THE DEVELOPMENT OF ROTOR AEROFOIL TESTING IN THE UK - THE CREATION OF A CAPABILITY TO EXPLOIT A DESIGN OPPORTUNITY

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Abstract

The current capability for evaluating aerofoil characteristics has developed over a period of some 20 years, during which time some 16 aerofoils have been tested in the ARA transonic wind-tunnel dynamic rig.

The availability of this test facility has been a key element in the development of the GKN Westland rotor design philosophy which is to avoid excessive excursions into retreating blade stall and seeks to exploit the benefits of thin aerofoils in the blade tip region; thicker, high lift aerofoils inboard of the tip; reflex camber aerofoils with compensating nose-up pitching-moment further inboard; and thick sections to satisfy bending stiffness criteria over the inner region. Design optimization demands a knowledge of dynamic stall characteristics of the full range of aerofoils and the ability to model these characteristics within the rotor design codes. This is possible only with the aid of a test capability such as that at the ARA, which provides near full-scale Reynolds number and covers the full Mach number range in a single facility.

With questions raised about the validity of steady tests for establishing steady stall incidence, and the need to specify steady stall incidence in the dynamic stall model, techniques for evaluating steady stall incidence from dynamic tests are of special interest and are demonstrated by example. They show clearly that it is not possible to assess the relative merits of different aerofoils on the basis of steady test data alone. The techniques have been validated in flight and employed with considerable success in the British Experimental Rotor Programme (BERP); the design of new blades for Lynx; and in the design of the EH101 main rotor. They remain a key element in the present and future UK rotor design capability but, with much still to learn, the test facility could be attractive to collaborative programmes.

List of symbols

C_L	lift coefficient
C_{Lmax}	maximum lift coefficient
C_m	pitching-moment coefficient
C_{mo}	value of C_m at zero lift
C_N	normal force coefficient
C_p	pressure coefficient
c	chord
f	frequency (hz)
α_1	incidence for pitching moment break
M	Mach number
R	Reynolds number
V	free stream velocity

Introduction

The current capability for evaluating aerofoil characteristics has developed over a period of some 20 years, following the initial appreciation of the major potential benefits that could accrue from new aerofoil designs. This capability centres on the oscillatory test rig developed under MOD contract at ARA for use in the ARA transonic aerofoil wind-tunnel, and the considerable data-base that has been built up through testing some 16 aerofoils. With the capability having reached the current level of maturity, it is worth taking stock of the elements that have contributed to the establishment of the capability, and reminding the rotorcraft world that the central testing capability is available to all.

There are many facets to aerofoil performance but the main reason for undertaking dynamic tests is to understand aerofoil stall behaviour in dynamic conditions, and the present paper therefore concentrates on the techniques for identifying stall and evaluating the incidence at which stall occurs. It does not address overall performance nor does it attempt to rank aerofoils in terms of overall performance. However, it analyses results from a range of aerofoils so as to identify the design features that influence stall behaviour and to demonstrate the need for the continued use of the dynamic facility.

Rotor Design Philosophy

At GKN Westland Helicopters, the rotor design approach is to size the rotor so as to avoid excessive excursions into retreating blade stall and into transonic flow on the advancing blade, both of which contribute to a divergence of control loads. Such an approach demands a knowledge of how a rotor blade section behaves aerodynamically - up to and beyond stall - in the rotor environment, and an ability to represent this behaviour within the rotor performance and dynamic loads prediction method that is used to design the rotor. This approach thus places a strong emphasis on aerofoil characteristics; the matching of aerofoil characteristics with design and performance objectives; and the development of improved aerofoil designs. Turning to the potential benefits from aerofoil developments, it was realized back in 1974 - on the basis of steady aerofoil tests - that considerable gains in rotor performance could in fact be achieved through new aerofoil designs which offered delays in the onset of retreating blade stall whilst satisfying other demanding requirements. At the same time, it was of course recognized that retreating blade stall is dynamic in nature, and that aerodynamic characteristics over the whole rotor disc are greatly influenced by dynamic effects. Clearly, a full understanding of aerofoil dynamic characteristics was required, and the need for a dynamic test rig for the ARA transonic aerofoil wind-tunnel was accepted. Such a rig was designed and built, under MOD contract, and first used for NACA 0012 tests (Ref 1). Results of initial tests on new cambered aerofoils were presented in 1979 (Ref 2). Over the years, a considerable number of wide ranging aerofoils has been tested, some of which are shown in Fig 1, providing a wealth of data and insight into dynamic effects and their importance in rotor design, and the dynamic test rig continues to provide a key contribution to the thinking on future rotor designs.

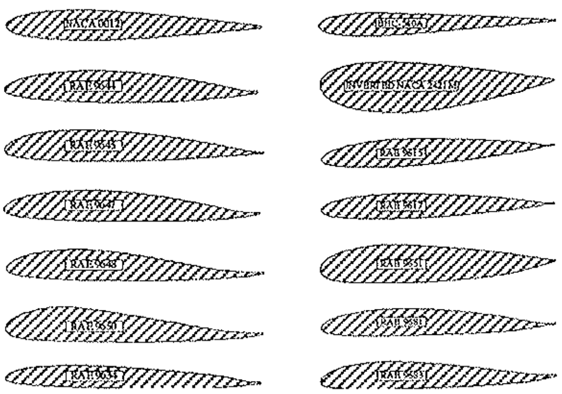


Fig 1 Aerofoils Tested

The range of aerofoils that has been tested reflects an aspect of the GKN Westland rotor design philosophy that needs to be highlighted at this stage (before entering into a discussion on the aerofoil dynamic characteristics) because the range may be a wider one than has been considered by other design teams, and because it has influenced the view that has been reached concerning the importance of dynamic testing. There are essentially 4 categories of aerofoil, each having a specific role in the GKN Westland design approach, and comments on each are provided below.

Thin Sections

- Provide high drag-rise Mach number for advancing tip.

- Minimize thickness and quadrapole noise.

- Although generating only a modest $C_{Lmax,}$ thin sections can be used at blade tips where planform controls stall behaviour.

Main Lifting Sections

- Typically 12% thick giving good balance between drag-rise Mach number and C_{lmax}, through judicious choice of camber and thickness distribution.

- Modest rear loading can be incorporated to maximise C_{lmax}, with modest nose-down C_{mo} being acceptable.

- Used on portion of blade where dynamic head is high enough to make avoidance of retreating blade stall mandatory.

- These sections determine rotor performance.

Reflex Sections

- Mid span sections with positive C_{mo} to balance nose-down moment from main lifting sections.

Thick Sections

- Used inboard to provide blade bending stiffness for containing blade excursions during rotor start up and shut down when centrifugal stiffness is not available

- Must also have positive $C_{mo.}$

- Must not have a large drag penalty.

- Must not stall significantly earlier than thinner reflex sections.

Examples of dynamic characteristics, from each of these categories of aerofoils, will be presented in this paper to highlight differences between characteristics of aerofoils from the different categories, and to demonstrate the importance of dynamic testing. The aerofoils examined are listed in table 1.

Table 1 Selection of aerofoils analysed in the present paper

Aerofoil	Thickness/chord	C_{mo} at M=0.3
RAE 9634	0.083	-0.005
RAE 9617	0.105	0
RAE 9615	0.113	0
RAE 9645	0.119	-0.035
RAE 9646	0.119	0
RAE 9647	0.117	-0.01
RAE 9648	0.119	0.035
RAE 9683	0.119	0.035
RAE 9651	0.16	0.035

Aerofoil Dynamic Test Capability

Within the constraints of a fixed free-stream Mach number, the ARA facility was designed to represent the dynamic conditions that are encountered by a rotor blade section throughout the flight envelope. In the first instance, there was strong emphasis on providing a full range of combinations of amplitude and frequency that might be encountered in high speed flight where retreating blade stall could be expected. With the small chord of the model aerofoils (125mm), it was essential to be able to generate higher frequencies than found on the full scale rotor, in order that the correct reduced frequency could be provided. With a full scale first harmonic of about 4 Hz, an equivalent model frequency of about 15 Hz is required, with a half amplitude of say 8°. In practice, the local effects of tip vortices will tend, in effect, to give pitch rates appropriate to a much higher frequency, thus the ability to generate high amplitude motion at say 30 Hz was a requirement. Such combinations of amplitude and frequency are realistic at low values of Mach number, but for higher Mach numbers - where shock induced separation controls aerofoil stall, and stalling incidence falls rapidly to zero as Mach number increases - there would be little value in large amplitude tests. With small amplitude tests, a higher frequency is required to give representative pitch rates, presenting the need for high frequency/low-amplitude test conditions. Such test conditions in the wind-tunnel in fact provide a reasonable replication of the conditions encountered on the rotor when stall is likely to be caused by a rapid rise in incidence as the blade passes over the vortex generated by the tip of another blade. In addition, the need was identified to be able to isolate pitch rate as a key parameter, thus a steady pitch rate - or ramp motion - capability was provided. This capability was later upgraded to provide pitch rates of up to 2000° per second.

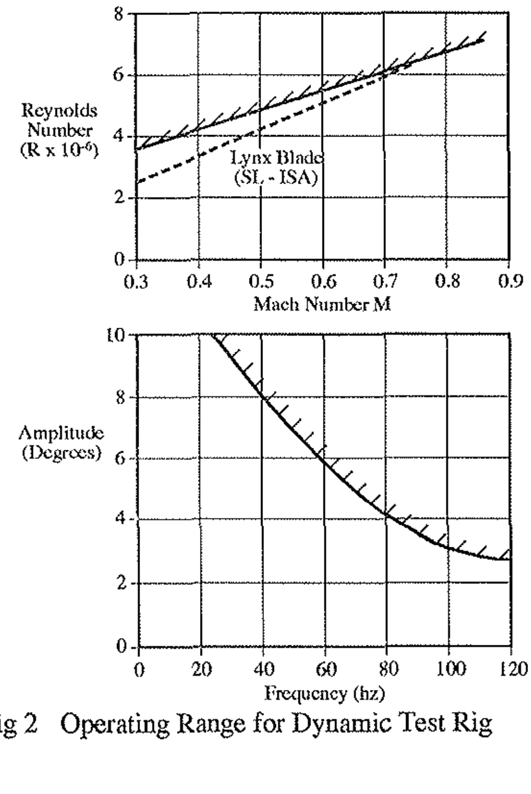


Fig 2 Operating Range for Dynamic Test Rig

Fig 2 provides a summary of rig capability, showing first of all the Mach number and Reynolds number range, followed by the limits for combinations of amplitude and frequency. The high Reynolds number, with such a small chord model, is made possible by the ability to pressurize the tunnel to 4 bars, and the combination of high Reynolds number and complete Mach number range in a single facility is perhaps unique, and certainly a very valuable feature. It is seen, for example, that full scale Reynolds number can be achieved, across the full Mach number range, for rotors of the dimensions of the Lynx helicopter.

Objectives for Dynamic Aerofoil Tests

In the first place, of course, the objective is to be able to assess the performance of an aerofoil in dynamic conditions that relate to the rotor environment, and to relate its performance to that of other candidate aerofoils. However, such a capability, although clearly essential, is not of itself sufficient for a total design capability. A further key element, as mentioned earlier, is the ability to model aerofoil dynamic behaviour within a rotor loads and performance prediction program. The modelling of dynamic behaviour at GKN Westland Helicopters has been developed by Beddoes (Ref 3 and 4) who derives dynamic behaviour from an analytical representation (or reconstruction) of steady characteristics. This reconstruction of the steady characteristics requires values to be assigned to a range of parameters which define such key features as the variation of C_N and C_m through the stall process. It is vital that such a reconstruction should be as firmly based as possible and reflect the key physical processes involved, and that the procedure for generating dynamic characteristics from this base should be verifiable. Of key importance is the representation of stall, and it is the determination of stall incidence that is the main theme of the present paper. It may at first sight come as a surprise that a paper concerned with dynamic tests should be concerned with the measurement of a parameter used to define steady characteristics. However, the difficulties of measuring a true steady stall incidence in a wind-tunnel are well recognized and have been discussed in (Ref 2 and 5), where it was suggested that steady tests can be pessimistic in evaluating stall incidence, and that dynamic tests are required to assess aerofoil stall behaviour. Subsequent analysis of experimental data has shown the situation to be rather more complex.

The determination of steady stall incidence is not however the only issue to be addressed, and the wider aspects of stall behaviour of different aerofoils over a range of dynamic conditions is of special interest. Only through studying a range of aerofoils is it possible to build up the understanding of the key design parameters that influence dynamic stall and of the physical processes involved. Such an understanding is of course essential for a well directed programme of aerofoil improvement. In the end, of course, dynamic tests are required to validate (and to guide) the method of modelling dynamic characteristics that is used within the rotor loads program.

Aerofoil Characteristics in Oscillatory Pitching Motion

Before moving to the evaluation of stall incidence, it is of value - with the wider interest in dynamic stall in mind - to gain an impression of how various aerofoils behave in dynamic conditions that are similar to those encountered on a helicopter rotor. Of particular interest to the designer is the maximum value of incidence that can be achieved during any rotor cycle without incurring stall at any point in the cycle. A technique for assessing this "critical" incidence, based on oscillatory aerofoil tests, was introduced in (Ref 2), and the procedure is illustrated in Figs 3 and 4 where test data for the RAE 9645 aerofoil are presented. Fig 3 shows the variations of C_N and C_m during a series of cycles for which amplitude and frequency

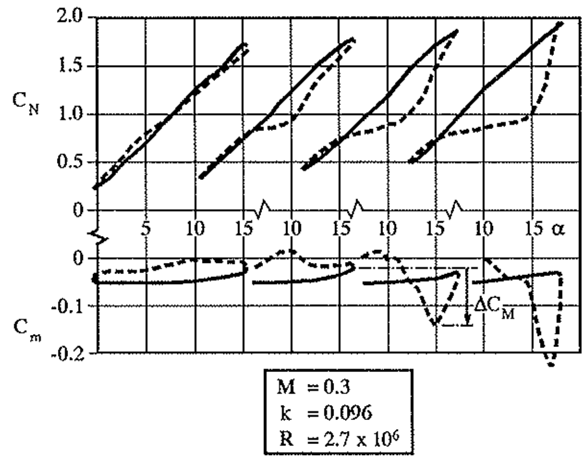


Fig 3 Variation of Normal Force and Pitching-Moment Coefficient with Incidence During A Series of Pitch Cycles for RAE 9645

remain constant but mean incidence is progressively increased. Eventually, stall is encountered, with the associated drop in C_N and C_m. Using the C_m break as a basis for a criteria for evaluating the critical incidence, values of the C_m divergence are plotted in Fig 4 against the

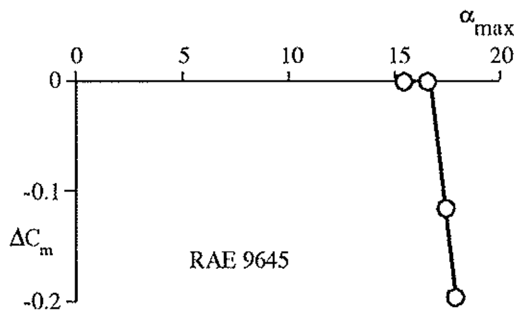


Fig 4 Pitching Moment Deviation in Oscillatory Pitch Cycles

maximum incidence achieved during the cycle. Interpolation defines a break point which is defined as the "critical" value of incidence. Values of "critical" incidence given by this method are compared in Fig 5 with stall incidence as measured in steady tests. It should be noted that as the present paper concentrates on test techniques and the interpretation of test data, the values of incidence that are quoted are the datum values (ie the inclination of the chord line to the free-stream direction) and make no allowance for the zero-lift angle which would be required for the assessment of comparative performance. This is more convenient when comparing the stall behaviour of aerofoils that are closely related geometrically.

It is thus of interest to compare the various RAE aerofoils represented in Fig 5 as they have, with one exception, related profiles. RAE 9645, 9646 and 9648 have common forward profiles (ahead of about 30% chord), but have different rear profiles to provide different values of C_{mo}. RAE 9647 and 9646 have common rear profiles but differ over the first 40% chord in an attempt to produce some changes in stall incidence over the Mach number range below 0.6 (ie to increase C_{Lmax} at M=0.5 at the expense of C_{Lmax} at M=0.3). The first point to note is that, for all 4 of these aerofoils, the "critical" incidence is well above the

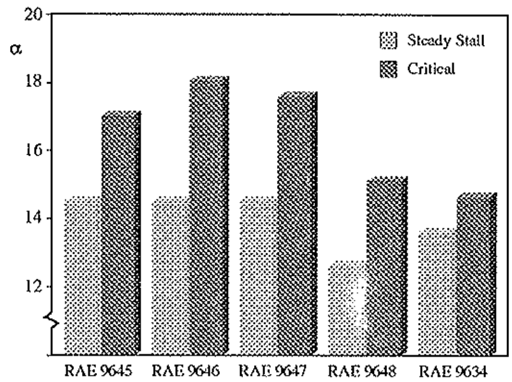


Fig 5 Comparison of Steady Stall Incidence with - "Critical" Incidence, at M = 0.3

steady stall incidence - by a margin of 2.5° to 3.5°. This margin contrasts with the relatively small margin of 1° for the thinner (8.3% thick) RAE 9634 aerofoil. The latter may be a feature of thin aerofoils, and is highlighted when comparing RAE 9634 and RAE 9648, with the latter having a lower steady stall incidence but a higher "critical" incidence. Fig 5 thus clearly demonstrates that steady tests can greatly underestimate the incidence that can be attained by an aerofoil - without stalling - in oscillatory pitching motion, and that steady tests do not provide a firm basis for assessing the relative merits of aerofoils in dynamic conditions.

A possible technique for steady stall incidence evaluation, involves the oscillatory pitch capability operated at very low frequency (low enough to avoid any unsteady effects). In such a test, stall can be approached from attached flow conditions and may avoid some of the problems associated with the steady state tests. Some results were presented in Ref 5, which suggested some lack of repeatability between successive cycles during a continuous tunnel run, with variations in the incidence for pitching-moment break of ±0.5°. More recent analysis of test data shows that this level of variability is not always present, but this is an aspect that needs to be borne in mind during data analysis and may require the use of averaged results in some instances. Nevertheless, this technique, referred to as the "quasi-steady" test, can be of value in obtaining a measure of steady stall incidence, and results will be presented later in the paper.

Flight Validation It is useful at this stage to be reminded of the flight validation of wind-tunnel test data that was reported in 1981 (Ref 6). A portion of a Puma blade was modified to the RAE 9647 profile and fitted with a chordwise array of pressure sensors from which C_N and C_m could be measured in forward flight. It was shown in (Ref 6) that the maximum C_N achieved in flight, without encountering stall, agreed very closely with the value of C_N corresponding to the "critical" incidence measured in oscillatory wind-tunnel tests at a matching Mach number. Thus, wind-tunnel oscillatory tests are seen to give a realistic assessment of aerofoil characteristics in the rotor environment.

Evaluation of Stall Incidence From Dynamic Tests

Stall Criteria There are various possible indicators of stall in 2-dimensional aerofoil tests, which include the point at which C_N reaches a maximum, or the point at which a break in C_m occurs, or the point at which trailing-edge pressure diverges. However, in many cases, these points are difficult to quantify with any precision, and in the case of the C_m break they can appear to be delayed well beyond the stage at which a major flow separation has developed. In dynamic conditions there is of course the well established fact that such parameters as C_N and C_m are much modified by the vortex that is generated and transported across the chord. Perhaps the most useful indicator of stall is the leading-edge suction peak which rises with incidence in attached flow, but collapses when the flow separates, even though incidence is still rising. The value of incidence at which the maximum leading-edge suction peak is achieved can then be taken to be the stall incidence. It is this criteria that will be used in this paper for the identification of stall.

Thin Aerofoil Effects The ability of the ARA rig to generate steady pitch rate motion at rates of up to 2000° per second is a major asset in the study of dynamic effects, and has produced some interesting results in terms of insight into the influence of pitch rate on stall delay for a range of aerofoil geometries. The variation of leading-edge suction peak with incidence is plotted for RAE 9634 and RAE 9617 in Fig 6 for various values of pitch rate, and it is seen for each aerofoil the value of suction peak at stall remains independent of pitch rate - which indicates that stall is of the leading-edge separation type throughout the pitch range. However, the incidence at which the peak leading-edge suction is achieved increases progressively with pitch rate (ie leading-edge suction peak increasingly lags behind incidence, as pitch rate increases - which is to be expected), leading to an increasing delay in stall. Stall incidence, ie the incidence at which the leading-edge

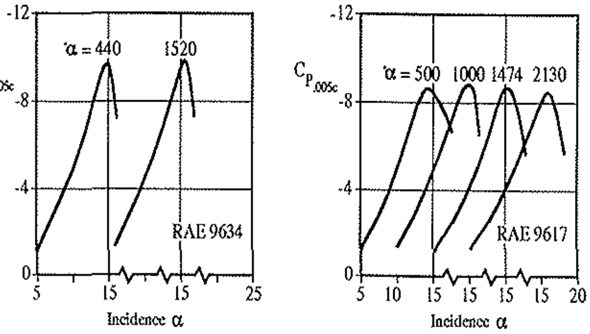


Fig 6 Variation of Leading-Edge Suction Peak with Incidence for Various Pitch Rates

suction peak attains its maximum, is plotted against pitch rate in Fig 7, where similar data for RAE 9615 is also included. The main feature of Fig 7 is the linear nature of the plot, and the fact that the slope of the plot is essentially the same for each of the 3 aerofoils. The behaviour of these 3 aerofoils can be regarded as typical of thin aerofoils, even though RAE 9615 is 11.3% thick and RAE

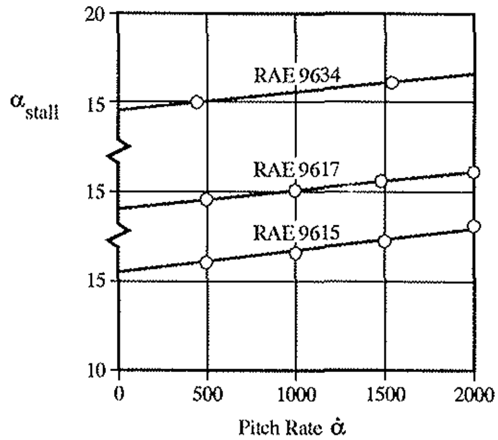


Fig 7 Variation of Stall Incidence with Pitch Rate

9617 is 10.5% thick. It is of course not only thickness that determines aerofoil behaviour, but also camber; and RAE 9615 and 9617 are only lightly cambered.

Before proceeding further, it is worth commenting on the measurement of leading-edge suction peak as this will be a key quantity in this paper. The chord-wise position at which leading-edge pressure is quoted may change from one aerofoil to another, and is selected simply on the basis of being the position of the pressure hole that records the peak suction for that particular aerofoil. The quoted pressure may or may not correspond to the actual suction peak which could of course lie between pressure holes.

With the linear nature of the plots in Fig 7 it is tempting to extrapolate to zero pitch rate and take the intercept as the steady stall incidence. On adopting this process, values of steady stall incidence of 14.5°, 14° and 15.5° are suggested for RAE 9634, 9617 and 9615 respectively. At this point it is interesting to transfer these conclusions to the quasi-steady test data presented in Fig 8 for M=0.3. Here, normal force, leading-edge pressure, and pitching-moment coefficients are plotted against incidence for the portion of the pitch cycle that encompasses stall; and one is immediately faced with a problem of interpretation. For RAE 9634 there are strong indications of separation as early as 13°, where leading-edge suction peak, C_N and C_m fall before recovering to a final peak value. However, attached flow appears to be re-established and the leading-edge suction peak climbs once more before reaching its final maximum value at 15° - close to the value of 14.5° suggested by the extrapolated ramp data (shown in Fig 8 by

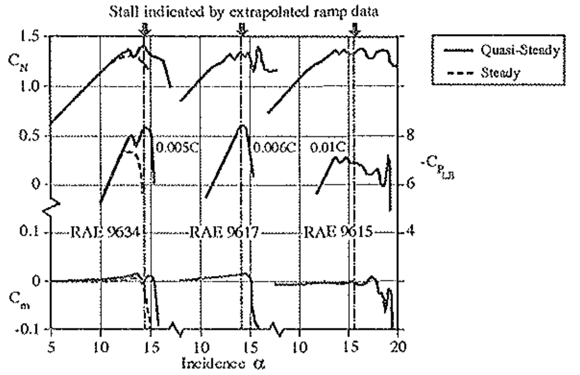


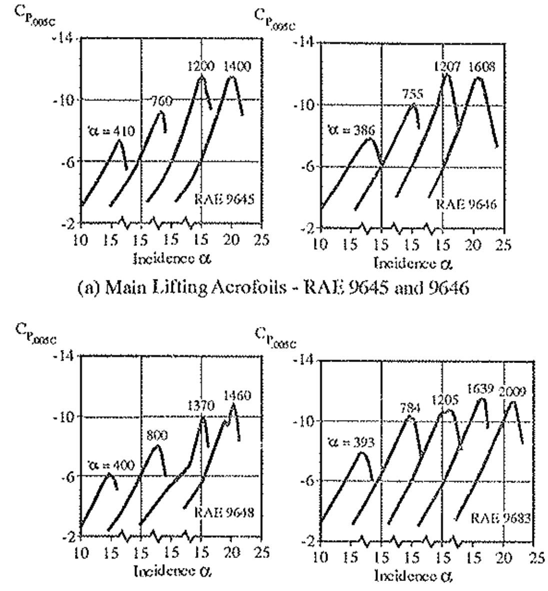
Fig 8 Quasi-Steady Test Data for Thin Aerofoils at M = 0.3

the vertical dashed line). Steady test data for RAE 9634 is also included in Fig 8 (short dashed lines), and shows a leading-edge suction reaching its peak at between 13° and 13.5°, which coincides with the first peak in the quasi-steady data. It should be noted here that the steady test data (apart from Mach number) is uncorrected for wall interference so as to be directly comparable with the dynamic test data. There is clearly some ambiguity in the quasi-steady test data as to what exactly is the stall incidence.

There is less ambiguity for RAE 9617, with a sharp fall in leading-edge suction coinciding with a rapid fall in C_m and a levelling off of C_N. The implied stall incidence of 14.5° agrees well with the 14° indicated by the ramp data. RAE 9615 on the other hand exhibits very different behaviour with C_m remaining steady even though leading-edge suction has reached a peak at 14°. However, leading-edge suction does not collapse in the way usually associated with stall until an incidence of 18.5° is reached. This range of possible stall incidences straddles the 16° point indicated by the ramp data. Clearly, any attempt to establish steady stall incidence on the basis of any single test technique leaves a considerable level of uncertainty, with several anomalies that are currently unexplained.

It should be noted that for RAE 9634 and 9617 there is good repeatability between successive pitch cycles, but for RAE 9615 there is considerable variability with the final break in pitching-moment lying in the range 17.5° to 19°. However, that range of variability - and hence the average value - lies well above the stall incidence suggested by the ramp tests, emphasising the anomalies mentioned above.

Main Lifting Aerofoils When plotting the variation of leading-edge suction peak with incidence at various pitch rates for these moderate thickness, high camber aerofoils, a very different picture emerges from that presented by thin aerofoils - as can be seen in Fig 9(a) for RAE 9645 and 9646. Here, the maximum value of leading-edge suction



(a) Main Lifting Aerofoils - RAE 9645 and 9646

(b) Reflex Aerofoils - RAE 9648 and 9683

Fig 9 Variation of Leading-Edge Suction Peak with Incidence for Various Pitch Rates

peak rises appreciably with pitch rate until it appears to stabilize at a constant value at the high rates, and on plotting the stall incidence against pitch rate (Fig 10) there are seen to be 2 quite distinct segments. One, at low pitch

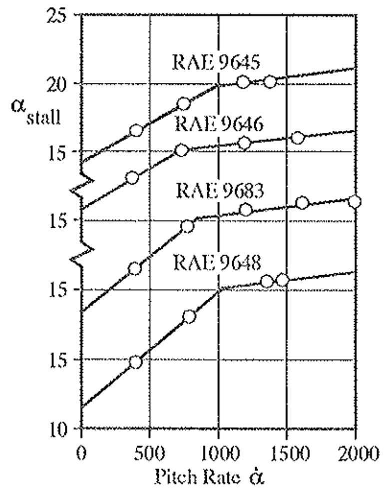


Fig 10 Variation of Stall Incidence with Pitch Rate

rates, has a high slope, and the other at the higher rates is relatively flat. These characteristics, and their differences from thin aerofoil behaviour was noted in Ref 5 where it was suggested that, with the thicker aerofoils, stall at low pitch rates is dominated by a rear separation, which becomes progressively suppressed at higher pitch rates until a leading-edge separation becomes the trigger for stall. The sparsity of data points and the two distinct elements of the plots in Fig 10 make it difficult to draw a line through the data points with any confidence, particularly for the relatively flat section. However, for this relatively flat element, a line has been drawn to have the same slope as the corresponding plot for thin aerofoils. This has been done on the basis that if leading-edge separation becomes dominant at high pitch rates, then a similar stall delay (with pitch rate) to that exhibited by thin aerofoils could be anticipated. The resulting plot does not appear to be incompatible with the data.

If the data points in Fig 10 are extrapolated back to zero pitch rate to give an indication of steady stall incidence, it is then interesting once more to compare the outcome with the quasi-steady, and steady test data, as in Fig 11(a). Once again there are difficulties in interpreting the quasi-steady data for RAE 9645, with the leading-edge pressure appearing to reach a maximum, only to recover and climb again to a final peak value - an effect still present with RAE 9646 but less pronounced. It is noted, however, that for RAE 9645 the value of stall incidence suggested by the extrapolated ramp data more or less coincides with the first peak in leading-edge suction for quasi-steady tests and

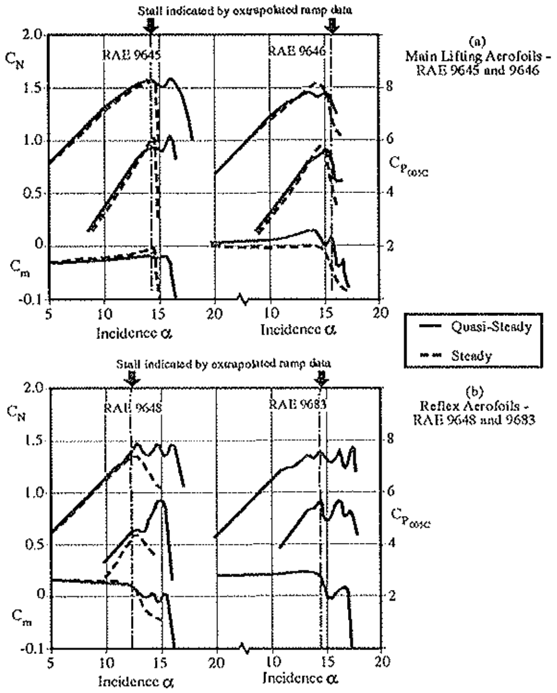


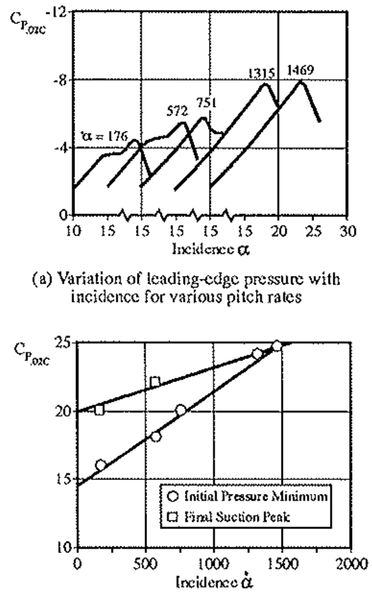
Fig 11 Quasi-Steady Characteristics at M = 0.3 with Stall Incidence from Extrapolated Ramp Tests

with the peak in the steady data, whereas for RAE 9646 the extrapolated ramp value lies above the incidence at which the final leading-edge suction peak occurs, with steady stall coming at an intermediate point. At this point it should be remembered that the RAE 9645 quasi-steady data exhibits some marked unrepeatability, but RAE 9646 was relatively free from such a problem. Once more, it must be concluded that no single test technique provides a clear indication of stall incidence.

Reflex Sections The process of ramp data analysis is repeated for RAE 9648 and 9683 (being representative of reflex camber aerofoils giving positive C_{mo}) in Figs 9(b) and 10. The overall pattern of behaviour is similar to the previous category of aerofoils, but differs in detail. The initial rate of change of stall incidence with pitch rate is higher for RAE 9683 and 9648 than for RAE 9646. This is compatible with the concept of the influence of a rear separation, as both are more susceptible to rear separation than RAE 9646. Carrying this concept of the influence of pitch rate on rear separation further, one would expect that the switch to a lower slope in Fig 10 would occur at a progressively higher value of pitch rate as susceptibility to rear separation increases. This in fact is seen to be the case for RAE 9646, 9683 and 9648; but RAE 9645 appears to be the odd one out - a point to be addressed later in the paper.

The values of stall incidence obtained from Fig 10 by extrapolation are compared in Fig 11(b) with quasi-steady results (and with steady test data for RAE 9648) and again some anomalies are found - but there are similarities with the results in Fig 11(a). For RAE 9648, the extrapolated ramp value for stall incidence falls slightly below the first maximum in leading-edge suction from the quasi-steady test data (which coincides with the steady stall angle), whereas for RAE 9683 it coincides with the first peak in leading-edge suction. However, remembering that the values for stall incidence suggested by the ramp test data are based on an analysis of leading-edge suction peak, the results of Figs 10 and 11 suggest that a leading-edge suction peak criteria for stall does provide a relatively consistent conclusion.

Thick Aerofoil Behaviour The interpretation of test data for some thick aerofoils (as exemplified by RAE 9651) provides some special problems, encountered first of all in the ramp test results in Fig 12(a) where leading-edge



(a) Variation of leading-edge pressure with incidence for various pitch rates

(b) Incidence at which minimum leading-edge pressure is achieved

Fig 12 Ramp Test Characteristics for RAE 9651 pressure is plotted against incidence for a range of pitch rates. At the lower values of pitch rate, the leading-edge pressure levels off to a short plateau before rising again to its final peak value. This plateau is not present at high pitch rates, where leading-edge pressure continues to rise right up to the final peak. Thus, at the lower values of pitch rate, there are now two possible criteria to apply when defining the stall incidence. One is to take the value of incidence at which the leading-edge pressure first reaches the plateau; and the second is to take the value of incidence at which the final peak is achieved. These values of incidence are plotted against pitch rate in Fig 12(b). Extrapolating to zero pitch rate produces the spread of steady stall incidence as superimposed on the quasi-steady test results in Fig 13 which exhibit a similar range of uncertainty - with oscillations in C_N and leading-edge suction, but with leading-edge suction tending to rise whilst C_N tends to level off. It is by no means clear as to what should be regarded as the stall incidence.

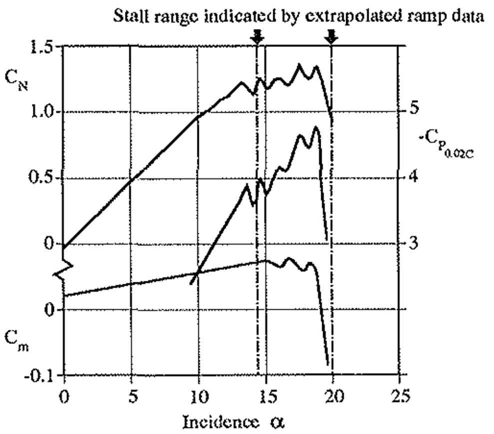


Fig 13 Quasi-Steady Normal Force and Pitching Moment Coefficients for RAE 9651 at M = 0.3

At this point it is instructive to refer to the "critical" incidence deduced from oscillatory tests which is approximately 18.5°. One would expect the steady stall incidence to be below this value. There is clearly a need here for the exercise of careful judgement in the interpretation of the data, and this is particularly important when modelling dynamic behaviour within the rotor loads and performance code (to be discussed later in the paper).

Aerofoil Optimization The variation of stall incidence with pitch rate for RAE 9645, 9646, 9648 and 9683 (Fig 10) merits further attention because, as mentioned earlier, all four aerofoils have a common forward profile. The twin regime nature of the plot has already been noted, but a further aspect that is apparent in Fig 10 is that the second regime - where leading-edge pressure probably controls stall - is essentially identical (within the accuracy of the analysis involved) for all four aerofoils. Furthermore, reference to Fig 9 shows that the suction peak at which stall is triggered appears to be much the same, at high pitch rates for all four aerofoils. Some differences from one aerofoil to another can be expected due to slight differences in the chordwise position of the pressure holes on the wind-tunnel models, with measured pressure being very sensitive to position in this region of very high pressure gradient. If then the second stall regime in Fig 10 is the same for all four aerofoils (due to their common forward profile) it is reasonable to suppose that the first regime - believed to be controlled by the rear separation - is essentially determined by the rear upper-surface profile, which of course is different for each aerofoil. For a given forward profile there is presumably an optimum rear profile (and optimum distribution of pressure gradient) for delaying the onset of rear separation. An aerofoil with the optimum rear profile would have a break point between the two regimes of Fig 10 that lies to the left of all other aerofoils in the family (ie with common forward profiles) as it would presumably require a less high pitch rate to suppress rear separation. On this basis, Fig 10 suggests that RAE 9646 has a rear upper-surface that is closest to optimum, but it cannot be determined whether or not it is the optimum. However, the suggestion is that if a family of geometrically related aerofoils is tested (preferably at close intervals of pitch rate) then a plot of the type shown in Fig 10 could be used to select the design that is closest to optimum (within the overall constraints of the family) or to guide the design of refinements in the rear upper-profile.

Returning to Fig 10, if the second stall regime is identical for all four aerofoils, then as the break point moves to the left, the value of steady stall incidence - as suggested by extrapolation to zero pitch rate - increases. This is of course entirely compatible with the hypothesis that rear separation has been delayed. Comparing RAE 9645 and 9646, it is seen in Fig 10 that the indicated steady stall incidence for 9646 is 1° higher than for 9645 - a similar difference is noted in "critical" incidence recorded in Fig 5. However, the zero lift angle for RAE 9646 is 1° higher than for 9645, so they should have the same effective stall incidence (where effective incidence is measured relative to the zero lift angle).

Influence of Thickness on Dynamic Behaviour Having now taken a look at the dynamic characteristics of four categories of aerofoil and three groups of thickness/chord ratio, a clear indication can be gained of the different dynamic behaviour of these categories - with particular reference to the influence of thickness. Figs 7, 10 and 12 present variations of stall incidence with pitch rate and it is noted that extrapolation to zero pitch rate for RAE 9634 (8.3% thick), RAE 9645 (11.9% thick) and RAE 9651 (16% thick) suggests that they all have the same steady stall incidence of 14.5°. However, at 1500 deg/sec these aerofoils have stall incidences of 16°, 20.5° and 24.5° respectively. Their responses to dynamic conditions are very different.

Summary of Test Data Analysis At this point in the paper, it is useful to summarize in tabular form (see table 2) the conclusions that have been reached concerning the values of steady stall incidence as indicated by the various test techniques. For completeness, values of "critical" incidence are also included. This helps to highlight the differences that have been identified in earlier sections. There are some gaps in the table where appropriate tests have not been run, and in 2 cases (RAE 9615 and 9617) the only steady test data was obtained in a different wind-tunnel and a direct comparison must be approached with caution.

The way in which thickness influences the difference between steady stall incidence and the stall incidence at high pitch rates has already been pointed out. Table 2 also shows how the difference between steady stall incidence and "critical" incidence increases with aerofoil thickness. This reinforces the conclusion that dynamic effects become increasingly important as thickness increases, and emphasizes the point that steady, or extrapolated ramp techniques are not good indicators of how aerofoils will behave in dynamic conditions.

Table 2 Values of steady stall incidence obtained by different processes, compared with "critical" incidence

(a) Thin Aerofoils

	RAE 9634	RAE 9617	RAE 9615
Steady	13.5	13*	13.5*
Quasi -steady	13/15	14.5	13.5/19
Ramp	14.5	14	15.5
"critical"	14.5		16.5

* from early data obtained in different wind-tunnel NPL

(b) Main Lifting and Reflex Aerofoils

	RAE 9645	RAE 9646	RAE 9648	RAE 9683
Steady	14.5	14.5	12.5	-
Quasi-steady	14.5/17.5	14/16.5	12.5/15	14/17
Ramp	14.5	15.5	11.5	13.5
"critical"	17	18	15	15

(c) Thick Aerofoils

	RAE 9651
Steady	-
Quasi-steady	14/19
Ramp	14.5 /20
"critical"	18.5

A further point highlighted by table 2 is that the difference between stall incidence measured in steady conditions, and that deduced from ramp test data, appears to diminish on moving from thin aerofoils to the thicker main lifting and reflex sections. This leads one to question the validity of the way in which a single line has been drawn through the ramp data in Fig 7 for thin aerofoils - remembering that two regimes are clearly defined for the thicker aerofoils. The possibility has to be accepted of a break in the plot at some point below the 500 deg/sec point - the lowest pitch rate for which test data exists. Any such break, to a higher slope, would lead to a lower value of incidence at the zero pitch-rate intercept. This would diminish or even remove the discrepancy, and re-emphasizes the need for running ramp tests at much closer intervals of pitch rate, especially over the lower range of pitch rate.

Reynolds Number and Mach Number Effects

A major attraction of the ARA test rig is that it covers the full Mach number range appropriate to rotor aerofoils, and through its ability to operate at up to 4 bars it offers full-scale, or near full-scale, Reynolds number. Aerofoil performance is quite sensitive to Reynolds number in the range that is of interest, as seen in Fig 14 which shows the pitching moment deviation for RAE 9646 during oscillatory pitch cycles with increasing mean incidence. At a Reynolds number of 3.5×10^{-6}, the "critical" incidence is 1° higher than at a Reynolds number of 1.3×10^{-6}.

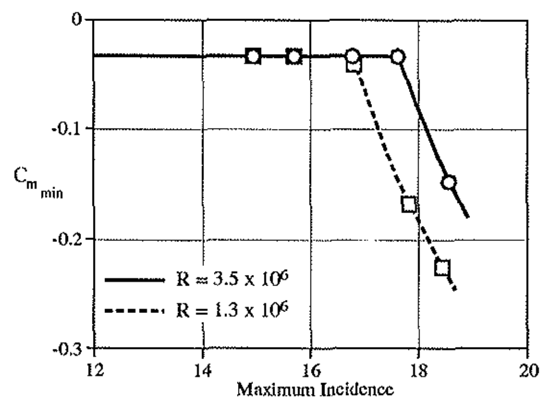


Fig 14 Effect of Reynolds Number on "Critical" Incidence for RAE9646 at M = 0.3

Unsteady effects are of course present and important throughout the Mach number range, as indicated in Fig 15 which plots the variation of stall incidence with pitch rate for RAE 9646 over the Mach number range 0.5 to 0.75. At

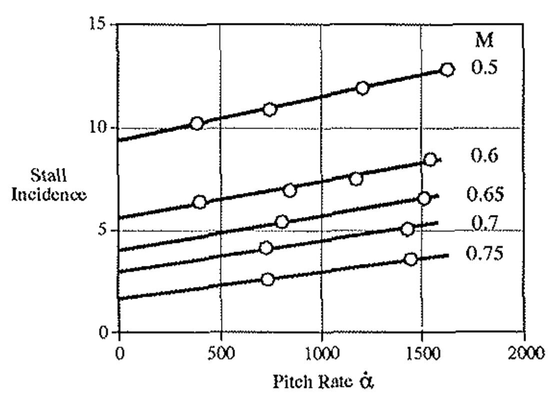


Fig 15 Variation of Stall Incidence with Pitch Rate for RAE 9646 at A Range of Mach Numbers

these Mach numbers, the pressure distributions are dominated by regions of transonic flow with terminating shock waves, and leading-edge pressure can no longer serve as the basis of a criteria for identifying stall. Stall incidence, as plotted in Fig 15, has therefore been taken to be the incidence for trailing-edge pressure divergence - the widely used criteria for transonic flow. The first point to note is that, for each value of Mach number, all the points lie on a single line, rather than forming two segments as found at M= 0.3. This suggests that, throughout the range of Mach number and pitch rate covered by Fig 15, stall is triggered by a single mechanism - which is shock-induced separation.

Extrapolating the plots in Fig 15 back to zero pitch rate gives once more an indication of steady stall incidence which is compared in table 3 with the values given by steady and quasi-steady tests. Given the rather imprecise nature of the stall criteria (demanding an element of subjective judgement) there is good agreement between all 3 sources, with less need for interpretation than is the case at lower Mach numbers.

Table 3 Values of stall incidence evaluated from different techniques at higher Mach numbers

M	Steady	Quasi-steady	Ramp
0.5	10	9.5	9.5
0.6	6	6.5	6
0.65	4.5	4.5	4
0.7	3	3.5	3
0.75	1.5	1.5	1.5

Modelling of Unsteady Aerodynamics in Rotor Loads Prediction

As mentioned earlier in the paper, the Beddoes model for unsteady aerodynamics generates dynamic characteristics from reconstructed steady data which is defined analytically using a set of parameters. A key parameter is α_1 which is the incidence at which the pitching-moment break (associated with stall) occurs. A further feature of the reconstructed data that is worth noting here is the adaption of the Kirchhoff law to model the influence of rear separation on C_N and C_m. This provides a representation of the fall-off in C_N (relative to the linear variation) that can occur ahead of stall. It is however concluded from the data presented in this paper that it is by no means clear exactly what value should be assigned to α_1, and that some element of judgement, and perhaps iteration, has to be exercised in order to achieve an acceptable level of modelling of the dynamic characteristics.

The output of the Beddoes model is of course a dynamic response and the key feature of dynamic response, as far as rotor loads are concerned, is the pitching-moment behaviour through stall. It is thus of interest to compare measured and modelled characteristics as in Fig 16 which plots pitching-moment deviation (as defined in Fig 3) during oscillatory cycles for 4 aerofoils. Each aerofoil represents one of the 4 categories of aerofoil discussed earlier in the paper and the test cases selected have a reduced frequency close to 0.1; an amplitude of 8°; and Mach number of 0.3.

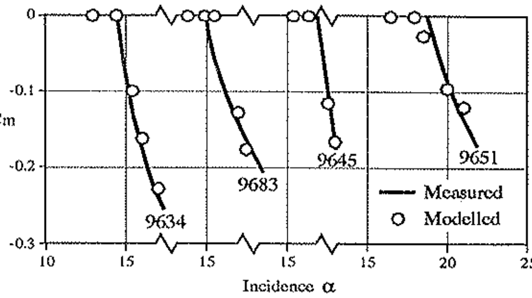


Fig 16 Modelled and Measured Pitching Moment Deviation in Oscillatory Cycles

Although the paper has concentrated mainly on dynamic behaviour at M=0.3, the dynamic model must cover the whole range of Mach numbers encountered on a rotor and it is of interest to compare modelled and measured behaviour at M=0.6 and M=0.7 in fig 17. At such Mach numbers, oscillatory cycles may not provide the best representation of rotor conditions, with stall more likely to be encountered as a result of a rapid increase of incidence due to a vortex interaction. Thus Fig 17 provides comparisons between modelled and measured variations of C_N and C_m during steady pitch motion, with a thin aerofoil (RAE 9634) being chosen as being most likely to encounter higher Mach numbers.

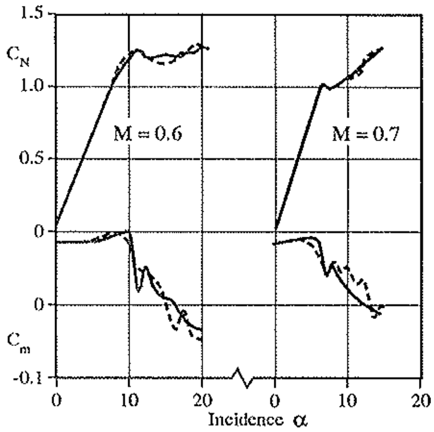


Fig 17 Modelled and Measured Variation of C_N and C_M with Incidence for RAE9634 at Steady Pitch Rate

Before commenting on the comparisons it is important to recognize that any dynamic model needs to be configured so that it can be applied to the full range of aerofoils and adequately represent the varying characteristics within and between each category of aerofoil, whilst reflecting the influences of the physical events involved in the stall process. This is particularly important where rotor blades have spanwise changes of section, with areas in which the section is changing (usually linearly) between one aerofoil and another. It must then be a requirement that sensible interpolation will be achieved between section characteristics. Furthermore, in covering the full Mach number range, the model must accommodate stall behaviour where leading- edge separation dominates and also where shock-induced separation dominates. The challenge is therefore considerable and a perfect match between modelled and measured characteristics cannot be expected. Bearing these points in mind, it is remarkable that such a good representation of dynamic behaviour, as seen in Figs 16 and 17, has been achieved.

The incorporation of the unsteady model into the rotor loads program has been described in Refs 3 and 4 and it is not appropriate to cover this aspect in the present paper.

Conclusions

A large range of aerofoils has been tested in the dynamic facility at ARA over a period of years and a considerable amount of data accumulated and analysed. The present paper has presented only a small fraction of the data but still serves to highlight several lessons learnt.

Steady tests are not a reliable means of measuring steady stall and do not provide a means of assessing the relative merits of aerofoils in dynamic conditions.

Dynamic tests are essential for comparing stall behaviour of different aerofoils in dynamic conditions and can be used to indicate steady stall incidences. However, due to the imprecise (and sometimes subjective) nature of the criteria for evaluating stall incidences, all available dynamic test techniques - oscillatory, quasi-steady and ramp - should be applied.

Pitch rate has a considerable influence on stall incidence, particularly for thick aerofoils where rear separation is believed to dominate stall behaviour. High pitch rates appear to suppress rear separation, with stall then being controlled by leading-edge pressures.

In oscillatory pitching motion, the margin by which the maximum achievable incidence (without incurring stall) exceeds steady stall incidence appears to increase with aerofoil thickness.

The representation of aerofoil dynamic characteristics within the method for calculating rotor loads and performance can be done with confidence only with an established understanding of aerofoil dynamic behaviour in general and detailed knowledge of the dynamic characteristics of the aerofoil in question. The full range of dynamic test techniques is required in the development of the dynamic model used, and to validate its applicability to any aerofoil in particular. It is important that the dynamic model should be applicable to all aerofoils so that sensible interpolation between aerofoils (within the rotor loads code) is possible, and that all the experimental data required to establish the parameters defining the characteristics of an aerofoil should ideally be gathered from a single facility, such as the ARA facility, so as to provide consistent and continuous data.

Created and developed over a number of years, the dynamic test capability has become the established way in the UK of assessing aerofoils in terms of their potential application in rotor design, with the ARA facility covering not only the full Mach number range, but also full scale Reynolds number for small and medium helicopters. It has proved to be a key element in the exploitation of large potential advances in aerofoil design, as demonstrated through the British Experimental Rotor Programme, the new rotor blade designs for Lynx retrofit, and the rotor blades for the EH101.

The UK is of course not alone in its interest in aerofoil dynamic behaviour, and other countries and organizations have their own test facilities, interpretation techniques, and mathematical models. There are still however aspects of aerofoil dynamic behaviour that are not properly understood and much can be gained from pooling experience. However, there would be added value from using data from a common facility, allowing direct comparisons; and perhaps the most effective way forward is through collaborative programmes.

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