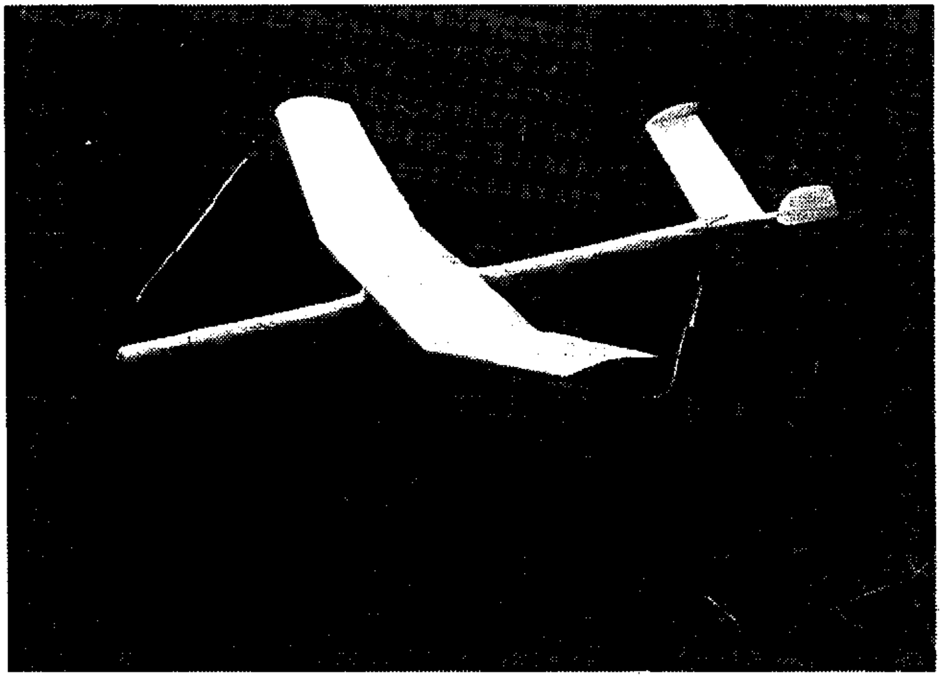


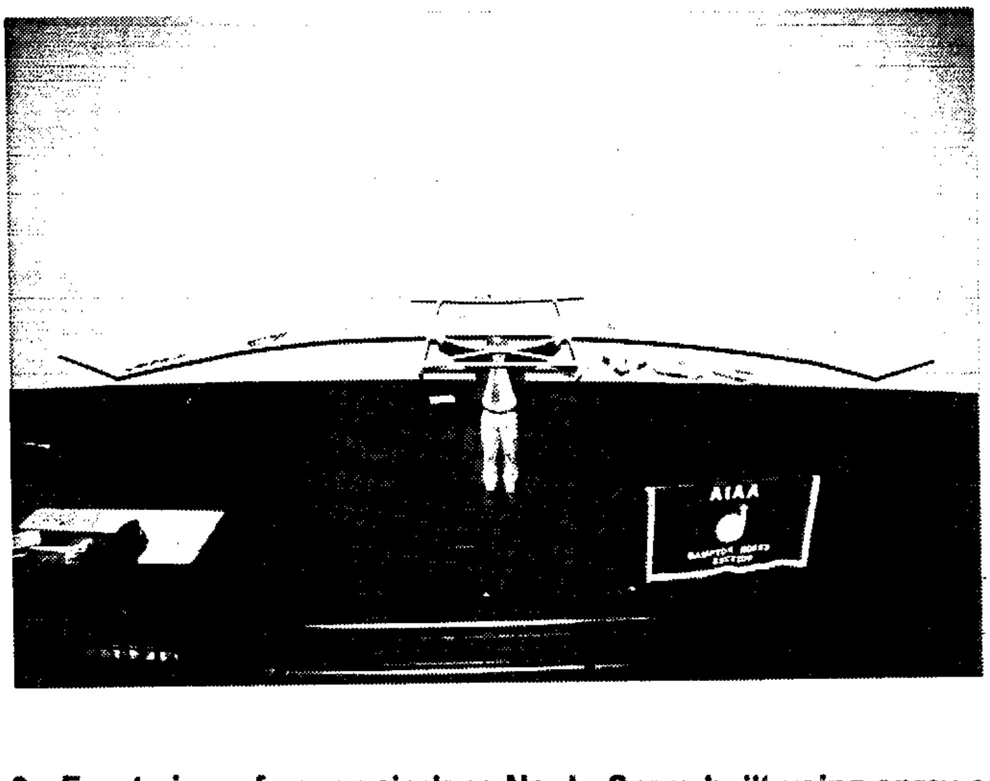




1. Paper airplane patterned after Lindbergh's "Spirit of St. Louis". Drawn from memory, 65 years later. Above: The Ryan NYP, "Spirit of St. Louis". and the Bell X-2.



2. Paper glider with 3 foot span, on a recycling container - a suitable place for it.

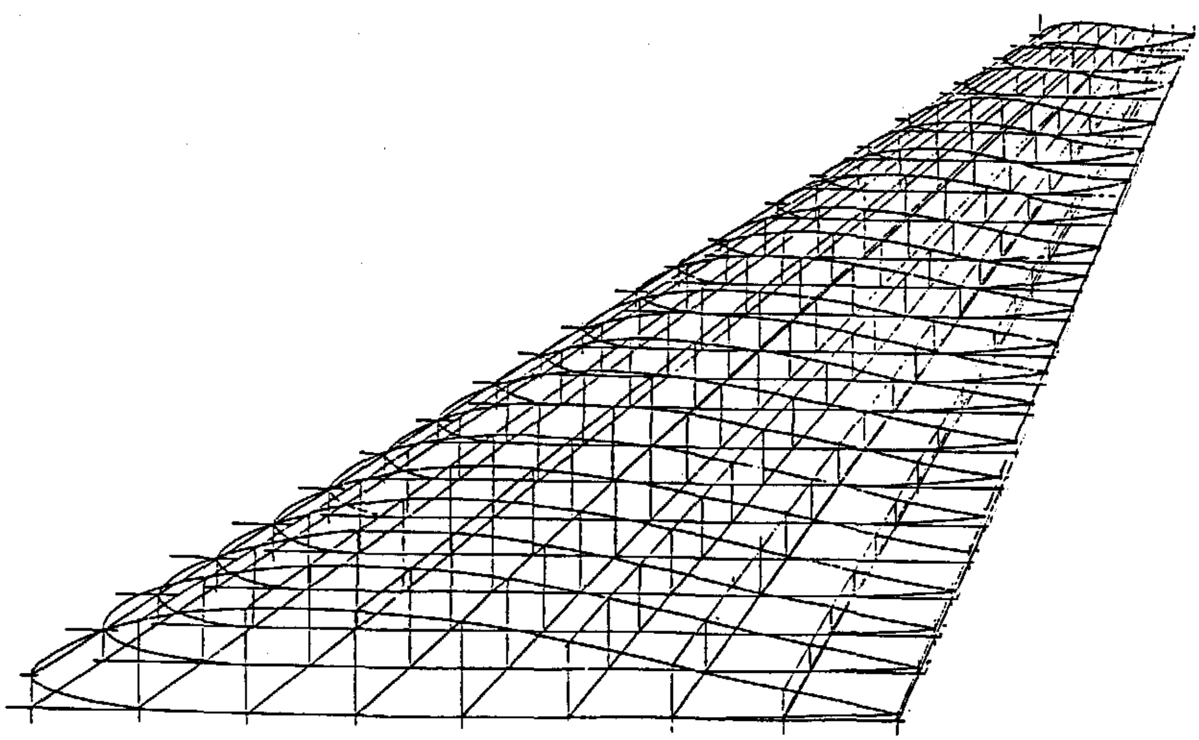


3. Front view of paper airplane No. I. Spars built using spray cement. 28 foot span, showing wing deflection under gravity.

ACCURATE LEADING EDGES

Many people still build sailplane wings from wood. No matter what construction method is used, the accuracy of leading edge contours is always a problem. By reflecting on this problem, instead of just doing it the same old way, Dennis Oglesby has come up with an improved method that is elegant, simple, and extremely effective. Adhesives and wood are very different in hardness and response shaping methods. In the process that Dennis presents here, the adhesive lines actually help, rather than hinder, the difficult process of achieving a consistent and accurate leading edge shape.

Is the day of the wooden model over? I think not, and although much attention today is directed toward the use of composites, most modelers, I think, still use wood of various types to build their models. Look in previous issues of Soartech to find data on all of the different types of wood that have been used to build models (and full scale aircraft as well). Wood is still a great medium for model building, and as the problems and toxicity of modern materials persist, we'll continue to need better techniques to for designing and building accurate wood model structures.



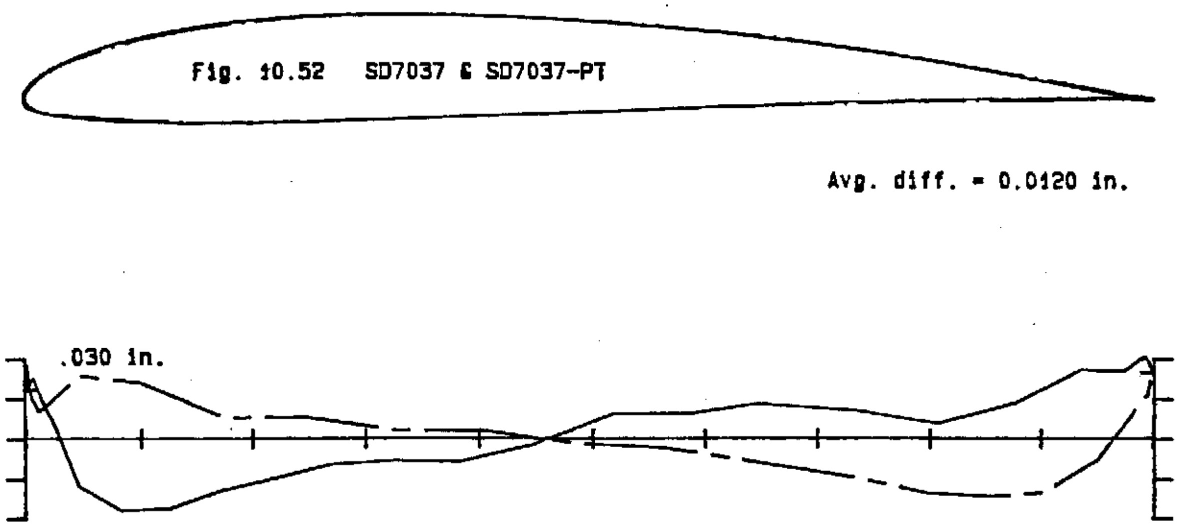


Fig. 10.52 SD7037 & SD7037-PT

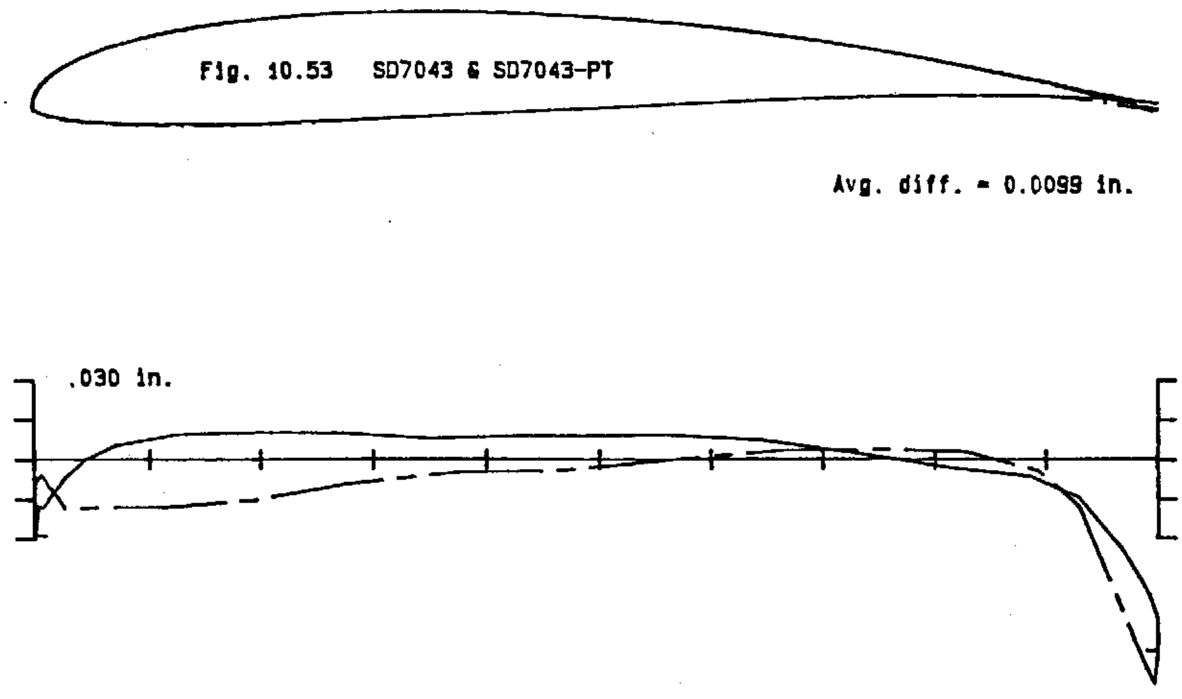


Fig. 10.53 SD7043 & SD7043-PT

BUILT-IN SHEETING

A Suggestion to Improve the Leading Edge Accuracy of sheet-on-ribs Wing Profiles.

Amongst the 400 pages of "Airfoils at Low Speeds" by Selig, Donovan and Fraser, is a most detailed study of the accuracy of "home built" wing panels. Trailing edges were found to be variable with various types of construction, but note also the following quoted passage:-

> "Built-up, sheeted models tended to have a problem with the blend between the leading edge and the beginning of the sheeting".

So why should one of England's least prolific model builders dare to attempt an article on construction techniques? The answer starts with at least 4 years of my engineering studies which involved the effects of loads on structural beams. We were encouraged to understand how each type of loading caused beams to adopt particular types of subtle curvature.

Later on, when my unskillful fingers fumbled to create good profiles from ribs and sheeting, this training helped me to see quite clearly what the problems were. Although I have produced a mere four new gliders in the last 19 years (ouch!), they have all featured "built-in sheeting" as described in this article. So far, I have not seen any other glider plan using this method. The above quotation induced me to publish it.

Rib and sheet construction involves the bending of sheeting onto ribs so that the sheeting outer surface, when covered, becomes that subtle curve that is the desired aerofoil surface.

Now try to visualise that sheeting as an enormously wide beam being loaded and bent to achieve the aerofoil profile. Fig.1 shows sheeting being bent onto ribs by loads A and B. Some diffuse loading between A and B is also necessary for accuracy and strong adhesion, but as long as the profile is curved all the way across, full sheeting contact demands considerable loading at A and B. In practice there will always tend to be a situation shown in the enlarged detail where, over a short length, the leading edge sheeting will muster enough resistance to hold itself off the rib profile. Here, the sheet curvature decays to zero (it becomes straight). This is not compatible with most aerofoils where profile curvature tends to be progressively increasing towards the leading edge (Fig.2). Just as important, there will be other distortions across the gaps between the ribs.

Fig.3 illustrates the classic cantilevered beam as taught to many types of engineering student. It is simply a beam which is "built-in" to a solid (ideally rigid) support at one end. The typical load "A" induces a natural curve in the beam which is actually zero (straight) at the point of loading, and increases progressively towards the built-in end.

Beginning to get the message? The remaining illustrations follow the construction that I use to assist in achieving accurate and consistent L.E. profiles.

Fig.4. Design Stage. Draw the nose of the desired profile to magnified scale. Decide how thick you need your L.E. strip ("a") and draw in it's aft face at 90° to the bottom of the profile curve. This, together with the thickness allowance for sheeting and covering, determines the profile of the rib - Fig.5.

Fig.6. Prepare the complete bottom sheeting flat with accurate butted sheeting joints as required. Trim L.E. of sheeting with a straight-edge and glue on the rectangular L.E. strip. Mark on the locations of the rib.

Fig.7. I do this stage in my hands, glueing the ribs into place one at a time, firmly forcing the L.E. strip onto the front of the rib. Be careful to place the corners of the ribs right into the corner between the L.E. strip and the sheeting. Providing an adequately sized L.E. strip is used, a built-in beam effect is achieved with a progressive increase in curvature towards the L.E. Also, this curvature should be closely held all the way across the gaps between the ribs.

Fig.8. After completing the spar and other wing internals, start the top sheeting by re profiling the top of the L.E. strip to be optically (i.e. eyeball!) in line with the tangent shown.

Fig.9. Prepare the top sheeting flat similar to the bottom. Then, with the wing well supported (with any intended twists set in), apply a "fast glue" to the L.E. strip and a "slow glue" to the rib tops. Fix the top sheeting firmly to the L.E. strip. When the "fast glue" has taken, apply closing forces (old magazines!) to the sheeting-to-ribs joints. The top sheeting will now be "built-in" so as to have progressively increasing curvature towards the nose. Again, this will be closely maintained across gaps between the ribs.

Accurate finishing of the nose profile is still required and could easily justify a separate article by builders better qualified than myself.

........./......

My method starts with the marking of ink lines all along the L.E. at D, E and F where the aerodynamic profile should be tangential to the current construction profile. My favoured tool is a really flat hardwood strip about 7" x 1¾" x 5/16" with fine and medium glass paper glued flat onto opposite faces. The ink lines should ideally not vanish. I do the job outside in clear sunshine so that the casting of light and shadow around the L.E. shows up any inconsistencies. Fig.11 shows how correct alignment of the wing, sanding tool and sun causes any local section down the wing to become visible. In Fig.11, the far edge of the shadow shows what I aim for, but the near side of the shadow shows a typical problem caused by the harder emerging glue line. Fig.10 shows how the sanding tool flatness is used to sand away the glue without removing any more of the surrounding wood than is needed.

Discussion with George Stringwell obtained his suggestion in Fig.12. The same principles are to be used to control the sheeting, but a double L.E. strip results which prevents the emergence of glue lines. The second strip is fixed after the top and bottom sheeting has been cut back into line. Glue is applied only to the centre zone of the joint, and one has the option of trying a harder material at the front.

Tapered Wings:

For constant aerofoil, taper the "a" dimension pro rata.

Heavily Swept Leading Edges:

The angle cut at the front of ribs will be affected by significant amounts of sweep. I have developed a solution in 3 dimensional trigonometry and applied it to my "Clockwork Kestrel" tailless mini glider.

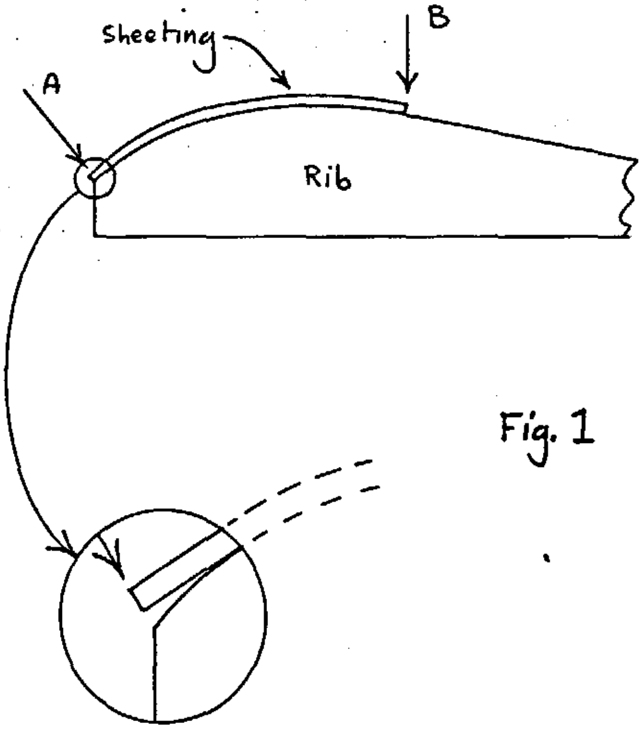


Fig. 1

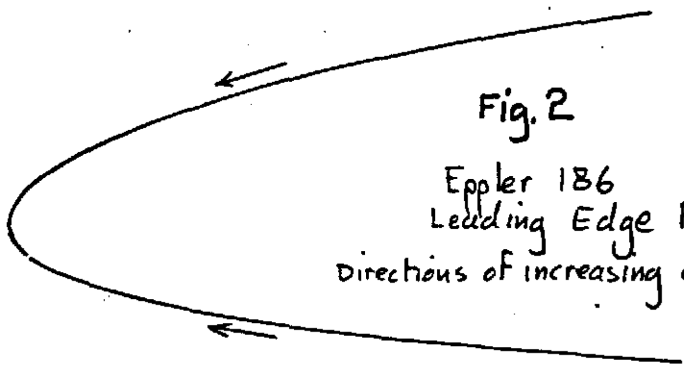


Fig. 2

Eppler 186
Leading Edge Profile
Directions of increasing curvature

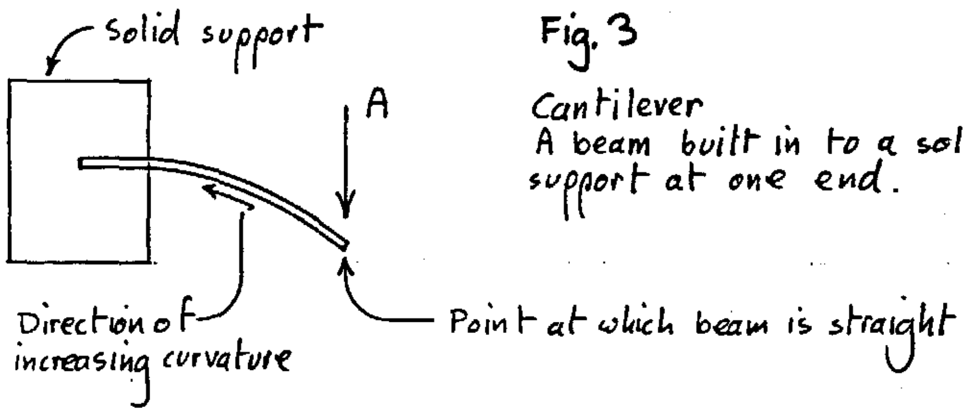


Fig. 3

Cantilever
A beam built in to a solid support at one end.

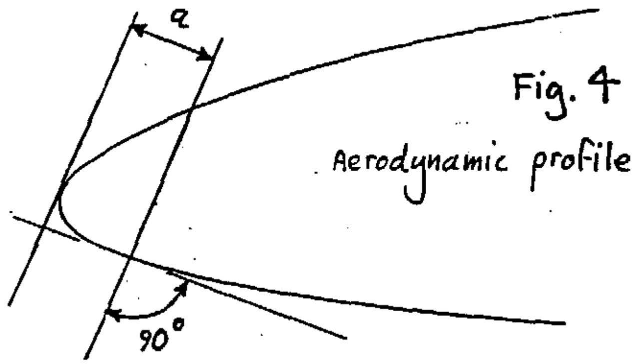


Fig. 4

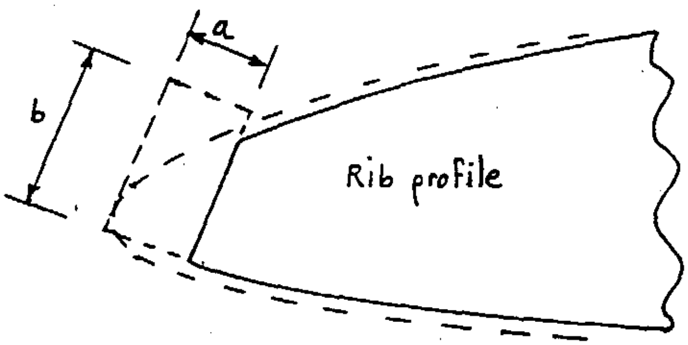


Fig. 5

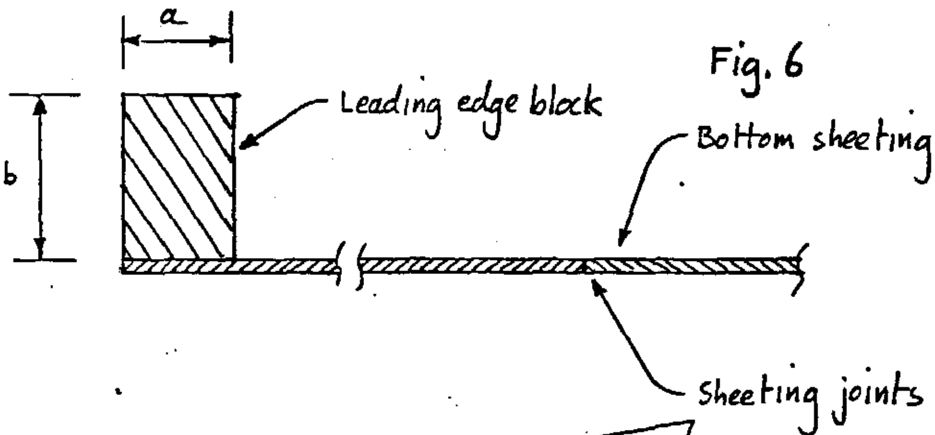


Fig. 6

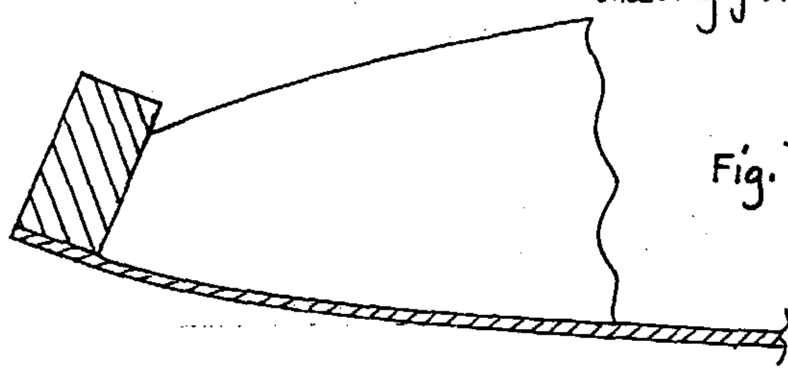


Fig. 7

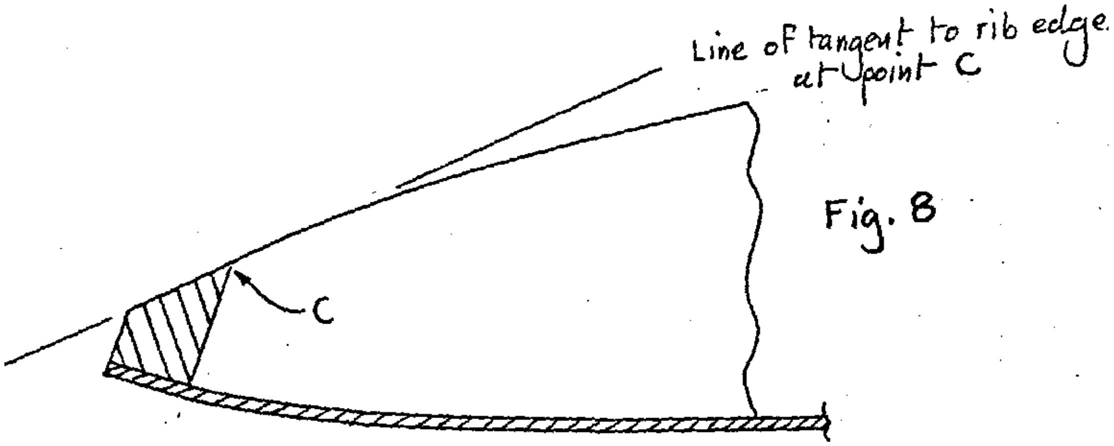


Fig. 8

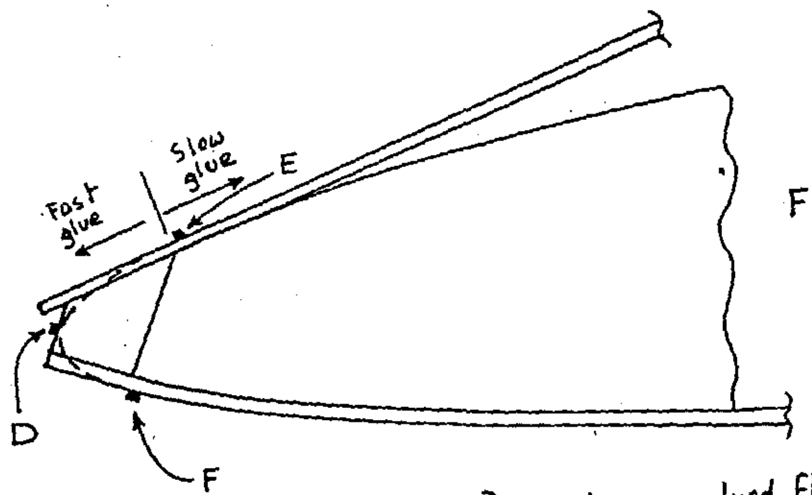


Fig. 9

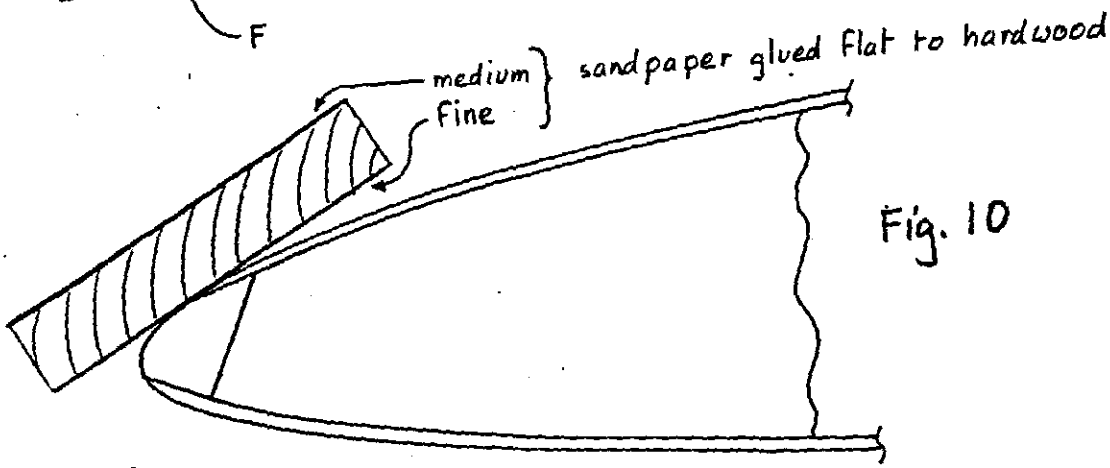


Fig. 10

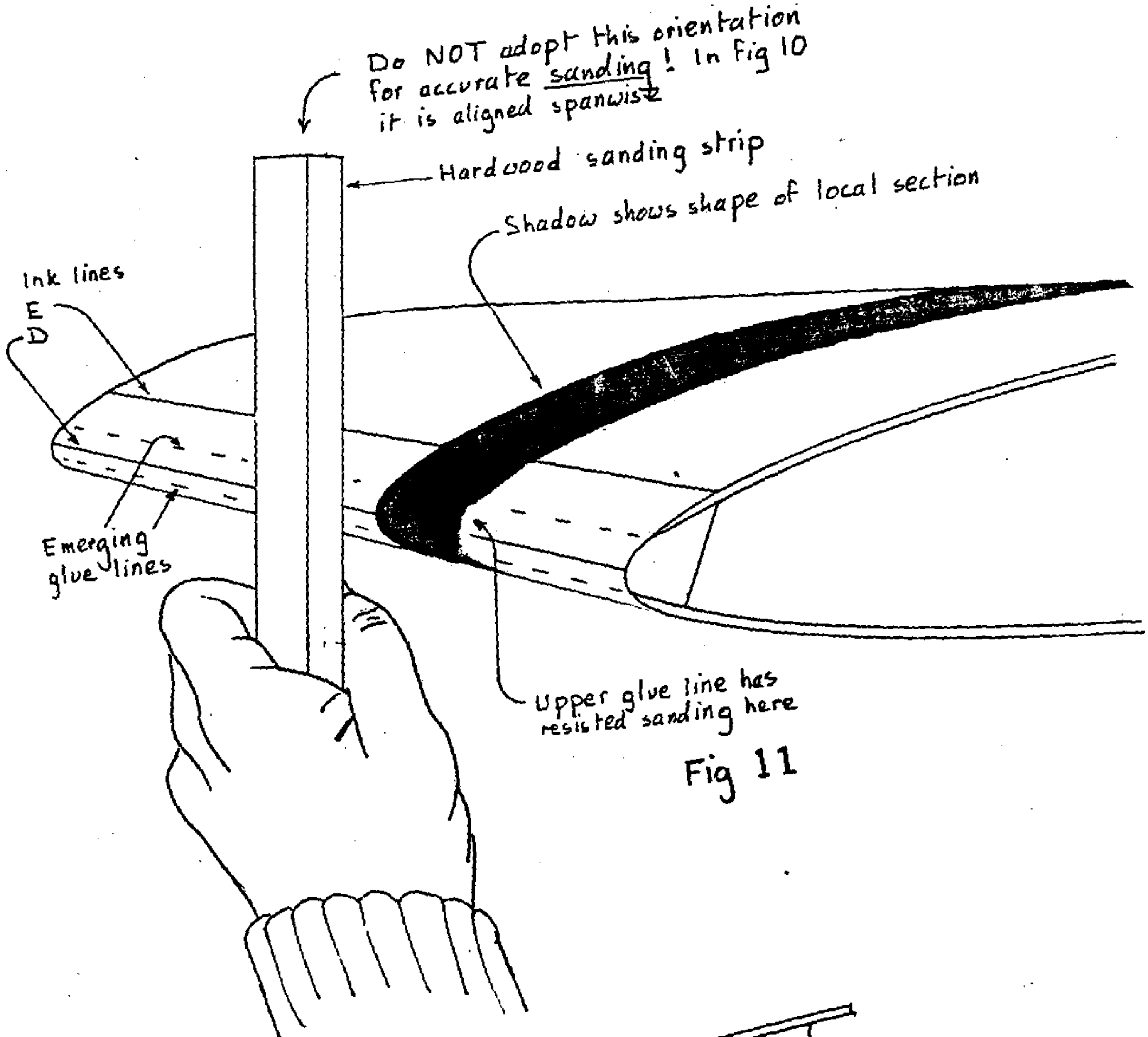

Do NOT adopt this orientation
for accurate sanding! In Fig 10
it is aligned spanwise
Hardwood sanding strip
Shadow shows shape of local section
Ink lines
E
D
Emerging glue lines
Upper glue line has resisted sanding here

Fig 11

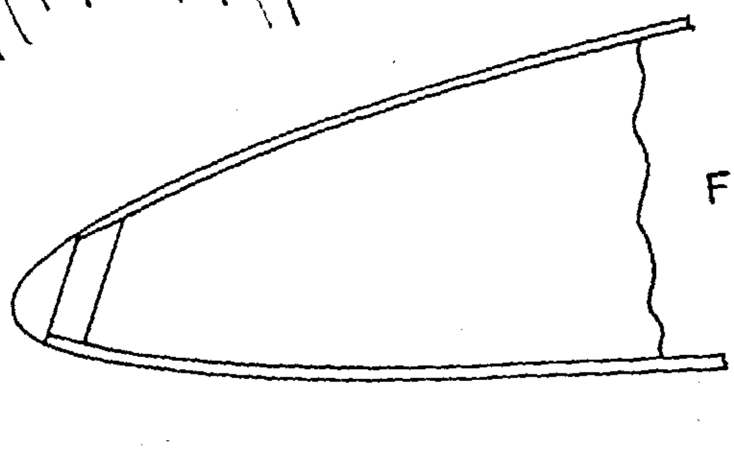
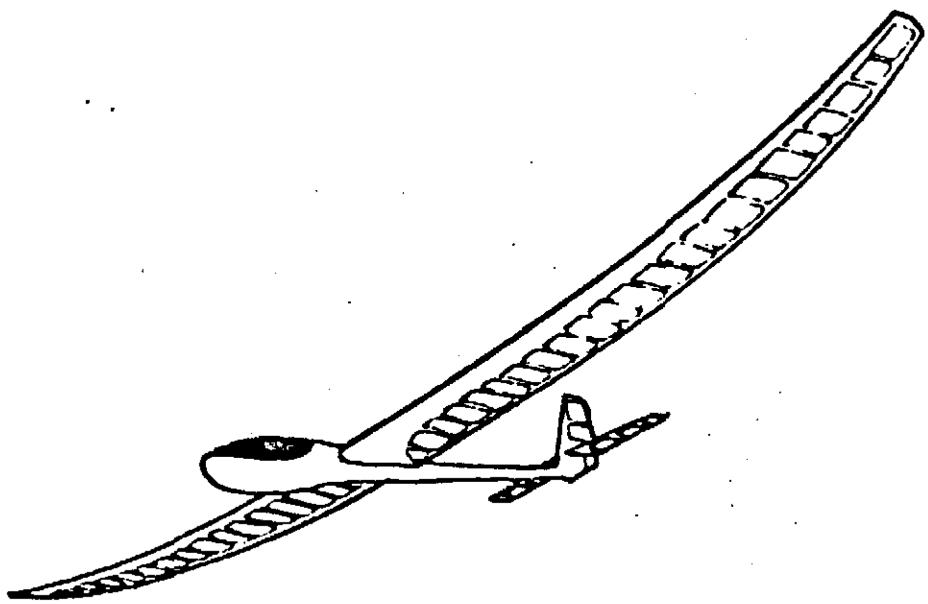
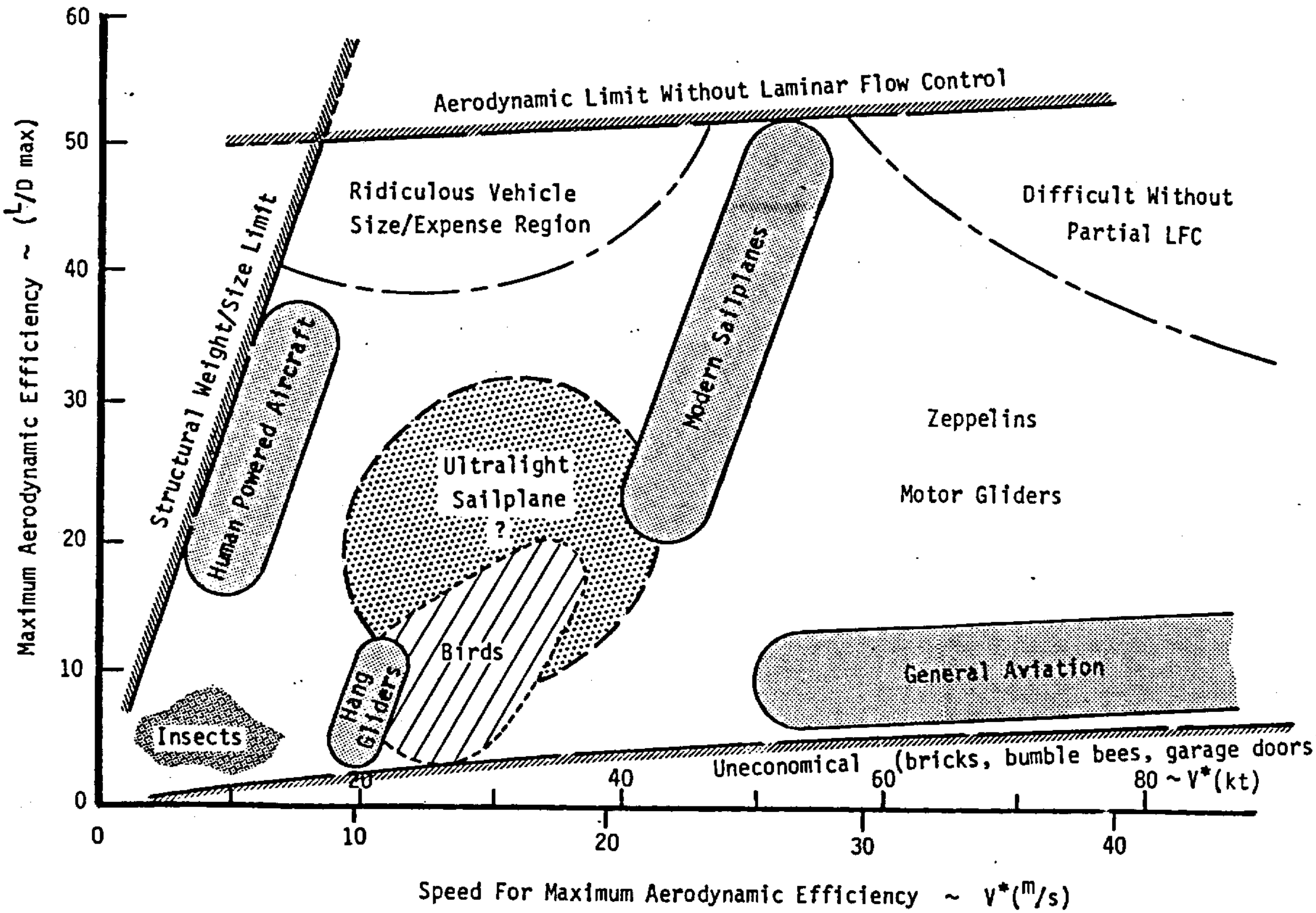


Fig 12





Maximum Aerodynamic Efficiency ~ (L/D max)
Speed For Maximum Aerodynamic Efficiency ~ V*(m/s)
80 ~ V*(kt)
Aerodynamic Limit Without Laminar Flow Control
Structural Weight/Size Limit
Ridiculous Vehicle
Size/Expense Region
Difficult Without
Partial LFC
Human Powered Aircraft
Modern Sailplanes
Ultralight
Sailplane
?
Zeppelins
Motor Gliders
Birds
Hang
Gliders
Insects
General Aviation
Uneconomical (bricks, bumble bees, garage doors)