Active Vibration Control of Trim Panel Using a Hybrid Controller to Regulate Sound Transmission

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This paper presents a method for actively controlling the sound transmission through an aircraft trim panel using a hybrid feedforward/feedback control technique. The method involves measuring the frequency transfer function of the trim panel system and then creating an autoregressive moving average model using frequency domain curve fitting. The control technique is designed to minimize the vibration of a panel that has a limited piston-like motion. The hybrid controller consists of an adaptive feedforward controller that operates in conjunction with a linear quadratic Gaussian feedback controller. The feedback controller increases the damping capacity of the secondary plant to augment the convergence rate of the adaptive feedforward controller. Experimental results indicate that the hybrid controller effectively reduces the vibration of active trim panels and therefore also reduces the sound transmission of the panel.

1. Introduction

Several active control techniques have been developed over the past decade for reducing low-frequency interior noise fields. Methods for active control of interior noise are generally classified as either active noise control (ANC) or active structural acoustical control (ASAC).¹² ANC uses destructive interference of sound waves to reduce the noise level, but usually requires many sources and sensors distributed in the internal space. ASAC uses a force transducer attached to a vibrating panel to change its radiation characteristics. Only a few actuators are required to achieve large reductions in the radiated sound levels of a vibrating panel with low modal density. This noise reduction is due not only to the suppression of the vibration amplitude of the panel but also to its change of response as it vibrates with low radiation efficiency (i.e., modal restructuring). Thomas et al.¹³ predicted analytically that considerable noise attenuation could be achieved using only three actuators when controlling a single rigid plate. If the motion is restricted to its out-of-plane piston mode, only one actuator is required. Using a control panel vibrating in a piston-like mode, Fuller¹⁴ was able to reduce the sound transmission through a composite panel using its volume velocity as the quantity to be minimized in the control error function.

Various control schemes have been examined for the practical implementation of ANC or ASAC.⁹ The practical difficulties encountered when trying to force a control panel to respond with a piston-like motion have also been described. Feedback control can be used when the reference signal coherent with the primary disturbance is not available. Feedback-based controllers, such as linear quadratic Gaussian (LQG) and $H_\infty$ optimal controllers, achieve good results for suppressing transient disturbances.⁷ Recent research into adaptive feedforward controllers, including filtered-x and filtered-u least-mean-square (LMS) algorithms, has demonstrated that robust performance in persistent disturbance rejection, such as driving the residual error to zero, can be achieved with little prior knowledge of plant dynamics.⁸⁻¹⁰ Snyder et al. noted that the convergence of these algorithms depends on the plant dynamics and the model error.¹¹,¹²

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NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$C_l$</td>
<td>closed-loop transfer function</td>
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<tr>
<td>$e(k)$</td>
<td>residual vibration at error accelerometer</td>
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<tr>
<td>$p(R,\theta,\phi)$</td>
<td>farfield sound pressure</td>
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<tr>
<td>$\text{Tr}(R_f)$</td>
<td>trace of auto-covariance matrix of filtered-x signal</td>
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<tr>
<td>$W_k$</td>
<td>adaptive feedforward controller</td>
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<tr>
<td>$\dot{w}$</td>
<td>panel acceleration</td>
</tr>
<tr>
<td>$\eta$</td>
<td>convergence factor</td>
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Saunders\textsuperscript{13} showed that a hybrid controller can effectively reduce a disturbance. A feedback loop in a hybrid controller generally enhances the characteristics of transient and steady-state responses, and performs main control functions like residual vibration control and command tracking. A feedforward loop in a hybrid controller reduces the resonant excitation energy by input shaping, such as zero vibration or pre-filtering.\textsuperscript{14,15}

This paper describes a method of controlling sound transmission through a panel by active vibration control of the panel using airborne plane wave excitation. We focused on the low-frequency noise fields found in an aircraft cabin. In general, this approach allows for global noise reduction using local vibration control of the trim panel, provided that all of the sound transmission paths into an enclosure are intercepted by an active panel. A hybrid control scheme is used as an active vibration controller. A feedback controller is designed using LQG methods to augment the convergence rate of an adaptive feedforward controller by increasing the damping capacity of the secondary plant. The feedforward controller actually reduces the vibration level of the trim panel. A feedforward controller update rule that automatically compensates for the effect of a feedback link is proposed to maintain performance control despite variations in the primary plant dynamics.

2. Active Vibration Control Design

2.1 Sound Transmission Control Concepts

The farfield sound pressure, $p(R,\theta,\phi)$, radiated by a vibrating baffled rectangular panel for the case of a uniform acceleration distribution, $\ddot{w}$, of a square panel with length $L$ is described by the following Rayleigh equation\textsuperscript{6}

$$p(R,\theta,\phi) = 2\rho e^{ikR} \frac{\ddot{w} \sin \gamma_L \sin \gamma_L}{\gamma_L^2},$$

where $(R,\theta,\phi)$ is the point in polar coordinates from the panel center, $\rho$ is the density of air, $k$ is the acoustic wavenumber, $\gamma_L = k \sin \theta \cos \phi$, and $\gamma_L = k \sin \theta \sin \phi$. At low frequencies where $\gamma_L \ll 1$, this equation reduces to

$$p(R,\theta,\phi) = 2\rho e^{ik\ddot{w} L^2}.\quad(2)$$

Since $\ddot{w} = j\omega w$ for harmonic vibration, Eq. (2) simply shows that the radiated pressure in the farfield can be reduced by making the acceleration or velocity of a panel very small in amplitude.

Figure 1 shows how the concept of active trim panels can be applied to aircraft cabin noise control. The lightweight trim panels in areas of high sound transmission into the aircraft cabin can be segmented into an array of smaller sub-panels that allow only rigid body motion independent of each other. Segmented panels can be actively controlled to reduce the radiated (or transmitted) sound power using embedded transducers such that the surface of each panel remains motionless to prevent sound radiation.

2.2 Feedforward Control Using a Filtered-x LMS Algorithm

Figure 2 shows a block diagram of the filtered-x LMS (FXLMS) algorithm. The residual vibration $e(k)$ at the error accelerometer is the result of destructive interference between the external disturbance and the vibration created by the control force. The secondary plant, which includes the dynamic characteristics between the actuator and sensor, including the low-pass filter, and the transmission path of the structural vibration may be modeled by a finite impulse response

(FIR) filter of order $p$, $H = [h(0), h(1), \ldots, h(p)]^T$. Assuming that the adaptive controller is represented by another FIR filter of order $q$, $W_k = [w_k(0), w_k(1), \ldots, w_k(q)]^T$, where subscript $k$ denotes the time at which the filter coefficients are updated, then $e(k)$ can be expressed as follows:

$$e(k) = d(k) - \sum_{j=0}^{q-1} h(j)w_{k-j}(i)x(k-j),$$

where the desired signal $d(k)$ is the vibration level induced by only an external disturbance at the error sensor and $x(k)$ is the single reference input that is coherent with the external disturbance but not corrupted by the actuator force, e.g., the rotational speed in rotary-wing aircraft.

The coefficients of the feedforward controller may be updated recursively based on the gradients of the instantaneous squared residual vibration as follows:

$$w_{k+1}(i) = w_k(i) + 2\eta e(k) \sum_{j=0}^{p-1} h(j)x(k-j) = w_k(i) + 2\eta e(k)f(k-i)\quad(4)$$

where $\eta$ is the convergence factor that determines the speed of adaptation and $f$ is the filtered-x signal, for which the reference input is filtered by the secondary plant.