Flight Test of Active Gear-Mesh Noise Control on the S-76 Aircraft

Thomas A. Millott
Sr. Acoustics Engineer
Sikorsky Aircraft Corporation
Stratford, CT

William A. Welsh
Sr. Technical Engineer
Chief of Acoustics
Sikorsky Aircraft Corporation
Stratford, CT

Charles A. Yoerkie Jr.
Active Control Theme Leader
United Technologies Research Center
East Hartford, CT

Douglas G. MacMartin
Active Control Theme Leader
United Technologies Research Center
East Hartford, CT

Mark W. Davis
Manager, Vibration Control
United Technologies Research Center
East Hartford, CT

ABSTRACT

Active noise control (ANC) offers significant potential for reducing cabin noise levels in helicopters, thereby enhancing ride quality and improving commercial acceptance. One of the most irritating components of helicopter interior noise comes from high frequency (>500Hz) structure-borne gear-mesh tones generated within the transmission. Sikorsky Aircraft Corporation is engaged in a multi-year program to develop a flight-worthy ANC system to actively cancel gear-mesh noise in the S-76 helicopter interior. The challenge in this ANC application stems from the high frequencies involved; from 700 Hz to 4 kHz. A major project milestone was reached in 1995 with the first flight test of a high frequency ANC system on a helicopter. In this initial flight test, reductions of 7-12dB in the primary gear-mesh tone (~800Hz) were achieved over a wide range of flight conditions. A second flight test, performed in 1996-97, achieved significant improvements in system performance and robustness by utilizing an improved system identification procedure. In this second flight test, 10-20dB reductions in the primary gear-mesh tone were achieved over a wide range of steady and transient flight conditions. This paper includes: (1) a description of the system architecture and control algorithms; (2) a brief summary of the development and ground-testing of the flight-worthy ANC system; (3) a description of the flight test set-up and procedure; and (4) a summary of the flight test results demonstrating the performance and robustness of the ANC system. This ANC system will provide noise suppression and create a quieter passenger environment in the Sikorsky S-92 Helibus™.

INTRODUCTION

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 [1,2]. ANC, properly integrated on a system level 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 interior.

Interest and activity at Sikorsky Aircraft Corporation (“Sikorsky”) in active vibration control (AVC) grew steadily in the 1980’s and reached a major milestone in 1994 with a flight test of an AVC system on a UH-60 helicopter [3]. Due to the successes of the AVC test program, interest in the more complex ANC problem increased. Recently a multi-year program was initiated 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 [1] and for the low frequency rotor harmonics in helicopters [2] is not practical for this problem due to the high frequencies and resulting number of participating acoustic modes involved. 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 [4]. The number of acoustic modes is plotted as a function of frequency in Fig. 2 for a 5’ x 6’ x 9’ acoustic volume representative of a commercial helicopter, such as the S-76. As shown in the figure there are several hundred acoustic modes present in the gear-mesh frequency range (>700Hz), 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. Earlier research at Sikorsky investigated passive choke-point isolation techniques such as elastomeric isolators and tuned absorbers. Though both of these approaches showed promise, neither approach made it into the product line. The elastomeric isolators raised aircraft flight certification issues since they were placed directly in the primary load path of the helicopter. In addition, they would have a significant impact on many aircraft system design considerations making it difficult to retrofit on existing aircraft designs. The tuned absorbers were unsatisfactory due to their limited effectiveness and narrow operating frequency range.

The approach described in this paper, and flight tested on the S-76 helicopter, involves active pseudo choke-point isolation using 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. 3. The approach taken in Refs. [5,6] to address helicopter gear-mesh noise used structural actuators mounted parallel to 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 [7]. The gear-mesh ANC system utilizes microphones distributed throughout the cabin as feedback control sensors, as shown in Fig. 3.

![Fig. 3 Schematic of gear-mesh ANC architecture.](image)

**CONTROL ALGORITHM**

The algorithm used in the gear-mesh ANC system is based upon that developed for helicopter higher harmonic control (HHC) of rotor vibrations [8,9], and successfully demonstrated in helicopter AVC applications [3]. 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. This approach is shown schematically in Fig. 4. In Ref. [10], numerous approaches for tonal control are described, and the connection between the underlying approach used for HHC, and other tonal control approaches, is illustrated.

![Fig. 4 Gear-mesh ANC algorithmic approach.](image)

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 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. [8,9] and is described more fully in Ref. [11]. Assuming linearity, the microphone response vector $z$ can be written as a global model:

$$z = z_0 + Tu$$

where $z_0$ is the slowly varying ambient disturbance, $u$ is the vector of control outputs and $T$ is the transfer function matrix. All variables refer only to the relevant quantities evaluated at the frequency of interest. Alternately, the system response can be written as a local model:

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

where $T$ is constant if the system is linear. This latter representation avoids the requirement of identifying the ambient disturbance $z_0$, since in this equation it is zero-mean.

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

$$J = z^Tz + u^TW_{u}u + \Delta u^TW_{\Delta u} \Delta u$$

which 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:

$$u_{k+1} = u_k - Y_k(W_{u}u_k + T_k^Tz_k)$$

where

$$Y_k = (T_k^TT_k + W_{u} + W_{\Delta u})^{-1}$$
The matrix $Y$ determines the rate of convergence, but does not affect the steady state solution [11]. Greater control over the stability of the above control law is obtained with a step-size multiplier $\beta < 1$:

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

The behavior of the above control law is described in detail in Ref. [11].

**ANC SYSTEM DEVELOPMENT AND TESTING**

The Sikorsky gear-mesh ANC project was an inter-divisional program involving participation by Hamilton Standard and the United Technologies Research Center (UTRC). Sikorsky led the team with UTRC bearing primary responsibility for the development and testing of robust and computationally efficient feedback control algorithms. UTRC also supported ANC architectural development and testing on their cabin interior noise facility; this work is documented in Ref. [11]. Hamilton Standard provided the flight-worthy prototype ANC computer based on their line of flight control computers. MOOG Inc. was selected as the actuator supplier, developing a new actuator specifically designed for the gear-mesh ANC application; these actuators are shown in Fig. 5.

![Inertial force actuators used in S-76 ANC flight test.](image)

Fig. 5

Extensive ANC development testing was performed on the SHADOW test vehicle, a specially modified S-76 used during early RAH-66 Comanche flight control law development. Use of the SHADOW permitted ground testing on an airframe having realistic transmission paths. Shakers mounted on the gearbox housing were used to produce representative disturbances for cancellation. The ground testing focused on: (1) developing optimal system architecture including placement of actuators and sensors for global noise control; (2) validating robust computationally efficient control feedback algorithms; (3) evaluating alternative feedback sensors; and (4) investigating alternative actuation technologies.

Much of the testing on the SHADOW aircraft was performed using a PC-based ANC system which was used extensively by UTRC in ANC development testing on their cabin interior noise facility [11]. This PC-based system was a fully integrated hardware/software platform based on digital signal processor (DSP) technology which permitted rapid hardware-in-the-loop prototyping of active feedback control systems. This system proved to be a valuable system development tool due to its greater capability and flexibility than the prototype ANC flight computer. Some typical results obtained on the SHADOW ground test aircraft using the PC-based ANC system are shown in Fig. 6. In this case, average reductions of 20dB were achieved on 32 controlled microphones distributed throughout the cabin.

![Typical gear-mesh ANC performance on SHADOW ground test aircraft.](image)

Fig. 6

The SHADOW ground test aircraft was also utilized as a platform for performing system integration, ground testing and evaluation of the ANC system prior to its installation on the flight test aircraft. A schematic of the ANC system installation is shown in Fig. 7. The SHADOW aircraft proved to be an invaluable asset in performing risk reduction testing prior to first flight since access was unrestricted, whereas access to the flight test vehicle was limited, and relatively expensive.
FLIGHT TEST SET-UP AND PROCEDURE

Two ANC flight tests were conducted on a Sikorsky S-76 commercial helicopter, similar to the one shown in Fig. 8. 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.

Flight Test #1

The flight test aircraft was a Sikorsky S-76B helicopter with a nominal gross weight of 10,000 lbs. The aircraft was equipped with a partial utility interior consisting of only the cabin ceiling and sidewall trim panels. A schematic of the ANC system flight test installation is shown in Fig. 7. The 24 control microphones were distributed throughout the cabin interior; the majority were mounted on the cabin ceiling, with 4-5 microphones located at seated head height on the aft bulkhead, and 2-4 located at seated head height on the sidewalls. Additional microphones were distributed throughout the helicopter interior to monitor noise level changes at locations other than at the controlled microphones. Several microphone configurations were evaluated during the flight tests. A schematic of a typical microphone configuration tested is shown in Fig. 9.

The Moog proof-mass actuators, shown in Fig. 5, were bolted to aluminum blocks mounted 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 testing on the SHADOW ground test aircraft 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 feedback control algorithm was implemented on a Hamilton Standard prototype ANC computer, consisting of analog-to-digital (A/D) converters, digital-to-analog (D/A) converters, digital signal processors (DSP) for I/O processing, and an Intel i960 RISC processor for performing the control calculations. A 64 channel RACAL recorder was utilized to record microphone data, and a 1553 bus recorder was used to extract data from the ANC computer. The ANC computer was also connected via a RS-422 bus to a flight-hardened PC for real-time monitoring of ANC performance, modifying of control parameters on-line, and recording of a small subset of performance parameters from the control processor.
The ANC flight test plan 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.

**Flight Test #2**

The second flight test was performed on the same S-76B helicopter using the same hardware and equipment as the first flight test, except for the addition of the aforementioned PC-based ANC system. For this pre-production flight test it was desired to validate ANC performance with a configuration more like the planned production ANC system, which utilizes more microphones than the prototype ANC system. The PC-based ANC system had the capability of controlling up to 64 microphones simultaneously, or, as done in the majority of cases, controlling 36 and monitoring the remaining 28 microphones. Furthermore, this PC-based system permitted real-time monitoring, processing and recording of all parameters of interest, which greatly facilitated data reduction and analysis, performance validation and algorithm debugging. Portions of the flight test were conducted using the prototype ANC computer, with the remaining flights utilizing the PC-based ANC system.

**FLIGHT TEST RESULTS**

**Flight Test #1**

This first developmental flight test of the gear-mesh ANC system was focused on performing in-flight validation of the control architecture, feedback control algorithm, prototype ANC computer and MOOG actuators. Initial testing involved ground runs at flat pitch (Q ~ 15%) to fine tune the system under relatively steady conditions before attempting control during forward flight and transient maneuvers. Cabin average reductions of up to 14dB on the primary gear-mesh tone (~800Hz) were achieved during ground runs, as shown in Fig. 10. Typical reductions ranged between 9-12dB, including the light-on-wheels condition (Q ~ 45%).

Encouraged by these results, the performance of the ANC system was evaluated over a wide range of flight conditions, from hover to maximum forward speed. A typical time history of ANC tonal noise reductions when the ANC system is activated, and then deactivated, is shown in Fig. 11 for an OGE hover condition. The quantity plotted in the figure represents the average reduction achieved on the 24 controlled microphones. As shown in Fig. 11, an average reduction of 9dB was achieved in the primary gear tone within 10 seconds of the ANC system being activated.

**Fig. 10** Gear-mesh ANC reductions achieved at controlled microphones during ground run.

**Fig. 11** Typical gear-mesh ANC performance time history in OGE hover.

Similar reductions to those shown in Fig. 11 were achieved over a wide range of steady flight conditions, as shown in Fig. 12, with tonal reductions of 7-9dB over this speed range, including 8dB at $V_{CR}$. The two curves plotted in Fig. 12 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 reductions achieved on the SHADOW ground test aircraft (Fig. 6). 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. As part of risk reduction testing prior to the second ANC flight test, this approach was implemented and fully validated on the SHADOW ground test aircraft using more realistic disturbances with higher background noise.

**Flight Test #2**

The second flight test focused on validating the pre-production ANC architecture and the modified control algorithms utilizing a refined system identification procedure. The new system identification method 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 the 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 gear-mesh tone reductions at each of the microphone locations are shown in Fig. 13 for a ground run condition (Q~15%). An average tonal reduction of 20dB was achieved on the 36 controlled microphones. This represents a 6dB improvement over the 14dB average reduction achieved on 24 controlled microphones during the first flight test (Fig. 10).

Typical noise reductions at the various microphone locations in an OGE hover condition are shown in Fig. 14. 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. 11). This 9dB improvement in ANC performance is even larger than that achieved in the ground run case. It is interesting to note from Fig. 14 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. 14; 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. 14 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. 14. 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 head, 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 Fig. 14. 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 $V_{th}$, compared to results obtained during the first flight test. As shown in Fig. 15, 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. 12).

Also included in Fig. 15 is the ANC performance during a transient maneuver consisting of a typical acceleration from OGE hover to $V_{th}$, 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. 15, 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. 16 for steady flight at 120 knots. The quantity plotted in the figure represents the average reduction achieved on the 36 controlled microphones. As 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 slight improvements in performance during transient maneuvers such as that shown in Fig. 15.

**CONCLUDING REMARKS**

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 also been shown to be 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 in the Sikorsky S-92 Helibus™.

ACKNOWLEDGEMENTS

A complete list of people who contributed to this effort is too lengthy to include. Special appreciation is extended to John Mancini (Sikorsky Aircraft), whose diligent efforts helped ensure the success of the ANC flight test program. Alan Finn (UTRC), who was responsible for the majority of the programming of the PC-based ANC system, and Al Covino (UTRC), who helped to install it into the flight test aircraft, both deserve special recognition.

REFERENCES


