THE EFFECT OF SPANWISE SURFACE DISCONTINUITIES ON THE AERODYNAMIC CHARACTERISTICS OF 2D WINGS AT LOW REYNOLDS NUMBERS.

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Abstract

Aircraft required to operate at low flight speeds and/or high altitudes, often require an understanding of the aerodynamic characteristics of aerofoil sections in the very low Reynolds number range. The design of these aircraft often require very low weight and low construction costs. In order to achieve this one option is to adopt a rib and film construction for the wings which results in the surface being distorted, both spanwise and chordwise, due to the tension in the skin material. Little is known about the likely effects of this distortion on the aerodynamic characteristics of the section profile used to construct the wing. The results from a series of 2D wind tunnel tests at Reynolds numbers, based on aerofoil chord(c) of 151,000 to 285,000, are presented. The wings are constructed from rib sections with spacings in the range 0.2c to 0.4c and covered with a heat shrink plastic film. In order to make comparison with previous work on 'solid' sections, initial tests were carried out on conventionally built models of the Wortmann FX63-137 and Gottingen 797 aerofoils. The influence of the rib and film construction is seen to be different for each aerofoil section. Both experience a reduction of C_{Lmax} with the larger rib spacing resulting in the greatest reduction. The data is used to establish a tolerance for each section to this type of construction.

keywords:
Low Reynolds Number, Wind tunnel, 2D Aerofoil, Ribbed Construction, Ultralight Aircraft.

Introduction

The majority of experimental data available for 2D aerofoil sections at low Reynolds number have been obtained using solid wind tunnel models with smooth surfaces. The nature of the flowfield at very low Reynolds numbers means that it is difficult to predict aerofoil behaviour under normal operating conditions particularly if freestream turbulence levels and aerofoil surface discontinuities, arising from manufacture, are such as to influence boundary layer transition.

Common requirements for aircraft designed to operate at low Reynolds numbers are often low weight and low construction cost. One way of achieving this is to adopt a rib plus spar construction with a fabric or film covering for the wing. With modern covering materials this is now an accepted method of construction for RPV's and ultralight aircraft. As a consequence, in addition to chordwise surface discontinuities, the aerodynamic behaviour of the wing may be influenced by spanwise discontinuities as a result of distortion of the fabric/film skin between the ribs.

Very little is known about the effect of such regular spanwise discontinuities on the aerodynamic characteristics of wings at low Reynolds number. This paper describes an investigation of the aerodynamic lift and drag forces on wings, made using typical aerofoil sections, each with regular spanwise surface discontinuities. The aim is to quantify the aerodynamic penalty arising from a rib plus spar and fabric skin type of wing construction.

The experimental programme involves the Gottingen 797 and Wortmann FX63-137 aerofoil sections. Both are used to manufacture constant chord wings which span the working section of a low speed wind tunnel from which essentially 2D aerodynamic force and moment data can be derived from balance measurements and wake surveys.

Experimental Arrangement

The measurements were made in the College of Aeronautics 'Brough' low turbulence wind tunnel which has a 0.61m. wide, 0.61m. high, 2.44m. long working section. The facility has an open return layout with a 9:1 contraction ratio nozzle containing five turbulence screens, a honeycomb and filter screen upstream of the working section and a four bladed fixed pitch fan, driven by an external 15kW motor, downstream. This arrangement results in a maximum empty working section flow velocity of 43 m/sec. measured by the pressure difference between static pressure rings in the nozzle and settling chamber walls. The working section centre line longitudinal turbulence intensity varies between 0.12% and 0.2% in the speed range 6 to 37 m/sec. The axial static pressure gradient is negligible over this speed range as a result of triangular corner fillets which reduce in size over the length of the working section.

The aerodynamic force and moment measurements were made using an external, six component platform strain gauge balance, (only lift, drag and pitching moment are considered in this 2D application). The model is mounted horizontally spanning the working section and connected to the balance by two cylindrical pins which pass through the 'end plates' and working section wall to vertical supports standing on the balance platform. Incidence adjustment is by two calibrated set pins at the top of each of the vertical supports which allow the model to be rotated about the cylindrical pins from -12 to +30 degrees.

Test Procedure

In view of the hysteresis phenomena a standard test procedure was adopted for all the tests. This involved an incidence traverse, starting at -8 degrees, in steps of 2 degrees until the stall is well established followed by a return in 1 degree steps to -4 degrees. Care was taken to keep the pitch rate of the aerofoil as low as possible during each incidence change.

Balance data in this instance is sampled with a PC and 8 channel A-D incorporating a 125Hz low pass filter taking the mean of a 5 second simultaneous sample for each balance channel plus the freestream dynamic pressure, and stagnation temperature.

Flow visualisation studies were carried out in the College of Aeronautics 2D smoke flow wind tunnel which has a 1m. high, 0.1m. deep and 1.6m. long working section in which the models are mounted between an adjustable back plate (for varying model incidence) and a glass observation window (which forms the vertical working section wall). Illumination is from axial light strips above and below the model. Smoke filaments are introduced from a full height comb mounted at the downstream end of the 15 : 1 2D contraction nozzle and upstream of the working section wall boundary layer removal slots.

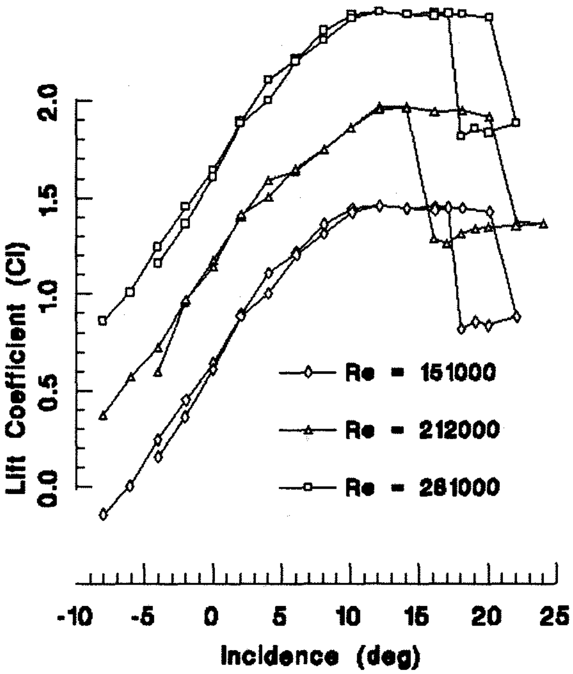

Figure 1. Variation of lift coefficient with incidence for the Gottingen 797 aerofoil over the Reynolds number range of interest.

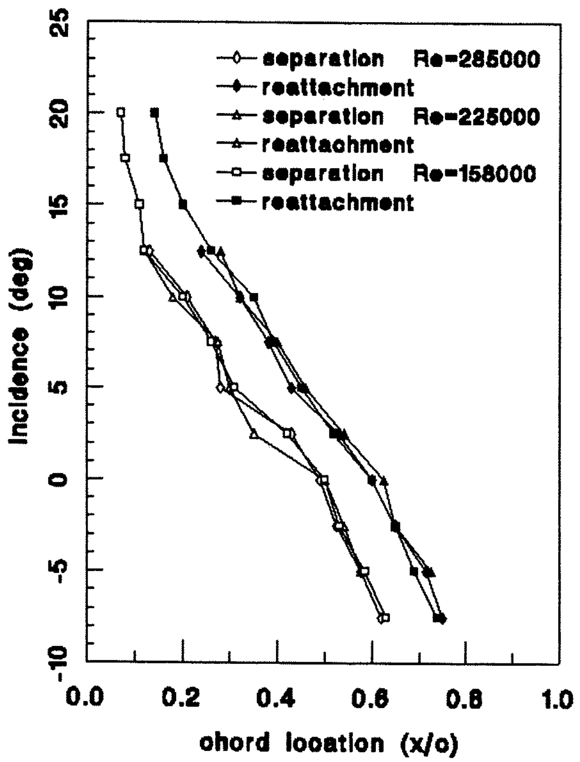

Figure 2.. Location of the laminar separation bubble for the 2D Gottingen 797 aerofoil using smoke flow visualisation.

Aerofoil sections

The aerofoil sections selected for the investigation, the Gottingen 797 and the Wortmann FX63-137, were chosen for the following reasons;

(a) a considerable amount of existing data was available from various sources at low Reynolds number for comparison and validation of the test technique. This is particularly true for the Wortmann aerofoil.

(b) The Gottingen section is flat bottomed and therefore relatively simple to manufacture. It is known from previous wind tunnel tests at Cranfield to have good low Reynolds number characteristics.

The solid wing models were manufactured from an epoxy resin with aluminium trailing edges, and finished in black cellulose.

The rib and spar aerofoils were built in each case around a brass frame which formed the leading edge (0.05c) and trailing edge (0.1c) of the wing with two wing tip ribs which act as mounting points to the balance struts. This frame was stiffened using spanwise cylindrical spars, one for the Gottingen and two for the Wortmann (due to it's more complex under camber). The spars were sized so as not to come into contact with the aerofoil surface, the effective geometry of the film covered wing is therefore determined only by the cross section of the ribs and the leading/trailing edges.

Each wing has 5 moveable brass ribs which can be positioned at any point along the span by sliding them along the cylindrical spar(s). Additional ribs were formed from balsa wood and located as required. Three rib and spar wings were available for each aerofoil section corresponding to rib spacings of 0.2c, 0.3c and 0.4c. where c is the aerofoil chord, 0.127m.

The surface covering used was Solafilm® a heat shrink material commonly used on model aircraft. The same basic frame was used for each rib arrangement, after the test the Solafilm was removed, the new rib pattern fitted and the covering then replaced. Subsequent repeatability tests showed that, providing a specific application procedure was adopted for the Solafilm, the geometry of the wing section was repeatable.

Summary of solid aerofoil aerodynamic characteristics

The basic aerodynamic characteristics of these two aerofoil sections, over the Reynolds number range of interest, have been investigated by previous authors. A brief description is included here for completeness and for validation of the experimental arrangement.

Gottingen 797

A carpet plot depicting the variation of lift coefficient (C_L) with incidence (α) for the three Reynolds numbers examined is given in Figure (1). The maximum lift coefficient (C_{Lmax}) obtained at each Reynolds number is as follows:

Re. No.	α	C_{Lmax}
151,000	12	1.49
212,000	12	1.47
281,000	12	1.46

Values of C_{Lmax} are seen to be relatively insensitive to Reynolds number in this limited range.

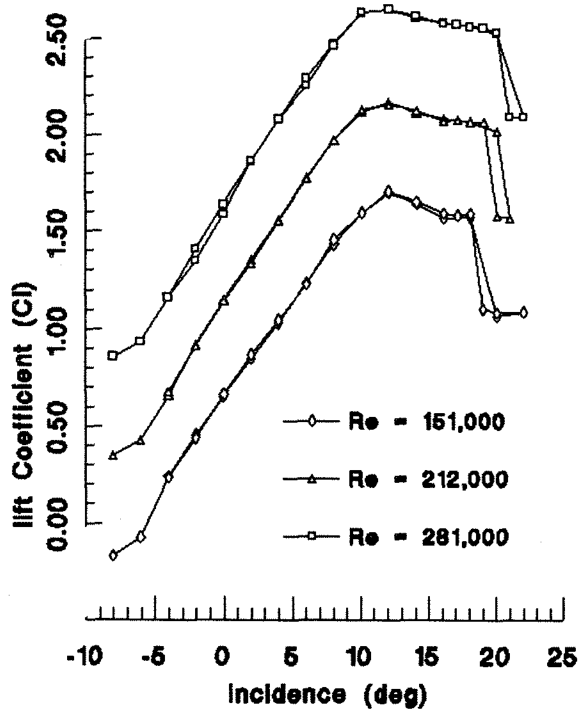

Figure 3. Variation of lift coefficient with incidence for the Wortmann FX63-137 aerofoil over the Reynolds number range of interest.

A characteristic of the lift variation with incidence for the Gottingen aerofoil is a clockwise hysteresis loop at incidences above the stall. This is typical of the formation of a laminar separation bubble. The point of flow separation and reattachment can be examined from smoke flow visualisation studies on 2D sections of the aerofoil with a chord of 0.5m. in the smoke flow wind tunnel. Figure (2) shows how the position of this separation bubble varies with aerofoil incidence and Reynolds number for the Gottingen 797 section. These data agree with the pressure measurements of Render [1] at Re = 300000.

Wortmann FX63-137

A carpet plot depicting the variation of C_L with α at the three Reynolds numbers tested for the solid Wortmann wing is given in Figure (3). The maximum lift coefficient (C_{Lmax}) obtained at each Reynolds number is as follows:

Re. No.	α	C_{Lmax}
151,000	12	1.62
212,000	12	1.70
281,000	12	1.66

Mueller and Bastedo [4] quote 2D lift coefficient data for this aerofoil section and Reynolds number range which is within 2.8% of the current study. Similarly, lift data from Robinson [3], whose measurements were made in the same facility, are within 2.2%

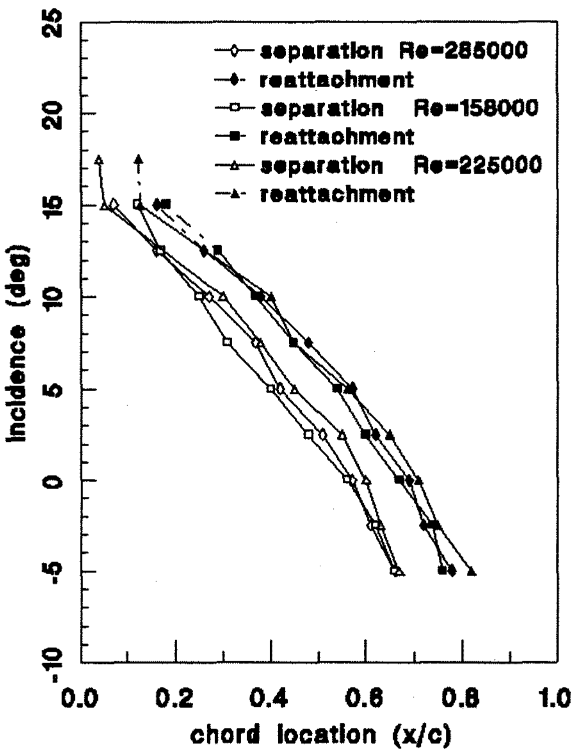

Figure 4. Location of the laminar separation bubble for the 2D Wortmann aerofoil using smoke flow visualisation.

The significant difference between the data for the Wortmann section and that for the Gottingen is the very much smaller hysteresis loop for the Wortmann over this Reynolds number range.

Smoke flow visualisation on the Wortmann section confirms the existence of a laminar separation bubble, the length of which is nominally 0.15c, depending on both Reynolds number and aerofoil incidence, see Figure (4).

Aerodynamic characteristics of the ribbed aerofoil sections

Initial measurements on the ribbed wing sections were made with the film covering adhered to the main brass frame of the wings. As a result, the effective aerofoil section between the ribs, was governed by the shrinkage of the film and the chordwise extent of the leading and trailing edge sections of the frame. The practical consequences of this shrinkage for both wing sections are:

(a) a reduction in the local thickness/chord ratio (t/c) between the ribs.

(b) a sudden discontinuity in the surface as the Solafilm looses the support of the sub-frame at the downstream edge of the frame leading edge section.

In addition the Wortmann section experiences a small reduction in the negative camber on the undersurface of the aerofoil between the ribs.

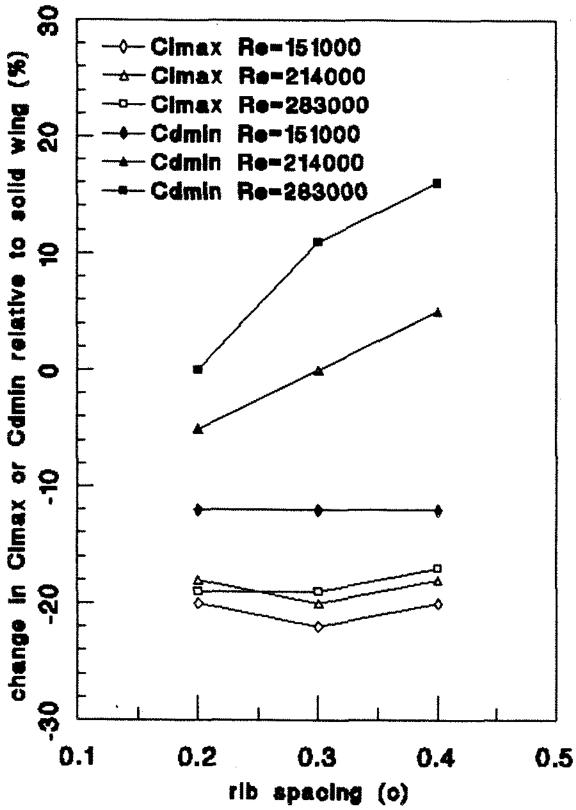

Figure 5. Change in C_{Lmax} and C_{Dmin} relative to the solid aerofoil for the Gottingen ribbed wing.

As a result of these local geometry changes both the Gottingen and Wortmann wings experience a reduction in C_{Lmax}.

The change in both C_{Lmax} and C_{Dmin} for the Gottingen 797 section wing with three different rib spacings is shown in Figure (5). The reduction in C_{Lmax}, typically 20%, is seen to be relatively insensitive to changes in Reynolds number and rib spacing. Changes in C_{Dmin} however are dependant on rib spacing at higher Reynolds numbers and show a reduction in C_{Dmin}, relative to the solid wing, at the lower Reynolds numbers and smaller rib spacing.

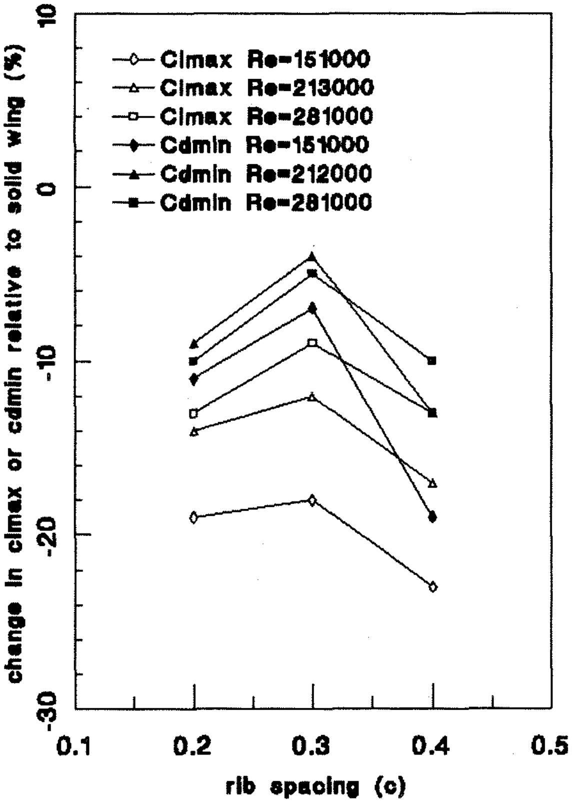

Figure 6. Change in $C_{Lmax}$and C_{Dmin} relative to the solid aerofoil for the Wortmann ribbed wing.

In contrast, the data for the Wortmann section wing suggests a more complex dependence on Reynolds number and rib spacing. While the reduction in C_{Lmax} is greater at the lower Reynolds numbers and larger rib spacing, the minimum drag coefficient (C_{Dmin}) is also seen to be reduced for all the Reynolds numbers and rib spacings measured.

Modified ribbed wings.

While the results for the rib and film wings are of interest, particularly in view of the apparent tolerance of the Wortmann section to distortion between the ribs, they are of limited practical significance since, with a large proportion of the wing leading edge made up of a thin flexible skin, the wing would be structurally weak. In view of this an additional series of tests were made on the 0.3c spaced ribbed wings for which the upper surface leading edge was extended to nominally the maximum thickness (0.32c for the Gottingen and 0.37c for the Wortmann). These wings will be referred to as the 'modified rib wings' for simplicity.

Modified ribbed Gottingen

An example of the relative effect of the modified ribbed surface for the Gottingen aerofoil is given in Figures (7) and (8) for a Reynolds number of 281,000

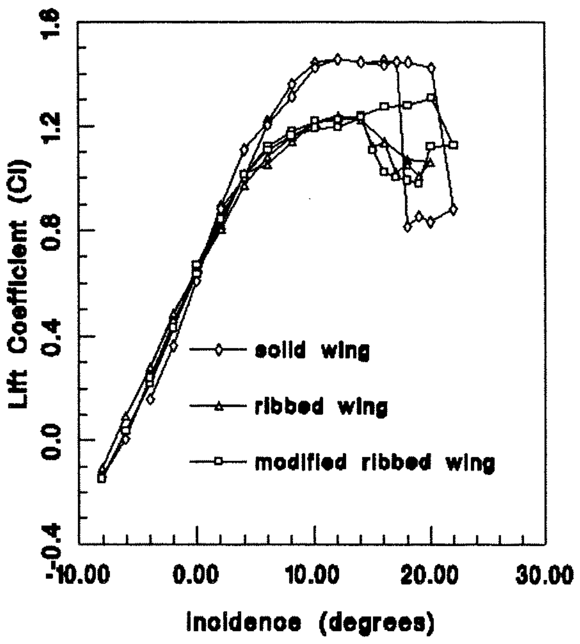

Figure 7 Influence of the three types of wing construction on lift coefficient for the Gottingen section at Re = 281,000

The solid upper surface leading edge is seen to increase $C_{L_{max}}$ (compared to the ribbed wing) and to delay the stall to a higher incidence. This result is typical for the Reynolds number range tested although the recovery of lift performance due to the modified ribbed wing is more noticeable at the lower Reynolds number. This trend is consistent with an increase in local camber near the leading edge, which the solid upper surface achieves by preventing shrinkage of the skin between the ribs in this region.

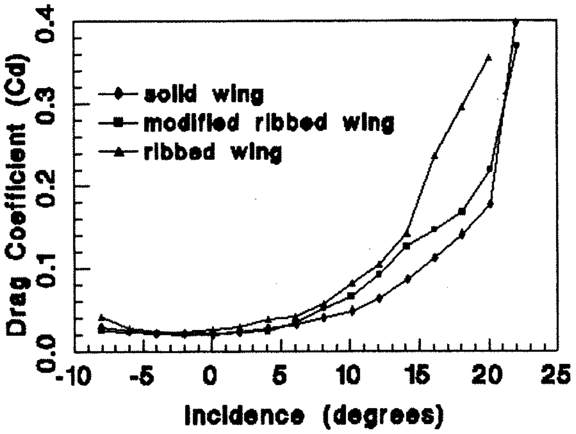

Figure 8 Variation of drag coefficient with incidence for the three types of Gottingen section wing. at Re = 281,000

Modified ribbed Wortmann

The variation of C_L vs α and C_D vs α for the three types of wing with the Wortmann section at a Reynolds number of 281,000 is given in Figures (9) and (10) respectively.

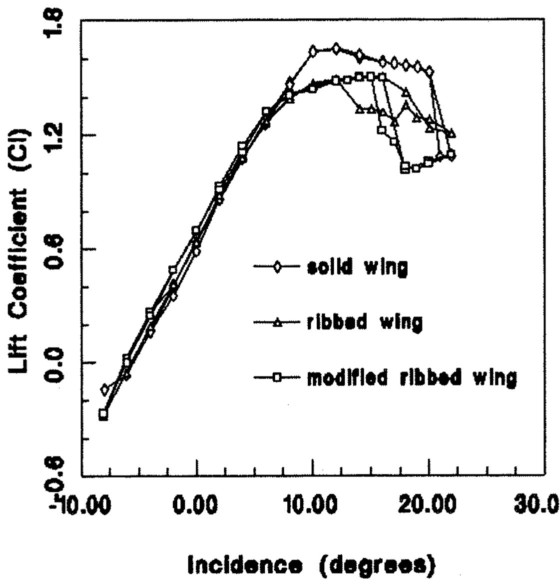

Figure 9. Influence of the three types of wing construction on lift coefficient for the Wortmann section at Re = 281,000

There is seen to be very little difference in the lift characteristics of the Wortmann section wing at incidences below the stall for the modified rib and ribbed wings. Above the stalling incidence C_L is seen to fall off more rapidly for the modified ribbed wing. Both these characteristics are equally apparent at the lower Reynolds numbers tested. The more severe stall of the modified rib wing is attributed to the slight discontinuity in the surface at the downstream end of the modified leading edge on the upper surface, which effectively fixes the separation point.

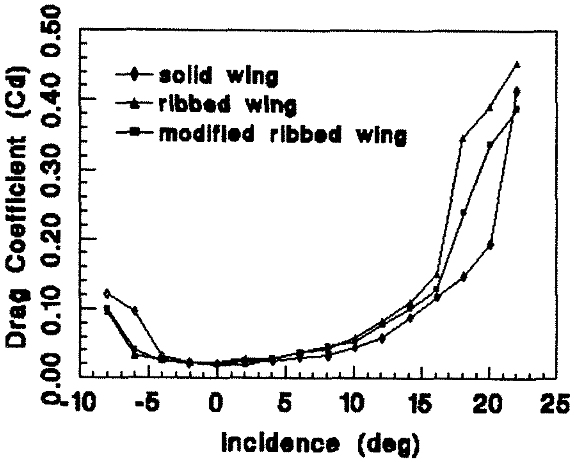

Figure 10 Variation of drag coefficient with incidence for the three types of Wortmann section wing at Re = 281,000

Profile drag measurements

In addition to the balance measurements of drag a series of wake surveys were made for both aerofoils from which profile drag coefficient (C_{D_0}) was evaluated. The wake surveys were made at various spanwise locations for the solid, ribbed and modified rib (with a spacing of 0.3c) wings in the incidence range -4 to +2 degrees.

The data for the solid wings show small variations of C_{D_0} across the span, this is particularly apparent for the Wortmann section wing, see Figure (12). It is assumed that this spanwise variation is due to local differences in the upper surface boundary layer transition point across the span but no experimental evidence is available to support this at the present time. Similar variations have been reported for solid wings by Donovan et. al [(7)] at lower Reynolds numbers.

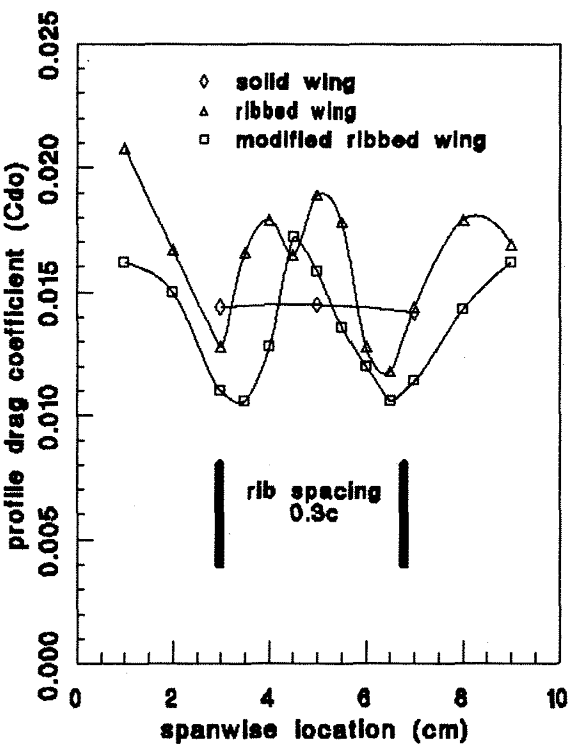

Figure 11 The spanwise variation of C_{D_0} for the solid, ribbed and modified rib Gottingen section wings at zero incidence and Re = 281,000

The spanwise variation of C_{D_0} is much greater for both the ribbed and modified rib wings, see Figure (11) which presents data for the Gottingen 797 section wing at zero degrees incidence and a Reynolds number of 281,000. The data for both ribbed wings exhibit a minimum local profile drag coefficient at spanwise locations downstream of the wing rib and a maximum C_{D_0} at the mid point between the ribs. There is a similar trend for the modified ribbed wings.

It is recognised that wake survey techniques for the measurement of profile drag are difficult at low Reynolds numbers, see McGhee et. al. [(6)], due to the possibility of large scale wake vorticity. In addition the likelihood of 3D flow in the wake for both the ribbed and modified rib wings makes it difficult to place real significance on the variation of local profile drag coefficient across the span. However, the high level of repeatability of this data and the constant trend for several stations across the span suggests that the localised three dimensional flow over the wing is at least regular and in phase with the rib spacing.

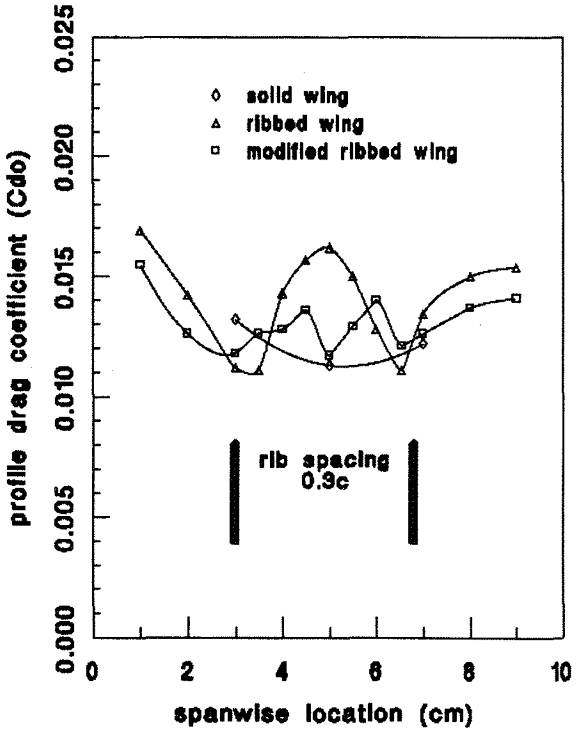

Figure 12 The spanwise variation of C_{D_o} for the solid, ribbed and modified rib Wortmann section wings at zero incidence and Re = 281,000

Discussion and Further Work

The apparent tolerance of these aerofoil sections to spanwise discontinuities of the type considered here is thought to warrant further investigation. Surface flow visualisation studies are planned to monitor the spanwise variation of the laminar flow region on these wings. Also, an investigation of additional rib spacings is needed to investigate the possibility of an aerodynamic optimum spacing for the ribs of a wing with a specific aerofoil section.

The choice of film/fabric skin covering is thought to play a significant role in determining aerodynamic performance. The tension in the skin and the materials' lateral stiffness will govern both the static geometry taken up by the surface between the ribs and the shape adopted by the surface under aerodynamic loading. Both these factors will make aerodynamic optimisation and prediction of flight characteristics from scale wind tunnel tests extremely difficult but warranted in view of the potential weight savings possible from this type of construction.

Conclusions

The results from a series of 2D wind tunnel tests on wings using the Wortmann FX63-137 and Gottingen 797 aerofoil sections in the Reynolds number range 150,00 to 285,000 are presented. In order to analyse the influence of regular spanwise surface discontinuities, three types of wing construction were investigated; (i) a solid conventional wing model, (ii) a rib and spar frame covered with a heat shrink film and (iii) a rib and spar frame with a solid upper surface leading edge extending as far as the maximum thickness, again covered in heat shrink film. Rib spacings in the range 0.2c to 0.4c were investigated for both aerofoil sections.

The results for the solid wings agree well with previous authors and suggest the existence of an upper surface laminar separation bubble on both wings.

In general both types of rib and spar wing reduce $C_{L_{max}}$ compared to the solid wing. This reduction is more Reynolds number dependant for the Wortmann than for the Gottingen section.

Values of $C_{D_{min}}$ are reduced for the Wortmann section with the rib and spar wings across the Reynolds number range tested. Values of $C_{D_{min}}$ for the rib and spar Gottingen section wing is seen to be dependant on both Reynolds number and rib spacing.

Measurements of local profile drag (C_{D_o}) taken from wake surveys at various spanwise stations show a near cyclic variation of C_{D_o} in phase with the rib positions. The local C_{D_o} is seen to have a minima in a plane downstream of a rib and a maximum at a mid point between adjacent ribs. Further work is needed to isolate the cause of this variation.

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