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**EH101 FUSELAGE MODAL IDENTIFICATION BY INFLIGHT EXCITATION**

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# EH101 FUSELAGE MODAL IDENTIFICATION BY INFLIGHT EXCITATION

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## Abstract

*This Paper presents the techniques developed at Westland Helicopters for measuring modal properties of a helicopter in flight.*

*Inflight excitation has an advantage over an on-ground shake in that the aircraft dynamic properties are measured on a helicopter with flight torque and lift loading and with the correct rotor impedance.*

*The EH101 has an active vibration control system, ACSR, which uses high frequency response hydraulic actuators to minimise vibration. These actuators were used to excite the helicopter to identify modal frequencies and response shapes in the range 10 - 30 Hz.*

*An extensive ground test on a fuselage has been used to verify the procedure, comparing modes obtained from internal ACSR excitation with those from a normal external multi-shaker test.*

*Inflight excitation has been performed on two aircraft at medium and heavy weight using different excitation techniques. The mode shapes and frequencies were compared with previously measured on ground shake test data. The dynamic effects of the installation of a structural bulkhead have also been measured.*

## 1) Introduction

This Paper presents the techniques of fuselage modal identification by inflight excitation developed at Westland Helicopters.

The modal properties of the EH101 at 10000 kg and 13000 kg have been measured during extensive on-ground shake testing. Since then, additional roles have been defined for the helicopter and the weight has increased to 14600 kg. An inflight shake test was proposed to evaluate the modes and frequencies of the basic airframe at the high weight. This test would be quicker than a conventional shake test and would allow the evaluation of the dynamic properties of an airframe with inflight loading and a true rotor representation.

The EH101 is fitted with an active vibration control system, ACSR (Active Control of Structural Response), which uses 4 high performance hydraulic actuators to input forces at the rotor forcing frequency to cancel rotor induced vibration. These actuators can be driven open loop to input vibratory forces over a range of frequencies and provide a built-in excitation system.

An inflight shake test using a single ACSR actuator had been previously performed on EH101

aircraft PP3 at a weight of 13000 kg. This test used a frequency sweep of over 2 minutes and provided useful data. Problems associated with extraction of sweep data from a signal dominated by the rotor forcing frequency were addressed. There was, however, some concern that not all the aircraft modes were excited by this single actuator.

To gain confidence in the procedure before further inflight testing was done, a ground test was performed on the Westland W30 ACSR test rig using, in turn, external shakers and internal ACSR actuators to excite the airframe. Modes and frequencies obtained from the different methods of excitation were compared and improved procedures for inflight shaking and data reduction were defined.

In September 1994 an inflight shake on EH101 aircraft PP1 at 14440 kg was completed. The airframe was excited by a series of 2 second dwells from each of the 4 actuators in turn. This required a method of data reduction to be developed. Several data reduction techniques were used to obtain transfer functions and modal properties. In particular, transfer functions due to individual actuator forcing were added to simulate pitch, roll and vertical forcing of the main gearbox.

During the test the effects of fitting a structural bulkhead were investigated and the resulting changes in structural dynamics were identified in the transfer functions.

The inflight shake test performed was notable for the speed at which data was gathered and for the insight into airframe dynamics obtained. A single flight was required to obtain baseline airframe dynamics and a further one to assess the bulkhead.

This work has demonstrated that inflight excitation to obtain modal properties is feasible. There are limitations, although these are greatly outweighed by the speed at which this testing can be done and the more realistic configuration of the aircraft compared to what can be achieved in a ground shake test.

## 2) The Active Vibration Control System On The EH101

Active Control of Structural Response (ACSR) on the EH101 reduces airframe vibration at the blade passing frequency (5R) of 17.5 Hz. The vibration transmission from the main gearbox to the airframe is changed by 4 active upper gearbox struts. Figure 1 shows the location of the active struts.

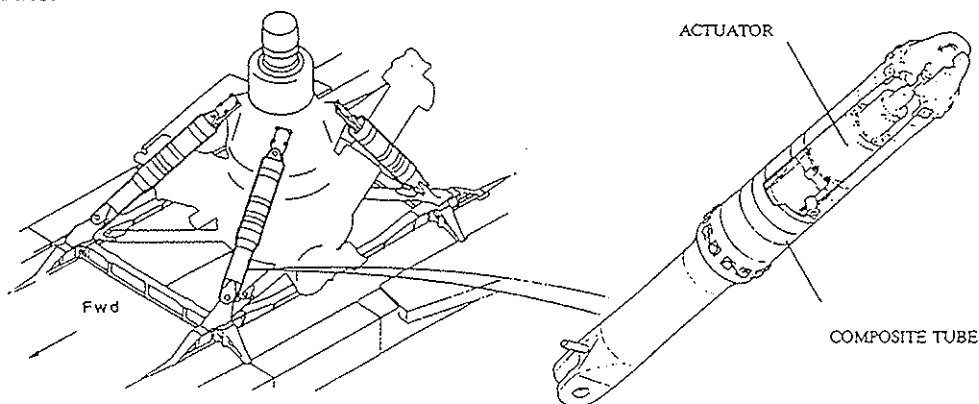


Figure 1 ACSR Struts On The EH101

Each active strut has an electro-hydraulic actuator which inputs vibratory forces whilst the weight of the aircraft is taken by a composite tube acting in parallel. There is a force feedback loop to ensure that no steady load is carried by the actuators.

A computer monitors 10 accelerometers located throughout the airframe. The computer then minimises vibration by demanding actuator forces which work to extend and compress the struts and apply forces to both the gearbox and the fuselage. This procedure is based on the 5R transfer functions between each actuator force demand signal and the response at the 10 accelerometers, known as T-matrices. The system is shown schematically in Figure 2.

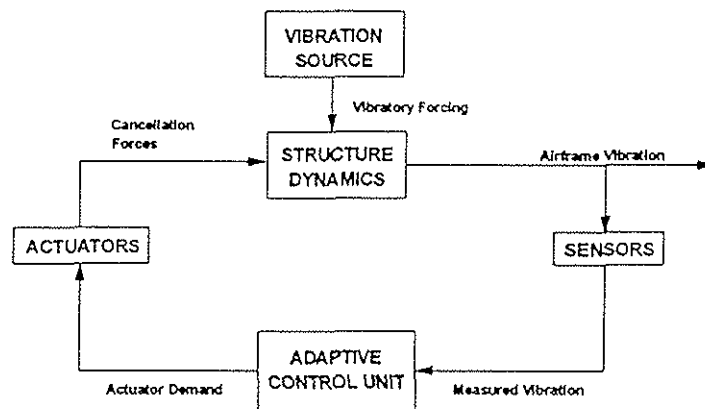


Figure 2 Active Vibration Control On The EH101

There are three modes of operation of the system:

- a) ACSR On - normal operation, airframe vibration control by the active system
- b) ACSR Off - active struts depressurised and baseline airframe vibration
- c) ACSR on Standby - active struts pressurised, force feedback loop in operation. Actuators producing a small damping force at 5R

To be effective, the actuators have to be located in the airframe where there is significant motion in the modes which are contributing to the rotor forced vibration. In the EH101, this motion is obtained by building in compliance in the active struts.

### 3) On-Ground Rig Testing To Assess Inflight Excitation Techniques

Experience gained in early PP3 testing, using a single actuator only and subsequent data analysis led to an improved procedure for inflight excitation and data analysis to be developed. The critical features were that all actuators were to be used to force the aircraft, all data was to be recorded on a common recording system and was to be input to a modal analysis system as a normal ground shake test. The accuracy and limitations of excitation by internal forcing and the presence of high rotor induced vibration were still to be addressed.

The main difference between external forcing and internal forcing using the ACSR is that the ACSR provides a two point internal excitation, applying equal and opposite forces at each end of the strut along the line of action of the strut. Figure 3 shows theoretical forced responses, two for forces applied independently at each end of a strut and one for the forces applied equal and opposite, which is the difference between the two independent responses.

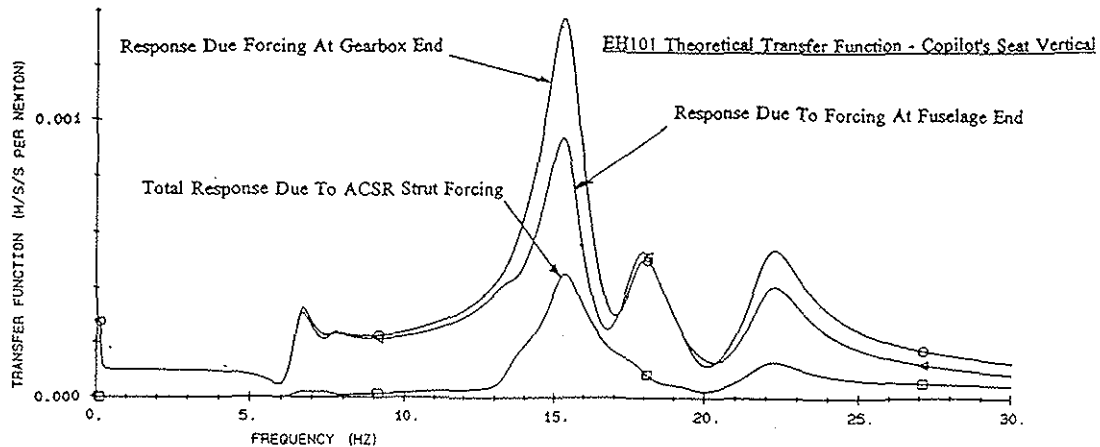


Figure 3 Example Of Response Characteristics Due To Two Point Actuator Forcing

These plots illustrate that,

- a) the airframe only responds in modes which have motion across the struts,
- b) the transfer functions appear to be "flattened"
- c) extraction of modal properties from these responses may prove difficult.

To evaluate these aspects, a shake test of the WHL W30 test rig was completed. The W30 test rig has a complete fuselage, a four point raft system, through which ACSR actuators operate in parallel with elastomers, but no engines. Figure 4 shows a schematic of the raft and ACSR actuators on the W30.

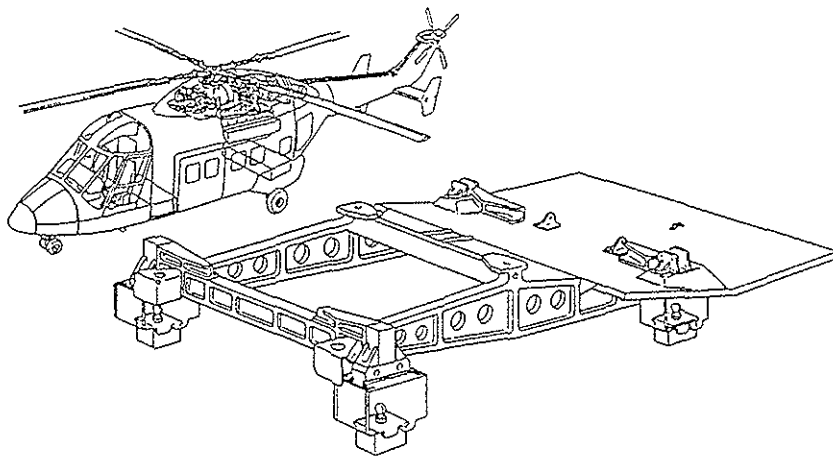


Figure 4 Westland W30 Raft And ACSR Installation

The aircraft was excited externally by shakers placed at a number of locations inputting random forcing. It was also excited internally by the ACSR actuators and the resulting modal data compared. Figure 5 shows the test installation with the aircraft mounted on a soft suspension system.

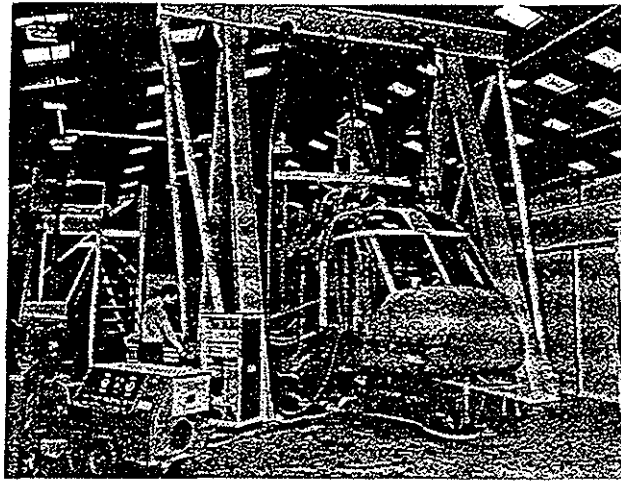


Figure 5 Westland W30 ACSR Test Rig

External shaking was by both single and multi-point random excitation. Response data was recorded at positions around the airframe and input directly to the modal analysis system. The resulting transfer functions were then used to extract modes and frequencies.

The aircraft was excited internally using each of the ACSR actuators in turn over the frequency range 3 - 40 Hz, using both random excitation and sine sweeping over 70 seconds. Additionally, rotor induced vibration was simulated by an external shaker applying a force directly to the head and of such a level to produce typical inflight response levels. Again, mode shapes and frequencies were extracted from the fuselage response.

Mode frequencies and shapes obtained from all the different types of excitation, internal and external, were compared. Figure 6 shows comparisons of modal frequencies obtained by internal and external shaking from each individual actuator. Comparisons are made between external random excitation and internal actuators forcing with both random and sinusoidal forcing. The frequency correlation for both types of internal excitation is generally good, with some variations around 27 Hz dependent on the actuator being used.

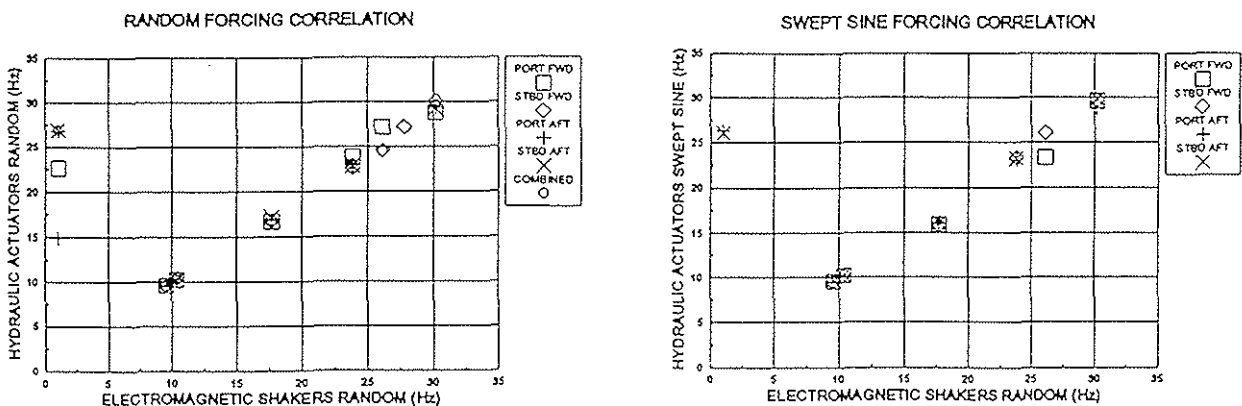


Figure 6 W30 Test Rig - Frequency Correlation Between Internal And External Excitation



Mode shape correlation was less good. The elastomers in the W30 raft system have high local damping and nonlinearities, consequently the measured modes are complex and the shapes are dependent on both the forcing levels and the locations at which the forcing was input.

Despite these problems, the test to evaluate internal forcing was successful. The quality of response data from internal shaking was satisfactory, and frequencies and modes could be extracted even with background rotor forcing. Structural nonlinearities to the level experienced on the W30 had not been noted on the EH101. Consequently modes and frequencies obtained inflight by internal excitation in this manner were expected to give more consistent results.

#### 4) Inflight Excitation Of EH101

Inflight excitation over a range of frequencies was achieved by inputting an open loop demand to the individual actuators via the Controller Computer.

Airframe response was recorded on the 10 control accelerometers and up to 40 additional accelerometers. Actuator forces and a phase reference signal were also recorded

The measurements were made at an airspeed where the vibration due to rotor forcing is a minimum. In the case of the EH101 this is 80 knots. The linearity of the airframe structural response with airspeed was confirmed by inspecting the actuator force transfer functions, T-matrices, measured at different speeds. These are shown in Figure 7, as vectors of response at the 10 control points due to each individual actuator forcing. These are seen to be independent of speed, justifying the testing at one speed only.

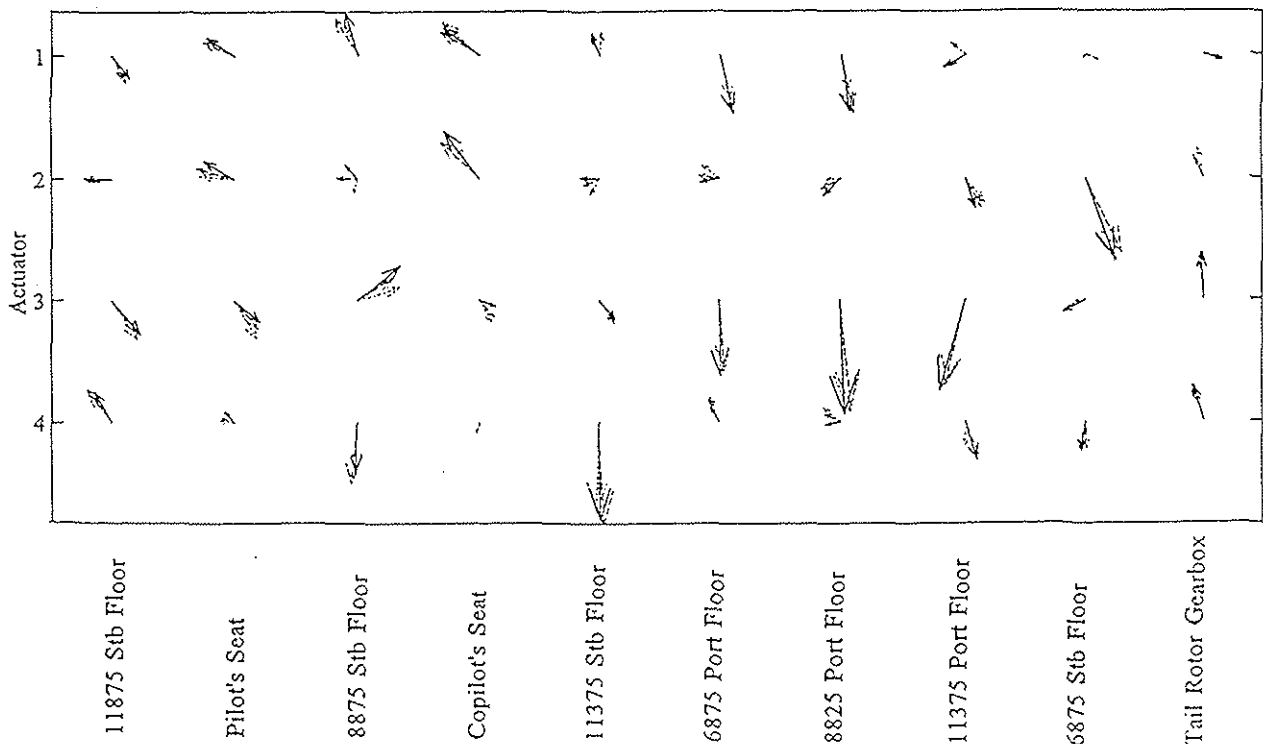


Figure 7 PP3 T-Matrices Measured At 40, 100 And 140 Knots, Demonstrating Structural Linearity



4.1) Early Inflight Excitation Of EH101 Aircraft PP3 Inflight excitation was performed on PP3 at a weight of 13000 kg. Excitation in flight was performed using the starboard forward ACSR actuator only, forcing with a random input and a sine sweep, both over a 2 minute duration. Strut forcing was obtained from the ACSR controller demand signal.

Response data was gathered at 80 knots, with the single actuator forcing and the other three acting in their Active Control mode, reducing 5R vibration. To obtain an accurate transfer function at 100% rotor speed, without the rotor forcing present, tests were performed with the rotor speed at 96% NR and again at 104% NR.

Sine sweep excitation was the most successful, concentrating the actuator force at one frequency in turn rather than always over the full frequency range. In doing this, there was a higher level of response at the sweep frequency which could be differentiated from the rotor induced response.

The transfer functions were obtained from the 2 minute force and response signals using the standard analysis methods available on the modal analyser. Figure 8 shows a typical transfer function measured at a rotor speed of 96% NR, 16.8 Hz. This transfer function contains the response to actuator forcing from 10 - 30 Hz and a discrete sinusoidal response at the rotor forcing frequency. The magnitude of the sinusoidal component is the combined response due to rotor forcing and three active ACSR actuators divided by the force from the single forcing actuator. Also shown on this plot is the transfer function synthesised from the extracted modal properties, omitting the 5R data.

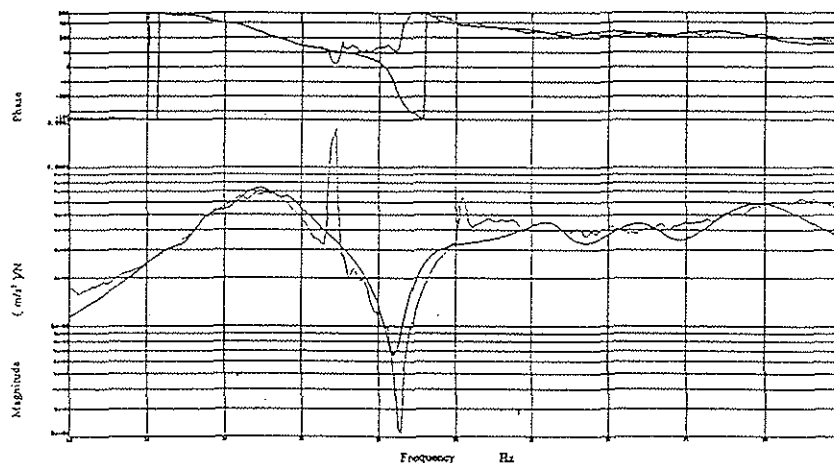


Figure 8 Transfer Function Measured In Flight At Main Gearbox In Fore And Aft Direction

Modal frequencies and an indication of mode shapes were obtained from these transfer functions, as discussed in Section 4.3. However, as only one actuator was used to excite the airframe, the data was believed to be insufficient for detailed mode shape extraction.

4.2) Inflight Excitation Of EH101 Aircraft PP1 An inflight shake test to identify the modal frequencies at high weight took place on EH101 aircraft PP1 in September 1994. The aircraft was to be tested with and without a structural bulkhead fitted at the rear of the cabin, and an assessment made of the change in structural dynamics.

In this test, all 4 actuators were used to excite the airframe. The aircraft was excited by each actuator in turn forcing with two 2 second dwells, using a feature of the standard ACSR Controller. It was possible to programme the Controller to input any frequency which was a multiple of 0.1 NR. The controller would then perform an automatic open loop test with each actuator in turn. This is a function the controller performs in normal operation at the start of each flight. This had the advantage that it saved time in modifying the control computer, but at the expense of coarseness of frequency resolution.

There were nine separate measurement periods during the automatic test. A 2 second measurement of baseline vibration was first made. The controller then demanded two 2 second excitations, the second with a 90 degree phase shift, from each actuator in turn at the chosen frequency. Whilst one actuator was forcing, the other 3 were in Standby mode. Each test was repeated once. The Controller was then reprogrammed for a further sweep at a different frequency. Excitation was from 10 - 30 Hz in 30 steps of 0.2 NR, giving a frequency resolution of 0.7 Hz.

Figure 9 shows the forces in Actuator 1 as all 4 actuators are stepped through a 10 Hz excitation. Initially there is low force in the actuator as ACSR is off, which is followed by 2 seconds on Standby whilst baseline vibration is measured. Actuator 1 then excites at 10 Hz over 4 seconds, and whilst the other 3 actuators are forcing, actuator 1 generates small forces at 10 Hz and 5R. These Standby forces are accounted for in the data reduction.

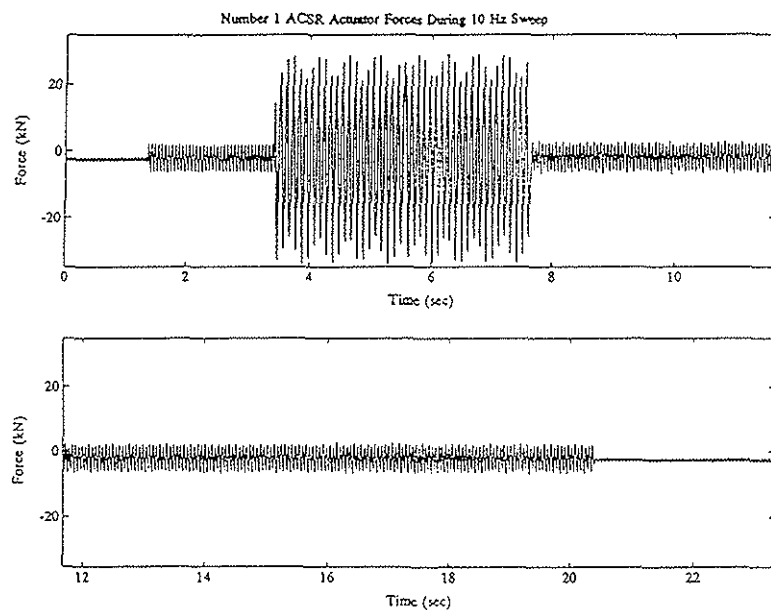


Figure 9 Forces Generated In Actuator 1 During Internal Forcing By All Four Actuators

As the timescale of the forcing was short, a method was developed to extract forced response data from the signal which had a high component of 5R forcing. In phase and out of phase components of each signal, force and response, were analysed using a frequency correlation technique as shown in Figure 10, in which the reference frequency is generated from the rotor azimuth and the factor of NR set on the Controller.

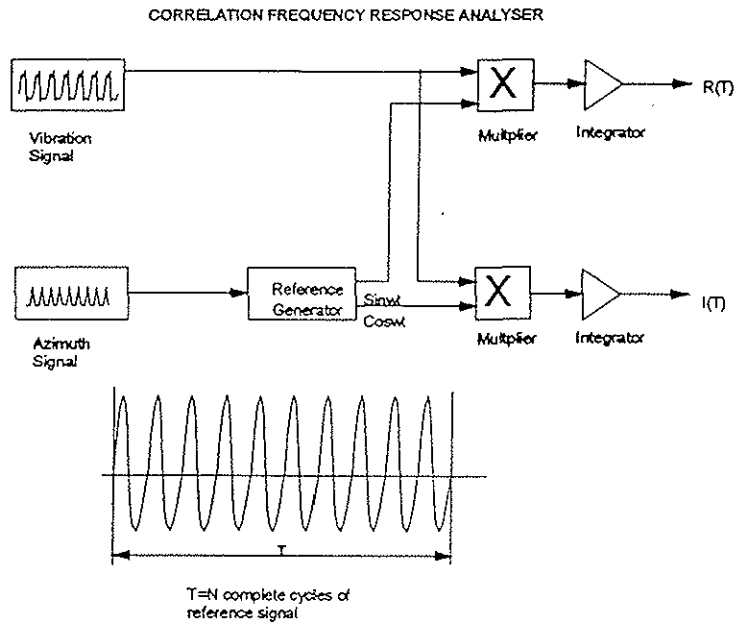


Figure 10 Frequency Correlation Analysis Methodology

The amount of corruption from 5R was minimised by selecting an optimum number of cycles for analysis. Figure 11a shows the leakage from the 5R response is dependent on the number of cycles chosen. By choosing an optimum number of cycles for each forcing frequency, which amounts to an even number of cycles at both the forcing frequency and 5R, the 5R effect was minimised, as shown in Figure 11b. Typically 20 - 30 cycles of response data was analysed.

Figure 11a)

17.85 Hz Disturbance - Leakage For 5, 6 And 7 Cycle Correlations

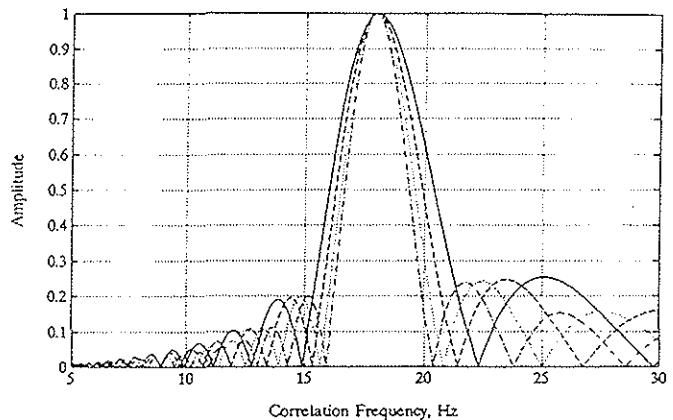


Figure 11b)

17.85 Hz Disturbance - Minimum Leakage For 10 - 30 Cycle Correlation



Transfer functions were obtained in the following manner. For each frequency step the phased baseline response, at the forcing frequency, was subtracted from the forced responses. This was generally low except at 5R and 1T, the tail rotor frequency. Knowing the magnitude and phase of the forces in all 4 actuators, demanded and standby, the true transfer functions due to individual actuator forcing only at each frequency could be calculated. These were then summed over the complete frequency range. These transfer functions were input to a modal analysis system for display and manipulation.

The transfer function data was processed further before modes were extracted. As the primary modes of the airframe involved gearbox pitching, rolling and bouncing, the transfer functions could be added to simulate pitch, roll and vertical forcing. For example, response to a pitch forcing was obtained by adding transfer functions from the two forward actuators and subtracting those from the 2 rear actuators. Similar calculations were done to obtain roll and vertical forcing. Typical composite transfer functions are shown in Figure 12. Note that the forcing indicated for the transfer functions remain KN to indicate that the transfer functions are not pure moment forcing.

Although the frequency resolution of 0.7 Hz was rather coarse, modes shapes and frequencies were extracted from the transfer functions. The results are discussed in the following Section.

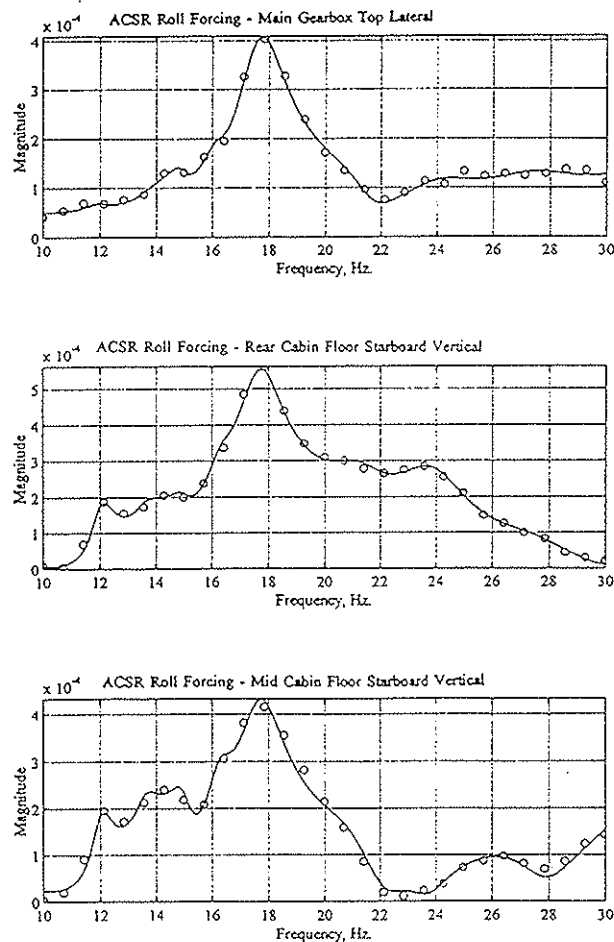


Figure 12 Composite Roll Forcing Transfer Functions - Magnitude And Phase At Three Locations

4.3) Results from Inflight Excitation Of EH101 Aircraft PP3 And PP1 Mode frequencies were extracted from the measured inflight transfer functions using a number of techniques. From the PP3 data, where only one actuator was used, frequencies and dampings were obtained directly from the measured data. Because the data was from a single actuator only, the reliability of the frequency estimates was in question. For PP1, where all 4 actuators were used, modes and frequencies and dampings were extracted from the enhanced pitch, roll and vertical transfer functions.

Table I shows the comparison of mode frequencies and damping obtained from a ground shake test at 13000 kg and inflight weights of 13000 kg and 14400 kg.

MODE	GROUND 13000 kg		FLIGHT 13000 kg		FLIGHT 14400 kg	
	Frequency Hz	Damping % crit	Frequency Hz	Damping % crit	Frequency Hz	Damping % crit
Gearbox Roll	13.4	0.9	12.8	3.0	11.8	3.4
?	-	-	13.7	3.2	-	-
Gearbox Pitch	14.3	0.7	14.9	6.2	13.7	5.2
Lateral Bending	15.9	0.8	15.6	1.4	-	-
Gearbox Bounce	17.0	1.5	-	-	16.1	5.3
Gearbox Roll	18.4	1.4	18.8	4.8	18.2	8.3

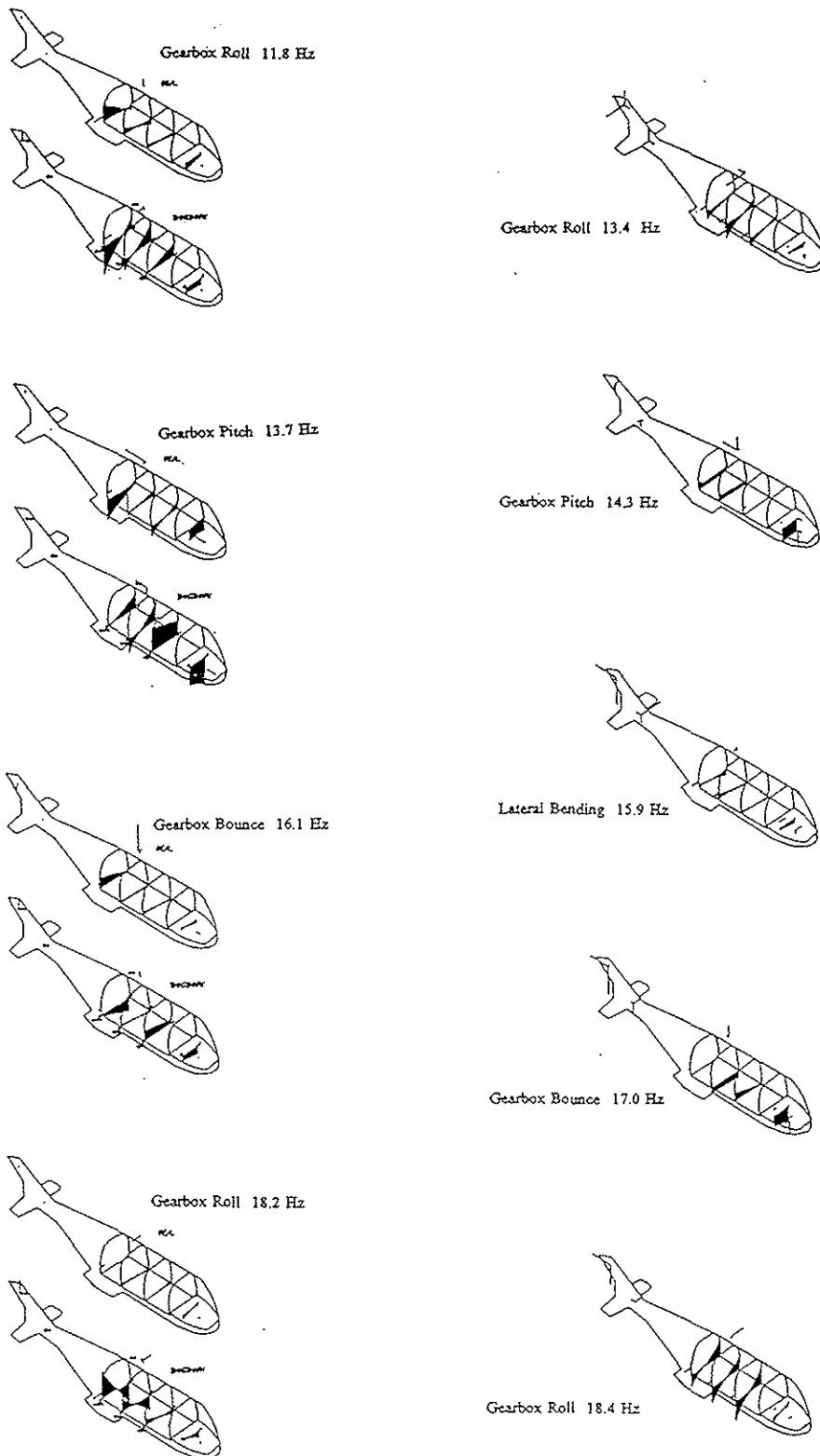
TABLE 1 Comparison Of Modal Frequencies Measured On Ground And In Flight

The inflight modal frequencies at 13000 kg are similar those measured on ground, and there is a reduction in frequency with increasing weight. The most significant feature is the increase in modal damping. The on ground shake test was performed on bare airframe, without trim, wiring etc, and had been considered rather low.

The mode set obtained from the PP1 data at 14400 kg is considered the most accurate as the modes, which were excited using 4 actuators, are main contributors to the airframe response and likely to be excited by the ACSR.

The inflight modes, although generally complex, had characteristics of the ground shake modes and a comparison could be made. Figure 13 presents the inflight mode shapes from the PP1 test in which all 4 actuators were used, compared to real ground shake test modes. The inflight modes

are presented as in phase and out of phase components. Note there are no tail rotor or intermediate gearbox measurements.



Complex Inflight Modes 14400 kg

Ground Shake Modes 13000 kg

Figure 13 Comparison Of Inflight And Ground Shake Test Measured Modes

Theoretical predictions of coupled rotor/fuselage modes, using ground shake modes and a theoretical rotor model have been made. The resulting modes are complex and there are shifts in modal frequencies.

These will be compared in detail with the flight data at a later date.

4.4) The Effect of a Structural Bulkhead on Aircraft PP1 Measurements of the baseline aircraft were obtained in one flight. A further flight was performed with a structural bulkhead fitted in the rear of the cabin. Figure 14 compares the transfer functions at the station where the bulkhead was fitted for each actuator excitation.

The two gearbox roll modes at 13.4 Hz and 18.4 Hz both contain significant fuselage shear deflection. Although there is an indication of a mode frequency increase which was expected as the bulkhead added shear stiffening, the most significant feature is the reduction in overall transfer function magnitude at that location at the two mode frequencies. This infers a definite change in mode shape as a result of stiffening. The resulting rotor induced 5R baseline vibration in this area is correspondingly reduced.

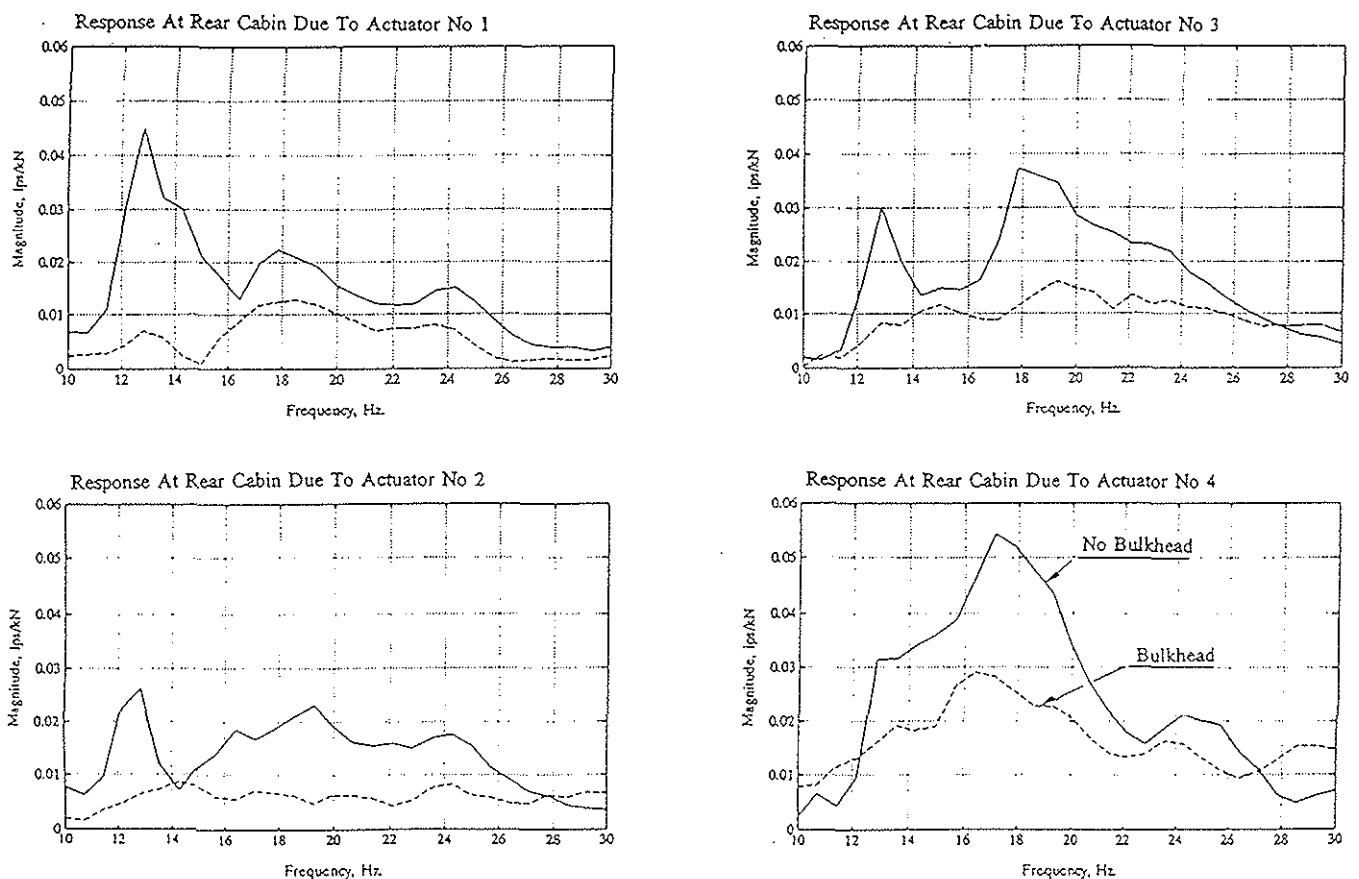


Figure 14 Effect Of Structural Bulkhead On Transfer Functions



## 6) Inflight Shake Testing - Summary and Conclusions

Different methods of inflight excitation have been assessed, both on ground rigs and in flight. Experience in testing and data analysis has been gained, and successful inflight tests have been performed.

On aircraft such as the EH101 with ACSR type systems an indication of modal properties can be obtained very quickly.

The main advantage of inflight excitation is that modal data can be gathered on an airframe which has flight loads applied. This is particularly important on aircraft which have structural nonlinearities, or redundant gearbox strut arrangements.

Inflight shake testing is most useful where ground shake test data is already available and specific vibration problems are being investigated. Practically, only limited response data can be measured in flight and should be supplemented by knowledge gained in detailed ground tests. This approach was used with some success in the EH101 tests.

The disadvantages of inflight excitation are associated with the high cost of flight instrumentation and the limitations on inflight data recording. On development aircraft which are fitted with instrumentation for other purposes, there is some saving, but the problems of gathering a lot of response data remains.

Even with limited response recordings the aim should be to treat the data as if it was from a ground shake test and process it using appropriate techniques. Data handling requires automation from the start and excitation methods should be consistent with the analysis methods available. In this way, modal extraction and plotting capabilities of packages can be used to the best advantage.

Work continues to improve the technique of inflight excitation and flight data analysis and to compare measured modes with predicted complex coupled rotor-fuselage modes.

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