Active control of sound reflection, absorption and transmission using thin panels

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This study explores the development of thin panels that can be controlled electronically so as to provide surfaces with desired reflection coefficients. Such panels can be used as either perfect reflectors or absorbers. They can also be designed to be transmission blockers that block the propagation of sound. The development of the control system is based on the use of wave separation algorithms that separate incident sound from reflected sound. In order to obtain a desired reflection coefficient, the reflected sound is controlled to appropriate levels. The incident sound is used as an acoustic reference for feedforward control and has the important property of being isolated from the action of the control system speaker. In order to use a panel as a transmission blocker, the acoustic pressure behind the panel is driven to zero. Detailed experimental results are presented showing the efficacy of the algorithms in achieving real-time control of reflection or transmission. The panels are able to effectively block transmission of broadband sound. Practical applications for these panels include enclosures for noisy machinery, noise absorbing wallpaper, the development of sound walls and the development of noise-blocking glass windows.

I. INTRODUCTION

Active noise cancellation (ANC) is achieved by introducing a cancelling "antinoise" wave of equal amplitude and opposite phase using a secondary source. Leug (1936) first suggested the idea of active noise cancellation. Early work on ANC used analog techniques (Hansen, 1991, Kuo and Morgan, 1996). Chaplin (1977) introduced digital techniques in his ANC patent. Since then, much work on ANC using digital processing techniques has been published. Adaptive feedforward control is the most popular and successful approach used in ANC (Kuo and Morgan, 1996). Feedforward control involves feeding a signal related to the disturbance input (called the primary noise) into the controller which then generates a signal to drive a speaker in such a way as to cancel the disturbance. This signal related to the primary noise is called the reference signal.

Results on many successful feedforward ANC systems have been published. However, the major limitations of ANC systems must be noted. First, most ANC systems need a reference signal. In the absence of a non-acoustic reference signal (such as from a speed sensor), reference microphones can be used to pick up signals from the primary source before the noise propagates to the secondary source. However, this leads to the "secondary source effect". The reference microphones will not only pick up signals from the primary source but also those from the secondary source. A second limitation is that a high coherence between the reference microphone and the primary source is needed to achieve good performance. An additional complication is that online secondary path (from secondary source to the error microphone) estimation is needed to achieve long-term performance due to the nonstationary nature of ANC systems. However, it is difficult to estimate the secondary path online since random signals need to be used to excite the system and this tends to degrade the performance. Even if all of the above limitations could be addressed, it would still only be relatively easy to cancel noise at a point, i.e., at the position of the error microphone. It is very difficult for an

ANC system to achieve global noise cancellation in a 3-D environment such as in an enclosure. This is especially due to the limitations in the number of speakers and microphones that can be used in practical applications. This current research aims to address some of these limitations of ANC.

In this paper, we concentrate on the development of thin panels which can be electronically controlled so as to achieve desired acoustic properties. We develop algorithms for controlling the reflection coefficients of such panels as well as for using these panels as noise transmission blockers. The advantages of this approach to active noise control are that such panels can be used to prevent the entry of noise or the creation of noise, rather than the control of noise by active cancellation after it has already entered an enclosure. For example, panels made of glass can be used as window panes to prevent the entry of sound through windows in houses close to airports. Similarly, panels can be used to develop an enclosure for noisy machinery so as to prevent propagation of noise from the machinery. Such panels can also be used as wallpaper in rooms with noisy machinery so as to prevent acoustic reflection and the occurrence of standing waves in the room.

II. FLAT PANEL ACTUATORS

We seek to use thin panels as actuators in our research. While a variety of exciter technologies can be considered for energizing the panel, we chose a moving coil electromagnetic motor manufactured by Kodel, Inc. The panels are different from conventional woofer speakers which operate under the "pistonic" mode of operation. Instead, they operate under a "distributed mode" in which the panel vibrates flexibly. The exciter is based on a technology developed by NXT (New Transducers Ltd.) under the principle of "optimally distributed modes of vibration." The following figure (Fig.1) shows a typical panel speaker consisting of both the panel and the exciter.

The typical response of the dynamics of a panel speaker (distributed modes loudspeaker, DML) is shown below in Fig. 2 and compared to that of a conventional cone speaker. It can be seen that the frequency response has many local valleys and peaks and does not offer the kind of flat response that would be ideal for feedback control. However, the dynamics have been found to be consistent and repeatable. Feedforward control has been successfully implemented using these panels.

III. ACTIVE CONTROL OF REFLECTION COEFFICIENT

A. WAVE SEPARATION USING THE INTEGRATION METHOD

The experimental system utilizes two microphones placed a few centimetres apart in front of the panel, as shown in Fig. 3 below. Normal incidence on the panel is assumed.

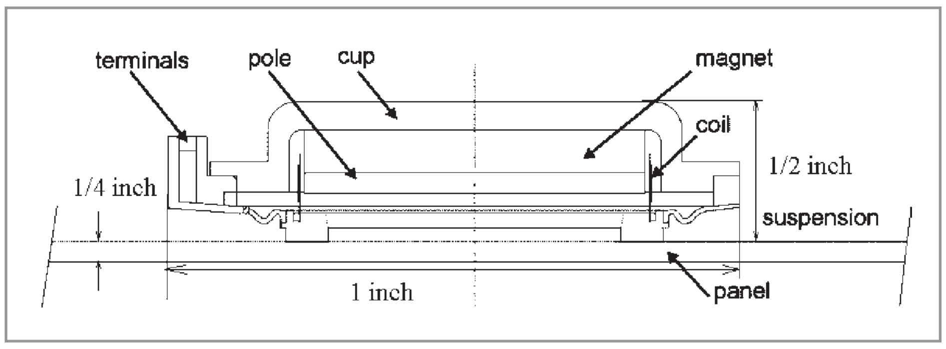

Figure 1. NXT Driver for a flat panel speaker

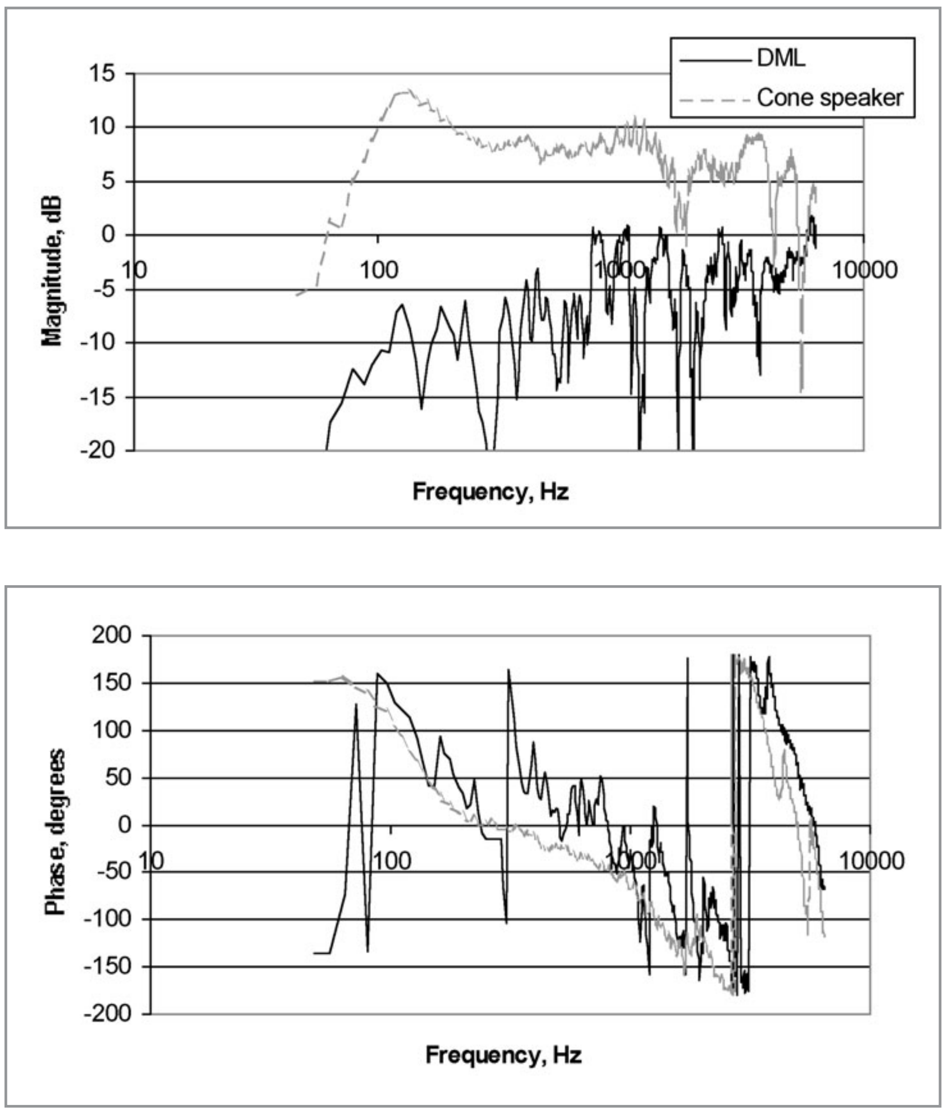

Figure 2. *Frequency response of DML and 8" standard cone speaker*

Let the acoustic pressure signals picked up by the two microphones be p_1 and p_2. If the distance d between the microphones is small relative to the smallest wavelength of the sound, the pressure at the mid point is approximately the mean. For a plane wave, particle velocity can be integrated via the momentum equation.

Since the incident wave can be expressed as (Beranek, 1954)

$$p_i = \sum_n A_n e^{j(w_n t - k_n x)} \tag{1}$$

where the wave number k_n is related to the frequency ω_n and the speed of sound c by the relation $k_n = \omega_n/c$, once we know the particle velocity, using momentum equation again, the incident wave and the reflected wave can be calculated by

$$p_i = \frac{1}{2}(p + \rho_0 cu) \tag{2}$$

and

$$p_r = \frac{1}{2}(p - \rho_0 cu) \tag{3}$$

To calculate p_i and p_r, p_1 and p_2 are first measured by the two closely positioned microphones. Numerical integration is then used to update the particle velocity u. Finally, equations (2) and (3) are used to calculate p_i and p_r.

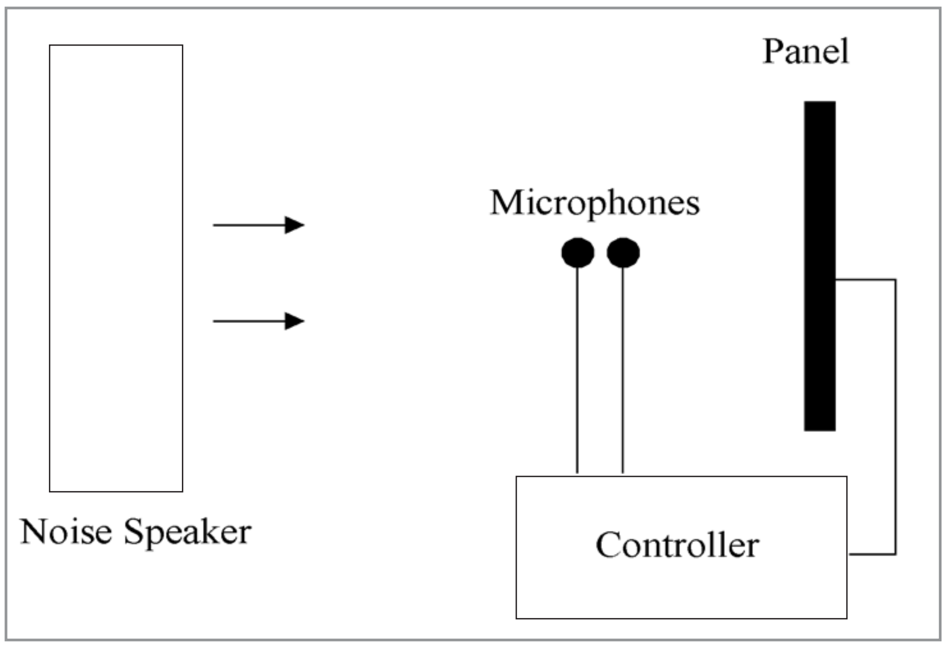

Figure 3. Panel configuration for reflection control

B. ACTIVE CONTROL OF ABSORPTION OR REFLECTION

The experimental setup for control of the reflection coefficient is shown in Figure 4. In the experiments, the primary noise is generated by a woofer speaker driven by a signal from a PC equipped with a data acquisition system. A 2 metre long duct is used to isolate the environmental effects and ensure plane waves. The cross-section of the duct is 17 cm by 17 cm. Thus its cutoff frequency is about 1000 Hz. Two microphones as described earlier are used to measure acoustic pressure. The analog circuit provides functions of amplification and filtering. A CIO-DAS6402/12 data acquisition board is used to support data communication between PC and speakers/microphones. The control algorithm is implemented via a PC real time toolbox with Turbo C used to develop the real-time code. Filtered-x least mean square (FXLMS) algorithm is used for the feedforward control (Kuo and Morgan, 1996).

Assume that the desired reflection coefficient is a transfer function R(s) that is the Laplace transform of the ratio

$$r = \frac{p_r}{p_i} \tag{4}$$

The desired transfer function of the reflected wave is

$$P_{rdes}(s) = R(s)P_i(s) \tag{5}$$

and the corresponding desired reflected wave $p_{rdes}(t)$ can be calculated from

$$p_{rdes}(t) = \int_0^t p_i(t-\tau)r(\tau)d\tau \tag{6}$$

The error $p_r - p_{rdes}$ is used as the residue for feedforward control. The incident sound $p_i(t)$ is used as the reference signal. The secondary path transfer function is obtained from

$$S(s) = P_r(s) - R(s)P_i(s) \tag{7}$$

Using the incident sound as a reference signal ensures that the effect of the secondary source on the reference signal is avoided. Reflection can be controlled to obtain any desired reflection coefficient including $r = 0$ (i.e., perfect absorption) and $r = 1$ (perfect reflection).

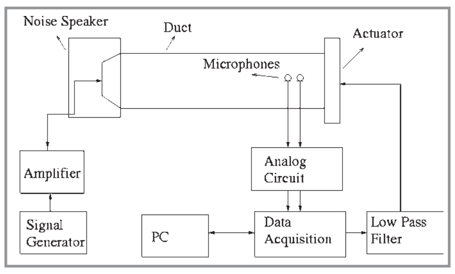

Figure 4. Experimental set-up for reflection coefficient control

V. ACTIVE CONTROL OF SOUND TRANSMISSION

A. EXPERIMENTAL SETUP

The experimental setup for sound transmission control is shown in Figure 5. This is very similar to that used in active reflection control (see Figure 4). A 2 metre long duct is used to isolate the environmental effects and ensure plane waves. The cross-section of the duct is 17 cm by 17 cm. Thus its cutoff frequency is about 1000 Hz. An additional third microphone is placed behind the panel speaker to measure the residual sound pressure that will be used for feedforward control. The objective of the sound blocker is to drive the pressure at this residual microphone to zero.

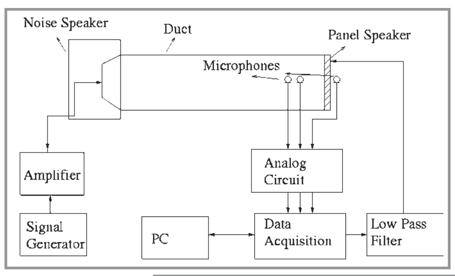

Figure 5. Experimental set-up for transmission control

B. METHOD

Several different panel materials including poster-board and glass can be used as speakers once equipped with the small electromagnetic motor actuators. Thus a glass pane with an electromagnetic motor actuator functions effectively as a panel speaker. The advantages of a panel speaker are that it is thin, space saving and inexpensive. The disadvantages are that it has uneven frequency response and is only able to provide limited power. Since the panel will not be boxed in an enclosure, it will generate and propagate sound from both sides of its surfaces. All these factors were carefully considered in the control design.

As can be seen in the experimental setup, the two microphones in the path of the incident sound measure both the incident sound and the sound created from the panel itself. With the separation method, the incident wave is separated and used as a reference signal for feedforward control. The microphone at the other side of the panel measures the residual sound pressure which is then controlled to zero. A major distinguishing feature of the control system here is that no non-acoustic sensor is needed for the reference signal. The incident sound is unaffected by the action of the speaker and hence we obtain a reference signal unaffected by the secondary source. All the signals from the microphones are sent to the PC via a data acquisition board. After wave separation, the reference signal is filtered by a FIR filter that represents the adaptive controller, the output signal is sent out to drive the panel speaker and the signal from the error microphone is fed back to adapt the FIR filter coefficients.

V. EXPERIMENTAL RESULTS ON REFLECTION CONTROL

1. PERFECT ABSORBER

A panel behaves as a perfect absorber if $p_r = 0$ i.e. if there is no sound reflected back. To achieve perfect absorption using active control, the value of p_r is controlled to zero using feedforward control. In the integration method of reflected sound estimation, the residual error is p_r. The secondary path is $S(s) = P_r(s) - R(s)P_i(s)$, as explained in section III. B.

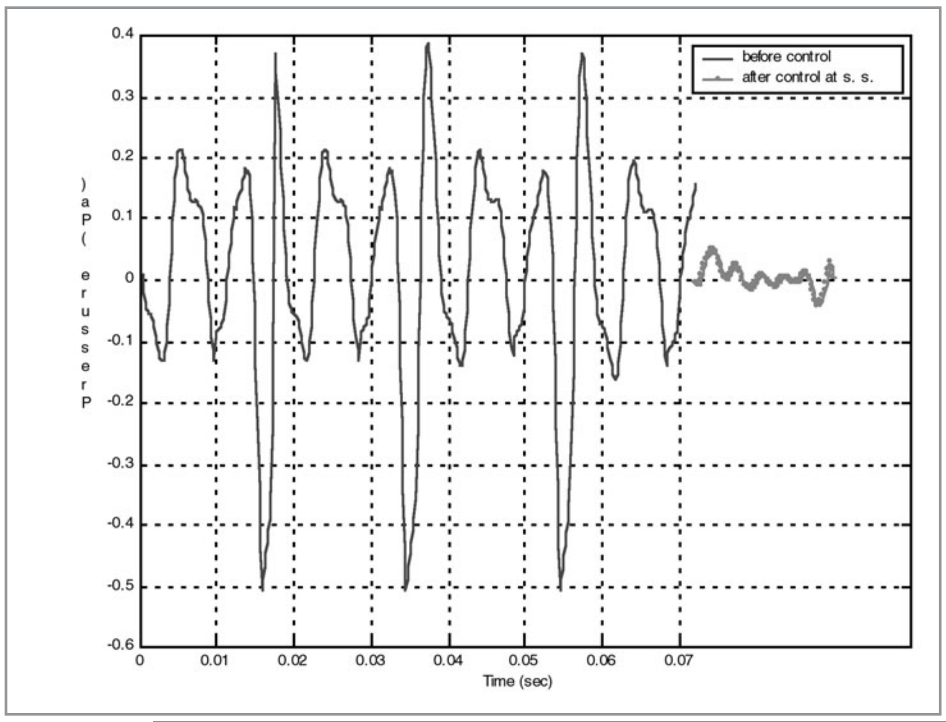

Figure 6. Reflection control to achieve perfect absorption via integration method (Primary noise consists of frequency components 150, 200, 250 and 300Hz)

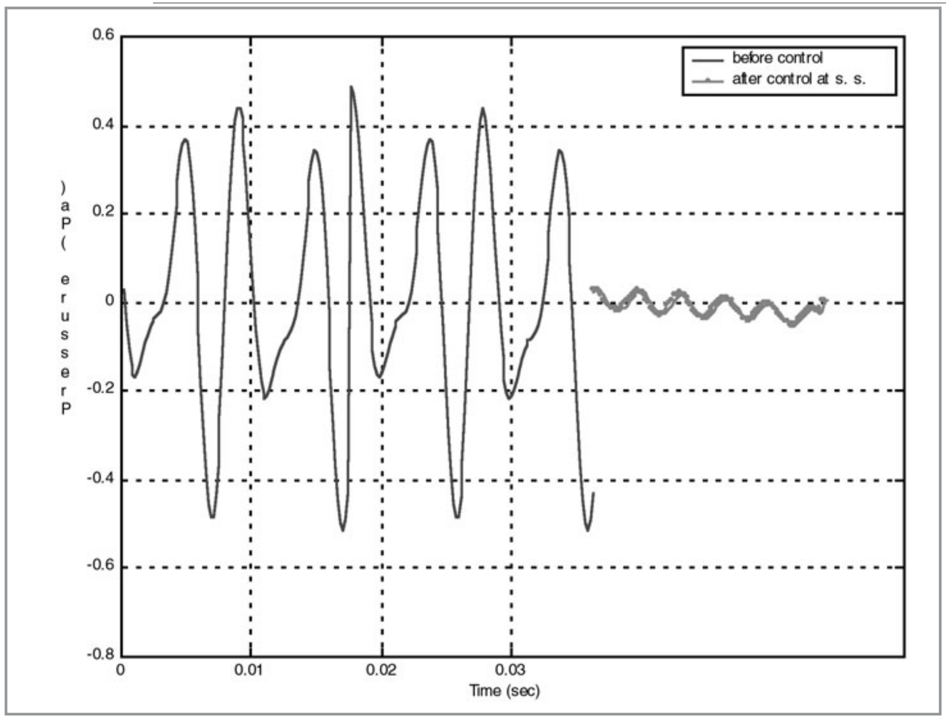

Figure 7. Reflection control to achieve perfect absorption via integration method (Primary noise consists of frequency components 100 and 300 Hz)

Experimental results on reflection control to achieve perfect absorption are shown in Figs. 6, 7, and 8. In the figures, the signals without any active control are compared with steady state (s.s.) signals after control. The signals shown in the figures are the separated reflected waves in each case. In perfect

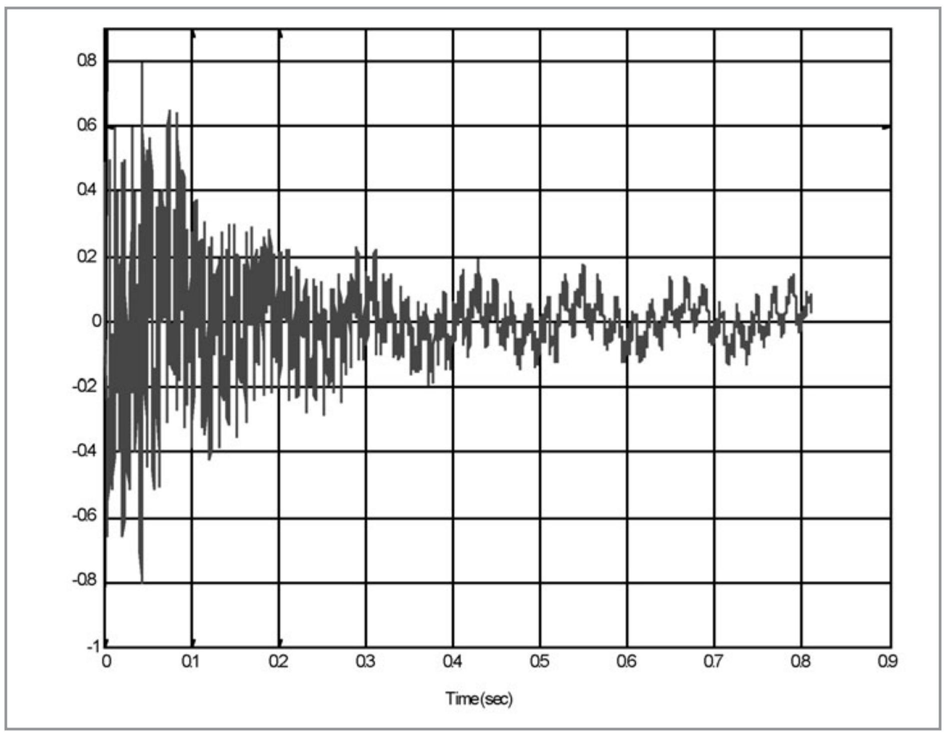

Figure 8. Transient performance during reflection control for perfect absorption via integration method

absorption, there should be no reflection. The signals are measured indirectly via the PC. In Fig. 6, the primary noise consist of 4 frequency components (150, 200, 250 and 300 Hz) while in Fig. 7, the primary noise consists of 2 frequency components (100 and 300 Hz). As can be seen in the figures, there is a better than factor of 10 reduction in the reflected sound pressure. The transient performance of the controller is illustrated in Fig. 8. The control system has a time constant less than 0.5 seconds. The reflected sound pressure is seen to reach close to steady state in about 0.6 seconds.

2. PERFECT REFLECTOR

A panel behaves as a perfect reflector if $p_r = p_i$, i.e., if all the incident sound is "reflected". To achieve perfect reflection, the reflected sound p_r is controlled to be equal to p_i using feedforward control. In the integration method, the secondary path is $S(s) = P_r(s) - R(s)P_i(s) = P_r(s) - P_i(s)$, as explained in section III. B.. The residual error is just $p_r(t)$–$p_i(t)$.

The experimental performance of the reflection control system for perfect reflection is shown in Figs. 9, 10, 11, and 12. As can be seen, the control system ensures excellent tracking between the incident sound and reflected sound waves. In every figure, there are two sub-figures. The top sub-figure shows the match between the incident wave and the reflected wave. The bottom sub-figure shows the error between the incident and reflected waves to further illustrate the match. Multiple tones are used in each experiment. Different multiple tone combinations are shown in each figure. As can be seen in the figures, the performance tends to get worse when there are more frequencies contained in the primary noise.

VI. EXPERIMENTAL RESULTS ON SOUND TRANSMISSION CONTROL

The experimental performance of the sound transmission controller described in section III is shown in the figures

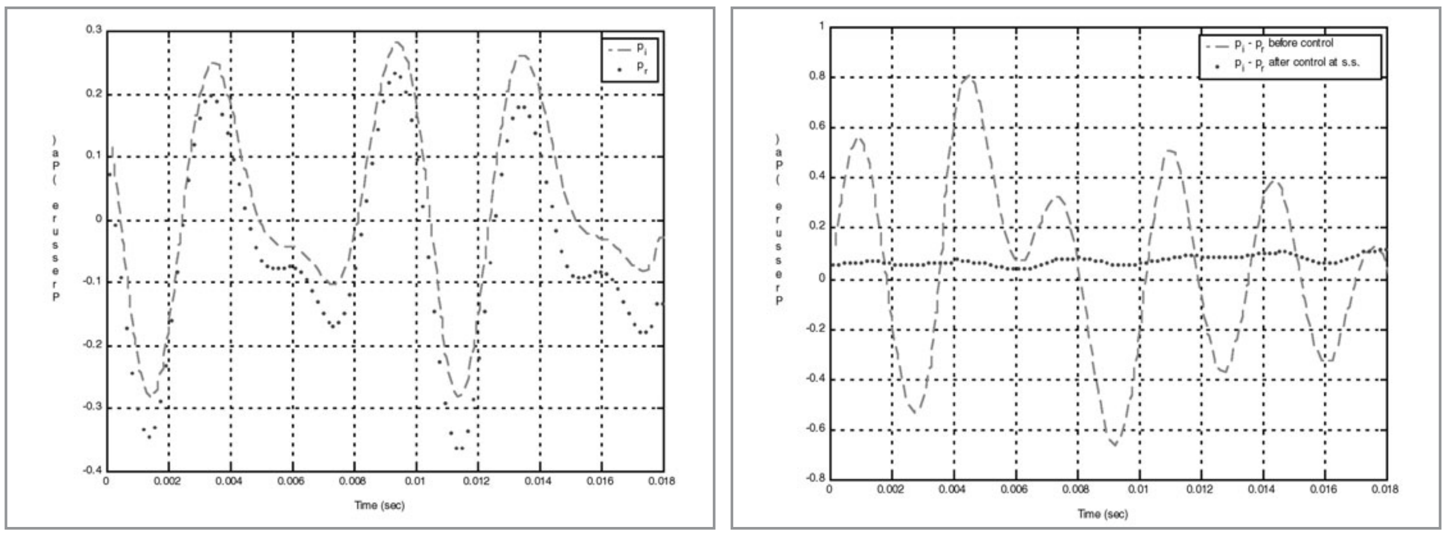

Figure 9. *Reflection control to achieve perfect reflection via integration method (Primary noise consists of frequency components 200 and 300 Hz)*

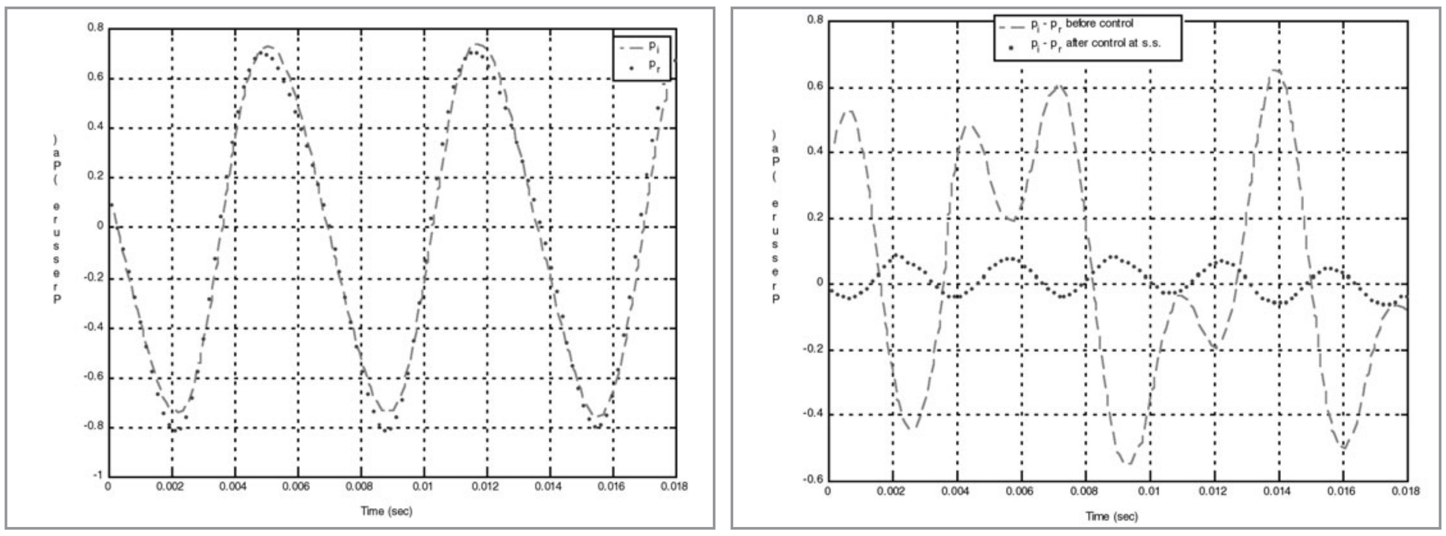

Figure 10. *Reflection control to achieve perfect reflection via integration method (Primary noise consists of frequency components 150 and 300 Hz)*

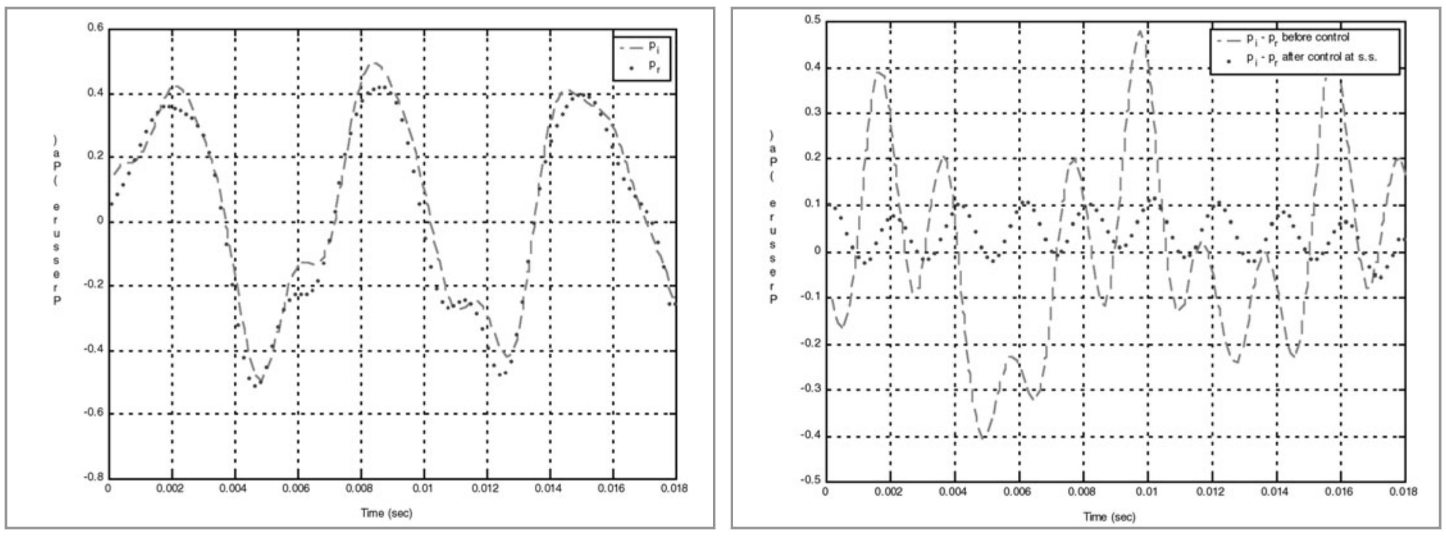

Figure 11. *Reflection control to achieve perfect reflection via integration method (Primary noise consists of frequency components 150, 350 and 500 Hz)*

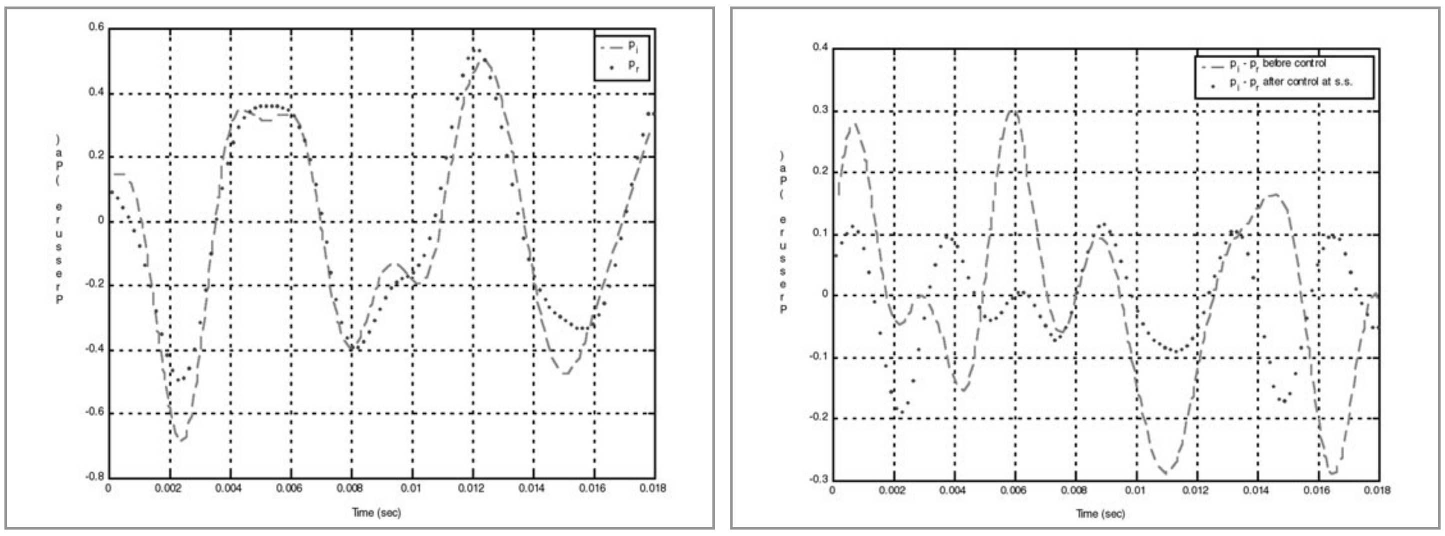

Figure 12. *Reflection control to achieve perfect reflection via integration method (Primary noise consists of frequency components 150, 250, 350 and 400 Hz)*

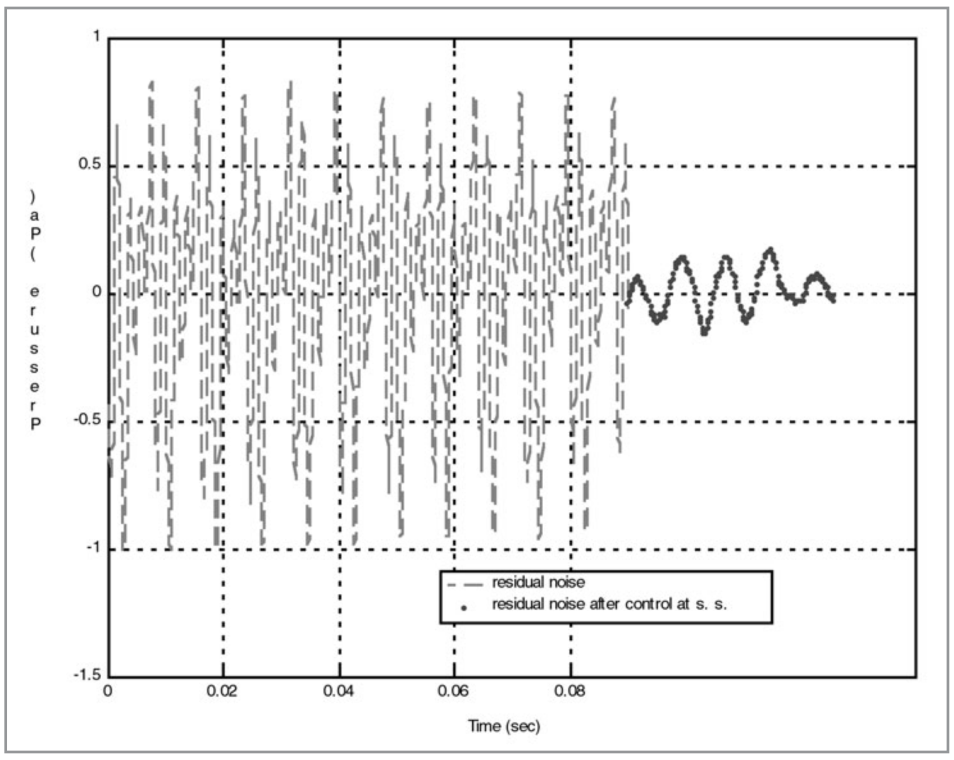

Figure 13. *Sound transmission control (Primary noise consists of frequency components 125, 375 and 500 Hz)*

below. In the experiment, a poster-board is used as the panel. The secondary path transfer function is measured off-line. An order of 32 FIR filter is used to estimate this transfer function. Another order of 32 adaptive FIR filter is used for the FXLMS algorithm. The sampling time used is 180 microseconds.

Fig. 13 show the performance of the transmission control system when the primary noise consists of discrete frequency components. Figs. 14 and 15 show the performance when the primary noise consists of random noise band-limited to frequencies below 800 Hz. In the figures, the signals without any active control are compared with steady state (s.s.) signals after control. The signals shown in the figures are residual noise picked up by the third microphone positioned behind the panel in each case which should be

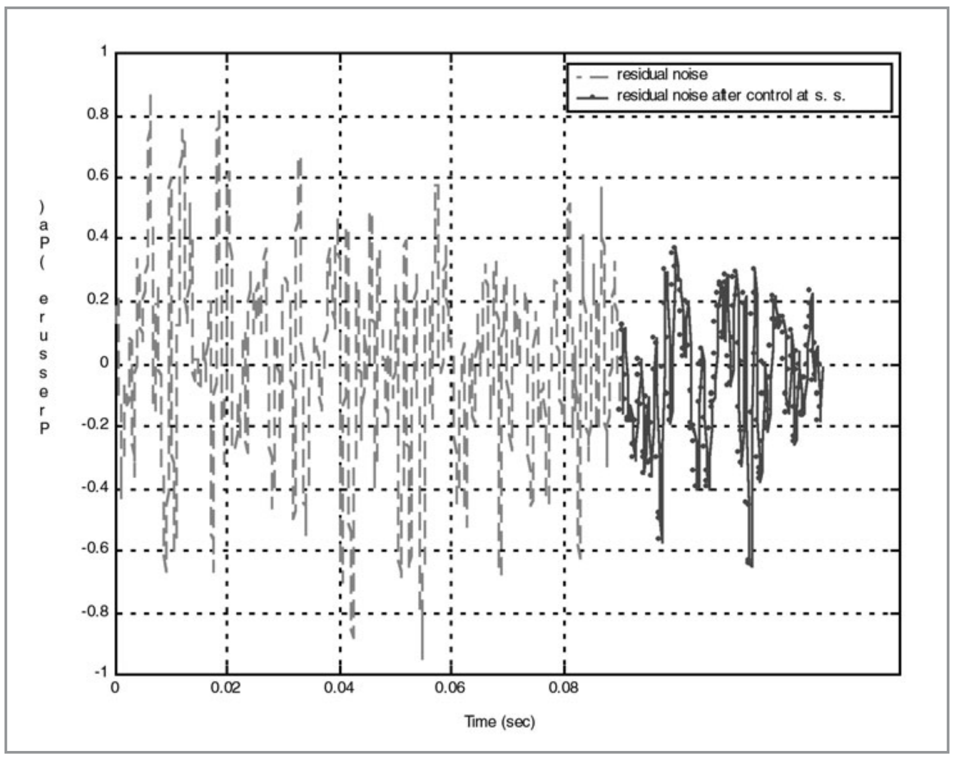

Figure 14. *Sound transmission control using a standard acoustic reference (Primary noise is random containing frequency components up to 800 Hz)*

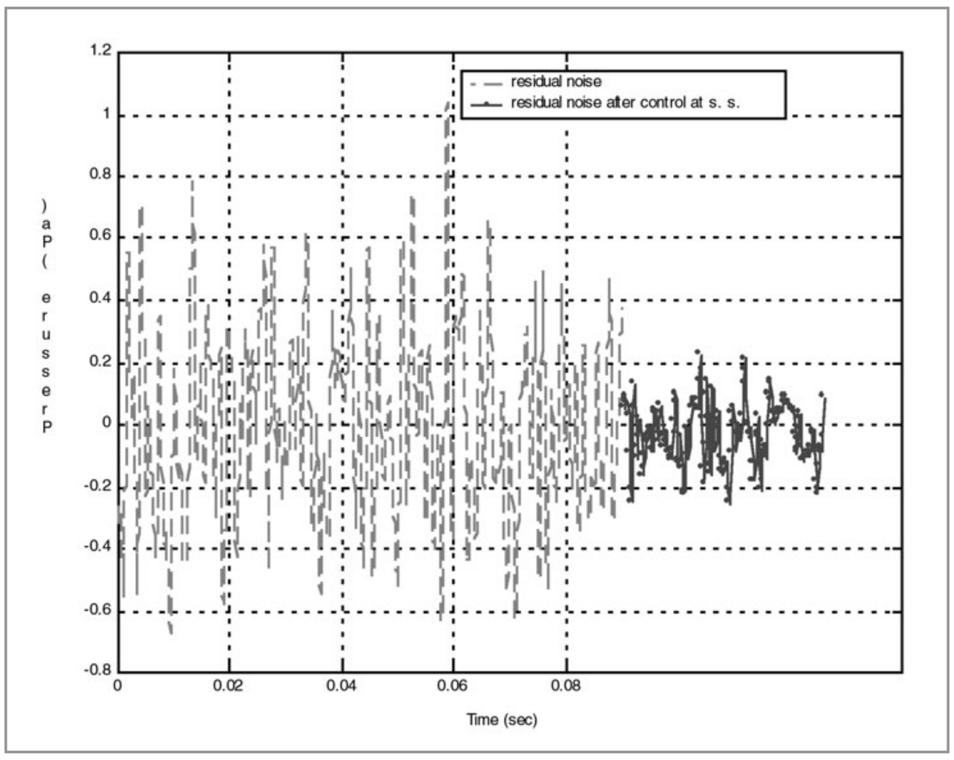

Figure 15. *Sound transmission using the separated incident sound as a reference (Primary noise is random containing frequency components up to 800 Hz)*

driven to zero in order to block the sound transmission through the panel. In Fig. 13, the primary noise consists of 3 frequency components (125, 375 and 500 Hz). As can be seen in the figure, there is a better than factor of 5 reduction in the residue noise for the case when the primary noise contains discrete frequency components, and the performance is worse when the primary

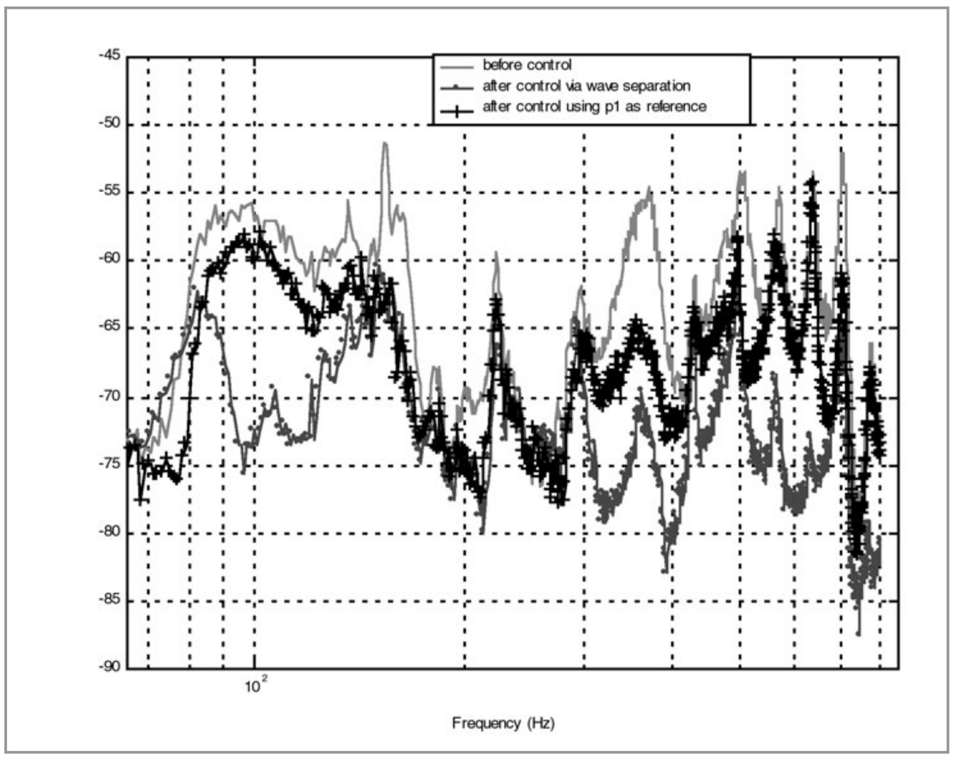

Figure 16. Sound transmission control – frequency response, this compares the noise before control and the residual noise after control using p1 as reference and using the separated incident wave as reference (Primary noise is random containing frequency components up to 800 Hz)

noise contains random noise band-limited to frequencies below 800 Hz.

In Fig. 14, a single standard microphone is used to pick up a signal which is then used as a reference. In Fig. 15, the wave separation method is used to separate the incident sound which is then used as the reference signal. As can be seen, the use of the incident sound as a reference provides significantly superior performance. This is also illustrated through frequency response plot in Fig. 16. Fig. 16 shows how the transmission control system provides significant noise attenuation over a broad range of frequencies. A comparison of performance obtained using just a single acoustic microphone to pick up the reference signal with the performance obtained when the incident sound is used as a reference is also shown. Clearly the use of the incident sound as a reference provides superior performance. Overall a performance of 10–15 dB is obtained over most of the frequency range via wave separation in Fig. 16.

A. PERFORMANCE IN TERMS OF GLOBAL SOUND ATTENUATION

Previous results show that active sound transmission control at a point is possible. To make it practically useful, a global performance check is carried out too. The experimental setup is the same as in Fig. 5 except that an enclosure is connected to the duct. The enclosure is used to check the global noise reduction performance. The primary noise comes from the duct. It goes into the enclosure via the thin panel. A cubic enclosure of size 0.4 x 0.4 x 0.4m^3 is considered. On the side of the enclosure that will be connected to the duct, a rectangular opening of the size of the duct is cut and a thin panel with an electromagnetic motor is mounted on this side of the enclosure. The primary noise is incident onto this thin panel. The panel is controlled so as to reduce noise

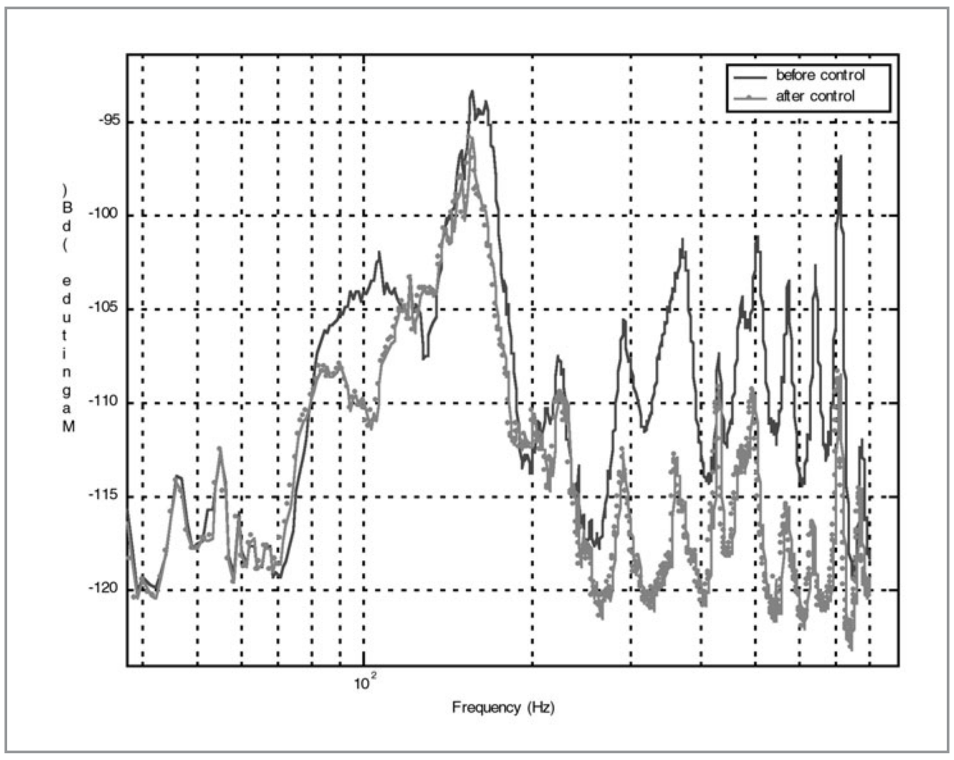

Figure 17. Effect of the transmission controller on global sound in an enclosure

transmission through the panel. Sound levels at different points inside the enclosure are then measured to evaluate if sound inside the entire enclosure is reduced by the use of this control system. Experimental results showed that the sound inside the enclosure was reduced everywhere. Fig. 17 shows the sound pressure (averaged over 20 points) as a function of frequency before and after control. It shows that sound transmission is reduced at all frequencies by the control system.

VII. CONCLUSIONS

This paper explored the development of thin panels that could be controlled electronically so as to be either perfect reflectors or absorbers or acoustic transmission blockers. The panels were constructed using poster-board and small rare-earth actuators. The development of the system was based on the use of a wave separation algorithm that separated incident sound from reflected sound. The reflected sound was then controlled to desired levels. The incident sound served an important purpose of providing an acoustic reference that is unaffected by the action of the control system speaker. The use of this incident signal reference also played a key role in the use of the panels as transmission blockers where the acoustic pressure behind the panel was driven to zero.

Detailed experimental results were presented showing the efficacy of the developed algorithms in achieving real-time control of reflection or transmission. The panels were able to effectively block transmission of broadband sound with the use of the incident wave playing a crucial role in allowing control without the use of a non-acoustic reference. The development of the panels is of practical importance with potential applications that include enclosures for noisy machinery, noise absorbing wallpaper, the development of sound walls and the development of noise-blocking glass windows. While the actuators will block light and are not transparent, they utilize rare-earth magnets and can be made with a diameter as small as 20 mm. These can be mounted near the corners of the window or hidden by patterned designs on the pane so as to be unobtrusive and therefore valuable for the glass windows application.

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WHALES' SOUND FISHING TRICK

Scientists believe they may have solved one of the mysteries of how humpback whales successfully hunt. It has long been known that some species of whale hunt by creating a cylindrical column of bubbles in which fish are corralled. But until now, no-one knew why the fish had refused to swim out. However, Professor Tim Leighton, of the Institute of Sound and Vibration Research at the University of Southampton, UK, has said he believes the whales use sound to scare the fish into staying put. "If sound is propagating through water, the most potent, naturally occurring entity it can meet is a bubble." The bubbles slow sound down – a beam of sound aimed towards the bubbles will be trapped, bouncing around within the column at a speed of 1km/s. "If [the fish] ever try to leave the net, what they encounter is a very loud wall of sound," Professor Leighton added. When humpbacks hunt, up to 30 of them will circle in the deep water, releasing bubbles. As these bubbles rise to the surface, they create a column, inside which fish congregate. The humpback whales will then swim up from beneath the cylinder and eat the fish. "We know fish will swim through bubbly water quite happily," Professor Leighton explained. "I think what is happening is that while the whales are producing this net, they are making a very loud, scary noise. "As these sounds get trapped within the cylinder of bubbles, the fish stay within the quiet region." What is more, the startled fish form a tight school, and so make a compact meal for the whales when they rise up from beneath the trap with their mouths open.

COMPLAINTS INCREASE

Complaints about noise are rising, with more than 310,000 recorded in 2002/03 throughout the UK. More than 225,000 of these are complaints about domestic noise nuisance. The effects of noise have been categorised in a survey carried out by the Building Research Establishment which revealed that where noise had reached problem levels, 28% of people had seen a GP, suffered stress, high blood pressure or migraines. Another 18% said they did not have visitors because of embarrassment or worry, while 13% had changed the use of a room or were intending to move. In 5% of cases, noise had caused also caused depression, the same percentage whose sex life had been affected.

INFANT RESPONSE TO SPEECH

For the first time, researchers have used functional magnetic resonance imaging (fMRI) to investigate infant brain activity in response to speech. They found that, almost from birth, the brain's left hemisphere plays the leading role in processing most language functions. These preliminary findings challenge the previously held belief that left- hemisphere dominance does not develop fully until puberty. "Language lateralization seems to be established almost from birth," said Shantanu Sinha, associate professor of radiology at the David Geffen School of Medicine at UCLA, where the study is ongoing. Lateralization is the activation of a function, such as speech, from the right or left side of the brain. "To the best of our knowledge, this is the first time fMRI has been used to study infants," Sinha said. "Using fMRI, we can non-invasively study the neuronal response of newborns to stimulation of different kinds, without any ionizing radiation or pharmaceutical injections."

REMEMBER THE RED RIVER VALLEY

Red River Valley resident Steve Stremich is threatening to take out a Court Order against the Red River Valley Fair. He's fed up with the noise, and wants the fair's daily concerts to end at 11pm instead of 1am. But locals don't think he'll get very far. The County does not have any noise regulations, and the fairground is not owned by the County, so there is nothing the County Commissioners can do. North Dakota does have a law which says that loud noises made for the purpose of harming someone, or in reckless disregard of other people, are illegal. But whether Mr Stremich can persuade a judge that fairground noise amounts to noise of that kind, is a moot point, locally.