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Active Sound Attenuation Across a Double Wall Structure

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In an approach different from established active noise control techniques, appreciable sound attenuation was achieved across double wall structures by placing control loudspeakers in the area between the walls. This technique was demonstrated in a transmission loss suite for a flat double wall structure radiating into an almost anechoic environment. The concept was also applied across the curved double wall of a plywood/Masonite® mock-up of an aircraft fuselage with a digital control system consisting of four error microphones and four control speakers. Substantial sound attenuation was obtained along the path of a rotating microphone in the semireverberant space of the fuselage for a 100-Hz sinusoidal signal. Less global attenuation was obtained when the frequency of the source signal was increased, or when fewer error microphones were used. The global attenuation increased as the distance between the error microphone and the source and control speakers was extended.

Introduction

INTERIOR noise in propeller-driven aircraft is traditionally controlled by the addition of noise control materials to the fuselage sidewall. However, the weight penalty associated with this approach is substantial, and in recent years active control of interior noise has been researched to avoid this disadvantage.[1–8] Analytical and experimental studies first concentrated on active noise control in cylindrical enclosures[2–4] and on active vibration control of a cylindrical shell.[5] Recently, active noise control has been successfully demonstrated in the passenger cabin of a 48-seat propeller-driven aircraft.[6,7] In all studies of active noise control[1–4,6,8] the control loudspeakers were located inside the cabin. An alternative approach, which is the subject of this investigation, is to place the control loudspeakers between the aircraft skin and trim panels, thus preventing the sound from entering the cabin. Placement within the area of the sidewall will require fewer control sources than placement throughout the volume of the cabin, assuming that the optimum spacing between the control sources is the same in both cases. The optimum spacing will depend on the wavelength of the sound to be controlled. The double wall between the skin and the trim of an aircraft is also a convenient place for these control sources as they do not interfere with the cabin layout. The purpose of the current study is to experimentally demonstrate the viability of active sound attenuation across a double wall structure. A patent for this concept was awarded in 1991.[9]

Sound Attenuation Across a Flat Double Wall

Test Configuration

A flat double wall partition with a 6-in. spacing was installed in the 4- × 5-ft window between the two rooms of the NASA Langley Research Center Transmission Loss Apparatus.[10] The partition wall facing the source speaker (wall A in Fig. 1) was a 0.063-in.-thick aluminum panel, while the opposing wall, B, was made of a 0.15-in.-thick, stiff, composite material with a surface mass of 4.2 lb/ft^2. A $\frac{1}{4}$-in.-thick, 1-ft^2, Lucite® panel was located in the center of wall B. These wall configurations were arbitrarily selected. The room on the receiving side of the double panel was 15 ft long (perpendicular to the double panel), 10 ft wide, and 11 ft high. The back wall was covered with 3-ft-long foam wedges, while the other walls (the floor and the ceiling) were treated with 1.5-ft-thick foam to minimize sound reflections. The source speaker enclosure contained two 1-ft-diam loudspeakers and was located 1.5 ft away from the center of wall A (Fig. 1). A cluster of four 4-in.-diam control loudspeakers, connected in parallel, was centrally located between walls A and B. Nine $\frac{1}{2}$-in. condenser microphones were arranged in a vertical plane 2 ft from the double wall partition, to determine the spatial variation of the transmitted sound. An additional microphone (Mic 10) was located 5 ft from the double wall.

Sound Attenuation Observations

An arbitrarily chosen 125-Hz sinusoidal signal was fed to the source loudspeaker, and the sound pressure levels at the nine microphone locations 2 ft from the panel were measured (Table 1). The center microphone showed the lowest sound pressure level (78.6 dB) as it was shielded by the control loudspeaker cluster and the Lucite panel. The highest level (94.5 dB) was measured at the bottom right which was chosen as the error microphone location. The same 125-Hz signal fed to the source loudspeaker was then routed to the cluster of four control speakers, and the amplitude and relative phase of this signal were manually adjusted until the sound pressure level at the bottom right error microphone was reduced to 55.3 dB. This was the lowest level that could be obtained as the error signal became buried in the background noise generated by the analysis equipment. The sound pressure levels at the other eight microphone locations were also measured and are shown in Table 2. Sound pressure levels at locations near the bottom right error microphone are attenuated, but the levels for the three microphones on the left, farther away from the error microphone, show a slight increase. The sound pressure levels at each of the other microphone locations could be reduced to 59 dB or below when the corresponding microphone was used as the error sensor.

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Table 1 Sound pressure levels (dB) at the nine microphone locations (2 ft from panel)

Top row	86.9	88.7	91.4
Center row	87.4	78.6	94.0
Bottom row	90.9	93.2	94.5

Table 2 Sound pressure levels (dB) at the nine microphone locations when actively controlled for the bottom right error microphone

Top row	89.6	79.3	77.0
Center row	89.9	69.4	72.1
Bottom row	91.1	84.7	55.3

Table 3 Sound pressure levels (dB) at the nine microphone locations when actively controlled for error microphone 10 at 5 ft from the panel

Top row	85.3	74.1	85.1
Center row	82.4	61.7	86.5
Bottom row	81.3	76.6	86.3

Table 4 Maximum attenuation at error microphone 10 for several frequencies

Frequency, Hz	125	150	180	200	250	400
Attenuation, dB	48.3	44.1	45.6	46.1	39	44

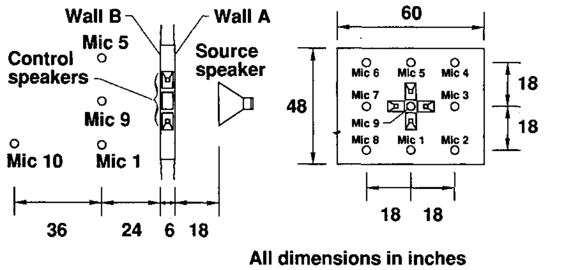

Fig. 1 Schematic of double wall sound attenuation setup.

Attenuation at all nine microphone locations was obtained when using a microphone at a distance of 5 ft from the panel as the error sensor (Table 3). At the location of this microphone (microphone 10 in Fig. 1), the difference between distances to locations on the sound radiating panel is smaller than at a location 2 ft from the panel. The sound at the microphone 10 location was attenuated by 48.3 dB, from the 96.8-dB sound pressure level measured for the original signal down to 48.5 dB (the background noise at that location). Similar attenuation could be obtained for several other arbitrarily chosen frequencies (Table 4). These results show that active control of the sound is possible by installing acoustic control sources in the double wall of a flat partition which separates a receiver from a source signal.

Sound Attenuation Across the Wall of the Aircraft Fuselage Apparatus

Active sound control was demonstrated across the flat double wall into an almost anechoic environment by manually adjusting magnitude and phase. The availability of an aircraft fuselage apparatus, which is normally used to evaluate human response to aircraft noise, provided an opportunity to demonstrate active control across a complex, curved double wall structure into a semireverberant environment. An electronic control system was used to adjust the magnitude and phase both faster and more accurately. This system was, in principle, the same as the two transducer/actuator control implementation developed in Ref. 11, but was extended to accommodate four error microphones and four control channels.

Test Configuration

The aircraft fuselage apparatus had a cylindrical cross section with inner wall radius of 71 in. The fuselage centerline was located 25 in. above the floor (Fig. 2). The apparatus was 24 ft long and consisted of a double wall with 0.75-in.-thick plywood on the outside and a 0.25-in.-thick Masonite interior finish. In between the double wall the structure was reinforced with plywood ribs and stringers. The apparatus resided in a 28-ft-long, 22-ft-wide, and 13-ft-high hard-walled (concrete) room. Parts of the walls, floor, and ceiling of this room were covered with 1-ft-thick foam and fiberglass to reduce the reflections from the walls of the room. The source loudspeaker was located on the outside of the aircraft fuselage apparatus at a distance of 4 ft from the outer wall (Fig. 3). Four control loudspeakers were mounted 40 in. apart on the outer wall, and radiated into the space between the inner and outer walls. The interior of the apparatus consisted of a one aisle, six abreast configuration with a typical seat pitch of 43 in. Two window and two aisle seats were chosen as error measurement locations, and $\frac{1}{2}$-in. condenser microphones were installed at those passenger ear locations (Figs. 2 and 3). An additional microphone was mounted on a rotating boom, 30 in. from the center of rotation. This microphone moved in a horizontal plane just above the seats and one revolution took 32 s to complete. Note in Fig. 3 that the rotating microphone passed very close to each of four error microphones.

Electronic System Configuration

The electronic system configuration, shown in Fig. 4, consisted of sound generation, analysis, and active control components. A pure tone was generated by a function generator, amplified by a power amplifier and reproduced by the source speaker. The sound was measured using the rotating microphone and a computer-controlled one-third octave band analyzer. The analyzer exponentially averaged the signal with an averaging time of $\frac{1}{4}$ s. The resulting sound pressure levels were digitally transferred, once every $\frac{1}{2}$ s, to the desktop computer

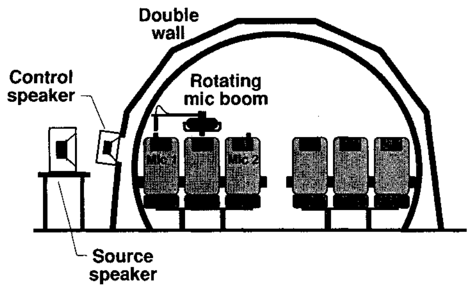

Fig. 2 Cross section of aircraft fuselage apparatus showing sound attenuation test configuration.

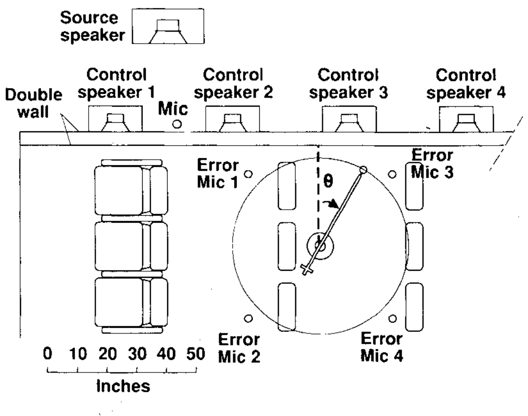

Fig. 3 Planform of aircraft fuselage apparatus showing source speaker, control speakers, and microphone locations.

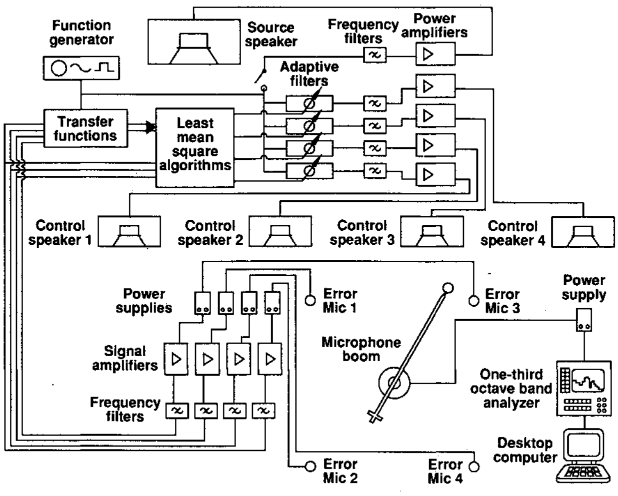

Fig. 4 Schematic of acoustic excitation, control, and analysis system in the aircraft fuselage apparatus.

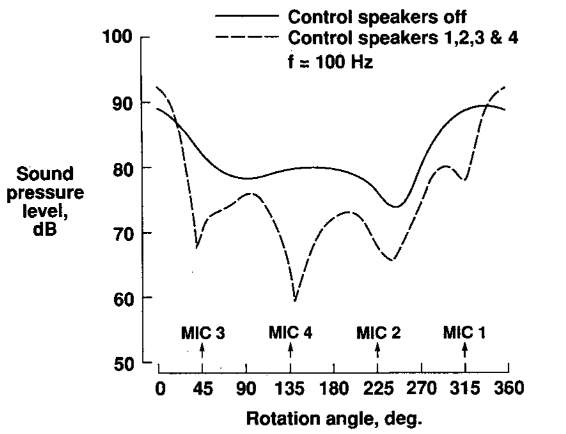

Fig. 5 Rotating microphone sound pressure levels with and without control derived from all four error microphone signals at 100 Hz.

which processed and stored this data and produced a graphical output. The active control arrangement consisted of four error microphones, a digital signal processing unit, and four control speakers along with analog power supplies, signal amplifiers and frequency filters. The sampling rate of the analog-to-digital and digital-to-analog converters was fixed at 2000 samples/s. The frequency filters were configured as bandpass filters for the one-third octave band in which the pure tone occurred. With the source speaker switched off, the pure tone from the signal generator was played through each of the control speakers separately and measured by each of the error microphones to obtain a total of 16 transfer functions. These transfer functions relate the amplitude and phase of the input to the output of the system. With the source speaker switched on, the transfer functions were used in the least-mean-square adaptive algorithm to provide the coefficients for the adaptive filters which controlled the amplitude and phase of the signals to the control loudspeakers. A least-mean-square algorithm was used to minimize the mean-square of the sum of the error microphone signals.

Sound Attenuation Observtions

Rotating Microphone Sound Attenuation

A sinusoidal signal, arbitrarily chosen at 100 Hz, was fed into the source loudspeaker which generated a sound pressure level of 103 dB at 0.5 in. from the exterior of the fuselage wall, halfway between control speakers 1 and 2 (Fig. 3). Figure 5 shows the sound pressure level inside the fuselage as a function of microphone boom rotation angle with the control speakers off, and with the control speakers actively attenuating the sound to satisfy the least-mean-square algorithm. The zero rotation angle corresponds to the microphone position closest to the wall of the aircraft fuselage apparatus.

An acoustic mode with two nodes between opposing walls, at the height of the microphones, was calculated to occur at 99.3 Hz. One of the nodes was predicted to be at microphone boom rotation angles of approximately, $\theta = 90$ deg and $\theta = 270$ deg (Fig. 5). With the control loudspeakers off, local minima were found near these locations, while maximum sound pressure levels were predicted near the wall and the center of the cabin. The region between microphones 4 and 2 is close to the cabin center and shows a local maximum in Fig. 5. With all the control speakers activated, the sound pressure level at the four error microphones was considerably reduced. These reductions ranged from 8 dB at the error microphone 2 location, to almost 20 dB at the location of error microphone 4. The sound was attenuated along the entire path of the rotating microphone except for locations very close to the wall, which might in part be due to radiation from evanescent modes.

At higher frequencies and shorter acoustic wavelengths, it is more likely that the acoustic control field, which attenuates the sound at an error microphone location, amplifies the sound at other locations. Figure 6 shows sound pressure levels measured by the rotating microphone in response to a 150-Hz sinusoidal source signal with and without the use of the active control. The sound is attenuated along the path of the rotating microphone, except near the wall and at locations between error microphones 4 and 2, where the sound pressure level of the controlled sound exceeds the original signal level. At higher frequencies, sound pressure levels are increased at more locations along the path as shown in Figs. 7 and 8 for source signals of 200 and 250 Hz, respectively. More error microphones and control speakers are needed to attenuate the sound at these higher frequencies.

Effect of a Single Error Microphone Location

It was found that when control loudspeaker 1 was switched off, the sound actively controlled by the other speakers no longer exceeded the uncontrolled sound near the surface of the wall. In subsequent tests this control loudspeaker was not used. When using a single error microphone, excellent attenuation was obtained at that microphone location as shown in Figure 9. Using microphone 2 or 4 as the error sensor resulted in more attenuation over a longer part of the rotating microphone path than by using either microphone 1 or 3. The difference in the distance from microphone 2 or 4, and either control speaker 2 or control speaker 3, is less than 16 in., the equivalent of $\frac{1}{8}$ wavelength at a frequency of 100 Hz. The

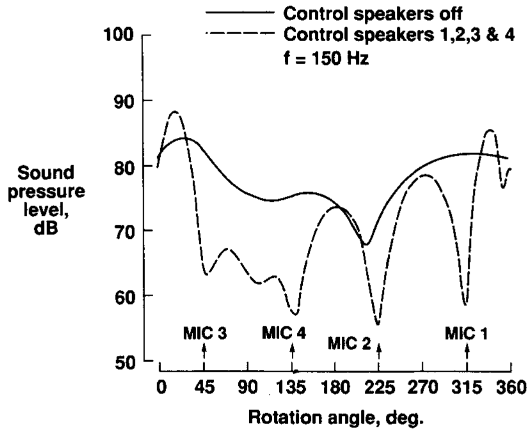

Fig. 6 Rotating microphone sound pressure levels with and without control derived from the four error microphone signals at 150 Hz.

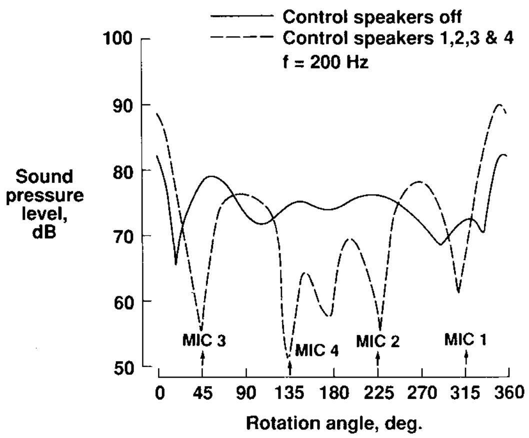

Fig. 7 Rotating microphone sound pressure levels with and without control derived from the four error microphone signals at 200 Hz.

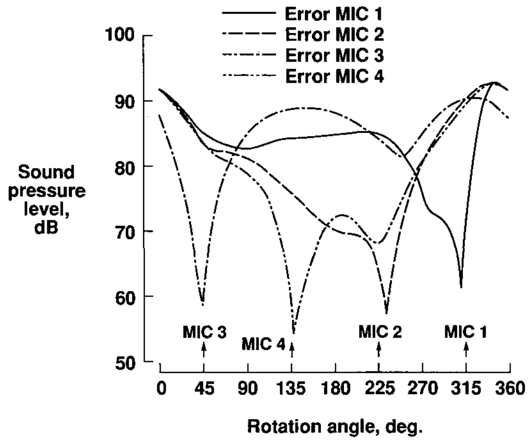

Fig. 9 Rotating microphone sound pressure levels with control from speakers 2, 3, and 4 derived from each of the error microphone signals.

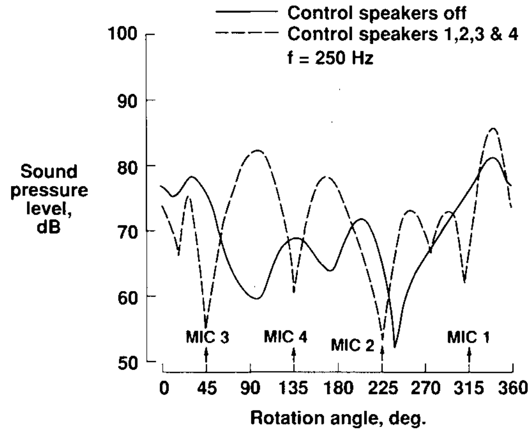

Fig. 8 Rotating microphone sound pressure levels with and without control derived from the four error microphone signals at 250 Hz.

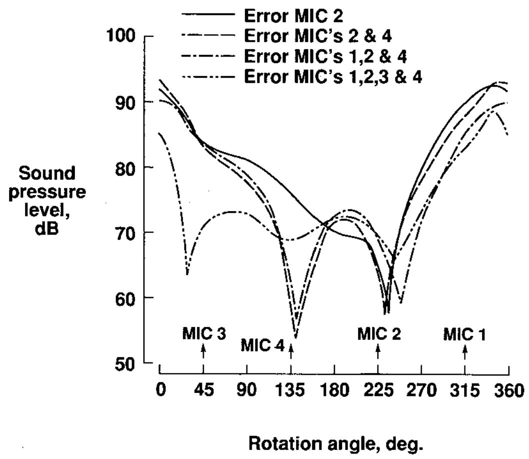

Fig. 10 Rotating microphone sound pressure levels with control from speakers 2, 3, and 4 derived from one or more error microphone signals.

difference in distance from these microphones to control speaker 4 is less than 30 in. or $\frac{1}{4}$ wavelength. Thus, when the rotating microphone moved from location 4 to location 2, the change in distance to any of the control speakers was small enough to allow considerable attenuation of the source signal when using error microphone 2 or 4.

When either microphone 1 or 3 is used as the error sensor, the difference in distance to the control speakers 2 and 4 is close to the distance between the two microphones themselves, the equivalent of almost $\frac{3}{8}$ wavelength at 100 Hz. This implies that on the path between locations 1 and 3 (Fig. 3), away from the error microphone, little attenuation and even amplification is to be expected. On the path between 3 and 1, by way of locations 4 and 2, the difference in measured source and control signals exceeds half the acoustic wavelength, thereby amplifying the original source signal. Having the error sensors farther away from the control sources therefore improves the overall attenuation, as was observed earlier for the flat double wall.

Effect of Number of Error Microphones

The effect of adding error microphones to the system of the three control speakers 2, 3, and 4, and error microphone 2, is illustrated in Fig. 10 for the 100-Hz tone. Using the two error microphones 2 and 4 gives additional attenuation at location 4, while the sound pressure levels at other locations along the path are not much affected. The use of three error microphones 1, 2, and 4 increases the attenuation of the sound pressure level between locations 2 and 1, as well as between 1 and 3. Finally, the use of all four error microphones gives the best overall attenuation along the path of the rotating microphone, although some of the previously obtained attenuation near locations 2 and 4 was lost by adding this fourth error microphone.

Conclusions

An active noise control system with control loudspeakers in the double wall of a partition which separates the source from the space where the sound is to be controlled has been experimentally evaluated. The technique resulted in excellent attenuation of an arbitrarily chosen sinusoidal signal at 125 Hz for the case of a flat double wall structure mounted as a partition between two acoustically isolated rooms. The amplitude and phase of the control signal were manually adjusted at each of nine microphone locations, 2 ft from the double wall partition, reducing sound pressure levels from as high as 94.5 dB to below 59 dB. Best overall attenuation was achieved at those nine locations by using an error microphone at a greater distance (5 ft) from the panel. Similar attenuation was obtained for several frequencies between 125–400 Hz.

The concept was also applied to the curved double wall of a plywood/Masonite mock-up of an aircraft fuselage with a digital control system consisting of four error microphones and four control speakers. Substantial sound attenuation was obtained along the path of a rotating microphone in the semireverberant space of the fuselage for a 100-Hz sinusoidal signal. Excellent attenuation was obtained at the error microphone location when single error microphones were used. Less global attenuation was obtained when the frequency of the source signal was increased or when fewer error microphones were used. The global attenuation increased as the distance between the error microphone and the source and control speakers was increased.

Acknowledgment

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