Helicopter Gear-Mesh ANC Concept Demonstration

Douglas G. MacMartin\textsuperscript{1}, Mark W. Davis\textsuperscript{1},
Charles A. Yoerkie, Jr.\textsuperscript{2}, William A. Welsh\textsuperscript{2}

\textsuperscript{1}United Technologies Research Center, 411 Silver Lane, East Hartford CT 06108, USA
\textsuperscript{2}Sikorsky Aircraft Corporation, 6900 Main St., Stratford CT 06497, USA

ABSTRACT

Active noise control (ANC) has significant potential for improving cabin noise in helicopters. One of the most irritating components of helicopter interior noise comes from high frequency structure-borne gear-mesh tones generated within the transmission gear box. The challenges in the control design for this problem result from the high frequencies involved; from 700 Hz to 5 kHz. Small changes in the system dynamics or disturbance frequency can result in significant changes in the transfer functions between the actuators and sensors. Thus, adaptation is required to retain stability and performance of the control solution in the presence of rapid time-variations. Control architectures and algorithms developed for this application will be discussed. Greater than 20 dB performance has been achieved simultaneously on multiple high frequency tones, on an experimental facility designed to be representative of the helicopter gear-mesh noise problem. The performance was stably maintained while significant changes in the system dynamics were introduced by varying the frequency.

Keywords: helicopter, enclosure, active noise control, active structural acoustic control, adaptive control

INTRODUCTION

Noise is increasingly an important discriminator for many commercial products, with acceptable noise levels traditionally being achieved passively. However, increasing performance demands, together with the importance of reducing weight in many products, and especially for aerospace applications, require innovative solutions such as active noise control to be investigated. Interest in ANC at United Technologies Corporation (UTC) spans numerous products, involving both air-borne applications (HVAC ducts, gas-turbine engines), and structure-borne applications (helicopters, elevators, automobiles). Among the latter set, helicopter cabin noise reduction has the potential for significant benefit, and provides an opportunity for the development of tools and methodologies that will be applicable to a variety of problems and products of interest to UTC.

There are three main components to the noise in a helicopter; large amplitude, low frequency rotor harmonics, broadband noise, and higher frequency structure-borne tones generated within the gear box, power train, and hydraulic system. A typical spectrum is shown in Figure 1. High
frequency gear-mesh tones fall into the speech interference range and are typically the most irritating component of noise. 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 degrees of freedom involved. An alternate approach is to use a quasi-choke point methodology to prevent the disturbance from entering the cabin. Thus, actuation is placed where the gear box is mounted to the structure. The approach taken in [3,4] to address helicopter gear-mesh noise used structural actuators mounted in the struts supporting the gearbox. However, for many helicopters, the mechanical interface between the gear box and the airframe is significantly different, and no such clear choke point exists. The actuators must be placed in parallel with the load path such as in [5], rather than in series. The lack of a clear choke point complicates the disturbance transmission mechanism, making structural feedback difficult. The approach presented herein uses microphone feedback. However, this results in a challenging adaptation problem to retain stability in the presence of constant variations in the plant. The algorithm used is based upon one developed for helicopter higher harmonic rotor control [6], and successfully demonstrated in helicopter active vibration control applications [7].

UTRC has constructed an experimental facility representative of the helicopter problem to test actuator and sensor placement methodologies, new actuator concepts, and control and adaptation algorithms. Greater than 20 dB performance has been achieved simultaneously on multiple high frequency tones, and stably maintained while significant changes in the system dynamics are introduced by varying the frequency. Remaining issues include improving the

![Figure 1. Spectrum of interior noise in a medium class utility helicopter](image-url)
actuator and sensor placement methodology, trading off control performance and adaptation tracking ability, minimizing the weight of the actuator system, and ultimately, ensuring adequate system performance when implemented in an actual flight environment. Further research will be required to address the remaining sources of noise.

**PROBLEM CHARACTERIZATION**

As noted earlier, the noise environment in a helicopter consists of three main sources, as shown in Figure 1. The low frequency tones and broadband noise result from distributed sources that enter the cabin through the external skins of the aircraft as well as through the gear box interface with the airframe. The gear-mesh tones propagate into the airframe primarily through the discrete structural mounting points of the gear box. Other product applications similarly involve a combination of distributed and point disturbances. Elevator cabins are subjected to wind noise, rope vibrations, and disturbances transmitted through the roller guides, while automotive noise sources include wind, road, and engine noise. The helicopter application is therefore relevant in developing tools and methodologies of use to a variety of United Technologies applications.

Figure 1 does not include any weighting, since, at the amplitudes involved, applying an A-weighting is not appropriate. Nonetheless, the low frequency tones are less dominant than this figure would imply. In particular, if one examines speech interference levels, the higher frequency gear-mesh tones dominate. An alternate measure of the irritation of a tone is its prominence, or the extent to which the 1/3 octave band centered about the tone is dominated by that tone. Depending on flight condition, the fundamental frequency of the bull gear mesh tone has a prominence ratio between 15 and 25 dB, with anything over 6 or 7 dB indicating a conspicuous and noticeable tone. To reduce this fundamental tone to inconspicuous levels would therefore require reductions on the order of 15 dB. To achieve these levels passively would incur a significant weight penalty. Because passive approaches are more effective at higher frequencies, the higher frequency gear mesh tones are less critical and require less reduction.

The challenges in the control design problem for the gear mesh application result from the high frequencies. The number of acoustic degrees of freedom is extremely high, making careful actuator selection and placement essential. Furthermore, complex algorithms cannot be used because of the computational burden associated with both the frequency, and the number of degrees of freedom of actuators and sensors required. Finally, and most importantly, the high modal density means that small changes in the system dynamics or in the disturbance frequency can result in significant changes in the transfer functions between the actuators and sensors. If microphone feedback is used, then sources of variation in the transfer functions include passenger motion, temperature and pressure induced changes in the acoustic dynamics, and variations in the structural modes caused by fuel burn-off and varying rotor speed and torque during maneuvers. Furthermore, a control approach based on estimating the transfer function only at the disturbance frequency will see apparent shifts in dynamics based upon changes in the rotor rpm. A control approach must be developed in the presence of all of these difficulties without an accurate model, since the modal density results in high sensitivity to any variation. As a result, although the general characteristics of the problem are consistent, repeatability of detailed measurements is often difficult.
CONTROL ARCHITECTURE

The success of an active control approach is critically dependent on the control architecture; that is, on the selection and placement of actuators and sensors. The simplest approach would be to place the control hardware in order to add damping. However, since the response is forced and some passive damping is already present, this is inadequate. At low frequencies, a global speaker/microphone control approach can be used. With this approach, the speakers must set up a sound field inside the cabin that matches and cancels that created by the disturbance. This requires no knowledge of disturbance transmission paths, but requires that the number of actuators be at least equal to the number of acoustic modes [8]. The number of acoustic modes is plotted as a function of frequency in Figure 2 for a 5’ x 6’ x 9’ (approximately 1.5m x 1.8m x 2.7m) acoustic volume representative of a relatively small helicopter, or an elevator. The speaker / microphone approach is therefore less practical for the gear-mesh application due to the several hundred acoustic modes present in the high frequency range of interest. However, knowledge of the disturbance transmission paths can be used to place actuators to cancel the disturbance before it enters the primary airframe structure. This requires only as many degrees of freedom as there are disturbance degrees of freedom at the mount location [3]. The potential for active control of structure-borne noise at choke points exists in other products as well, such as using engine mounts in automotive applications, or controlling elevator noise due to guide-rail imperfections at an appropriate mounting location.

The ideal architecture would be to feed back structural information. This could enable a decentralized or collocated control approach, greatly reducing adaptation requirements, and potentially enabling simple fixed control design. In principle, if the disturbance can be cancelled by opposing forces at the gear box mounting location, then it should be possible to sense the offending disturbance there as well. However, not all of the structural motion results in an

![Figure 2. Number of acoustic modes as a function of frequency, for representative 5’ x 6’ x 9’ enclosure (approx. 1.5m x 1.8m x 2.7m)](image-url)
acoustic response, and one must therefore identify which degrees of freedom couple and which do not. This is a subject of on-going research. Microphone feedback is used herein to avoid the difficulty in selecting appropriate structural sensor locations to achieve desirable noise reductions in the cabin interior. This does not present any causality problems because the gear mesh disturbance is tonal. However, this does result in significantly more sources of variation in the sensor / actuator transfer functions, as discussed in the previous section, and it remains to be seen whether this approach will be sufficiently robust in flight.

The control architecture used herein is shown schematically in Figure 3. The number of actuators $n_a$ is determined by the complexity of the disturbance. If the mounting points were truly single points as in [3,4], then 3 forces and 3 moments would be sufficient at each mount location [5]. However, for the structural interface considered here, significant foot flexibility exists at the high frequencies involved. To minimize the number of actuators required, and thereby minimize the ultimate cost and weight of the product, one must determine which degrees of freedom result in internal noise, and place actuators to cancel only these generalized forces.

Selection of the number of sensors $n_s$ is a trade-off between computation and cost, and improved global performance. With $n_s = n_a$, nearly perfect performance at the controlled microphones is possible, but this does not result in the maximum possible global reductions (e.g., at uncontrolled locations such as at a passenger’s ear where no feedback microphone can be placed). Increasing the number of sensors clearly results in better global performance. This can be explained by considering the case where there is some flanking path disturbance that the actuators do not cancel, in addition to the primary choke point disturbance that they do. With $n_s = n_a$, it is possible for the actuators to generate an appropriate combination of forces so that the combination of these and the flanking path disturbances are zero at the $n_s$ feedback locations. Due to the large number of acoustic degrees of freedom (and therefore small zone of quiet around each microphone), then on average, the noise at an uncontrolled location due to these forces will

![Figure 3. Control architecture for helicopter gear-mesh ANC. Structural actuators are mounted at the gear box mount locations, with feedback from cabin microphone sensors.](image-url)
increase. However, if the control must minimize the noise at several locations simultaneously, then the best strategy for the flanking path disturbance is to do nothing. This argument can be phrased mathematically by separating the ambient disturbance field into a component aligned with the actuator influence matrix T, and the remainder associated with the orthogonal subspace given by $T^\perp$.

There are two considerations for selecting the type of actuator. First, is the desire not to break the primary load path for rotor loading. Second, is to obtain sufficient authority. Various prime-mover approaches have been considered, including piezoelectric, magneto- and electrostrictive, and more conventional electro-magnetic technology. Given the tonal nature of the disturbance, one option would be to use a resonant device such as a proof mass to give some mechanical amplification at the frequency of interest, the drawback to this strategy is that control authority is desired at multiple frequencies.

**CONTROL ALGORITHM**

Having defined actuator and sensor selection and placement, the next step is to develop control algorithms to minimize the sensor response at the frequencies of interest. The high frequencies involved in the gear mesh application introduce two challenges beyond those observed in many tonal applications. First is that the computational burden is significant and must be minimized. The more critical issue, however, results from the fact that for any control problem, the transfer functions between actuators and sensors must be known at least implicitly. As noted in the problem characterization, these transfer functions are constantly changing, and the controller must adapt to these changes.

In the helicopter application, the disturbance frequency can be estimated very accurately because the disturbance frequency is related to the main rotor rpm. Because the tone amplitude and phase vary slowly with respect to the frequency of the tone itself, overall computations can be minimized by controlling these variables. The approach used is based on that developed for higher harmonic rotor control (HHC) in [6], wherein a harmonic analyzer is used to identify the desired tonal information, and a minimum variance control algorithm then generates control signals based on a continually updated estimate of the plant transfer function. Reference [9] describes numerous approaches for tonal control (without adaptation), and illustrates the connection between the approach suggested for HHC, and other tonal control approaches. This approach results in controller poles at the disturbance frequency, and hence this is equivalent from a performance perspective to any other tonal control approach.

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 a single quasi-steady complex transfer function matrix, denoted $T$. However, by doing so, yet another source of time-variation is introduced; as the rotor rpm varies, the frequency of interest changes, and therefore the $T$ matrix changes. Variations of 1 or 2% in disturbance frequency can result in shifts through several structural or acoustic modes, yielding drastic phase and magnitude changes in the $T$ matrix, and instability with any fixed-gain controller. Thus while the computational savings resulting from modeling the system as a single transfer function matrix are critical to a practical approach, it results in an additional burden on the adaptation process.

The derivation given below of the control and adaptation follows from [6]. Assuming linearity, then the microphone response $z$ can be written as
\[ z = T_g u + z_0 \]

where \( z_0 \) is the slowly varying ambient field, \( u \) is the control and \( T_g \) is the transfer function matrix. All variables refer only to the relevant quantity evaluated at the frequency of interest. Alternately, the system response could be written as a local model:

\[ \Delta z = T \Delta u + w \]

where \( T = T_g \) if the system is linear. This latter representation avoids the requirement of identifying the ambient field, since the disturbance in this equation is zero-mean. For notational simplicity, define \( y = \Delta z \), \( v = \Delta u \).

The control law is derived to minimize a quadratic performance index

\[ J = z^T z + u^T W_u u + v^T W_{\delta u} v \]

Solving for the control which minimizes \( J \) yields:

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

where

\[ Y_k = (T_k^T T_k + W_u + W_{\delta u})^{-1} \]

Solving for the steady state control \((u_{k+1} = u_k)\) yields

\[ u = -(T^T T + W_u)^{-1} T^T z_0 \]

The matrix \( Y \) determines the rate of convergence of different directions, but does not affect the steady state solution. This RLS control law attempts to step to the optimum in a single step, and behaves better with a step-size multiplier \( \beta < 1 \). An LMS gradient approach would give \( Y = I \) instead. For poorly conditioned \( T \) matrices, the equalization of convergence rates for different directions that is obtained with the RLS approach is critical.

Further insight into the behaviour of the control law can be gained by substituting for a singular value decomposition of \( T = U \Sigma V^T \). Define \( u = V^T u, \quad z = U^T z, \quad \sigma \) as a singular value of \( T \), and scalars \( \rho \) and \( \mu \) as the diagonal elements of \( W_u \) and \( W_{\delta u} \) respectively. Then

\[ u_{k+1} = [1 - \beta \rho / (\sigma^2 + \rho + \mu)] u_k - [\beta \sigma / (\sigma^2 + \rho + \mu)] z_k \]

The DC gain of this control law is \( \sigma/\rho \), and the corner frequency is at \( 1 - \beta \rho / (\sigma^2 + \rho + \mu) \). For \( \sigma \gg \rho \), the loop cross-over frequency is approximately \( \beta \sigma^2 / (\sigma^2 + \rho + \mu) \), normalized by the update rate. Thus decreasing the control weighting increases the low frequency gain, and decreasing the weighting on the rate of change of control increases the loop cross-over frequency. However, for a MIMO problem, the normalized weightings are different for different “directions” so that an overall gain and cross-over frequency cannot be identified; this has the benefit of reducing the impact of nearly singular (and hence highly uncertain) directions in a poorly conditioned problem.
The adaptation process is derived as a Kalman filter which minimizes the equation error for each row of the $T$ matrix (given by index $i$). For an estimated $T$ matrix, $T^e$, an error vector can be formed as

$$E = y - T^e v$$

Assume white process noise $q$ and measurement noise $w$, with covariances $Q$ and $R$ respectively. Then each row of the $T$ matrix and each sensor measurement evolve in time according to

$$(T_{k+1})^T_i = (T_k)^T_i + q$$
$$y_i = (T)^T_i v + w$$

The Kalman filter gain $K$ is based on the covariance of the error between $T$ and the estimate $T^e$, given by the matrix $P$

$$M = P_k + Q$$
$$K = Mv / (R + v^T M v)$$
$$P_{k+1} = M - K v^T M$$

The estimate for each row of the $T$ matrix is then updated via a standard Kalman filter approach. If the covariance matrices $Q$ and $R$ are the same for each sensor, then so are $P$ and $K$, and the resulting equations can be written in matrix form as

$$T^e_{k+1} = T^e_k + E K^T$$

The resulting approach works remarkably well, aside from issues related to parameter drift that will be discussed later.

**DESCRIPTION OF EXPERIMENTS**

Control architectures, algorithms, and actuator work were conducted on several experimental facilities constructed to be representative of the helicopter problem, with increasing realism in capturing the disturbance transmission mechanisms. Figure 4 shows the experimental V/NAC facility at UTRC, prior to mounting the aluminum skin and composite interior trim panels to the structural frame. The 5’ x 6’ x 9’ interior acoustic volume is similar to that of the passenger cabin of a small to medium class helicopter, with discrete disturbance force paths into the structure that are similar to those encountered in the helicopter application. Two transmission beams are mounted in the ceiling, with a mock-up of a helicopter gear box mounted on the beams at four locations. The gear box mock-up allows one or more shakers to be attached through stingers to provide disturbance inputs that propagate into the structure in a manner similar to the true gear-mesh disturbance. This mock-up can also be isolated from the structure for testing purposes so that disturbances enter the structure through only a subset of the four mounting locations.
Figure 4. Experimental V/NAC facility at UTRC, shown prior to completing skin panels, adding trim, and gear box mock-up.

Figure 5. Representative transfer function variation with frequency, on experimental facility.
The control architecture was validated by applying a disturbance and demonstrating global control with microphone feedback. Verifying the algorithm’s adaptation behaviour required the introduction of representative variations in the transfer functions to simulate what occurs in flight. In the lab, these variations were introduced by changing the disturbance frequency. Figure 5 illustrates the extent of these changes for a representative actuator and microphone. For a 2% change in disturbance frequency, the magnitude increases by 13 dB, and the phase drops by over 100 degrees. Further adaptation requirements result from slight non-linearities in some of the tested actuator concepts.

RESULTS

The performance of the active noise control approach is best illustrated by Figure 6, which shows the reductions at each of 32 microphones for each of three separate tones. For each tone, the first bar in the plot shows the overall rms noise reduction. This data was taken with a significantly reduced actuator configuration, wherein multiple actuators were discarded at each mounting point based on an understanding of the importance of different disturbance degrees of freedom. The good performance obtained illustrates the importance of identifying the contributions of each degree of freedom in order to minimize the number of actuator channels required. Better reductions were obtained at the first tone due to the increasing number of disturbance degrees of freedom participating at higher frequencies. Other tests with fully populated actuator sets obtained slightly better performance at the higher frequencies, achieving greater than 20 dB.
reductions at all three tones. Note that the dB axis is effectively arbitrary, since the open-loop levels were set by controlling the shaker, rather than through the physics of the gear-mesh mechanism.

The performance of the adaptation algorithm can be illustrated by comparing the controlled performance in the presence of a varying frequency with and without adaptation on, as shown in Figure 7. A $\pm 1\%$ variation was introduced, with a period of 10 seconds, giving a maximum slew rate of 0.63\% per second. This repeatable variation is not intended to be directly realistic, however, both the maximum rate of change of frequency and the total 2\% shift in frequency are consistent with the worst case condition in a normal flight regime (i.e., excluding severe transients such as transitions to and from auto-rotation.) With adaptation, only a few dB performance was lost throughout the period for this worst case. Without adaptation, the closed loop system is unstable in steady state operation at either extreme. Because the speed of frequency variation in this test is comparable to the time constant of the control signals, some performance is still obtained only because the control solution does not degrade too rapidly. That is, worse performance would be obtained if the frequency shifted suddenly to one extreme and then remained steady.

Figure 7. Performance with and without adaptation for a rapid variation in frequency (sinusoidal with period 10 seconds).
The control and adaptation algorithm behave as desired, and correctly minimize the feedback microphones. Also of interest is the behaviour of the uncontrolled microphones. This is shown in Figure 8. The control amplitude represents the largest control amplitude required of the entire set of actuators for a given control weighting. The plot shows the predicted behaviour; the experimental results are similar. For this square case \((n_s = n_a)\), as control weighting is decreased, ever increasing performance is obtained on the controlled microphones, at the cost of ever increasing control authority requirements. However, performance on the uncontrolled microphones reaches a minimum where further reductions in control weighting fail to improve the global performance. The behaviour is consistent with imperfect choke points. The continued decrease in the controlled microphones is obtained by cancelling the effect of flanking path disturbances at these microphone locations. With \(n_s > n_a\), the controlled and uncontrolled curves are closer, and there is an optimum control weight where further reductions have almost no effect.

The overall control approach has been demonstrated to be successful. The following are areas requiring further research:

(i) As noted earlier, any adaptive algorithm that uses only the control and output signals for plant estimation will exhibit parameter drift once the initial transients have passed. Typically, this results in bursting, which generates information that will correct the parameters, and the cycle continues [10,11]. The problem results from a lack of persistent excitation in the disturbance rejection problem, and is made worse by the presence of large disturbances and unmodelled dynamics. Numerous simple but somewhat ad hoc fixes can be used to improve the behaviour, but all of them involve trade-offs between maximizing the current performance and optimizing the ability to track variations. The best approach will invariably be problem dependent. Flight data is required to obtain a better model for representing the true

![Figure 8. Predicted performance as a function of required control authority with decreasing control weighting, for both controlled, and uncontrolled microphones.](image)
characteristics of the time variation of the plant, and eventually for determining if these simple fixes can be made to work in flight.

(ii) Determination of the optimum set of actuators, once the overall architecture has been determined, is based primarily on a down-selection process. Ideally, one would like a tool that allows one to instrument a helicopter (or other application) with sensors, collect data, and directly establish the optimum actuator locations. Furthermore, the ideal control architecture would involve feedback of structural information, rather than acoustic; to do so would also require the development of tools to assess what structural information couples with the acoustics and is therefore necessary, and what information does not couple.

**CONCLUDING REMARKS**

An approach for actively controlling high frequency structure-borne tonal noise in helicopters has been discussed. Structural actuation has been used to cancel the disturbance before it enters the structure. The key challenges in the control algorithm are computation, and maintaining performance in the presence of rapid time-variations. The former is solved by controlling only the slowly varying envelope of the tone. The latter is solved with a Kalman filter adaptation process. Significant performance was obtained on a representative experimental facility, and maintained while representative time-variations were introduced. It remains to show that the approach investigated can be made to work in flight.

**ACKNOWLEDGEMENTS**

A complete list of people who contributed to this effort is too lengthy to include. Key contributors include Alan Finn and Bill Weller at UTRC, and Tom Millott at Sikorsky.

**REFERENCES**


