Simulation of Helicopter Operating Conditions in Ground Tests

By RAOUL HAFNER

Had Daedalus, prior to his legendary flight from Crete on wings of wax and feathers, resorted to a little ground testing under simulated flight conditions, he would possibly not have lost his son Icarus and the art of aeronautical engineering might have joined the ranks of the great classics However, this Greek aircraft designer did not happen to have on this occasion the benefit of a development contract for such test work Indeed, I understand the whole venture was undertaken strictly without the authority of the local Ministry of Aviation, and so the chances for a successful completion of this note-worthy effort were somewhat restricted The designer then, very wisely and no doubt realising the short-comings of the situation, advised strict adherence to a very limited flight envelope, so that there would be a safety margin for contingencies during the ensuing flight Such philosophy, however, did not appeal to the adventurous and optimistic mind of the youthful son who threw the father's warnings to the winds, and climbed beyond the prescribed limits into the lofty heights and the sunlight In those days, apparently, little was known about the behaviours of wax in stratospheric conditions, or else the wax used did not come up to specification standard Whatever the cause, the wing on coming close to the sun disintegrated and Icarus met his fate Thus goes the story of the first recorded aircraft accident , one, which incidentally could have been avoided by sensible ground testing

The value of testing under simulated conditions was known already in ancient times After completion of a bridge or lofty structure, the procedure was to march across it a gang of slaves, carrying or pulling heavy loads, and if the structure withstood this " test " satisfactorily, it was considered to be safe for general use This form of testing was, of course, crude both technically and morally, but it contained the nucleus of the subject under discussion The idea was to procure in advance a set or sets of conditions, similar to those which were expected to arise later in normal use, and to employ for reasons of economy, as there was a risk of a failure, cheap expendable substitutes With this brief historic reference we may proceed to the problem of ground testing of helicopters

THE PURPOSE OF GROUND TESTING

The helicopter is characterised by the combination of two major features firstly it is complex both in construction and in underlying principles, secondly it is dangerous insofar as failures or mistakes are generally costly in lives and property. This serious characteristic of the helicopter imposes a heavy responsibility on its constructor. He must be able to master the complexity of problems with which he is confronted, and he must be doubly sure on this point because of the serious consequences of his decision. It is for this reason that usually he will not accept theoretical considerations and calculations as sufficient evidence of airworthiness. This applies especially to the present state of the art, which is still in its infancy and liable to spring surprises from many unexpected angles. Whilst he will find it convenient to use the theoretical approach for the purpose of exposition of the problems and for their *qualitative* solutions, he will be inclined to follow this up by testing and similar treatment in order to obtain realiable *quantitative* results. Moreover the empirical approach often discloses phenomena which previously have not been suspected and sometimes it is the sole approach in complicated cases, where the theoretical treatment is laborious and time consuming or even impossible. Ground resting in essence is making doubly sure that the design is satisfactory in all material respects before it is released for production and general use.

GENERAL CONSIDERATIONS FOR GROUND TESTING

In the first instance there is a need for defining the term ground testing. It can be said to mean that a test specimen, which may be anything from a selected component to the whole aircraft, is placed in a suitable ground rig, which again may be anything from a simple platform to an elaborate device, and is subjected there to a set of selected conditions which are similar to corresponding conditions in the normal use of the component. From the behaviour of the test specimen under these selected conditions, certain conclusions can be drawn as to the behaviour of similar components in normal use. One of the important features of ground testing is, therefore, the simulation of operating conditions. The most complete simulation is obtained if a whole helicopter is subjected to all conditions of operation in general use. However, such a complete test is economically not practicable, nor is it technically necessary. Generally only critical components of the helicopter and critical operating conditions need be selected for testing, or in other words only partial simulations need be attempted. Examples of such partial simulations are the ground testing of a rotor assembly for all important conditions of flight, or a blade link or tie rod for conditions of stress with emphasis on fatigue, or a gear box for deformation or oil circulation or heat dissipation. In attempting a partial simulation it is important that the abstraction made from the complete picture is self contained. It must contain sufficient factors, to permit safe conclusions to be drawn from the test results by means of relatively simple arguments. Thus, for instance, in a fatigue test the simulation should include temperature, because the arguments necessary to bridge a discrepancy in temperature are too involved to permit safe conclusions. For the same reasons in a fatigue test of a large assembly, the whole vibratory system should be included in the simulation, or alternatively missing parts substituted by dynamic equivalents.

Simulation involves two distinct actions. Firstly, there is the act of determining all elements and factors essential to the simulation and assessing their magnitude. If the prototype aircraft has not yet flown, then the relevant factors can only be obtained from calculations   Any errors made therein, or in the preceding assumptions, are necessarily carried forward into the ground tests   On the other hand, the prototype aircraft may be available for test flying   In this case the required information is best furnished by records from suitable instruments carried during the test flights, such as strain gauges, pressure gauges, thermometers, time or frequency meters, flow meters, accelerometers, etc   In this case the errors involved come from the instruments and the reading, as well as from the scatter between different flights

The second act comprises the copying of these features with a test specimen together with appropriate substitutes in a ground rig   Here too, errors will arise because of scatter simplifications and other short-comings

It is obvious, therefore, that the simulation cannot be perfect   The more uncertainty that exists on the operating conditions or the test conditions or both, the less valid the conclusions that can be drawn from the ground test   It is, however, generally possible to recognise whether an error is on the conservative or the optimistic side of perfection   It is, therefore, possible to arrange the conditions in the ground tests to be more severe than those furnished from test flights so that the conclusions from these tests will be " on the safe side "   The outlook is characteristic of a new engineering field in the pioneering stage

The problem of simulation is particularly involved in the case of tests for establishing fatigue life   It is obvious that the fluctuating stress in a component, whilst perhaps generally conforming to a given pattern, is subject to random variations from minute to minute, from flight to flight and even from one aircraft to another of normally identical construction   The question arises then what is to be simulated in a fatigue test ?   It is clear that the individual minutes of flying are immaterial to the fatigue aspect, that small changes from one condition of flight to another do not matter a great deal   The thing that matters is the cumulative damage caused by a long period of flying under these various conditions   The problem in fatigue testing is therefore the simulation of the cumulative effect, the aggregate of conditions   There is as yet no generally accepted theory on fatigue   There have been in use tentatively certain cumulative damage rules, which are accepted by some and rejected by others   Thus, simulation of cumulative damage in fatigue testing is today to a great extent a matter of individual opinion, and a matter for agreement or arbitration if more persons are involved

In the following list, by way of example, some typical helicopter ground tests are quoted

TYPICAL EXAMPLES OF PARTIAL SIMULATION IN HELICOPTER GROUND TESTS

Component	*Simulated Conditions*
Gearbox	Deformation under various torques resulting in a misalignment of bearings and gear teeth
Gearbox and Oil Pump	Oil circulation and oil levels at various rotor speeds and altitudes
Tie Rod	Steady and fluctuating stresses and fretting between tie rods sectors (cumulative fatigue and wear damage) for an extreme combination of end load and torque (Endurance Test)

Rotor Blades, Blade Articulations, Rotor Hub, part of Rotor Control	Steady and Fluctuating Stresses, wear in bearings, abrasion on blades due to airflow, exposure to sun and rain (cumulative fatigue and wear damage) for typical conditions of flight (Endurance Test)
Main Rotor Controls	Steady and Fluctuating stresses, wear in bearings (cumulative fatigue and wear damage) for conditions of high speed flight (Endurance Tests with factorised loads)
Freewheel and Transmission	Dynamic effects after sudden engagement and disengagement of the rotor Steady and fluctuating torque
Power Plant, Transmission, Fan, Air Cooling Ducts, Oil Cooler, major part of Airframe	Steady and fluctuating stresses, wear in bearings, temperature of oil, gearboxes and engines (cumulative fatigue and wear damage) (Endurance Test)
Clutch, Engine, Transmission	Stresses and temperatures in clutch during engagement Heat generation and heat dissipation
Shafting and Bearings	Whirling stresses at critical speeds of rotation

In the following, three of the more important ground tests have been selected for closer examination They are an endurance test on main rotor controls, an endurance test on power plant and transmission, and an endurance test on the main rotor

It will be shown how the general considerations and requirements for ground tests which have been outlined earlier in this paper, apply to these specific cases and how, with proper procedure, it is possible to draw valid and useful conclusions from such tests

GROUND TEST ON THE MAIN ROTOR CONTROLS

The rotor controls, commencing in the pilots cabin and terminating at the rotor head, comprise a long train of rods, levers, pulleys, cables, dampers, irreversible linkages and the like They form a complex dynamic system, which shows a manifold response to extraneous forces Owing to their complexity it is generally not practicable to establish by calculation their various modes of oscillation As the system in normal use is only excited from the rotor head, it is profitable to fit an exciter to this end of the controls and study from suitably placed recorders the dynamic behaviour of the system under various frequencies and amplitudes of excitation Also considered must be the effect of possible errors in the manufacture of the rotor blades or their adjustments on the magnitude of control excitation, as experience has shown that the difference in this respect between " smooth " and " rough " rotors can be considerable This preliminary investigation may reveal critical conditions in certain areas which require a closer attention during the following flight test programme For these flight tests the prototype aircraft which preferably carries a " rough " rotor, is suitably instrumented and strain gauges are placed in the critical areas of the control system A schedule of test flights is then drawn up which contains the critical conditions discovered in the preliminary investigation The test results are then analysed (Fig 1) and an assessment is made of the cumulative damage in fatigue and wear due to a given period of typical flying This then establishes the datum for the ground tests

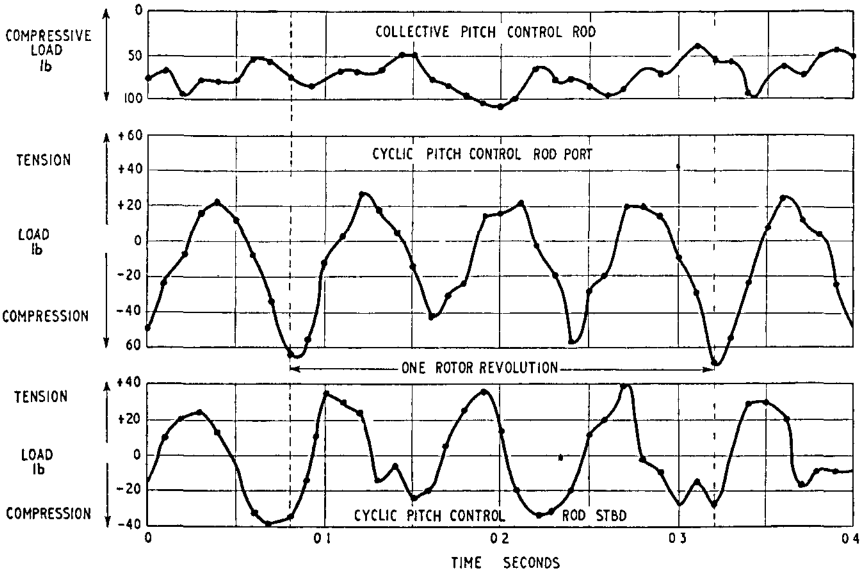

Fig 1 Strain guaging of control rods on the Bristol 171, at 250 r p m , 90 knots I A S with Rotor in rough condition

(By kind permission of ' Flight)

The control system, complete with strain gauges and relevant instrumentation is then placed into a ground rig, and is loaded by synthetic means in such a way that the cumulative damage in any part of the system from a given period of ground testing is at least as great as that from the same period of typical flying This simulation is verified by comparing strain gauge records from flight tests with those from the ground rig Endurance tests of a given duration are then made, at the end of which the various components of the control system are examined and their condition compared with that at the beginning of the test Further periods of ground testing can then be carried out until a stage is reached where certain conclusions can be drawn

(1) The system has an infinite fatigue life,
or (2) certain components have a limited fatigue life
(3) After a given period of use certain parts require reconditioning,
or (4) replacing
(5) It is advisable to provide at certain intervals, a given measure of inspection

These conclusions are applicable to most forms of endurance ground testing under simulated conditions, including the following examples —

POWER AND TRANSMISSION SYSTEM

This system is dynamically very complex and a theoretical investigation on linear and torsional vibration is generally useful as it provides information on critical rotor speeds, regions of stress, etc , which require special attention during the ground test The linear vibrations are mostly concerned with shaft whirling and most important here is the critical whirling speed and the bending moment variation along the shaft under these conditions As regards torsional vibrations the system can be regarded to consist of a number of masses with interposed elasticities (Fig 2) Such a system is capable of swinging in a corresponding number of natural modes and frequencies (Fig 3) At the same time the system is subject to extraneous cyclic forces at various frequencies, which come mainly from the engine and the rotors (Fig 4) A condition of resonance will then exist whenever a forcing frequency is at or near that of a natural mode of swinging Very high stresses can be experienced during such resonance, especially in the proximity of torsional nodes The theoretical analysis must, therefore, aim at establishing critical speeds and areas, in order to ensure a judicious placing

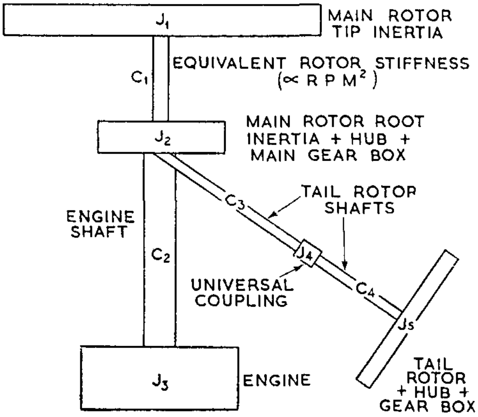

Fig 2

Diagrammatic scheme of the Bristol 171 trnsmission layout

(By kind permission of "Flight)

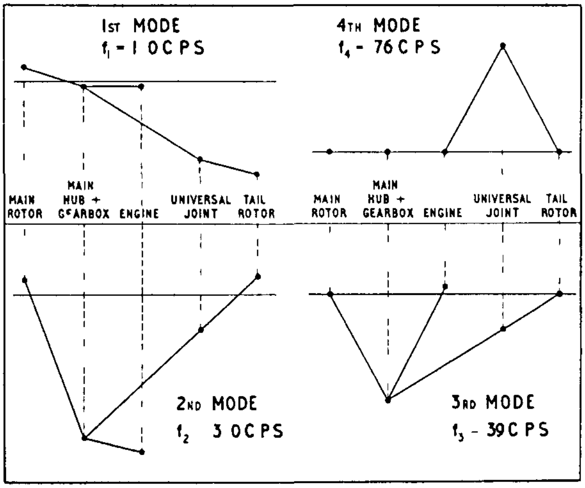

Fig 3

Transmission swinging form diagrams of Bristol 171

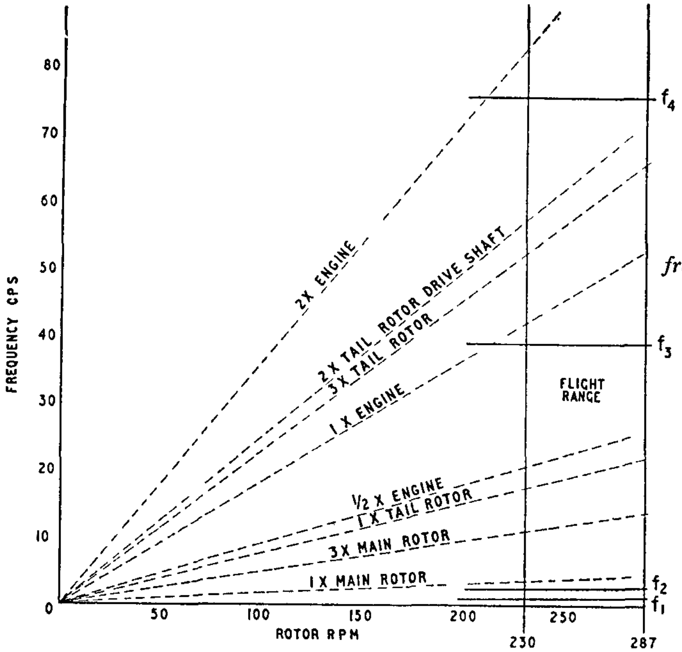

Fig 4

Natural frequencies of the Bristol 171 transmission system

of strain gauges and provision of other instruments (Fig 5), as well as a sensible flight test programme Such a programme consists of a number of short flights, each being a critical combination of forward speed, rotor speed, power, normal acceleration, etc The information obtained from such test flying, which contains steady and fluctuating strain at selected datum points in the transmission, torsional frequencies, gearbox temperatures, etc, can then be related to the operation envisaged for the type of helicopter under investigation and an assessment made of the cumulative damage with respect to both fatigue and wear, caused in a given period of typical operation This completes the first part of the simulation namely the establishment of all relevant factors The second part comprises the actual simulation It

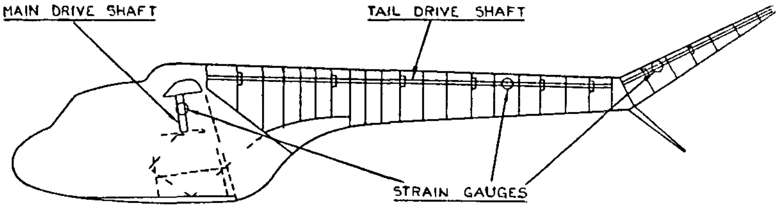

Fig 5 Type 171 Helicopter Torsional vibration Position of strain guages on drive shafts

is advisable to include in the simulation of the transmission and power system the major part of the aircraft structure and at least all parts which serve to locate the transmission and the engine and the air ducts required for the cooling of the engine and the gearboxes As most of the simulated conditions are those of flight, it is advisable to suspend the test specimen below a gantry on a length of cable which is attached to the rotor hub This represents a low frequency suspension in the plane of rotation with a constant normal acceleration of one ' g ' acting on the specimen, which corresponds to the condition of rectilinear flight This feature is particularly important for those parts of the transmission which carry the weight of the aircraft It is generally necessary to replace the rotor of the helicopter by a large fan with adjustable drag plates, in order to permit a wide variation in rotor torque without interfering with the condition of suspension The rotor, in respect of the dynamics of rotational movement, is a two mass system There is essentially one mass at the rotor centre to which is articulated the combined mass of the rotor blades The centrifugal force acting on the blades during rotation constitutes in effect an elasticity interposed between hub and blade mass, the stiffness of which varies with the square of the rotational speed As the fan must be a dynamic equivalent of the rotor, it too must be made of two separate masses of appropriate magnitude, which are connected elastically It has been found expedient to use a spring as the elastic coupling, the stiffness of which can be varied by suitable adjustment The test specimen must be instrumented like the prototype aircraft during flight testing, and in particular the same datum points must be chosen for the strain gauges It is then possible to compare the test specimen with the aircraft and verify that the critical condition obtained in the aircraft can be reproduced in the specimen The schedule for ground testing can then be established It is, of course, not possible, nor is it necessary, to simulate on the ground every condition of operation, but only the cumulative damage in fatigue and wear of a given period of typical flying This can generally be achieved by substituting in the ground test a small number of conditions—that is suitable combinations of boost and rotor speed—for the wide range of conditions which are possible in the air, in such a way that the cumulative damage from the ground test conditions is at least as great as that from the air condition In the ground test, therefore, engine and gearbox temperatures will be kept high by artificial means and care will be taken that fluctuating stresses are sufficiently high and the time run in conditions of high power is sufficiently long The errors made in the simulation are, therefore, on the " safe side," and the ground test performed in this manner will give conservative information, not only on fatigue life but also on suitable overhaul periods

THE ROTOR AND THE HUB

In ground testing the rotor it will be found convenient to follow a procedure similar to that of transmission testing Included for this purpose are the following parts the rotor blades, their articulations, the rotor hub and the part of the rotor control that is carried in the rotor head In the first instance it is necessary to establish by calculation the natural swinging modes of the blade and the corresponding frequencies Most important besides the fundamental torsional mode are the flexural modes in the vertical plane The fundamental flexural mode is the blade flapping about the flapping pin combined with a small amount of in phase bending of the blade (Fig 6) It is characterised by one node, which lies at the flapping pin The flapping frequency of this mode is 0 for a stationary rotor and increases with rotor speed (Fig 7) For conventional blade articulations the flapping frequency NF_1 is about that of revolution thus NF_1 is a straight line at slope 1 in Fig 7 The next higher mode contains an additional node at a point about 2 3 of the rotor radius, the outer part of the blade swinging in anti-phase with the inner part (Fig 6) At vanishing rotor speed the only elasticity is that of the blade structure, which then determines the frequency of this mode As, however, the rotor speed increases, the rapidly growing centrifugal force stiffens the blade and thus increases the frequency of this mode (Fig 7) Indeed at high rotor speed, C F is the predominant factor controlling the frequency of the mode (line NF_2 in Fig 7) Similar arguments apply to the higher flexural modes which are characterised by an increased number of nodes and higher natural frequencies (lines 3 NF_3, NF_4 in Fig 7)

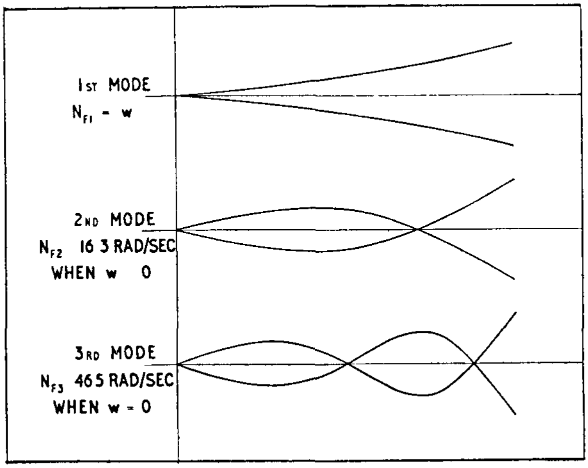

Fig 6
Natural flexural modes

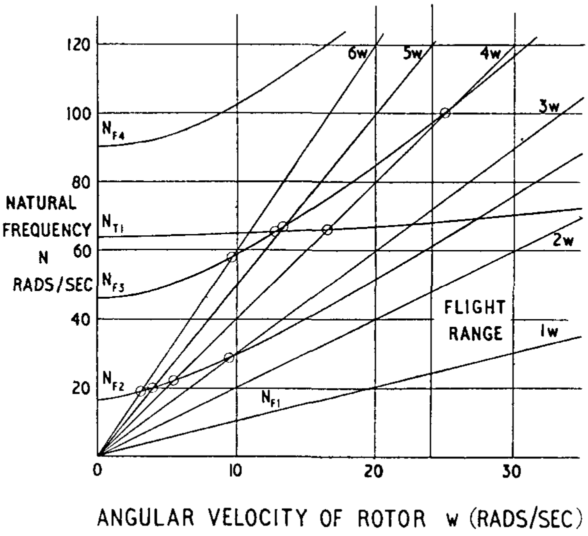

Fig 7
Resonance Diagram

In forward flight the blade is subject to aerodynamic lift forces which can be resolved into Fourier components

$$L = C_0 + C_1 \sin(wt + S_1) + C_2 \sin(2wt + S_2) + \quad + \\ Cu \sin(uwt + Su)$$

that is a constant term denoting mean lift and a range of harmonic terms Thus the blade is subject to the forcing frequencies of w, $2w$, $3w$ nw which are shown in Fig 7 It is clear that the points of intersection between the natural frequency and forcing frequency lines are conditions of resonance The ordinates of the points measure the blade frequency at resonance and the abscissae the corresponding critical rotor frequency A considerable amount of investigation on this subject has been made in the Cornell Aeronautical Laboratory, U S A [1], [2] There is, therefore, a need for a theoretical analysis to show critical regions in the blade as well as critical rotor speeds which must be considered in deciding on the instrumentation of the prototype aircraft and on the subsequent flight test programme The rotor blades are then equipped with a suitable number of strain gauges (Fig 8) and various flights with critical combinations of rotor speed, forward speed, power, etc , etc , are carried out, and the results analysed with a view to fatigue and wear damage

The next part comprises the ground running of the test specimen This is conveniently done on a rotor testing tower Such a tower consists of a structure which permits the spinning of a rotor at a height sufficient to avoid aerodynamic ground effects The tower is preferably mounted universally at its base and braced by a number of slack and weighted steel cables which produce a low frequency suspension of the rotor in its plane of rotation Moreover, means are provided for varying collective pitch of the blades as well as rotor speed These arrangements constitute a fair simulation of flight conditions, however, the test tower is deficient in one material respect It does not provide a forward speed component, which produces the harmonic terms of lift referred to earlier Such lift variation, however, can be produced by artificial means, two of which are considered in the following

(*a*) *Lift variation by cyclic change of blade incidence*

This method has been suggested by several American investigators[3] It consists of a harmonic change of collective pitch at a given frequency By a combination of a number of such sine-oidal pitch oscillations of selected amplitudes and frequencies, it is theoretically possible to reproduce any pattern of lift distribution in time and space However, the great disadvantage in this scheme is the fact that it is necessary to produce this high frequency blade pitch oscillation in order to achieve the required lift variation It is difficult already to build rotor blades stiff enough for the pitching oscillation of rotor frequency used in the normal rotor control (see NT_1 in Fig 7) let alone those of higher harmonics Once the frequency of the fundamental torsional mode of the blade is approached, the blade becomes twisted and consequently stressed in a manner which does not exist in flight This, of course, must be avoided

(*b*) *Lift variation through obstruction in the rotor slipstream*

A rotor when producing lift on a rotor tower developes a considerable slipstream, which is constant in both blade azimuth and time By placing

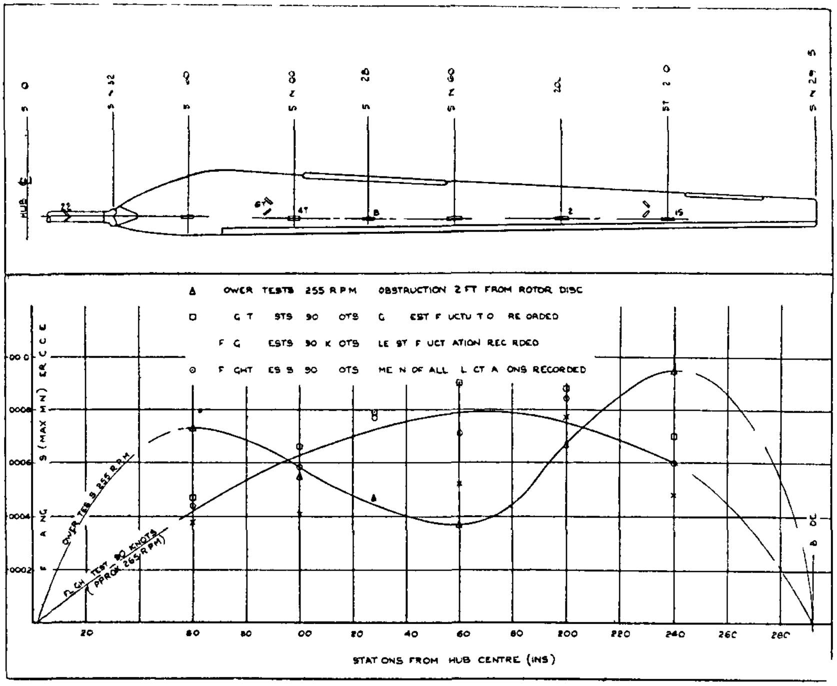

Fig 8 Location of strain guages and measured strains

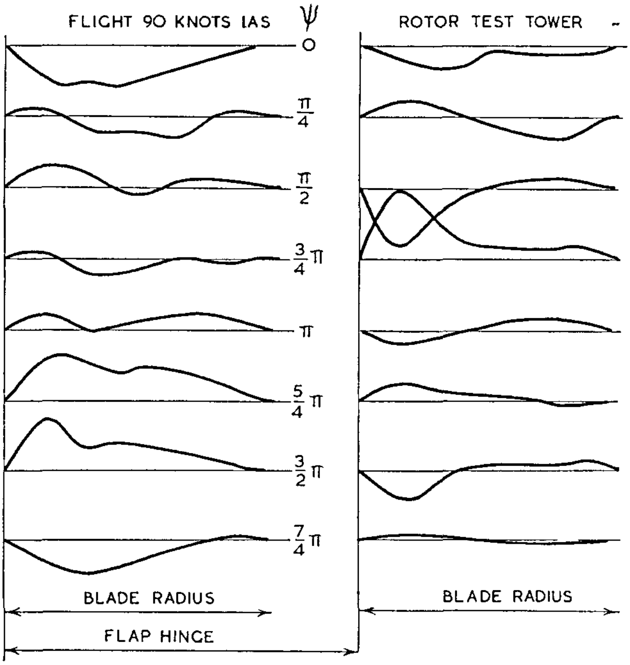

Fig 9

Variation of blade bending moment with azimuth angle

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obstructions in the slipstream a cyclic variation can be introduced with corresponding effect on blade incidence and thus blade lift The obstruction can take various forms, one independent variable, being in the radial direction and the other in azimuth Thus on the one hand lift variation can be concentrated upon certain regions of the blade and on the other the frequency of this variation can be adjusted by selecting a suitable number of obstructions around the disc, and thereby exciting the desired modes of swinging It has been found very difficult to produce a good simulation of flight conditions on the rotor tower A comparison between blade bending in flight and on the rotor tower is shown in Fig 9 and in a film which will be shown later It applies to a single obstruction placed in the outer part of the rotor disc I believe, however, it is generally possible to produce a fair simulation of cumulative fatigue and wear damage A comparison between maximum fluctuating strains in flight and on the tower is given in Fig 8 In the tower the strain is too low in the middle of the blade This can be corrected by the use of more than one obstruction

The foregoing exemples represent, of course, only a very small part of the ground testing necessary to establish airworthiness of a new type of helicopter, which may involve anything up to 600 tests of various kinds It will be appreciated, therefore, that ground testing is an extremely costly business and every endeavour must be made to devise these ground tests in such a way that as many general conclusions as possible can be drawn therefrom for the benefit of later designs There will, however, always remain the need for the basic type testing of helicopters in ground rigs

My acknowledgements are due to the Ministry of Supply and the Bristol Aeroplane Co for making available films and other material for this paper I am indebted to my colleagues, Dr W Strang for reading the draft and Messrs J D Sibley and C Jones for the drawing of the graphs

Rererences

1 H Hirch *The contribution of higher mode resonance to helicopter rotor blade* bending

2 A H Flax and L Goland Dynamic affects in rotor blade bending

3 J Winson The testing of rotors for fatigue life

The Chairman Mr Hafner has given us a very interesting, thorough and instructive discourse on the wider issues involved in this very big problem of fatigue His paper covers the wide aspect and indeed some of the philosophical aspects of fatigue testing, leading up to the stage of describing how specific tests are to be done Mr Brennan's paper has covered the technical aspects of the work which follows and these two papers have between them provided a well balanced evening's programme

Before we begin the discussion I should like to indulge in my prerogative as Chairman and put one question, namely Mr Hafner referred to the concept of " cumulative damage " quite a lot How does he assess " cumulative damage " and in particular does he agree with the common current theory put forward by the C A A in a recent paper by Rosenbaum and subsequently reflected in their legislation ?

To open the discussion I should like to call upon Mr Fisher of the Royal Aircraft Establishment, Farnborough