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The effect of trip wire roughness on the performance of the Wortmann FX 63-137 airfoil at low Reynolds numbers

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Abstract. An experimental investigation was conducted on the performance and boundary layer characteristics of the Wortmann FX 63-137 airfoil with and without trip wire roughness. Data were obtained through use of a three-component strain gage force balance and static pressure measurement equipment at a test Reynolds number of $R_c = 100{,}000$. Emphasis was placed on determining the effect of trip wire placement and size on such performance parameters as $(C_l/C_d)_{\max}$ and $(C_l^{3/2}/C_d)_{\max}$. Prediction of transition location by the criterion due to Tani and Gibbings was found to have limited application. Most trip wire locations resulted in degraded performance, but for some locations, minimum drag was reduced, maximum lift to drag ratio increased, and hysteresis averted.

Nomenclature

C_d	airfoil sectional drag coefficient
C_l	airfoil sectional lift coefficient
$C_{l\alpha}$	airfoil sectional lift curve slope coefficient
$C_{m\,c/4}$	airfoil sectional moment coefficient measured about the quarter-chord location
C_p	pressure coefficient
c	chord length of airfoil model
k	roughness height
R	refers to the occurrence of reattachment
R_c	Reynolds number based on chord c
S	refers to the occurrence of laminar separation
S'	refers to occurrence of turbulent separation
s	arclength distance from stagnation point
T	refers to occurrence of transition
U	flow velocity
w	roughness width
x	distance along chord line

Greek symbols

α	angle to attack
δ_1	boundary layer displacement thickness
Λ_1	pressure gradient parameter defined as $[\delta_1\,(dU/ds)]/\nu$
ν	kinematic viscosity

Subscripts

cr	refers to critical value for some effect on transition
e	refers to velocity external to the boundary layer at a particular location
k	pertains to roughness height or location
max	refers to the maximum value of a parameter
min	refers to the minimum value of some parameter
p	static pressure
t	pertains to the location of transition

1 Introduction

When the chord Reynolds number (R_c) drops below 500,000 significant problems develop pertaining to the management of airfoil boundary layers. Lissaman (1983) states that as a general criterion there exists a critical Reynolds number of about 70,000 below which airfoil performance is quite poor and above which dramatic improvements are observed. However, airfoil performance between this critical value and a Reynolds number of 500,000 still presents problems that can be directly traced to the existence of such phenomena as boundary layer separation and transition. Also, there exists the special, but not uncommon, case that separation is followed by reattachment of the flow forming what is known as a "separation bubble". The presence of such a flow structure and its behavior can have great influence on airfoil performance.

Unfortunately, a basic understanding has yet to be developed for low Reynolds number boundary layer behavior under the influence of airfoil-type pressure gradients. For this reason, design of airfoils for low Reynolds number applications remains somewhat of an imperfect science. Practical aircraft design efforts require information that is indicative of what performance levels can be expected of a particular airfoil or wing. Such information is needed not only for smooth sections in benign environments, but also for airfoils operated under conditions of wind shear, flow unsteadiness, and accumulated roughness. Unfortunately, credible data of use to the design engineer remains sorely lacking. The extreme sensitivity of the low Reynolds number flow regime to small disturbances results in problems of an experimental nature which are not easily circumvented. However, if proper care is taken to eliminate or at least account for such phenomena, then meaningful results can be obtained (Mueller et al. 1983; Mueller 1985).

It has been well known for some time that airfoil performance in the low Reynolds number regime can be greatly enhanced by the addition of devices which encourage transition. This process serves to energize the boundary layer and so prevent flow separation. Such devices include boundary layer trips (wires, tape strips, grit, etc.), surface suction or blowing, and vortex generators. However, the application of trips in particular may not always lead to performance improvement and instead can result in severe losses. The possibly detrimental effects of such surface disturbances take on added importance when one realizes that under normal operating conditions, wing sections will be contaminated with insect debris, dirt, and precipitation. Therefore, it is important that the effect of such disturbances be well documented so that realistic estimates of aircraft performance can be made in the design phase. It is the purpose of this study to investigate the performance of one airfoil operated at a low Reynolds number and under the influence of applied trip wire roughness. This work is part of a more extensive investigation dealing with the effects of a variety of surface roughness forms on airfoil performance and the interested reader is directed to the work of Huber (1985) for more information of the kind presented here.

2 Roughness considerations

Investigations into roughness induced transition have in general attempted to form correlations involving the following parameters: roughness height (k), roughness width (w), local freestream velocity external to the boundary layer (U_e), velocity at a height k but in the absence of roughness (U_k), velocity gradient (dU/dx), roughness position (x_k), location of transition (x_t), roughness spacing, and boundary layer parameters such as the displacement thickness, δ_1. Distinctions are often made about the type of roughness used (two or three-dimensional, geometry, etc.), the character of the movement of the location of transition, and the "efficiency" of a certain roughness type relative to others.

Of interest is whether such correlations can be used to fix the location of transition on an airfoil surface. Unfortunately, most studies in the roughness field have dealt almost exclusively with flat plates over which only the most mild, if any, pressure gradients have been applied. Hence, the applicability of such criteria for use with airfoils is questionable. Nevertheless, no other alternatives are available and so the existing criteria must be used.

A trip wire placed across a surface at a constant reference position is a two-dimensional type of surface roughness. For two-dimensional roughness heights below some critical value no effect on the natural transition location is noted. However, as the height is increased above the critical value for a given flow condition, transition will gradually move forward until it occurs at the roughness element itself. Therefore, if the appropriate height is known, transition can be fixed at a particular position.

From their studies using flat plates, Tani and Sato (1956) gave the following criterion for the Reynolds number required to cause transition at a trip wire roughness of height (i.e. diameter) k,

$$R_{k,\mathrm{cr}} = \frac{U_e k}{\nu} = 840 . \tag{1}$$

Gibbings (1959) provided the more accurate value of 826 for this criterion and further work by these researchers (Tani 1964) extended this relation to include the effects of a favorable pressure gradient.

$$R_{k,\mathrm{cr}} = 826 \exp(-0.6 \Lambda_1) . \tag{2}$$

Here, Λ_1 is a non-dimensional pressure gradient term given as

$$\Lambda_1 = \frac{\delta_1^2}{\nu} \frac{dU_e}{ds} . \tag{3}$$

(This expression has application for $0 < \Lambda_1 < 0.3$ and is zero outside this range.) Smith and Clutter (1959) provided a criterion similar to Eq. (1) for transition at a "spanwise wire", but give it in terms of the roughness height velocity, U_k.

$$R_{k,\mathrm{cr}} = \frac{U_k k}{\nu} = 300 . \tag{4}$$

Other investigators have compiled similar criteria with the critical roughness Reynolds number varying between 200 and 400. For the study described in this paper, Eqs. (1) and (2) were used to determine roughness height as required at a particular location on the airfoil. The appropriate expression would therefore be:

$$k = \frac{826 \nu}{U_e} \exp(-0.9 \Lambda_1) . \tag{5}$$

Note that inputs to this relationships are ν, U_e, and Λ_1. The first is dependent on the atmospheric conditions during the experiment, while the second is derived from the flow velocity external to the boundary layer above a specified point on the airfoil. U_e and Λ_1 were determined from pressure data obtained for the smooth airfoil at the desired test condition. Λ_1 was evaluated from Eq. (3) using the approximate method of von Karman and Pohlhausen and the Thwaites-Walz integral approximation. The equation was also solved using potential flow input valves for U_e and Λ_1. However, more credence was given to the experimental data, and the roughness heights calculated from this source were used more often than not.

3 Apparatus and procedure

All experiments were conducted in the Notre Dame Aero-Dynamics Laboratory South Low Speed Wind Tunnel (see Fig. 1). This tunnel is of the in-draft, non-return type and has an operating range of between 7 and 35 m/s. The tunnel possesses a 24:1 contraction ratio and a square test section 0.61 m on a side and 1.83 m in length. Side plates mounted inside the test section permit airfoil measurements that approximate the two-dimensional assumption. This tunnel produced turbulence intensities below 0.1% for the experiments reported in this paper.

The airfoil section used for these experiments was the Wortmann FX 63-137 which has a design chord Reynolds number of about 500,000. This airfoil section is shown in Fig. 2. Two models were utilized, each possessing a 15.24 cm chord, cast from a single mold, and made of epoxy which was wet sanded with No. 400 grit paper to ensure a smooth finish. The only difference between the two models was that one is fitted with forty "staggered" static pressure orifices which were connected by way of tygon tubing to pressure sensitive equipment. This model permited the measurement of pressure distributions about the airfoil while the other was used for force balance and flow visualization experiments.

The Notre Dame force balance is a three-component (lift, drag, moment) strain gage device capable of low magnitude load measurements with a high degree of accuracy and repeatability. This instrument is interfaced with an Apple microcomputer data acquisition system which, considering its voltage input resolution, allows the measurement of drag forces as small as 0.0044 N. The uncertainty in the lift and drag coefficients is estimated to be less than +/− 7% while the uncertainty in the moment coefficient is estimated to be less than +/− 10%.

Pressure distributions were measured with a dual Scanivalve arrangement in which Setra System 339H electronic manometers were used to sense the static pressure at each airfoil tap. The tunnel freestream total and dynamic pressures were measured using a pitot-tube and a third electronic manometer. Data acquisition and reduction for these measurements was accomplished through use of a DEC PDP-11/23 minicomputer with 12-bit D/A and A/D conversion capabilities. The Scanivalves were switched by the computer from one orifice to the next using Scanivalve CTRL 10P/S2−S6 Solenoid Controllers. The uncertainty in $|C_p|_{max}$ is estimated to be less than +/− 5%.

The trip wires used in this study were stainless steel wires of uniform diameter. Listed sizes were checked using a digital caliper and in all cases were found to be accurate. A roughness arrangement consisted of both a trip wire and a layer of Scotch brand double-stick tape which was used to secure the wire to the airfoils' surface. This brand of tape possesses a thickness of 0.076 mm and a width of 6.35 mm. Also, being transparent, the tape can be punctured to permit pressure measurements at those taps which it covers. The roughness height to chord ratios (k/c) of the wire-tape combinations presented herein are 0.583% and 0.300% which correspond to wire diameters of 0.81 and 0.38 mm respectively. These two diameters were chosen with regard to the range of trip wire heights necessary to achieve the critical Reynolds number for the given conditions. Table 1 presents the critical wire diameters necessary to cause transition at the tripwire itself, determined by using Eq. (5), which gives the height, k, necessary to bring transition to the roughness site. Note that all values are calculated for the 15.24 cm airfoil at a representative $R_c = 100{,}000$ condition. Also, for each of the angle of attack settings, the forward roughness site corresponds to the suction peak location, while the aft position is the laminar separation point. The roughness height at the leading edge is an average of the heights calculated for the coordinate points immediately on either side of the leading edge. Given the added height of the tape strips, the height to width ratios (h/w) are greater than one.

The procedure for applying the trip wires to the airfoil surface was as follows. Airfoil chord positions were marked across the full span of a model using a "photo-blue" pencil. These lines were accurately placed by refer-

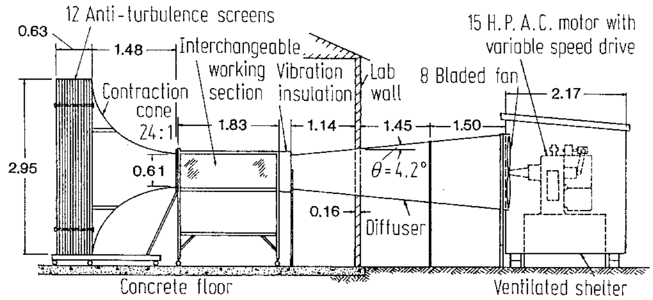

Fig. 1. A Notre Dame subsonic indraft wind tunnel arrangement. (indicated lengths in meters)

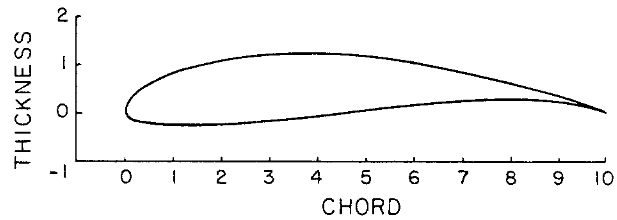

Fig. 2. The Wortmann FX 63-137 airfoil section

Table 1. Roughness height from Eq. (5)

x/c (%)	LE	1.0 (15°)	3.0 (7°)	5.0 (15°)	30.0 (7°)
U_e (m/s)	12.7	22.3	17.7	20.8	15.8
k/c (%)	(0.337)	0.383	0.483	0.412	0.541

ence to airfoil templates consisting of the sectional contour and chord position lines drawn by a computer-directed plotter. A double-stick tape strip was then placed along the airfoil surface at a particular chord-wise location and a trip wire "rolled" along the surface up to the leading edge of the tape. After a test, any applied roughness was removed and the airfoil surface checked to see if any adhesive still remained on the surface. Occasionally, the surface was wiped with a towel soaked with alcohol to ensure a smooth, clean finish.

While force balance data is to be presented for the effect of trip wires placed at a variety of airfoil surface locations, two positions are the focus of attention with regard to pressure distribution measurements. Results are shown for roughness located at the respective suction peak and laminar separation points for two different angles of attack. The two trip wire heights used represent values both larger and smaller than the heights calculated by Eq. (5) as necessary to bring transition to the roughness site. All force and pressure coefficient values presented herein were corrected using standard AGARD procedures for the effects of solid body blockage, wake blockage, streamline curvature and longitudinal buoyancy.

4 Results

4.1 The smooth airfoil

The experimental data collected as part of this investigation is presented in the following manner. First, the smooth airfoil's performance is documented with reference to force balance plots which show lift, drag, and moment coefficient variation with angle of attack. Then, the effects of roughness are summarized with respect to the variation of performance parameters with roughness location and height. Additionally, pressure plots are presented which demonstrate the effects of trip wire placement and size on such boundary-layer phenomena as separation and transition.

Figure 3 provides performance curves of the smooth Wortmann airfoil at an R_c of 100,000. The most dominant feature in these curves is the hysteresis loop which is of the "clockwise" or "high $C_{l\max}$" type and which extends across three degrees. The maximum lift coefficient ($C_{l\max} = 1.54$) occurs at $\alpha = 15°$ and is followed by a gentle decrease in lift until an angle to attack of 18° at which the lift coefficient abruptly decreases to 0.96. This large drop in lift is due to the bursting of a leading edge separation bubble which initially forms toward the rear of the airfoil at low angles of attack and moves forward with increasing incidence. Coincident with this forward movement of the bubble is its gradual decrease in length. However, the stall of this airfoil should not be characterized as one of the "leading-edge" variety since the gentle decrease in C_l past $C_{l\max}$ indicates that turbulent separation is contributing to the drop in lift. Airfoils which possess a gentle degradation in lift are said to exhibit "trailing-edge" stall. Following the nomenclature used by Chappell (1968), the stalling character of the Wortmann airfoil is known as a "combined" stall due to the occurrence of both turbulent separation and bursting of the leading edge bubble.

The abrupt drop in lift at $\alpha = 18°$ is accompanied by a large increment in drag and an increase in the magnitude of the quarter-chord moment coefficient. However, when the angle of attack is decreased again through 18° the lift, drag, and moment do not return to their original values until $\alpha = 14°$ at which time the lift suddenly increases while the drag and moment decrease in magnitude. This occurrence completes the hysteresis loop and is due to the reattachment of the upper surface flow as the leading edge bubble reforms.

For angles of attack between $-6°$ and 12°, the lift variation is seen to be non-linear with slight "kinks" at $-1°$ and 4°. These "kinks" are more pronounced at $R_c = 80{,}000$ and the airfoil's performance degrades to that of a flat plate at $R_c = 70{,}000$ (Huber 1985). For higher R_c's (i.e. $> 150{,}000$), these kinks disappear and the airfoils' performance approaches that of the design condition. At an R_c of 100,000, the minimum drag coefficient is found in the region of maximum $C_{l\alpha}$ and is 0.038 at $\alpha = -3°$. The quarter-chord moment coefficient reaches its largest magnitude, other than when the airfoil is stalled, at $\alpha = -1°$ where the value is -0.170. While not apparent in the drag plot, the moment curve also demonstrates a "kink" at $\alpha = 4°$. For angles of attack lower than $\alpha = -6°$, the lower surface flow is fully separated.

From the drag polar one could infer that (C_l/C_d) and $(C_l^{3/2}/C_d)$ attain relatively large values as compared to most airfoils operated in the low R_c regime. This inference is substantiated as the maximum lift to drag ratio peaks at 16.63 for $\alpha = 8°$ and $(C_l^{3/2}/C_d)$ reaches a value of 18.85 at 9° angle of attack. Also, note the region of decreasing drag with increasing lift corresponding to $-8° < \alpha < -2°$ which is typical for low Reynolds numbers airfoils.

At this point, it is appropriate to address the issue of differences in results obtained with the Notre Dame force balance (such as those presented here) as compared with those procured at other facilities. The different testing procedures used by different facilities provide the best explanation for these discrepancies; a brief summary follows.

Results compiled for lift coefficients at Notre Dame tend to agree well with those obtained by other research laboratories. Mueller and Jansen (1982) determined that at low Reynolds numbers the use of endplates in two-dimensional model testing with the force balance can lead to measured values for the drag coefficient that are larger than one would expect. Tests conducted in the Notre Dame Laboratory have shown that the corner vortex that develops at the model/endplate juncture may extend

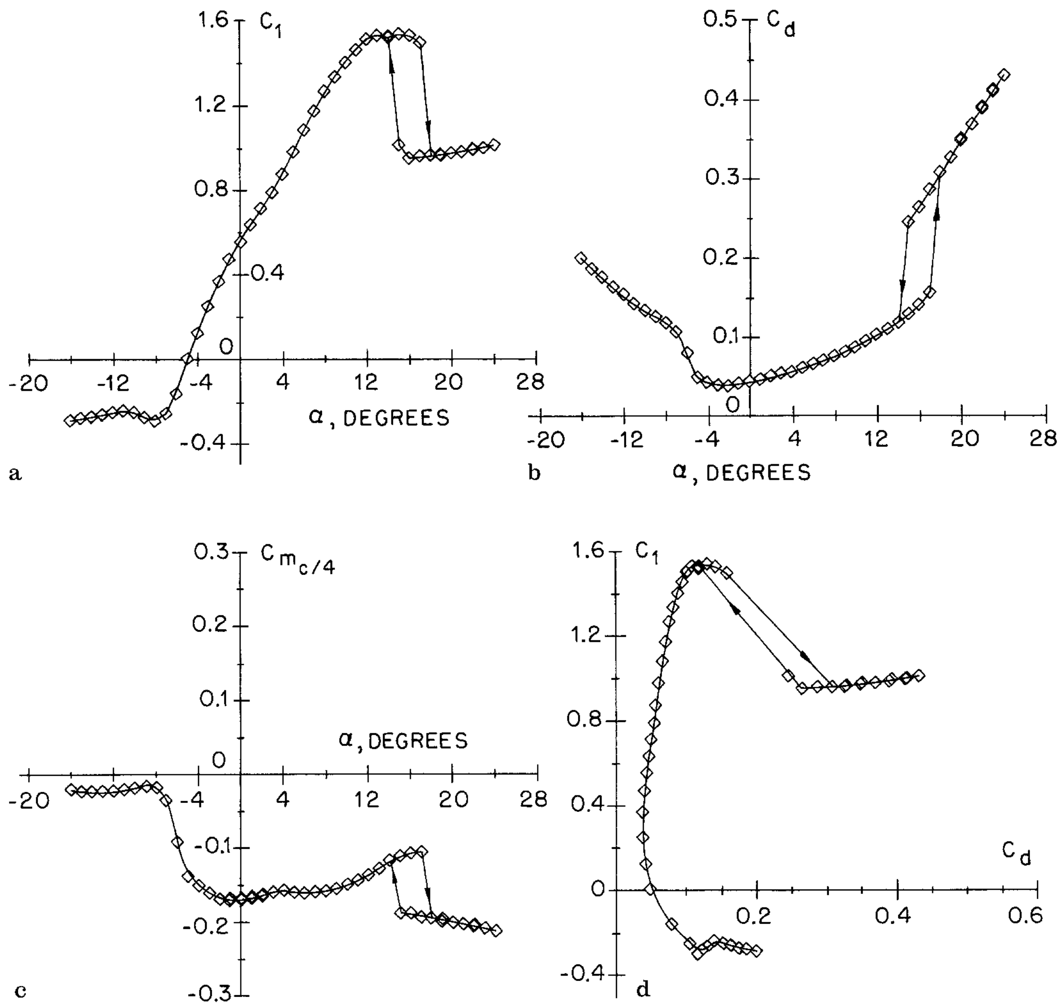

Fig. 3a–d. Performance curves for the smooth Wortmann FX 63-137 airfoil at $R_c = 100{,}000$ (force balance measurements); **a** Sectional lift coefficient versus angle of attack; **b** sectional profile drag coefficient versus angle of attack; **c** sectional quarter chord moment coefficient versus angle of attack; **d** lift/drag polar

across 5% of the model span (10% if both endplates are considered). The presence of this corner vortex results in the measurement of drag coefficients that may be as much as 15% higher than when no such vortex is present. The effect appears to decrease with increasing Reynolds number and does not seem to significantly alter the measured lift coefficient.

At the University of Stuttgart and Delft University, where much aerodynamic work at low Reynolds numbers has been performed, the wake rake survey method is utilized to determine drag. This method apparently records much lower values for drag than does the force balance at Notre Dame. While the data at Notre Dame is admittedly high, the magnitude of the discrepancies (e.g. 70% for the Wortmann airfoil at $R_c = 200{,}000$ and $\alpha = 9°$) indicates that another explanation is necessary. As discussed by Mueller and Jansen (1982), the wake rake method of drag determination is itself suspect due to the nature of the flow that develops behind models tested in the low Reynolds number regime. This method determines the drag by measuring the momentum deficit in the streamwise direction downstream of the model. If the flow is of a highly oscillatory or vortical nature, the accuracy of the technique becomes questionable with an evident bias towards low drag measurements. Althaus (1981) noted that spanwise variation of the measured drag coefficient for an airfoil can be quite large even for a chord Reynolds number as high as one million. All things considered then, it is felt that while the drag coefficient as measured by the Notre Dame force balance scheme is conservatively high, it is more representative of what should be experienced in actual operation.

4.2 The roughened airfoil

In contrast to the smooth airfoil's performance curves of Fig. 3 are the drag polar and moment curves of Figs. 4–6. These curves present data for the airfoil's performance

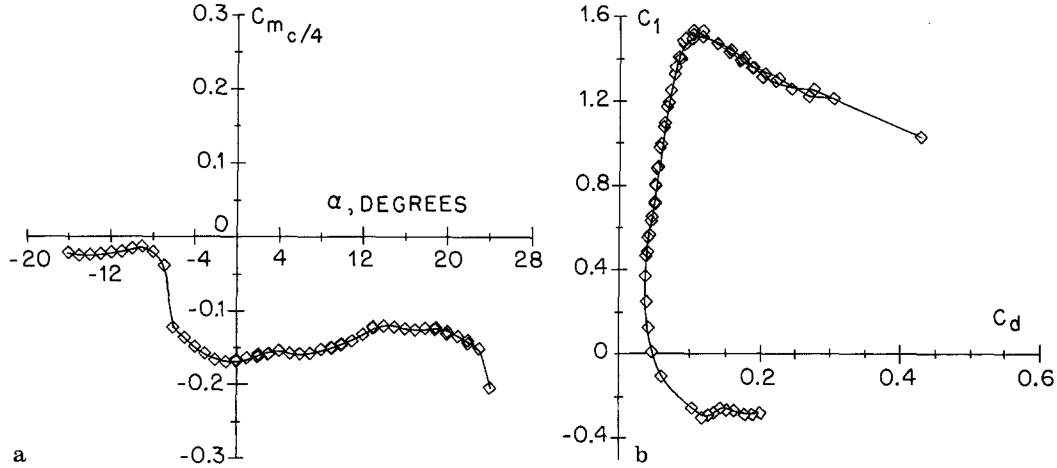

Fig. 4a and b.

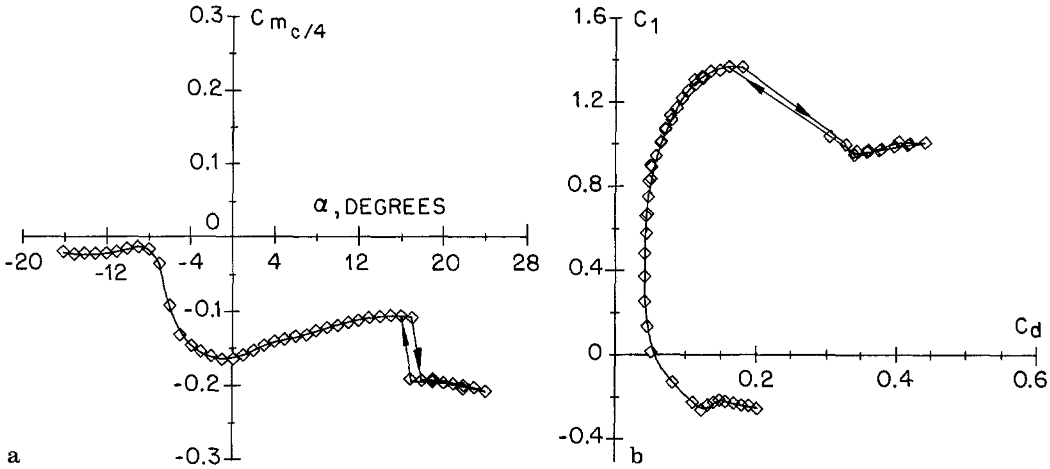

Fig. 5a and b.

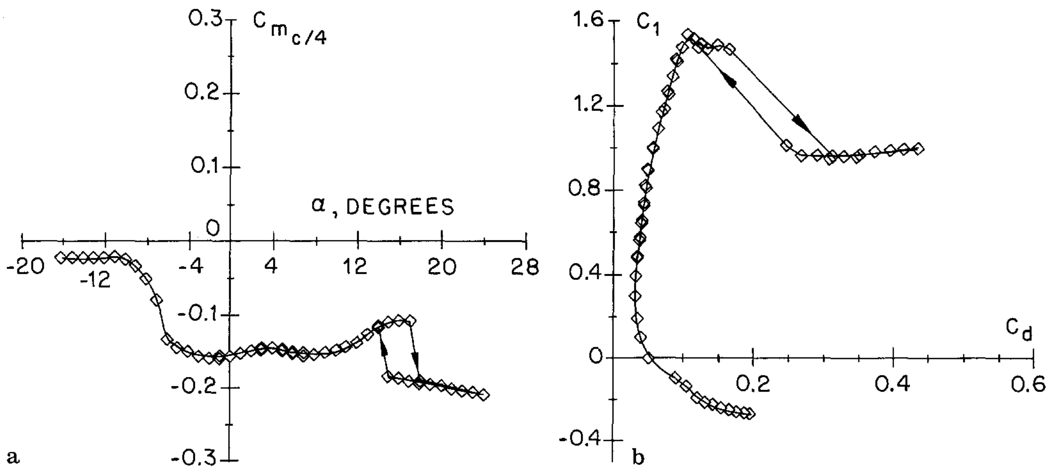

Fig. 6a and b.

Figs. 4–6. Performance curves for the Wortmann airfoil with a trip wire **4** at the leading edge and $k/c = 0.300\%$; **5** at $x/c = 3.0\%$ (upper) and $k/c = 0.300\%$; **6** at $x/c = 30.0\%$ (upper) and $k/c = 0.300\%$. **a** Sectional quarter chord moment coefficient versus angle of attack; **b** lift/drag polar with the smaller ($k/c = 0.30\%$) trip wire applied at the leading edge, 3.0% and 30.0% chordwise locations, respectively. As is evident from these figures, trip wire placement can have significant and varied effect on the airfoil's behavior.

The most prominent feature of Fig. 4 is the lack of a hysteresis loop at high angles of attack. Instead, the stall character is gentle with a large drop in lift occuring only for the highest angle of attack tested (24°). Roughness located at the leading edge appears to prevent separation bubble formation on the upper surface by causing transition of the flow almost immediately. While this alteration of the upper surface flow has little effect at angles of attack less than 13°, it results in the prevention of an abrupt loss in lift. Accordingly, turbulent separation continues to move forward as the incidence is increased providing a gentle stall up to very large angles of attack. It is only when the point of turbulent separation moves sufficiently close to the leading edge and/or the adverse pressure gradient becomes exceedingly severe that leading edge separation finally occurs. This explanation also accounts for why the moment coefficient fails to increase in magnitude at high incidence. Since less lift is produced on the forward part of the airfoil, the center of pressure remains aft and the moment coefficient is large and negative. For this condition, $C_{l\max}$ is slightly lowered with most other performance parameters ($C_{d\min}$, $(C_l/C_d)_{\max}$, etc.) improving slightly or remaining nearly the same. The larger trip wire reduces $C_{l\max}$ further and increases $C_{d\min}$. In spite of this trend, it would seem that definite benefits can be obtained with the use of leading edge roughness of the appropriate size. Hysteresis can be eliminated, a gentle stall substituted, and little sacrifice made with regard to other performance parameters.

The case of a trip wire located at $x/c = 3.0\%$ and with $k/c = 0.30\%$ is shown in Fig. 5. Here, the hysteresis loop reforms, but it only spans one degree with separation and reattachment occurring at 18° and 16° respectively, as compared with the smooth airfoil's three-degree hysteresis loop. Maximum lift is reduced by over 11% to 1.36 and $(C_l^{3/2}\,C_d)_{\max}$ suffers a 14% reduction to 16.12. However, maximum lift to drag ratio actually shows an increase over the smooth airfoil value reaching 17.12 (a 3% increase) at $\alpha = 4°$. This increase is due to both a reduction in the drag and an increase in the lift as compared to the smooth airfoil's values at this incidence angle. Note the almost linear decrease in the magnitude of the moment for positive angles of attack prior to stall.

Performance curves for trip wire roughness located at the point of maximum airfoil thickness, $x/c = 30\%$, are presented in Fig. 6. Except for the more nearly linear lift curve slope, the curves are somewhat comparable to those recorded for the smooth airfoil. The hysteresis loop is once again three degrees wide with flow separation and reattachment occurring at 18° and 14° respectively. The maximum lift and endurance factors are only slightly lower than the smooth airfoil values; however, minimum drag and $(C_l/C_d)_{\max}$ both show improvement. The increase in the latter parameter is the result of reduced drag and increased lift at $\alpha = 4°$ as compared to the smooth airfoil's performance. Of interest is the steady increase in lift with incidence across all negative angles of attack. This contrasts with all other conditions in which the lift slightly increases then decreases prior to the rapid rise in lift coincident with reattachment of the lower surface flow.

Figure 7 represents a summary of force balance data showing variations in certain performance parameters with trip wire height and placement. Beginning with $C_{d\min}$ (Fig. 7a), it is apparent that this parameter is increased for virtually all trip wire heights located on the lower forward surface or leading edge. Large heights have the more undesirable effect and roughness at $x/c = 1.0\%$ produces higher values than to trip wires further aft. Roughness on the upper surface is more complex in that various results can be obtained depending on height and location. Trip wires at $x/c = 1.0\%$ cause higher minimum drag values, yet as one moves aft, the effect can become beneficial, with larger heights actually reducing minimum drag. (One would expect, however, that some critical size exists where a further increase in k/c would reverse this favorable outcome.) When roughness is placed at the location of maximum airfoil thickness, $C_{d\min}$ attains its lowest recorded value using the smaller roughness height.

As seen in Fig. 7b, trip wire location and height have significant effect on maximum lift for the forward region of the upper surface. Lower surface roughness and upper surface roughness at $x/c = 30.0\%$ have minor effect on this parameter. When situated on the leading edge, a trip wire may have a small or large effect with severe reductions occurring in $C_{l\max}$ as k/c is increased. Roughness located at $x/c = 1.0\%$ reduces $C_{l\max}$ the most, the effect worsening with increasing trip wire height. As roughness is moved aft, losses in maximum lift apparently become less and less severe.

Figure 7c indicates that trip wires of varying height have little effect on $(C_l/C_d)_{\max}$ when placed on either the forward lower surface or the leading edge. However, a trip wire located on the upper surface between 1.0 and 5.0% of chord can significantly increased or decrease this parameter depending, of course, on its height. A critical value for k/c (depending on position) appears to exist for which smaller values can increase $(C_l/C_d)_{\max}$ and for which larger values decrease it. Naturally, one would suspect that another critical height exists in the lower height range at which this parameter reaches a maximal attainable level. This trend also seems to hold true for trip wires located at $x/c = 30\%$ where the greatest values in $(C_l/C_d)_{\max}$ were observed.

The effect on the maximum endurance factor for propeller-driver aircraft, $(C_l^{3/2}/C_d)_{\max}$, of a trip wire located on either the lower surface or the leading edge is

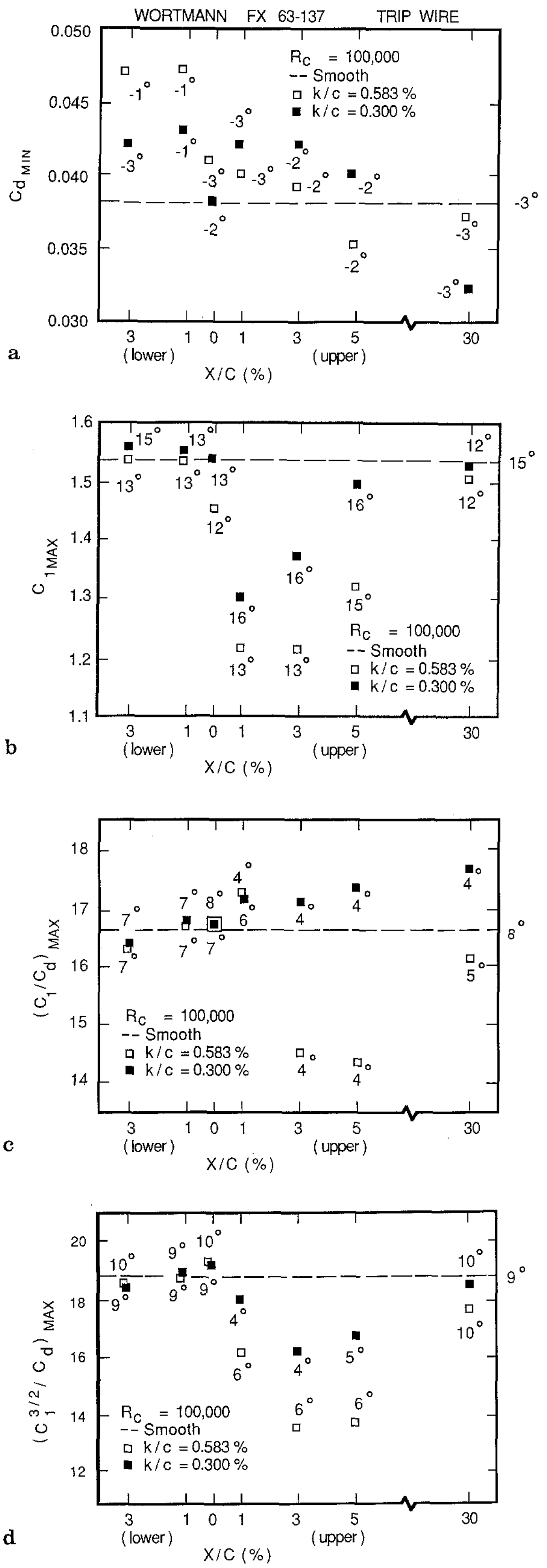

Fig. 7a–d. Performance parameter variation with roughness location and height (angles of occurrence indicated in degrees); variation of **a** $C_{d\,\min}$, **b** $C_{l\,\max}$, **c** $(C_l/C_d)_{\max}$ and **d** $(C_l^{3/2}/C_d)_{\max}$ with trip wire height and location on airfoil for $R_c = 100{,}000$

minimal (see Fig. 7d). In contrast, trip wires on the upper surface consistently lower this parameter with the decrease most significant for a large trip wire located at $x/c = 3.0\%$. Additionally, the angle of occurrence for this parameter can shift downward by as much as five degrees when the trip wire location corresponds to a forward position of the airfoil's upper surface.

A final set of data is presented in Figs. 8 and 9 which are pressure distributions of the smooth and roughened airfoil at 7° and 15° angles of attack respectively. The points of laminar separation, transition, reattachment, and turbulent separation are marked on the smooth airfoil plots by the symbols *S*, *T*, *R*, and *S'* respectively. Along with the smooth airfoil's distributions are plots which demonstrate the effect of trip wire placement at the suction peak and laminar separation points for each angle of attack condition. For the 7° case, the suction peak occurs at $x/c = 3.0\%$ while laminar separation occurs at approximately $x/c = 37.5\%$. Thus, trip wire placement for the latter condition is actually a head of the true separation point and instead corresponds to the point of maximum airfoil thickness. At $\alpha = 15°$ the suction peak moves to $x/c = 1.0\%$ while separation is found at the 5.0% chord location.

As shown in Fig. 8, the smooth airfoil demonstrates the presence of a laminar separation bubble from about $x/c = 37.5\%$ to $x/c = 70.0\%$. Transition occurs in the laminar free shear layer at approximately $x/c = 60.0\%$ forming a turbulent free shear layer which eventually reattaches just forward of the $x/c = 70.0\%$ location. The effect of trip wire placement at the $x/c = 3.0\%$ position is to create a short separation region behind the roughness element which leads to rapid transition and a large pressure recovery. No laminar separation bubble forms downstream since the flow is turbulent and entrains sufficient flow energy to remain attached. The pressure plateau region just behind the trip wire represents accelerated flow that is more unstable, but not sufficiently so that transition occurs at the element itself.

Trip wires placed closer to the laminar separation point for the case of 7° incidence demonstrate that increased k/c leads to more rapid transition and a higher pressure plateau immediately behind the roughness element. Tests involving other roughness types and a greater range of heights have substantiated this trend (Huber 1985). However, one should again note that neither trip wire positioned at $x/c = 30\%$ forces transition at the element site.

Figure 9 provides pressure distributions of the $\alpha = 15°$ condition and as one can observe in the smooth airfoil plot, a classic leading-edge bubble is present from about $x/c = 5.0\%$ to $x/c = 20.0\%$. Turbulent separation is also apparent at the 75.0% chordwise location. Moving from right to left in this figure, it is observed that an increase in trip wire height significantly decreases the suction peak value when the trip wire is located at the point of laminar separation ($x/c = 5.0\%$). Both wire heights produce an

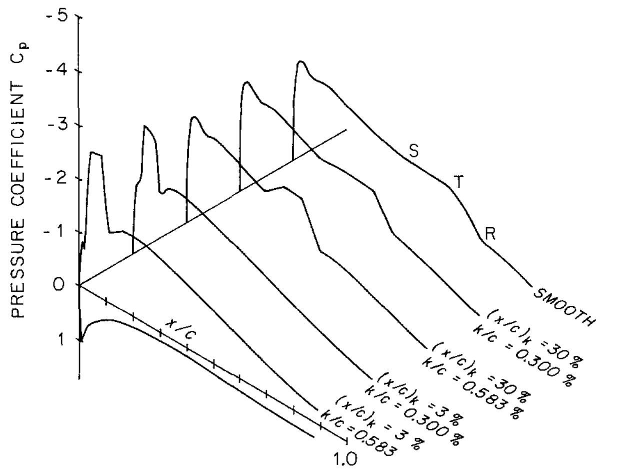

Fig. 8

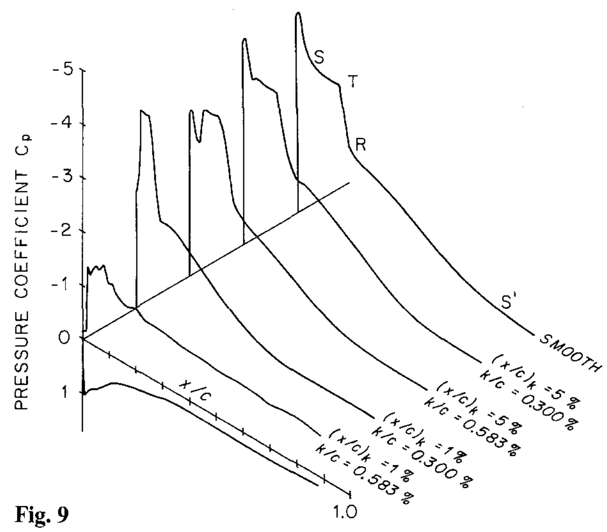

Fig. 9

Figs. 8 and 9. Pressure distributions of the smooth Wortmann airfoil and the airfoil with trip wire roughness **8** at $x/c = 3.0\%$ and 30.0% ($\alpha = 7°$), and **9** at $x/c = 1.0\%$ and 5.0% ($\alpha = 15°$)

earlier transition although the turbulent separation point seems unaffected. As in the 7° case, neither trip wire brings transition to the roughness location.

When the trip wires are moved to the smooth airfoil's suction peak location, the effects on the pressure distribution become much more pronounced. With a trip wire at $x/c = 1.0\%$ and $k/c = 0.300\%$, the resulting pressure plateau region is near the suction peak level, but is very short in length. Transition occurs relatively soon and leads to a sharp pressure recovery. Turbulent separation also moves forward and occurs at mid-chord. For $k/c = 0.583\%$ at the $x/c = 1.0\%$ location, the upper surface flow separates leading to a stalled condition. The lift is significantly reduced and the airfoil's pitch-down tendency greatly increased.

5 Conclusions

The results of this study indicate that the Wortmann FX 63-137 is a high performance low Reynolds number airfoil even when operated at off-design conditions. Experimental data show that separation phenomena, most notably the formation of laminar separation bubbles, greatly influence this airfoil's performance characteristics. Additionally, the occurrence of other boundary layer phenomena, such as turbulent separation, have significant effects.

The effects of the addition of trip wire roughness to the airfoil's surface are variable depending on location and height. In general, it can be stated that roughness located on the forward lower surface ($0.01 < x/c < 0.03$) has little effect on the performance of the FX 63-137 except to increase the minimum drag coefficient. In contrast, For $R_c = 100{,}000$ trip wires located on the upper surface aft of the leading edge can significantly reduce $C_{l\max}$ and $(C_l^{3/2}/C_d)_{\max}$ while improving or degrading $(C_l/C_d)_{\max}$ depending on the roughness height. Trip wire roughness located on the upper surface near the point of maximum airfoil thickness has limited, detrimental effect on the maximum lift and endurance factors, but can lead to reductions in $C_{d\min}$. A trip wire located at this position can also improve the maximum lift to drag ratio.

Performance of the airfoil with leading edge roughness indicates that if the appropriate height is used, hysteresis can be eliminated with little detrimental effect to other performance parameters. This finding is significant in that it suggests hysteresis can be avoided altogether and the airfoil's excellent performance exploited for aircraft application where uncertainty in lift cannot be tolerated.

From the pressure distribution data, it is evident that transition can be induced to occur at positions further forward than those at which it naturally occurs. However, in this study, it was not possible to bring the transition point to the roughness element itself. Typically, the flow is measurably accelerated aft of the trip wire before transition quickly occurs in the separated free shear layer. Once the flow entrains sufficient energy from the freestream, reattachment ensues while the pressure rises. Depending on the angle of attack, roughness height and position, such effects may or may not represent an improvement over the smooth airfoil's performance.

The usefulness of Eq. (5) to determine roughness heights appears to be questionable. Admittedly, this relationship was not developed for application in large pressure gradients, but unfortunately no other criteria are available in the literature. Transition at the trip wire location is not guaranteed as was the original desire. From additional experiments (Huber 1985), it is indicated that knowledge of the boundary layer thickness provides a good first guess as to what range of roughness heights one may want to investigate. One should investigate a range of heights since changes in k/c can occasionally lead to a reversal of effect causing an airfoil operating above its smooth performance levels to then perform far below them.

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Announcements

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Purpose: To communicate information of the relative merits of available instrumentation for measuring properties of the flows in the combustion chambers of gas-turbine and internal-combustion engines and to provide a forum for the discussion of new ideas and their application.

Sessions: The Institute comprises formal lectures by experts from various organisations and countries. The first week is devoted to instrumentation for gas turbine combustors and the second week to instrumentation for internal combustion engines. In both weeks, several sessions have been made available for the presentation of research work and contributions are welcome on all aspects of the subject matter of the Institute including:
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- Particle sizing.
- Probes and probe orientation effects.
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Abstracts: Paper selection will be based upon a reviewed abstract of not less than 300 words which should be typed double spaced and state the purpose, results and conclusions of the work with supporting figures as appropriate. Three copies of the abstract should be submitted to:
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Authors informed concerning acceptance:	June 30, 1987
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