A TWO-LAYER ADAPTIVE ACTIVE STRUCTURAL NOISE CONTROL SYSTEM

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Vibrating plates have been gaining increasing interest for active noise reduction or isolation systems. Unfortunately, they are much harder to control than loudspeakers. Plates have multimodal response with high variations of amplitude response. To effectively excite multiple vibration modes multiple actuators are usually needed. Using multiple actuators mounted on a single plate significantly increases the number of control signals to be worked out. This could be a severe problem for active control systems with multiple vibrating plates. Such system would have a large number of secondary paths and necessity to adapt many control filters. However, secondary paths for the same vibrating plate are not fully independent.

In this paper a lower-layer single-input multiple-output controller is designed first for the vibrating plate to be seen as a single-input single-output plant of equalized frequency response. Then, a higher-layer active controller is designed to reduce noise. The control system is experimentally verified and obtained results are reported.

1. Introduction

Acoustic noise is a common problem in industrial halls. In many cases passive noise reduction methods cannot be applied because of operational and technological reasons, like size limitations or requirements for effective cooling. In some cases, especially for low frequencies, passive noise reduction methods could be applied but with high cost because of large dimensions needed for effective isolation. In many cases only personal hearing protectors and active noise reduction methods can be applied. The active noise reduction is usually preferred if wearing of personal hearing protectors reduces user’s comfort too much for given circumstances.

Active Noise Control (ANC) systems usually use loudspeakers as secondary sound sources. In many industrial halls classical loudspeakers cannot be used because of harsh environment conditions such as high humidity or dust. Vibrating plates are considered to be possible replacement for loudspeakers in ANC systems for such applications.

Plates can be used as passive, semi-active or active sound barriers [1, 2]. A double wall structure with passive Helmholtz resonators can achieve high reduction for selected low frequencies [3]. Semi-active systems can use shunt damping with switching of selected electric circuits [4, 3].

The active barrier using a plate can be thinner that comparable in sound isolation parameters passive barrier. When the barrier thickness is not critical, two plates separated with a cavity can be used for active control to provide improvement of transmission loss compared to a single plate application [3].
Unfortunately, vibrating plates have worse sound radiation properties than loudspeakers. This causes problems for Active Noise Control systems. Plates have multimodal response with high variations of amplitude response. To effectively excite multiple vibration modes multiple actuators are usually needed. Multiple actuators mounted on a single plate significantly increase the total number of control signals to be worked out. ANC systems are then required to have a large number of secondary paths. Some of the secondary paths that share the same vibrating plate are not fully independent and cannot be used to effectively provide reduction of noise in multiple zones of quiet. The purpose of this paper is to design a double-layer control systems, which first equalizes the plate response, and then takes advantage of the easier to control system in order to reduce noise more efficiently.

2. Active Noise Control

The straightforward approach for using vibrating plates to reduce noise is to consider them like classical loudspeakers. Many different control algorithms are used for such systems including Notch filters [5], LQG controllers [6], adaptive RST feedback controllers[7] or a large number of simple feedback controllers [8, 9]. However, for such systems, when the noise can be non-deterministic and non-stationary, adaptive linear feed-forward ANC systems are usually used [10].

Fig. 1 presents the block diagram of typical adaptive multichannel feedforward ANC system with the FXLMS algorithm [10, 11]. The number of secondary paths is equal to \( C \). In this figure \( x(i) \) is the reference signal, \( e(i) \) is the error signal, \( d(i) \) is the primary noise at the point of interest, \( P \) stands for the primary path representing the acoustic space between the noise source and error microphones, \( S_1 \text{-} S_C \) are the secondary paths with the control signals being the inputs and the error signal as the output, the symbols with hats stand for models of respective paths, \( W_1 \text{-} W_C \) are control filters, one for each secondary path, and \( E \) is the reference path, i.e. the path between primary noise source and reference microphone.

![Active Noise Control system diagram](image)

The \( j \)-th control signal value is equal to reference signal \( x \) filtered by control FIR filter \( W_j \):

\[
    u_j(i + 1) = w_j(i)^T x_u(i),
\]

where \( w_j(i) = [w_{j,0}(i), w_{j,1}(i), \ldots, w_{j,N-1}(i)]^T \) is a vector of parameters of the \( j \)-th control filter and \( x_u(i) = [x(i), x(i-1), \ldots, x(i-(N-1))]^T \) is a vector of last \( N \) reference signal values.
For adaptation of FIR control filters the Normalized Leaky Filtered-reference LMS algorithm is used.

This algorithm scales linearly with the number of secondary paths. In case of vibrating plates the secondary paths are not fully independent.

3. Control of sound radiation from a plate

To simplify ANC systems with vibrating plates, it is convenient to consider a single plate as a single sound source. However, to effectively excite multiple vibration modes multiple actuators are usually needed. Similar problem exists also in classical loudspeakers, where in many cases multiple speakers are used to build a single multi-way loudspeaker. In case of loudspeakers, each speaker is used to emit sound in a given frequency band. The loudspeaker input signal is filtered by a set of crossover filters to generate control signal for each speaker. Because speakers have flat passbands simple analog crossover filters are successfully used. In case of vibrating plates with multiple actuators, the problem is more complicated because each actuator usually controls multiple nonconsecutive modes and the same mode is controlled by multiple actuators.

The simplest approach is to filter the input signal by fixed parameter filters, one for each actuator. The $j$-th control signal value is equal to input signal $x$ filtered by control FIR filter $F_j$:

$$u_j(i + 1) = f_j(i)^T x_u(i),$$

where $f_j(i) = [f_{j,0}(i), f_{j,1}(i), \ldots, f_{j,N-1}(i)]^T$.

The goal for designing control filters is that the whole transfer function from input signal and radiated sound is equal to the desired transfer function. In real applications it’s not possible and the difference between the actual transfer function and desired one should be minimized. When the $H_2$ norm is used the $F_i$ can obtained be by minimization of following cost function:

$$L = E\{e^2(i)\}$$

$$e = \sum_{i=0}^{C} F_i(z^{-1}) \hat{S}_i(z^{-1}) x(i) - H(z^{-1}) x(i)$$

where $F_i$ is the control filter for $i$-th actuator and the $\hat{S}_i$ is the model of secondary path. In case of $C > 1$ this problem have infinite number of solutions and some additional requirements, like minimization of control power, should be formulated.

Because in case of vibrating plates, huge changes can be caused by temperature changes [12] the fixed-parameter feed-forward solution cannot be sucessfully used for such systems. Such changes can be compensated by gain-scheduling or by adaptive feed-forward system. The sound radiation can be measured at a single point or at many points with microphones and used to adapt weights of the control filter. When the expectation operator is discarded from Eq. (3) the optimization problem can be solved by using the FXLMS algorithm.

The structure of the single-channel adaptive control system is presented in Fig. 2 [13]. The input signal, $x(i)$, is filtered by control filter, $F$, and then it drives the plant, $S$. The radiated sound is compared with the input signal filtered by the reference path, $H$. The difference is used by the FXLMS algorithm with leakage to adapt parameters of control filter, $F$ [13]. This system can be easily extended to multiple secondary paths and error signals—the differences between measured radiated sound by microphones and the desired sound at specified points.

When compared to typical application of FXLMS for Active Noise Control the primary path is replaced by arbitrary chosen desired path model and the output of the model $H$ is subtracted from the plant output (not added as for classical ANC systems where sound interference is concerned).
The adaptive plate controller can also use plate vibration sensors, such as accelerometers, for adaptation [14]. This eliminates the need to place error microphones in the acoustic environment. The plate controller might also be used for reduction of nonlinear distortions [15].

4. Two-layer Active Noise Controller

Fig. 3 presents a proposed two-layer system—active noise control with plate radiation control. The ANC controller drives the plate with only one control signal per plate. The plate radiation controller is, in turn, responsible for driving actuators using this signal. Additionally, the plate radiation controller can improve response of the whole plate, and the number of parameters of the new secondary path model required for adapting the ANC controller may be much smaller.

A fixed-parameter feed-forward controller can be used as the plate radiation controller without any changes. If multiple actuators are used, a radiation control filter is necessary for each actuator. In that case only one ANC adaptive filter per plate is used. This allows for a faster adaptation and may reduce computational cost.

The adaptive plate controller cannot be directly used because of problems with concurrent adaptation of control filters in ANC system and plate controller. Additional care must be taken to provide convergence of both adaptive filters. A proposed structure is presented in Fig. 4.

The error signal yielded during operation of the ANC system is equal to:

$$e(i) = P(z^{-1})x(i) + W(z^{-1})F(z^{-1})S(z^{-1})x(i) + F(z^{-1})S(z^{-1})\varepsilon(i)$$

(5)

where $z^{-1}$ is the one-step backward time shift operator.

The adaptive plate controller adds additional noise $\varepsilon(i)$ to the output of the ANC controller $c(i)$:

$$y(i) = c(i) + \varepsilon(i) = W(z^{-1})x(i) + \varepsilon(i)$$

(6)
The secondary path control error signal $e_F(i)$ is equal to:

$$e_F(i) = P(z^{-1})x(i) + (F(z^{-1})S(z^{-1}) - H(z^{-1}))y(i)$$

and it can also be written as:

$$e_F(i) = P(z^{-1})x(i) + (F(z^{-1})S(z^{-1}) - H(z^{-1}))W(z^{-1})x(i) + \left( F(z^{-1})S(z^{-1}) - H(z^{-1}) \right) \varepsilon(i)$$

In this structure, the reference signal, $x(i)$, cannot be used for adaptation of both filters $W$ and $F$, because only the product of those filters can directly be estimated. Because of this problem, the additional signal $\varepsilon(i)$ was introduced and the adaptation of filter $V$ uses $\varepsilon(i)$. When the ANC filter converges, the term $P(z^{-1})x(i) + W(z^{-1})F(z^{-1})S(z^{-1})x(i)$ should be minimized in appropriate sense, and the effect of $x(i)$ signal on adaptation of $F$ filter should be small.

In this system the ANC controller is exactly the same as described in Section 2, but the plate sound radiation controller must be modified as in Fig. 4. In this case the error signal required for adaptation of filter $F$ is expressed as:

$$e_F(i) = e(i) - H^T y_H(i)$$

where $y_H(i) = \begin{bmatrix} y(i), y(i-1), \ldots, y(i-(N_H-1)) \end{bmatrix}^T$ is a vector of regressors of the introduced noise $\varepsilon(i)$.

If the radiation control filter were designed to control radiation to the same point in the acoustic field, the difference between $F(z^{-1})S(z^{-1})$ and the desired model $H(z^{-1})$ should be small, and the desired model $H(z^{-1})$ could be used for reference signal filtration in the FXLMS algorithm. Additionally if the $H(z^{-1})$ is pure delay the FXLMS algorithm used for adaptation of ANC filter becomes much simpler Delayed LMS. When different points are used, a model of the whole cascade $F(z^{-1})S(z^{-1})$ can be identified.

The two-layer structure might be also useful when one or both layers are nonlinear. The nonlinear plate controller [15] might be used to linearize plate and use it for larger linear ANC system. Also the system with linear plate controller and nonlinear ANC controller have some advantages, because such structure can be used to reduce number of required nonlinear filters and significantly reduce computational load [16].
5. Experimental results

The control system was experimentally verified for reduction of noise transmitted through a vibrating plate from a small-dimensional enclosure to a laboratory room (see Fig. 5). The enclosure is acoustically isolated, except the area where a fully clamped aluminum plate is placed. The plate is of dimensions 400 mm × 500 mm × 1 mm.

Three 5 W actuators of type NXT EX-1 are mounted on the plate (see Fig. 5). Positions of the actuators were chosen to maximize the minimal eigenvalue of the controllability Gramian matrix for the first 25 plate model modes [17].

For all experiments the sampling frequency has been set to 2 kHz. The 8th order Butterworth low-pass analogue filters with 600 Hz cut-off frequency have been used as antialiasing and reconstruction filters. Fig. 6 shows the amplitude response of secondary paths for different EX-1 actuators and the combined amplitude response of plate with sound radiation controller with desired path \( H = z^{-16} \).

The goal of the control system is to reduce sound pressure level at zone around error microphone placed in the laboratory room.

The order of the FIR path models has been set to \( M = 256 \). The order of the FIR control filters for ANC controller and plate controller has been set to \( N = 256 \). For top-level ANC controller the desired model \( H \) was used as secondary path model for FXLMS.

A-weighted results of noise control at the position of the error microphone, obtained with different systems are presented in Fig. 7. A pulverizer noise was used. It is a broadband noise with a dominating 330 Hz tonal component due to fan operation. The classical single-layer ANC system reduced the A-weighted noise pressure level by 8.5 dB compared to the case of plate passive isolation only. In case of the two-layer system the reduction was decreased to 7.1 dB. For this system, the distance between the reference microphone and the plate is too small and the anti-aliasing and reconstruction filters increase the secondary path delay over the delay in the primary path. In such case, a small increase of the delay of the secondary path caused by the plate controller involves prediction action of the ANC filter, what degrades the noise reduction level. The delay added by the plate control system is tuned by the desired path model \( H \).
For the simple deterministic tonal and multi-tonal disturbances no differences in obtained reduction levels were observed.

6. Conclusions

The two-layer control system structure presented in this paper allows for reducing the number of control signals to be worked out by the ANC controller. With such structure the ANC use one control signal per plate, instead of one control signal per actuator on plate. It is especially important when multiple reference signals, are used, because it reduces the number of adaptive control filters.

The total number of adaptive filters is reduced, when adaptive plate vibration controller is used. Consequently, it reduces the computational load. This, however, comes with cost of an increased
delay of the secondary path. This delay can decrease performance of the overall system for broadband disturbances, if the reference signal is not provided well in advance.

Additionally, the two-layer system can yield a faster convergence. The maximum LMS step coefficient in the higher-layer ANC controller for stable operation was higher than in case of the single-layer system. Obtained reduction of the number of ANC controller outputs reduces the number of ANC filters, and hence it reduces the number of adapted parameters. Equalization of the secondary path response also contributes to a faster adaptation of the ANC filters.

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REFERENCES


