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A DEMONSTRATION OF ACTIVE CONTROL FOR HELICOPTER CABIN NOISE REDUCTION

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Abstract

Typical sound measurements in helicopter cabins indicate that a major contributor to the sound results from airborne transmission of the low-frequency sound (below 400 Hz) created by the main and tail rotor. At these low frequencies, passive acoustic treatments are generally not practical for reducing interior noise, due to size and weight limitations. Results in this paper indicate that active noise control (ANC) systems can provide marked reductions in the low-frequency noise within helicopter cabins, while further work is needed to reduce the higher frequency noise created by the transmission(s). Experimentation was conducted on a helicopter fuselage with an ANC system that consisted of four optimally placed speakers, eleven microphones located in the ceiling trim and an adaptive broadband feedforward controller. The laboratory demonstration showed that the ANC system provided 10 - 20 dB reduction of the main and tail rotor tones between 40 Hz to 200 Hz. This corresponded to a 3 - 13 dBA overall noise reduction at the passenger head level. Furthermore, noise reductions were spatially global below 80 Hz.

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Introduction

Human factors and consumer preference are demanding quieter helicopter interior environments. Increased competition among helicopter manufacturers is providing rapid focus for development of active systems to improve passenger comfort in helicopter transportation.

For many years, passive elastomeric isolation systems have been employed very successfully to reduce rotor induced structure-borne cabin noise and vibration. Reduction of low frequency (50-200 Hz) airborne noise is more difficult to achieve passively due to restrictions on the size and weight of various treatments. In this frequency range, the benefits of an active system over conventional passive treatments include:

1) significant performance (greater dBA reductions) advantages for noise control

2) lower weight vs performance

3) lower cost vs performance

Active noise control systems provide enhanced noise reduction performance without adding unreasonable size and weight penalties. Active systems enhance passenger comfort, as well as provide a competitive edge for helicopter manufacturers in the marketplace. Furthermore, manufacturers must meet increasingly stringent industry standards and passenger/crew expectations for quieter cabins. In support of that goal, Lord Corporation introduced NVX™ Systems, a new active noise control technology that offers manufacturers increased flexibility in addressing severe noise and vibration problems.

Lord NVX Systems include a variety of solutions for active noise control in aircraft. In addition to traditional approaches for noise control, Lord has developed Active Isolation Control, Active Structural Control and Active Noise Control. These systems feature electronically controlled actuators and speakers, coupled with strategically located sensors that monitor noise and/or vibration. Driven by small power amplifiers, the actuators and speakers react to changing situations, generating a canceling noise or vibration to counter the disturbance noise. This self-adjusting system results in noise/vibration reduction over a wide range of conditions for a wide range of aerospace applications including rotary wing and fixed-wing aircraft, for reducing both airborne and structure-borne interior noise and vibration.

NVX Systems are designed without compromising other aspects of aircraft interior design. Active Isolation Control systems incorporate actuators inside isolators to cancel noise and vibration. Active Structural Control systems utilize actuators that can be placed inside the fuselage structure, between the transmission and the fuselage, on the engine-beam pylon, on the transmission, on aircraft trim, on airframe ribs/stringers, etc. Furthermore, Active Noise Control systems feature electronically controlled speakers to perform noise cancellation. Like the Active Isolation Control and Active Structural Control systems, Active Noise Control systems are self-adjusting systems that provide noise reduction over a variety of operating conditions, or as the structure changes over time.

Lord established a major licensing agreement with Digisonix, Inc., a world leader in adaptive broad band control technology. This agreement provides Lord with a unique, state-of-the-art broad band controller technology that has adaptive/on-line modeling capability [1-7].

Lord NVX Systems utilize an upstream error sensor (an accelerometer typically). A patented control method allows NVX Systems to control both *narrow band* and *broad band* disturbances. Not only do NVX Systems drastically reduce the tones, but they reduce broad band "background" levels as well. NVX Systems are well-suited for aerospace applications, since many sources of aircraft noise and vibration are broad band.

Lord Corporation performed a laboratory demonstration on a helicopter fuselage that an Active Noise Control (ANC) system can substantially reduce low-frequency helicopter cabin noise. The laboratory demonstration showed that the ANC system provided 10 - 20 dB noise reduction of the main and tail rotor tones (below 200 Hz) in the cabin. The methodology and the system used to obtain these reductions measured in the laboratory using an actual fuselage is discussed.

Dynamic Characterization of the Acoustic Interior

The performance of any ANC system is highly dependent on the acoustic dynamics within the enclosure. Consider a frequency range where the response can be characterized by light damping and low modal density. In this frequency range, added damping can significantly reduce the resonant activity and provide marked/noticeable noise control performance. However, adding passive damping treatments and soundproofing to reduce the noise at low frequencies is impractical due to the long wavelengths of the sound (the passive treatments required would be too bulky and heavy). In addition, when the acoustic response is resonant, it is generally very difficult to determine where the noise source is located.

Passive treatments tend to work better for reducing noise in the higher frequency ranges, where the acoustic modal density is high; the acoustic modal density increases with the cube of frequency [8]. Furthermore, in the higher frequency ranges, the acoustic response tends to be directional - a person can actually detect where the noise is being produced; e.g., sitting in a running helicopter, a person can usually detect that the transmission noise propagates downward into the cabin from above.

In order to determine the nature of the acoustical dynamics in the helicopter cabin, a microphone and speaker were placed at various locations within the cabin and frequency response functions (FRFs) were measured. A typical microphone-speaker FRF is shown in Fig. 1. Note that below 70 Hz, the acoustic response tends to display lightly-damped modal behavior, and the modal density is low. Above 70 Hz, the sound field tends to become more heavily damped resulting in a more diffuse-like spectrum. This transition between low and high modal overlap regions can be analytically determined by calculation of the Schroeder frequency [8, 9]. The Schroeder frequency - a function of modal density and acoustic damping - can be approximated by

$$f_{Sch} = 2000\ (T_{60}/V)^{1/2}$$

where a sound speed of 360 m/s is assumed, T_{60} is the reverberation time in seconds and V is the volume of the cabin. The Schroeder frequency was calculated to be about 70 - 100 Hz for the helicopter cabin. Below the Schroeder frequency, since the cabin displays lightly-damped acoustic behavior, we expect an ANC system to provide global noise reduction of the interior sound field [8]. Above the Schroeder frequency, we expect that the ANC system will not globally cancel the sound field created by the noise source(s). At these higher frequencies, only localized noise reduction at the microphone error sensors will be obtained, basically because the sound field becomes more "directional," and the noise cancellation is highly dependent on the locations of the control speakers. As discussed in Ref. [8], there are three fundamental rules of thumb which dictate whether the ANC system will provide global or local control of the interior sound. The three rules of thumb are:

1) Global control of interior noise can be obtained in frequency ranges where the acoustic dynamics display lightly-damped, low modal density behavior, i.e., below the Schroeder frequency (e.g., below about 70 Hz in the helicopter cabin).

2) In sound fields possessing high modal density and overlap, i.e., above the Schroeder frequency, global control can only be obtained when the control speakers are located within one quarter wavelength of sound in air from the source. This is practically impossible in situations such as the helicopter cabin, where the noise source (i.e., the vibrating cabin roof and walls) is highly distributed.

3) When cases (1) and (2) above do not apply, only localized noise reduction can be obtained at the microphone error sensors. The noise reduction is a sphere or "zone of quiet" whose diameter is approximately one-tenth the wavelength of sound in air. For example, consider noise cancellation at 200 Hz in the cabin. The wavelength at 200 Hz is approximately 170 cm. Hence, controlling noise at an isolated microphone error sensor would provide little or no noise reduction 170 cm / 20 ≈ 9 cm away from the mic.

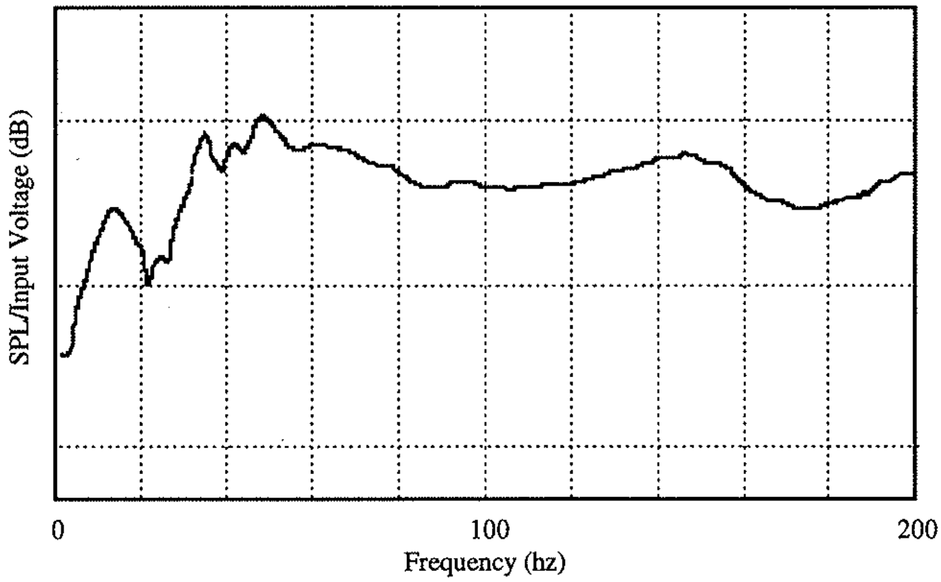

Figure 1: Typical frequency response function between a speaker and microphone inside the helicopter cabin.

ANC System Performance Prediction Method

The performance of an active control system can be predicted analytically by using experimentally derived transfer functions. At a single frequency, the steady state system response can be expressed as:

$$\boldsymbol{e} = \boldsymbol{C}\,\boldsymbol{u} + \boldsymbol{d} \tag{1}$$

where $\boldsymbol{e}$ is a vector of microphone (mic) signals, $\boldsymbol{C}$ is a matrix of complex numbers that represents the transfer function matrix from the speakers to the mics at a given frequency, and $\boldsymbol{Cu}$ and $\boldsymbol{d}$ are the control and disturbance contributions to the microphone signals, respectively. We further assume that $\boldsymbol{e}$ consists of a set of control mics and a set of monitoring mics. Now, Eq. (1) can be partitioned as

$$\begin{bmatrix} e_c \\ e_m \end{bmatrix} = \begin{bmatrix} C_c \\ C_m \end{bmatrix} u + \begin{bmatrix} d_c \\ d_m \end{bmatrix} \tag{2}$$

where the subscript c denotes control and the subscript m denotes monitoring. So, for example, $\boldsymbol{C_m}$ is the transfer function matrix from the speakers to monitoring mics, and $\boldsymbol{d_m}$, is the disturbance contribution measured at the monitoring mics. The control mics are those that the control system attempts to minimize. The monitoring mics measure the system performance at locations other than at the control mics. Hence, the monitoring mics can provide an indication of the noise reduction throughout the cabin.

The performance prediction method that we employ requires experimental system identification. System identification involves measuring transfer functions between the control speakers and mics, i.e., $\boldsymbol{C_c}$ and $\boldsymbol{C_m}$, at a number of discrete frequencies over the frequency range of interest. In addition, the magnitude and phase of the disturbance field is measured at each mic at these same frequencies, i.e., $\boldsymbol{d_c}$ and $\boldsymbol{d_m}$. From these measurements, predictions of noise reductions at the microphones can be established and various control configurations can be compared.

In principle, the controller converges upon a $\boldsymbol{u}$ that minimizes the cost function:

$$J_c = \boldsymbol{e_c}^* \boldsymbol{e_c} \tag{3}$$

where * denotes the conjugate transpose. The well-known optimal control that accomplishes this is [8]:

$$\boldsymbol{u}_{opt} = -\boldsymbol{C_c}^+ \boldsymbol{d_c} \tag{4}$$

where $\boldsymbol{C_c}^+$ is the pseudo-inverse of $\boldsymbol{C_c}$ [10]. By substituting Eq. (4) into (2), the noise levels at each microphone can be calculated at a single frequency for a given controller configuration.

The overall system performance is assessed by means of a performance index which averages the system performance over the frequency range. For the present tests, the following performance index was chosen:

$$J = 10\ \log_{10} \frac{1}{N} \sum_{i=1}^{N} \left(\frac{2}{n_c} J_{c_i} + \frac{1}{n_m} J_{m_i}\right) \tag{5}$$

where N is the number of frequency points, J_c is given in (3), $J_m = \mathbf{e}_m^* \mathbf{e}_m$, and n_c and n_m are the number of control and monitoring mics, respectively. Note that the performance index J is simply a dB reduction averaged over each of the control and monitoring microphones and averaged over the frequency range. Also, the control mics are weighted twice as much as the monitoring mics.

Experimental Control Configuration

The experimental work consisted of two parts. In the first, transfer functions were measured and system performance predictions were made as shown in the previous section. These were used to select the best 2, 4, and 6 speaker locations out of twelve candidate locations. In the second part, actual control experiments were performed and the results were documented. The experimental configuration is discussed below.

Microphones were distributed throughout the helicopter cabin and served two functions: as control or error mics and as diagnostic mics. Control mics were used by the controller for facilitating the adaptation of the signal passed to the control speakers. Diagnostic mics were used to monitor the noise level at locations other than those of the control mics. For this reason, they provide a more global indication of the sound field within the cabin. The control microphone configuration is shown in Figs. 2 and 4.

For the system performance predictions, eight monitoring mics were used. Their locations are shown in Fig. 4. During the control tests, a grid of diagnostic mics was used to monitor the noise level throughout the cabin. Figure 3 shows the 48 point mic grid of diagnostic sensors. Twelve candidate locations for speakers were chosen and are shown in Fig. 4. From these, the best locations were chosen for possible systems of two, four, and six speakers.

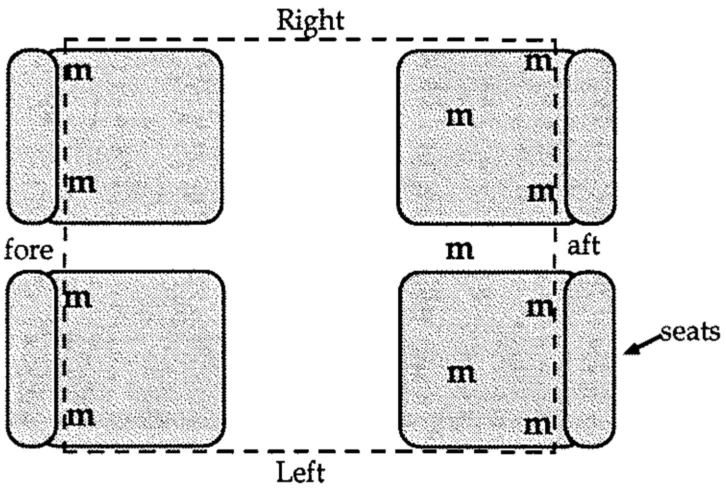

Figure 2: Control microphone configuration. The eleven control mics are indicated by **m**. The dashed line indicates the control mic plane located about one inch below the cabin ceiling.

Speaker placement optimization involved finding the best n (=2,4, or 6) out of 12 speaker locations, where the performance index (Eq. (5)) was used as the basis for optimization. The frequency range evaluated was 40 Hz to 200 Hz with the microphone signals A-weighted. Eleven microphones located in the passenger head-plane as shown in Fig. 2 were used as control mics and eight additional mics located in the passenger chest and waist planes were used as monitoring mics. By using different combinations of the 12 speakers, optimal configurations were determined for n = 2, 4, and 6 speakers. These are given in Table 1. The numbers in Table 1 refer to the locations shown in Fig. 4. Note that the optimal locations for a two speaker system are not optimal for a four or six speaker system. This indicates that interaction between the speakers is important in determining the optimal locations.

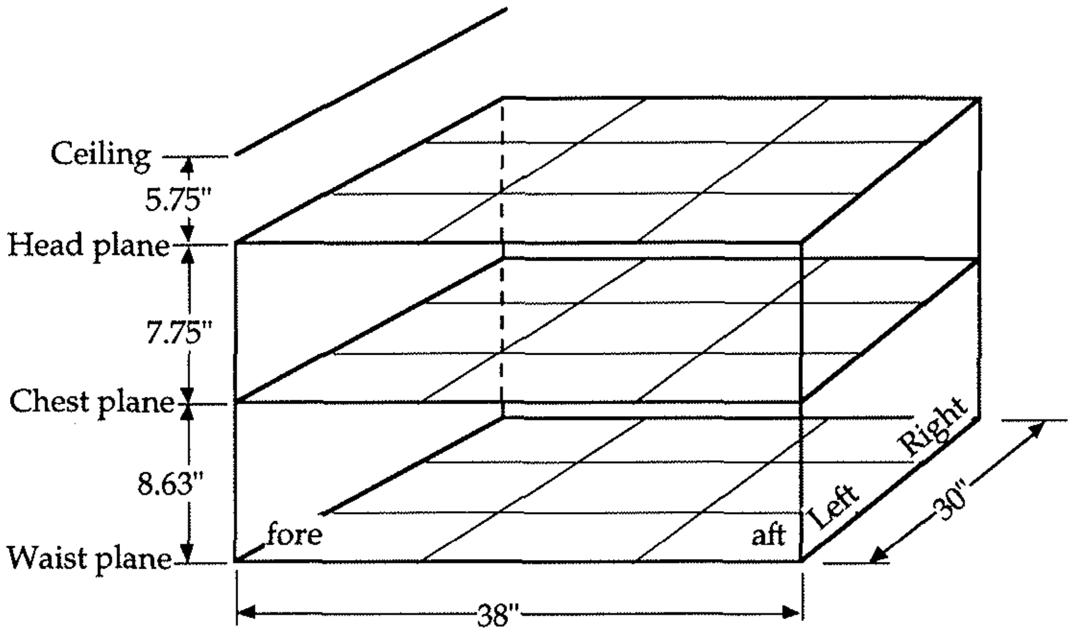

Figure 3: Forty-eight point diagnostic microphone grid.

Table 1: Optimal speaker locations.

Number of Speakers	Configuration
2	4,7
4	0,1,6,7
6	0,2,5,6,7,9

Broad Band Adaptive Control

A broadband multi-channel development controller was used for this demonstration. The controller utilized unique adaptive digital filter technology to calculate optimum signals to drive the optimal four speaker set such that the mean-squared pressures at the control microphone locations were minimized. The control algorithm is designed to minimize the mean-square of the control mic signals (i.e., minimize the scalar $J=\text{mean}\{\mathbf{e}^T \mathbf{e}\}$ where $\mathbf{e}$ is the vector of control or error mic signals).

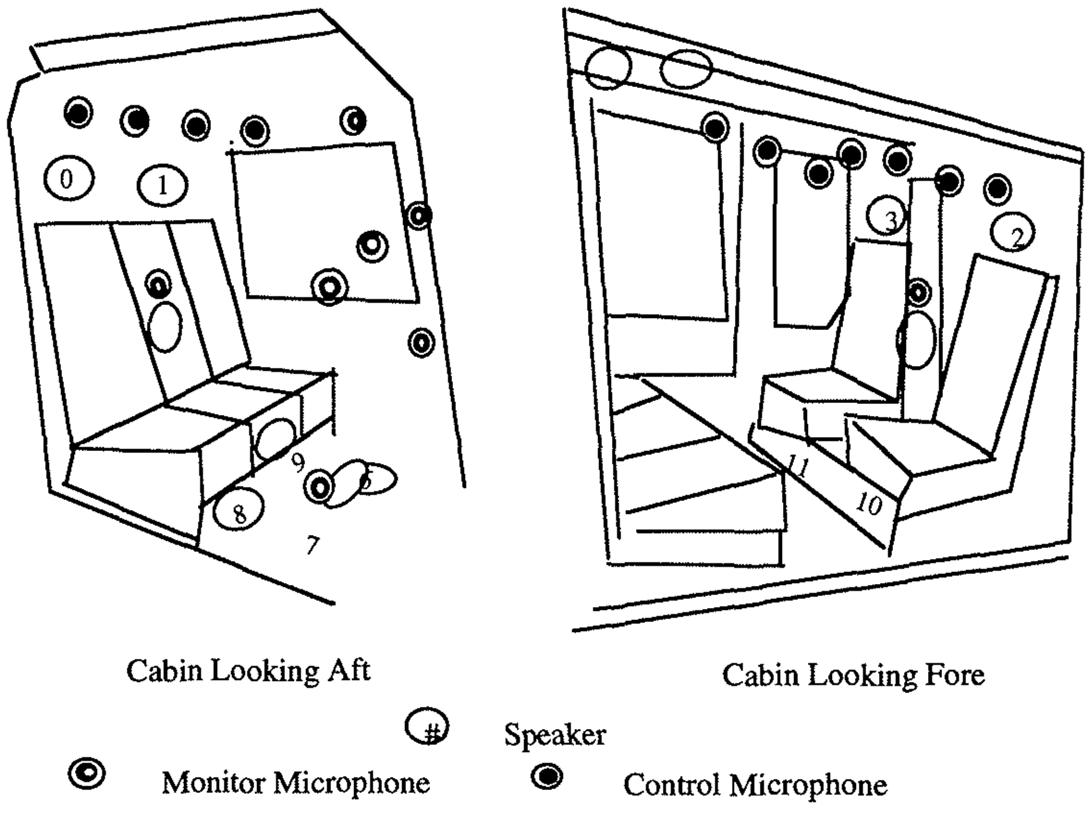

Figure 4: Candidate speaker locations and the microphone locations used for optimization of speaker locations.

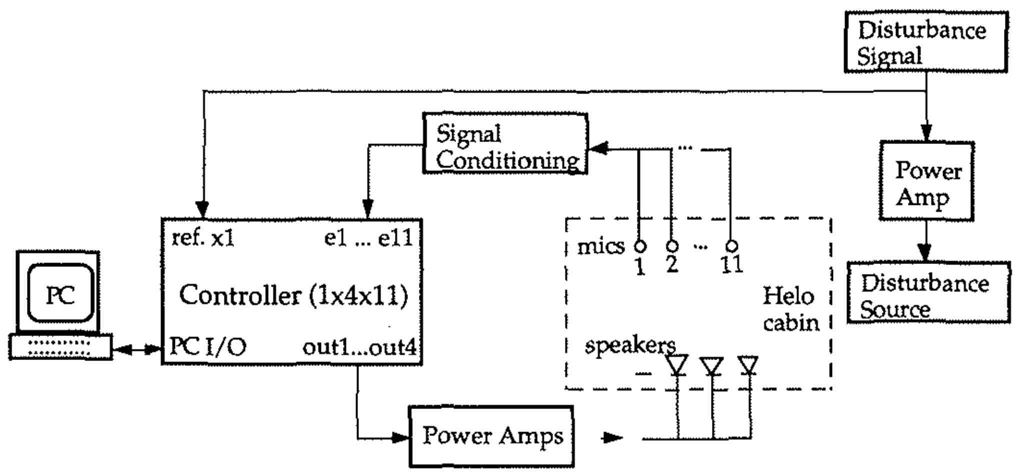

Figure 5: Control system (1x4x11) configuration.

The active noise controller and the experimental set-up are shown in Fig. 5. The multi-input, multi-output (MIMO) controller was configured to have a maximum dimension of 1 reference input, 6 control actuator outputs, and 11 control (error) sensor inputs (1x6x11). Within these bounds, the controller had the flexibility to be reconfigured to test other dimensions. The configuration used for the final test and demonstration was 1x4x11. The optimal speaker locations were chosen to be 0,1,10,11. These locations performed similarly to the optimal locations as given by Table 1 (0,1,6,7). Locations 10 and 11 were more practical than 6 and 7 and thus were used instead.

The simulated disturbance signal was used as the reference signal. This signal provided the controller with a prediction of the disturbance that would eventually propagate into the cabin. Within the controller, the reference signal was passed through a set of digital filters which calculates the proper control signals. The control outputs were then amplified and used to drive the control speakers. The signals from the control (error) microphones were conditioned and input to the 11 control sensor inputs of the controller. These error signals provided the controller with a measure of the instantaneous level of noise control performance and were used to adapt the control filter coefficients.

In general, the controller has the ability to attenuate broadband noise as well as multiple tones [1-7]. This ability is due to the use of a system identification method of disturbance cancellation. The controller models the acoustical-mechanical path between the reference sensor and the points of cancellation. Therefore, given an accurate model, and an appropriate reference signal, broadband and/or tonal disturbances can be canceled and changes in the disturbance do not require remodeling.

The MIMO algorithm structure models the complex acoustic field so that the numerous speakers can provide control authority to attenuate the multiple control/error sensors. This algorithm accounts for all dynamic interactions between sensors and actuators and can compensate for any acoustical feedback to the reference sensor, as well as complicated dynamic systems such as lightly-damped enclosures.

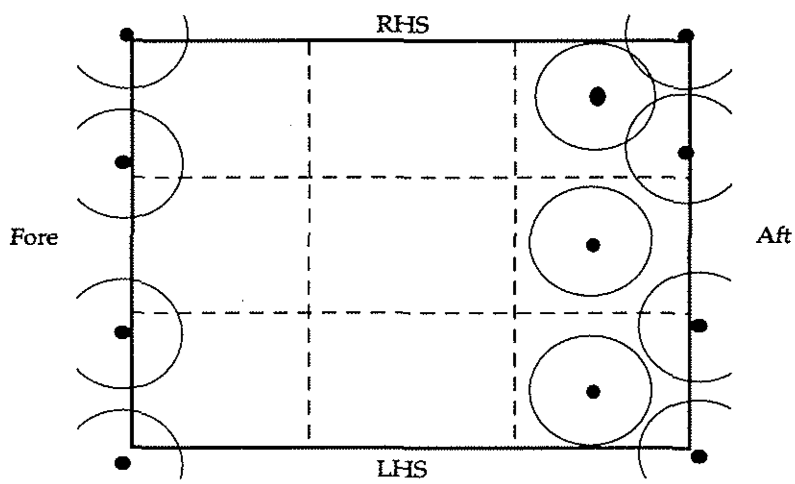

Figure 6: Zones of effective noise attenuation (~ 9 cm radius) around control mics at 200 Hz within helicopter cabin.

Active Control Results and Discussion

First, recall that the Schroeder frequency is the crossover frequency between lightly-damped modal behavior, and behavior typical of high modal density and/or heavy damping (diffuse spectrum). This frequency was found to be about 70 - 80 Hz for the helicopter cabin. The Schroeder frequency is also the crossover frequency between the low frequency part of the spectrum, where spatially global noise control is possible, and the high frequency part of the spectrum, where control is possible only in zones around the control microphones. It was stated, as a rule of thumb, that the radius of this "quiet zone" is a sphere of radius about 1/20 the wavelength of sound in air. An illustration of the zones of noise cancellation is shown in Fig. 6.

Figures 7 through 9 show the performance of the active noise control system. Three planes - head, chest and waist - are shown, corresponding to the three mic planes in Fig. 3. The best results are achieved in the head plane (Fig. 7), because this plane is the closest (within 10 cm) to the control mic plane. In the forward head plane, reductions of 5 to 9 dBA are achieved while in the aft head plane reductions of 7 to 13 dBA are achieved. Better reductions were achieved in the aft head plane for two reasons: the uncontrolled sound field was slightly louder, and more error mics were located aft as compared to forward. Assuming that the 160 Hz tone dominates the spectrum, the experimental head-plane results are consistent with the rule of thumb illustrated in Fig. 6. Performance decreases moving from the head plane to the chest plane (Fig. 8) and finally to the waist plane (Fig. 9) where zones of dBA reduction are almost evenly matched with zones of dBA increase. This performance decrease is due to the increasing distance from the control mic plane. This trend is illustrated in Fig. 10 which shows a vertical plane contour.

Lastly, the effect of ANC system on the noise field in the cockpit was evaluated with the hand held SPL meter. No significant increase or decrease in the noise level could be measured after several trials.

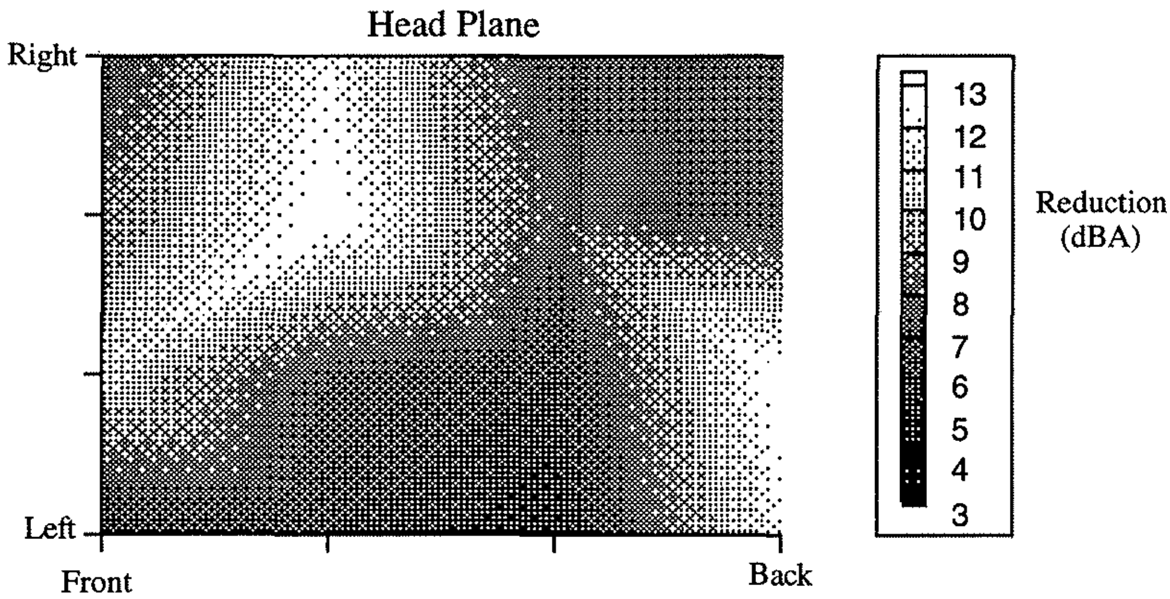

Figure 7: Head-plane SPL contours: dBA reduction with control.

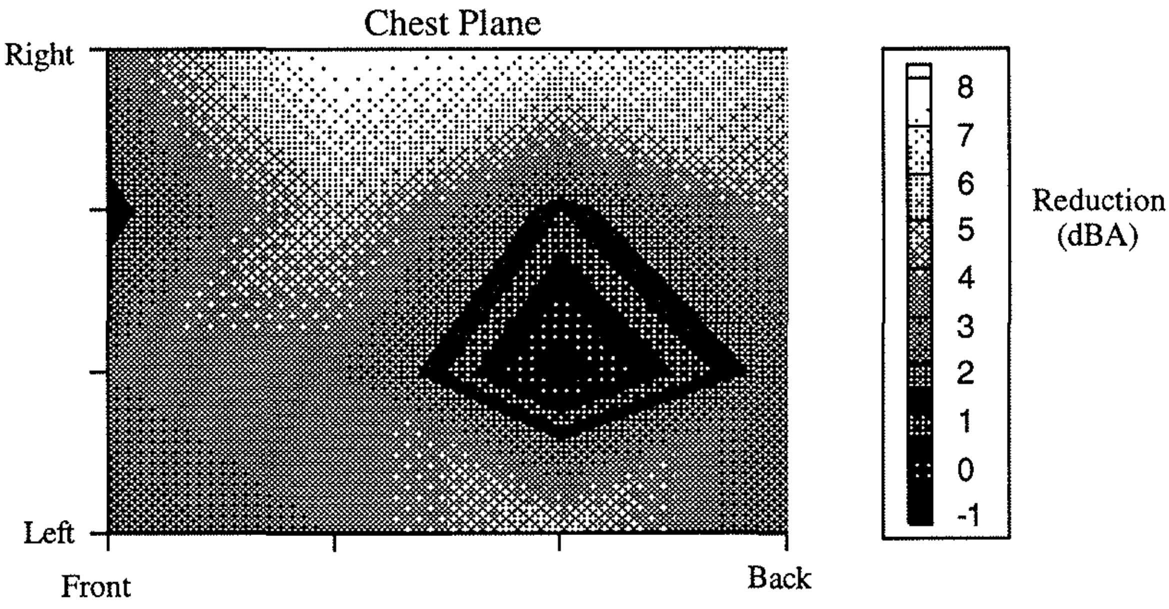

Figure 8: Chest-plane SPL contours: dBA reduction with control.

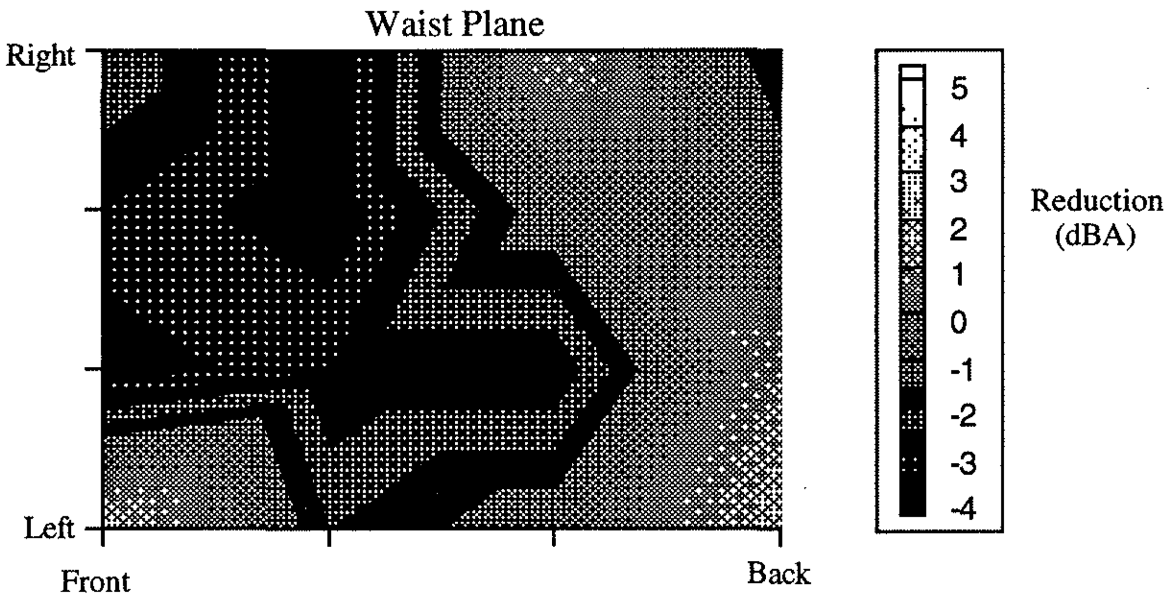

Figure 9: Waist-plane SPL contours: dBA reduction with control.

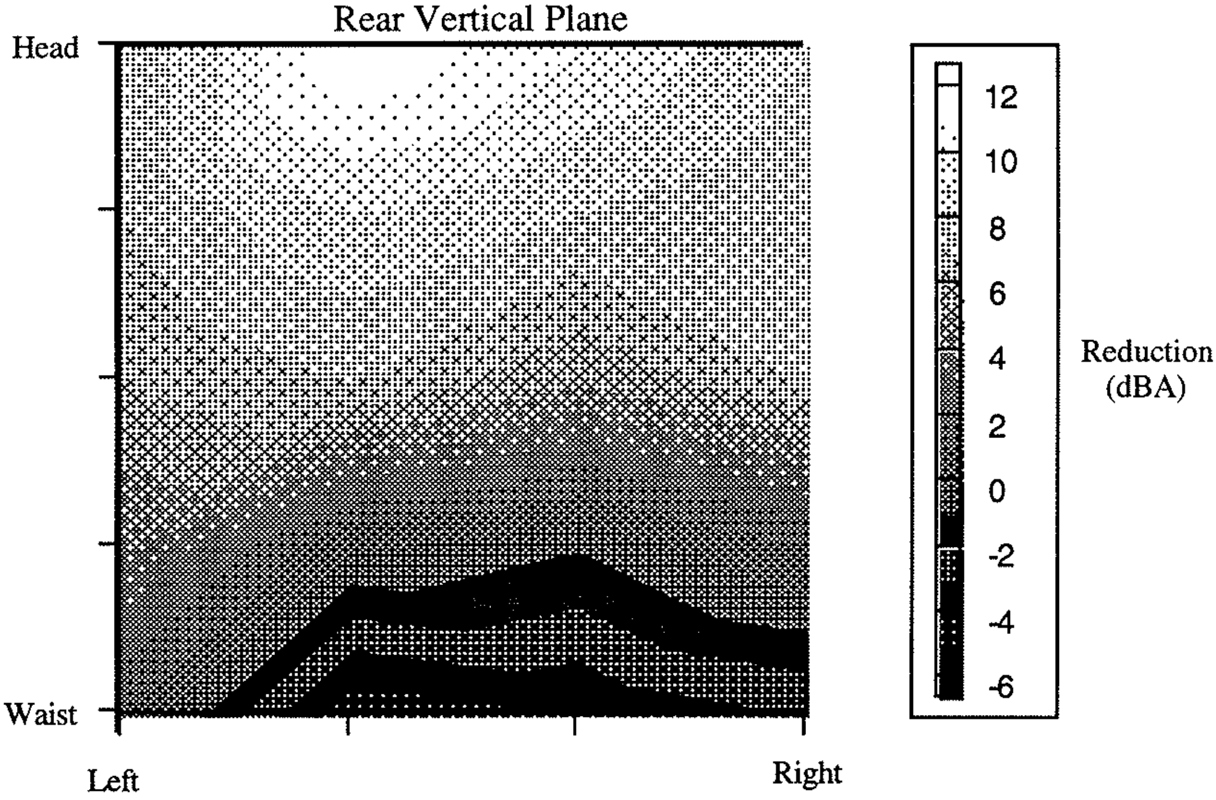

Figure 10: ANC noise reduction in dBA in the aft-most plane of the helicopter cabin.

Conclusions

Typical sound measurements in helicopter cabins indicate that a major contributor to the sound results from airborne transmission of the low-frequency sound (below 400 Hz) created by the main and tail rotor. At these low frequencies, passive acoustic treatments are generally not practical for reducing interior noise, due to size and weight limitations. Laboratory results reported in this paper indicate that Active Noise Control systems can provide marked reductions in the low-frequency noise within helicopter cabins.

In the laboratory, Lord implemented an Active Noise Control system to reduce interior noise in a helicopter fuselage. The system provided 10 - 20 dB noise reduction of various tones below 200 Hz. In addition, the noise control demonstration showed that the subjective performance of the ANC system is dependent on the "tonal emergence" of the sound. Indeed, the system provides greater subjective noise reduction when the sound is largely tonal; i.e., when there are dominant tones in the spectrum.

The demonstrated ANC system consisted of speakers, microphones and a controller. Measurements in the interior of the cabin were used to compute optimal locations and numbers of speakers and microphones to provide the "best" noise control performance. The ANC system used four speakers inside the cabin and eleven microphones, which all can be incorporated in the trim of the production cabin.

The primary conclusions of this study are:

1. With the present ANC system, noise reductions of 7 dBA to 13 dBA can be expected in the head plane. Noise reductions of up to 9 dBA can be expected in the chest plane. Overall, ANC has no significant effect on the average noise levels in the waist plane and cockpit.

2. In the helicopter fuselage, the Schroeder frequency is about 75 Hz. Below the Schroeder frequency, global noise attenuation was achieved. Above the Schroeder frequency, noise attenuation was restricted to zones around the error mics. In general, above the Schroeder frequency, more speakers and error microphones are required to obtain noise reductions in other cabin zones (e.g., the waist-plane and cockpit area).

Future Lord efforts will be devoted to verifying laboratory results in-flight. Furthermore, Lord is currently performing laboratory evaluations of active control to reduce transmission noise from helicopter gearboxes.

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