EXPERIMENTS ON THE ESTABLISHMENT OF FULLY ATTACHED AEROFOIL FLOW FROM THE FULLY STALLED CONDITION DURING RAMP-DOWN MOTIONS

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Abstract

The paper presents data collected, for various aerofoils, during ramp-down tests carried out in the University of Glasgow's dynamic stall test facility. Although a reasonable picture of the boundary-layer behaviour has been obtained, the normal force variation with incidence caused concern over the possibility of tunnel interference effects. In order to investigate this phenomenon, tests were conducted which included variations in starting and stopping incidences, and aspect ratio. The main purpose of the paper will be to present the analysis of this data, provide a description of the overall flow structure within the tunnel, and discuss the validity of utilising ramp-down tests to study the phenomenon of reattachment.

Nomenclature

- c - Aerofoil chord (m)
- C_n - Normal force coefficient
- f - Non-dimensional separation point (x/c)
- r - Reduced pitch rate $(\dot{\alpha}\pi c)/(360U)$
- t - Time (s)
- U - Freestream velocity (m/s)
- v - Reattachment velocity (m/s)
- x - Chordwise distance
- α - Incidence (degs)
- $\dot{\alpha}$ - Pitch rate (degs/s)
- τ - Non-dimensional time $(\Delta t.U)/c$

I. Introduction

The use of non-sinusiodal variations in incidence during experimental investigations into the unsteady aerodynamic behaviour of an aerofoil has been well established [1-13]. These experiments have used ramp-up motion inputs to assess the effect of pitch rate alone on the dynamic stall process. As well as isolating the effect of pitch rate, ramp tests avoid the large data sets associated with oscillatory testing,. where variations in amplitude, mean angle, and frequency must be considered. Thus, in general, experimental investigations into dynamic stall have concentrated on the aerofoil loadings and flow structure up to and during the stall, with little attention being given to the subsequent reattachment process. During sinusoidal motions the reattachment behaviour is often complicated by the presence of shed vortices being swept downstream. Thus by using ramp-down motions it may be possible to isolate reattachment and specifically analyse the phenomenon under dynamic conditions.

A major part of the helicopter flight envelope is determined by the stall flutter boundary of the retreating blade as it encounters dynamic stall effects. This limit is determined by a combination of the torsional stiffness of the blade and the aerodynamic damping contained within the Cm hysteresis loop, which depends on both the stall behaviour and the reattachment process. There is also interest in using ramp type motions on lifting surfaces for combat aircraft to utilise the high dynamic forces required for supermaneuverability [14].

II. Experimental Apparatus

The general arrangement of the aerofoil in the wind tunnel is illustrated in Figure 1. The test aerofoils, of chord 0.55m and span 1.61m, were constructed of a fibre-glass skin filled with epoxy foam and bonded to an aluminium spar. Each aerofoil was mounted vertically in the University of Glasgow's Handley page wind tunnel which is a low speed (57 m/s max) closed-return type with a 1.61 x 2.13m octagonal working section. The aerofoil was pivoted about the quarter chord using a linear hydraulic actuator and crank mechanism.

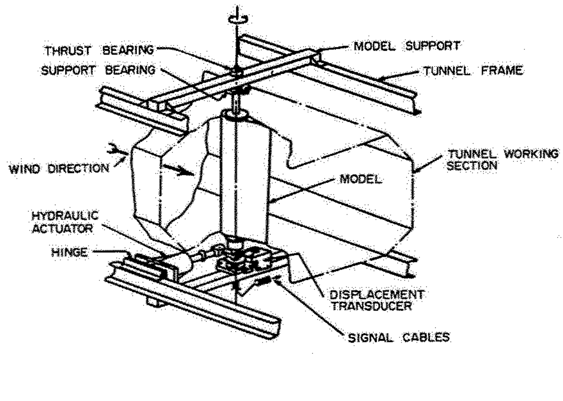


FIGURE 1 DYNAMIC STALL TEST FACILITY

Instantaneous incidence was determined by a linear angular potentiometer geared to the aerofoil's lower support. The dynamic pressure in the working section was obtained from the difference between the static pressure in the working section, 1.2m upstream of the leading edge, and the static pressure in the settling chamber, as measured by a Furness FC012 electronic micromanometer.

Thirty miniature pressure transducers were installed below the surface of the centre section of each test aerofoil. These consisted of both Kulite XCS-093-5-PSI-G and Entran EPIL-080B-5S transducers. All transducers were tempreature compensated and factory calibrated.

Each ramp-down test was normally initiated from a geometric incidence of around 36 degrees and terminated in the region of -6 degrees. The imposed pitch rate could be adjusted between -0.75 and -400.0 degs/s, allowing the reduced pitch rate to be varied between -0.001 and -0.05. The effective freestream velocity was 40 m/s resulting in Reynolds and Mach numbers of 1.5 million and 0.11 respectively.

For the ramp-down tests, 256 samples per cycle were recorded with a maximum sampling frequency of 550 Hz being attained at the high pitch rates. The data were then transferred to a *VAX 11/750* for processing, storage on a designated database and analysis.

Figure 2 illustrates the aerofoil sections whose aerodynamic behaviour is considered in the paper.

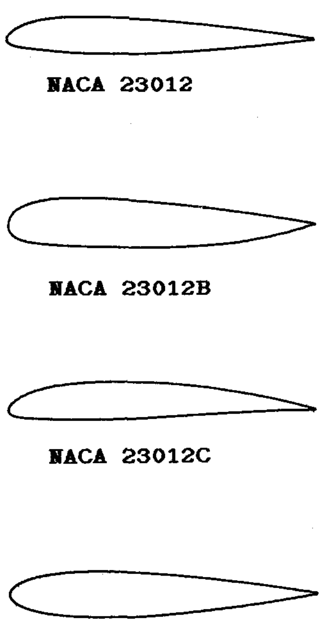


FIGURE 2 TEST AEROFOILS

III. Analysis Methodology

Terminology

For the purpose of the present paper the following definitions are made:

(i) The reattachment point is located at the base of the constant pressure region normally associated with the turbulent boundary-layer separation. Therefore, under the present terminology, the separation point and the reattachment point describe the same physical phenomenon.

(ii) The process of reattachment is taken to mean the movement of the turbulent separation point as it travels downstream from the leading edge to the trailing edge.

These definitions of reattachment should not be confused with the turbulent flow associated with the closure of a laminar separation bubble.

The word 'wake' will be taken to describe the region of separated flow which lies above the aerofoil's upper surface.

Analysis Technique

Figure 3 illustrates that, generally, the reattachment point was relatively easy to locate since the constant pressure region was well defined. However, obtaining the exact incidence at which fully attached flow was achieved was found difficult since the traling-edge pressure gradient became small during this condition.

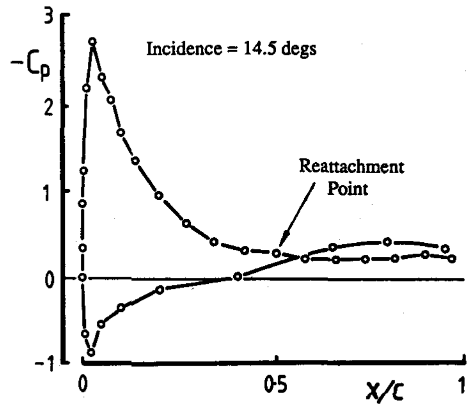


FIGURE 3 TYPICAL CHORDWISE PRESSURE DISTRIBUTION

A complementary method of locating the formation of localised disturbances within the boundary layer is the inspection of the response of individual pressure histories monitored at various chordwise locations. The rate at which a particular pressure history diverges can often be used to infer boundary-layer separation. The current database storage of the unsteady aerodynamic data allows individual pressure histories to be displayed on a graphics terminal. The screen cross-hairs can then be utilised to select a chosen pressure divergence point and store its respective incidence and non-dimensional time in a data file. Figure 4 illustrates five pressure histories each complete with their chosen reattachment point. Generally it was observed, from correlation between chosen pressure history signals and discrete chordwise pressure distributions, that a rapid rise in local suction indicated the movement of the reattachment point over the respective transducer. The implementation of this technique allowed sustantial amounts of data to be easily analysed.

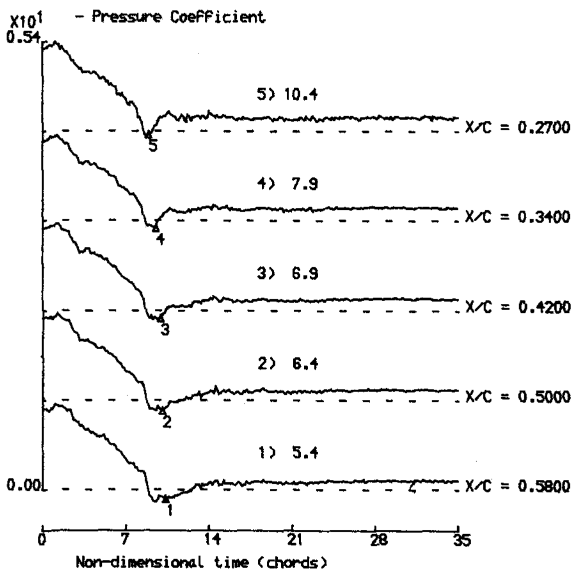


FIGURE 4 UPPER SURFACE PRESSURE HISTORIES NACA 23012B
r = -0.03

IV. Normal Force Behaviour

During a preliminary consideration of the ramp-down data [15] an interesting feature of the normal force behaviour became apparent. It was observed that negative lift was being generated at positive angles of incidence (as indicated by the aerofoil's chord line and the tunnel centre line). This behaviour gave rise to the question; was this response a valid two-dimensional characteristic of the flow ? One of the purposes of this paper is to discuss this particular question and in doing so it inevitably raises others. In addressing the problem the effects of tunnel interference, pitch rate, start incidence and aspect ratio are considered. Even with such data to hand no definitive conclusions have been made.

Tunnel Interference Effects

Figure 5 illustrates the variation of normal force with incidence for the three test aerofoils considered. It may be observed that the NACA 23012B displays negative lift at positive geometrical incidences. This behaviour is unusual and begs the question as to whether or not the confined flow of the wind tunnel caused the actual incidence of the aerofoil to differ from the geometric value.

It is well known [16,17] that the presence of the wind tunnel itself may affect the results obtained. The principle contribution to the interference comes from the streamlines of the flow about the test aerofoil being constrained by the presence of the tunnel walls. This effect is generally known as 'wall interference' and it may affect both the flow conditions at the aerofoil and the distribution of downwash within the tunnel. Though the influence of the tunnel walls on the flow is complex, it is generally assumed that the interference can be divided into independent components whose effects are additive. Thus changes in stream incidence and curvature, associated with the circulatory flow around the aerofoil ('lift effects'), are considered to be independent of changes in effective stream velocity due to tunnel volume occupied by the aerofoil and its wake ('blockage effects'). Additionally, if the tunnel-wall boundary layers are not removed, undesirable corner flows may develop at the junction of the aerofoil and the wall.

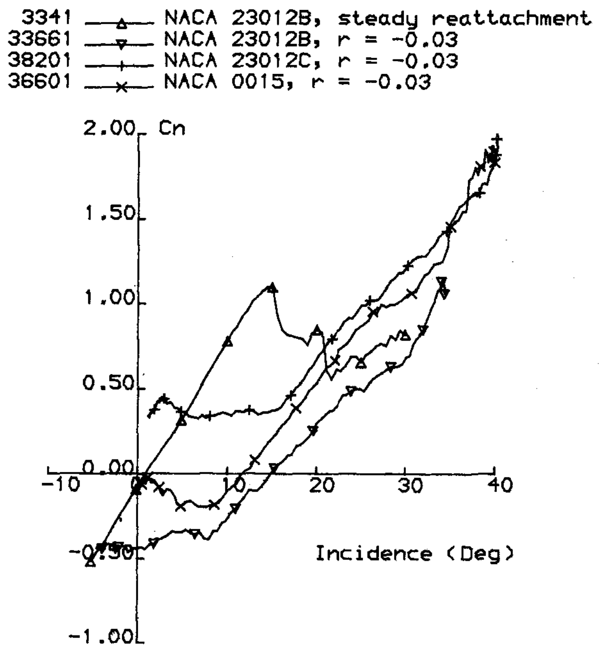


FIGURE 5 NORMAL FORCE BEHAVIOUR
r = -0.03

Figure 6 illustrates a typical flow structure interpreted from oil-flow tests [18] and summarises the main flow components associated with any two-dimensional steady wind tunnel test. It is a well known [19] that the boundary-layer flow approaching the stagnation zone of an obstacle separates and forms an unstable vortex sheet, which rolls up in a 'horseshoe like manner'. Bippes and Turk [20] showed that, at high angles of incidence, the interference of the horseshoe vortex and the separated region on the aerofoil prevented symmetrical flow conditions. It was further suggested that the result of this interference was the formation of an additional vortex, on the aerofoil's upper surface, near the tunnel wall. If this flow phenomenon is coupled with a minor tunnel flow imbalance then a highly asymmetrical flow separation will occur. The resulting separation patterns are often described as 'stall cells' [21] and the associated distribution of trailing vorticity can induce complex distributions of upwash/downwash along the aerofoil span.

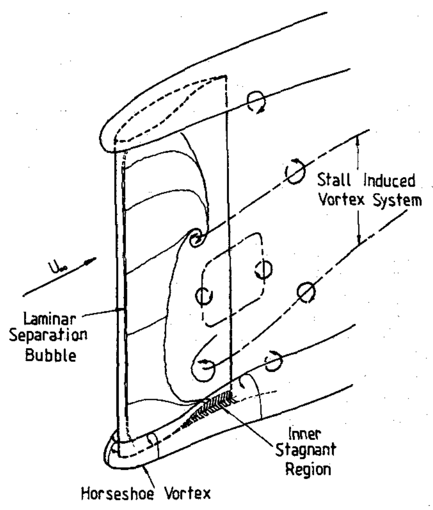


FIGURE 6 TYPICAL FLOW SEPARATION PATTERN

With the above in mind, it is prudent to consider whether or not the suspected anomoly in the normal force response is soley a consequence of the tunnel environment. To test this all pitch rate effects on the flow, whether known or not, were temporarily ignored and comparisons of measured unsteady pressure distributions were compared with computed steady equivalents. The predicted steady pressure distributions were obtained from a vortex panel algorithm which included the facility to model flow separation and wake formation [22]. It was noted that the vortex panel method had the following limitations: steady potential flow; steady wake geometry; did not include any boundary-layer thickness effects. Also the ratio of wake length to height was related to aerofoil thickness to chord ratio using a correlation based on steady data. It is therefore unlikely that this correlation will be applicable to an unsteady wake. However, comparisons with the experimental data can both significantly assist in its interpretation and help isolate any anomalous transducer outputs. Figure 7 illustrates the panel method's capablity in predicting both fully attached and highly separated steady flow.

If the negative lift was caused by a tunnel-induced downwash, then the induced incidence would need to be less than that indicated when the aerofoil is producing zero lift in steady flow. Also the leading-edge stagnation point would lie on the upper surface which, as indicated in Figure 8(a), is clearly not the case. In fact, the agreement between the predicted lower surface pressure distribution and that observed experimentally is good in trend but not in magnitude. This lack of agreement in magnitude may be due to the combined effect of the lower surface boundary layer and any incidence errors induced by the flow confinement.

An attempt to estimate the induced incidence was made by varying the incidence input to the panel method, but keeping the separation point fixed. This procedure, illustrated in Figure 8(b), was carried out until the best fit was achieved around

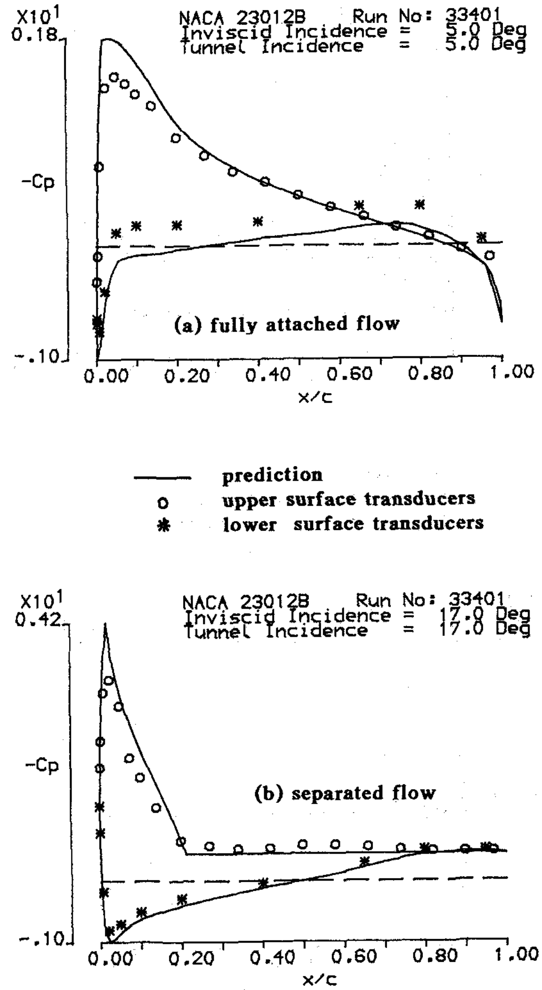


FIGURE 7 COMPARISON BETWEEN PANEL METHOD AND STEADY TEST DATA

the forward stagnation point and over the lower surface. Any effects the motion or the unsteady wake geometry may have on the stagnation point position were ignored.

For the test cases considered, it was noted that, for separation points greater than 5% chord, the geometrical incidence always had to be reduced to achieve an improved comparison between the panel method and the tunnel data. This result implies that there exists a downwash distribution around the aerofoil. This is apparently the opposite behaviour from steady aerofoil tests [21] which often imply the existence of an upwash due to three-dimensional flow separation patterns. The conclusion from this reasoning is that, during the ramp-down motion, the flow separation front is perhaps more uniform, and it is the shed vorticity in the corner flow, at the aerofoil/wall junction, which is inducing the downwash distribution.

Although the validity of the above technique is unclear, the results do imply that any error in geometrical incidence, induced by the confined flow separation, cannot account for the normal force behaviour.

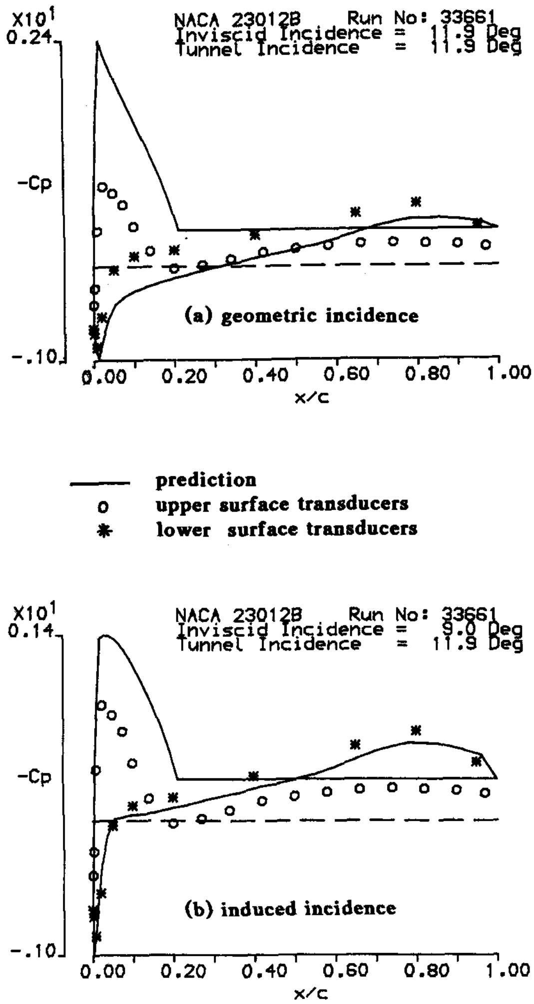


FIGURE 8 COMPARISON BETWEEN PANEL METHOD AND RAMP-DOWN DATA, r = -0.03

Pitch-rate Effects

If we accept the above then the remaining differences in predicted and experimental pressure distributions, illustrated in Figure 8(b), may be attributed to the imposed pitch rate. Temporal dervatives will effect both the potential flow and the boundary layer behaviour [23]. During ramp-up motions the growth of leading-edge suction, for a given incidence, is delayed with respect to the steady state response [8]. However, this characteristic is for nominally attached flow and it is uncertain whether this response would be observable when large amounts of flow separation are present.

Distortion of the wake geometry due to the motion will have a dominant effect on the global velocity field. This effect would influence both the suction peak and the pressure distribution over the free shear layers. Even in strict two-dimensional flow, wake compression, between the freestream flow and the aerofoil upper surface, is easy to visualise.

Variable Start Incidence

Ramp-down tests from variable starting incidences, and hence differing initial blockage conditions, were conducted to investigate whether the initial flow separation, and any associated flow three dimensionality influenced the normal force characteristic. Figure 9 summarises the test results.

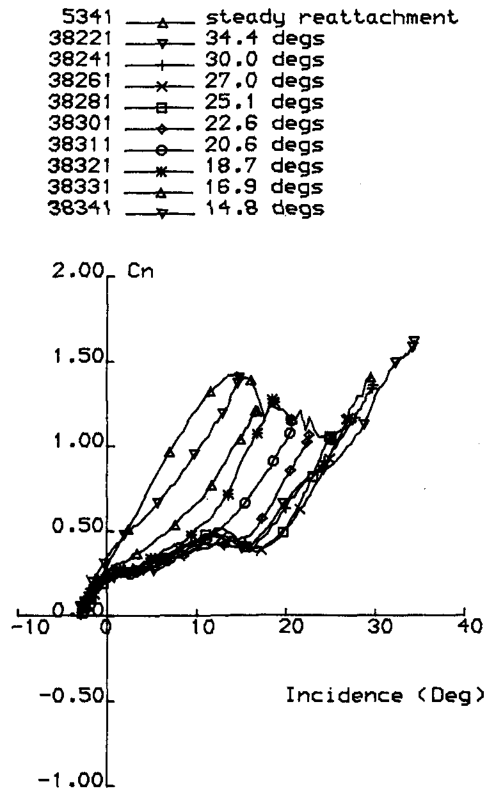


FIGURE 9 VARIABLE START INCIDENCES NACA 23012C, r = -0.03

For start incidences above 22° the upper surface flow was initially fully separated. Previous analysis [15] has conluded that the incidence at which leading-edge reattachment commences was, to a first order, insensitive to pitch rate and occurred at a value close to its steady-state counterpart. For the NACA 23012C the critical incidence is 22°. Therefore, prior to leading-edge reattachment, the normal force variation with incidence will be greatly influenced by the flow over the lower surface and the free shear layers. Thus if fully separated flow conditions exist at the motion onset, a similar normal force response would be expected. This reasoning may explain the uniformity in the variation of normal force with incidence for each start incidence above 22°.

If leading-edge reattachment has been establised prior to the commencement of the motion (i.e., for the NACA 23012C, start incidences below 22°) then the subsequent boundary-layer behaviour, wake development, leading-edge suction growth and lower surface pressure distribution response will now all contribute to the normal force. This gives each test case its own individual characteristic (Figure 9).

Figure 5 shows that, for high incidences, the rate at which the normal force decreases is very similar for the three significantly different aerofoil sections. For large amounts of separated flow, at a given pitch rate, the instantaneous wake geometry may be expected to be insensitive to the aerofoil profile. Furthermore, Figure 10 shows that the fully separated normal force variation with incidence was also effectively independent of pitch rate. The conclusion from these observations is that prior to significant leading-edge reattachment it is the incidence which controls the magnitude of the normal force and that the pitch rate is only important in so much as it suppresses any growth in leading-edge suction. Therefore the normal force must be determined by the lower surface pressure distribution which is governed by the aerofoil geometry and the instantaneous flow incidence.

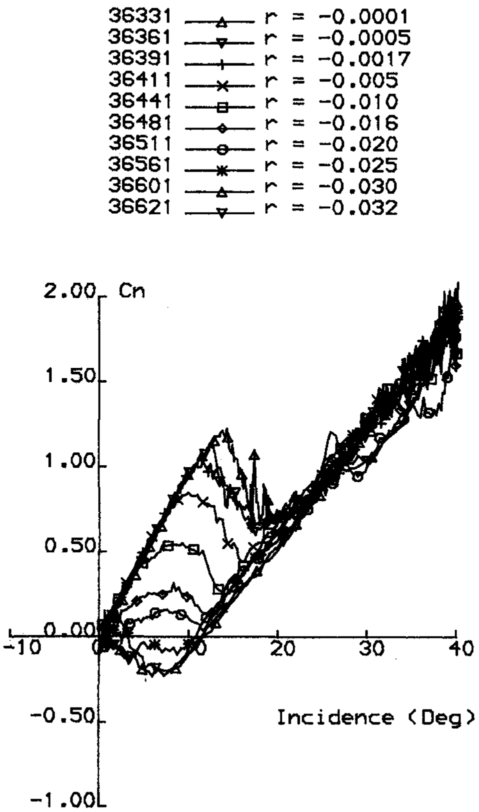
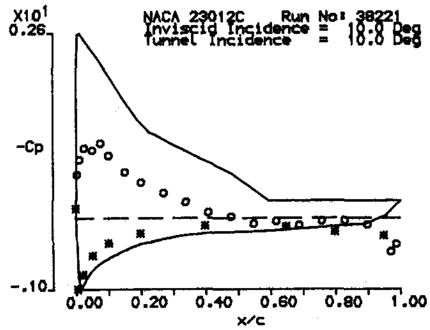
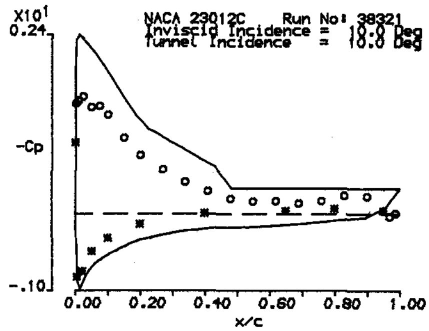


FIGURE 10 VARIABLE REDUCED PITCH RATE, NACA 0015

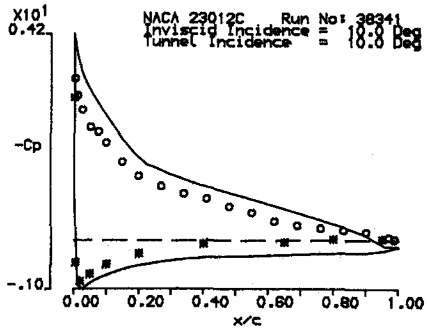
Figure 11 shows the results of a comparison between the variable start incidence data and the panel method at a fixed incidence of 10°. As the start incidence is reduced the agreement between the computed pressure distribution and the test data becomes better. The instantaneous pitch rate was not considered responsible for this behaviour since it was approximately constant at 10° over the range of start incidences. These results imply that, if tunnel interference effects are influential, the amount of separation at the motion onset is perhaps important in determining the temporal development of the downwash distribution around the aerofoil. Alternatively, the aerofoil's motion history may be influencing its instantaneous pressure distribution. Classical unsteady aerodynamics [24,25] includes the motion history of the aerofoil by considering the effect of the shed vorticity on the aerodynamic loads. Although the analysis techniques utilised are strictly only applicable to fully attached flow, a similar response may be expected for any aerodynamic situation which has a time varience of shed vorticity.



(a) start incidence = 35 degs



(b) start incidence = 19 degs



(c) start incidence = 15 degs

—— **prediction**
o **upper surface transducers**
* **lower surface transducers**

FIGURE 11 COMPARISON BETWEEN PANEL METHOD AND RAMP-DOWN DATA, r = -0.03

Variation of Aspect Ratio

The effect of aspect ratio on the aerofoil's aerodynamic behaviour can be considered by mounting two large fins (splitter plates) equidistant from the aerofoil's centre span [21]. The fins have to be large enough to isolate the flow between them from any corner flow effects at the aerofoil/wall junction. For the present tests the aspect ratio was reduced from 2.92 to 1.6. An additional benifit of the fins is to reduce the size of the corner flow interaction at the aerofoil/fin junction. This can help suppress any corner flow separation. However this does not necessarily reduce the amount of three-dimensionality within the stall cell [21].

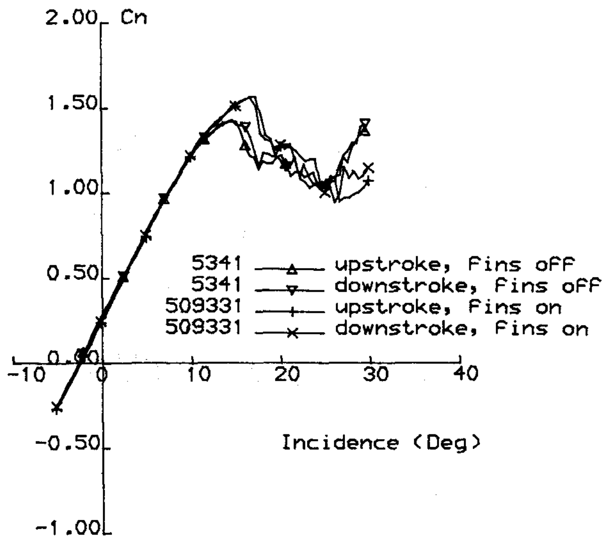


FIGURE 12 EFFECT OF SPLITTER PLATES ON STEADY DATA NACA 23012C

Figure 12 displays the normal force characteristics for the NACA 23012C with and without the splitter plates. The identical lift-curve response up to 10° indicates that two-dimensional conditions existed for essentially attached flow. Figure 13 shows that the differences in separation behaviour explains the modification to the aerodynamic loadings in the region of stall.

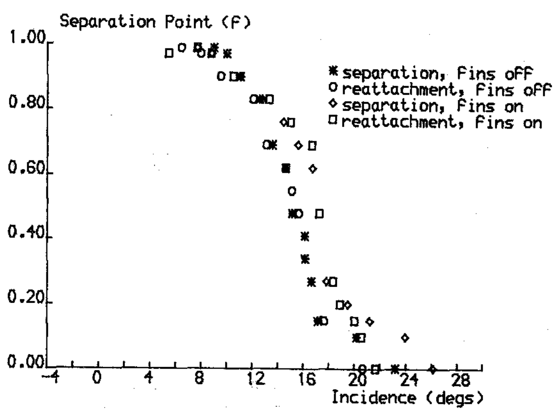


FIGURE 13 EFFECT OF SPLITTER PLATES ON STEADY SEPARATION CHARACTERISTICS NACA 23012C

Figures 14 and 15 illustrate the normal-force behaviour obtained from various ramp-down tests with and without the splitter plates. Whilst the small differences in normal force can be attributed to the differences in reattachment characteristics, the overall trend is very similar. It is interesting to note that prior to significant leading-edge reattachment (i.e. for the NACA 23012C start incidences above 22°), the normal force variation with incidence is apparently an extension of the appropriate steady bluff-body behaviour. If there is a three-dimensional flow structure within the tunnel, which is influencing the aerofoil's aerodynamic behaviour, then a reduction in aspect ratio does not appear to modify its structure.

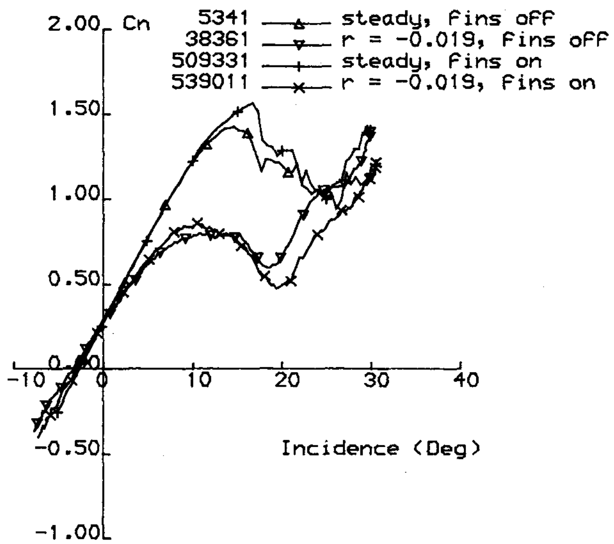


FIGURE 14 EFFECT OF SPLITTER PLATES FIXED PITCH RATE NACA 23012C, r = -0.02

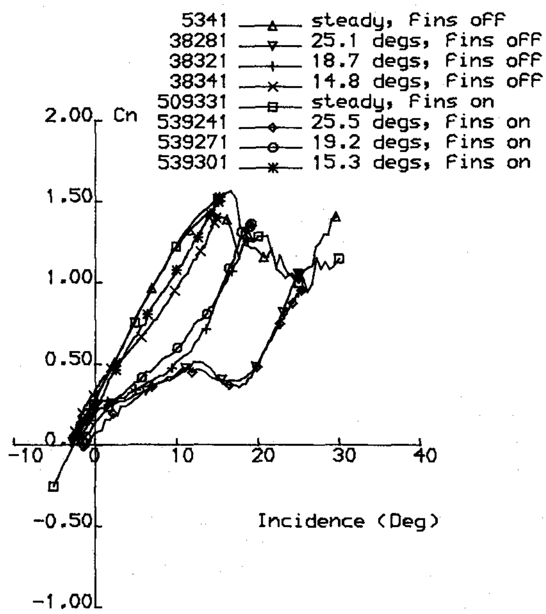


FIGURE 15 EFFECT OF SPLITTER PLATES VARIOUS START INCIDENCES NACA 23012C, r = -0.03

V. The Reattachment Process

It is apparent from the previous sections that accurate assessment of any tunnel interference without modelling the entire wind tunnel/aerofoil flow is fraught with difficulties. Even a simple estimation of a possible induced incidence is complicated by the present ability only to isolate the effect of pitch rate in a heuristic manner. Therefore the following analysis, which focuses on the reattachment process, utilises the data as recorded and no corrections have been applied.

Early investigations [15] of the reattachment behaviour noted the non-dimensional time delay between the rise in suction at the 2.5% chord and the establishment of fully attached flow (as indicated by the chordwise pressure distribution).

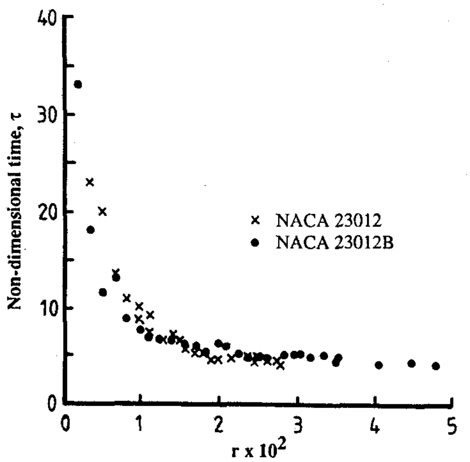


FIGURE 16 NON-DIMENSIONAL TIME FOR FULL REATTACHMENT (from [15])

Figure 16 illustrates this time delay as a function of reduced pitch rate. Based on this graph the following conclusions were made. At low pitch rates, the downstream advancement of the reattachment point was influenced by the build-up in upstream pressure distribution and the associated pressure gradients. Therefore, its movement was influenced by the aerofoil geometry. At the high pitch rates, however, the establishment of a pressure distribution upstream of the reattachment point was retarded by the rapid decrease in incidence, and therefore any effect of aerofoil geometry was reduced. In order to explain why the change of phase from fully separated to fully attached flow did not occur within one chord length of flow, it was postulated that the reattachment process is controlled by the time scales associated with the development of the free shear layer into an attached boundary layer.

The present approach was to monitor the downstream translation of the reattachment point by studying the response of each upper-surface transducer pressure history in the manner described in Section III (Figure 4). Figure 17 illustrates the variation of the reattachment point with non-dimensional time for each of the test aerofoils at a pitch rate of -0.03. It was generally observed that as the pitch rate was increased the variation of the reattachment point with non-dimensional time became approximately linear after leading-edge reattachment had been established. The gradient of a least-squares regression line passing through these data describes a reattachment velocity as a fraction of the freestream velocity. It is interesting to note

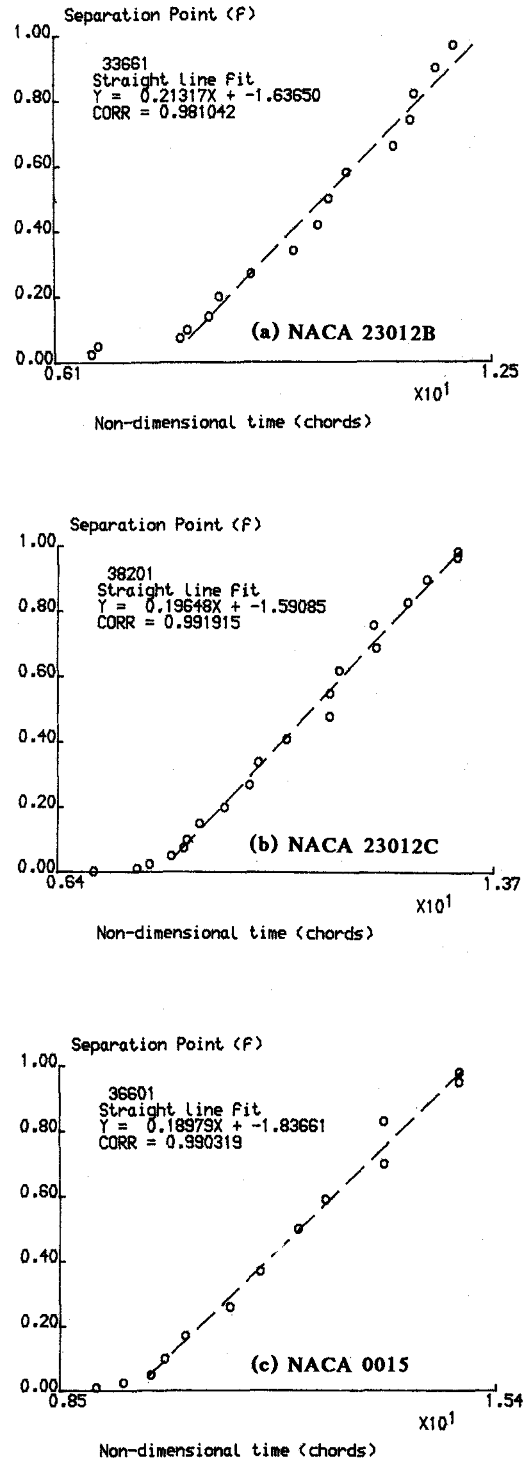


FIGURE 17 NON-DIMENSIONAL REATTACHMENT VELOCITY

that the reattachment velocity over the leading edge was significantly lower than that over the remaining chord. This may be due to the high surface curvature in this region. Also downstream movement of the reattachment point may be retarded by the moving wall [26] (or leading-edge jet [27]) effect destablising the boundary layer around the leading-edge.

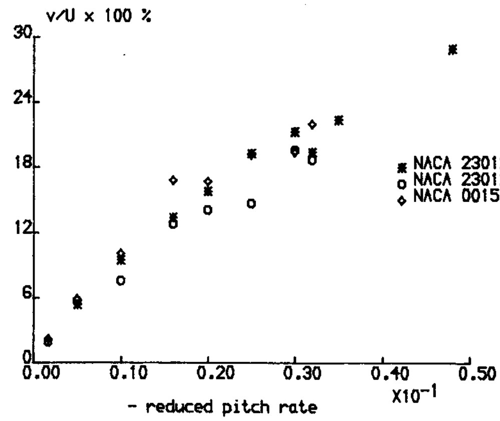


FIGURE 18 EFFECT OF REDUCED PITCH RATE ON NON-DIMENSIONAL REATTACHMENT VELOCITY

Figure 18 illustrates the variation of the non-dimensional reattachment velocity with reduced pitch rate. Although the reattachment velocity does not approach a constant value as convincingly as the time delay results, shown in Figure 16, it is perhaps a more appropriate calculation since it does not include the non-linear behaviour over the leading edge. For the chosen test cases, the reattachment velocity does not appear to be dependent on the test aerofoil. The reduced pitch rate is apparently controlling the downstream advancement of the reattachment point. Further evidence of this behaviour can be obtained from the variable start incidence tests. It was found that, irrespective of the initial separation position, the reattachment loci quickly adopted a response common to each start incidence. Figure 19 illustrates an example of this behaviour. It was

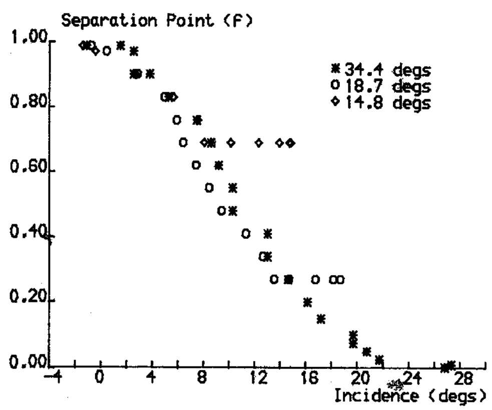


FIGURE 19 REATTACHMENT BEHAVIOUR FOR VARIOUS START INCIDENCES NACA 23012C, r = -0.03

also noted that the non-dimensional reattachment velocity was effectively constant at 0.19 over the range of start incidences. Since the aerofoil's motion history was different for each start incidence, this result implies that the reattachment process is apparently responding to the instantaneous pitch rate.

VI. Conclusions

Based on the above analysis the following conclusions have been made:

(a) A simple estimation of any error in geometrical incidence, induced by the confined flow separation, could not account for the negative normal force at positive geometrical incidences.

(b) Prior to any significant leading-edge reattachment, the normal force was dominated by the lower surface pressure distribution which was governed by the aerofoil geometry and the instantaneous flow incidence.

(c) The rate at which the reattachment point moves downstream appears to be dependent on the reduced pitch rate and unaffected by aerofoil geometry.

The paper has left many questions open ended and the authors anticipate that new facilities and software being developed will resolve the dilemmas encountered. In particular, flow visualisation and unsteady discrete-vortex simulation are planned.

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