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AN EVALUATION OF ACTIVE CONTROL OF STRUCTURAL RESPONSE AS A MEANS OF REDUCING HELICOPTER VIBRATION

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SUMMARY

This paper details the design, implementation and testing of an active technique for reducing helicopter structural vibration, termed Active Control of Structural Response (ACSR). The ACSR technique employs high-frequency force actuators located within the vibrating structure. The vibration response arising from these controlled secondary actuator forces is superposed onto the baseline response generated by the primary vibratory forcing source, the main rotor, such that the resulting structural response is minimised. The basis for the technique is described and the practical design requirements detailed.

The first successful implementation of ACSR was on a Westland 30 helicopter. Results from the ground vibration test and flight trials programme are presented, which indicate the significant potential of the technique for maintaining minimum structural vibration throughout the helicopter flight envelope.

1. INTRODUCTION

The need to reduce helicopter vibration remains a major challenge to the helicopter industry. The harsh vibration environment experienced by both aircrew and passengers has a direct influence on crew fatigue and passenger comfort. In addition, vibration contributes to the cost effectiveness of the helicopter, particularly with respect to engines and equipment. Furthermore, the technological advances made in novel rotor systems has increased the forward speed range and improved manoeuvrability. This trend towards a widening of the helicopter mission range has resulted in ever more stringent vibration specifications. The advantages of reduced vibration levels are obvious and as a consequence, much research effort has been expended to alleviate the problem.

The helicopter dynamicist's ability to understand and predict the behaviour of complex rotors and airframes is continually improving. However, the source of vibration will always remain as an inherant helicopter problem, since it is a consequence of the asymmetric airflow arising from flying the rotor edgewise through the air. Therefore, it is unlikely that such design techniques will provide a sufficient improvement for the next generation of rotorcraft.

The proliferation of passive devices fitted to many in-service helicopters indicates the magnitude of the vibration problem. Although such devices have served the industry well, they are usually only palliatives and their effectiveness is limited by practical constraints such as weight and drag. Furthermore, the inability of passive devices to adapt to a wide range of flight conditions represents a severe technology limitation. Therefore, the recent advances in active systems for vibration alleviation represent a major step towards achieving a 'jet-smooth' ride in rotorcraft.

With the advent of increased computing power and improvements in actuation technology, the practical implementation of active techniques to control helicopter vibration has become a reality. Research, and more recently, flight demonstrations have concentrated on the Higher Harmonic Control (HHC) of rotor blade pitch as a means of reducing vibration at source. Flight trials (ref 1 and 2) have shown very promising results, at least for flight well within the rotor performance envelope. However, a number of potential difficulties exist with the implementation of HHC. These include a possible degradation of the rotor performance, due to the conflict between retreating blade stall at high forward speeds and the requirements of vibration reduction. In addition, HHC can have significant airworthiness implications, since modifications may be required in the primary flight control circuit.

This paper considers the development by Westland of a new approach to helicopter active vibration control, termed Active Control of Structural Response (ACSR), and in particular presents the results of the pioneering ground vibration and flight tests conducted on a Westland 30 helicopter. The research and development work conducted at Westland shows that ACSR not only provides enhanced vibration suppression capabilities compared to HHC, but has major advantages regarding ease of installation, minimal airworthiness impact and low power consumption.

The basis of ACSR is that force-actuators are mounted at or across locations in a structure which possess relative motion in the dominant vibratory modes. A number of sensors measure the vibration response at key locations on the structure, the signals of which are fed to an adaptive computer-controller. This controller, in turn, provides optimal signals to the actuators to produce forces which minimise vibration at the sensor locations. The fundamental principle of ACSR is therefore one of superposition, whereby the summed effect of the rotor-induced vibratory response and the actuator response is maintained at a minimum. The theoretical basis for ACSR is described in more detail in reference 3. It should be emphasised that the ACSR approach differs from conventional passive techniques, which either isolate given load paths or absorb vibration through local force cancellation. The ACSR control system approach is shown schematically in figure 1.

2. THE IMPLEMENTATION OF ACSR

In order to implement the ACSR approach careful consideration must be given to the three primary system elements, actuation, control and vibration sensing. The technique of ACSR is generally applicable to any vibrating structure. However, the success of ACSR in providing vibration suppression depends on optimal actuator and sensor positioning, combined with an appropriate control strategy and implementation. These key system requirements are discussed in the following text and the approach adopted for the Westland 30 ACSR demonstration is detailed in the subsequent section.

The overall ACSR system objective is to maintain significantly reduced vibration levels throughout the helicopter flight regime. In practical terms, the control system needs to address the troublesome vibration frequencies which occur at harmonics of the main rotor speed and, in particular, the dominant blade passing frequency at bR (where b is the number of blades and R the rotor rotational speed). Furthermore, in order to operate throughout the flight envelope, the system must be able to adapt to the changing vibration environment which results from variations in the frequency, magnitude and phasing of the rotor vibratory forcing components and variations in the airframe dynamics characteristics determined by aircraft all-up weight and centre of gravity. Moreover, in designing a new ACSR installation it is necessary to resolve the conflict between optimal actuator positioning and the practical requirements of minimal weight and power penalties.

2.1 Actuation Options

The location and design of the actuation system is a crucial consideration in determining the effectiveness of ACSR. The primary criterion for selecting actuator positions is that of maximising vibration reduction with minimal actuator force and displacement, and thus minimal power and installed weight. An optimisation approach has been developed based on finite element dynamics modelling techniques to predict ACSR performance. The theoretical predictions from such studies have been now been validated against ACSR ground vibration tests on Westland 30, Lynx and EH101 helicopters. Such modelling techniques provide an essential start point in evaluating ACSR potential, but they must be combined with an assessment of the practicality of installation.

Essentially, two forms of actuation approach have been considered as applicable to ACSR. The first option is based on dual point actuation, where actuators are mounted between pairs of points in the structure that exhibit relative motion in those modes which dominate the structural vibration response. The second approach is that of single point actuation, where the actuator is connected to the structure at one point but uses a seismic mass to generate the required forcing. The prime advantage of this approach is that it is easier to determine practical locations for the devices, and unlike the dual point scheme, it is able to modify the rigid body response at blade passing frequency. However, in practical terms such devices are limited to those applications where the level of vibratory forcing is sufficiently low as to allow a feasible design. In most helicopter applications, the dual point actuation approach is the only practical means of realising an ACSR installation, since the level of vibratory rotor forcing is high, and consequently the level of actuation force needs to be of a similar magnitude (typically the maximum force required is in the range of 9 - 20 kN at between 15 and 25 Hz).

In theory, the dual point approach can work with actuators located throughout the structure, in-parallel with structural members. However, both theoretical predictions and test experience has shown that actuators located close to the vibratory source are most effective in providing global vibration reductions in the helicopter structure. Therefore, to date, the practical realisation of ACSR on rotorcraft has taken the form of dual point actuators which apply controlled vibratory forcing at or close to the main gearbox attachment points.

2.2 Control Strategies and Implementation

The control strategy is required to minimise the measured vibration whilst maintaining the actuator forces within practical limits. Therefore, the control problem can be expressed as one of minimising a quadratic performance index, comprising the weighted sum of the vibration measurements and the weighted sum of the actuator demands. The relative size of the sensor and actuator weightings determines the overall reductions achieved and the degree of actuator force limiting. Furthermore, such an approach allows the control system to optimise vibration in specific areas of the airframe through changing the relative sensor weightings.

The optimal control formulation can be applied to problems in either the time or frequency domain. Since the helicopter vibration problem is one of periodic exitation at known frequencies, most active techniques have relied on a frequency domain control solution. A micro-processor based control unit incorporating nine frequency domain algorithm options (reference 3) was developed for the Westland 30, which operated at blade passing frequency. The frequency domain approach has been favoured due to the relative ease of implementation. These control algorithms developed for ACSR operate on a cyclic basis, as shown in figure 2, where during each control cycle the actuator demands are maintained at constant magnitude and phase, the common frequency being synchronised to the blade passing frequency. In parallel with this operation, the control algorithm calculates the minimising actuator demands for the next control cycle based on a three stage process:

(a) Digital Signal Processing - the basis of the frequency domain algorithms is the assumption of a linear airframe response to the actuator inputs at the frequency of interest. All algorithm calculations are conducted in the frequency domain and thus, the function of the digital signal processor is to accurately measure the bR content of the vibration signal, using discrete Fourier transform techniques.

(b) Dynamics Parameter Estimation - the estimator uses prior actuator input and vibration measurement data to continually update an estimate of the airframe dynamics at the bR frequency. The preferred technique is based on a Recursive Least Squares estimator, incorporating a variable forgetting factor (reference 3). The estimator approach is based on iteratively adjusting the dynamics estimate according to the error between the internal controller prediction of the vibration and the actual measurement. Although the dynamics may remain relatively constant for most of the flight regime, the estimator provides the controller with robustness, since it is able to adapt to changes in dynamics caused by rotor speed fluctuations and variations in airframe loading and distribution.

(c) Optimal Control - substitutes the vibration measurement and the dynamics estimate into an optimal control formulation based on an iterative or local-linear model of the structural response to determine the forcing for the next control cycle.

The implementation of this scheme on a Westland 30 helicopter resulted in a control cycle time of around 1 second, comprising 0.6 seconds (ie. 3 rotor revolutions) for signal processing and 0.4 seconds for the estimator and optimal control calculations. During transient conditions, such as rapid manoeuvres and gusts, the controller performance is determined by the update rate, since this limits the speed at which the controller adapts to changes. Therefore, a reduction in update rate should improve manoeuvre response. However, there is a physical limit to the speed at which the frequency domain approach can update, based on the fundamental assumption of linearity and the consequent need to accurately measure the forced response resulting from actuator inputs alone. Simulation studies showed that if calculation rates were reduced to zero, then the minimum controller update time which ensured control stability was of the order of 0.5

seconds.

In practice, rapid manoeuvres such as the transition to hover are characterised by a rapid increase in the baseline vibration during 1 to 2 seconds. Since, the control update rate is of the order of 1 second, then the increase in vibration will go unchecked until a new measurement is calculated, by which time the vibration may have further increased. It was anticipated that such rapid manouevres may effect the stability of the controller. However, despite this potential problem, the flight trials (see later section) showed conclusively that the controller was able to maintain significantly reduced vibration levels even for the most severe manoeuvre conditions.

2.3 Sensor Options

The control approach adopted for the Westland 30 demonstration was based on a 10 sensor and 4 actuator configuration. The control system requires either an equal or greater number of sensors than actuators. However, in theory, for a system with an equal number of sensors and actuators, the controller will attempt to achieve zero vibration at the control sensors provided the actuator weighting is zero. This approach may be acceptable if cabin and cockpit vibration were the only consideration. However, since the aim of the system is to provide reductions throughout the entire airframe, it is important to have sufficient sensors which are distributed to measure the response of all the dominant modes.

3. THE WESTLAND 30 DEMONSTRATION PROGRAMME

A schematic of the Westland 30 ACSR system is shown in figure 3, which primarily consists of the vibration control system, the hydraulic power system, pilot and flight test engineers interface and data recording equipment.

The ACSR control unit receives airframe vibration signals from 24 accelerometers located around the airframe, 17 in the cabin and cockpit area, 4 on the engines and 3 on the tail rotor gearbox, as detailed in table I. In order to ease the task of sensor optimisation, the set of 10 control locations was selectable from the engineer's station. Control unit synchronisation of the vibration sensor measurements and actuator force demands was via a reference azimuth marker derived from the main rotor shaft position. The secondary actuator force control loop was provided by digital means within the control unit, based on differential pressure measurements from transducers mounted either side of the actuator piston.

With regard to the actuator installation, ACSR was ideally suited to the Westland 30, whose raft construction, shown in figure 4, allowed electro-hydraulic servo-actuators to be incorporated into the gearbox/fuselage interface at the four elastomeric mount locations. These elastomeric units are relatively soft in the vertical and fore-aft directions and relatively stiff in the lateral direction. The modified elastomeric unit, figure 5, shows that the actuator operates in parallel with the elastomer spring, applying vibratory forcing in the vertical direction alone. The use of local force feedback around each device ensures that the actuator does not react any primary quasi-static loads, which are transmitted through the elastomer in the normal manner. The actuation devices were designed to provide a maximum of +/- 9 kN at blade passing frequency (22 Hz for the Westland 30), with a maximum vibratory displacement of approximately 0.25 cm. Furthermore, the hydraulic system was designed to provide sufficient flow at the maximum forward speed condition, supplying a maximum of 3 kW to the four ACSR actuators at a system pressure of 140 bar.

It is worth noting that, although the Westland 30 installation has the appearance of an isolation system, the system operates through modification of the vertical load path alone, where forces are applied to both the raft and airframe to significantly reduce the total generalised force in the dominant modes.

In order to realise the system on the Westland 30 it was necessary to develop an actuator design which would continuously inject forces in to the structure at relatively high frequencies without significant performance degradation over the life of the aircraft. The actuation devices for the Westland 30 were specifically developed by Moog Controls Limited. These were of a differential area double acting type, employing mechanical feedback Moog Series 30 servo-valves. Activation of the actuator is controlled by the control unit through an electrically operated by-pass solenoid. The actuators employed lapped fit, metal to metal seals. Furthermore, in order to prevent leakage, Moog have developed a unique arrangement based on a metal bellows and check valve assembly, which prevents high-frequency motion between the actuator shaft and the fluid-to-air seal. The actuators were performance tested and qualified to satisfy demanding endurance requirements. Such developments have proved crucial to the establishment of ACSR as a viable technology for current rotorcraft.

The control unit was designed to interface with a Modular Data Acquisition System (MODAS), which logged all analogue and digital controller data for later analysis.

Finally, the controller included an operator interface to allow both the pilot and flight test engineer to monitor and control the system operation. The pilot's panel provided the pilot with the overide control for the system and included system status indicators. The engineer's station consisted of a VDU monitor and keyboard, allowing the engineer to monitor the vibration levels and controller data during flight. Also, a facility was provided to select, edit, execute and terminate a number of pre-programmed algorithm tasks.

3.1 Ground Vibration 'Shake' Test Results

The shake test was conducted on the flight demonstration vehicle (a Westland 30 series 160 aircraft) with aircraft configuration as flight standard, but the aircraft was suspended by soft springs through a dummy rotor head in order to excite the free-free vibration airframe response. Rotor head loads representative of the flight environment were applied through electro-magnetic shakers acting at the dummy rotor head. Power for the ACSR system was provided via the normal aircraft systems fed by external hydraulic and electrical ground supplies. Two prime test phases were conducted, namely actuator feedback tests and vibration control tests. Furthermore, a vital element of these tests was the validation of the basic control assumptions, these being structural linearity and superposition.

Analysis of flight load data had shown that a vibration distribution representative of flight levels could be achieved in the shake test through a roll moment excitation at the head. The tests were conducted with a 900 N-m amplitude roll moment, resulting in a maximum airframe vibration level of 0.27 g. Analysis of the corresponding structural vibration characteristics indicated the dominance at 22 Hz of a fuselage torsional response combined with a raft roll response.

Preliminary tests were conducted to characterise the structural dynamics, represented by the transfer relationship at the operating frequency between actuator inputs and the resulting structural response. These data were produced by on-line calculations within the ACSR control unit which were based on measurements of structural response to a pre-defined sequence of vibratory actuator inputs. This procedure was incorporated as an 'open-loop' control routine, whereby, following determination of the structural dynamics, optimal control forces are formulated by the controller and then applied to the vibrating structure. During the shake tests control unit operation was based on this 'open-loop' transfer matrix derivation followed by immediate execution of the 'closed loop' vibration control law discussed in section 2.2. During these intial tests it was observed that on taking the actuators out of the by-pass condition but before applying an actuator demand, average airframe vibration was attenuated by around 30%. This 'semi-active' effect is a result of the coupling of the actuators with the structural dynamics and the tendancy for the secondary force control loop to provide a degree of isolation of the vibratory transmission across the raft in the vertical direction. However, this modification of the airframe dynamics by the actuators is accounted for in the vibration control loop, which then provides the optimal actuator demand for minimal vibration. A summary of the shake test results is given in figure 6, which compares the vibration response for the baseline airframe dynamics with that for the ACSR system at the nominal blade passing frequency and the extremities of the rotor speed range (22 Hz +/- 5%). The ten control sensors were selected (see table I), based on those locations exhibiting highest vibration response at 22 Hz, and yielded a reduction in average vibration in excess of 80% independent of rotor speed. On average at the 24 monitoring locations, the 22 Hz vibration was reduced by 67% from 0.12 g to 0.04 g, whilst at 20.9 Hz the average vibration was reduced by 87% from 0.19 g to 0.02 g. In fact, the 20.9 Hz condition is characterised by relatively high baseline vibration since it is almost co-incident with the frequency of one of the dominant airframe modes. Clearly, ACSR is better able to deal with a resonant airframe, since the control action is not compromised by the need to provide different forcing for a number of equally dominant modes.

A series of tests was also conducted to establish the control performance for degraded system operation, based on reducing the number of actuators and sensors included in the vibration control loop. The most serious degredation tested was a change in the normal operating situation of ten control sensors and four actuators to four control sensors and two actuators. The tests showed that the forward two actuators contributed most to the vibration reduction, and the corresponding sensors were selected to maintain the maximum overall vibration reduction. At 22 Hz the reduction in average vibration at the 24 monitoring accelerometers was degraded by only 8%, from 67% to 59%.

Throughout the shake tests, an impressive indication of the performance of the ACSR system was given by the virtual elimination of structure-borne noise, and the visible reduction in vibration at the undercarriage and cockpit, where the baseline vibration levels were generally quite severe.

3.2 Flight Test Results

An eight hour flight test programme was conducted during early 1987. The flight tests were carried out at two aircraft loading conditions; the baseline aircraft loading at 11,800 lbs take-off weight with a neutral centre-of-gravity, and the higher loading of 12,800 lbs take-off weight with a forward centre of gravity. The first part of the flight trials dealt with the evaluation of the vibration reduction performance of the ACSR system under steady flight conditions, including forward speeds from 40 to 124 knots, a rotor speed range of 100 to 104 % of the normal operating speed, and a loading variation. Following this, the performance of the ACSR system was assessed for progressively more severe manoeuvre conditions.

Firstly, two datum flights were carried out to characterise the datum vibration levels for the baseline aircraft loading, both with and without the rotor mounted head absorber fitted, for the range of forward speeds. It was shown that the head absorber provided consistent reductions in vibratory forcing at most airframe positions, the average level of reduction exceeding 45% throughout the forward speed range.

Initial tests of the ACSR system performance were conducted at a steady speed of 80 knots. Vibration performance was assessed for two sensor selections (summarised in table I), the first of which was optimised for global airframe reductions and included the two dominant engine response directions, while the other was tailored to the cabin/cockpit area and included only one engine sensor. The results shown in figure 7 indicate that including two engine locations in the control set prejudices vibration reduction in the cabin and cockpit area, and that replacing one of these engine sensors with an additional cabin sensor degrades the vibration alleviation on the engines. For the latter case, the average level of cabin and cockpit vibration was lowered to 0.09 g, a reduction of about 75% from the baseline response (with no vibration treatment). The reduction in average vibration for all twenty-four monitoring positions was maintained at about 50% for both sensor selections. Tests were then conducted for the forward speed range of 40 to 100 knots, and the average vibration levels in the cabin and cockpit are compared in figure 8 for the baseline aircraft loading, with no vibration treatment, with the head-absorber and with the ACSR system active. Note that the ACSR case relates to the optimum control set of cabin and cockpit locations. For the ACSR system, reduction in average vibration lies in the range of 72% to 82%, while for the head-absorber, the figures are 47% to 63%. For the complete set of twenty-four monitored locations, reductions were between 55% and 60% for ACSR, and between 40% and 55% for the head-absorber. The superior performance of ACSR was further emphasised by the fact that the reduction in the average vibration for the ten control locations was at least 80%. These figures highlight the fact that ACSR achieves better vibration control in respect of the whole airframe compared to the head absorber, and it has the ability to provide excellent vibration reductions at desired specific locations. Tests were then conducted to assess the performance of the ACSR system against a +/-2% variation in rotor speed. Figure 9 indicates that, in addition to its generally superior forward speed performance, ACSR is less sensitive than the head-absorber to the changes in rotor speed. This latter fact is not particularly suprising, since the head-absorber was specifically designed to provide optimal vibration control at the normal operating rotor speed of 102% Nr. Flight limitations did not allow rotor speed variations outside +/- 2%, but extrapolations suggest that outside this range, the performance of the head-absorber would become significantly worse when compared with the performance of the ACSR system.

The robustness of the ACSR control approach was further confirmed by changing the aircraft loading as detailed above. The average vibration for the aircraft with no vibration treatment was increased by about 25%, which restricted the flight speed range to 40 to 100 knots. Figure 10 shows that the levels of vibration achieved by ACSR (using control sensor set 1) are close to those for the baseline loading with ACSR active. For example, over the speed range of 40 to 100 knots, the average 4R vibration response for the 17 cabin and cockpit locations is reduced by ACSR to 0.14 g, compared to an average reduction to 0.12 g for the baseline aircraft loading.

The comparative performances of the various control algorithms was assessed throughout the above steady forward speed tests. The major difference between the algorithms performance proved to be in their initial response on activation of the ACSR system, while the steady-state vibration reductions achieved were nearly identical for all the algorithms. The initial tests were conducted with a "cautious" local-linear, stochastic, recursive least square algorithm , which required, on average, 10 to 12 control cycles to reach a steady condition. It was quickly established that the local linear, deterministic, recursive least squares algorithm provided the best transient response, reducing the transient period to 2 to 3 control cycles; this algorithm was used for the duration of the steady flight tests and the subsequent manoeuvre tests. The only steady flight condition where rapid reductions in vibration response were not achieved was the weight-changed configuration. This is attributable to the large difference between the real aircraft structure dynamics and the initial, pre-programmed estimates. In this case, the transient period was increased to around 5 control cycles, during which time the controller adjusted its dynamics estimates to more optimal values.

The full authority ACSR system was tested for an extensive range of manoeuvre conditions, including the following:

Rapid Acceleration from 40-100 knots
Up to 30 degree banked turns to port and starboard
30 degree Roll Reversals at 80 knots and Wingovers
Rapid Deceleration from 100-40 knots, into full Autorotation
Maximum Power Climb
Rapid Entry and Recovery to Autorotation in Descent
Rapid Pitch Attitude changes
Low Speed Manoeuvres (including Sideways/Rearward Flight)
Transitions to Hover (including rapid stop)
Landing and Take-off

Throughout the complete range of manoeuvres tested, ACSR provided substantial vibration reductions. For the light manoeuvres, such as banked turns and slow rates of acceleration/deceleration, there was little noticeable change in the reduced levels of 4R vibration, and the performance of ACSR in severe manoeuvres was also impressive. From an airframe vibration perspective, the transition-to-hover manoeuvre remains one of the most severe cases. The results for this case are presented in figure 11, which shows that ACSR maintains a reduced level of 4R vibration throughout the manoeuvre, which is most pronounced when the baseline response is at a maximum. Furthermore, the manoeuvre tests indicated that ACSR performance is generally superior to the head absorber. It had been anticipated from simulation studies that the manoeuvre performance of the ACSR system could prove to be a problem, but the results from the manoeuvre tests clearly refute these expectations.

The general subjective assessment by the pilot and flight crew indicated that ACSR gave improvements when compared to the head absorber equipped aircraft, especially for the high and low speed regime. For example, at 120 knots, pilot Cooper-Harper ratings of 7 were recorded for the baseline helicopter, 4 for the head absorber equipped helicopter and between 1 and 2 for ACSR system. Furthermore, the pilots report recorded that the most noticable improvement attributed to ACSR, was in the reduction in vibration in the cockpit area. In particular, this reduced structural vibration was manifest as low lateral vibration on the interseat console, cabin window glazing, cockpit instrumentation panels, roof structure and sliding windows. Associated with this reduced vibration response was a pronounced reduction in noise levels. In addition, it was noted that ACSR gave improvements throughout the manoeuvre regime. Smoothly flown manoeuvres gave little variation in the 4R vibration levels. In comparison to the head absorber equipped aircraft, improvements were most marked during the transition to hover and low speed flight. The flat charactersitics of ACSR for varying rotor speed was also noted.

4. RECENT DEVELOPMENTS

The impressive flight demonstration on the Westland 30 in 1987 has prompted Westland to pursue ACSR technology development programmes aimed at both the Lynx and EH101 helicopters. The control system technology has been developed to enhance performance, incorporating improved micro-processor technology to reduce control update rates. This development work has resulted in a pre-production control unit which employs parallel frequency domain control loops to minimse vibration at up to four main rotor harmonics. It is intended to fly this improved control system on the EH101 in the near future.

In terms of understanding ACSR system design and implementation issues, experimental programmes are being conducted on both Lynx and EH101. These studies have focused on the development of a design optimisation approach and have recently resulted in very encouraging ground vibration tests on both aircraft.

5. BENEFITS AND COSTS

The benefits of reduced vibration on rotorcraft are reasonably well established. However, the excellent flight test results for ACSR indicate the significant benefits of an active system when compared to the more established passive techniques, these include:

- The active nature of the ACSR system allows it to adapt to the large variations in helicopter vibration characteristics experienced in flight, such as those changes influenced by forward speed, manoeuvres, rotor speed, weight and centre of gravity. In particular, ACSR overcomes one of the major limitations of the passive devices, since it is largely insensitive to rotor speed variations.

- Although an ACSR installation is more complex than most passive devices, the system failure modes are benign, since the system has a self-monitoring capability which allows automatic re-optimisation of control action upon failure of sensors or actuators.

- Typically, a production installation of ACSR would have a weight penalty of 40-80 kgs, depending on the particular actuator configuration. In Westlands experience, the weight penalty for ACSR is less than the most effective passive solution. For example, on the Westland 30 it was estimated that a production ACSR installation would weigh approximately 36 kgs, compared to 55 kgs for the rotor mounted absorber, currently fitted to in-service aircraft. Moreover, unlike the head absorber, ACSR imposes no drag penalty.

- ACSR can operate at a multiplicity of frequencies, minimising the airframe response through optimising the differential weighting between frequencies according to their dominance, and including the ability to operate at 1R. Passive techniques do not possess such capabilities without increasing device size and introducing weight.

- ACSR can be optimised for vibration reduction in specific areas of the airframe. For example, during cruise, cockpit and cabin vibration can be controlled to reduce crew fatigue and improve systems reliabilty, while during combat, vibration reductions may be tailored to crew stations and weapons platforms.

The latter two characteristics of the ACSR system are becoming even more important, in the light of the changing perspective reflected in new vibration specifications such as ADS-27 (reference 4), which specifically focuses on human factors, equipment and dynamic (or rotating) components. The recent control improvements allowing multi-frequency operation combined with the ability to optimise vibration at specific locations, provides a strong basis for meeting the ADS-27 specification. Since ADS-27 focuses on key locations in the airframe through the specification of a maximum 'intrusion index', then the sensor locations and frequency weightings for ACSR become obvious. In this respect, the specifications may need to be further modified to reflect the need to reduce vibration throughout the helicopter structure.

Many of the above performance advantages are common to active techniques, such as HHC. However, a comparison between HHC and ACSR shows the latter to overcome many of the disadvantages of HHC in relation to the following:

- A rotating frame actuation implementation of HHC may yield a minor improvement in vibration performance compared to ACSR in the mid-speed range. However, at high forward speed conditions the necessarily high angles of attack of the retreating blade act to degrade the HHC system performance. Such absolute limits to system performance are not found with an ACSR installation.

- The study of HHC has shown that its use results in some increase in rotor bending moments, an increase in control loads and reductions of blade stall margins. The impact of ACSR on rotor performance is minimal.

- By its very nature fixed frame HHC will have some impact on the primary flight control system. Any failures of the HHC system must still allow the safe operation of the helicopter. Rotating frame actuation through individual blade control may overcome some of the control system airworthiness problems, but introduce others, such as tab flutter. Since the ACSR system consists of actuators in parallel with existing primary structure, then minimal airworthiness issues are involved.

- Since a rotating frame HHC actuation system operates in series with the existing flight control system, the power requirements necessary to maintain primary control displacements are high. In practice, ACSR will require significantly less hydraulic power, as the actuators apply vibratory loading only, and carry no mean loads.

6. CONCLUSIONS

The principles of Active Control of Structural Response (ACSR) have been established on a Westland 30 series 160 helicopter through a programme of research and flight demonstration. The flight trials demonstrated the significant vibration alleviation potential of ACSR throughout the forward speed range. The ability of the control system to optimise vibration reduction for specific areas of the airframe was demonstrated, whereby average cabin/cockpit vibration was reduced to below 0.09g across the normal speed range. Analysis of the vibration reduction at the selected ten controlled sensor locations, showed consistent reductions in average vibration exceeding 80%. Furthermore, ACSR was shown to be able to maintain significantly reduced vibration levels for a range of manoeuvres, including rapid manoeuvres such as the transition to hover. The active scheme was shown to be superior to the best passive means of attenuation on the Westland 30, namely the rotor-mounted vibration absorber.

These excellent flight test results for ACSR represent a major technical breakthrough in achieving minimal vibration levels for current and future generations of rotorcraft. The benefits which accrue from such reduced vibration levels are many, and include improved crew and passenger comfort, increased component lives, increased systems reliability and reductions in unscheduled maintenance. The use of active vibration control has additional benefits, as the technique can be integrated with a range of technologies now under development such as Health and Usage Monitoring and structural protection. Furthermore, the successful demonstration of ACSR has emphasised its advantages over the alternative active technique, that of Higher Harmonic Control (HHC). The principle advantages of ACSR over HHC are improved performance, lower power requirements, ease of installation and minimal airworthiness impact.

7. ACKNOWLEDGMENTS

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Sensor Location	Direction	Control Sensors	
		Set #1	Set #2
Cockpit Sensors			
Co-Pilots Feet	Vertical	*	*
Co-Pilots Seat	Vertical		
Pilots Feet	Vertical		*
Pilots Seat	Vertical		
Rear Cockpit Centre-Line	Fore/Aft		
Rear Cockpit Centre-Line	Lateral		
Cabin Sensors			
Forward Cabin Floor Port	Vertical		
Forward Cabin Roof Port	Lateral	*	
Forward Cabin Floor Starboard	Vertical	*	
Forward Cabin Roof Starboard	Lateral	*	
Mid-Cabin Floor Port	Vertical		*
Mid-Cabin Roof Port	Lateral	*	*
Mid-Cabin Floor Starboard	Vertical	*	*
Mid-Cabin Roof Starboard	Lateral	*	*
Aft Cabin Floor Port	Vertical	*	*
Aft Cabin Floor Port	Lateral		*
Aft Cabin Floor Starboard	Vertical		*
Engine Sensors			
Engine Power Turbine Port	Vertical	*	
Engine Power Turbine Port	Lateral		
Engine Power Turbine Starboard	Vertical	*	*
Engine Power Turbine Starboard	Lateral		
Tail Sensors			
Tail Rotor Gearbox	Vertical		
Tail Rotor Gearbox	Lateral		
Tail Rotor Gearbox	Fore/Aft		

TABLE I. Westland 30/ACSR Shake and Flight Test, Sensor Set

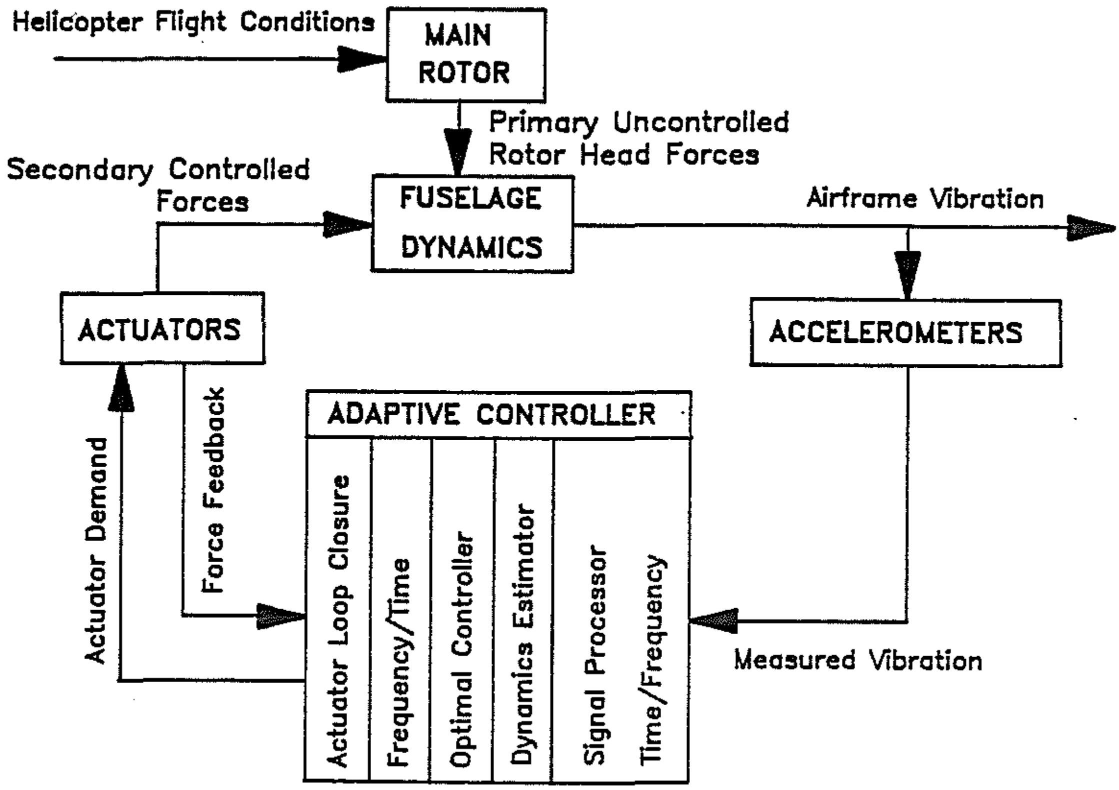

FIGURE 1. ACSR Helicopter System Schematic

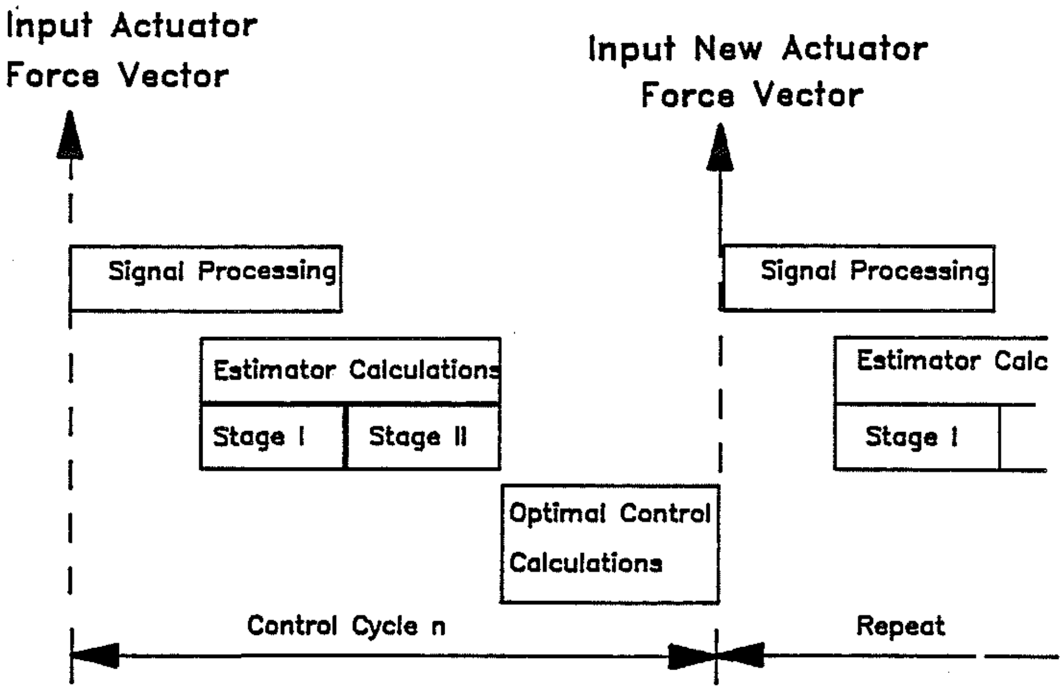

FIGURE 2. Control System Timing Diagram

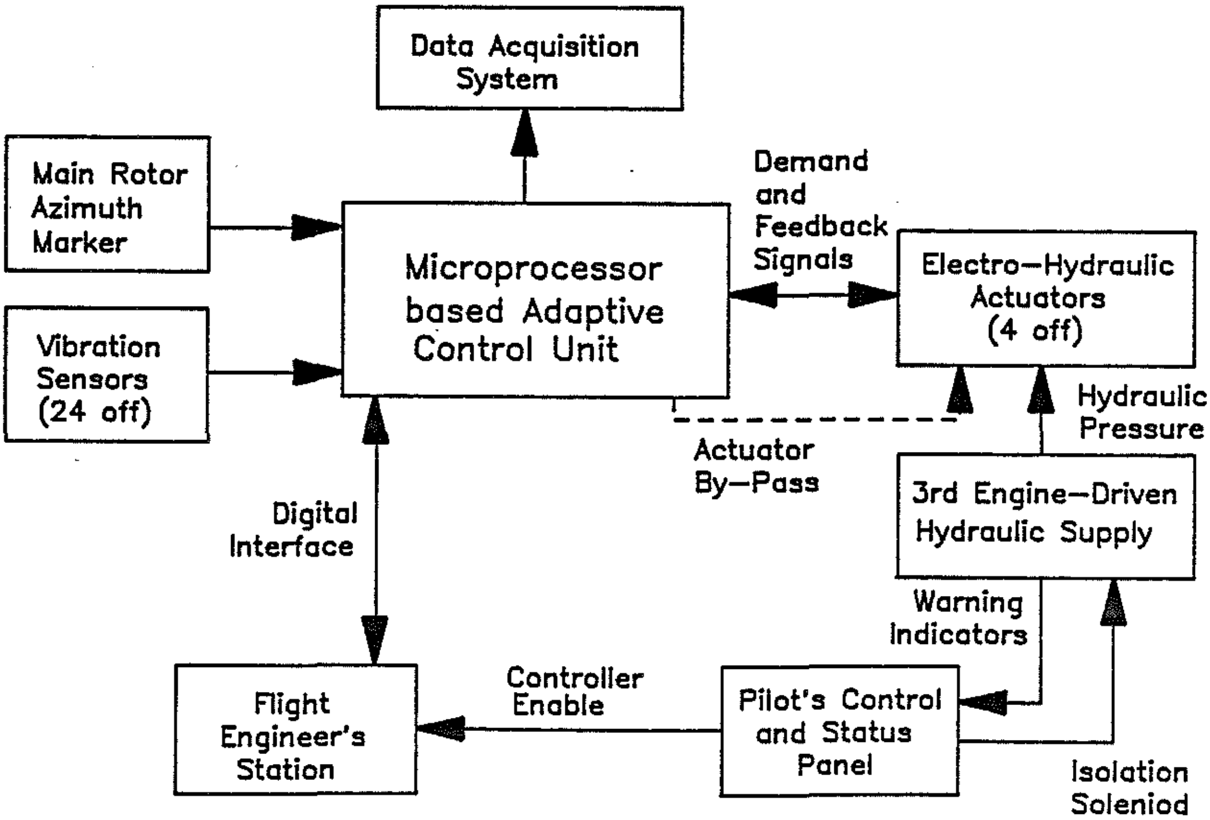

FIGURE 3. Westland 30/ACSR System Installation

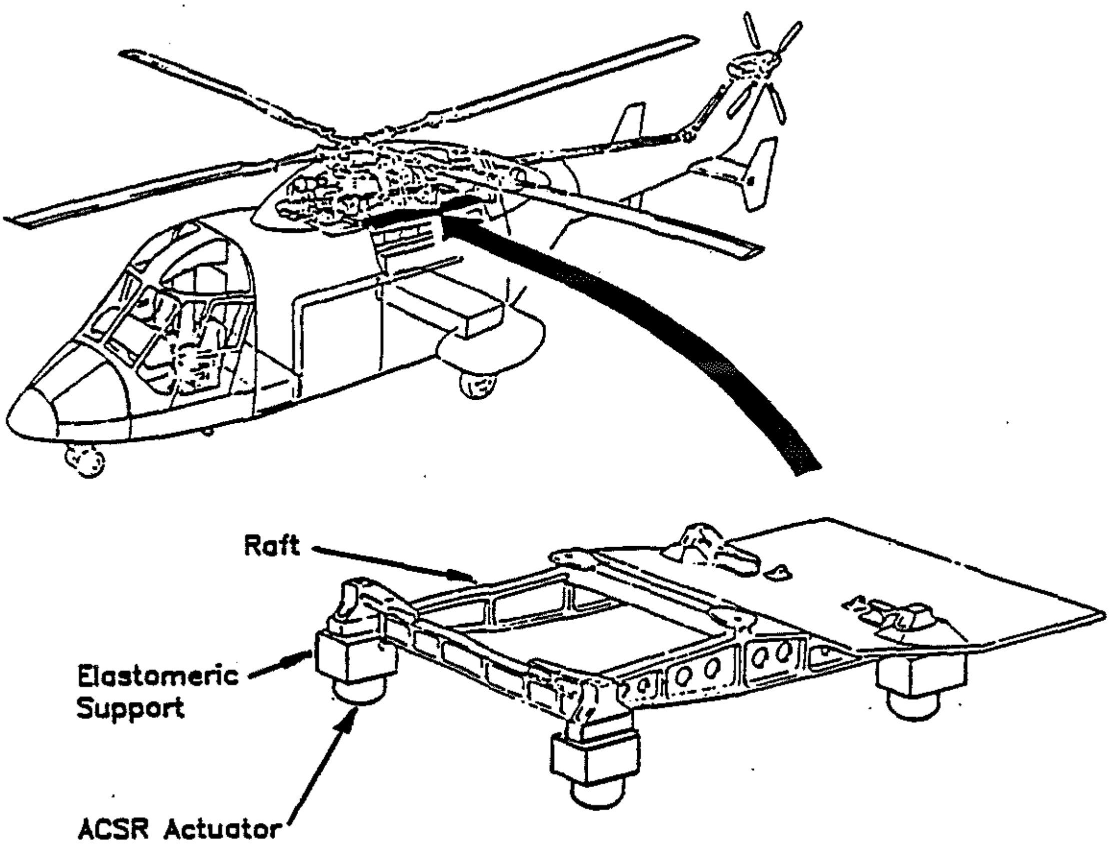

FIGURE 4. Westland 30/ACSR Actuator Location

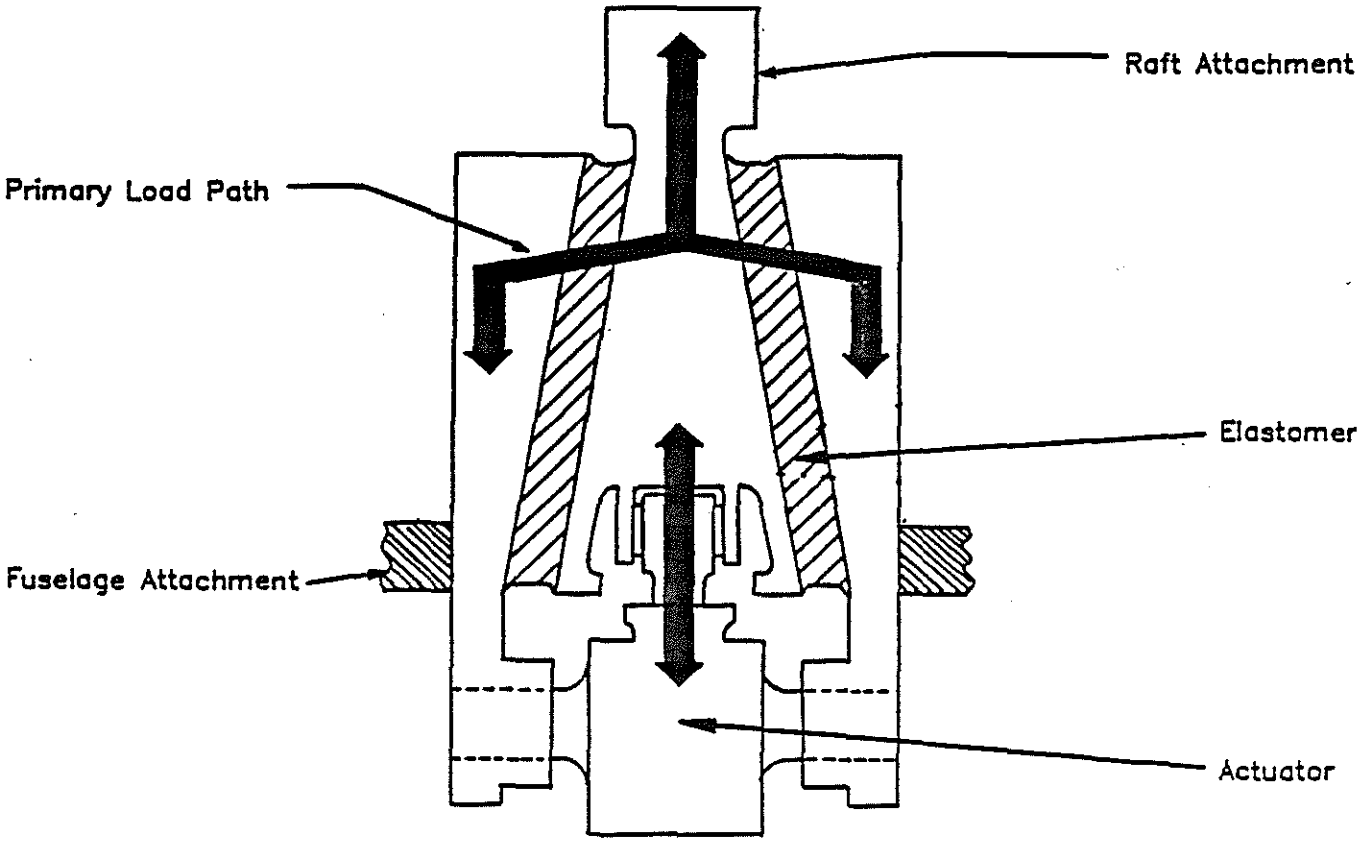

FIGURE 5. WESTLAND 30/ACSR Actuator Installation

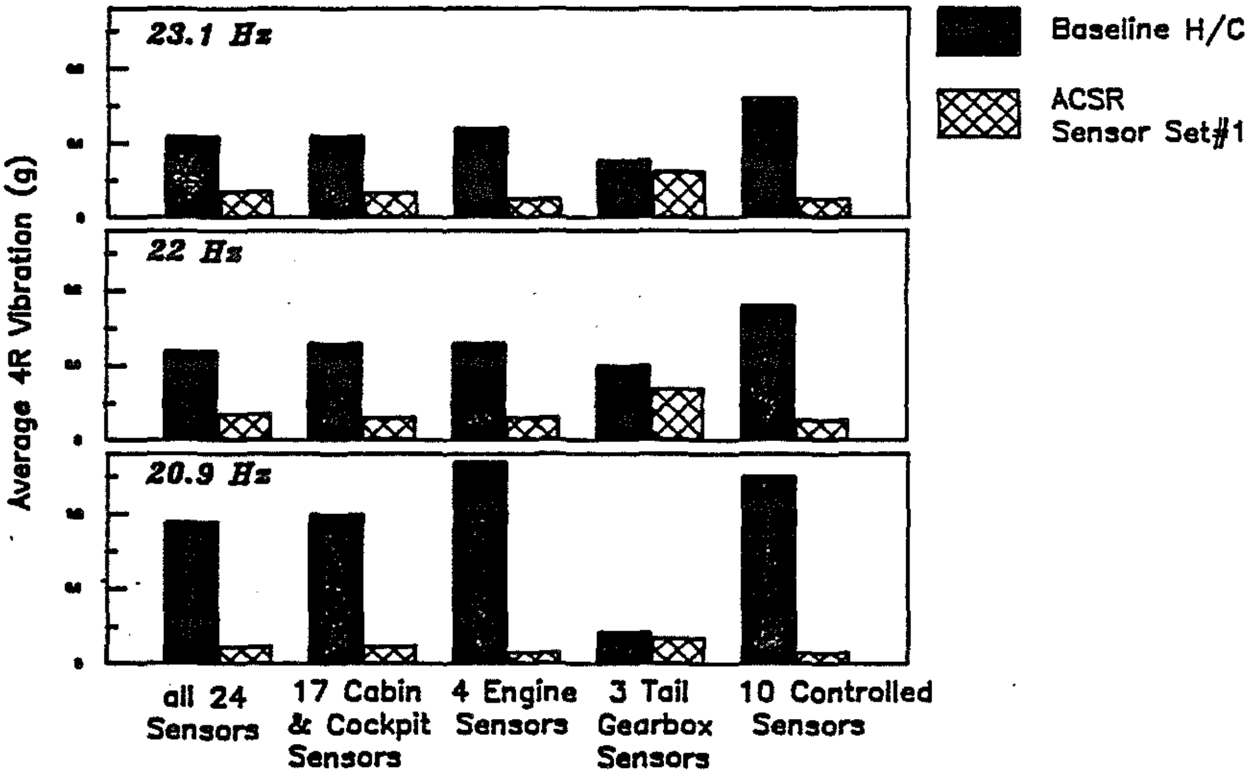

FIGURE 6. Westland 30 ACSR Ground Vibration Test, Performance for 900 N–m Roll Moment

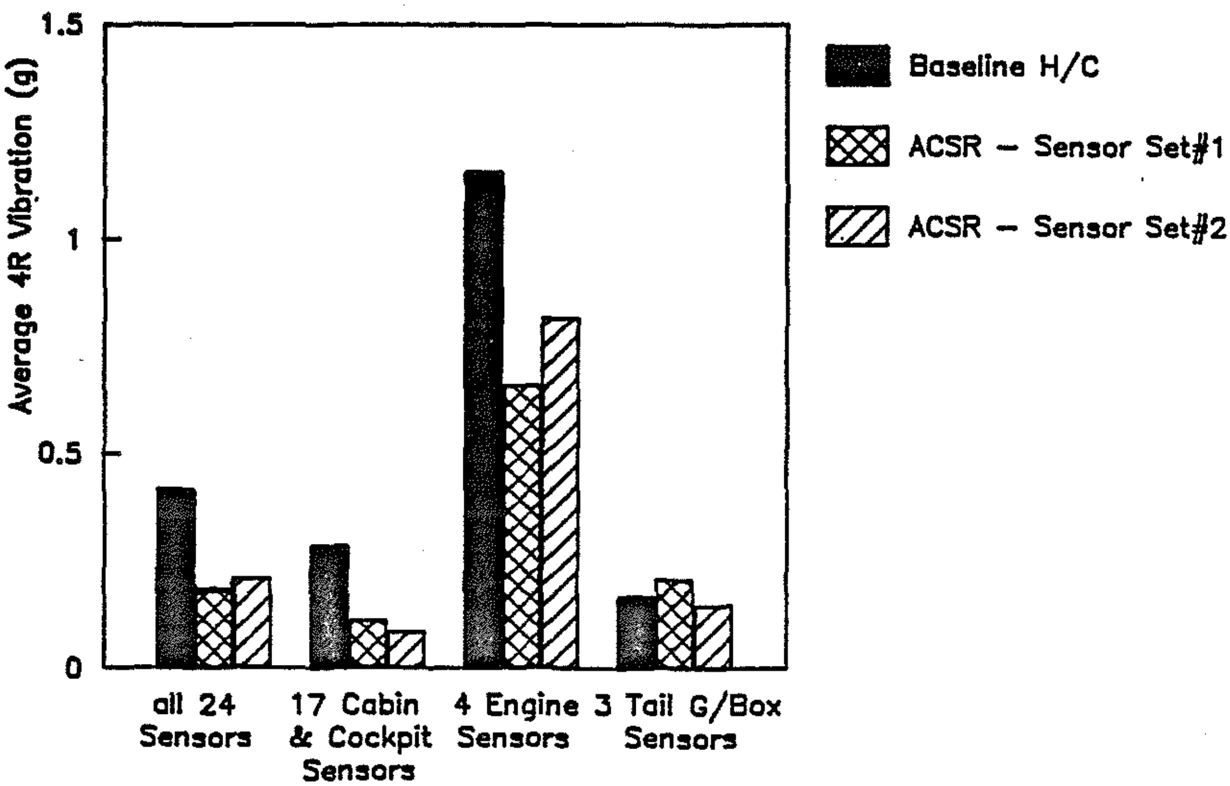

FIGURE 7. Westland 30 Flight Test, Effect of ACSR Sensor Selection @ 80 knots

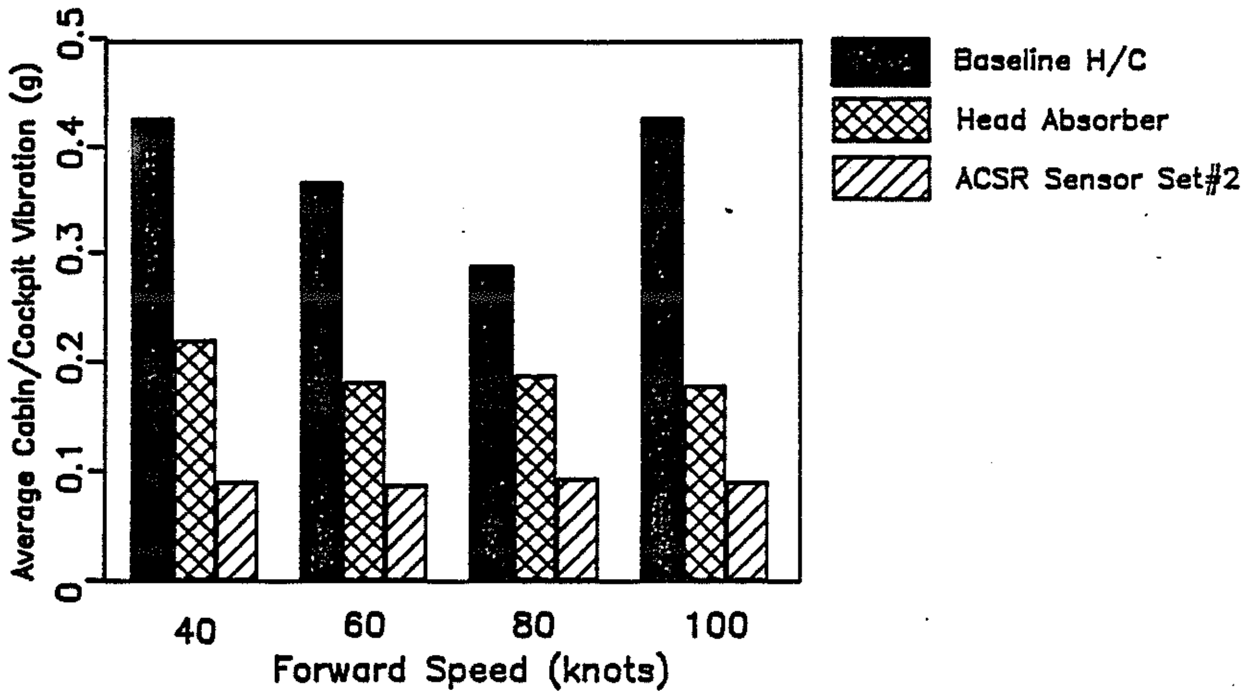

FIGURE 8. Westland 30 Flight Test, ACSR Forward Speed Performance

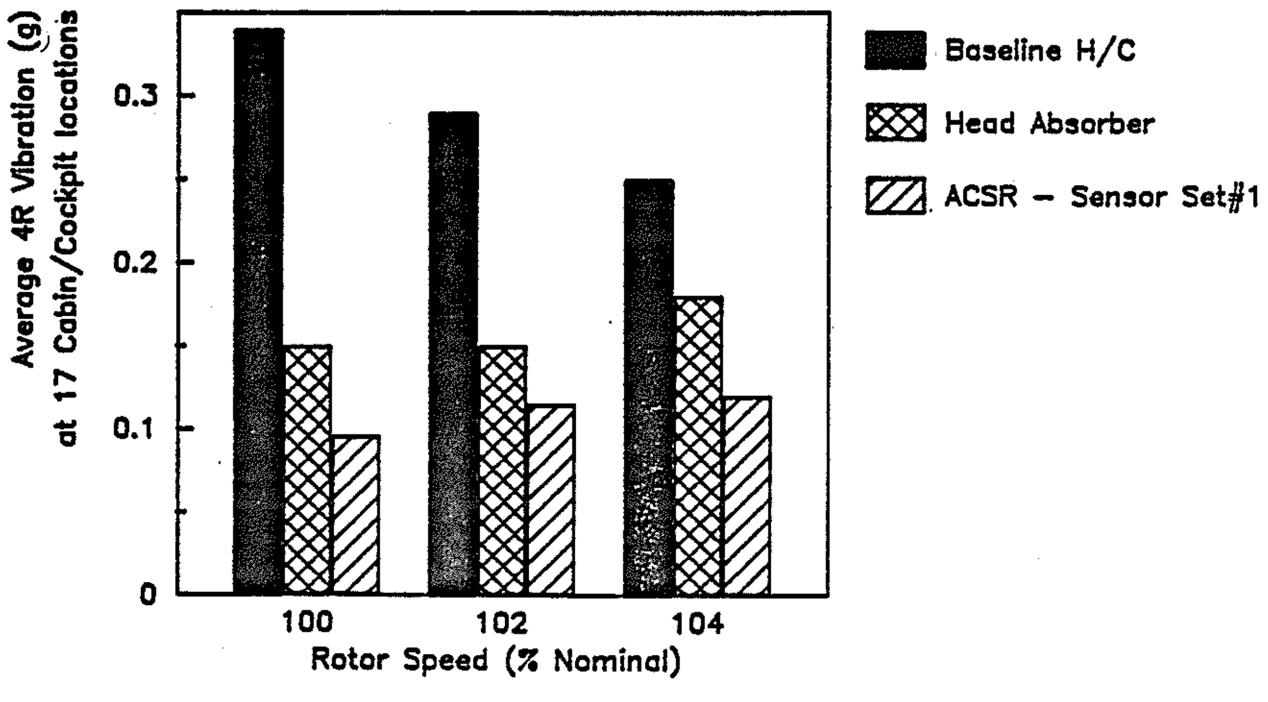

FIGURE 9. Westland 30 Flight Test, Variation in Rotor Speed

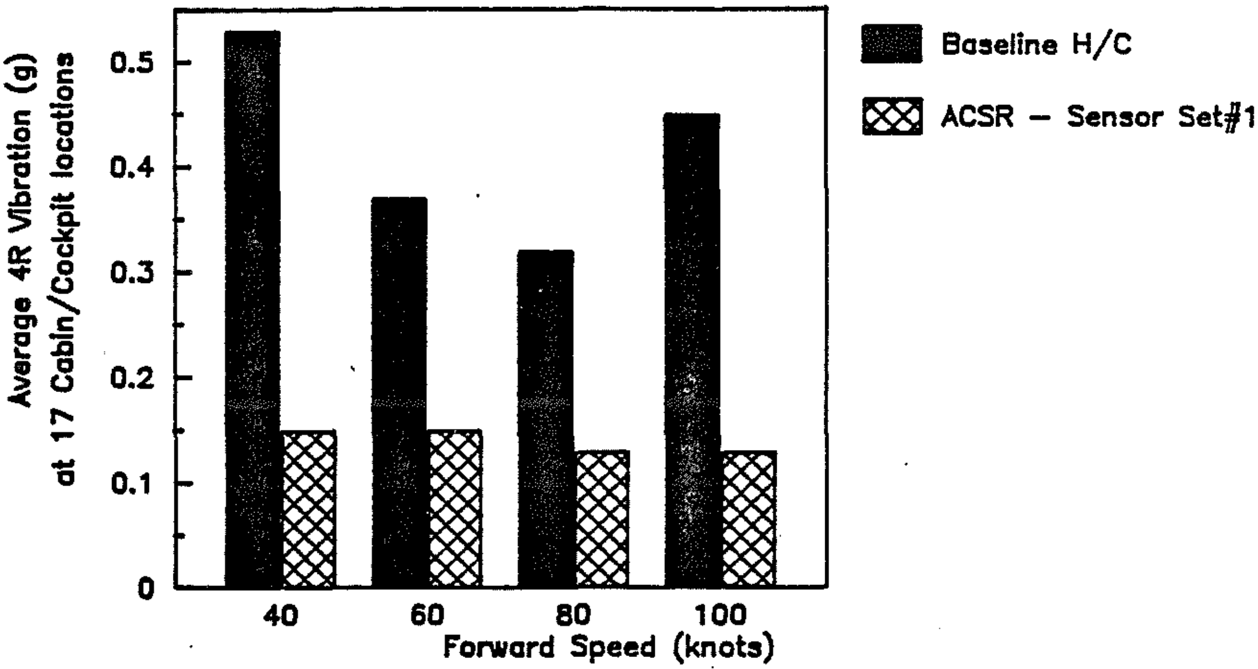

FIGURE 10. Westland 30 Flight Test, ACSR Performance for Modified Aircraft Weight and Distribution

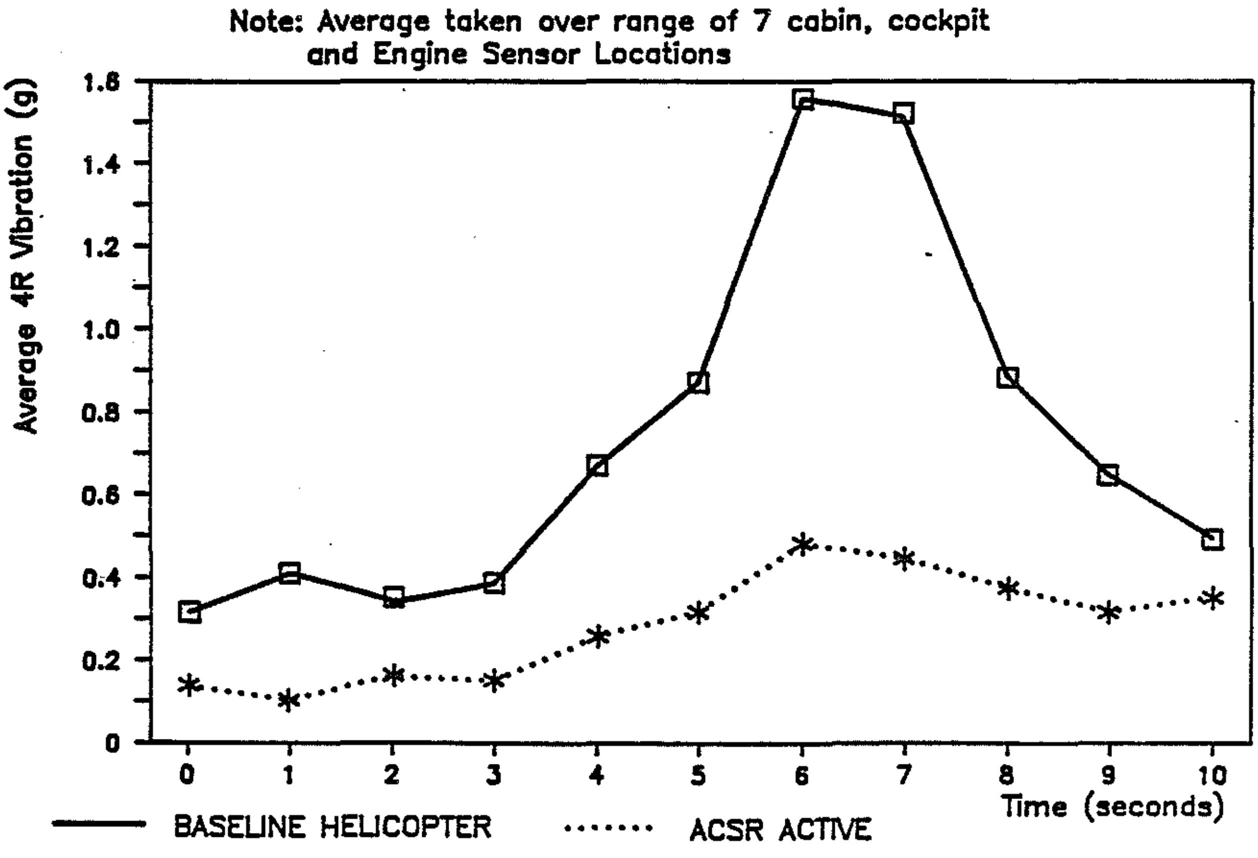

FIGURE 11. Westland 30 Flight Test, ACSR Performance for Transition to Hover Manoeuvre