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HELICOPTER ACTIVE NOISE AND VIBRATION REDUCTION

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HELICOPTER ACTIVE NOISE AND VIBRATION REDUCTION

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1 ABSTRACT

High levels of noise and vibration continue to hamper the utility of helicopters. Lower cabin noise and vibration levels will reduce crew and passenger fatigue, resulting in fewer crew task errors, and thereby improving the mission effectiveness of helicopters. Reduced airframe vibration levels will lead to longer life spans for critical components, lower maintenance costs, and higher reliability. Although passive approaches for these problems have been implemented, they carry significant cost and weight penalties. In addition, passive technology has reached its limit in attaining further reductions within helicopter cost and weight constraints. The innovative use of active control technology provides the potential to reduce noise and vibration levels below those currently achievable with purely passive approaches, or alternatively, to achieve reductions comparable to passive approaches but with a lower weight penalty. Sikorsky has developed and flight tested active noise and vibration control systems. A prototype active vibration control (AVC) system has been flight tested on an UH-60 aircraft and achieved significant reductions in the main rotor 4P vibrations felt inside the helicopter cabin and cockpit. A productionized version of the AVC system is currently undergoing development flight testing on the Sikorsky S-92 Helibus™. Also, an active noise control (ANC) system has been successfully flight tested on an S-76 aircraft and achieved tonal noise reductions of up to 20dB in the helicopter cabin.

2 INTRODUCTION

Active Noise Control

Interior noise is an increasingly important discriminator in the commercial helicopter market, with "acceptable" noise levels traditionally being achieved passively, albeit with substantial weight penalties. Increasing performance demands (i.e., longer range, higher payloads) have driven the pursuit of lighter-weight solutions. Furthermore, continuing reductions in the noise levels commonly experienced by passengers in various other modes of transportation, including ground vehicles and commercial fixed-wing aircraft, have heightened the awareness and sensitivity of passengers to helicopter internal noise. In the last decade the continuing trend towards cheaper, faster, and more powerful computers has lead to the evolution of active noise control (ANC) from a laboratory experiment to a practical approach for reducing aircraft cabin noise levels (Ref. 1-2). ANC, properly integrated with traditional passive techniques, offers substantial promise of reducing helicopter cabin noise levels with lower weight penalties than purely passive treatments. This will benefit the helicopter industry by improving commercial acceptance and expanding the helicopter market.

There are three primary components of helicopter interior noise: (1) large amplitude, low frequency rotor harmonics; (2) broadband noise; and (3) higher frequency structure-borne tones generated within the gearbox, power train, and hydraulic system. A typical spectrum is shown in Fig. 1. The low frequency tones (<200Hz) are less important to passenger comfort than this figure would imply due to the natural attenuation of the ear at low frequencies. The high frequency gear-mesh tones (>700Hz) fall into the speech interference range and, since these tones generally rise far above the broadband noise floor (Fig. 1), are generally considered the most intrusive and irritating component of noise in a typical helicopter. The primary gear-mesh tone generally falls in the frequency range of 700-1000Hz, and is typically much louder than its higher harmonics. It is this tone which is typically the most irritating to passengers and crew, and unfortunately falls into a frequency range in which traditional passive treatments are not very weight efficient.

Recently, a multi-year program was initiated at Sikorsky Aircraft Corporation to develop a flight-worthy ANC system to actively cancel gear-mesh noise inside the cabin interior. Initial concepts explored for the helicopter gear-mesh ANC problem included both structural acoustic control of accelerometers/microphones using force generating actuators and acoustic control of microphones using speakers. However, the speaker/microphone control approach that has proven successful in lower frequency tonal applications such as turbo-prop aircraft (Ref 1) and for the low frequency rotor harmonics in helicopters (Ref 2) is not practical for this problem due to the high frequencies and resulting number of participating acoustic modes. In this approach, the speakers must set up a sound field inside the cabin that matches and cancels that created by the disturbance. For global noise reductions this requires that the number of speakers be at least equal to the number of relevant acoustic modes (Ref 3). There are several hundred acoustic modes present in the gear-mesh frequency range (>700Hz) for a cabin the size of the S-76 (Ref. 4), thus requiring at least as many speakers to achieve global noise reductions.

A more promising approach for the gear-mesh ANC problem is to use a choke-point methodology to prevent the structure-borne gear-mesh vibrational energy from entering the cabin by placing actuation where the gearbox is mounted to the structure. The approach described in this paper, and flight tested on the S-76 helicopter (Ref. 5), involves the use of point force (proof-mass) actuators surrounding the gearbox mounts to actively cancel the gear-mesh vibrations before they enter the airframe. This approach avoids interrupting the primary load path of the helicopter, thus avoiding flight safety concerns, and is generally more effective with a wider frequency range of operation than tuned passive absorbers. A schematic of the gear-mesh ANC approach is shown in Fig. 2. The approach taken in Refs. 6-7 to address helicopter gear-mesh noise used structural actuators mounted parallel with struts supporting the gearbox to introduce the canceling forces directly into the load path. However, in the case of the S-76, the mechanical interface between the gearbox and the airframe is significantly different, in that the gearbox is bolted directly to a pair of transmission beams integral to the airframe structure. Thus the actuators were mounted on the transmission beams near the gearbox mounting points as in Ref. 8. The gear-mesh ANC system utilizes microphones distributed throughout the cabin as feedback control sensors, as shown in Fig. 2.

Active Vibration Control

Helicopter vibration is largely a result of vibratory aerodynamic loads generated by the rotor as it moves edgewise through the air in forward flight. Traditional passive approaches to reducing vibrations involve the use of tuned-mass absorbers. These absorbers tend to be very heavy, are only effective in a very narrow band about the tuned frequency, and generally only reduce vibrations in close proximity to their mounting location. Furthermore, passive systems appear to be approaching an asymptotic limit in terms of weight efficiency. A major leap forward in terms of passive vibration reduction in helicopters was the introduction of the hub absorber. The hub absorber, which reduces the inplane NP (blade passage frequency) vibratory loads at the hub, results in significant reductions in the NP vibrations in the cockpit and the cabin. An example of the magnitude of vibration reduction provided by the hub absorber is shown in Fig. 3 for the Sikorsky S-61. As described in Ref. 9 and also shown in Fig. 3, significant reductions in the failure rates of critical components were observed in connection with the lower vibration levels, which ultimately translated into reduced maintenance costs.

Since the introduction of the hub absorber, however, the vibration levels of modern helicopters appear to be hovering about an asymptotic limit of 0.10-0.15 g. This is due to the fact that the hub absorber does not affect the vertical vibratory hub load component that propagates unattenuated into the airframe. This component is generally attacked in Sikorsky helicopters using tuned passive absorbers located in the cabin. These devices are generally very heavy and incur significant weight penalties. Lower vibration levels can be achieved by increasing the number of passive absorbers, but this tends to result in diminishing returns. Thus modern helicopters appear to be approaching a vibration limit driven by weight efficiency. What is required is a paradigm shift in vibration reduction technology.

Active vibration control (AVC) systems have the potential for significantly reducing helicopter vibration while decreasing weight dedicated to vibration reduction. Many studies and tests have shown that active systems are effective. Early AVC studies summarized in Refs 10-12 focused on higher harmonic control (HHC) and showed that significant vibration reduction could be achieved using this approach. HHC systems introduce additional higher harmonic control inputs into the conventional swashplate to attempt to minimize NP vibrations as measured by accelerometers located in the helicopter cockpit and cabin. Although receiving considerable attention over a period of 25 years, HHC has yet to be incorporated into production aircraft. Some of the major impediments are the excessive hydraulic power requirements of HHC (Ref 10) and concerns that high frequency operation of the main rotor servos may potentially cause excessive wear to this flight critical system. A similar approach commonly referred to as individual blade control (IBC) utilizes active pitch links instead of the conventional swashplate to oscillate the blade (Ref 13). This approach has some advantages over HHC such as enabling greater control over the blade motions, but suffers from the same drawbacks of high power consumption and, in this case, being in series with the primary flight control system of the helicopter. A third approach, commonly known as active blade control (ABC), utilizes control surfaces such as trailing edge flaps on the blade to affect the blade motion (Ref 13). Moving a flap requires an order of magnitude less power than oscillating the entire blade, and does not use components of the primary flight control system. This approach offers significant promise of providing significant vibration reduction, in addition to possibly reducing the helicopter radiated noise signature and enhancing performance. However, there are many technological barriers that must be overcome before this approach can be implemented on a production helicopter.

For implementation on production aircraft, several criteria should be met by an AVC system. It must: 1) reduce aircraft vibration more effectively and over a greater range of flight conditions than passive systems; 2) result in a lower weight penalty that passive systems; 3) have low energy consumption; 4) be based on proven, reliable technology; and 5) have reasonable life-cycle costs.

One AVC approach that seems to fulfill these criteria is derived from the active control of structural response (ASCR™) method. ACSR, developed by Westland Helicopters Ltd.

(Refs. 14-15), places its actuation between two hardpoints in the fuselage to produce equal and opposite forces between these two hardpoints. The ACSR approach utilizes these dual-point actuators to minimize the response of the fuselage to the NP vibratory loads. In the case of the production ASCR system for the Westland/Agusta EH101 helicopter (Ref. 15), dual-point actuators are integrated into four of the struts supporting the main gearbox.

Unlike the EH101, Sikorsky Aircraft helicopters such as the UH-60 bolt the main gearbox directly to the airframe instead of using struts. As a consequence, ACSR dual-point type actuators are not applicable. The AVC actuator configuration discussed in this paper, and flight-tested on the UH-60 (Ref. 16), utilized single-point inertial actuators mounted at various locations in the helicopter fuselage. Unlike dual-point actuators that produce a force on the fuselage by actuating between two fixed points, single-point inertial actuators produce a force by oscillating a reaction mass that is free to vibrate. In general, to develop large forces either a large reaction mass or a large stroke of the mass is required. These two approaches, however, are neither weight efficient or power efficient. In the former case the system mass is excessive, and in the latter case the power consumption is excessive.

The single-point actuators used in the flight test, termed servo-inertial force generators (SIFGs), solved this problem by utilizing a mechanical resonance and a novel inner-loop electronic control system. Tuning the SIFGs to be near the NP frequency minimizes the required mass and power to achieve a given vibratory force output. The SIFG actuation system was designed and developed by Moog Inc. The SIFGs are devices that integrate a Sikorsky UH-60 passive vibration absorber with a hydraulic servo-actuator. The moving mass of the absorber is usually connected to the helicopter structure via three leaf springs. However, by inserting a hydraulic actuator between the structure and the middle spring, the passive vibration absorber is transformed into an active device. A schematic of the SIFG is shown in Fig. 4. Since the SIFGs were based on a modification of the passive absorber, they were capable of operating in two different modes – a passive mode (i.e., hydraulics off) in which they operated like a traditional tuned passive absorber, and an active mode in which the hydraulic actuator drives the SIFG to a desired force output. Each SIFG was capable of generating +/- 1500 lbs at NP.

A schematic of the AVC system flight tested on the UH-60 is shown in Fig. 5. The AVC system utilizes accelerometers distributed throughout the cockpit/cabin as feedback control sensors, as shown in Fig 5. The tuned passive absorber typically installed in the cabin overhead just forward of the main gearbox and in the helicopter nose were removed and two SIFGs were installed in the cabin overhead. The SIFGs could be operated in passive mode to operate just like the passive absorbers, or alternatively, operated in active mode as part of an AVC system. When in active mode, a closed-loop controller utilizes feedback from the accelerometers to determine the optimal SIFG commands to minimize the NP vibrations.

3 CONTROL ALGORITHM

The algorithm used in the ANC and AVC systems is based upon that developed by Sikorsky Aircraft and United Technologies Research Center for helicopter higher harmonic control (HHC) of rotor vibrations (Ref 17-18). In this approach the disturbance frequency is obtained from a tachometer sensor, a harmonic analyzer is used to identify the desired tonal information (i.e., magnitude and phase of frequency components of interest), and a minimum variance control algorithm is used to generate control signals based on an estimate of the plant transfer function. In Ref. 19, numerous approaches for tonal control are described, and the connection between the underlying approach used for HHC, and other tonal control approaches, is illustrated.

In the narrow bandwidth required for control about each tone, the actuator/sensor transfer function is roughly constant, and thus the system can be modeled in the frequency domain as linear time-invariant using a single quasi-steady transfer function matrix, denoted by T. The derivation of the control algorithm given below follows from Refs. 17-18 and is described more fully in Ref. 4. Assuming linearity, the change in the sensor response vector z due to a change in the actuator command vector u can be written as a local model:

$$\Delta z = T\,\Delta u + w$$

The control law is derived to minimize the quadratic performance index:

$$J = z^T z + u^T W_u u + (\Delta u)^T W_{\delta u} (\Delta u)$$

that is a weighted sum involving the squared magnitudes of the sensor measurements, control commands, and rates-of-change of control. Substituting the local system model into the above expression and solving for the control u which minimizes J yields:

$$u_{k+1} = u_k - Y_k(W_u u_k + T_k^T z_k); \qquad Y_k = (T_k^T T_k + W_u + W_{\delta u})^{-1}$$

The subscript k has been added to indicate the recursive nature of the feedback control algorithm resulting from the introduction of control rate weighting. The matrix Y_k determines the rate of convergence, but does not affect the steady state solution (Ref. 4). Greater control over the stability of the above control law is obtained with a step-size multiplier $\beta<1$:

$$u_{k+1} = u_k - \beta Y_k(W_u u_k + T_k^T z_k)$$

The behavior of the above control law is described in detail in Ref. 4.

4 FLIGHT TEST SETUP AND PROCEDURE

Active Noise Control

Two ANC flight tests were conducted on a Sikorsky S-76B commercial helicopter with a nominal gross weight of 10,000 lbs. The first flight test, conducted in 1995, is the first known successful flight test of a high frequency gear-mesh ANC system on a helicopter. The primary focus of this developmental flight test was proof-of-concept and architecture validation. The second flight test, conducted in 1996-97, focused on validating the pre-production ANC algorithms and architecture, and determining system requirements and performance tradeoffs for production.

The aircraft was equipped with a partial utility interior consisting of only the cabin ceiling and sidewall trim panels. A total of 64 microphones were distributed throughout the cabin interior, with the majority mounted on the cabin ceiling. Several microphone configurations were evaluated during the flight tests. A schematic of a typical microphone configuration tested is shown in Fig. 6.

Proof-mass actuators were bolted to each side of the transmission beams. The actuators were located on the beams as close to the gearbox mounting points as possible, since this is where the gear-mesh vibrational energy enters the airframe. Extensive ground testing validated that this approach was capable of achieving greater than 20dB tonal noise reductions. This method of mounting the actuators on the transmission beams is considered a viable approach for retrofitting an ANC system on current helicopter production lines and aircraft already in service.

The ANC flight tests included conditions such as: (1) ground runs at flat pitch (Q ~ 15%) and light-on-wheels (Q ~ 45%); (2) out-of-ground effect (OGE) hover; (3) steady flight ranging from 40 knots to V_{CR} at 145 knots, up to V_H at ~155 knots; and (4) transient maneuvers such as takeoffs, accelerations, turns, autorotations, decelerations, approaches and flares to landing.

Active Vibration Control

The AVC testing was performed on a UH-60 BlackHawk that was ballasted to 16,800lbs. The UH-60 is a four-bladed helicopter with a nominal rotor speed of 258 rpm, yielding a NP frequency of 17.2 Hz. The two baseline UH-60 tuned passive absorbers were removed and the resulting NP vibrations were measured in flight to establish a baseline. Two SIFGs were then installed in the cabin overhead just forward of the main gearbox (see Fig. 7). Accelerometers were installed at ten locations on the cockpit-cabin floor, as shown in Fig. 7, in both the vertical and lateral directions. Ten of these accelerometers, 8 in the vertical direction and 2 in the lateral direction, were selected as AVC feedback sensors.

Several flights were performed with the SIFGs operating in both passive and active mode to evaluate the benefits of AVC over conventional passive vibration reduction. The performance of the AVC system was evaluated in steady level flight at various airspeeds and rotor speeds, and during maneuvering flight.

5 FLIGHT TEST RESULTS

Active Noise Control – First Flight Test

All results presented for the ANC flight tests are for the reductions achieved in the primary bull gear tone (778Hz) of the S-76. A typical time history of gear-mesh tonal noise when the ANC system is activated, and then deactivated, is shown in Fig. 8 for an OGE hover condition. The quantity plotted in the figure represents the average reduction achieved on 24 controlled microphones. As shown in the figure, an average reduction of 9dB was achieved in the primary gear tone within 10 seconds of the ANC system being activated.

Similar reductions to those shown in Fig. 8 were achieved over a wide range of steady flight conditions, as shown in Fig. 9, with tonal reductions of 7-9dB over this speed range, including 8dB at V_{CR}. The two curves plotted in Fig. 9 represent the average gear tone level at the 24 controlled microphone locations with ANC "off" (upper curve) and with the ANC system "on" (lower curve), for various steady airspeeds.

Though the performance of the ANC system during this first flight test was sufficient to validate the system architecture for proof-of-concept, the noise reductions were much poorer than the 20dB expected based on extensive ground testing of the ANC system. Post-flight simulations based on T-matrix and ambient measurement data collected during the flight test indicated that much greater reductions should have been achieved with the architecture implemented. Analysis of flight test data revealed excessively poor signal-to-noise ratios during the system identification procedure used to construct the T-matrix. Thus, in preparation for the second flight test, a more sophisticated system identification procedure was developed which better accounted for the high background noise levels encountered during the flight test.

Active Noise Control – Second Flight Test

The new system identification method developed for the second flight test greatly improved the estimate of the T-matrix, which resulted in dramatic improvements in ANC performance compared to the first flight test in all conditions tested, including ground runs, hover, steady forward flight, and transient maneuvers such as speed sweeps. It should be noted that all the results presented in this section were obtained using a PC-based ANC system. This system was utilized more extensively than the prototype ANC computer since the PC-based system was capable of controlling a greater number of microphones, which is more representative of the planned production version of the ANC system.

Typical noise reductions at the various microphone locations in an OGE hover condition are shown in Fig. 10. This figure shows an average reduction of 18dB on the 36 controlled microphones, compared to only 9dB on 24 microphones achieved during the first flight test (Fig. 8). It is interesting to note from Fig. 10 that the maximum tonal noise level measured in the cabin was 23dB lower with the ANC system "on" than with the ANC system "off". This is a very substantial improvement. The gear-mesh tonal reductions achieved in all steady flight conditions are very similar to those shown in Fig. 10; the OGE hover case was selected for presentation as a critical ANC condition due to the relatively high gearbox torque and resulting high gear-mesh noise levels in this condition.

Further examination of Fig. 10 reveals some interesting qualities of the noise reductions which are very noticeable to a passenger in the helicopter cabin, but may not be evident from a casual examination of the figures. The high degree of spatial variation in the ambient noise levels (i.e., with ANC "off") with microphone position should be noted in Fig. 10. For example, there is about a 20dB difference in the ambient tonal noise level between microphones 9 and 10, even though they are only about one foot apart. This spatial variation is quite evident to passengers whenever they move their heads, even for small motions, e.g. when just leaning forward. With the ANC system activated ("on") however, this spatial variation is significantly reduced, as shown in the figure. Due to the reduced overall noise levels, this reduced spatial variation is almost imperceptible to passengers, even when moving about the cabin.

ANC performance was substantially improved over the entire flight envelope, including speed sweeps from hover to V_H, compared to results obtained during the first flight test. As shown in Fig. 11, average gear-mesh tonal noise reductions of 14-16dB were achieved during a quasi-steady speed sweep, compared to typical reductions of only 7-9dB obtained during the first flight test (Fig. 9).

Also included in Fig. 11 is the ANC performance during a transient maneuver consisting of a typical acceleration from OGE hover to V_H, followed by a deceleration back to hover. It should be mentioned that the acceleration commenced immediately after take-off to hover without waiting for the ANC system to fully converge to a steady state solution. This was done to simulate actual flight procedures. As shown in Fig. 11, the ANC system not only remained stable, but maintained 8-14dB reductions relative to steady state ambient levels during the acceleration phase, and 12-14dB reductions during the deceleration phase. During accelerations, the actual ambient gear tone levels (not shown on the figure) are typically ~3dB higher than steady flight levels due to the higher torque loads required from the gearbox. Conversely, ambient gear-mesh tonal levels are generally ~3dB lower during decelerations due to reduced gearbox torque requirements.

A typical time history of ANC performance is shown in Fig. 12 for steady flight at 120 knots. The quantity plotted in the figure represents the average reduction achieved on the 36 controlled microphones. As is evident from the figure, the controller achieved a 10dB noise reduction after three seconds, a 12dB reduction after five seconds, and then slowly converged to a steady 16dB noise reduction after 30-40 seconds. Faster convergence rates (i.e., higher controller bandwidths) were also tested without driving the controller unstable. However, these faster rates had no impact on ANC performance during steady flight conditions, and produced only minimal improvements in performance during transient maneuvers such as that shown in Fig. 11.

Active Vibration Control

The NP vibration results for 145 knots and 100% Nr are shown in Fig. 13. The three bars in the figure for each of the ten accelerometer locations represent a comparison of the ambient vibration, passive vibration control, and active vibration control cases. Also shown in the figure is a comparison of the average value of the ten accelerometers for the three cases. As expected, the AVC levels shown in Fig. 13 are lower than for the ambient case, but more significantly, these levels are substantially better than the passive case. This is a crude indication that AVC is more efficient than passive vibration control, i.e. that lower vibrations can be achieved for the same or lower weight. Especially interesting is that the vibration reductions are global in nature, i.e. reductions are realized at the forward cabin accelerometer locations which are not part of the AVC feedback sensor suite.

A global measure of the aircraft vibration is the average vibration level defined as the root-mean-square of the NP vibration magnitudes measured by the cockpit-cabin accelerometers. The average vibration measured at 12 accelerometer locations (10 AVC and 2 midcabin accelerometers) are plotted in Fig. 14 for a forward speed sweep at 100% Nr. Notice that the average NP vibrations are dramatically reduced over the entire range of flight speeds, and that the AVC reductions are significantly better than the passive case.

As discussed previously, one major advantage of AVC over passive systems is their ability to adapt to changing rotor speeds. The passive system on the UH-60 aircraft is a fixed tuned vibration absorber system optimized to a rotor speed of 100% Nr. A comparison between the passive and AVC system performance versus rotor speed is shown in Fig. 15. The classical "bucket" is shown for the passive system, i.e. the vibration is a minimum at 100% Nr. In contrast, the AVC system can readily follow the rotor speed variation, producing a virtually flat response. Of special interest is that the AVC case yields lower vibration levels than passive at 100% Nr. This is further confirmation that AVC can be more efficient than passive methods. Of course the SIFG hydraulic actuators must work harder as the Nr departs from 100%, but sufficient hydraulic power is available over the typical range of rotor speeds.

Sikorsky S-92 AVC

Encouraged by the SIFG flight test on the UH-60, a trade-off study of AVC versus tuned passive vibration absorbers was performed during the preliminary design phase of the S-92, and the decision was made to include the AVC system as baseline on all S-92 aircraft. The results of the trade study indicated that an AVC system would provide a lighter-weight solution than a comparable tuned passive absorber system. Furthermore, an AVC system of comparable weight to a passive system would provide greater vibration reduction.

The S-92 began development flight testing in December 1998 and included an AVC system from first flight. Typical AVC performance is plotted in Fig. 16 for a steady Vcruise condition. The plot compares the NP vibration levels with AVC off and AVC on at 10 accelerometer locations in the cockpit-cabin. The AVC system is similar to the SIFG system, except that the SIFGs have been replaced with purely mechanical actuators referred to as force generators (FGs). The results shown in Fig. 16 were obtained with 3 FGs. It should be noted that the FG locations flight tested so far are trial locations only and are most likely not optimal. But as shown in the figure, AVC achieves substantial vibration reduction in cruise. Developmental flight testing of the AVC system on the S-92 will continue through 1999 and 2000 and will focus on optimizing the FG locations with the goal of maximizing vibration reduction for systems with one, two or three FGs.

6 CONCLUDING REMARKS

Active Noise Control

An approach for actively controlling high frequency structure-borne tonal noise in helicopters has been validated in a flight test program on the S-76 aircraft. Structural actuation near the gearbox mounts has been used to cancel the disturbance before it enters the airframe. This approach has been successfully demonstrated to produce substantial reductions in the primary gear-mesh tone of the helicopter, over a wide range of flight conditions. These reductions have bee maintained during maneuvers such as typical accelerations and decelerations with good system stability. Application of this ANC technology will provide noise suppression and create a quieter passenger environment.

Active Vibration Control

AVC systems using single point actuators is a viable vibration reduction technology. The system uses minimal power due to the resonant behavior of the SIFGs and can revert to a passive absorber in the event of a controller failure. A global vibration metric shows that AVC is more efficient than passive systems for a wider range of forward speeds and rotor speeds. AVC systems have the capability to adapt to changes in helicopter loading and rotor speed whereas traditional passive tuned absorbers cannot. AVC technology, properly integrated with traditional passive vibration reduction systems, offers promise of yielding a significant improvement in helicopter vibration levels.

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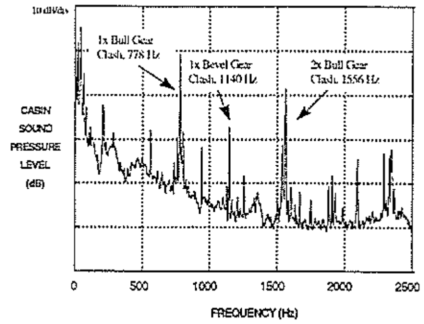

Fig. 1 Interior noise spectrum (unweighted) of a S-76 helicopter

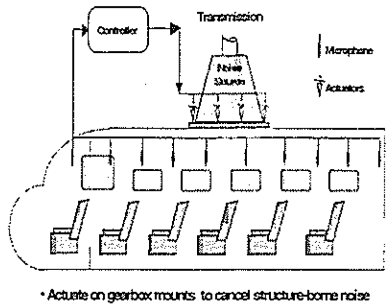

Fig. 2 Control architecture for helicopter gear-mesh ANC

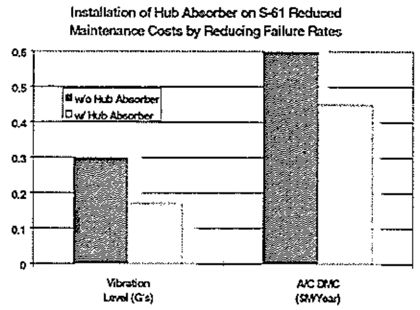

Fig. 3 Impact of hub absorber on vibrations and maintenance costs

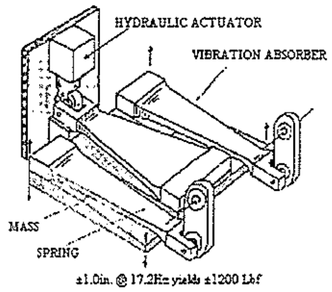

Fig. 4 Servo Initial Force Generator (SIFG)

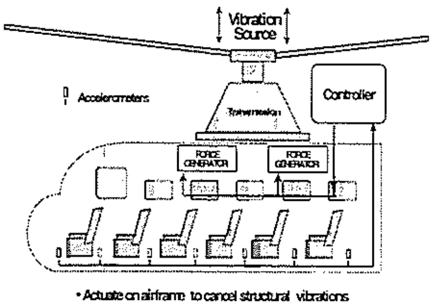

Fig 5 Control architecture for AVC

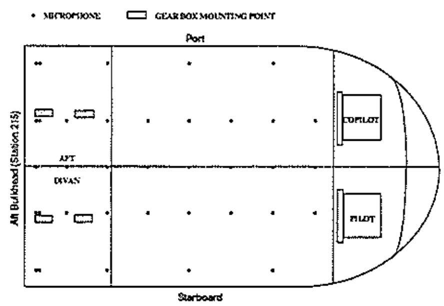

Fig. 6 Typical arrangement of feedback control mics used in S-76 ANC

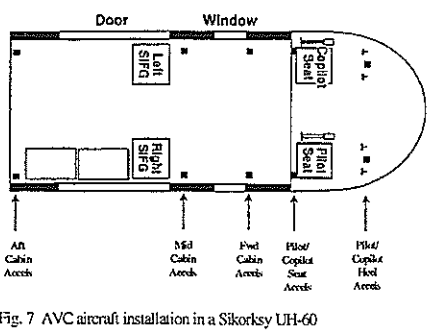

Fig. 7 AVC aircraft installation in a Sikorksy UH-60

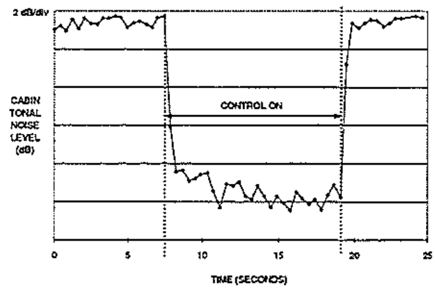

Fig. 8 Typical gear-mesh ANC performance time history in OGE hover.

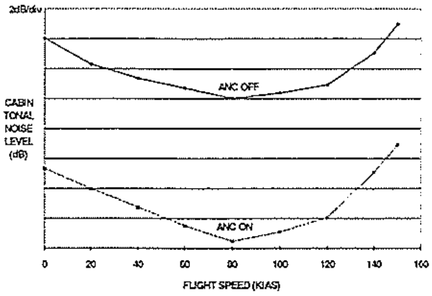

Fig. 9 ANC performance achieved during quasi-steady speed sweep.

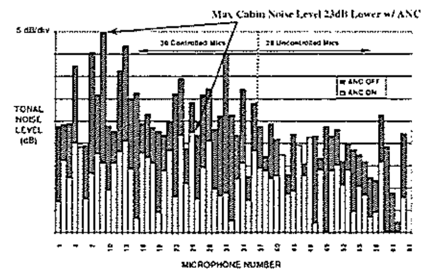

Fig. 10 ANC achieves 18 dB average reductions in OGE hover.

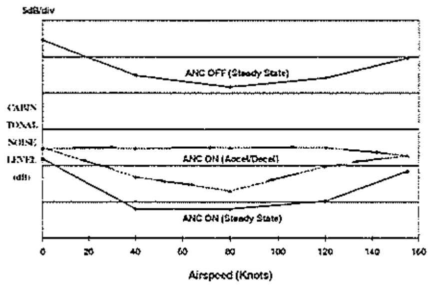

Fig. 11 ANC performance during quasi-steady & transient speed sweep.

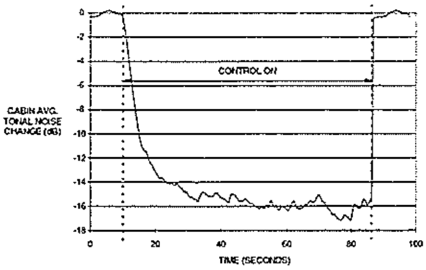

Fig. 12 Typical time history of gear-mesh ANC performance at 120 knots.

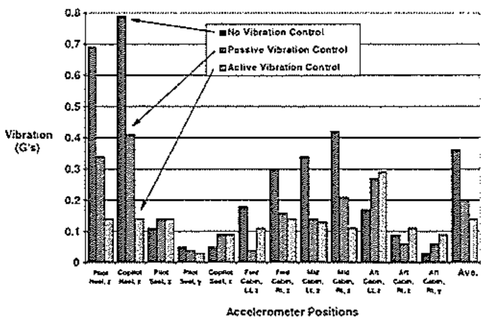

Fig. 13 SHFG vibration reduction during steady flight at Vcruise

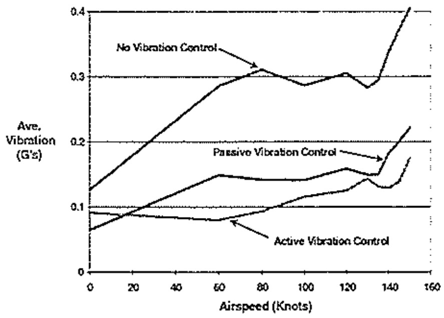

Fig. 14 SHFG vibration reduction during a speed sweep at 100% Nr

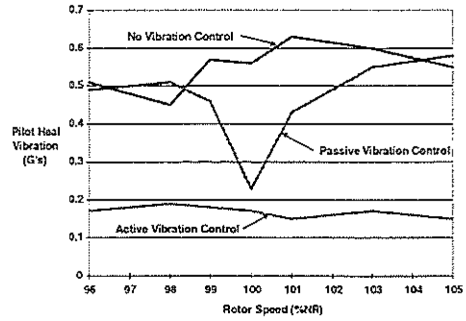

Fig. 15 SHFG performance versus rotor speed

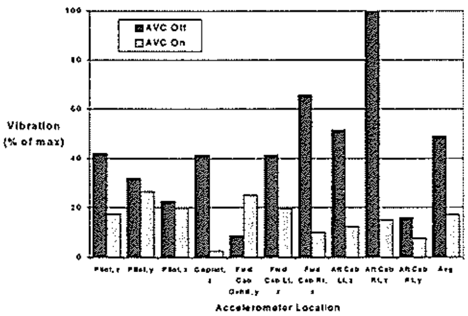

Fig. 16 S-92 AVC performance at Vcruise