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THE FLIGHT PERFORMANCE OF AN RPV COMPARED WITH WIND TUNNEL AND THEORETICAL (CFD) RESULTS

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Abstract

A number of aerofoil sections suitable for remotely piloted vehicles were tested at full scale Reynolds numbers in the College of Aeronautics 2.4m x 1.8m low speed wind tunnel. From force measurements, pressure distributions and flow visualisation three were selected for further study, namely the Göttingen 797, NACA 64_3-418 and Wortmann FX63-137 aerofoils.

The pressure distributions and force measurements on these three wings were used to validate the mathematical model proposed by Williams at RAE. The difficulties involved in predicting the flow around aerofoils at these low Reynolds numbers ($3x10^5 < Re_c < 10^6$) include transition, laminar separation bubbles, turbulent re-attachment and turbulent separation. Williams' theoretical program is able to cope with these phenomena and comparisons between theory and experiment show that the CFD code has great promise.

The three wing sections were further tested experimentally with roughness added. The performance was degraded by roughness for all three aerofoils but overall the Wortmann section was superior.

A full scale solid model of the RPV (X-RAE 1) was tested in the RAE 7.3m tunnel with its original (flat bottomed) wing and with a new wing of FX63-137 section. Substantial gains in C_{Lmax} and L/D ratio were recorded.

A fully instrumented and radio controlled example of X-RAE 1 was then made available and a new wing of FX63-137 section was built at Cranfield. Extensive flight trials were made using X-RAE 1 with both the 'old' and 'new' wings. Sixteen channels of information were telemetred to the ground control unit to enable lift and drag measurements to be made in flight. The flight tests confirm the superiority of the Wortmann section but also show the large drag increases due to the many practical features of a real flying vehicle such as cooling, roughness, gaps, cut-outs, bumps and wing/tail/fin/body interference.

I. Introduction

The Royal Aerospace Establishment at Farnborough has been developing a series of small remotely piloted vehicles with a wing mean chord of typically 0.3m. At a flying speed of between 20 and 50 m/sec the relevant Reynolds numbers are between 3×10^5 and 1.0×10^6. Wind tunnel measurements in this range are relatively sparse. Under an MoD contract experimental data on seven different smooth aerofoils were obtained by Render (Ref.1). The sections tested were the Göttingen 797, NAC 64_3-418 and Wortmann FX63-137, plus four modified Wortmann Sections in which the underchamber was progressively reduced. In Render's tests both the Göttingen and unmodified Wortmann sections had superior lift/drag ratios and the FX63-137 had the highest C_{Lmax}.

Davidson (Ref.2) repeated some of Render's tests in the same wind tunnel before going on to investigate the effects of roughness bands placed close to the leading edge on both upper and lower surfaces. Davidson concentrated on the three unmodified aerofoils (64_3-418, 797 and 63-137) and showed that the performance of all three was degraded but the Wortmann section suffered least and retained its overall superiority. All the sections tested are shown in Fig.1(a).

As a result of these investigations the RAE built a full scale solid wind tunnel model of X-RAE 1 and tested it with the original wing, whose flat bottomed section is drawn in Fig.1(b), and then re-tested it with a wing of FX63-137 section. The report by Trebble (Ref.3) showed the new wing to be better.

The final step in the investigation was to undertake flight trials of a fully instrumented RPV using each of the two wings. The flight trials were made at Cranfield during 1987 and the results are given here.

II. Experimental Details

The wind tunnel measurements were made in the College of Aeronautics 8'x6' (2.4m x 1.8m) closed-working-section, closed-return, low-speed facility at velocities between 10 and 45m/s. The experimental arrangement is shown in Fig.2. The quasi-two-dimensional tests were made with the constant-chord model reaching from roof to floor with a 3mm gap at the lower end. This gap enabled force measurements to be made using the overhead six component electro-mechanical balance. A removable tip section converted the model into a three-dimensional half wing of known aspect ratio.

Tests were made at Reynolds numbers (based on the wing chord of 343mm) of 3×10^5, 5×10^5 7×10^5 and 1×10^6.

The models were made of wood and had a smooth polished finish. In this condition there were large areas of laminar flow over both the top and bottom surfaces (Ref.1). Under real conditions the leading edge of an RPV wing is likely to become roughened and in order to measure the likely degradation of performance some of the test were repeated with roughness strips added.

The roughness used was a 13mm (half-inch) band of 100 grit sand-paper with adhesive backing. The band was placed near the leading edge (between 0.04 and 0.08 x /c) on both upper and lower surfaces. Although the grit size was only 0.15mm the average height of the grit including the paper backing was 0.53 mm and it was probably the 'steps' at the leading and trailing edges of the roughness band that promoted transition.

The roughness criterion given by Schlicting (Ref. 4) states that for transition to be at the roughness station the roughness height K must exceed $900\nu/U$ (i.e. $K/c > 900/Re_c$). Given K = 0.53 mm and c = 343 mm this means that Re_c should exceed 0.58×10^6. This suggests that for the tests at $Re_c = 3 \times 10^5$ reported here, transition will have been promoted but may not have occurred at the roughness station.

Force and moment measurements were made using the six component balance located above the tunnel roof. A Betz manometer measured and monitored the wind tunnel test velocity.

The pressure measurements used about 40 ports in each surface, coupled via Scanivalves to Setra or Furness pressure transducers. The pressure ports were in a single line near the mid-span position. They were sealed with wax when force measurements were being made.

The conditions in the wind tunnel test section are known to be particularly important for tests at low Reynolds numbers. Recent measurements along the tunnel test section centre line indicated a turbulence intensity of 0.07% at a freestream velocity of 20 m/s rising to 0.14% at 50 m/s. Spectra taken for the frequency range 0 - 1000 Hz showed no obvious peaks which suggests that the turbulence is small scale and covers a broad band of frequencies.

Further details of the test procedures and wind tunnel corrections are given in Refs. 1 and 2.

The wind tunnel tests made at the Royal Aircraft Establishment (RAE) Farnborough, used a smooth, solid, wooden full-scale model of X-RAE 1 as drawn in Fig. 3. The model was wire mounted in an inverted position from the overhead balance in the RAE 24 ft (7.3 m) diameter open-jet low-speed-wind-tunnel. Lift, drag and pitching moment measurements were made at velocities of 20, 30, 40 and 50 m/sec. with the original wing (whose section is shown in Fig. 1b) and with a wing of FX63-137 section (see Fig. 1a).

The full scale flight trials were conducted on the aerodrome at Cranfield. An alternative wing of FX63-137 section was built using the same materials and techniques as the original (wooden spars and ribs completely enveloped in a plywood skin).

The aircraft used for the flight tests is shown in Fig. 4 and some of the changes needed to carry the instrumentation are immediately apparent (e.g. a large fairing on top of the nose and booms mounted from both wings).

Although the wing and tail are of all-wood construction, the fuselage is a mixture of wood and glass fibre. The wing span is 2.7 metres and the launch weight 17.0 kg. Power is supplied by a Webra 91 two-stroke engine producing 1.1 kw at 10,500 rpm.

The aircraft is fitted with the Cranfield Digital Flight Control System (DFCS) which was designed and developed under an earlier MoD(PE) contract. The DFCS consists of a telecommand receiver to receive uplink signals from the ground station, a 16 bit digital Flight Control Computer (FCC) and a telemetry encoder for generation of downlink data for transmission from the aircraft to the ground station.

Sensors used in the aircraft are as follows: A J-TEC true airspeed sensor (TAS) is mounted in the nose fairing. The TAS operates by counting the vortices shed from a strut, the frequency being proportional to true airspeed.

The boom from the starboard wing carried a Prosser airspeed sensor, which operates on the hot wire anemometer principle. An angle of attack vane (AoA) is mounted forward of the port wing on a boom extending from the wing leading-edge.

Accurate calibration of the airspeed and angle of attack sensors was of vital importance to the flight trials. Calibration of both airspeed sensors and of the AoA vane was carried out using two of Cranfield's low speed wind tunnels. The JTEC TAS was calibrated in situ on the aircraft with the engine both running and static. The Prosser sensor and the AoA vane were calibrated individually, the results being corrected using data from the RAE 24 ft tunnel tests.

A sensitive barometric pressure sensor (designed and manufactured at Cranfield) is used to provide both absolute pressure data and subsequently height data, after processing in the DFCS.

Engine RPM are measured using an optical sensor to provide a pulse input to the DFCS which effectively counts the signals.

A three-axis rate gyro pack, using Smiths Industries type 902 gyros measures angular velocity of the aircraft in roll, pitch and yaw.

The aircraft controls are ailerons, elevator, rudder, throttle and airbrakes. The software installed for the flight trials provides three-axis rate-stabilisation, AoA acquire and height acquire modes.

The UHF telemetry downlink is received in the mobile ground station (a Ford Transit 22 cwt LWB van) and recorded, together with telecommand data, time data and voice communications, on a Racal Store 7 tape recorder.

The flight trials consisted of several flights to carry out long straight descents, using idle power, from typically 300 metres down to 100 metres.

Post flight analysis of the recorded data used angle of attack, true airspeed, barometric pressure, height, air temperature, time and RPM information (hence the thrust from propeller calibration data) along with the aircraft particulars.

III. Results and Discussion

The 'two-dimensional' data on seven aerofoils are summarised in Figs.5 and 6. At $Re_c = 3x10^5$ the Göttingen and Wortmann sections have a similar L/D ratio at lift coefficients up to about 1.2 (Fig.5a) but the Wortmann Section has a higher C_{Lmax}. At the higher Re_c of 1×10^6 the Wortmann section is clearly superior (Fig.5b). To help draw a curve through somewhat scattered data in the vicinity of the maximum (L/D) region for the FX section the experimental data at $Re_c = 7x10^5$ are also shown for this aerofoil.

The good performance of the Göttingen section is partly attributable to the flat bottom. This supports a zero or helpful pressure gradient so maintaining entirely laminar flow over the lower surface at these Reynolds numbers. It was therefore decided to modify the FX section by progressively flattening the lower surface as shown in Fig.1a. The results (Fig.6) show that the (L/D) ratios are slightly increased in the range $0 < C_L < 0.7$, the maximum (L/D) values are much the same but that C_{Lmax} is progressively lost as the undersurface is flattened.

The two-dimensional C_{Lmax} values as measured by Render on a smooth model are given in Table 1. The variation with Re_c is quite small. In fact the entire C_L-α curve changes little with Re_c within the range tested. However, the drag coefficients do change, decreasing progressively with increasing Re_c. This means that the (L/D) ratios improve with Re_c as can be seen by comparing Figs.5a and 5b.

By analysing all of Render's data it became clear that of the seven aerofoils tested the unmodified FX63-137 section was preferable. The lift/drag ratios were good throughout the C_L range, the maximum L/D values were similar to or better than any others measured, the maximum lift coefficient was the best recorded and C_{Lmax} changes very little throughout the range of Reynolds numbers of interest.

Davidson[2] studied the question of performance degradation due to roughness. Some typical results are shown in Fig.7 at $Re_c = 1x10^6$. This time the tip sections have been removed giving the characteristics shown in Table 2.

The measurements made with Göttingen 797 have been corrected to an aspect ratio of 8.9 so that sensible comparisons can be made.

Fig.7a shows that C_{Lmax} is significantly reduced by roughness and the 797 section suffers most. Fig. 7b confirms the '2D' smooth data in which the FX63-137 wing has higher lift/drag ratios than the Gö797 at the large C_L's and both are superior to the NACA section. The superiority of the Wortmann section is even clearer for the 'rough' aerofoils. The roughness strips promoting earlier transition, lead to much earlier separation of the turbulent boundary layer on the top surface of the Göttingen section.

The values of C_{Lmax} for the rough and smooth wings at an aspect ratio of 8.9 are given in Table 3. Comparison with Table 1 suggests there is a little loss of C_{Lmax} with aspect ratio in the range 8.9 to 'infinity'.

Because the Wortmann section looked so promising Trebble carried out tests on the experimental RPV designated X-RAE1. The characteristics of the vehicle are given in Fig.3 and the original wing section in Fig. 1b.

Some results from Trebble's[3] report are shown in Fig.8. Although the drag results are similar (in fact both models have the same drag over the C_L range 0.2 - 1.0) the gain in C_{Lmax} from the Wortmann section is dramatic. For comparison some estimates from our tunnel data for a wing alone with the same aspect ratio as the X-RAE model are included. The loss of C_{Lmax} due to wing body intereference is clearly visible and the drag increase due to fuselage drag,fin drag and interference drag is very significant.

Finally the flight data are shown in Fig.9 in comparison with Trebble's wind tunnel measurements. The C_L values are for the complete model in the trimmed condition whereas the C_D tunnel values are tail-off though this would only account for a small drag difference in comparison with the flight values.

The first thin to notice is the scatter in the flight data. Great care was taken butflight measurements are infinitely more difficult than those made in the well controlled environment of the wind tunnel. In particular it is very difficult to measure C_{Lmax} in flight. Nevertheless, the flight data (Fig.9a) confirm most of the C_L - α curves measured in the RAE tunnel and the benefit in C_{Lmax} in flight is clearly demonstrated.

The drag values measured in flight show a large scatter and a least squares fit has been made to the data. Fig.9b shows that the flight drag values are considerably greater than the tunnel values and reference to Figs.3 and 4 shows why. The flying vehicle had a much blunter nose,with a large airspeed sensor mounted in a fairing on top, instrumentation booms on both wings, cut outs, excrescences, propellor interference, engine cooling drag, tail drag and trim drag. The result is that the flight values are nearly double the tunnel values. A real production RPV would not have all the 'instrumentation drag' of our vehicle so the comparison is a harsh one. Nevertheless the comparison in Fig.9b serves to highlight the very real differences between actual flight vehicles and smooth wind tunnel models. To emphasise the point Fig.10 shows the L/D vs C_L plot for a rectangular wing-alone of aspect ratio 7.5, the tail-off data of Trebble and the flight data measured at Cranfield. The wing section is the Wortmann FX63-137 for all the data shown. Starting with a clean wing-only the $(L/D)_{max}$ is around 25.

This reduces to about 18 for the smooth wind tunnel model of the complete vehicle (less tail), whilst the actual experimental example of X-RAE1 in flight only manages a value of 10.

The values of C_{Lmax} for the various configurations are given below for the Wortmann aerofoil FX63-137 at $Re_c = 1 \times 10^6$.

2D wind tunnel value (smooth)	1.68
AR = 8.9 wind tunnel value (smooth)	1.68
AR = 8.9 wind tunnel value (rough)	1.40
Full scale model of X-RAE1	1.55
Flight data	≃ 1.45

IV Comparisons Between Theory & Experiment

The Computational Program

Full details are given in the paper by Williams[5]. The program uses an integral boundary layer method which has been extended to calculating separated flow by assuming a two parameter description of the separated profiles. The program is of the semi-inverse type in which a direct inviscid calculation is coupled to an inverse calculation of the boundary layer.

The outer inviscid flow is assumed here to be both incompressible and irrotational so that it can be described by the relevant solution of Laplace's equation.

The inner viscous flow is more difficult. The laminar portion of the boundary layer is calculated by Thwaites method and natural transition is predicted using Granville's correlation. If laminar separation occurs before transition then the development of the laminar separation bubble is calculated using Horton's semi-empirical technique. The development of the turbulent boundary layer and wake are calculated by the inverse formulation of Green's lag-entrainment method as outlined in the report by East et al[6].

Williams has given a number of comparisons between his calculations and our experiments in Ref. 7. Fig. 11 shows how well his method can predict the pressure distributions even when there are large areas of separated flow on the upper surface. Fig. 12 gives a more demanding comparison in which the measured and predicted transition points and separation points are plotted. As noted in previous comparisons the prediction of transition is rather earlier than measured and occurs through a short bubble rather than 'naturally' as measured. Overall the predictions are remarkably good. Fig. 13 compares the measured and predicted values of drag for the wing of FX63-137 section with an aspect ratio of 8.9 at a Reynolds number of 7×10^5. The predicted values take the form drag as calculated by Williams and add the induced drag calculated by $C_{Di} = 1.04\, C_L{}^2/\pi A$. The prediction is in good agreement with the measured values. The greatest difference between the predicted and measured values of form drag (obtained from experiment by subtracting C_{Di}) is less than 0.002.

V Conclusions

1. Of the aerofoils tested the FX63-137 and the Göttingen 797 achieved a high C_{Lmax} and good L/D ratios in the relevant Reynolds number range ($3 \times 10^5 < Re_c < 10^6$) for small RPV's.
2. Roughness strips degraded the performance of the three aerofoils tested (NACA 64_3-418, Gö797 and FX63-13) but the Wortmann section was the least affected.
3. The CFD program developed by Williams is very useful. It can cope with the phenomena of laminar separation, transition, turbulent re-attachment and turbulent separation down to Reynolds numbers of 5×10^5.
4. Flight trials are very difficult in comparison with wind tunnel tests. They demand extreme care and great perseverance. Nevertheless, the flight data are the final proof of the value of any modification. In our tests the flight results confirmed the benefit in C_{Lmax} from changing the wing section. The drag measurements showed that excresence and interference drag dominated the total drag figure and completely swamped any small benefits achieved by the wing alone.

VI Notation

A or AR	Aspect Ratio
c	Mean chord
C_D	drag coefficient
C_L	lift coefficient
C_p	pressure coefficient
D	drag
K	roughness height
L	lift
Re_c	Reynolds number $U\nu/c$
t	Aerofoil thickness
U or U_0	test velocity or flight speed
x	streamwise co-ordinate
α	incidence
ν	kinematic viscosity of air

VII References

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   see also:
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VIII Acknowledgements

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IX Tables

Table 1. Maximum lift coefficients measured from quasi two-dimensional tests in the 8' x 6' wind tunnel. Ref. 1.

Section \ Re_c	3×10^5	5×10^5	7×10^5	1×10^6
NACA 64_3418	1.21	1.22	1.24	1.26
Gö 797	1.56	1.55	1.52	1.49
FX63-137	1.69	1.69	1.68	1.68
FX63-137 I	1.64	1.57	1.55	1.55
FX63-137 II	1.59	1.53	1.52	1.51
FX63-137 III	1.57	1.51	1.49	1.48
FX63-137 IV	1.49	1.44	1.41	1.40

Table 2.

Wing Section	64_3-418	FX63-137	Göttingen 797
Chord	343mm(13.5")	343mm(13.5")	343mm(13.5")
Semispan	1.523m(60")	1.423m(60")	1.366m(53.8")
Effective AR	8.9	8.9	8.0

Table 3. Maximum lift coefficients measured from finite aspect ratio half model tests in the 8' x 6' wind tunnel Ref.2.

Section	NACA 64_3-418		Gö797		FX63 - 137	
Re_c	Smooth	Rough	Smooth	Rough	Smooth	Rough
	AR = 8.9		AR = 7.9		AR = 8.9	
3×10^5	1.25	1.13	1.59	1.13	1.67	1.51
5×10^5	1.25	1.11	1.57	1.08	1.64	1.50
7×10^5	1.27	1.10	1.55	1.05	1.68	1.41
1×10^6	1.30	1.11	1.55	1.05	1.68	1.41

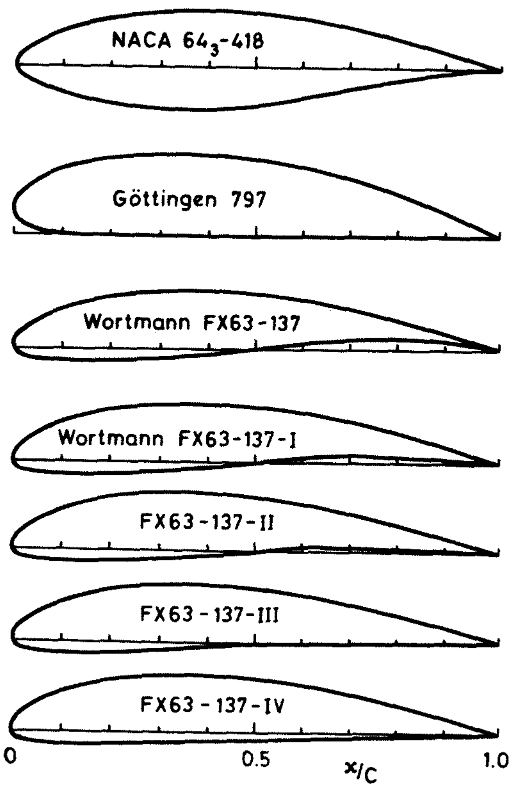

Figure 1.a. The seven aerofoils wind tunnel tested.

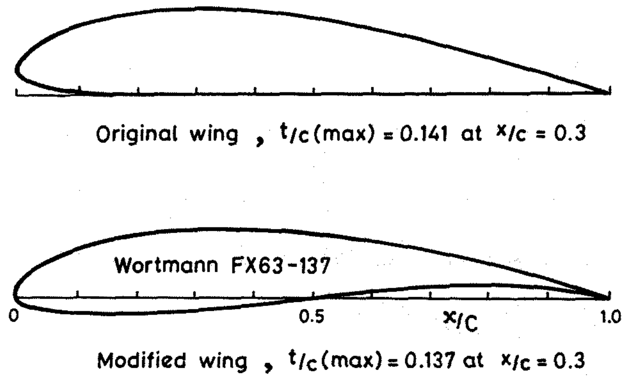

Figure 1.b. The wing sections for X-RAE 1.

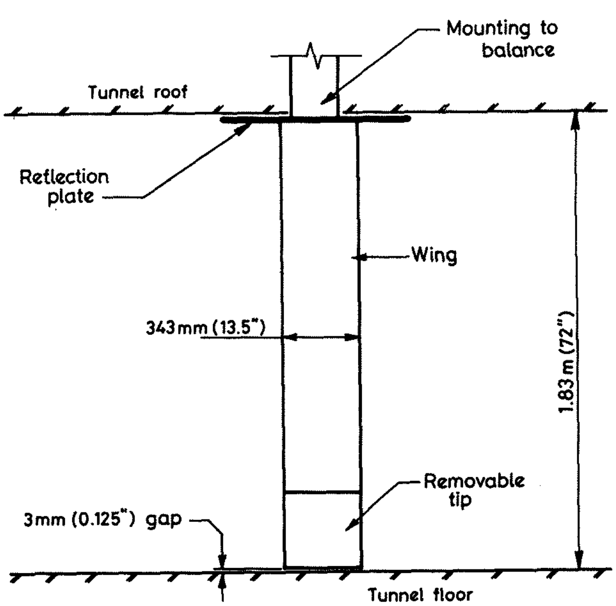

Figure 2. Experimental arrangement in 2.44 m x 1.83 m (8 ft x 6 ft) low speed wind tunnel.

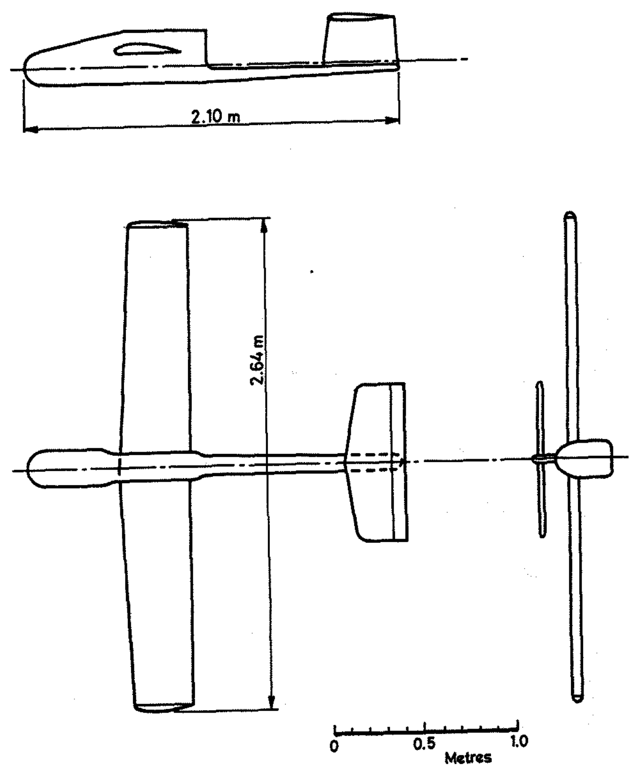

Figure 3. Wind-tunnel model of X-RAE 1 with rounded tips.

Figure 4. The X-RAE 1 RPV ready for launch.

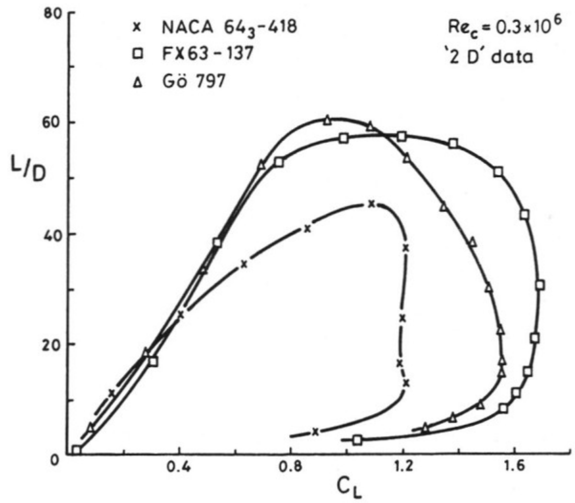

Figure 5.a. Lift-drag ratios for the 3 wings.

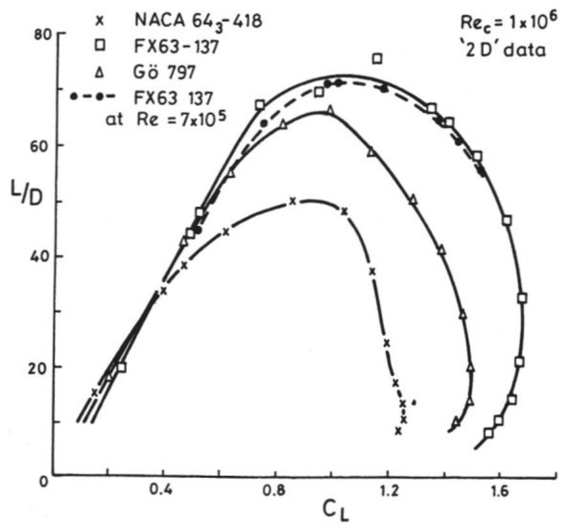

Figure 5.b. Lift-drag ratios for the 3 wings.

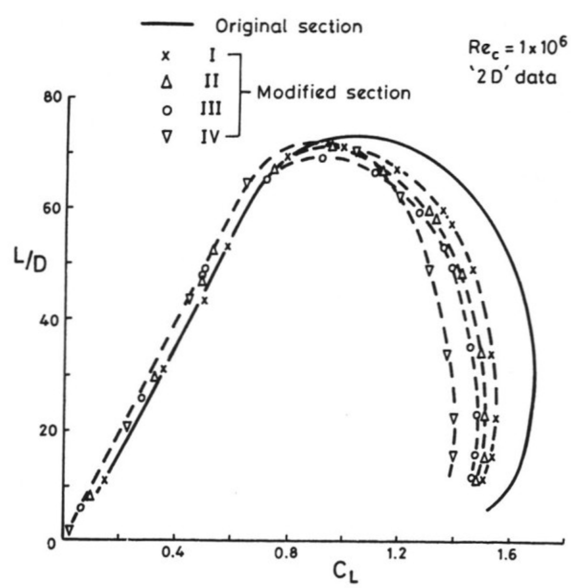

Figure 6. Lift-drag ratios for the original and modified versions of FX63-137.

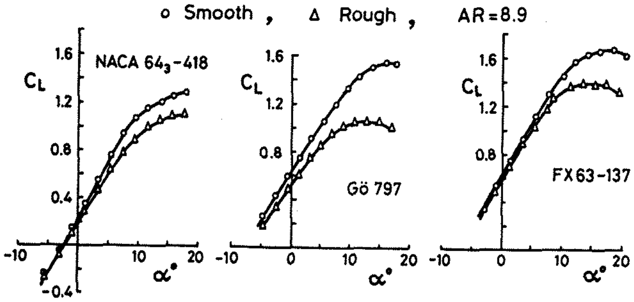

Figure 7.a. Effect of roughness on lift for three aerofoils at $Re_c = 1 \times 10^6$

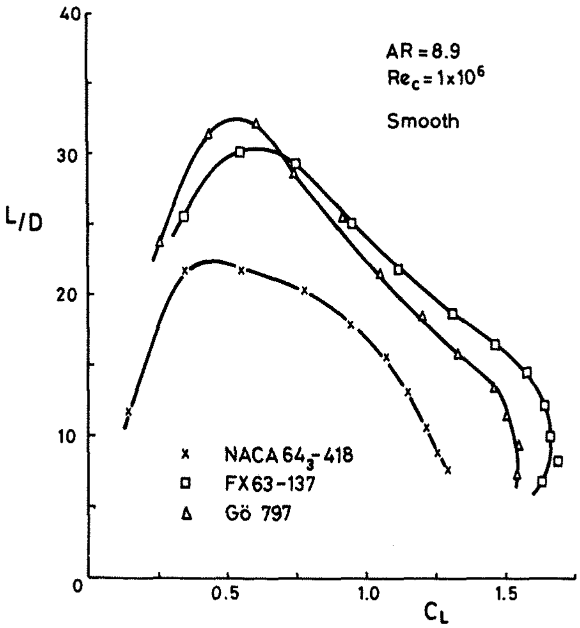

Figure 7.b. Lift-drag ratios for the smooth wings.

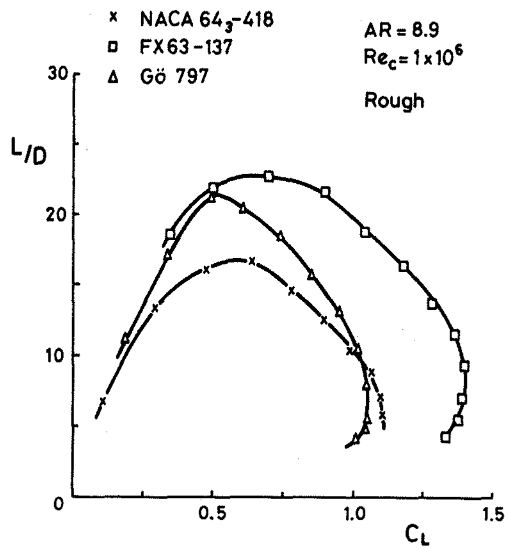

Figure 7.c. Lift-drag ratios for the rough wings.

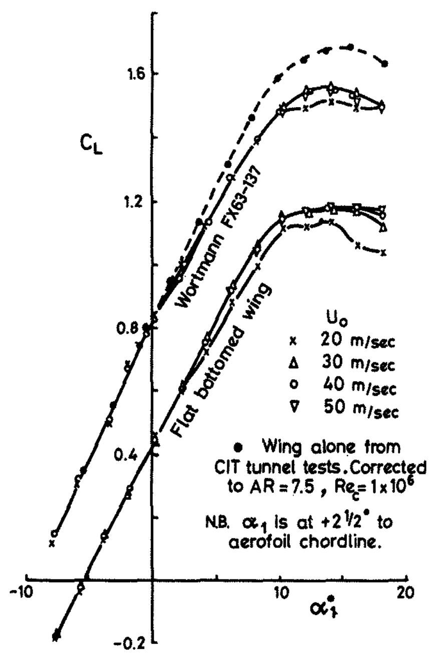

Figure 8.a. Lift of X-RAE 1 without tailplane, rounded wing tips.

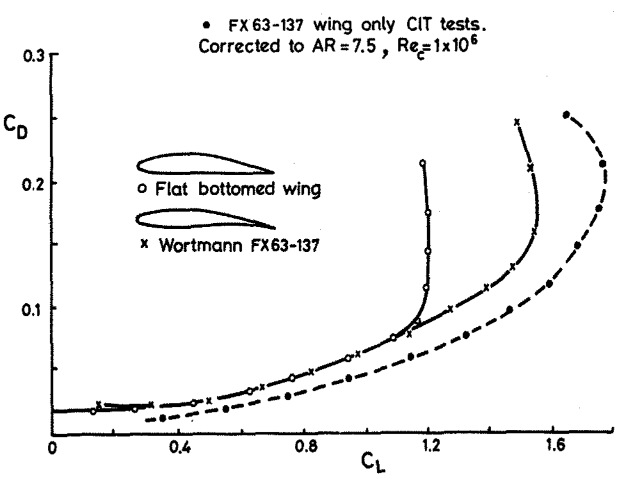

Figure 8.b. Drag of X-RAE 1 without tailplane, rounded wing tips, $U_o = 40$ m/sec

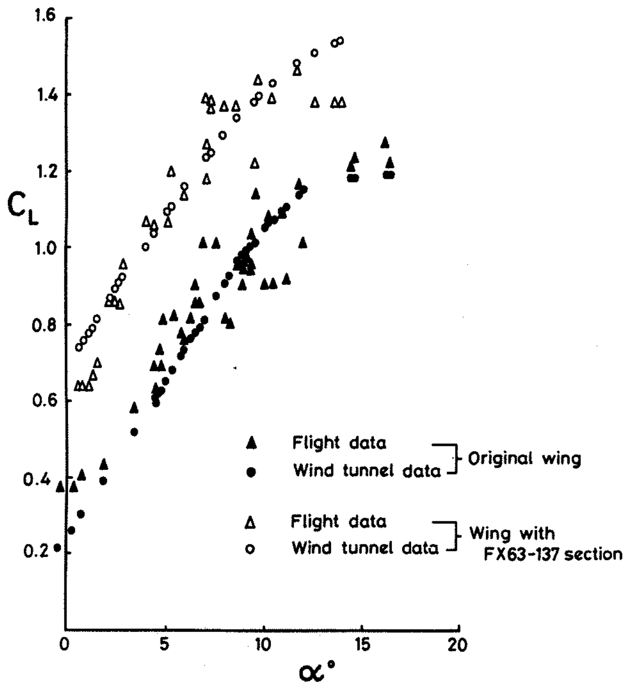

Figure 9.a. Comparison between flight and wind tunnel data for X-RAE 1.

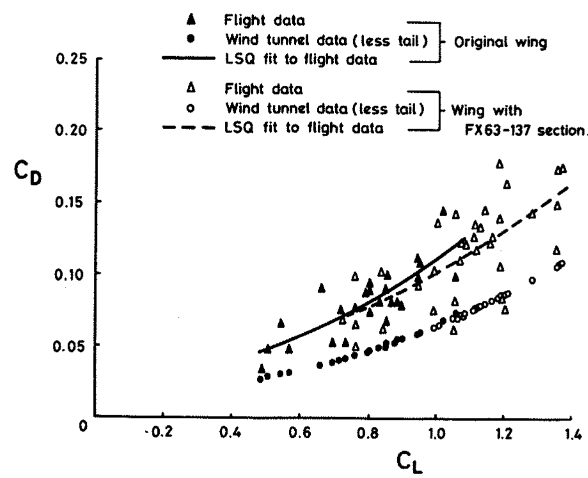

Figure 9.b. Comparison between flight and wind tunnel data for X-RAE 1.

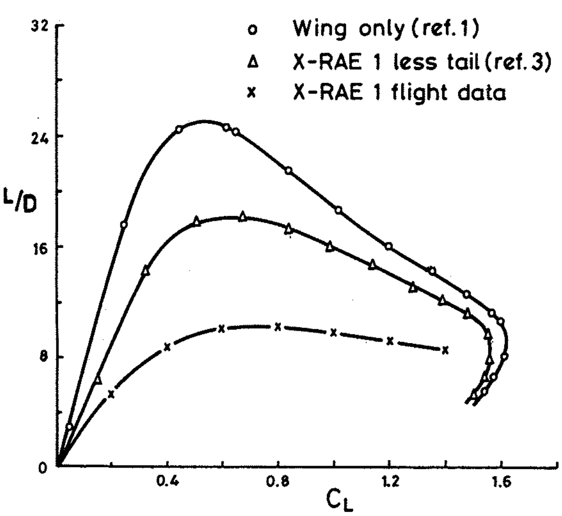

Figure 10. Lift-drag ratios for vehicles with wings of AR = 7.5, section = FX63-137, $Re_c = 1 \times 10^6$.

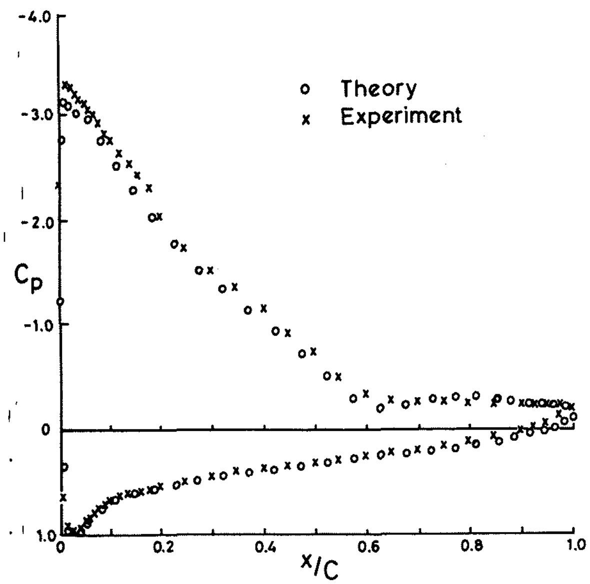

Figure 11.a. Göttingen 797, $\alpha = 12°$, $Re_c = 0.7 \times 10^6$

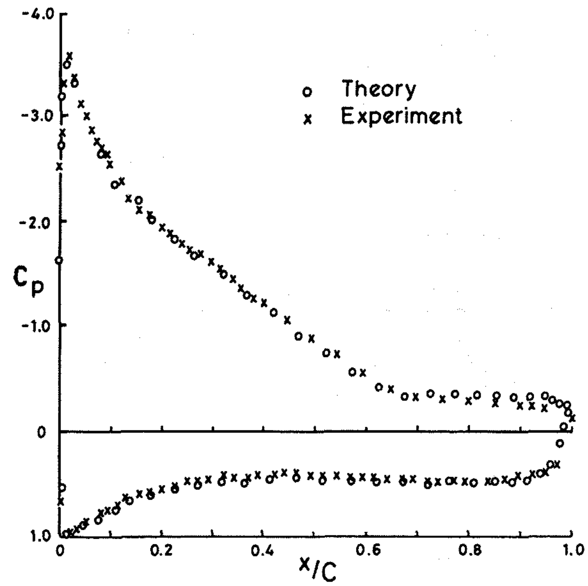

Figure 11.b. Wortmann FX63 137, $\alpha = 12°$ $Re_c = 0.7 \times 10^6$.

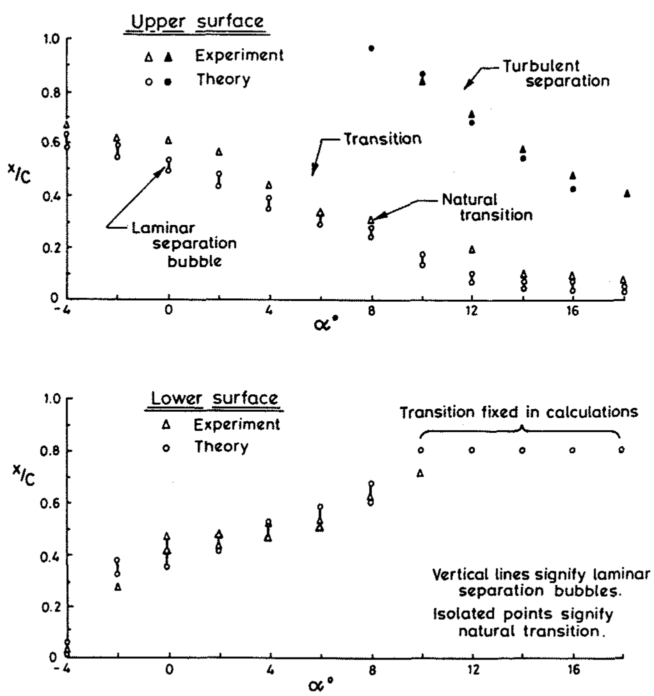

Figure 12. Wortmann FX63-137 transition and separation points, $Re_c = 0.7 \times 10^6$.

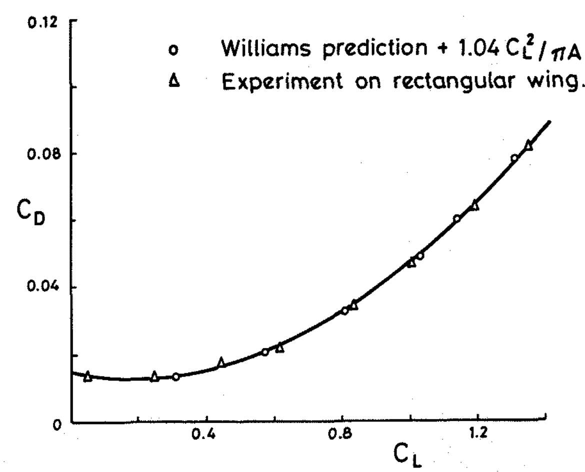

Figure 13. A comparison between prediction and experiment, wing only AR = 8.9, section = FX63-137, $Re_c = 0.7 \times 10^6$.