THE DEVELOPMENT AND TESTING OF AN ACTIVE CONTROL OF STRUCTURAL RESPONSE SYSTEM FOR THE EH101 HELICOPTER

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SUMMARY

The continuing search for a solution to the vibration problems associated with rotary-winged aircraft has resulted in the widespread use of conventional passive vibration devices on in-service helicopters. Many researchers have identified the limitations of the passive technology and hence, the development of active techniques for minimising helicopter vibration has received increasing attention in the last decade. Despite this continuing research effort, the benefits promised by active control have yet to be realised in an in-service application. This paper details the recent developments at Westland of Active Control of Structural Response (ACSR) and provides an insight into the in-service potential for such a system on a new generation rotorcraft, the EH101.

Following on from the successful pioneering flight trials on a Westland 30 helicopter in early 1987, a development and flight test programme was initiated on the EH101 helicopter. The ACSR system installation for the EH101 is detailed and the results of a comprehensive ground and flight test programme are reviewed. In addition, a preliminary evaluation of the potential benefits and costs of the ACSR system for the EH101 is given.

1. INTRODUCTION

The helicopter suffers inherently from vibration, generating its own rough ride as a natural consequence of aerodynamic forces arising from flying the rotor disk edgeways through the atmosphere in forward flight. Despite careful rotor and airframe design, an unsatisfactory level of vibration is often transmitted to the airframe, degrading passenger comfort, crew performance and reliability of dynamic and avionic systems. The vibration environment is dominated by distinct harmonics of the main-rotor rotational frequency (R), the most dominant usually being the blade passing frequency bR (where b is the number of blades).

Although the application of improved dynamic modelling techniques has led to improvements in the basic vehicle vibration environment, the tendency to expand the flight envelope has generally aggravated the vibration problem. The trend for increased forward speed combined with the requirement for extended mission endurance has resulted in ever more stringent vibration specifications. A widely adopted industry standard (applicable to the EH101 helicopter) is MIL-H-8501A which places an upper limit on the blade passing frequency vibration in the cabin and cockpit of 0.53 inches per second (0.15'g' at 17.5 Hz, the EH101 blade passing frequency). However, the use of improved design techniques has not provided the much sought after breakthrough and thus, the use of palliative passive vibration alleviation devices is widespread. A prime drawback of such devices is that they may be optimised for a particular operating condition and variations from normal operation result in performance degradation, since they are unable to adapt. Furthermore, their performance is often constrained by considerations of parasitic weight and in the case of the rotor mounted absorber, drag. In many helicopters, the weight penalty associated with achieving satisfactory levels of vibration can be considerable, in excess of 1% of aircraft gross weight. In fact, the current industry specifications probably represent the limit of that achievable with current passive vibration alleviation technology.

With the advent of active vibration

alleviation techniques, such as ACSR, it is anticipated that cabin vibration levels of below 0.05 g will become a reality for the next generation of rotorcraft. Indeed, the adoption of more rigorous vibration standards, such as the US Army design standard ADS-27, represents a more challenging task for the helicopter designer, and one which may only be met through the use of active vibration control techniques. The relative severity of the helicopter vibration environment is most pronounced when comparing with passenger aeroplanes, where vibration levels rarely exceed 0.01g, an order of magnitude lower than most passenger helicopters. Therefore, the potential benefits of active vibration control techniques applied to the helicopter may go some way toward the more widespread acceptance of the helicopter as a passenger carrying vehicle. The need for minimal vibration levels is particularly important for passenger helicopters, such as the civil EH101 which is expected to set new standards for safety, comfort and reliability.

The main principle of the active vibration alleviation techniques employed is that they apply controlled secondary excitations to cancel the effect of vibration generated by the primary uncontrolled excitation from the main rotor. Unlike passive techniques (where the device effectively responds mechanically through feedback of vibration local to the device), the active techniques are usually based on the feedback of vibration from sensors dispersed around the airframe, and therefore, will adapt the secondary excitation to account for changes in vehicle operating condition.

A variety of implementation schemes have arisen through differing cancellation philosophies. Much of the early work concentrated on Higher Harmonic Control (HHC), a technique based on the application of vibratory motions to the main-rotor, which attempts to cancel vibration at source. Other researchers have focused on the active isolation of the airframe from the vibration source. However, both these techniques suffer from performance constraints, the former in terms of power requirements and limited high-speed performance and the latter in terms of the high weight requirement for effective isolation of all the vibratory loading paths. It was for these reasons that Westland has been developing a unique active technique, termed Active Control of Structural Response (ACSR), which overcomes the difficulties associated with these alternatives. The ACSR technique differs in that it is based on the superposition of the primary uncontrolled vibration response and the controlled secondary vibration response, controlled in such a way that the vibration is minimised throughout the airframe, as shown schematically in figure 1. In this respect, ACSR differs from HHC as the controlled forces are applied directly to the structure across or at points which possess relative motion in all the dominant vibratory modes. Furthermore, ACSR differs from active isolation since it does not attempt to directly control the vibratory load paths across an isolation interface.

The ACSR technique was first successfully flight tested on a Westland 30 helicopter in early 1987, which demonstrated reductions in average blade passing frequency vibration in the cabin and cockpit area of 72 to 84%, to a level below 0.09g independent of forward speed (reference 1). Subsequently, ground vibration test programmes on a Sikorsky S-76 (reference 2) and the Westland Lynx have demonstrated the general applicability of the technology and further enhanced the system performance. In the former case it was particularly noteworthy that the system was optimised to meet the ADS-27 requirements, exceeding the specification in many areas.

2. THE EH101 VIBRATION CONTROL PROGRAMME

As part of the EH101 development activity an integrated vibration reduction programme is being pursued to achieve vibration levels below the specification requirements. In particular, the primary focus of this activity has been to reduce the cabin and cockpit 5R vibration levels to below 0.15g throughout the normal forward speed regime. Early flight trials on the basic untreated aircraft indicated that the 5R vibration levels were unacceptable. The initial development activities were concerned with the quantification of the airframe dynamic characteristics, through a modal survey of a representative airframe, and optimisation of the airframe structure (reference 3). Airframe optimisation has provided improvements in vibration in critical airframe regions, such as the engines but the effects are usually localised. Subsequently, a number of passive devices have been flight tested, including cabin and rotor-head mounted absorbers. Although the head absorber yielded major improvements in the airframe 5R vibration, additional passive treatment would be required to achieve the stated vibration standard.

The timely ACSR proof-of-concept demonstration on the Westland 30 prompted a feasibility study into the application of ACSR to the EH101, which indicated the potential of ACSR to greatly reduce 5R vibration levels in the airframe. A flight demonstration programme was initiated in late 1988 and culminated in the first flight of ACSR on PP3 in March 1990. The trials illustrated the performance advantages of ACSR in comparison to the previously tested passive techniques, generally reducing 5R vibration to below the specification requirements, as detailed in section 4. It is now intended to retro-fit the EH101 development fleet and work has commenced to optimise the ACSR system for incorporation into the basic aircraft standard. Despite the successful application of ACSR it is intended to continue refining the basic airframe modelling and structural optimisation to achieve the optimal baseline airframe vibration standard.

3. EH101-ACSR SYSTEM DESCRIPTION.

The major aspect that critically affects the successful performance of any ACSR installation is the positioning of the actuators within the structure in question. The ACSR feasibility study conducted for EH101, based on forced response simulations using a finite element (NASTRAN) generated dynamics model of the EH101, identified the configuration of an ACSR actuator placed in parallel with each of the four main gearbox support struts as offering potentially significant vibration reductions, as well as being a practical installation.

The design and manufacture of the integral strut/ACSR actuator was carried out by WHL in conjunction with MOOG Controls Ltd., the latter being solely responsible for the actuator. In parallel with this activity, the development of the ACSR adaptive control unit was undertaken by Normalair-Garrett (a company within the Westland Group), leading to a light, robust and fully flightworthy unit with significantly enhanced capabilities when compared to the previous experimental unit tested on the Westland 30. In total, the incremental weight of the development standard ACSR system fitted to PP3 is approximately 1% of gross aircraft weight, this relatively high figure caused by the integral strut/actuator being necessarily conservatively designed in the absence of detailed design criteria.

3.1 ACSR System Functional Configuration.

The functional configuration of the EH101 ACSR system is shown in figure 3. The central element of the system is the adaptive control unit, whose primary function is to determine and schedule the vibration controlling force demands to the four ACSR actuators, based on the vibration information provided by ten airframe accelerometers. The control unit operates at up to four harmonics of the fundamental main rotor frequency, for which information is provided by an existing rotor speed sensor incorporated in the main gearbox. A Pilot Control Panel gives the pilot top level control of ACSR operation, and an optional Test Interface Terminal permits interactive set-up, running and optimisation of the ACSR system in flight by a flight test engineer.

3.2 ACSR Adaptive Control Unit and associated peripherals.

As the heart of the ACSR system, the control unit monitors vibration from a number of accelerometers, calculates and schedules the vibration reducing force demands to the ACSR actuators and self-adapts its control algorithm to maintain optimum performance against varying flight conditions and aircraft weight and centre of gravity. The system operates in the frequency domain on vibration at distinct harmonics of the main rotor fundamental frequency, which in the case of the EH101 is 3.5Hz. Operation is on a cyclic basis, and the cycle update time can be varied between 0.5 and 0.8 seconds, the minimum being dictated by the requirement to accurately measure and extract the required frequency components from the total vibration time history.

During each cycle, and following the self-adaptation of the model of the structural dynamics, the actuator demands for the next cycle are calculated. These are based on the minimisation of a performance index consisting of a weighted sum of the measured vibration and the ACSR actuator forces. Off-line manipulation of the accelerometer and actuator weighting matrices enables optimisation of ACSR system performance and these matrices are part of a set of parameters covering various aspects of ACSR system operation. Three default parameter sets are pre-programmed into the control unit, which can be selected and edited during flight if required.

The control unit requires information on the main rotor fundamental (1R) frequency for the discretisation of both accelerometer inputs and actuator demand outputs. This is provided by a sensor in the main rotor gearbox via the Rotor Timing Interface Unit (RTI), which phase-locks the control unit frequency domain operation to the main rotor rotational speed, and allows immediate tracking of rotor speed changes. Both the control unit and the RTI are mounted in the main avionics cabinet, the control unit being packaged in 3/4 ATR format and weighing approximately 5Kg.

Operation of the control unit is governed in the first instance by the pilot via a master 'On/Off' switch on the Pilot Control Panel (PCP). In addition, the PCP incorporates a 'mode' switch, with indicator lamps, for the selection of the desired set of algorithm defaults and indication of the failure status of the ACSR system.

Normal operation of the control unit is in 'standalone' mode, whereby the ACSR system functions in continuous and autonomous (subject to overall Pilot control via the PCP) closed-loop vibration control mode based on the chosen default algorithm set-up, and provided that the main rotor speed is within a prescribed range (nominally >90% of normal rotor speed, Nr). To facilitate the test evaluation of the ACSR system, the control unit is configured with an alternative 'test' mode, which is automatically invoked on connection of the Test Interface. This consists of a VDU and keyboard mounted on top of the main instrumentation console in the cabin. In 'test' mode, the flight test engineer has secondary control of the ACSR system via the keyboard, and menu based software allows execution and termination of the closed-loop operation, and editing of the algorithm parameter set up for performance optimisation of the ACSR system or to test various aspects of operation. During closed-loop vibration control, various ACSR parameter data are displayed on the VDU and are updated on a periodic basis. Data can be permanently recorded by the use of portable battery operated printer.

The ten ACSR accelerometers are a flight-proven inertial type and are located at strategic points within the aircraft, including the cockpit and cabin floor, the top structure and tail rotor gearbox.

Additional looming is incorporated into the main conduits, and the ACSR system uses both the 115V 400Hz AC and 28V DC electrical supplies; power requirements are minimal.

3.3 Integral Actuator / Strut.

The ACSR main gearbox support actuator/strut configuration is depicted in figure 3, the combined unit being an assembly of three components - the compliant 'ring' element, the force-generating actuator and the strut down tube. In common with other ACSR helicopter applications, the actuator is mounted in parallel with the primary load bearing compliant element, and is simply required to input the controlling vibratory forces while accommodating quasi-static primary flight loads.

The design of the actuator and strut was carried out in an integrated fashion with MOOG Controls, particularly in respect of the ring element stiffness and the actuator 5R force amplitude capability. The design criteria were generated from the feasibility study, since no relevant flight data were available. The EH101 ACSR feasibility study identified a roughly linear relationship between ring element stiffness and actuator force for vibration control, and this has led to an actuator design capable of about 30 kN force amplitude at the 5R blade passing frequency of 17.5Hz, in association with a ring element stiffness of about 91 kN/mm (cf. average 200 kN/mm for standard struts).

The actuator is a dual-chamber single-piston electro-hydraulic type, is controlled by a MOOG Series 30 servo-valve, and incorporates pressure transducers for force feedback and an isolating solenoid valve; operation of both the servo-valve and solenoid valve is signalled by the ACSR control unit. The actuator is divided into two sub-assemblies, the chamber/piston and the control block, the latter incorporating the servo-valve, solenoid valves, pressure transducers, pressure relief valve and connections to the hydraulic supply. MOOG have embodied novel sealing and surface finish techniques for long life under continuous high frequency operation.

Mechanical connection between actuator and strut is made by the piston rod to ring element lug end joint, with the actuator body clamped at the flange joint between the ring and tube elements.

Hydraulic power is provided by the aircraft's number 3 system, which also powers the rotor brake and undercarriage, and minimum length hydraulic circuits were incorporated to route hydraulic fluid to the actuators. The maximum power consumption of the ACSR system has been conservatively estimated at 5kW.

3.4 Failure Monitoring and Safety Features.

Two levels of failure status are indicated by the control unit at the PCP, namely, Built-In-Test (BIT) and SYSTEM fail and the control unit continuously monitors both itself and its ancillary hardware during closed-loop operation. The control unit checks the received signals against preset limits, and if an accelerometer signal exceeds the 'g' limit or an actuator pressure feedback signal exceeds full system pressure, the control unit will indicate a BIT fail. In this event, the particular device is, in effect, switched off by the control unit, which subsequently adapts itself to the failure condition while continuing closed-loop vibration control. In the event of a preset number of cumulative BIT failures, or if certain other ACSR operation-critical failure conditions occur, the control unit will indicate a SYSTEM fail and shut down.

It is theoretically possible for the ACSR system to fail in closed-loop in such a manner that incorrect actuator forces are applied. In this event, if vibration increases significantly, multiple accelerometer BIT failures will be followed by a SYSTEM fail. This in-built safety mechanism is augmented by the Pilot's top level control, whereby the system can be simply disabled at any time via the 'On/Off' switch on the PCP.

The ACSR main gearbox support strut/actuator has been designed and tested to the original static and increased fatigue load specifications, and the actuator, since it is mounted in parallel with the primary load path, is not a flight critical component and thus airworthiness issues are minimal.

A non-recoverable failure of the ACSR system will cause a reversion to baseline levels of vibration. While the structural health of the aircraft will be minimally affected, the Pilot and passenger discomfort can be minimised by reducing speed to a more benign flight condition.

4. ACSR DEVELOPMENT TEST PROGRAMME.

Following the feasibility study that defined the basic ACSR actuator installation, the next phase of the EH101 ACSR programme was a ground-based vibration 'shake' test. This stage is vital in any ACSR programme, in order to validate in particular the actuator installation and to provide a practical indication of the potential ACSR vibration reduction performance in flight. In the case of the EH101, the detail design (followed by component manufacture) and the shake tests were conducted in parallel, with final assembly of the development standard ACSR system held until the shake tests were satisfactorily concluded in autumn 1989. Final manufacture and installation of the ACSR system on PP3 was conducted during early 1990, and a 14 hour flight evaluation was performed during March/April 1990. The results of these tests are described below.

4.1 Ground-based 'Shake' Test.

A flight representative airframe was used in conjunction the experimental standard ACSR hardware previously employed in the Westland 30 ACSR demonstration, in 'free-free' vibration tests, the airframe being hung via a dummy main rotor-head by a very low frequency suspension arrangement.

The major emphasis of the shake test was to assess the ACSR 5R vibration reduction performance for the six main rotor-head forcing directions. Each forcing direction was tested separately using representative 5R force magnitudes applied to the rotor-head by electromechanical shakers.

The results proved very encouraging, with significant vibration reductions achieved for all forcing directions bar that of yaw. Figure 4 shows predicted average baseline and ACSR-reduced vibration levels for straight and level flight at 140kts, based on the reductions measured in the shake test and scaled according to the predicted main rotor 5R flight loads. This represents a 'worst case' algebraic summation, but the results were impressive, indicating a 90% vibration reduction in the cockpit and cabin and 75% for the airframe as a whole (including engines). This, together with satisfactory multi-frequency and transient performance observed gave the necessary confidence to commit fully to the procurement, installation and flight test of the development standard ACSR system on PP3.

4.2 Flight trials on PP3.

Following installation on PP3 and a short period of system integration tests, the 5R vibration reduction performance of the ACSR system was assessed against the following flight envelope :

- straight and level forward speeds in the range 40 to 160 kts at 2000 feet altitude.
- basic manoeuvres, including take-off and landing, max. power climb, banked turns, autorotation and transition-to-hover.

In addition, various aspects of ACSR system operation were investigated, including :

- Optimisation of actuator and sensor weightings.
- Degraded operation, three-actuator system.
- Multi-frequency 5R and 10R operation.

The results for the steady state conditions were most impressive, and confirmed the potential indicated by the 'shake' test predictions. Figures 5 to 8 show the 5R vibration levels for ACSR and the baseline aircraft at 13,000Kg all-up-weight. It can be seen from figure 5 that significant reductions in 5R vibration are achieved, with the Co-Pilot seat vertical vibration reduced from 0.38 'g' to 0.10 'g' at 40 kts and from 0.85 'g' to 0.07 'g' at 140kts, representing 74% and 92% reduction respectively.

An examination of the vibration averages shown in figure 6 reveals substantial reductions for the ten ACSR control locations (between 59 and 88%), for the cabin and cockpit (between 61 and 75%) and for the aircraft as a whole, including engines and gearboxes (52 to 75%). Of most significance is the result for the cockpit and cabin, where average vibration is maintained well below the 0.15 'g' specification throughout the speed range tested, although at a few locations, the reduced vibration was still slightly above this level at the 40 knot condition.

Improvements in vibration reductions in the cockpit and cabin were achieved by adjusting the ACSR accelerometer control weightings, but these were marginal and led to slight degradations of the reduced levels elsewhere in the aircraft.

The actuator degraded operation tests were aimed at establishing the loss of vibration control following an actuator failure, but also to assess the potential of a three-actuator based system. This was carried out by weighting out the actuators in the ACSR control algorithm in turn. Results for straight and level flight for the least degrading case, removal of the aft starboard actuator, are given in figure 7. It is clear that the ACSR system performs equally well without this actuator, giving confidence in the validity of this configuration as the basis for an eventual production standard ACSR system for the EH101.

For the majority of the manoeuvre cases, the ACSR system maintained significantly reduced levels of 5R vibration, the benefits being most marked in take-off and power climb. However, the performance of ACSR in the transition-to-hover was not as impressive since the actuators were operating at full capacity due to the very high peak baseline vibration levels. Even so, useful reductions, in the order of 50%, were achieved, as figure 8 shows.

Multi-frequency operation at 5R plus 10R was assessed against the forward speed range. Though not presented here, the results were satisfactory, with the low baseline 10R vibration reduced by approximately 50% to levels probably at the noise threshold of the ACSR system, while the 5R performance was unchanged from the single frequency operation.

The subjective reactions of the flight crew were very favourable, with Cooper-Harper vibration ratings reducing from 5/6 at 40kts, 4 at 80kts and 7/8 at 140kts to level 2 or less throughout the entire speed range for ACSR operation. Visiting pilots and other passengers reiterated this response, and it was claimed by at least one person that with ACSR operating, PP3 had the most benign vibration environment of any helicopter he had experienced.

Further flight testing is planned, aimed at improving ACSR performance in both steady-state and manoeuvre conditions, particularly for the transition-to-hover. The former is to be achieved by investigating alternative locations for the ACSR control sensors, while the latter may require redesign of the integral actuator/strut to provide increased ACSR authority. These development activities will lead to the definition of a production standard system, and in this context, the best three-actuator based ACSR system is to be pursued given the obvious benefits on terms of overall system complexity, weight, reliability and cost.

5. AN ASSESSMENT OF THE BENEFITS AND COSTS OF ACSR

The benefits associated with an improved rotorcraft vibration environment for the pilots, aircrew and passengers are obvious, although they may be difficult to quantify. However, the wider impact through improvements to the vehicle reliability and maintainability are more readily apparent. A comprehensive test programme conducted on a fleet of CH-3 aircraft (reference 4), comparing the failure rates for a untreated aircraft and a rotor-mounted absorber equipped aircraft have shown a direct correlation between reduced vibration and reduced failure rates. The vibration levels on the absorber equipped aircraft were of the order of 54% lower than the baseline, resulting in a reduction in the overall failure rates of 39% and a subsequent reduction in life cycle costs of around 10%. Similar results have been obtained on the Lynx with a head absorber fitted. Clearly, the additional performance improvements offered by ACSR in comparison to the head absorber, should yield further reductions in unscheduled maintenance and an an additional incremental reduction in the vehicle life cycle costs. These improvements in vehicle reliability would more than adequately offset the higher initial system costs and complexity compared to the alternative passive treatments.

In comparison to the alternative passive vibration control techniques, apart from the improved levels of steady state attenuation, ACSR is able to adapt to changes in flight condition, structural dynamics and rotor speed, and thus will always operate at the minimal vibration condition. Furthermore, the ACSR system is able to operate at a multiplicity of frequencies; a capability which is not available on passive devices without large increases in their complexity and size. The ability to optimise the system for particular areas of the airframe provides an added benefit for multi-role vehicles where the system can be easily tailored to specific mission requirements.

In addition to the performance benefits of ACSR, the weight penalties for an ACSR system are generally lower than those associated with the most effective passive schemes. Typically, the weight penalty of an optimised ACSR installation would be in the range of 0.6 to 0.8% of gross aircraft weight, in comparison with passive treatments which range from 1 to 3%. The improved effectiveness of ACSR compared to the best passive approach is illustrated by the EH101 analysis, where the ACSR system provides in excess of 0.85% reduction in average vibration per kg of incremental weight, as opposed to a maximum effectiveness for the head absorber of 0.31%/kg.

6. CONCLUSIONS

Flight trials of a pre-production standard ACSR system on the EH101 helicopter have shown excellent vibration reductions. Average 5R vibration levels in the cabin and cockpit have been reduced by 75% or more at the cruise speed of 140 knots, for a range of aircraft all-up weight conditions. In particular, the vibration levels were generally reduced to below the target requirement of 0.15'g' throughout the forward speed range and in some areas of the airframe, levels were reduced to below 0.05'g'. The multi-frequency capabilities of the system have also been demonstrated through effective simultaneous control of both 5R and 10R forcing components. Furthermore, very good 5R reductions were achieved for a range of manoeuvring flight regimes.

The vibration reduction performance of ACSR has been shown to be superior to the best passive technique, namely the rotor-mounted absorber. If a passive solution were to be incorporated onto the aircraft then a substantial weight penalty would be required to meet the specification and therefore, ACSR represents the most effective alleviation technique. The ability of ACSR to meet the vehicle vibration standards and in many areas exceed the requirements provides comfort levels on the EH101 that are well beyond those achieved on comparable current generation aircraft. Furthermore, the potential for improvement in aircraft reliability, reductions in maintenance effort should provide a consequent benefit to the operator in terms of reduced lifecycle costs.

Currently a retro-fit programme is underway to equip all the EH101 pre-production aircraft with ACSR and development activities are planned to further optimise ACSR performance. The demonstrated benefits of ACSR have led to the decision to include the system as part of the basic aircraft fit and thus, it is envisaged that the vibration environment of the EH101 will set new standards for the next generation of rotorcraft.

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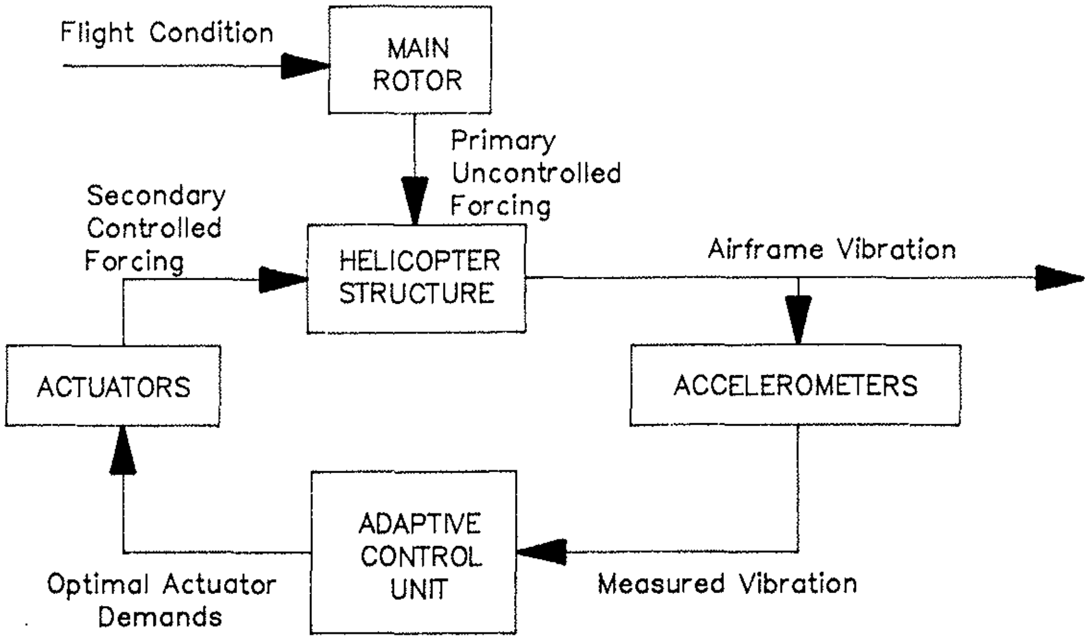

FIGURE 1 : ACSR OPERATIONAL PRINCIPLES

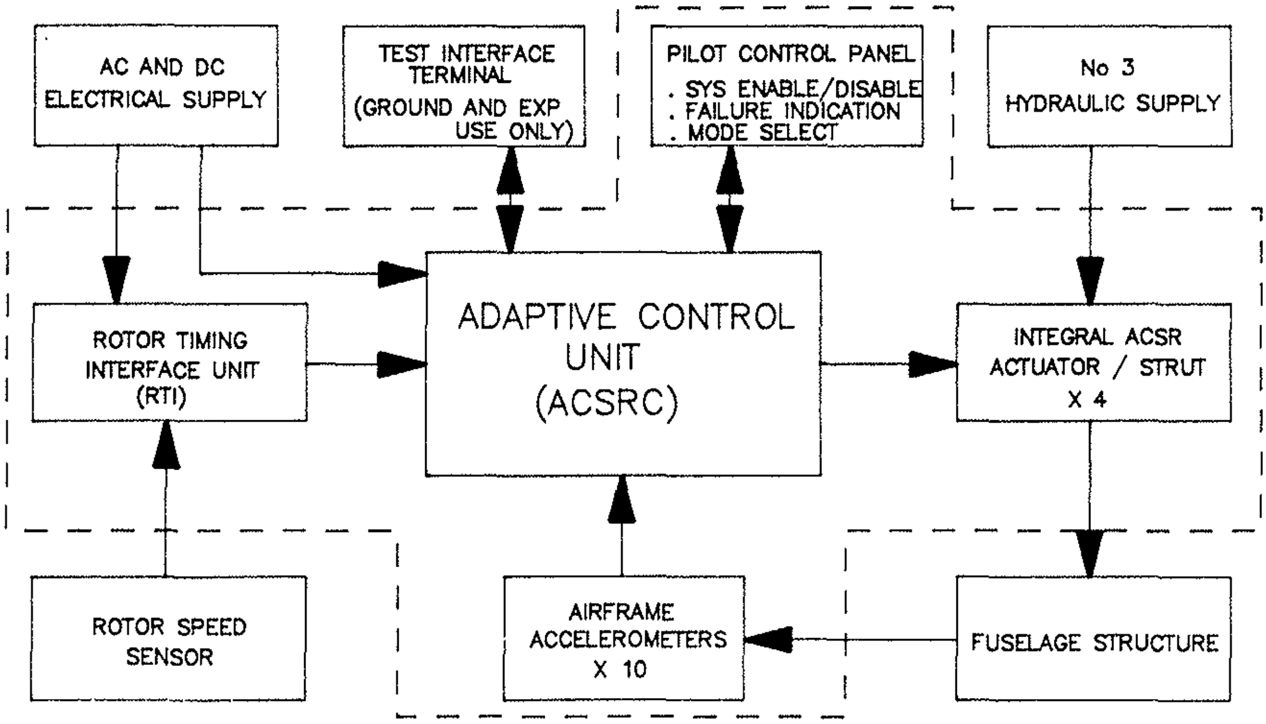

FIGURE 2 : EH101–ACSR SYSTEM INSTALLATION SCHEMATIC

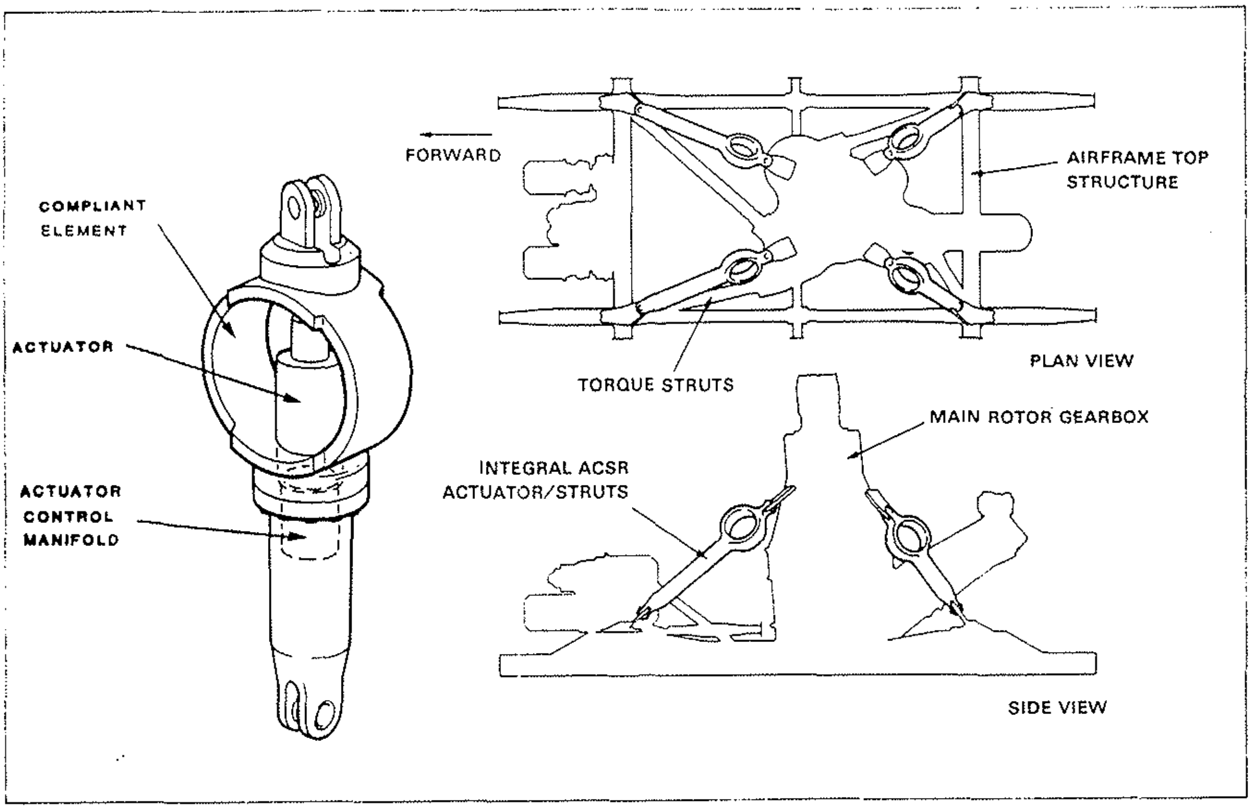

FIGURE 3 : EH101–ACSR INTEGRAL STRUT/ACTUATOR AND CONFIGURATION

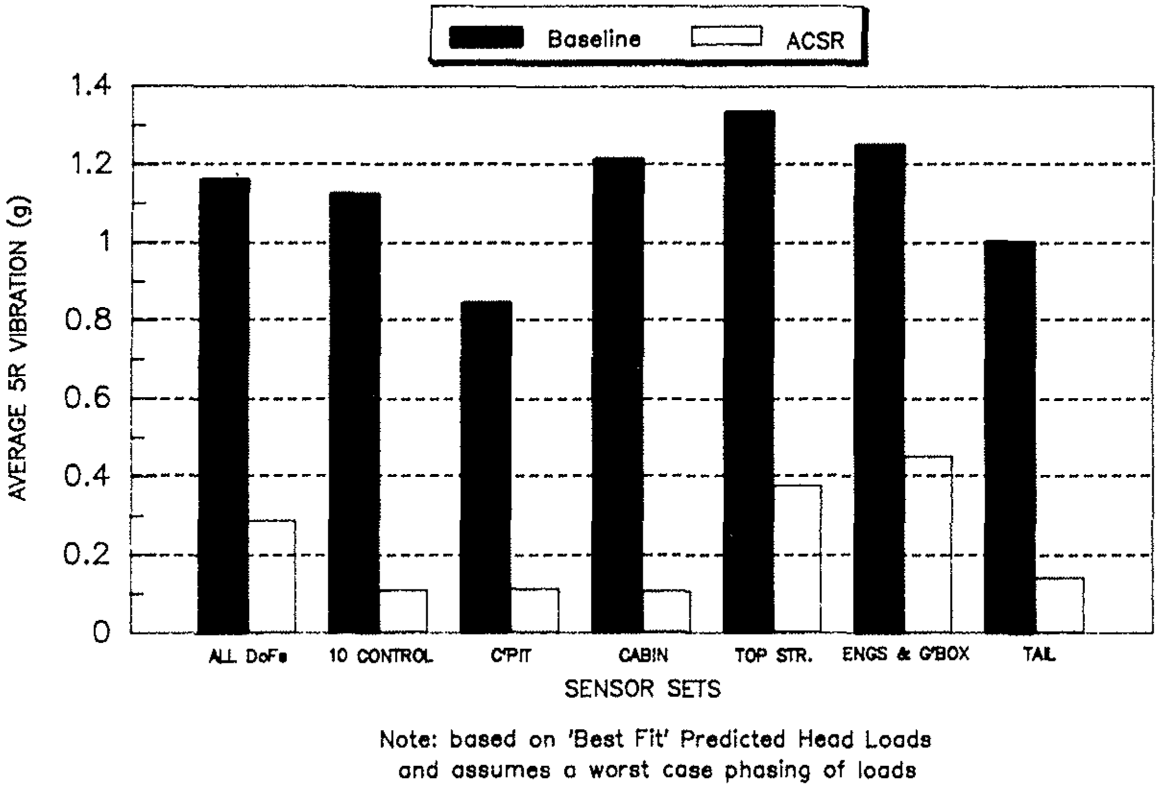

FIGURE 4 : EH101–ACSR SHAKE TESTS, PREDICTIONS OF IN–FLIGHT VIBRATION AT 140 KTS.

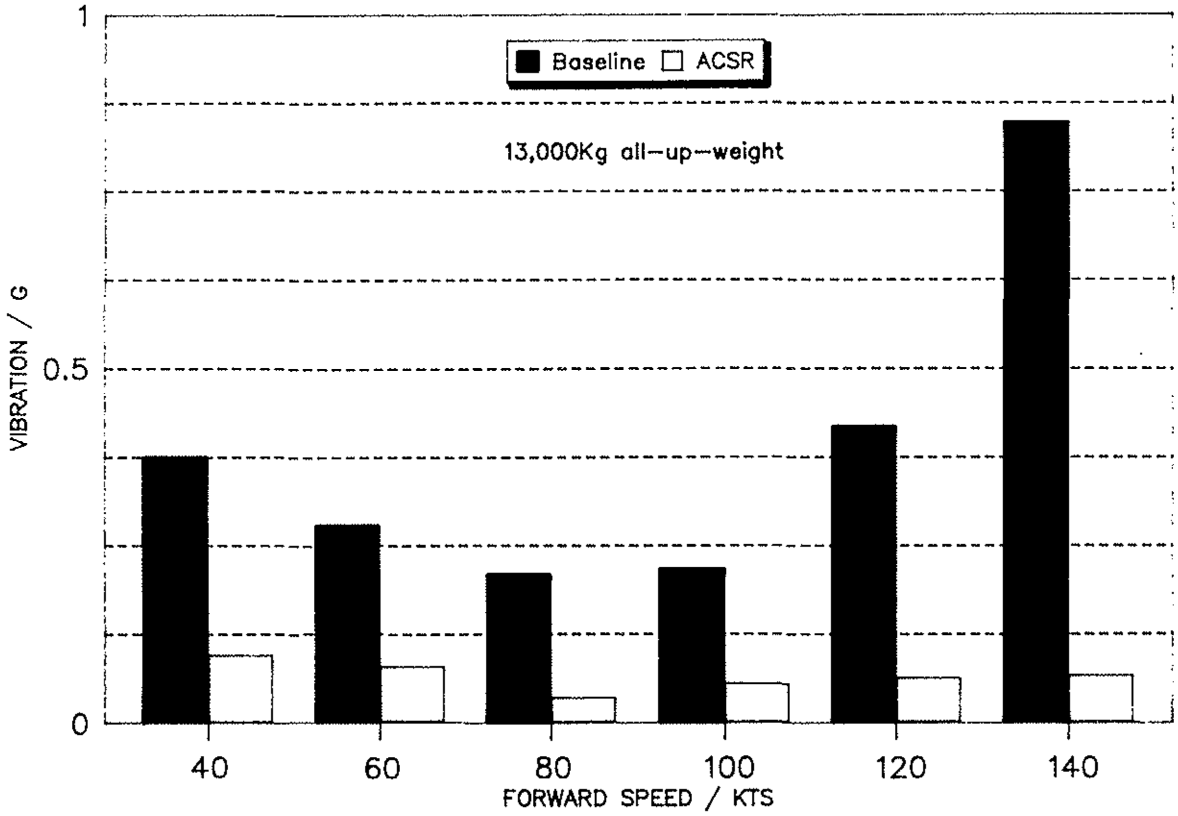

FIGURE 5 : EH101-ACSR FLIGHT TESTS - CO-PILOT VERT VIBRATION VS FWD SPEED

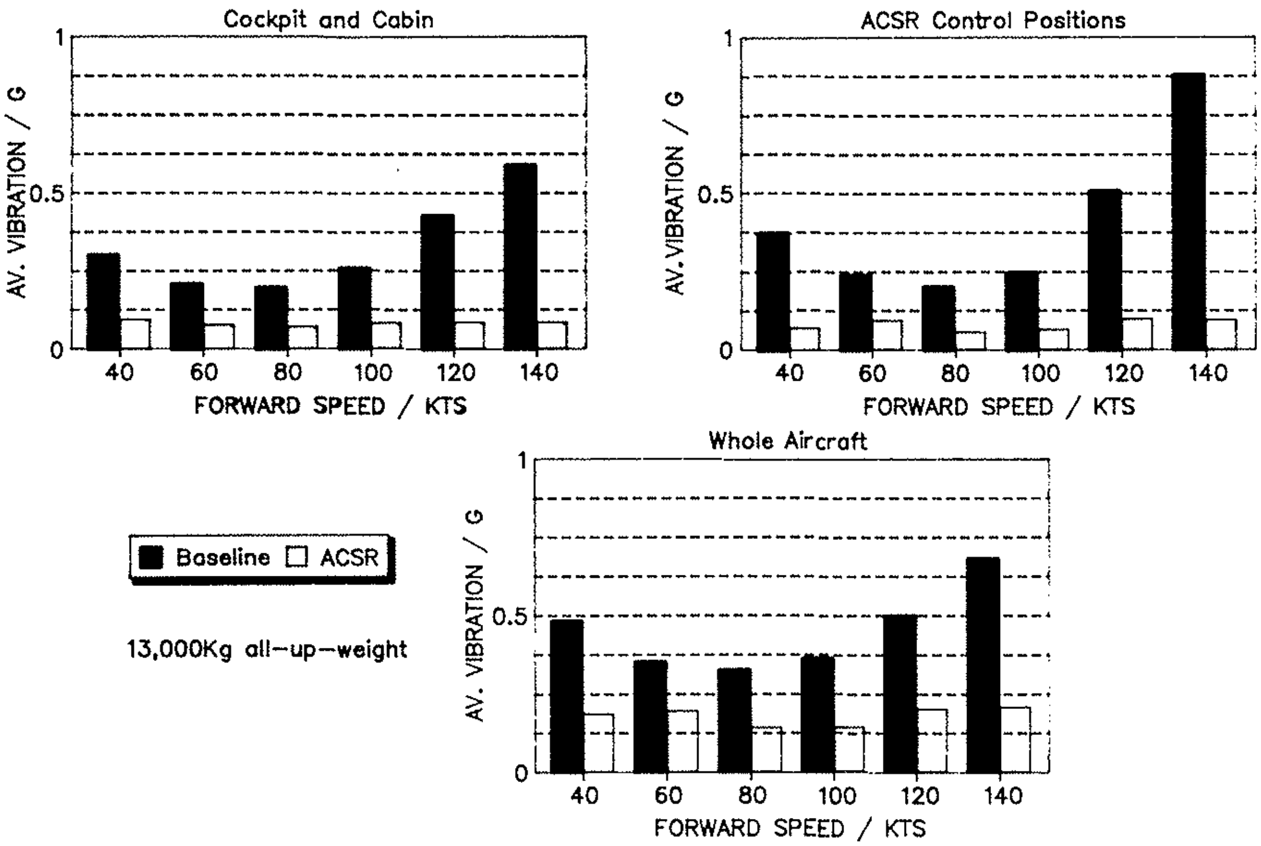

FIGURE 6 : EH101-ACSR FLIGHT TESTS - VIBRATION AVS VS FWD SPEED

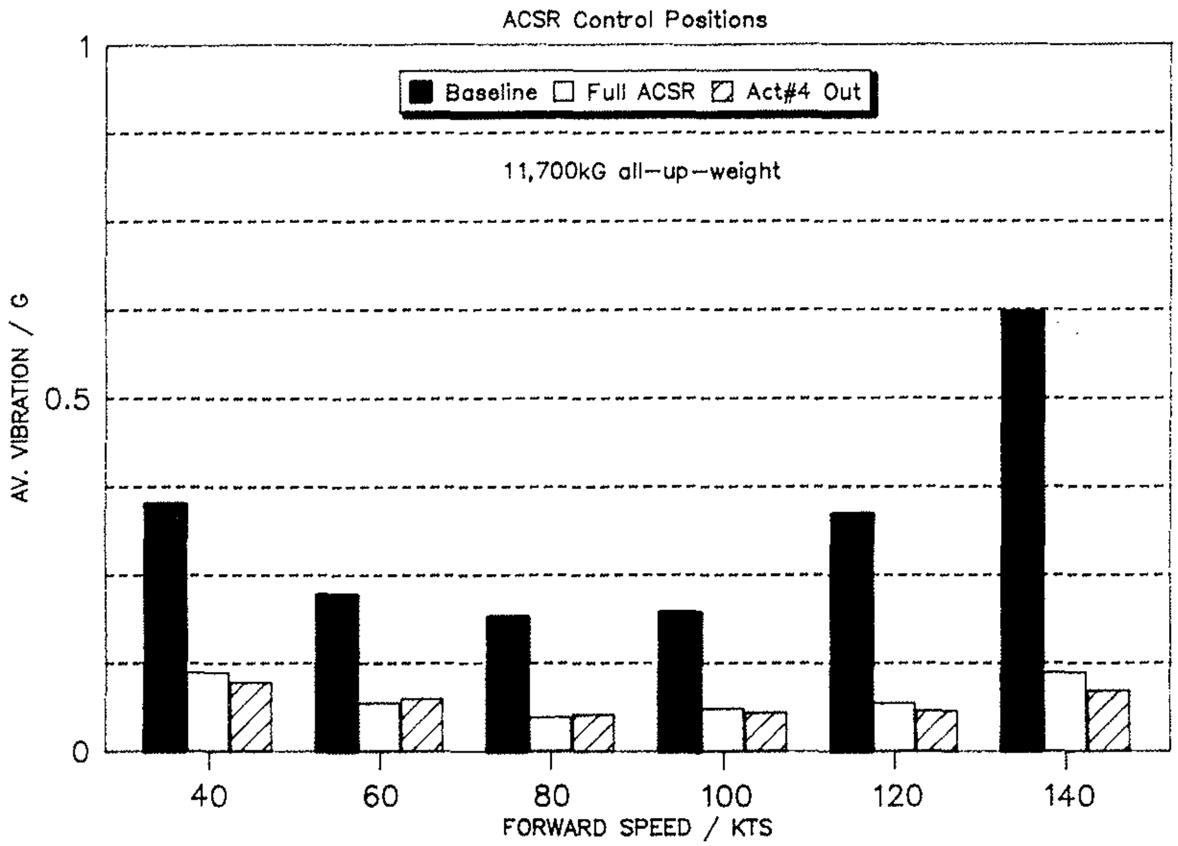

FIGURE 7 : EH101–ACSR FLIGHT TESTS – AV. VIBRATION VS FWD SPEED FOR OPTIMUM 3–ACTUATOR CONFIG (#4=AFT STBD)

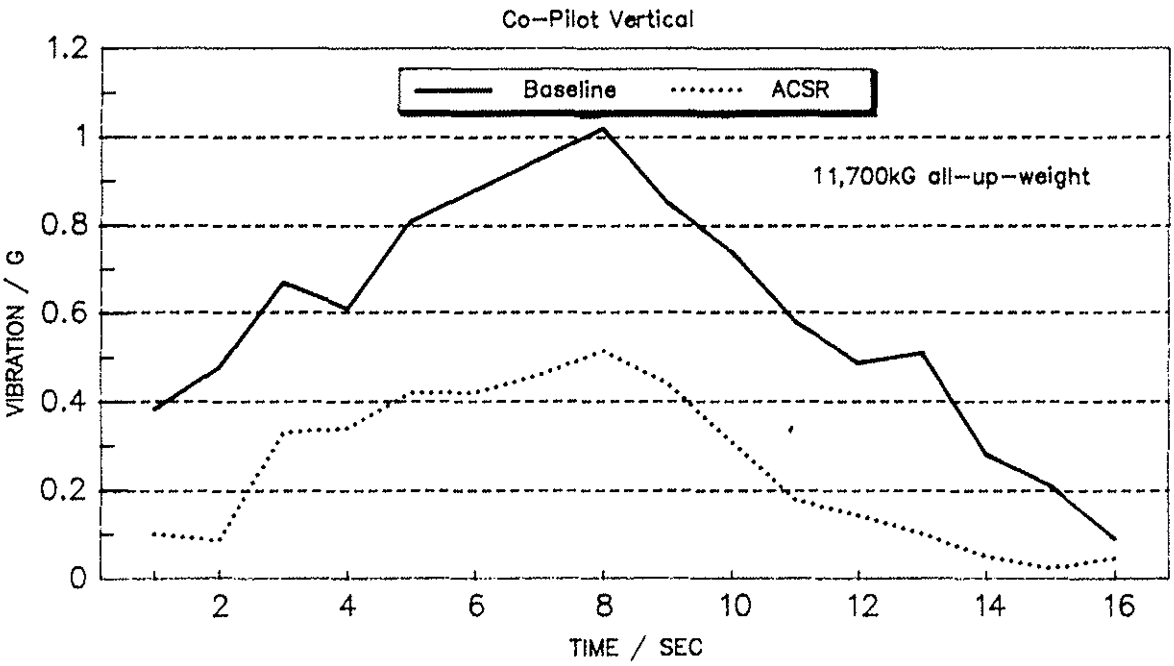

FIGURE 8 : EH101–ACSR FLIGHT TESTS – TRANSITION–TO–HOVER