THE DYNAMIC APPROACH TO ROTOR BLADE RESEARCH - ARA's OSCILLATORY TEST FACILITY

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Abstract

Helicopters' forward flight performance is limited by the rapid build up in blade and control loads which occur when rotor blades enter stalled conditions. Due to a combination of the helicopter forward speed and the rotor rotational velocities the rotor sections experience a wide range of local onset conditions, this leads to vastly different flow characteristics across the span and through the rotational cycle. A great deal of time and effort has been devoted to studying this flow phenomena. Consequently, information covering all aspects of unsteady aerodynamics is easily available. However, one area that needs up-dating is the description of the experimental test facilities that are able to simulate these flow conditions. The dynamic rig at the Aircraft Research Association was designed and built in the 1970s. Since then, as new technology became available, the rig's capabilities have been steadily improved. Now is the time to report on these amendments.

Introduction

In the early 1970s the Royal Aircraft Establishment and Westland Helicopters Limited agreed that advances in rotor design would be severely restricted without the ability to predict the unsteady behaviour of the rotor blades in the region of stalled conditions. Westlands had already developed an empirical model of dynamic stall hysteresis but were hampered by the limited availability of experimental data to confirm their results. The Aircraft Research Association was commissioned by the UK Ministry of Defence to design and build an oscillatory test facility that would provide unsteady aerofoil data representative of helicopter blade operational conditions, at full scale Mach numbers and Reynolds numbers. This feat was successfully accomplished in 1977.

A recent (January 1993) research study (Ref.1) focused its efforts on the collection, reduction and analysis of an extensive unsteady data base. Such a comprehensive analysis had not previously been undertaken. From an initial list of over 200 citations, only 40 reports were considered to contain unsteady results of significant substance. The Aircraft Research Association's dynamic rig did not feature in the review. Therefore a primary purpose of this paper is to provide up to date material on the dynamic rig's capabilities, and to include information on published reports that have used ARA's experimental dynamic data in their analysis.

Background History

The preliminary design, specification and development of ARA's oscillatory rig are fully described in references 2 to 9. The aerofoil used in the development trials was the NACA 0012 section. This section has been extensively tested in many two-dimensional wind tunnel facilities and has become the datum aerofoil for validating results from wind tunnels.

In November 1978, four years after it's inception, the two-degree-of freedom pitch and heave rig was fully operational. Ref 10 provides a comprehensive set of experimental data obtained from the NACA 0012 aerofoil secton. Oscillatory pitch and ramp motions covering a range of Mach numbers (0.3-0.9) are included, together with data repeatability and effects caused by varying test parameters e.g. frequency, amplitude, mean angle of attack etc. These results served as a datum for a series of helicopter rotor blade sections designed at the Royal Aircraft Establishment, (Ref 11). Experimental data from six of these aerofoils is examined in Ref 12., Here, Wilby illustrates the effect of aerofoil design features on dynamic stall onset. Comparisons of flight tests on the RAE Puma research helicopter and some experimental data is also available in Ref 13. Wilby concludes "Two-dimensional oscillatory aerofoil tests give a close simulation of dynamic stall as it occurs on the retreating side of the rotor, in terms of the maximum value of C_N that can be achieved without stall and in the post stall behaviour of lift and pitching moment".

Westlands performed extensive correlation studies using test data gathered from several facilities. The information was used to further evaluate and refine their time delay model for dynamic stall. Main references to unsteady experimental data from ARA's rig are found in Beddoes' studies (Refs 14-17). Markiewicz (Ref.18) has also produced an in-depth analysis of ice accretion studies using the RAE 9645 and NACA 0012 experimental results. A particular success has been the use of aerofoils developed in the facility on the blades of the Westland G-Lynx which broke the helicopter speed record on 11 August 1986 (Ref 19). The pitch and heave rig had proved itself as an essential facility for helicopter blade investigations.

On-going improvements have modernised the dynamic rig to such an extent that an up-date on the current features and capabilities is necessary.

ARA's Two Dimensional Wind Tunnel Facility

The two-dimensional wind tunnel facility at ARA, illustrated in Fig 1, is a variable pressure, intermittent blowdown wind tunnel with a working section of 0.457m height by 0.203m width. The working section is 1.245m long and has solid sidewalls with slotted top and bottom walls. Each slotted wall has six slots of 0.94mm width and two slots of 0.46mm width giving an open area ratio of 3.2%. For dynamic testing the aerofoil models have a standard chord length of 0.127m and the quarter chord point is positioned 0.635m downstream of the 9:1 contraction.

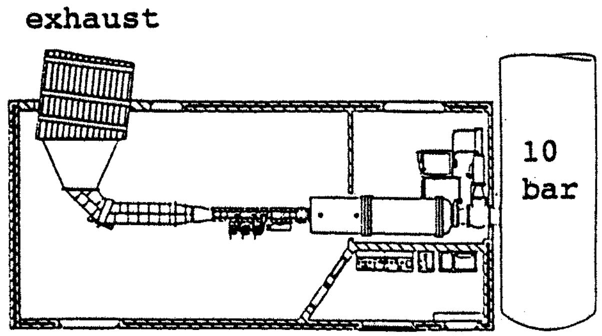

Fig 1 ARA's 2 Dimensional Wind Tunnel

The Mach number in the working section is controlled by a second throat over the range $M=0.30$ to $M=0.87$ under calibrated conditions, however, the tunnel will run in excess of $M=0.9$ but with uncertain lift interference and blockage effects and some stream-wise pressure gradient. The stagnation pressure is variable from 1.5 bar to 4 bar. High pressure dry air stored at 10 bar is used to drive the tunnel with typical run times of between 5 and 7 seconds, with no limitation imposed by the pumping capacity. Further details are reported in Ref 20. Table 1 provides a summary of the operating conditions.

Mach Number	0.30 to 0.87
Stagnation Pressure	1.5 to 4 bar
Stagnation Temperature	Ambient
Frequency	0 to 140 Hz
Maximum Amplitude	±20°
Ramp Rates	0 to 2200°/s
Model Length	0.127m

Table 1 Summary of Operating Characteristics

The Enhanced Rate Pitching System

The pitch and heave rig was modified in the mid 80's to allow pitching mode only tests. This development, renamed the Enhanced Rate Pitching System (ERPs), achieved a 50% increase in the reduced frequency rate. The increase of model chord length from 0.102m to 0.127m and the change of material from steel to titanium/aluminium achieved a 25% improvement. The remainder was obtained by uprating the hydraulic pitch drive system. Reversion to the original pitch and heave rig is stll possible if combined pitching and heaving or heaving only tests are required.

Photographs of the ERPs rig are shown in Figs 2 and 3, of the port side with the pitch encoder and a general view of the starboard side. A diagrammatic layout is provided in Fig 4, which details the location of the ERPs rig in ARA's 2D tunnel. Also shown are the hydraulic balance pipes which remove the out of balance forces from the rams, which may result from phase differences of individual servo valve/ram combinations or from hydraulic or electrical failure of either side.

The Hydraulic System

The 37kW hydraulic power pack (supplied by Tungum Hydraulics Ltd.) is capable of delivering a maximum flow rate of 2229 mm^3/s. Each ram is fitted with a Dowty Hydraulic Units fast response servo valve type 4659 with a maximum flow rate of 934 mm^3/s, leaving 16% excess capacity in the hydraulic power pack. Both servo valves were

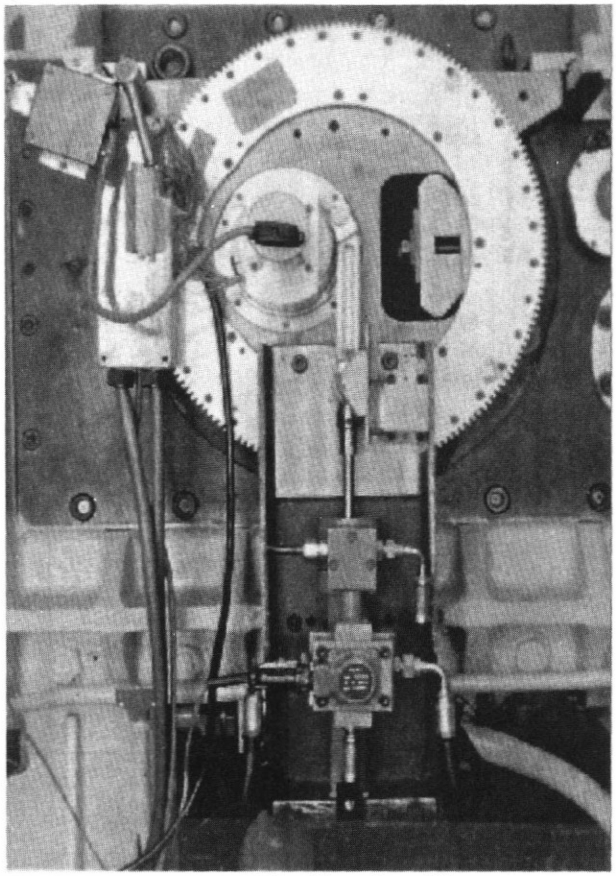

Fig 2 The ERPs Rig - Port View

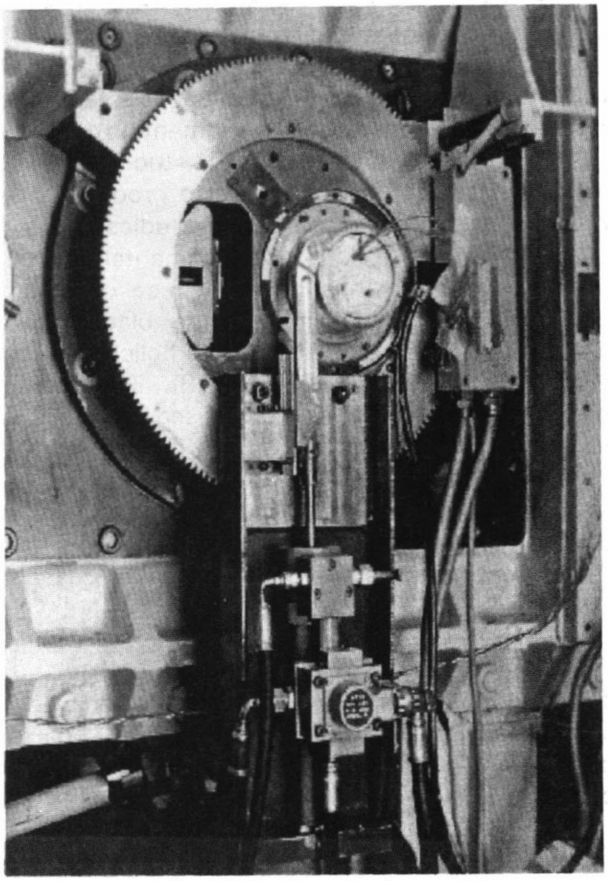

Fig 3 The ERPs Rig - Starboard View

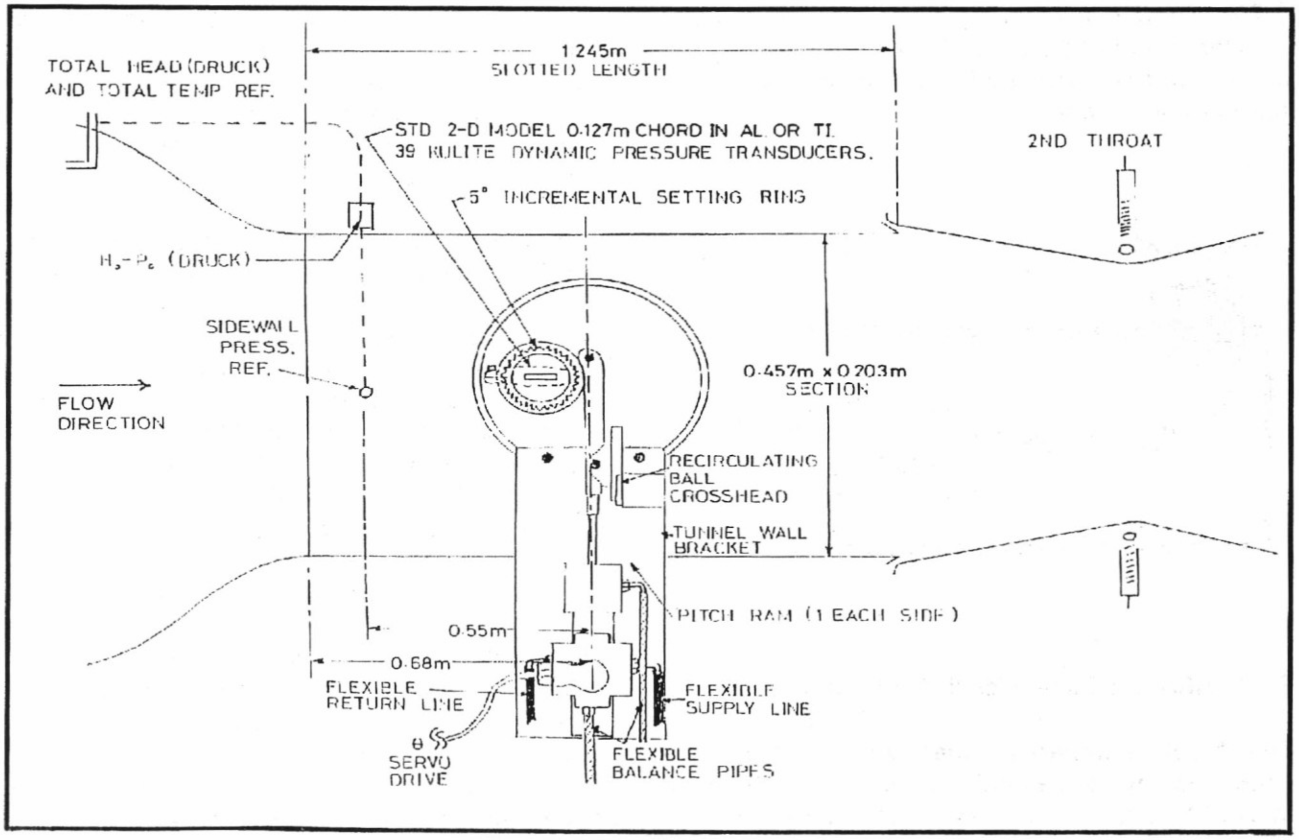

Fig 4 Location of the ERPs Rig in the 2D Tunnel

matched and calibrated by Dowty Hydraulic Units.

The hydraulic pack has a filter with a replaceable element which is periodically changed and the pressure drop across the filter is monitored whenever the hydraulics are in use. Oil samples are also frequently taken and analysed to ensure long life and reliability of the equipment, in particular to protect the servo valves.

Running time for the hydraulic equipment is approximately two minutes per run and natural cooling is often sufficient to maintain acceptable tank temperatures throughout a full working day. However, in summer, conditions can make the oil reach the limiting temperature of 65°c, so an oil cooler has been fitted to ensure efficient running times for the facility.

For safety reasons, several fast acting emergency stop buttons and push bars have been provided to short circuit the high pressure oil supply. Fatigue failures of the highly stressed parts have been a problem in the past, and often one single failure can cause an avalanche of subsequent damage. A regular replacement programme and constant monitoring of the rig integrity is, unfortunately, the only safeguard action that can be taken.

Pitch Servo Drive Amplifier

The data logger generates a sine wave which is received by the closed loop system servo drive amplifier. Position feedback is obtained via a signal from the pitch encoder. The servo drive amplifier consists of four high voltage operational amplifiers in a series/parallel arrangement. This supplies the very large voltage variations needed to produce the necessary drive current to the servo valves, whose impedance varies considerably over the frequency range of operation. The output from the servo drive amplifier is connected to the type 4659 servo valves. To give sufficient drive current, whilst retaining a degree of fail-safe, the pairs of coils in each servo valve are wired in parallel and the pairs series wired to each other.

Test Programmes

Programmes to cover a range of test parameters are provided to match the data storage capability of the data logger with typical run times of seven seconds duration. Generally between 4 and 8 cycles of dynamic data are digitally recorded for analysis and the ability to vary the model incidence or amplitude allows the maximum utilisation of the equipment. This built in flexibility of running allows a wide range of conditions to be covered in a test programme with a minimum of setting up and running time.

The wide frequency range DC-140 Hz permits a range of test regimes. Figs 5 to 8 provide the summary performance curves of the ERPs rig. A typical oscillatory pitch test requires the tunnel Mach number to be set by manual adjustment of the second throat $(0.3<M<0.87)$ and the servo for the stagnation pressure to be set $(1.5\text{bar}<H<4\text{bar})$. Initial mean incidence is infinitely variable, and the data logger drive programs allow either this value to be maintained throughout the run or modified by 2 or 5 increments for subsequent cycles. The pitch amplitude can be set to any value as dictated by the frequency limits, the maximum amplitude of $|\alpha| = \pm 20°$ reduces logarithmically when increasing the frequency from 0 to 140Hz (Fig 5). If required, the amplitude in subsequent cycles can be incremented with 2 or 5 steps similar to the mean angle test programme. The available steps are listed in Table 2.

Switch Setting	Mean Angle Increment	Amplitude Increment
1	0°	0°
2	+½°	±½°
3	+1°	±1°
4	+2°	±2°
5	+4°	±4°
6	+2½°	-

Table 2 **Mean Incidence and Amplitude Increments**

Quasi-static tests cover conventional 2D steady test programmes in a fraction of the overall time. Such tests are conducted using a relatively low frequency rate (1Hz). A complete incidence traverse with very close increments is performed, with separate runs needed only for Mach and Reynolds number changes.

One form of incidence variation that can occur on a rotor is due to the passage of a blade over a tip vortex that lies mainly in a span-wise direction. In this situation a large incidence change in the form of a steep ramp can occur almost instantaneously. The high ramp rates achievable with the Enhanced Rate Pitching System require complex shapes to be input to the pitch drive servo to avoid large overshoots. A Serially Loaded Function Generator (SLFG) described in Ref 21, is used to create both complex wing gust loading wave forms and ramp shapes, and ensures the required model response. A step input covering $\alpha = 35°$ range of incidence can reach the maximum ramp rate of $\dot{\alpha} = 2200°/s$ in the first 5 degrees of travel.

The range of incidence of up to $\alpha = \pm 20°$ can be mechanically selected by changing the coupling of the drive arms onto the wing mounting. Due to the mechanical arrangement, a whole circle is possible, therefore reverse flow angles can also be tested.

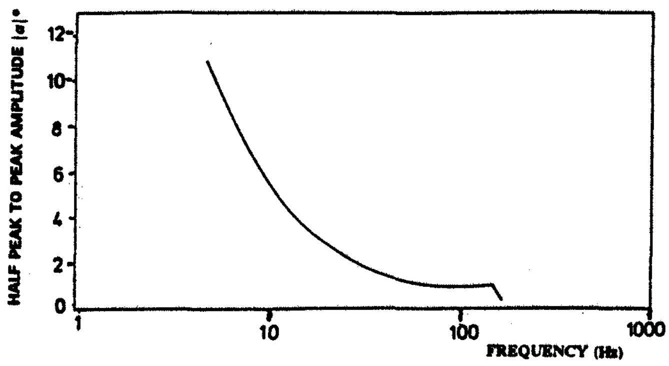

Fig 5 Amplitude v Frequency

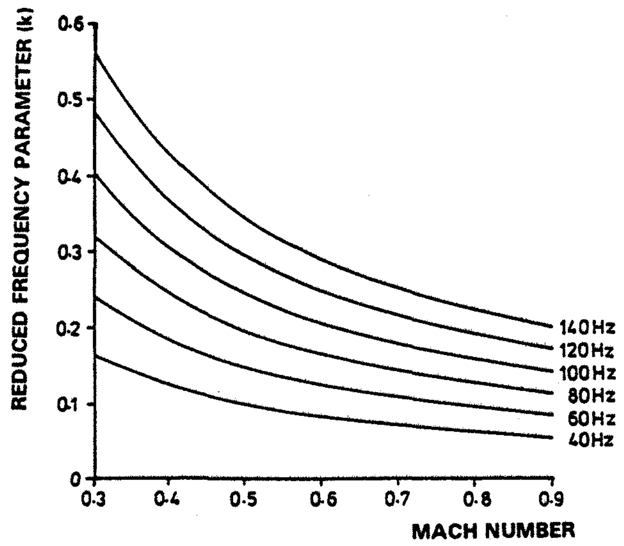

Fig 6 Reduced Frequency Parameter as a Function of Mach Number

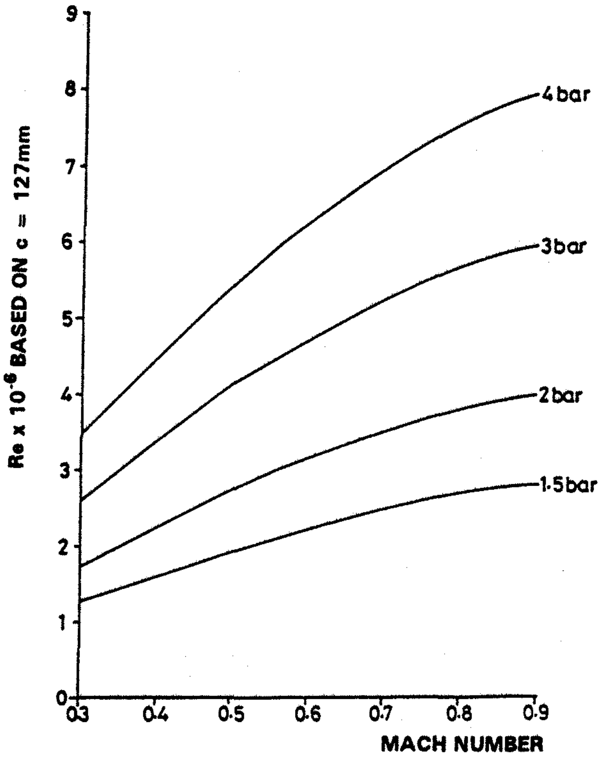

Fig 7 Reynolds Number as a Function of Mach Number

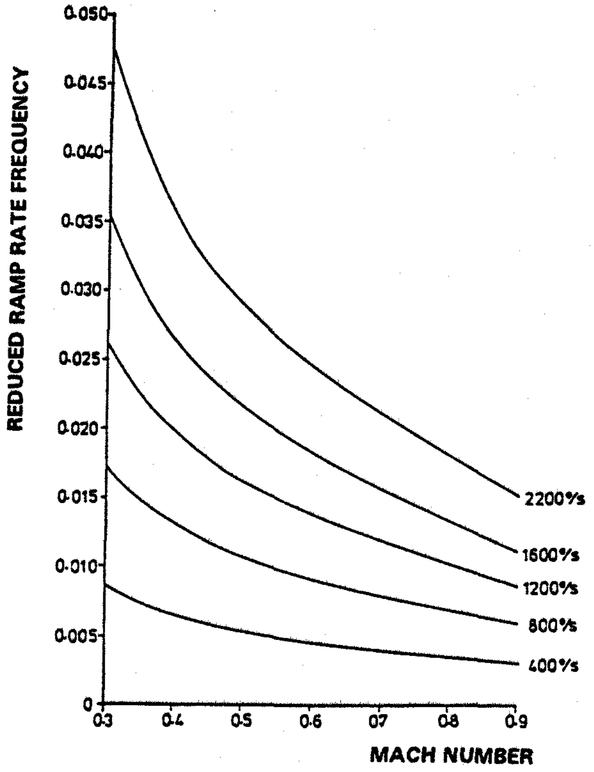

Fig 8 Reduced Ramp Rate Frequency as a Function of Mach Number

Model Scaling

The standard chord length for aerofoil testing in the 2D wind tunnel is 0.127m. The full size chord of a helicopter rotor blade is typically between 0.4m and 0.73m. For aerodynamic similarity the Mach number and Reynolds number for the model and the full scale rotor blade should be identical. This similarity can be achieved by testing at full scale velocity in a pressurised wind tunnel. The ARA 2D tunnel operates over the Mach number range of 0.3 to 0.87, and stagnation pressure range of 1.5 to 4 bar (Fig.7). The model Mach number can therefore be matched to that for the full scale rotor blade and with a tunnel stagnation temperature of, say 288K (normal range 273K-298K) and stagnation pressures of up to 4 atmospheres - close to full scale Reynolds number at sea level conditions can be simulated.

It can be shown that

$$\text{Reynolds No.} = \frac{\rho V c}{\mu} = \frac{\rho a M c}{\mu}$$

can be closely approximated in the wind tunnel by

$$\frac{\rho_o\, a_o}{\mu_o}\, Mc \left(1+\frac{M^2}{5}\right)^{-2.2}$$

where o denotes wind tunnel stagnation conditions.

If it is assumed that the flight sea level static conditions are T_o, a_o, μ_o and ρ_o/H, where H is the ratio of wind tunnel stagnation pressure to ambient pressure,

then flight Reynolds No. is $\dfrac{\rho_o\, a_o}{H\, \mu_o}\, Mc_{flight}$

For a model of scale 1/n, equating the flight and wind tunnel Reynolds nos. realises full scale simulation. Thus

$$\frac{\rho_o\, a_o\, Mc_f}{H\mu_o} = \frac{\rho_o\, a_o}{\mu_o} Mc_{W/T}\left(1 + \frac{M^2}{5}\right)^{-2.2}$$

ie $H = n(1+0.2M^2)^{2.2}$

The other parameter that needs to be scaled is the reduced frequency parameter

$$k = \frac{\omega c}{2V} = \frac{\pi f c}{V}$$

$$\therefore f_{flight}\, c_{flight}\, \frac{a}{a_o} = f_{W/T}\, c_{W/T}$$

for a model of scale 1/n

$$f_{W/T} = n\,(1 + 0.2M^2)^{-0.5} f_{flight}$$

Dynamic similarity is therefore achieved by increasing the model oscillation frequency in proportion to the decrease in model chord, allowing for the small change associated with the compressibility term.

Aerofoil Models

The high geometric fidelity aerofoil models are made from aluminium or titanium, with the choice of material being dependant on the thickness/chord ratio, titanium for ratios less than 12%, and aluminium for those greater. The aerofoil profile is machined by numerically controlled machines and hand finished. Model accuracy is inspected by a probe contact ordinate measuring machine with a ruby stylus. Leading edges are checked optically using 20x model scale comparisons with acrylic templates cast around the section at three spanwise stations. Achieved accuracies are normally with ±0.012mm for the leading edge region, and ±0.038mm aft of 10%c. Local surface slope errors are checked from adjacent error readings at approximately 3 mm intervals and are normally maintained within 1 in 400. The geometry of each aerofoil is documented in an Inspection Report issued to the customer.

The aerofoil is designed to fit the 0.203m width of the two-dimensional blowdown tunnel. This requires the model span to be a loose fit on this dimension. Rubber seals are used to inhibit the possible leak path between the sidewalls and the ends of the aerofoil. The standard chord length for all aerofoils tested in the ARA two-dimensional tunnel (for both steady state and dynamic test regimes), is c = 0.127m which gives an aspect ratio of 1.6 for each aerofoil tested.

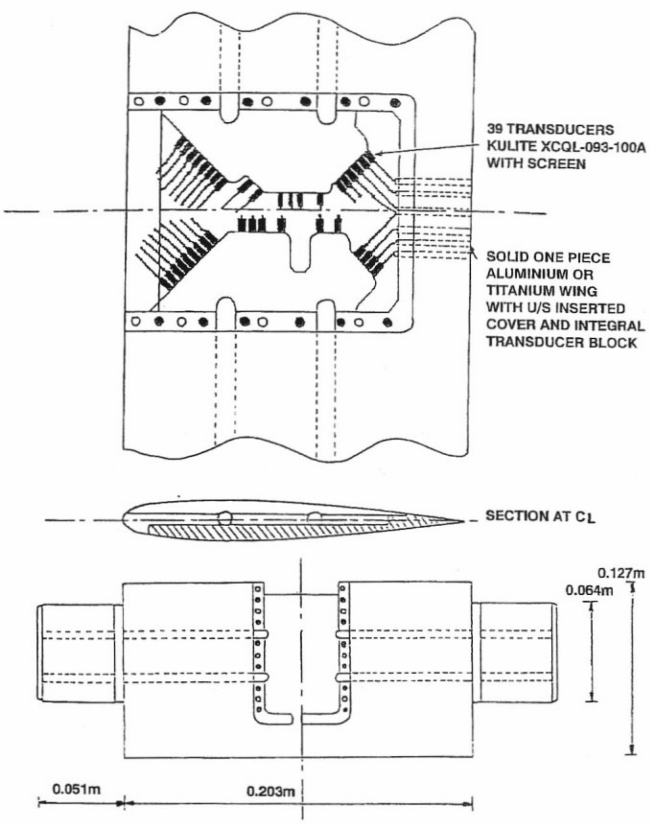

Fig 9 Transducer Assembly Design

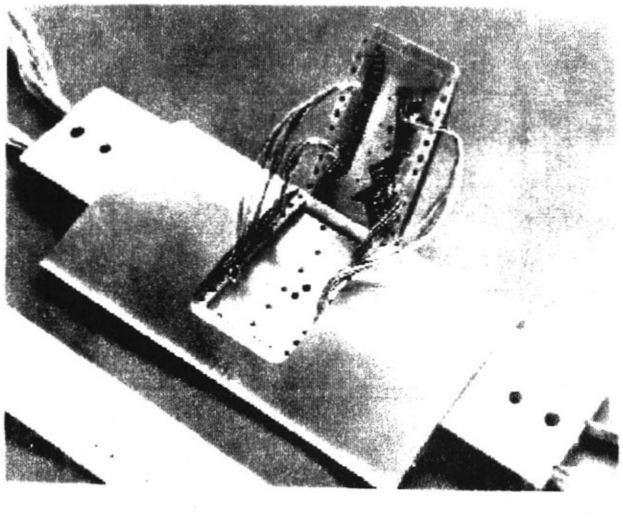

Fig 10 Aerofoil with Kulites assembled in transducer block

Aerofoil surface static pressures are measured by highly responsive pressure transducers. The mechanical design of the aerofoil model and the method of transducer assembly is shown in Fig.9. A separate transducer block is fitted in the mid-part of the aerofoil which has a corresponding cavity. Sufficient flange area, screws and dowels are used to ensure an acceptable proportion of load carrying material. Thirty nine Kulite pressure transducers (type XCQL-093-100-A with screen) can be installed in the aerofoil model, to measure absolute pressure at 39 locations around the profile in a 13mm spanwise band centred on the mid-span. The pressure holes are 0.25mm diameter from the leading edge to 10%c, and 0.30mm diameter the remainder. The re-usable transducers are mounted using a high density wax. This is applied around the transducer body and by melting the wax locally, the transducer is then sealed into the transducer block.

Data Recording System

The specially designed, dedicated purpose data logger is used to program and control the tunnel runs. It can record 50 channels at up to 4kHz, with a total capacity of 768 data points per run.

The 39 dynamic pressure transducer outputs are amplified to a constant level per unit pressure, offset to half amplifier range and low pass filtered to avoid aliasing errors in the sampled data. Matched filters are provided in the 48 data channels (there are two time channels). These 4 pole active Butterworth filters have a sharp cut off beyond the -3db point at 670Hz and an approximately linear phase shift up to cut-off to minimise frequency distortion and provide an acceptable response to step functions.

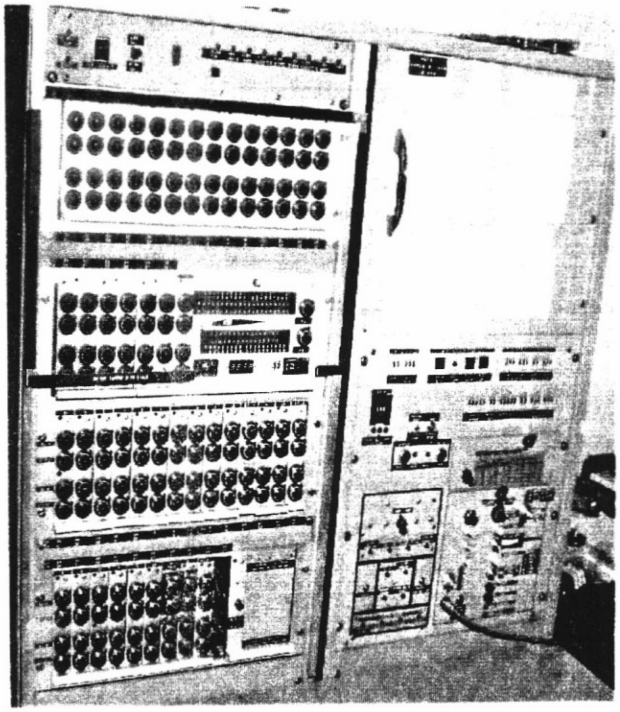

Fig 11 Front Panel of High Speed Data Acquisition System

The signals from the 50 data logger channels are recorded on a 64K store. Transmission of the data to the main computer takes two minutes and is performed post test. Tabulated data with corresponding C_N and C_m plots are available 10 minutes after the start of the run. A comprehensive suite of on-line computer programs assists the monitoring of test campaigns and the facility. Of these, the dynamic stall visualisation program is worthy of special comment.

This program plots one chosen surface of the aerofoil pressure distribution for each consecutive data point at the graphical VDU. The plotting is so arranged that pressure distributions for three consecutive data points are shown at any one instant and as the next (4th) pressure distribution is added, the first is removed. The result is a slow motion picture of the pressure distribution changes which are affected by the flow breakdown and motion of the dynamic stall vortex. This program enables an on-line check of whether dynamic stall has occurred or not, and if so, identifies the start incidence and data point number.

Kulite Transducer Calibration

The 39 pressure transducers are calibrated in situ, by placing the aerofoil model in a pressure box. This has two chambers interconnected via a large valve. Pressures over the range 5 to 55 psi, are applied and monitored by a Texas Instruments quartz pressure set. The data logger amplifiers' zeros and gains are then adjusted to give absolute pressures with a sensitivity of 50 counts/psi, where one count is equivalent to 2.441mV.

Sensitivities are documented for the effects of steady temperature over the temperature range -30°C to +30°C. The pressure response times of each transducer are checked by applying a rapidly increasing and decreasing pressure ramp in the box, and computing the time constant of each gauge. This simple test ensures that all of the transducers have similar response times.

Tunnel Reference Conditions

The wind tunnel stagnation pressure, H, is measured using a Druck absolute pressure transducer connected by a pitot tube at the entrance to the contraction. Total temperature is measured at the same location using a fast response semi-conductor transducer.

The tunnel static pressure is determined from the pressure difference (H-P) measured on a Druck transducer. The static tapping is positioned in the tunnel starboard sidewall 0.55m upstream of the centre of rotation.

Data Reduction

Each run comprises 760 data points from the 50 channels with additional data for calibration zeros. The program selection switches offer a range of sampling points per cycle (8 to 128 in binary steps) which are coupled to frequency, and 1, 3 or 6 settings of incidence or amplitude, (Table 3).

Sampling pts/cycle	Max sampled Frequency	No .of cycles rec Programme steps 1	3	6
8	480 Hz	96	32	16
16	240 Hz	48	16	8
32	120 Hz	24	8	4
64	60 Hz	12	4	2
128	30 Hz	6	2	1

Table 3 **Pitch Drive Programs**

As the data logger's store capacity is constant, a variable number of cycles can be recorded, at equally spaced and repeatable points in the cycle. Repeatable cycles are required to provide analysis of the flow phenomena and subsequent modelling of the flow allowing design values of full size rotor characteristics to be obtained. Organising the mass of data generated by the rig is the function of the data reduction program, which determines and selects for output those cycles which comply with a set of repeatability criteria. If 4 cycles or less are selected then the reduced data is output completely. If more than 5 cycles are run, 5 cycles are selected on the basis of the variability of nine criteria based on the digital force integrations, as follows:

The pitching moment data is sampled at the data point at, or nearest to, the following eight points in each cycle:-

1. C_m at minimum incidence
2. C_m at the mean, increasing incidence
3. C_m at maximum incidence
4. C_m at the mean, decreasing incidence
5. C_m minimum value
6. C_m maximum value
7. C_m at the point where C_N is a minimum
8. C_m at the point where C_N is a maximum

These positions are illustrated in Fig 12.

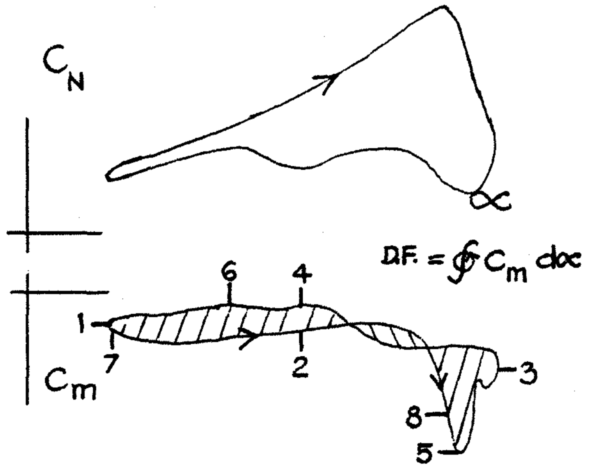

Fig 12 C_m sampling positions

The damping factor of each complete cycle is calculated by numerically integrating the pitching moment against incidence loop. This represents the net work done by the aerofoil on the surrounding air which is proportional to the integral,

$$\text{WORK DONE} = \oint C_m \, d\alpha$$

which is positive for an anticlockwise circuit. Net negative damping represents net energy extraction in a cycle and indicates unstable conditions.

Aerodynamic loadings on the aerofoil are obtained as a function of time by chordwise integration of the measured surface static pressures. These values are tabulated and plotted against mean incidence, which has a mean repeatability of 0.08° and a standard deviation of 0.034°.

Conclusions

The Enhanced Rate Pitching System achieves rates of up to 0.5 in reduced frequency parameter at M=0.30 (140Hz) and 0.25 at M=0.70, with half amplitudes of at least 1°. Non-sinusoidal excursions in incidence, in particular the form of a linear increase, pause and decrease, together with a high degree of linearity and 'sharp' corners, has proved of great value in quantifying and modelling rate effects on dynamic stall.

An up to date account, including performance characteristics is given. References to the many successful test campaigns are provided, along with acknowledgements that the rig has been, and still is, a vital design tool for future blade research.

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