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WIND TUNNEL TESTING OF MODEL ROTORS AT RAE FARNBOROUGH

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1 Introduction

Several years ago, with the build-up of effort on improving theoretical prediction of rotor performance and instantaneous blade loads, it was considered essential to obtain sufficient systematic experimental data to provide verification and guidance. It was seen that this would be particularly true for future designs of rotor blades with significant departures from previous practice as regards the dynamic coupling of flap, lag and torsion modes.

In pursuit of this objective it was decided that a series of test programmes should be carried out in a wind tunnel on a model of a hingeless rotor. The tunnel chosen was the RAE 24ft (7.3m) diameter open-jet tunnel because it was the largest available, although by modern standards its maximum speed of under 50m/s is very low and the quality of the flow poor. These limitations make the tunnel of no use for certain classes of rotor research but were considered to be of secondary importance in a fundamental study of blade dynamic response, so long as the two-dimensional aerodynamic characteristics of the blade profile were adequately known over the range of Reynolds and Mach number of the test.

When the present test team was formed, the 24ft wind tunnel had no apparatus of any use for model rotor testing apart from a manually operated mechanical lift/drag balance; there were no electronic systems for data acquisition or processing, nor any on-line computing facilities. This meant that the rotor test rig and the associated instrumentation had to be designed *ab initio*. Although numerous improvements and additions could still be made to both the mechanical and the electronic components of the test facility, a useful programme of research is now in hand. In this paper a brief description is given of the present state of the facility.

2 The Rotor Test Rig

Fig.1 shows the test tower with a three-bladed model rotor in the working section of the RAE 24ft wind tunnel. The top part of the tower, about 1½m high, can be tilted 30° fore and aft of the vertical. The lower part, about 3m high, mainly exists for the purpose of getting the model rotor up to the level of the tunnel centre line. For the current type of test programme on the dynamic response of an elastic blade, it was considered that, in the interest of saving time, the development of a multi-component balance, although desirable, was not essential. Up to the present, rotor thrust has been measured on the existing lift/drag mechanical balance situated below floor level. However, we have incorporated at the bottom of the tower a mechanical linkage and load cell which measures rotor lift when tests are made in the hover in a site outside the working section of the tunnel. Because rotor lift and drag are measured from below tunnel floor level, the whole tower has to be enclosed in an aerodynamic fairing starting below the level of the tunnel air stream and stretching up to the rotor hub (i.e. higher than shown in Fig.1).

The measured rotor lift and drag are corrected for the aerodynamic tare loads acting on the exposed part of the rotor hub by measuring the forces with the blades removed. In early tests we were mystified by substantial lift and drag forces which appeared to be exerted on the rotor hub and which could not possibly be genuine. These forces appear to be generated by pressure fields acting at the base of the test tower below the level of the tunnel open jet. In the current test programme, just starting, this will be investigated further.

The top part of the tower, above the axis of fore-and-aft tilt, contains at its lower end four variable-frequency electric motors of about 15kW each, although normally only a fraction of this power is used. The motors are connected to the rotor shaft via a gear box incorporating a strain-gauge torquemeter. Measured rotor torque therefore includes the friction of all bearings between the torquemeter and the rotor hub, but a small correction can be made for this by testing with blades removed.

All the mechanism above the gear box can be easily removed in one piece for development and overhaul at ground level (Fig.2). At the lower end of this unit is a 50-way slip ring and above that a slotted disc with two photocells for producing 1/rev and 60/rev azimuth pulses, and above this is the swash-plate.

Unlike full-scale practice, in which cylic and collective blade pitch settings are controlled separately by a system of levers, which in turn control the swash-plate, in our case space considerations dictated a symmetrical arrangement of three actuators directly linked to the swash-plate. Its position is measured by three linear potentiometers each spaced 30° round the azimuth from its corresponding actuator. Above the rotor model itself are first-stage amplifiers handling strain-gauge signals from the blades.

On the three vertical faces of the rotor hub (Fig.3) can be bolted wedges to give combinations of blade preconing from 5° downwards to 10° upwards, and blade sweep from 10° forwards to 10° rearwards. The blade pitch bearings are attached next, the blade pitch links having semi-conductor strain-gauge bridges for monitoring pitch link loads.

At the root of each blade, outboard of the blade pitch angle bearing, are steel flexible elements. First there is a flapping flexure, starting at 8.7% blade radius, then a chordwise flexible element starting at 14% blade radius. There are no lag dampers; the chordwise stiffness is high and there is no danger of ground resonance but the lack of dampers means that we do occasionally run into chordwise resonances which can build up rapidly if not equally rapidly avoided. The flexible blade itself starts at 23% radius.

The test rig, together with the aerodynamic fairings, weighs about 1500kg. When it is not in the tunnel working section, it is transported by an overhead crane into a 'hover' site nearby surrounded by protective netting.

3 The Model Blades and the Present Test Programme

One of the three blades can be seen in Fig.4. Normally the black-painted area extends well inboard; its purpose is to allow us to identify the onset of blade stall on the retreating side of the disc by means of tufts viewed by an overhead TV camera. The strobe-flash system allows us to observe the blade over a large range of azimuth position.

The method of construction of the blades will not be of particular interest because nowadays glass or carbon-reinforced plastic would be used, as indeed they will be in our own future tests. However, at the time our test rig was first ready to run, no suitable plastic blades were available, so we developed some blades with an aluminium alloy D-spar and a hollow balsa trailing edge. Once having started on a serious research programme it seemed sensible to complete it with them rather than change to a new plastic set, although the strength of the metal blades is not as high as we would have liked, and specimen tests showed that they would be liable to a sudden structural failure, with none of the gradual weakening which is the great advantage of laminated plastic construction.

Blade chord is 100mm and we chose NACA 0012 as profile because, even at our low Reynolds number, there is a fair amount of two-dimensional aerodynamic data, and the profile is known to be reasonably amenable to perturbations from the theoretical shape without unduly upsetting its performance.

There is no twist. The mass, and flap and lag stiffness, which are uniform along the span, are dynamically scaled from a hypothetical and greatly simplified contemporary full-scale design. Torsional stiffness is relatively high. Obviously, the effective stiffness of the model depends on the chosen rotational test speed; however, neither Mach number nor Froude number are of the slightest relevance in the present test programme, so by running the rotor at a series of speeds between 300 and 700rev/min it has been possible to simulate a range of blade stiffness.

Fig.4 shows the strain-gauge bridges distributed over the flexible elements and the blade itself. Measurement is made simultaneously of six flatwise (i.e. normal to blade chord) bending moments, three chordwise bending moments, and blade root torsion moment. Pitch-link load is also recorded, mainly for general safety monitoring. Because of friction in the feathering bearing and its inertia, I much prefer to think in terms of blade root torsion than pitch-link loads as far as test results are concerned.

Most of these measurements are made on all three blades, but one of the blades has been chosen as the 'master' blade for which the results are to be analysed. Signals from the other two blades are used to check for faulty circuits, and any major discrepancy would immediately show if one blade were about to misbehave, for example, owing to an incipient stall or structural weakness. Simultaneous recordings of these 11 channels on the 'master' blade are made, as will be described later, and also of rotor thrust and torque. Normally 100 successive rotor revolutions are taken so that the small variations that sometimes occur from revolution to revolution can be subsequently averaged out or examined in detail.

Systematic changes are made to rotor speed, wind tunnel speed up to an advance ratio of 0.4, blade angle and the amount of preset cone or sweep of the blade root. So far all tests have been made with 5° forward tilt of the rotor shaft. Normally blade angle is adjusted to remove first harmonic flapping (discussed further later), but, at the request of the theoretical workers who are using the test results, some measurements are also made with zero cyclic pitch as far as blade strength limitations will permit.

4 The Instrumentation of the Test Rig

The instrumentation of the test rig is of course designed to perform the same functions as wind tunnel testing of model rotors requires everywhere else, namely 'flying' the rotor, data acquisition, display and recording, and, not the least, safety monitoring.

The fact that the test team started with no equipment or previous experience has naturally lead to mistakes but it has allowed us to develop a very purpose-built system to meet the problems encountered when carrying out the tests. While the instrumentation has centred round the processing of oscillatory strain-gauge signals it should be equally well suited to any other oscillatory data, for example from pressure sensors, as we intend to try in an ensuing test programme. Fig.5 shows the basic philosophy.

4.1 Strain-Gauge System

The signals from the blade strain-gauge bridges are initially processed by integrated circuit amplifiers housed in the saucer-shaped package on top of the rotor head that can be seen in Figs.2 and 3. This can handle up to 45 channels of information. One reason for using amplifiers on the rotor head was to halve the number of connections we had to make through the slip rings, since the amplifiers have differential inputs and single-sided outputs. However, we were also concerned before we started that the use of electric driving motors inside the test mechanism together with the high level of electrical interference in the building might lead to excessive noise. After the slip rings the signals pass through 30m of cable to the control room. Here each channel divides to follow two parallel routes, one giving the time-average value and the other the fluctuating component.

4.2 Data Processing and Recording

The time-average component of the strain-gauge signals is fed to a data logger and from there to a Wang programmable calculator. An IBM typewriter is used to produce a real-time print-out of average bending moments on all three blades.

The oscillatory component of the signals from all three blades can be visually displayed on oscilloscopes and recorded on UV-sensitive paper and an Ampex FM tape recorder, but the number of channels that can be simultaneously recorded on paper or tape is restricted to 11, and the signals chosen are normally the 11 from the 'master' blade (i.e. nine bending moments, one torsion moment and the pitch link load). A 12th channel on both the UV paper recorder and the tape recorder is used for a 1/rev pulse, and a 13th and 14th channel on the tape recorder are used to give respectively, a 60/rev pulse and digital information concerning test case number, revolution number and which group of signals (e.g. from which blade) is being recorded.

A problem encountered in our earlier tests was that of spacing the UV traces across the paper, each with the largest scale possible and yet without traces getting too mixed up with one another. A trial-and-error process caused a great deal of paper to be wasted and meant that the running time of a test had to be extended, leading to increased danger of blade fatigue. To avoid this an 11-channel oscilloscope has been developed which shows exactly what will be recorded on the paper, and controls have been provided to adjust the position and amplification of each trace individually. The signals recorded on the FM tape are similarly affected, although this is not really necessary when the tape channels are subsequently analysed by computer, but it has the important advantage that if the FM tape channels are subsequently played back, the 11-channel oscilloscope will display the same neat and tidy presentation as it did during the test.

Playing back the 11 oscillatory signals, perhaps many days or weeks after the conclusion of the tests, has in fact proved to be of considerable value and interest. If the tests were made so that, say, 100 revolutions were recorded at a given test condition, and then blade angle, wind velocity or amount of cyclic pitch was gradually and systematically altered, a picture emerges of how the distribution of oscillatory load along a blade gradually changes. Fig.6 shows how the oscillatory pattern during one revolution has changed with an increase of 4^{o} in blade collective angle, the cyclic angle being adjusted in both cases to remove the first harmonic of blade root flatwise bending moment.

To obtain a harmonic analysis of the oscillatory component of the signals there were two courses open to us. In the first method the traces from the UV paper can be turned into 60 x, y co-ordinates by means of a graph-reader, and a computer program used to produce the first 30 harmonics. Obviously this is a very slow process; in some test conditions the wave form will repeat very closely from one revolution to another, but sometimes there are considerable variations, so that choosing which particular revolutions to analyse off the UV paper presents problems. The second method, and that normally used, is to analyse the records on the FM tape, and to keep the UV traces merely as an analogue presentation and also for making an occasional harmonic analysis as a check on the correct functioning of the tape system.

Two alternative methods of digitising the tape records have been developed. In the first, only a few, say 1 to 4, cycles are digitised and this gives an accurate Fourier analysis of particular wavelengths. The second method involves the averaging of a large number of cycles, say 20 to 500. In this case we build up a stored average of the signal voltage at given azimuth angles before the process of digitising. We have noticed that the finer details of a waveform sometimes appear to change and in smoothing these out they may affect the final value of quite low harmonics, but we have not carried out enough analyses so far to appreciate what uncertainties may result. Whether these variations are caused by random interactions between the rotor blade and the rotor wake, or by variations in the tunnel flow, is not clear.

This paper is not the occasion to discuss the large amount of theoretical work which is in progress and for which these experimental results are being obtained. It is to be hoped that this may be presented at a future European Forum. However, Fig.7 shows the bending moment variation round the azimuth, consisting of the measured time-average value together with the measured first six harmonics, compared with a theoretical prediction by Westland Helicopters Ltd. Flatwise bending moment at 9% radius and chordwise at 15% radius are shown for one test condition.

4.3 Control Instrumentation

I would now like to say a few words about some of the associated equipment. Fig.8 shows the control room layout. Five people are needed to operate the system, while two more are needed to record the readings of the mechanical lift/drag balance and to control tunnel speed.

On the left is a bank of oscilloscopes for safety monitoring. In this the behaviour of the three blades is compared. Six bending or torsion moments, i.e. two signals from each of the three blades, are compared on each of six of the oscilloscopes, and the three pitch link loads appear on a seventh. This allows us to see at once any circuit fault or proximity to a strength limitation. The signals normally appear as vertical bars but if desired a once-per-revolution sweep can be switched in for any or all channels so that their wave form can be observed, for example when resonance with a natural frequency is anticipated. The eighth oscilloscope shows a spot of light which follows the oscillation of the top of the tower, derived from accelerometer readings.

Next on the right is the UV recorder and the 11-channel oscilloscope and the associated controls for position and amplification of the signals. Beyond this is the 'pilot's' position; the operator can set up the required collective and cyclic pitch by adjusting three 10-turn potentiometers or by means of a joy-stick. There are two modes of controlling the swash-plate actuators; in one the three actuators all take the same time to move from one setting to another irrespective of the difference in their travel distances. This avoids any transient build-up of blade bending moment. Alternatively, the three actuators can be made to travel at their maximum speed.

In most of the tests, as already noted, we aim to trim out first harmonic blade root bending moment. The best way of defining this condition would have been zero time-average rotor hub rolling and pitching moment but, as we had not incorporated a suitable balance, we tried to achieve the condition initially by displaying the oscillatory component of flatwise blade root bending moment on a large oscilloscope and removing the once-per-revolution shape of the wave-form by eye. Certainly it was usually possible for an operator to repeat closely the values of cyclic pitch he judged to be best, but this was not always so in cases with large-amplitude higher harmonic content. We found in these cases, on subsequent harmonic analysis, that we were sometimes leaving in the signal a peak-to-peak first harmonic amplitude of up to 25% of the total peak-to-peak signal. A circuit has now been developed with an oscilloscope display of a vector representing the amplitude and phase of any residual first-harmonic content to overcome this trouble.

To the right of the 'pilot's' station are the strobe-flash controls and TV screen. One TV camera looks down vertically at the rotor to observe surface tufts and the other gives a side view of the rotor disc and is used mainly for blade tracking. On the far right are the Ampex FM tape recorder and the time-average data recording system already referred to.

5 Testing at High Mach and Reynolds Number

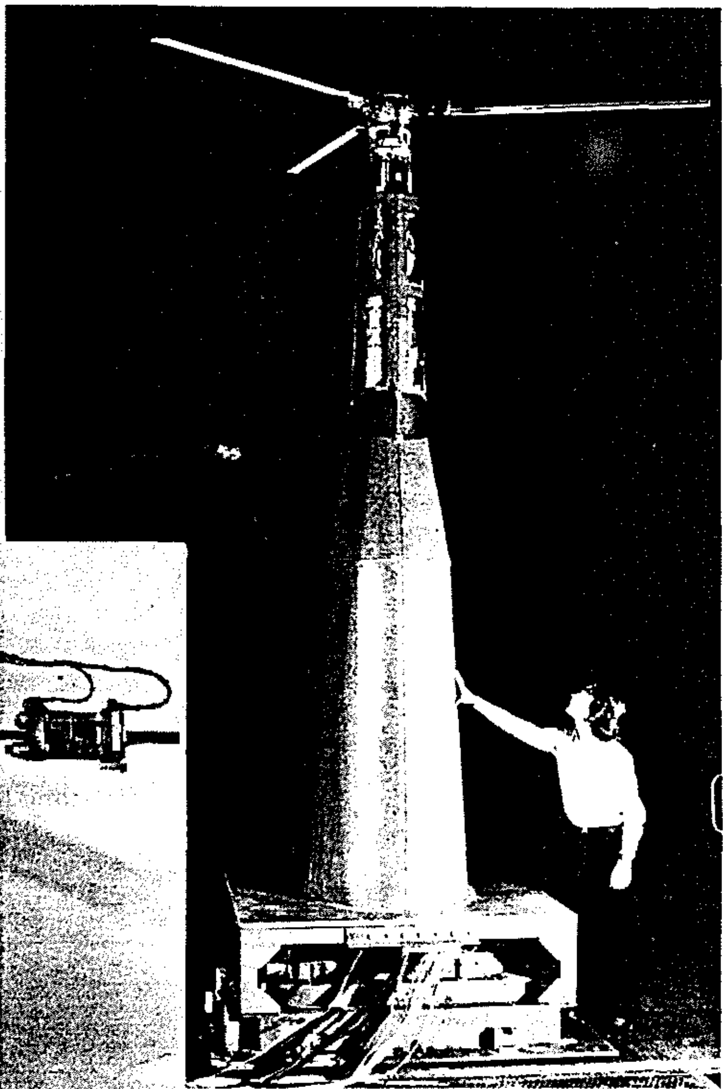
There are a large number of research programmes, mainly concerned with the interaction of blade aerodynamic loading and blade dynamic response, that can be carried out in a large low-speed wind tunnel like the RAE 24ft in support of fundamental theoretical modelling. However, this sort of tunnel cannot help investigate what really happens at full-scale when there are compressibility effects and a flow pattern over the blade which, on many modern blade profiles, could be sensitive to Reynolds number. In other words we could not in this wind tunnel prove the safety and performance of an advanced design of blade prior to flight testing. For this, the wind tunnel must achieve full-scale speeds, preferably over 200 knots, and a Reynolds number approaching the full-scale value, or at least close enough to it for the flow mechanisms controlling shock-induced separations to be representative of full-scale.

A new wind tunnel at Farnborough, now being commissioned, achieves these objectives, but it does so by a small size of working section, 5m × 4.2m, and a 3-atmosphere pressure. Based on our experience in the 24ft unpressurised tunnel, we feel that a suitable mechanical test rig could be developed for rotor testing in the 5m tunnel, although the high loads and small size would make this a difficult task. However, it is not yet clear whether model rotor blades could be built to suit all the tests we might wish to make.

It is I think agreed that a rotor of say 3m diameter can be made in fibre-reinforced plastic with sufficiently accurate blade profile and dynamic properties for reliable results to be obtained at one atmosphere pressure, and to this extent testing in the 5m tunnel at one atmosphere offers an attractive solution to some of the limitations of the 24ft, namely higher speed, better flow, far better computing facilities and, not the least, a system of quickly-removable model carts so that short tests can be made in aid of clearing some doubtful test result or proving the instrumentation without a major interruption of other tunnel programmes. Rotors of 3m diameter should not lead to significant tunnel constraint uncertainties at the higher advance ratios.

With the tunnel at 3-atmospheres pressure it should be possible to construct a virtually solid blade with high stiffness and mass, instrumented with surface pressure sensors, which would be useful for proving basic aerodynamic theory, because the smaller the flexible motion of the blade the easier it will be to interpret the results. However it is doubtful whether mass and stiffness distributions representative of full-scale practice could be incorporated. The problem is currently under study.

Fig.1 Rotor test rig in 24ft wind tunnel



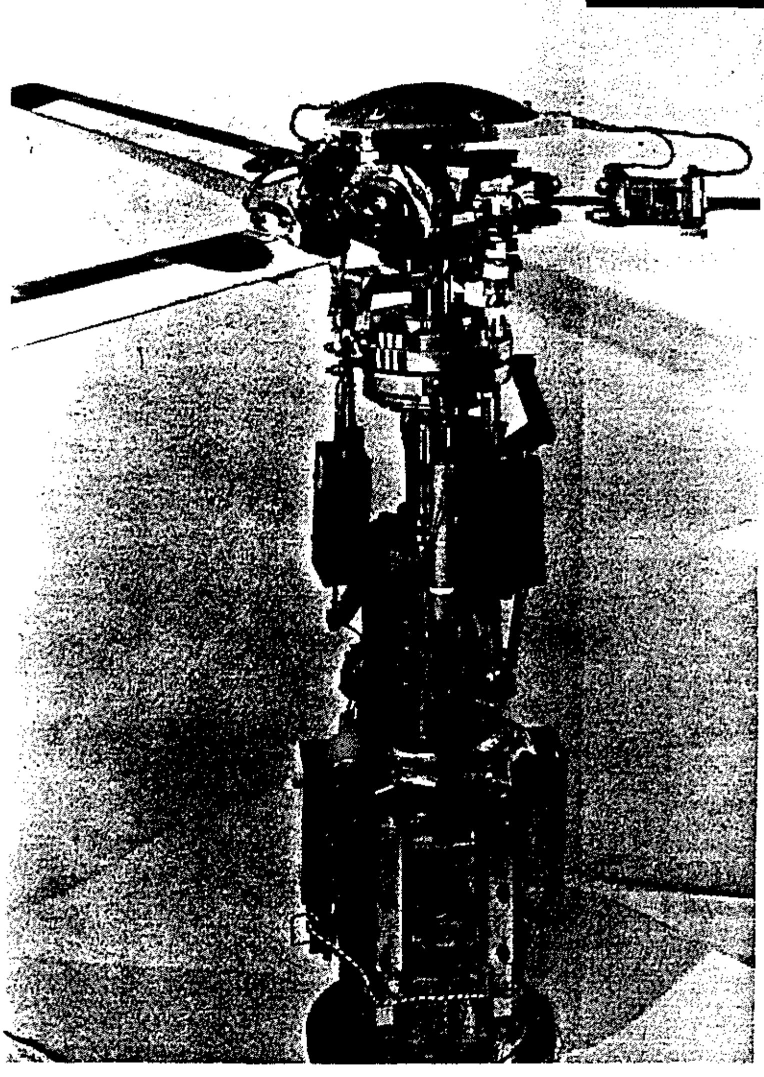


Fig.2 Upper rotor shaft assembly

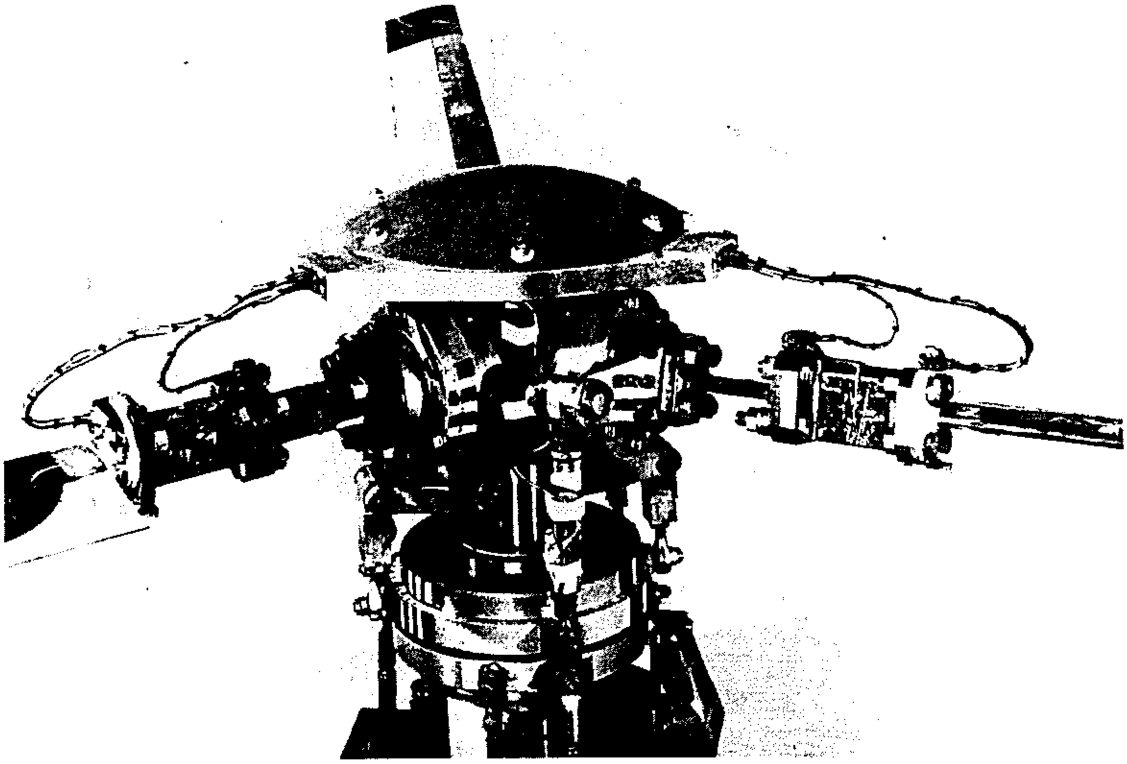


Fig.3 Rotor head

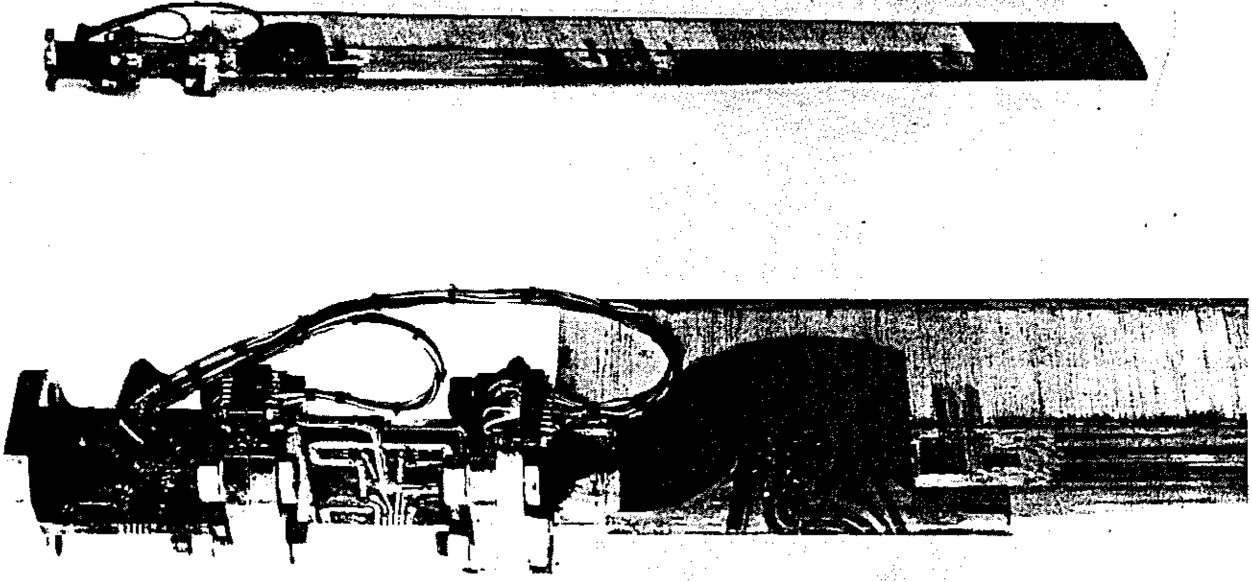


Fig.4 Model rotor blade

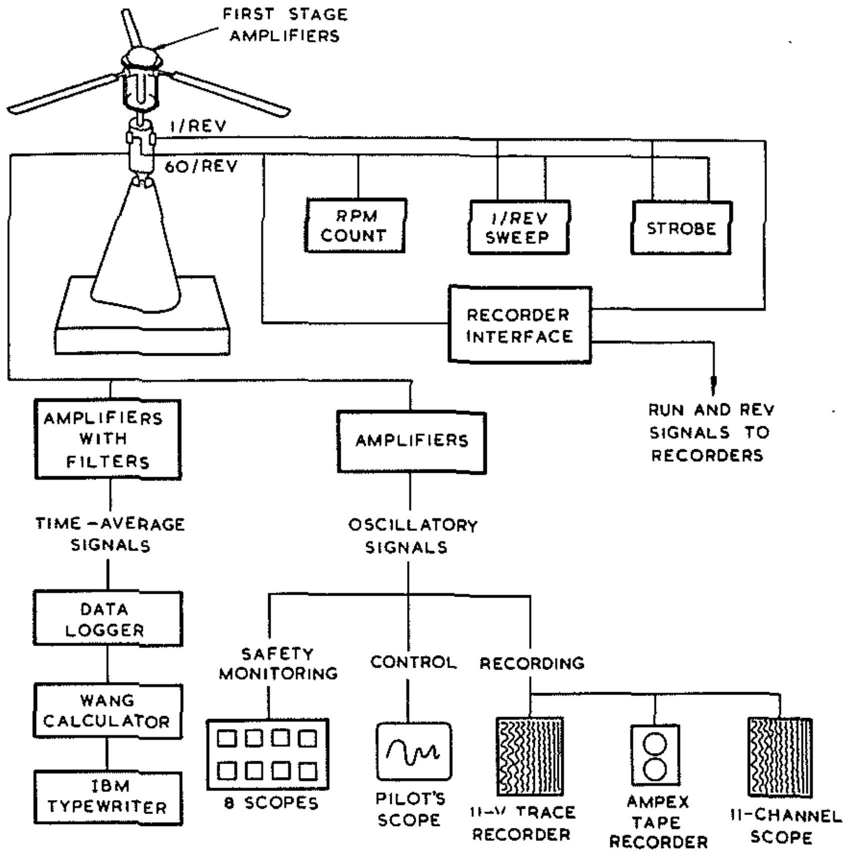
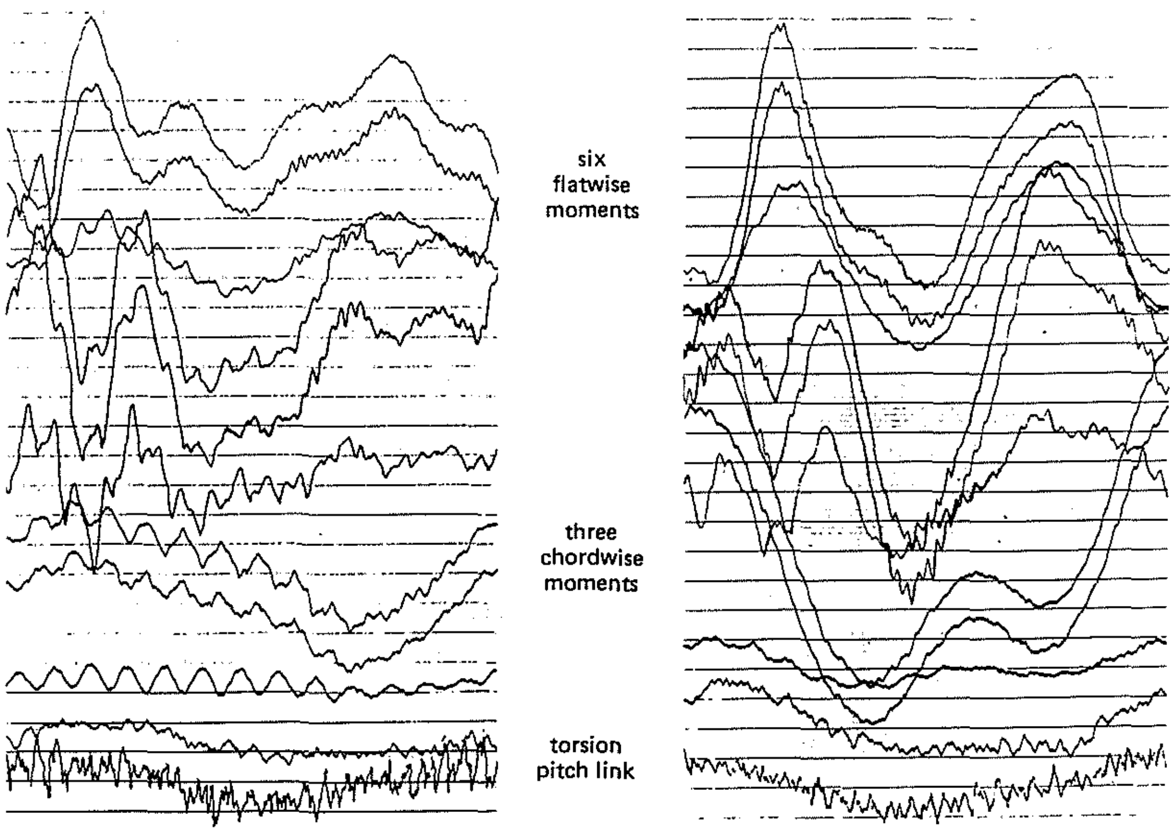


FIG.5 DATA HANDLING SYSTEM



(a) θ_0 = 5.1 deg A_1 = −1.8 deg B_1 = 2.4 deg (b) θ_0 = 9.2 deg A_1 = −3.3 deg B_1 = 5.4 deg

2½° cone 0°sweep N = 500rev/min μ = 0.3

Fig.6 UV paper traces

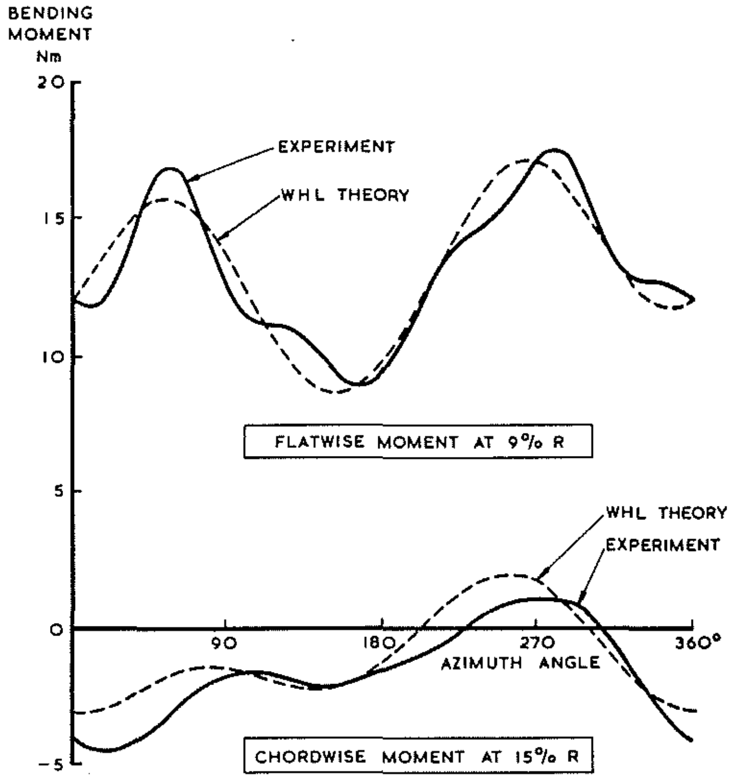


FIG.7 COMPARISON OF THEORY AND EXPERIMENT

$\theta_0 = 4{\cdot}7^\circ \quad A_1 = -1{\cdot}3^\circ \quad B_1 = 2{\cdot}6^\circ$

ZERO CONE ZERO SWEEP N=500 rev/min $\mu = 0{\cdot}3$

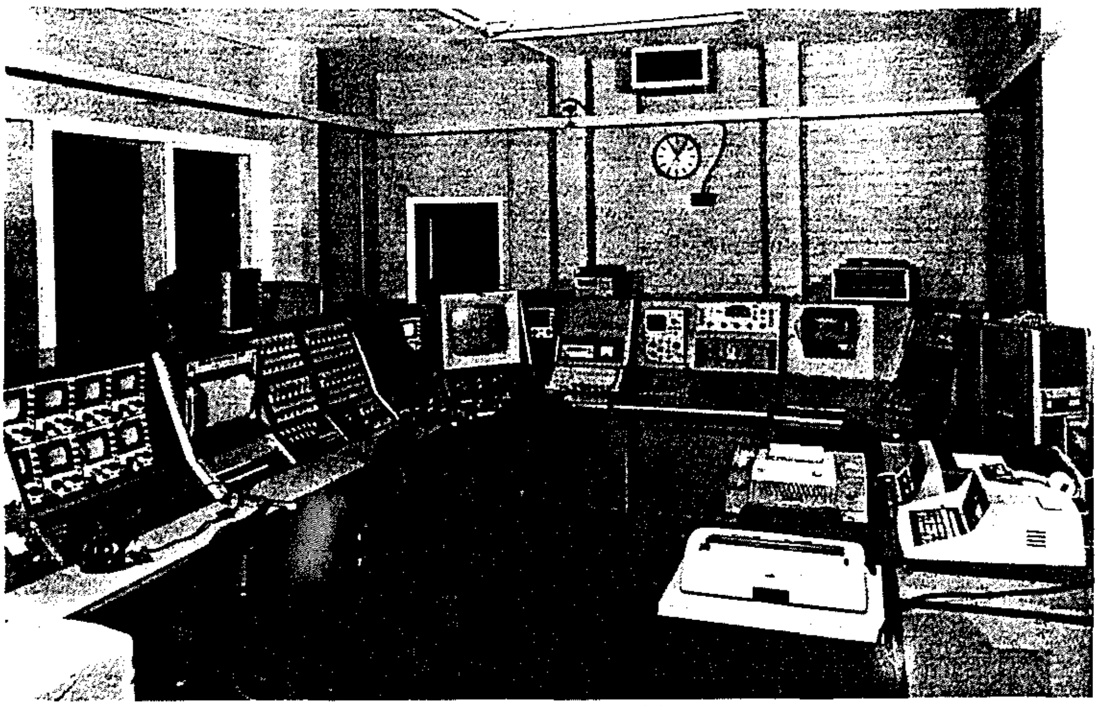


Fig.8 Rotor test control room