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HELICOPTER GROUND RESONANCE

EXPERIMENTAL VALIDATION OF THEORETICAL RESULTS

BY THE USE OF A SCALE MODEL

S P KING WESTLAND HELICOPTERS LIMITED, ENGLAND

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OF THEORETICAL RESULTS BY THE USE OF A SCALE MODEL

S P King Westland Helicopters Limited England

ABSTRACT

The validation of theoretical predictions for the onset and degree of instability in ground resonance has been obtained by the use of a scale model of the Lynx rotor system. The theoretical model is described, as is the experimental rig. The effect of some important parameters which can influence ground resonance - lag stiffness, fuselage frequencies and mode shapes, blade incidence and flap stiffness - is assessed. In general good agreement between the theoretical and experimental results is obtained; sufficient to give confidence in the use of the theory as a design tool.

INTRODUCTION

The basic mechanism governing ground resonance is the frequency coalescence of the sub-once per rev. forward whirl of the rotor cg, with a mode of the fuselage involving in-plane motion of the rotor hub. The rotor cg displacement arises from the in-plane motion of the blade in the fundamental lag mode. A good description of the phenomenon has The stiffness term in the fuselage mode been given by Done (1). arises from the relative motion between the fuselage and the ground and is controlled by the undercarriage flexibility, whereas the leadlag stiffness comes from both structural and centrifugal effects. The instability is usually avoided by the addition of lag plane dampers, and sometimes by additional damping in the undercarriage, although it can be prevented by designing the undercarriage to avoid a frequency coalesence within the permissible rotor speed range. Theoretical analysis has shown that the amount of additional damping required depends to a first order upon the frequency of the lag mode; the blade mass; and the fuselage/undercarriage characteristics. Second order effects include the impressed collective pitch, coning angle, pitch-flap-lag coupling and aircraft automatic stabilization systems.

The theory of helicopter ground resonance was originally developed by Coleman and Feingold (2), and although confined to articulated rotors with only the lead-lag degree of freedom and without aerodynamic effects it remains the standard reference on the subject. The advent of the Lynx semi-rigid rotor system necessitated an improved theoretical analysis which included additional degrees of freedom and aerodynamic loads, especially representation of the considerable amount of blade flap damping. This theoretical tool has been under development at Westlands for a number of years and required experimental validation. Furthermore, minimization of rotor system weight will only be achieved if sufficient but not excessive lag damping is supplied, whether the rotor is articulated, semi-rigid or elastomeric. Thus experimental confirmation of the new ground resonance theory was important from both the safety and performance aspects of rotor system design.

Good experimental data are not easily obtained at fully scale due to the difficulties of operating within the unstable region and the problems inherent with tie-down snatch rigs. To avoid these complications a model capable of being operated within the unstable region has been built, and the experimental results compared with theory.

In the remaining sections the mathematical and experimental models are described and a brief discussion of the instrumentation and test technique is given. The measured and predicted stability characteristics for a range of parameters are then presented. All parameters are expressed in model scale terms.

THE MATHEMATICAL MODEL

The basic mathematical model for the study of ground resonance is shown in Fig. 1. The fuselage is modelled as a rigid body with five degrees of freedom; three translations plus pitch and roll rotations. Experience has shown that the yaw degree of freedom plays only a minor role in the ground resonance phenomenon. The fuselage is connected to the ground by a set of linear springs and dampers. The fuselage/ undercarriage system is described mathematically by a mass matrix and a set of five mode shapes, frequencies and dampings; proportional viscous damping is assumed.

Attached to the fuselage is a rotor system consisting of b equally spaced blades rotating at a constant mean angular velocity. Each blade is allowed two degrees of freedom, the fundamental flap and lead-lag modes of the rotor. These mode shapes and frequencies are calculated using a technique developed from Houbolt and Brooks (3) and similar to the Dowell and Hodges (4) analysis. For simplicity in the ground resonance calculations the modes are assumed to be uncoupled, ie. one mode is pure flap and the other pure lag. The nature of the semi-rigid hub on the Lynx is such that this condition is almost The blade modes are calculated at the 'normal operating fulfilled. rotor speed', and for exactness should be re-computed at each rotor speed of interest. This however is impractical due to the excessive computer effort required. To overcome this problem the stability analysis program incorporates a routine to calculate the proportion of stiffness, in both the flap and lag modes, due to structural and centrifugal effects. By assuming the modes shapes do not change as the rotor speed is varied it is simple to calculate the total stiffness at any other rotor speed, from which the frequency may be found. This frequency will not be quite correct due to the change in strain energy distribution resulting from the change in mode shape; it has been found for the model that the error is however very small over a wide range of rotor speeds, less than 2% for speeds between 60 and 100% of normal operating. It is also assumed that the steady coning angle does not vary as the rotor speed is changed. Again this is not precisely true due to the influence of gravity and the built-in precone but the error is slight.

The aerodynamic forcing terms are calculated using quasi-steady theory with reverse flow, compressibility and unsteady effects being ignored. The induced velocity is calculated using momentum theory, and in axial flow is assumed to be uniform over the entire rotor disc. Structural damping may also be included in the rotor modes.

The equations of motion are obtained by the use of Lagrange's equation, and describe small perturbations about an equilibrium position. Since this includes the steady coning angle flap lag coupling due to Corioli forces are included. The resulting set of 5 + 2b linear second order differential equations have periodic coefficients which for a rotor possessing polar symmetry and operating in an axial flow environment may be reduced to constant coefficient form by the application of the Coleman transformation (2) to multi-blade coordinates. When this transformation is carried out it is found that only some of the rotor modes couple with the fuselage motion, reducing the number of simultaneous equations requiring solution. For this symmetric case the stability information is obtained from an eigenvalue analysis of the homogeneous linear equations, the roots being found for a range of rotor speeds.

THE EXPERIMENTAL MODEL

An essential property of the model is that it should re-create the ground resonance characteristics of a full scale helicopter whilst maintaining a degree of flexibility to enable the investigation of a number of parameters. The model is shown in Fig. 2 and is approximately a 1/6th Froude scale model of the Lynx with an overall rotor diameter of 2m.

The model was designed, manufactured and operated at the Experimental and Electronic Laboratories Division of the British Hovercraft Corporation Ltd., Cowes, Isle of Wight. A detailed description of the model, and results, has been given by Higgs (5).

The fuselage is a box structure containing the motor, gearbox and sliprings and behaves as a rigid body over the frequency range of interest. The fuselage is suspended by four adjustable cantilevers, allowing motion in heave, pitch and roll only. By varying the geometry and stiffness of the cantilevers the pitch and roll frequencies and centres of rotation can be independently changed. In particular, it is possible to arrange the suspension such that the model has freedom in roll only; this was frequently done to simplify the interpretation of results. The damping in the fuselage modes can be augmented by fitting an hydraulic damper between the fuselage and ground, and the degree of damping can be adjusted by using fluids of differnt viscosity.

A pneumatically operated locking arrangement consisting of four tapered bolts engaging in conical recesses in the undercarriage support channels is provided, and has the effect of raising the fuselage natural frequencies well clear of the ground resonance frequency.

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This system is engaged whenever the stress levels during an instability approach the limiting values, thereby preventing damage to the model. In fact the model is generally run with the locking mechanism engaged and only released during a test condition.

The rotor is powered by a 'Gast' air motor capable of delivering 3 Hp at 2000 RPM when being driven by a 100 psi air supply. The air supply hose was looped to minimise its stiffness effects.

The rotor system, Fig. 3, consists of a hub with flexible metal flap and lag elements and a mechanical feathering hinge attached to the shaft in the order flap element, feathering hinge, lag element. Since these elements are simply bolted together various combinations of flap and lag stiffness can be investigated. In fact, 3 sets of flap elements and 5 sets of lag elements have been made.

The blades are untwisted, of NACA 0015 section and made from GFRP. The flap, lag and torsional stiffnesses and the mass distribution closely follow the scaled values, although the materials and methods of construction are completely different. Blade pitch can be adjusted by altering the vertical position of the pitch link attachment on the rotor shaft, with fine adjustments/tracking being made by altering the length of the track rods by turnbuckles. These pitch changes can only be made with the rotor stationary.

Flap and lag stresses in the rotor system are monitored by the use of strain-gauges in the flap and lag flexible elements. Fuselage motions in pitch and roll are determined by small strain-gauged cantilevers attached between the model and the ground.

TEST TECHNIQUE

For each test configuration the non-rotating flap and lag frequencies and dampings are obtained by observing the free decay characteristicis to an initial disturbance. Similarly, the fuselage pitch and roll modal properties are measured, with the rotor system removed. After clearance through the rotor speed range with the fuselage locked the speed is stabilised and the model released. During this period the strain gauge signals are recorded on paper trace and the lag bending stress observed on an oscilloscope; experience has shown that this is the stress most likely to approach a damaging level. The action of releasing the model is sufficient to impart a disturbance to the system which in the unstable region will grow. When the lag stress reaches the monitor limit, or a sufficient length of trace is obtained, the fuselage is locked. The procedure is then repeated at the next test point.

The degree of instability is obtained from the rate of growth of the lag signal. A typical trace is shown in Fig. 4, where the growth in lag amplitude when the model is released can be clearly seen, followed by a slow decay when the model is relocked. Also shown in Fig. 4 is the growth of the fuselage roll motion, to a different time base. As would be expected from the theoretical analysis of ground resonance the lag response occurs at the fundamental lag mode frequency (7.5 Hz in this case) whereas the roll motion takes place at the difference between this frequency and once per rev., that is 4 Hz. In conditions more unstable than shown in Fig. 4 only a short length of trace can be obtained, making the estimation of the rate of growth difficult. Consequently the measured peak values of instability may be less well defined than the onset of instability.

In some conditions where the degree of instability is slight and the rotor speed is such that the fundamental lag mode frequency is close to once per rev. a beating may occur between these two responses. An example of this is shown in Fig. 5, the beating effect being most pronounced for blades 2, 3 and 4. The different behaviour of the blades has not been explained, but whenever beating occurs blades 2 and 4 always exhibit the characteristics shown in Fig. 5. That is, one blade increases in amplitude as the other decreases. Determination of the degree of instability from a measurement such as that shown is difficult, but by taking the mean of the estimates for blades 2 and 4 it is hoped that the effect of the beating is minimised. Fortunately the phenomenon does not often occur.

DISCUSSION OF RESULTS

Comparisons between the theory and experiment through the rotor speed range have been made for the following parametric variations:

Lag stiffness Flap stiffness Blade incidence Fuselage roll stiffness Fuselage roll centre position Fuselage roll damping

In each case a single parameter is varied in both the theoretical and experimental models, and the results compared over a range of rotor speeds. A complete description of the results has been given by White (6).

Fig. 6 shows a typical comparison of the predicted and measured stability, obtained in fact from the investigation into roll damping. The scaled value of normal operating rotor speed is 900 RPM, and the degree of instability is expressed in terms of the percentage of negative critical damping, relative to the rotating lag frequency. The results in Fig. 6 show that the peak value of instability is in this case predicted very well but that the onset of instability occurs some 50 RPM later than expected. This error is not considered particularly significant, since it represents only some 5.5% of the normal operating speed.

Results similar to Fig. 6 have been produced for each case, approximately 40 different configurations. To reduce these results to more manageable proportions the results for each parameter variation are expressed in terms of the range of rotor speeds over which the system is unstable, and the value of the peak instability.

Lag Stiffness

Fig. 7 compares the experimental and theoretical results for the effect of lag stiffness, expressed in terms of the lag frequency at normal operating speed, on both the width of the unstable region and the maximum rate of divergence. Both the degree of instability and the width of the unstable region decrease as the lag stiffness is increased. Good agreement is obtained for the region of instability, but less good agreement on the peak value. This is one of the situations when beating occurs, the value of peak instability shown being the average of that measured on blades 2 and 4.

Extrapolation of the results indicates that a lag frequency of 0.75R should be sufficient to completely suppress ground resonance for this particular fuselage configuration. The original intention was to examine lag frequencies up to 0.8R, but this was prevented by the chordwise flexibility of the blade which becomes significant in the overall flexibility as the lag element stiffness is increased. To achieve a frequency of 0.8R would have required a new, and stiffer, blade.

The reduction in the degree of instability as the lag frequency increases is partially due to the way the results are expressed, as a percentage of critical damping relative to the rotating lag frequency. This has the effect, for a fixed rate of growth, of decreasing the apparent damping as the frequency increases. The major effect however is due to the stiffness change.

Flap Stiffness

The increased flap stiffness for semi-rigid rotors increases the coupling between fuselage pitch and roll motion and the blade flapping, thereby introducing additional damping into the fuselage modes due to the high aerodynamic flap damping. This could have some effect on the lag damping requirement. The experimental investigation shows, Fig. 8, that the effect of flap stiffness is not large, although a greater effect is found on the model than is predicted by the theory.

The effect of flap stiffness depends upon the shape of the fuselage modes, since if the centre of rotation is a long way from the rotor hub the amount of aircraft rotation will be small compared to the in-plane displacement at the hub. Consequently the flap motion will be weakly coupled to the fuselage and the effect on the overall fuselage damping will be small. In addition it will be shown below that fuselage damping does not have a large effect on ground resonance. Thus semi-rigid rotors will in general require additional lag-plane damping, unless the undercarriage design is compromised to avoid the frequency coalesence.

Blade Incidence

Theoretical calculations show that blade incidence can influence ground resonance stability directly, in addition to any effects the rotor thrust may have on the undercarriage stiffness and damping. In Fig. 9 the results of the investigation into incidence are presented, where it is shown that the effect on the lower bound of the unstable region is small, and that the agreement between test and calculation is good. The predicted value of peak instability is much lower than the test results, although the trends are similar, and show a significant sensitivity to blade incidence.

Detailed theoretical analysis shows that increasing the blade pitch has two effects. The first is a consequence of the increase in aerodynamic loads which increases the blade lagwise damping. The second effect is the increase in coning angle which increases the Corioli coupling between flap and lag motion and is strongly destabilizing. A one degree change in coning angle can produce a change of one percent of critical in the damping requirement. Thus, the effect of increasing the blade pitch is a trade-off between these two effects, with the coning angle being the more powerful.

The sensitivity to blade pitch shown in Fig. 9 may explain some of the discrepancies between measured and computed results since the coning angle is not directly measured. Thus the computed coning angle may be in error.

Undercarriage Effects

With the model set up with only the roll degree of freedom the effects of roll mode stiffness, damping and roll centre position were investigated. The results and comparisons are shown in Figs. 10 to 12. In the case of roll stiffness Fig. 10 shows that good agreement is obtained for both the degree and range of instability. As expected both quantities increase as the stiffness increases. This result shows that the worst frequency for a fuselage mode is that which produces a coalescence with the lag mode frequency at the maximum ground running speed.

Varying the roll centre position, Fig. 11, also has a significant effect, but in this case principally on the peak value of instability. Poor agreement is obtained for the peak instability, but good agreement for the range. With the roll centre 6 inches above the cg no instability could be found.

A simple measure of the effect of roll centre position is given by the effective mass at the main rotor hub of the fuselage mode. This is given by

$$\frac{1 + ml^2}{(1 + h)^2}$$

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- I = fuselage roll inertia about the cg
 - m = fuselage mass
 - h = distance from the cg to the hub
 - 1 = distance from roll centre to cg, +ve when cg above roll centre

Simple analysis shows that the degree of instability is inversely proportional to the square root of this quantity, and this is also shown, arbitrarily scaled, in Fig. 11. Neither the experimental nor theoretical results follow this simple variation precisely, but the trends are similar. The discrepancy may be due to the varying effect of the flap damping as the roll centre is moved.

Finally, increasing the amount of undercarriage damping, Fig. 12, reduces the degree of instability, but has little effect on the rotor speed at which the system becomes unstable. Again, the experimental model is more sensitive than the theoretical, but in either case it shows that a large change in undercarriage damping is required to have any significant effect upon the overall stability.

GENERAL DISCUSSION

The work described shows that the experimental investigation of ground resonance is possible by the use of small, easily controlled, and above all safe, scale models. In assessing the differences between the experiments and the predictions it is worth remembering that the degree of instability is very low, and that the maximum discrepancy between the measured and predicted peak values of instability is only 1.1% of critical. Similarly, the error in the prediction of the onset of instability never exceeded 12% N_R . Viewed in this light the results are of excellent quality.

The errors that have been found could be due to a number of factors. The importance of the thrust and coning angle was not appreciated before the tests commenced and a direct measurement of these quantities may afford some insight. Structural lead-lag damping was only measured with the rotor stationary and could easily vary by 0.5% of critical when the centrifugal force is present, due to the change in the lag mode shape. The change in mode shape means that different parts of the rotor contribute different proportions to the overall curvature, thereby producing a redistribution in the internal loads, and as a consequence, the rate of energy dissipation. Also, repeat measurements of the non-rotating lag-plane damping on separate occasions have produced results varying from 0.4% to 0.9% of critical.

The measurement of the rate of growth in itself must be subject to some error, although repeat experiments have generally produced very consistent results.

Numerous omissions in the theoretical program could be mentioned. For example, structural coupling between flap and lag motion; the effects of higher order blade modes; limitations in the aerodynamic representation, and a legion of non-linear effects. An important aspect could be the coning angle, which depends upon a number of parameters - rotor speed, aerodynamic section performance, built-in coning angle and gravity. Since the coning angle is derived within the stability program, there could well be errors in the computed values, and it has been shown that coning is important.

CONCLUSIONS

The ability to investigate ground resonance at model scale has been established and the theoretical analysis comprehensively validated. The effect of a number of parameters effecting ground resonance has been investigated, and the need for lag-plane dampers on the Lynx confirmed.

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FIGURE 1 DEGREES OF FREEDOM IN MATHEMATICAL MODEL



FIGURE 2 THE EXPERIMENTAL RIG















FIGURE 8 EFFECT OF FLAP STIFFNESS ON STABILITY





FIGURE 12 EFFECT OF ROLL DAMPING ON STABILITY