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GROUND RESONANCE CLEARANCE OF WESTLAND/AGUSTA EH101 HELICOPTER

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EH101 GROUND RESONANCE CLEARANCE

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ABSTRACT

Ground resonance clearance for the EH101 Helicopter has been achieved in three stages. Stage one was the theoretical analysis of both the rotor and fuselage. Stage two was an impedance test of the airframe, on its undercarriage, to check the predictions of undercarriage stiffness and damping. Stage three was the actual clearance of the aircraft.

This third stage was achieved by a careful and progressive exploration of rotor speed, rotor thrust and fuselage all-up-weight ranges. The blade and fuselage motions were continuously monitored, and the degree of stability assessed by using the moving block technique. No fuselage snatch rig was used. This is the first time Westland have cleared a completely new aircraft for ground resonance without using a snatch rig.

The paper describes all three stages, with special emphasis on the third stage.

1. INTRODUCTION

The demonstration of ground resonance stability of the EH101 has been achieved by theoretical analysis, impedance testing, and finally, ground resonance testing.

Ground resonance testing was completed without the conventional Westland 'snatch rig'. Instead, reliance was placed on theoretical predictions and on signal analysis of responses obtained during ground resonance testing.

The aircraft was successfully cleared for all operational thrusts, weights and rotor speeds in a safe manner.

This paper presents a review of the procedure adopted by Westland for ground resonance clearance of the first prototype EH101 helicopter. After a brief description of the aircraft, the steps in the clearance procedure are outlined. The theoretical stability analysis is reviewed, as is the rotor/fuselage impedance matching procedure. The impedance test method, together with typical results, are presented. Finally, the procedure for ground resonance testing and the methods of excitation, monitoring and data analysis are discussed.

2. THE EH101

The EH101 is a joint Westland/Agusta design, with operational weights between 19800-31250 lb. The aircraft has a main undercarriage with one offset wheel per side. The nose undercarriage has twin wheels (Figure 1). Both main and nose oleos have 3-stage damping, and non-linear load/deflection characteristics.

The main rotor has 5 carbon/glass fibre composite blades, fully articulated on a combined flap, lag and pitch elastomeric bearing. Each blade weighs approximately 480 lb, including root fittings. Lag damping is supplied by a conventional hydraulic damper.

A view of the rotor head is seen in Figure 2.

The aircraft is now in early stages of development testing.

Figure 1 The EH101

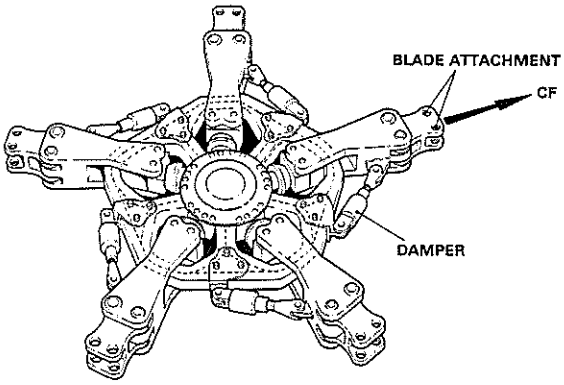

Figure 2 Main Rotor Head

3. GROUND RESONANCE CLEARANCE PROCEDURE OUTLINED

The aircraft was to be tested without the security of a "snatch-rig". Consequently the emphasis lay in (a) the accuracy of ground resonance stability calculations based on impedance test results and (b) the identification and analysis of critical blade and fuselage responses, during ground resonance testing.

Ground resonance stability calculations were made using a previously proved WHL program (Reference 1). Initial calculations were based on design oleo and tyre stiffness and damping, and blade lag damping. The analysis was updated after fuselage impedance testing. The analysis predicted stability margins for a wide range of cases and was used to define the order of configurations for ground resonance testing.

The fuselage head impedance test provided impedance data as a function of frequency for several head amplitudes and a wide range of aircraft configurations and weights. The measured modes, frequencies and dampings were used in the rotor/fuselage stability analysis calculations. In addition, the measured impedance data was used directly in a rotor/fuselage impedance matching procedure to obtain an independent assessment of stability.

The ground resonance test was monitored by telemetry. Fuselage and blade responses were analysed during the test in real time. Moving Block Analysis was used to estimate aircraft modal damping at each rotor speed. The aircraft was tested over a wide range of thrust, rotor speed and weights, for brakes on and released, covering all likely operational configurations. The steps in the clearance procedure are discussed in detail below.

4. THEORETICAL ANALYSIS

Stability analysis was performed on the coupled rotor/fuselage system. Five fuselage freedoms and individual blade flap and lag freedoms were considered. Blade aerodynamics and effects of pitch/lag and pitch/flap couplings are included. Predicted and measured fuselage mode shapes, frequencies and dampings are used in the analysis, together with predicted blade lag and flap mode shapes. Stability predictions were obtained for a range of lag mode damping.

Lag mode damping is defined in percentage of critical damping, based on the lag mode frequency at 100% NR, where critical damping D_{CRIT} is:

$$D_{CRIT} = 2 I_{\xi} \omega_L$$

D_{CRIT} □ CRITICAL DAMPING lb/ft/s

I_{ξ} □ BLADE LAG INERTIA IN SLUG FT^2

ω_L = LAG MODE FREQUENCY AT 100% NR (RAD/S)

The equations of motion are solved in terms of Coleman variables, and system frequencies and dampings are obtained in a fixed reference frame.

The analysis had previously been used and proven on bearingless and semirigid rotor ground and air resonance stability calculations, (Reference 1), where good correlation between theoretical and experimental results was obtained.

Figures 3A, and 3B show the stability solution for a typical configuration. Measured fuselage dampings, and a low value of blade lag mode damping has damping has been used in the calculation. Note that because the lag mode is critically damped, the progressing $(\Omega + \omega_L)$ and regressing $(\Omega - \omega_L)$ modes lie almost along the Ω line. Above 100% NR, the blade damping becomes subcritical, blade lag motion is oscillatory, and progressing and regressing rotor lag modes are evident.

The critical coupling for all configurations considered involved the lightly damped lateral mode as shown.

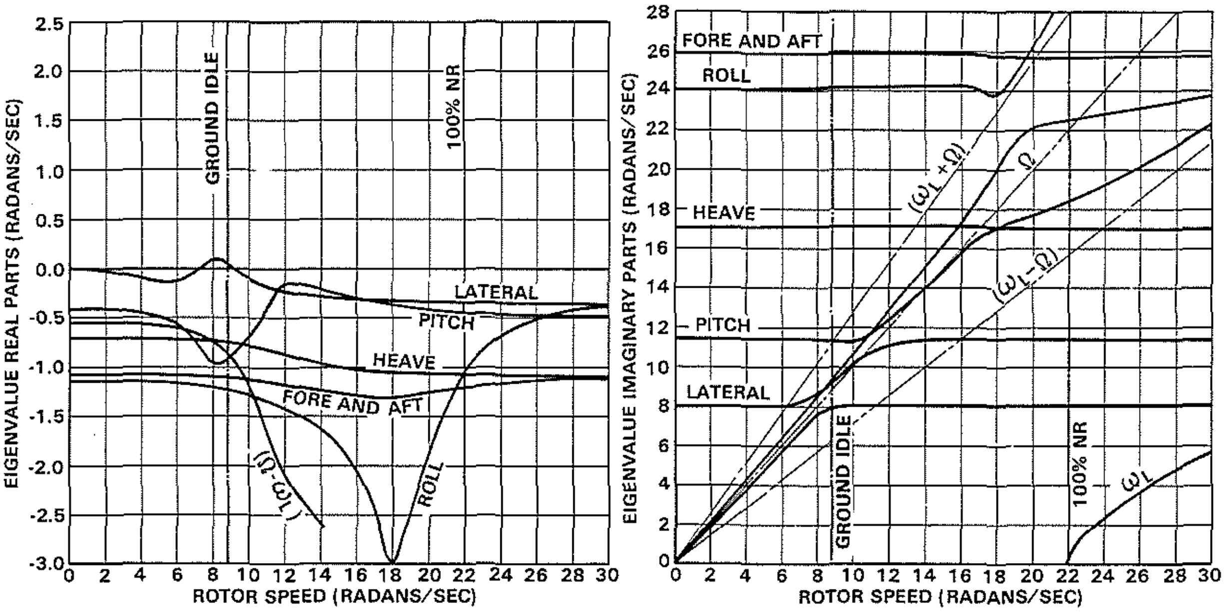

Figure 3A Real Parts

Figure 3B Imaginary Parts

Ground Resonance Stability Calculation for Heavyweight Aircraft.
Nominal 100% Lag Damping, 4% Fuselage Mode Damping

The characteristics of the blade lag damper are shown in Figure 4. This is approximated by an equivalent linear damping coefficient, which varies with frequency and amplitude. These curves are shown in Figure 5. These curves show, for a particular lag mode frequency, the range of blade swing over which a certain damping value is exceeded. For instance, at 36% NR, where the peak of the instability in Figure 3A is predicted, the lag mode frequency is .36 Hz. Figure 5 indicates that the nominal 100% lag damping in the stability analysis is exceeded for oscillatory blade lag amplitudes between approximately 0.3 and 3.2°. Blade lag damping may infact reach 300% at certain lag angles.

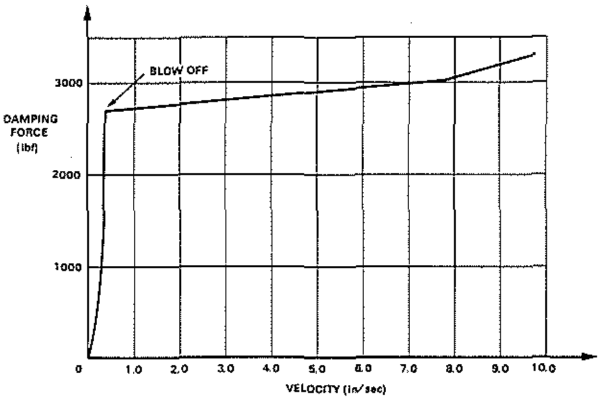

Figure 4
Main Rotor Blade Lag
Damper Characteristics

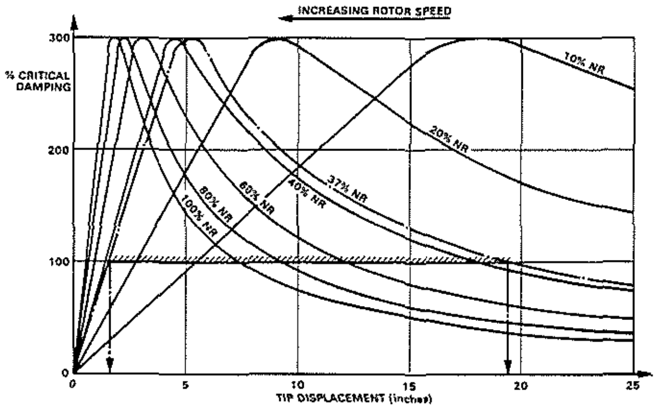

Figure 5
Variation of Effective Linear
Damping in Fundamental Lag Mode,
As Function of Rotor Speed

A response analysis of an uncoupled rotor, free to move in only one inplane direction provided rotor impedance for a range of rotor speeds and lag dampings. These rotor impedance lines were used with measured fuselage head impedance in an impedance matching method which predicted rotor speeds for neutral stability of the coupled system.
The theoretical analysis was used to define the degree of stability of each configuration tested, and defined the order of test, from least critical to most critical. As shown below the theoretical predictions agreed well with test data.

5. IMPEDANCE TESTING

Fuselage inplane head impedance in lateral and fore and aft directions was measured over a wide range of head amplitudes and frequencies. A stiff rig was specially designed to react input loads. Tests were performed at constant head amplitude, controlled by a displacement feedback system. The aircraft in the test rig is shown in Figure 6.

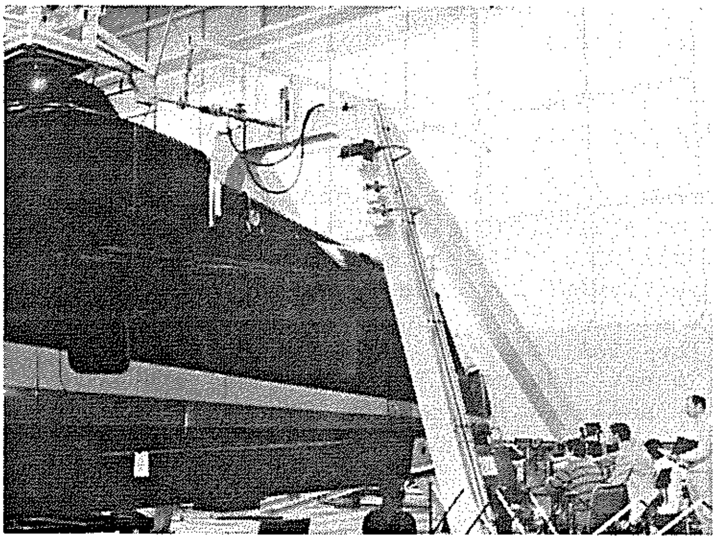

Figure 6 EH101 Impedance Test Rig

Schematics of the test equipment, showing force control and data analysis systems, are shown in Figures 7A and 7B. Head response to forcing was processed using a Solatron Transfer Function Analyser. Circle plots were used to define Modal frequencies. A simple program was written to provide impedance data.

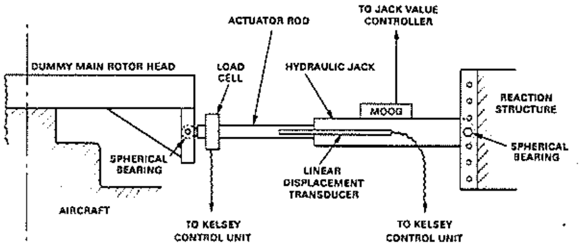

Figure 7A
Schematic of Force Input and
Displacement Measurement
Systems used in Impedance Test

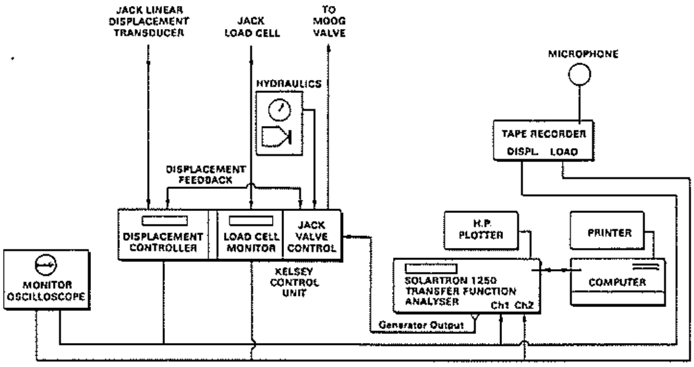

Figure 7B
Schematic of Force Control and
Data Reduction used in Impedance
Test

The aircraft was tested at minimum and maximum weight in the following configuration:

i) Brakes on.

ii) Brakes off.

iii) Brakes off, nosewheel turned through 90°

iv) With simulated 12000 lb lift.

v) Tyres deflated.

Figure 8 shows a plot of typical lateral head impedance over the frequency range .5 - 5.0 Hz at a head amplitude of 0.040 inches for a heavy weight configuration. Modal resonances at local minima of the impedance magnitude are indicated. This data was used directly in the rotor/fuselage impedance matching.

The maximum head amplitude input during testing was ±1.2 inches at resonance.

Figure 9 shows the effect of head amplitude on pitch mode frequency for a lightweight aircraft. As head amplitude increases the nose oleo breaks out of internal friction, reducing modal frequency and increasing damping.

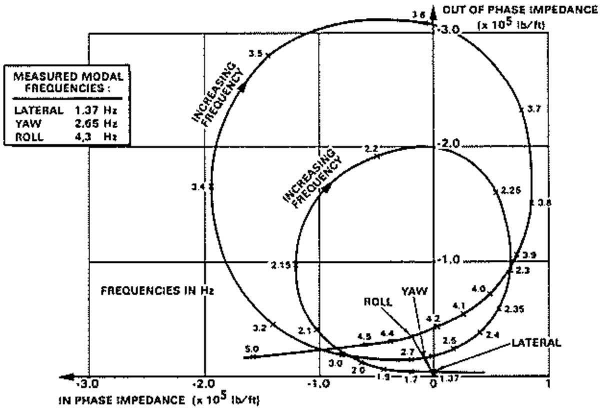

Figure 8
Measured Fuselage Lateral Head
Impedance, Heavyweight Aircraft
+.040" Head Amplitude

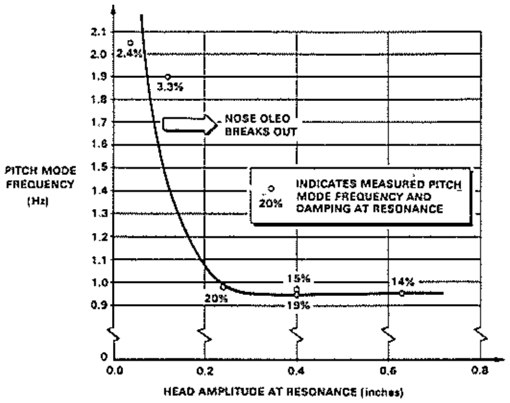

Figure 9
Variation of Pitch Mode Frequency
with Head Amplitude for Lightweight
Aircraft

The significant feature to emerge from the impedance test was the lack of main oleo movement due to high internal friction forces caused by the offset wheel. Maximum lateral mode damping was 4% critical, coming from the tyres only.

Load/deflection characteristics of the oleos and tyres were obtained by hoisting the aircraft up and measuring loads and deflections. Loads in excess of 2,500 lb per leg were required to break the main oleo legs out of friction. As a result of this the oleos would only operate at high lift conditions where undercarriage reactions, and internal friction, are reduced.

Mode shapes, frequencies and dampings were measured in all configurations for a range of head amplitudes. This data was used to update the rotor/fuselage stability analysis to give the final ground resonance stability predictions.

The impedance test is considered an essential part of the ground resonance clearance. In addition to the theoretical correlation, the modal responses during ground resonance testing were easily identified. Furthermore, the direct use of measured impedance data in rotor/fuselage impedance matching gave an additional, confirmatory, assessment of stability.

6. IMPEDANCE MATCHING

Rotor/fuselage impedance matching was performed for most configurations, mainly to verify the ground resonance stability predictions. The proceedure used is outlined below, and a particular impedance match is shown.

Neutral stability of the coupled rotor/fuselage system occurs when the inplane impedance of the rotor is equal, but of opposite sign, to the head impedance of the fuselage, at the same frequency.

Figure 10 shows the principle of impedance matching. Rotor inplane impedances, with 100% critical lag damping, are shown for rotor speeds of 10, 16 and 22 Radians/sec., where 22 Rad/Sec corresponds to 100% NR. The measured lateral head impedance of the heavyweight configuration, Figure 8, is plotted negative on the rotor impedance. It is apparent from Figure 10 that:

(a) Only the lower impedance fuselage lateral mode can match rotor impedance. The yaw and roll modes have high effective mass at the head which will stabilise any coupling.

(b) Only the measured fuselage impedances in the right hand quadrant of Figure 8, before modal resonances, are likely to couple with the rotor.

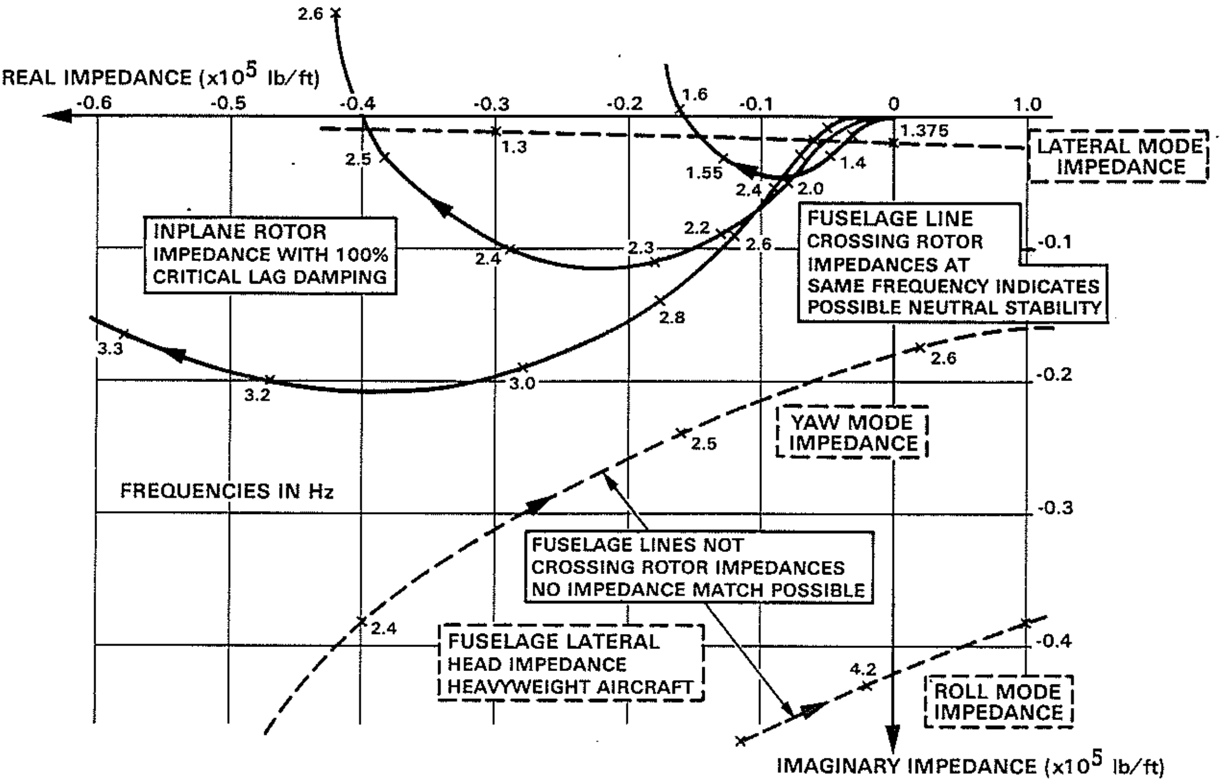

Figure 10 Principle of Rotor/Fuselage Impedance Matching

Figure 11 shows in detail the rotor impedances over the speed range where there is a possible fuselage lateral mode match. The figure shows rotor impedances for rotor speeds of 7 - 10 Rads/sec. A selection of constant frequency lines are drawn across the rotor impedance lines. An impedance match occurs where the frequencies on the fuselage impedance line are coincident with the rotor frequencies. The rotor speed at which these matches occur are interpolated from the rotor speed lines.

Figure 11 indicates that there are frequency matches at 1.15 Hz and 1.3 Hz, corresponding to rotor speeds of 7.5 and 9 Rads/sec respectively. These are rotor speeds at which there is neutral stability, zero damping, in the coupled rotor/fuselage system.

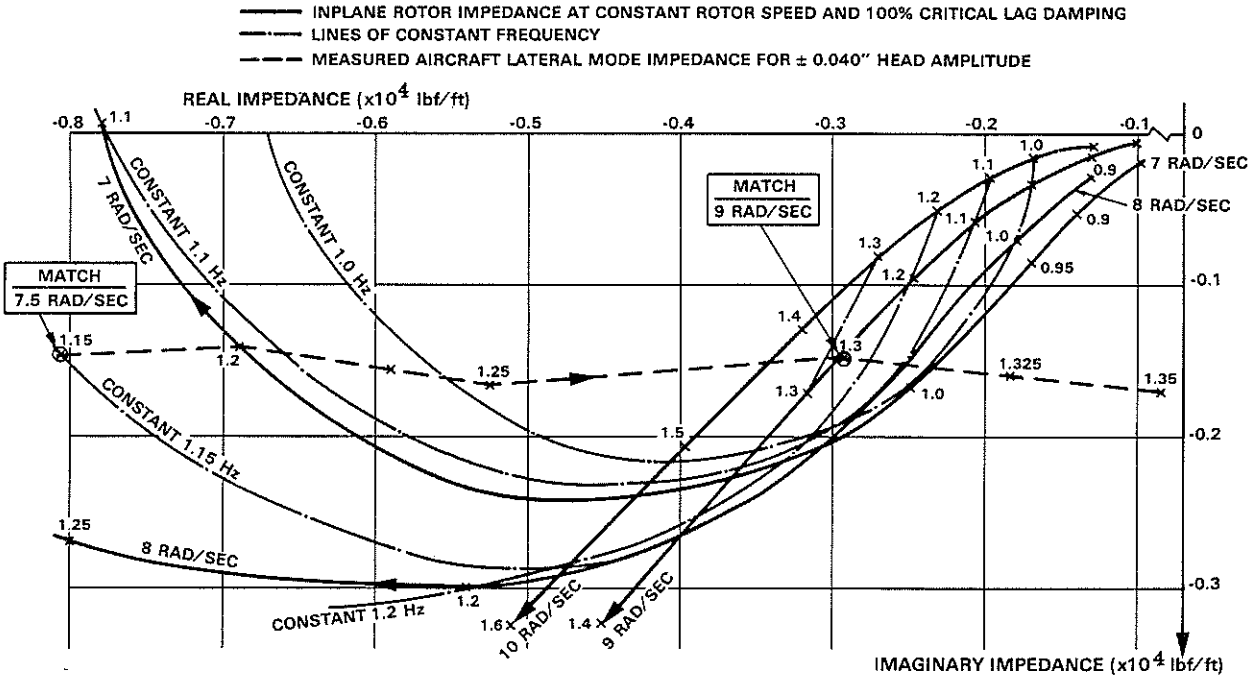

Figure 11 Heavyweight Aircraft - Lateral Mode Impedance Match

The theoretical stability analysis of this configuration, Figures 3A, B, using measured modes shapes and damping predicts 7 and 9 Rads/sec. Consequently both methods indicate a potential instability around ground idle speed, 8.8 Rads/sec, 40% NR. Note that this potential instability is predicted for the nominal 100% critical lag damping.

The impedance matching proceedure can also accommodate the undercarriage non-linearities in Figure 9. By plotting the pitch mode impedances at different head amplitudes, stability can be assessed. As the nose oleos break out, damping increases and pitch mode frequency decreases. The effect is to move the fuselage impedance down the plot, away from an impedance match. The pitch mode was found to be stabilised for head motions in excess of +.12 inches. This is a mild instability, adequately stabilised by nose oleo damping.

The effect of increasing rotor lag damping is, not surprisingly, to move the rotor impedance lines to the left and up, away from fuselage impedance.

In conclusion, the impedance matching generally confirmed the ground resonance stability calculations. The proceedure also gave an indication of likely fuselage motion to stabilise any ground resonance mode.

7. GROUND RESONANCE TESTING

The ground resonance test was entered with the knowledge that:

(a) The aircraft was predicted to be stable at all rotor speeds above 45% NR.

(b) A region of marginal stability occurred around 40% NR, ground idle.

(c) The region of marginal stability occurred at a higher rotor speed as aircraft weight reduced.

(d) This marginal stability was as a result of the lack of main oleo movement, due to internal friction and would not improve as amplitudes increased.

EH101 was ground resonance tested without a snatch rig. Consequently it was essential that critical blade and fuselage parameters were monitored. Additionally, aircraft modal frequency and damping had to be assessed at each rotor speed and lift condition in order to monitor damping trends.

The following parameters were monitored via telemetry:

Blade lag bending, outboard of damper.
Blade flap bending, outboard of damper.
Blade lag damper stroke.
Fuselage lateral acceleration - on Main Gearbox.
Fuselage fore and aft acceleration - on Main Gearbox.
Lateral cyclic stick position.
Longitudinal cyclic stick position.

The parameters were displayed on screens in real time, and played out on strip charts as required. Selected data channels were input to the GenRad computer for Moving Block Analysis. All data was stored on tape for future analysis.

The aircraft was monitored visually by video monitors, which provided an aft view and side view of the aircraft.

Additional critical stress channels were monitored separately by a stress engineer who had direct contact with the ground resonance test controller. A view of the Telemetry Room is shown in Figure 12.

Figure 12 Telemetry Room - EH101 Ground Resonance Test

The test procedure in general was to stabilise at a particular rotor speed, apply a stick stir and monitor fuselage and blade response. The moving block analysis was used to establish frequency content of the decay, and an estimate of damping in each modal decay. Generally two stick stirs at each condition were performed. Modes were identified mainly by frequency. For large fuselage responses, however, modal responses were also seen on the video monitor.

During the initial rotor run-ups with a new configuration the predicted marginally stable region below ground idle was approached with caution. The rotor was first run up to 30% NR, engine shut down, and a stick stir input. The rotor was at the speed long enough to obtain a decay. This was repeated at 35 and 40% NR. Large amplitude fuselage rocking was evident as the rotor ran up through 30-35% NR, which was later found to be due mainly to rotor out of balance caused by initially unequal blade lag angles exciting the low damped lateral mode. After confidence was gained the rotor was stabilised on ground idle. Testing then followed the previously described procedure.

The aircraft was tested at heavy, intermediate and lightweight, brakes on and off, over the lift and rotor speed ranges defined in the table below:

Brakes	Lift % Aircraft Weight	Rotor Speed % NR
OFF	ZERO	0 - 100%
	50%	50 - 80%
	75%	50 - 80%
ON	ZERO	0 - 100%
	50%	50 - 100%
	75%	50 - 100%
	75 - 95%	100%

Note that 50% lift means that the test was carried out with main rotor collective constant at the value which would give 50% lift at 100% NR.

The lift conditions were covered in some detail as the non-linear oleo characteristics are a function of oleo load, and alter the fuselage modal frequencies.

Figure 13 shows the fuselage response to stick stirs over the rotor speed range, clearly showing fuselage mode decays.

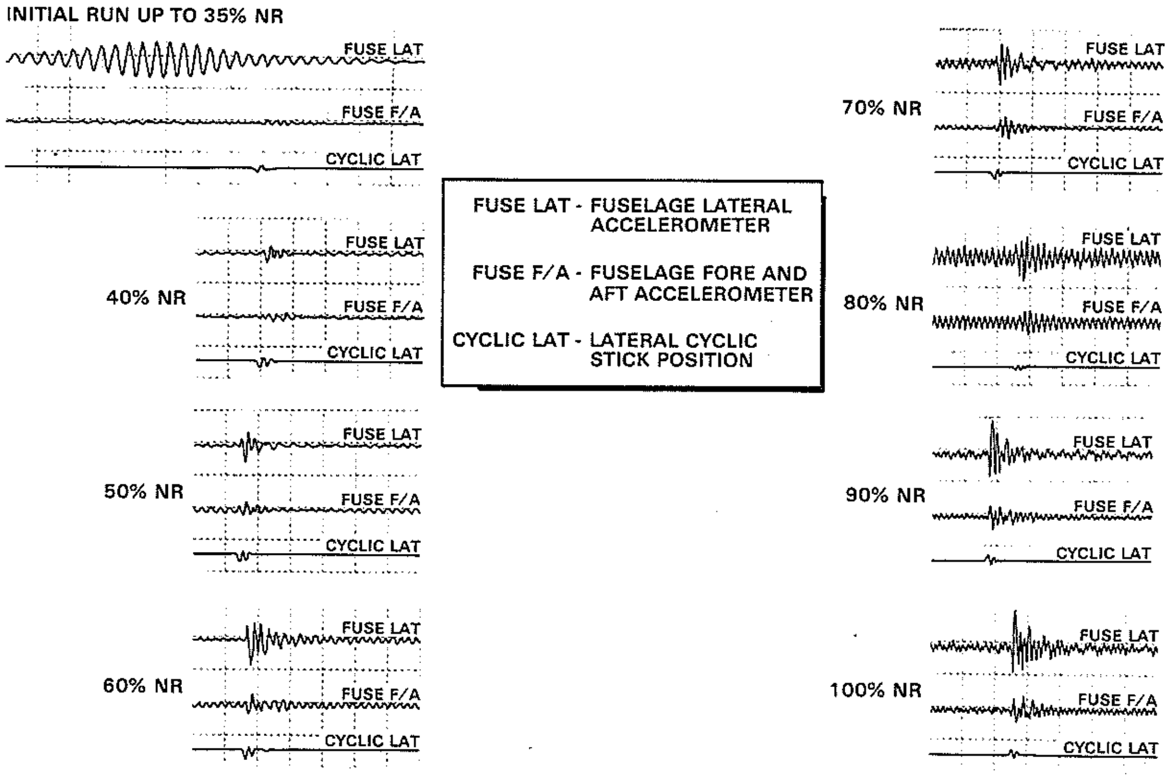

Figure 13

EH101 Ground Resonance Test - Fuselage Response to Cyclic Stick Stirs Over the Rotor Speed Range

A schematic of the moving block data analysis procedure is shown in Figure 14. The program was written in WHL for use on the GenRad computer. A spectrum of the complete data block containing the decay is first produced. Frequencies in the response are then selected for moving block analysis, which estimates damping from the decay at that frequency.

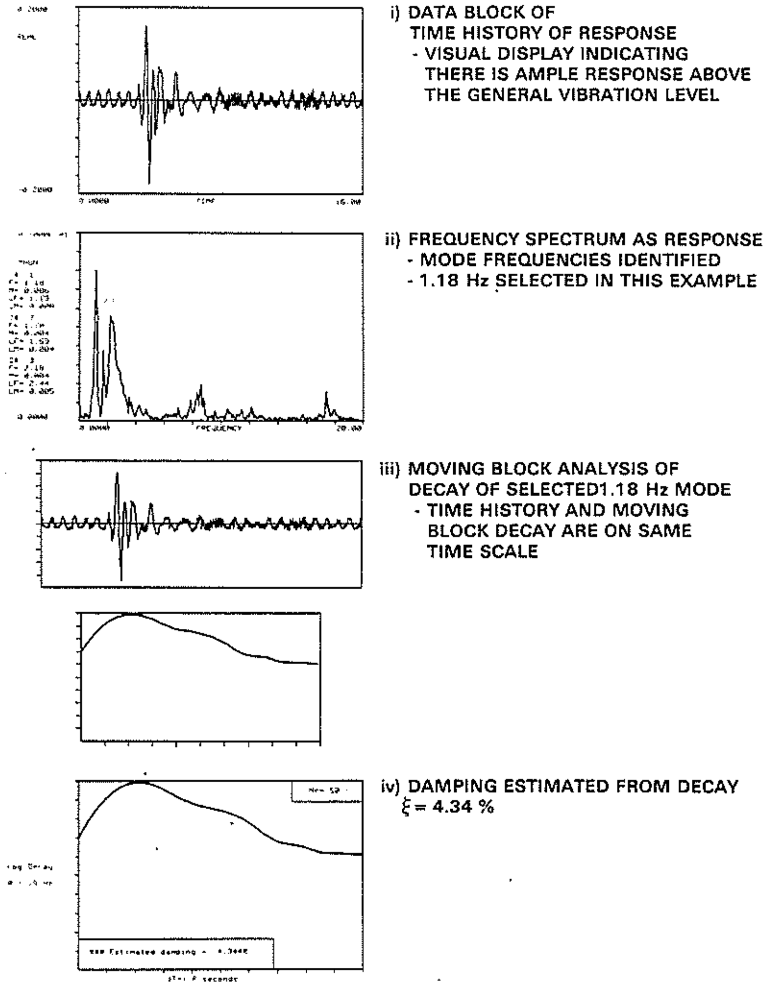

Figure 14

Steps in Moving Block Analysis of Fuselage Lateral Response at 50% NR

This was completed within 1 minute of acquiring data. One particular parameter was input to the GenRad and could be analysed on line. If analysis of a further parameter was required, the data tape in the telemetry room was rerun.

The analysis requires an adequate response above the steady levels of vibration. Main Rotor 1R levels were reduced by tracking, balancing and applying steady cyclic. All responses on the fuselage were considered adequate to obtain good decay data.

A comparison between measured and predicted fuselage damping throughout the rotor speed range is shown in Figure 15 for the heavy weight configuration. The comparison is generally good.

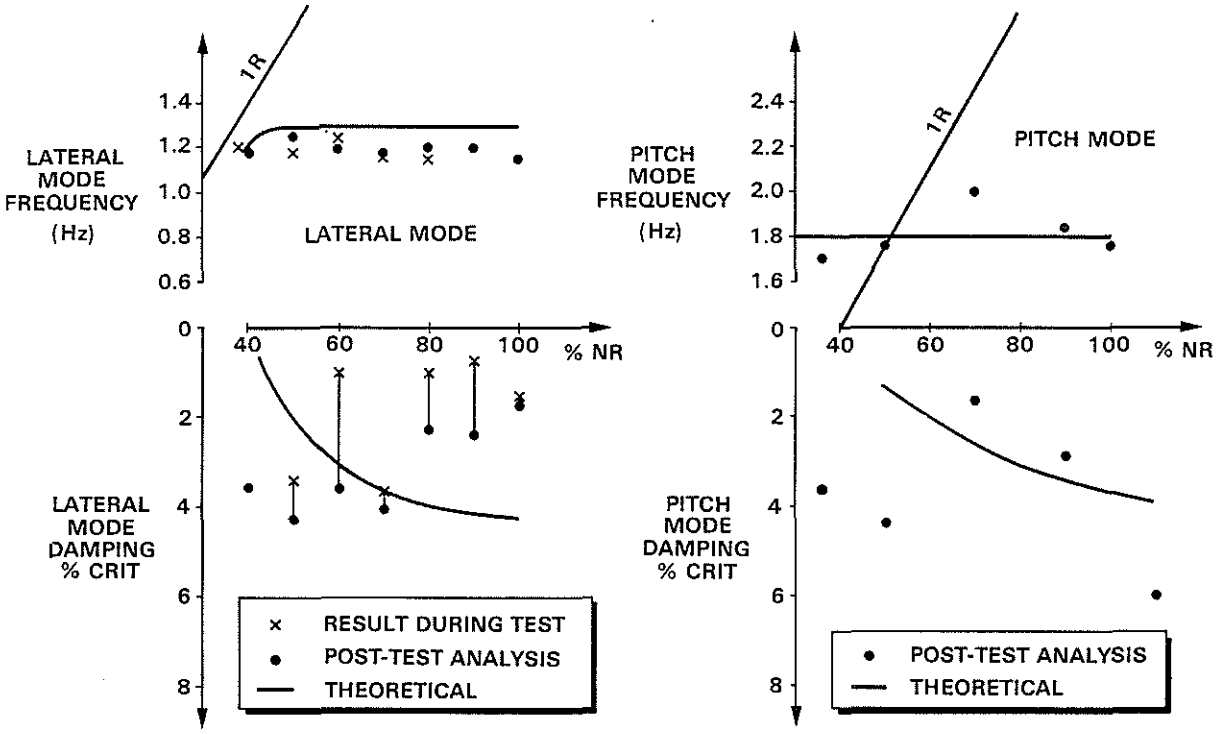

Figure 15

Predicted and Measured Modal Frequencies and Dampings for Heavyweight Aircraft

8. GROUND RESONANCE TEST REVIEW

The test was completed successfully and safely.

Fuselage damping measurements compared well with predictions.

Blade oscillatory fundamental lag motion was minimal throughout the test. The large amount of blade lag damping prevented lag motion, and effectively compensated for the lack of fuselage damping. As a result of this, the response on the blade was composed of 1R, higher blade mode response, and fuselage response in the rotating system.

The character of blade response to stick stirs was in sharp contrast with a similar test on a W30-300, where blade lag motion dominated blade response. The W30-300 has a semi-rigid hub and only 6% critical lag mode damping.

The telemetry and on-line moving block analysis gave engineers and flight crew a high degree of confidence in monitoring the test.

The data obtained was adequate evidence for certification compliance.

The procedure will be used in future ground resonance clearance at Westland.

9. FURTHER TESTING

At the time of writing, the ground resonance clearance of EH101 in basic, fully operative configurations has been completed. The following modes of operation, and failure cases have still to be addressed.

9.1 AFCS/ASE Operation

Analysis has indicated only marginal changes in stability. The most critical configuration will be tested.

9.2 Taxi and Various Surfaces

Tests will be completed at a range of taxi speeds and thrusts to assess stability. Further stability assessments will be made on grass and inclined surfaces.

9.3 Failures

9.3.1 Lag Damper Failure - Calculations are to be completed for this case. Testing will involve a gradual reduction in damper performance before complete elimination of lag damping is considered. Motions of the undamped blade and a normally damped blade will be monitored, in addition to fuselage motion.

9.3.2 Collapsed Oleo - Calculations indicate that the pitch mode is marginally stable with nose oleo locked. The lateral mode stability remains unchanged as the main oleos generally behave as if locked. A test of the most critical configuration will be completed.

9.3.3 Deflated Tyre - Calculations show adequate stability - impedance test results are also available. A test again will demonstrate stability.

10. CONCLUSIONS

The EH101 Ground Resonance clearance was successfully and safely completed for a range of aircraft configurations. The procedure outlined is comprehensive, and considered adequate for certification of the aircraft.

The aircraft was demonstrated to be stable in all configurations tested over the complete range of operational rotor speeds. The aircraft is presently operating without restriction.

11. REFERENCE

1. P T W Juggins "Substantiation of the Analytical Prediction of Ground and Air Resonance Stability of a Bearingless Rotor, using Model Scale Tests." Twelfth European Rotorcraft Forum, Paper 83, 1986.