FOURTEENTH EUROPEAN ROTORCRAFT FORUM

Paper No. 11

ANALYSIS OF REATTACHMENT DURING RAMP DOWN TESTS

D.G.F. HERRING - A.J. NIVEN - R.A.McD. GALBRAITH

UNIVERSITY OF GLASGOW
SCOTLAND

20-23 September, 1988
MILANO, ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

ANALYSIS OF REATTACHMENT DURING RAMP DOWN TESTS

D.G.F. HERRING - A.J. NIVEN - R.A.McD. GALBRAITH

Abstract

The paper considers the reattachment of the flow over the upper surface of an aerofoil, whilst undergoing a constant negative pitch rate motion, from an incidence well above the static stall value. Experimental data from a variety of aerofoils tested using the University of Glasgow facilities, have been recorded. All data were collected at an effective Mach and Reynolds numbers of 0.11 & $1.5x10^6$ respectively. Various improvements for future work are noted, and the predominant features of the reattachment process are discussed. Finally a preliminary consideration of the Beddoes predictive method is presented for reattachment.*

Notation

α = Incidence (degs)

$\dot{\alpha}$ = Pitch Rate (degs/sec) #

c = Aerofoil Chord (m)

f = x/c = Non-dimensional Chord

fs = Sampling Frequency (Hz)

r = $(\dot{\alpha}\pi c)/(360U)$ = Reduced Pitch Rate #

n = Sweep Number

U = Freestream Velocity (m/s)

$\tau = (\Delta t.U)/c$ = Non-dimensional Time

(Note: both pitch rate and reduced pitch rate are treated as positive values within the paper).

1. INTRODUCTION

For particular flight conditions, the retreating blade of a conventional helicopter experiences incidences in excess of the profile's static stall value. These excursions may become so severe that the blade will dynamically stall. Once full dynamic stall is initiated, there follows an inevitable and well known sequence of aerodynamic phenomena (Carr et al, 1977). These events are concluded by the return to the fully attached conditions by a process of reattachment.

Reattachment has received only limited consideration, albeit many dynamic modellers have intuitively proposed mathematical descriptions of it, (Beddoes, 1982, Leishman and Beddoes,1986, Nash and Scruggs, 1977, Ganwani, 1983, Vezza, 1986, etc), and they have met with varying degrees of success (Galbraith, 1985, Beddoes, 1980, McCroskey, 1978). This, perhaps, may be associated with both the complex nature of reattachment and the available experimental data which, primarily, is for sinusiodal motions. As can be imagined, such data are both extensive (to cover an appropriate range), and complicated by the non-linear motion. To alleviate the problems of non-linear motions, various investigators (ARA, 1983 Jumper and Shreck, 1986, Seto and Galbraith, 1985, Lorber and Carta, 1987, Ahihara et al, 1985, Robinson and Luttges, 1983) have considered stall development during constant pitch rate (ramp) displacements. The succinctness of the data, and its clarity of content, have been most useful in aiding our knowledge of the stall process.

It is conceptionally easy to perceive that constant negative pitch rate, or ramp down, will yield an equivalent wealth of information about reattachment phenomena. As was discovered during the present investigation, however, the practicalities of implementing this concept require more consideration than the straight forward positive pitch rate ramp. In particular, each test starts with an obvious tunnel blockage which reduces to a small value at the low incidence fully attached case. Additionally, at what incidence does one start a given test, and is averaging of the data permissible?

The data considered in the present work have been taken from the current University of Glasgow Database of aerodynamic phenomena. The main portion of the data base relates to dynamic stall data covering four aerofoils. Each of the test programmes considered pitching displacements which were not of immediate importance, but would be of future interest. One such motion was

* The predictive code used has been developed from the equations defined in References 11 and 12.

contained in a series of ramp-down tests which were a simple inverse of ramp-ups.

The aerofoils considered in the paper form a family of four which has the NACA 23012 as the generic shape, from which three modifications have been considered (Figure 1). In total, 1967 different test cases have been considered (Table 1), and around one hundred of these were ramp-downs. Data from all the these tests have been averaged and analysed to assess the manner, and rate, of the reattachment process together with an initial attempt to predict the time dependent loadings using the Beddoes model.

The main observations were, that ramp-down experiments are more complicated than ramp-ups; that leading-edge reattachment is always initiated at an incidence close to its static stall counterpart, and the subsequent rate of reattachment is significantly effected by model geometry up until reduced pitch rates of around 0.015, whereafter reattachment is significantly affected by the time scales of the unsteady turbulent boundary-layer response.

2. TEST FACILITY

The general arrangement of the aerofoil in the wind tunnel is illustrated in Figure 2. The models, of chord length 0.55m and span 1.61m, were constructed of a fibre-glass skin filled with epoxy resin foam and bound to an aluminum spar. Each model was mounted vertically in the University of Glasgow's "Handley Page" wind tunnel which is a low speed (max speed = 57 m/sec) closed - return type with a 1.61 x 2.13m octagonal working section. The model was pivoted about the quarter chord using a linear hydraulic actuator and crank mechanism. The input signal to the actuator controller was provided by a function generator, comprising of a BBC microcomputer and two 12-bit digital to analogue convertors; one to control the shape of the motion, and the other to set the desired voltage governing the amplitude or arc length of the motion. A range of different functions were programmed and tested using this set up (Table 1).

Thirty miniature pressure transducers were installed below the surface of the centre section of each model. These consisted of both KULITE XCS-093-5 PSI G and ENTRAN EPIL-080B-5S transducers. All transducers were temperature compensated and factory calibrated. Whilst these calibrations were accurate, the necessary cabling and signal conditioning of the transducer output may render a slightly different system performance. As a consequence of this, the entire measurement system was calibrated for each model. The method used was to apply a time varying calibrated reference pressure to each of the model's pressure transducers in turn. Both reference and model transducer outputs were simultaneously recorded to yield a well defined calibration.

Instantaneous aerofoil incidence was determined by a linear angular potentiometer geared to the model's tubular support. The dynamic pressure in the wind tunnel working section was obtained

Figure 1. "Family" of Aerofoils Tested Under Dynamic Stall Condition.

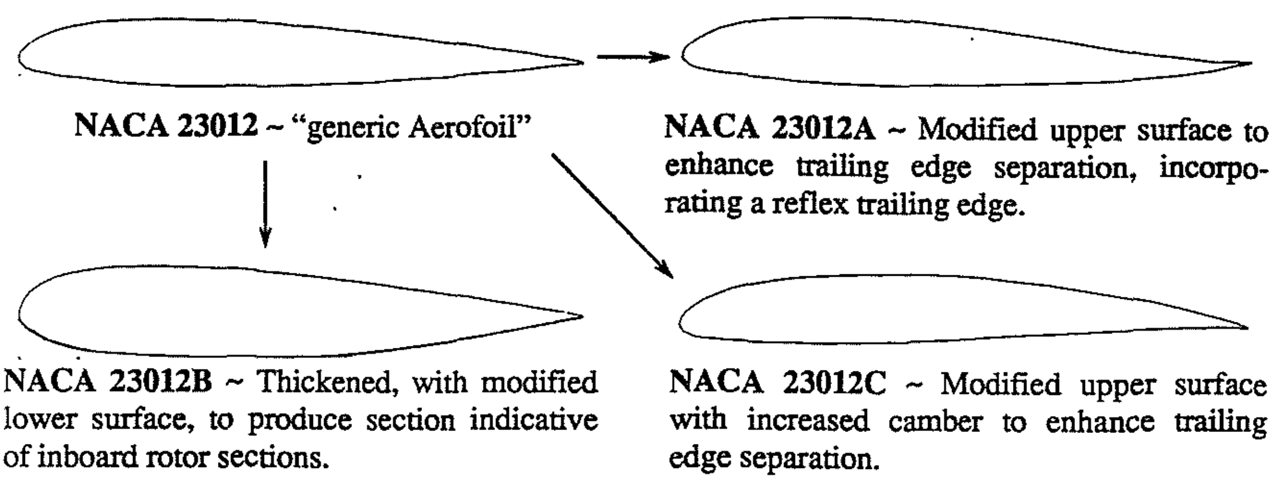


Table 1. Summary of Dynamic Stall Database of the NACA 23012 Family.

Model	Static	Sine	Ramp Up	Ramp Down	Unsteady Static	Vawt	Other	Total
NACA 23012	47	550	87	37	0	0	0	721
NACA 23012A	1	85	32	13	34	0	0	165
NACA 23012B	56	282	119	45	89	29	45	665
NACA 23012C	23	230	77	32	54	0	0	416
TOTAL	127	1147	315	127	177	29	45	
								grand total = 1967

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.

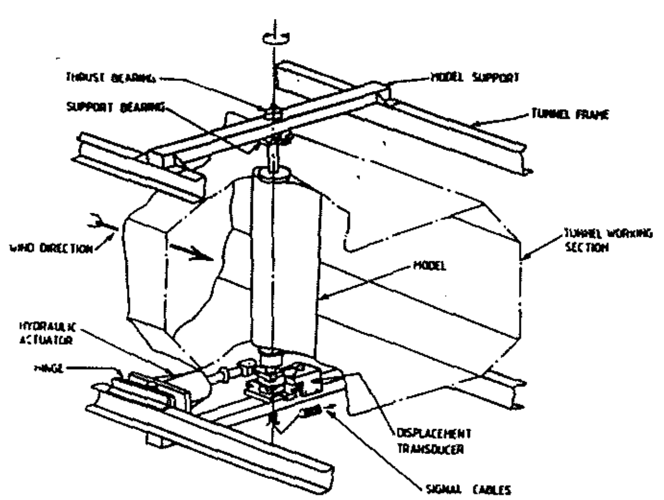
For the ramp-down tests, 256 samples per cycle were recorded at a maximum sampling frequency of 550.0 Hz. Five cycles of data were recorded using a DEC MINC 11/23 micro-computer system (Galbraith, 1984). The data were then transferred to a VAX 11/750 for processing, storage and analysis. The subsequent data reduction and presentation is a standard for all such tests, and a typical output is given in figure 3.

3. EXPERIMENTAL RESULTS

3.1 Introduction

The data discussed herein pertain to the NACA 23012 section and its three derivatives. Each ramp-down test was normally initiated from

Figure 2. Dynamic Stall Test Rig.



a geometric incidence of around 36 degrees and terminated in the region of -6 degrees. As will be appreciated, pure ramps were not achieved due to start-up and slow-down requirements, but, as will be shown in Section 3.3, leading-edge reattachment was always initiated within the linear region of the motion. The aerofoil angular velocity was progressively increased from 0.75 to 400.0 degs/sec, allowing the reduced pitch rate to be varied between 0.001 and 0.05. At the highest reduced pitch rate, the aerofoil completed one ramp-down cycle in 0.1s. The effective freestream velocity was 40.0 m/sec resulting in Reynolds and Mach numbers of 1.5 million and 0.11 respectively.

Figure 3 illustrates a standard output, from which a variety of salient features may be observed. For example, at this medium pitch rate (100 degs/sec), there is a marked variation of loading from the equivalent static case, and the detailed time dependent pressure distribution illustrates the causation of this via the evident lag in suction build up. The effect of increasing pitch rate is to further this variation in loadings, and at the faster pitch rates the expected leading-edge pressure build-up became non-existent.

3.2 Method of Analysis

Of particular interest is the timing of the reattachment process, and this may be investigated by assuming the following:

- The process develops from the leading to the trailing edge.
- The reattachment location is located at the start of the constant pressure region normally associated with trailing-edge separation. As can be imagined, the location of this

DYNAMIC CHARACTERISTICS FOR THE NACA23012B MODEL03

RUN REFERENCE NUMBER: 33531

REYNOLDS NUMBER = 1471248.

DYNAMIC PRESSURE = 1009.99 Nm^{-2}

NUMBER OF CYCLES = 5

MOTION TYPE: RAMP DOWN

START ANGLE = 35.00°

RAMP ARC = -41.000°

AVERAGED DATA OF 5 CYCLES

DATE OF TEST: 6/12/87

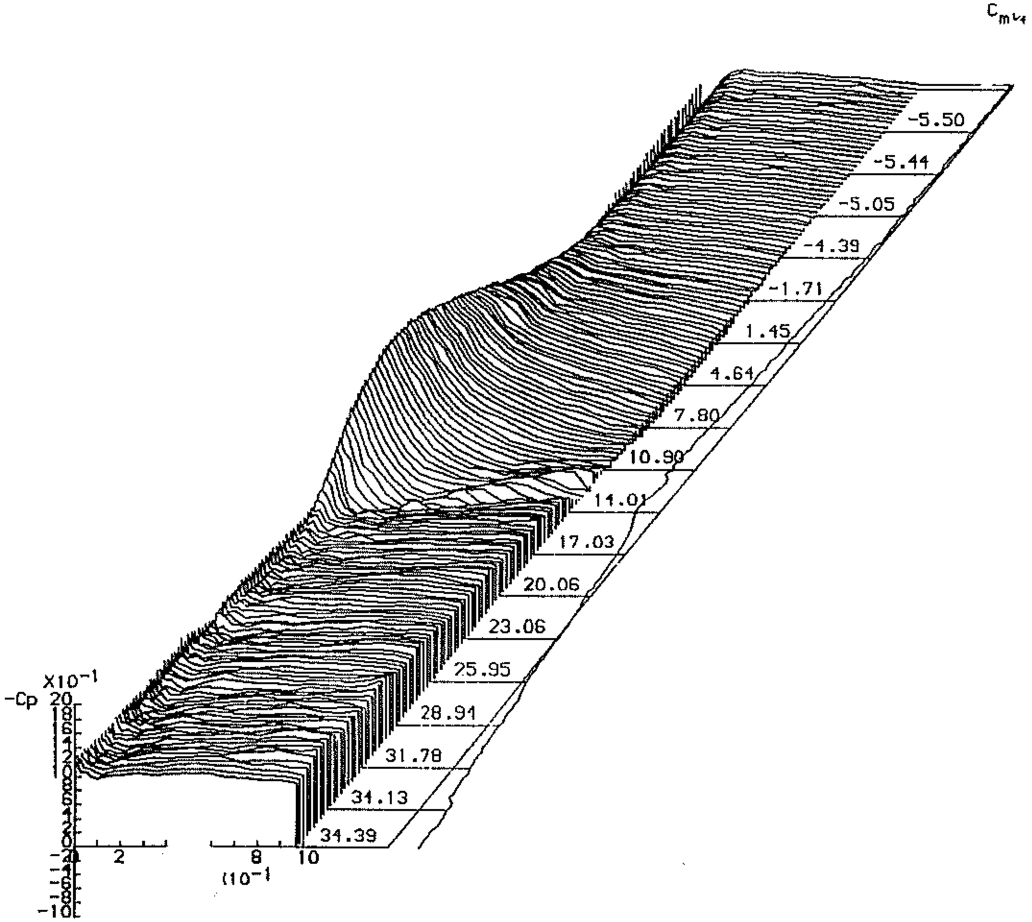
MACH NUMBER = 0.119

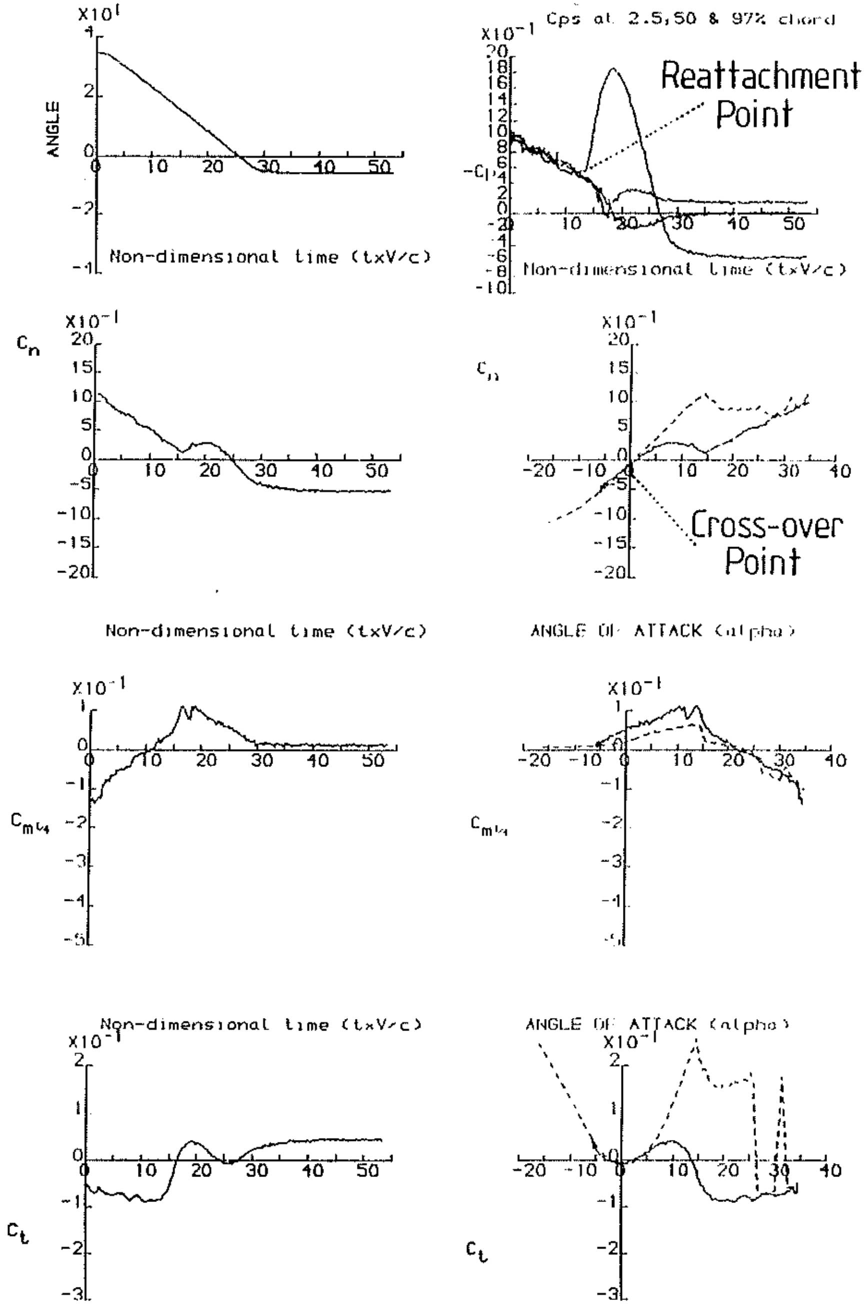
AIR TEMPERATURE = 29.3°C

SAMPLING FREQUENCY = 359.97 Hz.

REDUCED PITCH RATE = -0.01242

LINEAR PITCH RATE = -107.04$°S^{-1}$



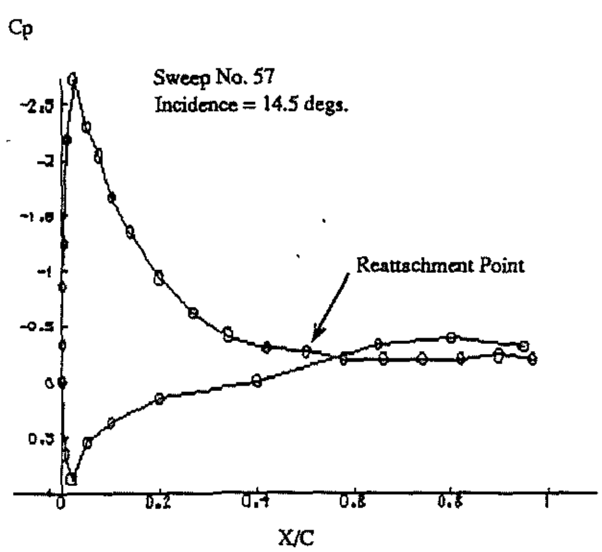


point is often difficult to discern, but efforts have been made to define a consistent approach.

This method is illustrated in Figure 4, where the reattachment point is relatively easy to observe, and the constant pressure region is well defined. Obtaining the exact incidence above which fully attached flow cannot be sustained, however, can be difficult, since the trailing-edge pressure gradient may become small at this condition. A complementary method of locating the formation of localised protuberances within the boundary layer, is the inspection of the response of individual pressure-time histories monitored at various chordwise locations. As shown in the top right graph of Figure 3, the rate at which a particular pressure-time history diverges can often be used to infer boundary-layer separation and reattachment. Therefore, a heuristic analysis involving both pressure-time histories and discrete chordwise pressure distributions may be used to monitor the translation of the reattachment point across the aerofoil's upper surface. Having established a functional method of extracting the relevant aerodynamic data, the non-dimensional time delay between two particular events, which occurred during a selected ramp-down test, was calculated from the difference in sweep numbers, associated with each event, (Δn), and the sampling frequency in the following manner:

$$\tau = (\Delta n.U)/(fs.c)$$

Figure 4. Typical Chordwise Pressure Distribution.



3.3 Leading-Edge Reattachment

On inspection of selected ramp-down test cases, it was noticed that, at the initial high incidence values, there was a distinctive change in pressure-time history at 2.5% chord (Figure 3) which accompanied the establishment of a small suction peak at the leading edge of the aerofoil. For some test cases a very small suction peak was discernible at 1% chord, but its size and position remained insensitive to incidence variation. It is suggested, that this suction peak was due to the flow curvature over the leading edge, at the initial high incidence values, and therefore its use as the indicator of the onset of reattachment was inappropriate. Only when the suction at 2.5% chord began to rise, did the reattachment process appear to move downstream; this finding was consistent over the entire pitch rate range.

Figure 5 presents the variation in leading-edge reattachment incidence with reduced pitch rate for a selection of aerofoils from the Glasgow University Database. It is interesting to note, that the initial reattachment incidence is relatively insensitive to pitch rate. For each aerofoil, the average value of the leading-edge reattachment incidence, obtained from the ramp-down tests, was found to approximately coincide with its steady-state counterpart. Also illusrtated is the similarity between initial reattachment incidence for the NACA 23012 and its derivatives 'A' and 'C'. During the development of the 23012A and 23012C profiles, a specified design constraint was, that the leading-edge geometry was not to be significantly altered from that of the NACA 23012. This therefore implies, that the initiation of reattachment depends significantly on the leading-edge geometry, and would explain the differing result obtained for the NACA 23012B (Figures 1 and 5).

3.4 Speed of Reattachment

Figure 6 illustrates the effect of pitch rate on the reattachment characteristics of the NACA 23012B aerofoil. If the aerofoil was within the linear incidence region of the ramp, then, for a particular chordal position, the instantaneous non-dimensional reattachment velocity can be estimated in the following manner:

$$vr = (\dot{\alpha}c/U)/(df/d\alpha)$$

Figure 5. Angle of Reattachment @ 2.5% chord Versus Reduced Pitch Rate.

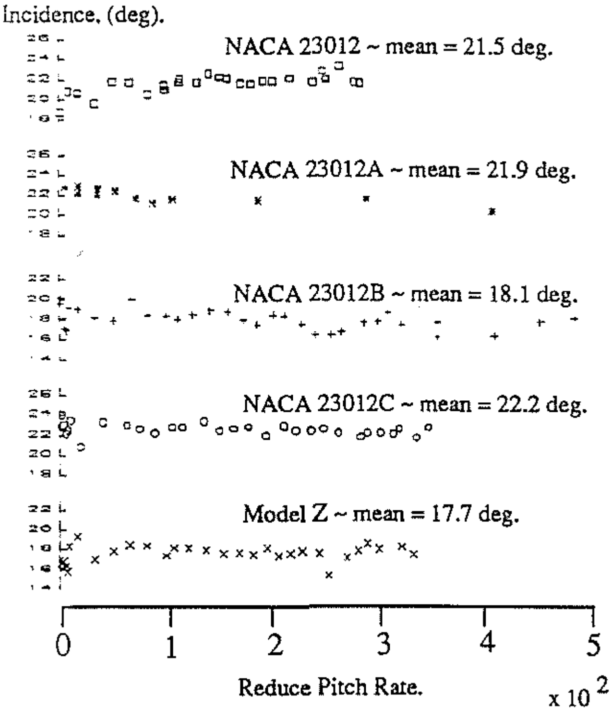
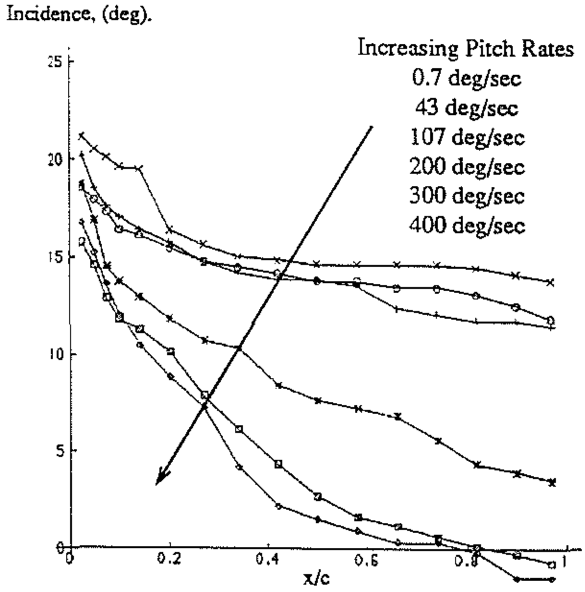


Figure 6. Reattachment point variation with increasing pitch rates.



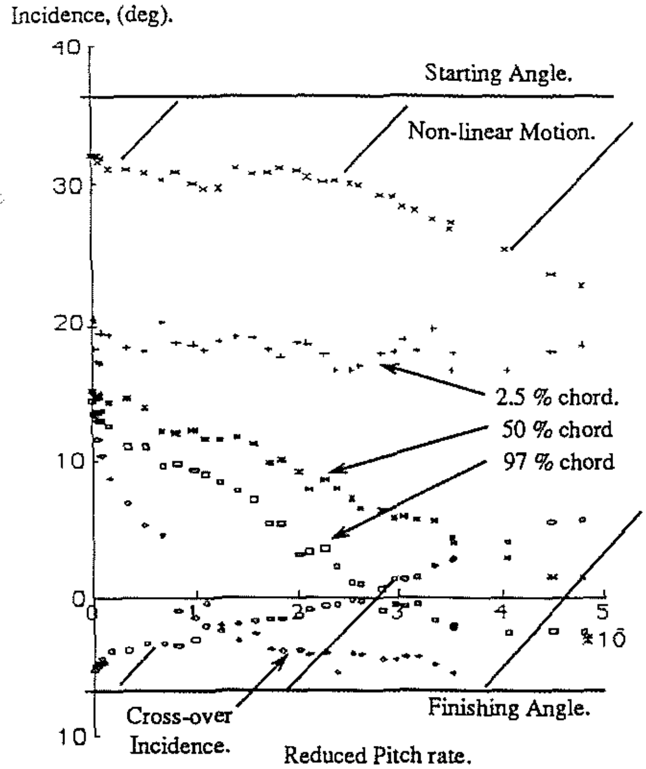
Expressed in this form, the variation in instantaneous reattachment velocity with chordal position can be easily observed from Figure 6 since, for a particular pitch rate, its value is inversely proportional to the local gradient of the reattachment curve. If, as was occasionally apparent, the reattachment point moved a large chordal distance within one sample sweep, the instantaneous reattachment velocity, at intermediate points, could not be calculated. This was due to the maximum sampling frequency of 550Hz, used during data acquisition, not being of sufficient magnitude, and therefore, with regard to this specialised area of interest only, was seen to be a limitation of the existing test facility.

3.5 Reattachment Time Delays

Figure 7 illustrates the estimated incidence values for 50% and 100% attached flow as a function of reduced pitch rate. Also marked on this figure are the regions of acceleration and deceleration associated with the range of ramp-down tests, and the cross-over incidence where the dynamic Cn intersects the static Cn curve (Figure 3). It may be noticed that, for reduced pitch rates above 0.028, the incidence at which fully attached flow is established lies within the deceleration region. However, as will be shown later, for these values of pitch rate, the reattachment process displays a reduced dependency on the aerofoil motion, and therefore the non-linear incidence variation becomes unimportant.

Having defined the points of leading and trailing edge reattachment, a characteristic time delay associated with the establishment of fully attached flow over the aerofoil's upper surface can be calculated. Figure 8 illustrates the full reattachment time delay results associated with the NACA 23012 and 23012B aerofoils. At low pitch rates, a small difference in time delay occurs, and therefore a weak dependence on aerofoil geometry is implied. The apparent convergence in time delay at the higher pitch rates implies that the influence of both aerofoil geometry, and motion, on the reattachment process has now become reduced. Unfortunately, the data available for the NACA 23012 did not cover pitch rates greater than 220 degs/s, and therefore, any differences between the two aerofoils at pitch rates above this value are obscured. What is apparent, though, is that for values of reduced

Figure 7. Reattachment point at 2.5,50 and 97% chord over the range of reduced pitch rates.



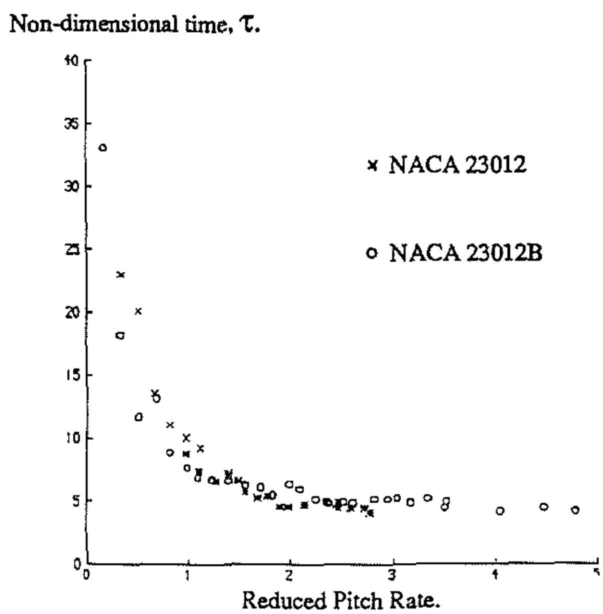
pitch rate above 0.015, the effect of aerofoil geometry is significantly reduced allowing the full reattachment time delay to approach a value of 4; equivalent to 25% of the freestream velocity.

3.6 Boundary-Layer Response

Associated with the reattachment process there must be a finite length of time within which the free shear layer develops into an attached boundary layer. Similar to that of boundary-layer detachment, the process of reattachment may be expected to be influenced by the external pressure gradient. At low pitch rates, the downstream advancement of the reattachment point will be influenced by the build-up in upstream pressure distribution and the associated pressure gradients. Therefore, its movement may be expected to be dependent on the aerofoil geometry.

At the high pitch rates, the establishment of a pressure distribution upstream of the reattachment point is retarded by the rapid decrease in incidence, and therefore any effect of aerofoil geometry will be reduced. If this is the case, why does the change of phase from fully separated to fully attached flow not occur within one chord length of flow i.e., at a average velocity equal to that of the freestream? Kline et al (1981) observed that two-dimensional turbulent flow detachment was not a single event, but a phase change from attached to detached flow. For a turbulent boundary layer, zero wall shear stress is created by the averaging to zero of strong unsteady motions of opposite sign, and therefore full detachment occurs over a zone. The same remarks, concerning zero wall shear, apply qualitatively to reattachment, but Kline noted that the motions at reattachment were even stronger in the turbulent case, owing to larger fluctuations in the free shear layers. It is postulated here, that the reattachment process consists of a damping out of characteristic turbulence structures whose length scale varies from that appropriate to a free shear layer to that of an attached boundary layer. Therefore, there will exist a finite period of time within which the large scale turbulence structures must relax before boundary-layer

Figure 8. Non-dimensional time for full reattachment to occur once initiated at 2.5% chord.



reattachment and downstream advancement can occur. Once the effect of aerofoil geometry has been suppressed, i.e., at high ramp-down pitch rates, the rate of reattachment is determined by the detailed fluid mechanics of this process.

At present, further data analysis, involving the reattachment characteristics of other aerofoils, available on the Glasgow University Database, is in progress to either substantiate or refute the above postulation.

4. MODELLING

The present approach in attempting to model the test data has been to code an existing semi-empirical model (Beddoes, 1982, Leishman and Beddoes, 1986). It is noted that the Beddoes model is only appropriate down to Mach numbers of about 0.15 (Leishman, 1986), below this, additional nonlinear lift and moment overshoots may occur. These limitations are partially due to the restricted number of available low Mach correlations, and it is hoped that the current work will contribute to this area of interest.

The necessary empirical time constants, required for appropriate modelling, have been extrapolated from table 1 of reference 11; the static separation loci was experimentally determined, and an exponential curve fit applied (Figure 9); the angular forcing has been filtered through a five point moving average.

Figure 11 illustrates three examples of the predictive code in modelling Cn. At the slowest pitch rate good agreement is observed. As the pitch rate increases, however, the model fails to predict the drop in Cn. This rapid lowering of Cn can be regarded as a following of a lift curve appropriate to an aerofoil within close proximity of its wake; experimentally shown to predominate up until the point of three chord lengths of flow after the initiation of reattachment (Figure 10). Modelling this behaviour by using a Cn/α relationship representative of "aerofoil plus wake", and allowing a smooth exponential transition back to the Beddoes model radically improves the overall prediction (Figure 12). This method requires further investigation, and correlation with sinusiodal data. It does, however, model a physical flow event which is consistent with the overall concept of the Beddoes model.

5. CONCLUSIONS

The following conclusions have been inferred from the data presented herein:

1. The initiation of reattachment, as measured at 2.5% chord, was insensitive to pitch rate, and occurred at an incidence approximately equal to its steady-state counterpart.
2. The non-dimensional time delay associated with the full reattachment was a strong function of reduced pitch rate for low to medium values, whilst the higher rates tended to a constant value of 4.

Figure 9. Trailing Edge Separation Movement For Static Tests.

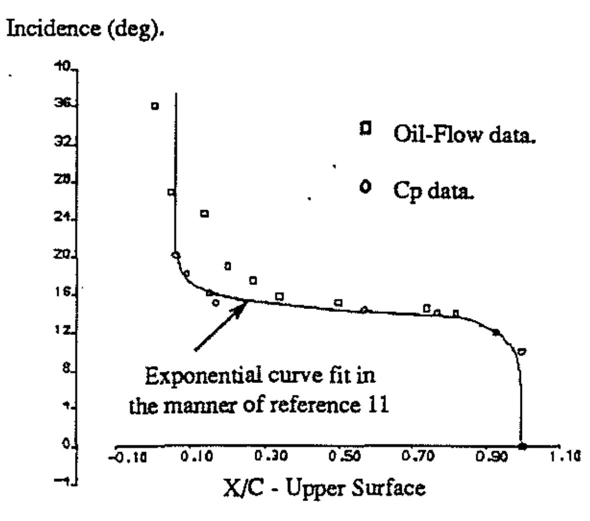


Figure 10. Cn versus Incidence for a range of pitch rates.

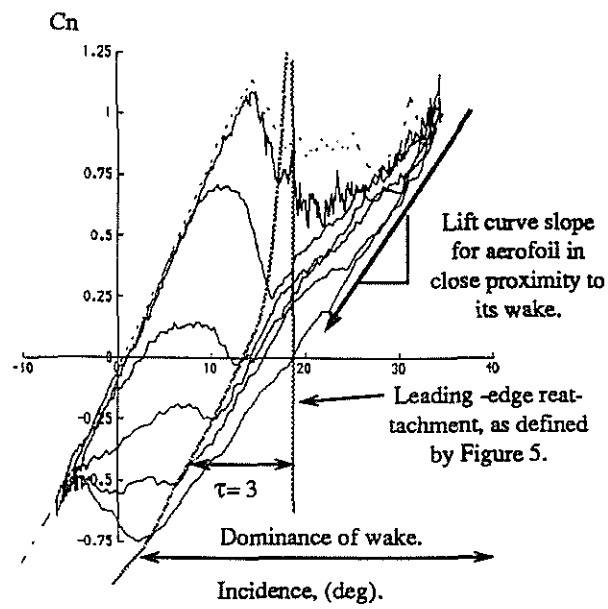
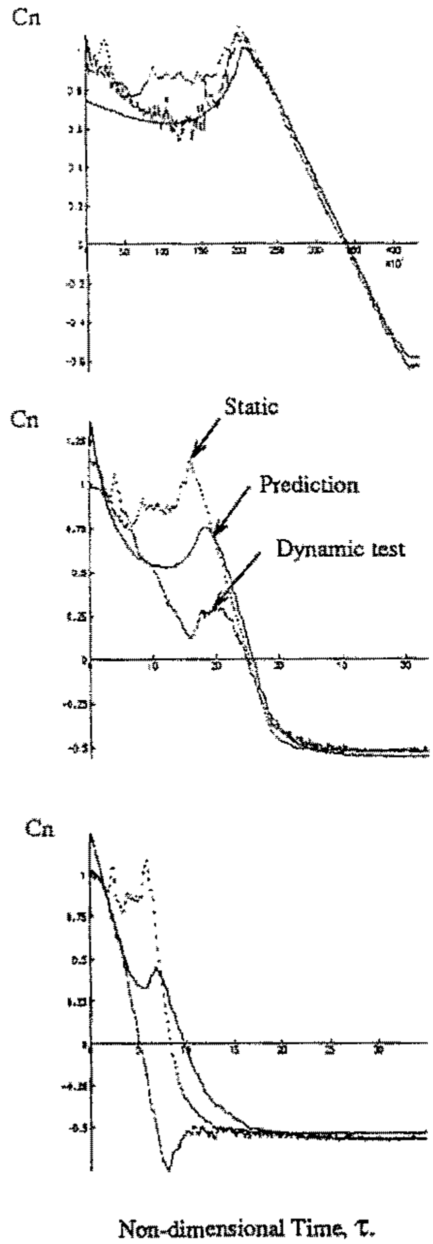


Figure 11. Correlation of Cn from predictive method and test data.

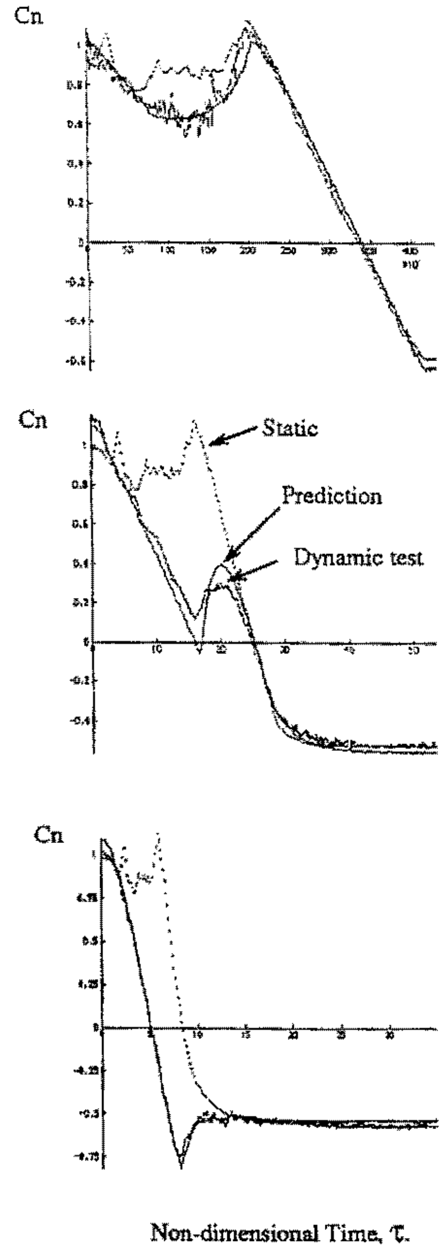
Figure 12. Correlation of Cn from predictive method with wake modelling inclusion and test data.



0.7 deg/sec.

100 deg/sec.

400 deg/sec.



3. The presence of the wake takes a finite time to diminish, until which it remains a significant component in determining the airloads.

Acknowledgments

The authors wish to acknowledge the encouragement and support of Professor B.E. Richards and their colleagues both academic and technical. Also the advice and help offered by Mr. T. Beddoes of Westland Helicopters Ltd, in the coding of the model, is warmly acknowledged.

The work was principally carried out with Department of Trade and Industry funding via M.o.D. agreement number 2048/033.

References

1. Aihara, Y. H. Koyama and Murashige, A. ***Transient Aerodynamic Characteristics of a Two-Dimensional Airfoil during Stepwise Incidence Variation.*** Journal of Aircraft, August 1985.
2. A.R.A. Private communication. 1983.
3. Beddoes, T.S. ***Prediction Methods for Unsteady Separated Flows.*** AGARD Report 679, Paper 15, 1980.
4. Beddoes, T.S. ***Representation of Airfoil Behaviour.*** AGARD CP-337, paper 2, 1982.
5. Carr, L.W., McAlister, K.W. and McCroskey, W.J. ***Analysis of the Development of Dynamic Stall based on Oscillating Airfoil Experiments.*** NASA TN D-8382, January 1977.
6. Galbraith, R.A.McD. ***A Data Acquisition System for the Investigation of Dynamic Stall.*** Proceedings of the 2nd International Conference on Computational Methods and Experimental Conference, June 1984.
7. Galbraith, R.A.McD. ***Comments on the Prediction of Dynamic Stall.*** Glasgow University internal report No. 8501, March 1985.
8. Gangwani, S.T. ***Sythesized Airfoil Data Method for Prediction of Dynamic Stall and Unsteady Airloads.*** Vertica Vol.8, No.2, pp93-118, 1983.
9. Jumper, E.J. and S.J. Shreck. ***Lift Curve Characteristics for an Airfoil Pitch at Constant Rate.*** 24th Aerospace Sciences meeting, January 1986.
10. Kline, S.J., Bardina, J. and Strawn, R. ***Correlation and Computation of Detachment and Reattachment of Turbulent Boundary Layers on Two-Dimensional Faired Surfaces.*** AIAA Paper 81-1220, 1981.
11. Leishman, J.G. and Beddoes, T.S. ***A Generalised Model for Airfoil Unsteady Aerodynamic Behaviour and Dynamic Stall using the Indicial Method.*** 42nd Annual forum of the American Helicopter society, June 1986.
12. Leishman, J.G. ***Practical Modelling of Unsteady Airfoil Behaviour in Nominally Attached Two-Dimensional Compressible flow.*** University of Maryland, UM-AERO-87-6, April 1987.
13. Lorber, P.F. and Carta, F.O. ***Unsteady Stall Penetration Experiments at High Reynolds Number.*** UTRC Report R87-956939-3, April 1987.
14. McCroskey, W.J. ***Prediction of Unsteady Separated Flows on an Oscillating Airfoils.*** AGARD LS-94, February 1978.
15. Nash, J.F. and Scruggs, R.M. ***Unsteady Boundary Layers with Reversal and Separation.*** AGARD CP-227, September 1977.
16. Robinson, M.C. and Luttges, M.W. ***Unsteady Flow Separation and Attachment Induced by Pitching Aairfoils.*** AIAA 21st Aerospace Sciences meeting, January 1983.
17. Seto, L.Y. and R.A.McD. Galbraith. ***The Effect of Pitch Rate on the Dynamic Stall of a NACA 23012 Aerofoil.*** Eleventh European Rotorcraft Forum - paper 34, September 1985.
18. Vezza, M. ***Numerical Methods for the Design and Analysis of Aerofoils.*** Ph.d thesis, University of Glasgow, 1986.