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Effects of Cross-Sectional Dimensions on Active Noise Control in Rectangular and Round Ducts

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Active noise control (ANC) works best to reduce low frequency noise. Because many industrial noise sources are broadband, ANC may be used more if it can be successfully applied to higher frequency ranges. This study explored one method to increase ANC effectiveness at higher frequencies. ANC is particularly useful in hard-walled ducts where plane waves propagate. Higher order mode waves are much more difficult to control. Basic acoustic principles dictate that the cut-on frequency at which higher order modes will first begin to eclipse simple plane waves in a duct will be determined by the cross-sectional geometry of the duct. The lowest frequency for higher order modes increases as duct diameter decreases; therefore the range of frequencies where plane waves dominate will be greater and effective control using ANC will be better as duct diameter decreases. The result is that somewhat higher frequencies can be controlled with ANC for smaller diameters. Below the first higher order mode cut-on frequency for the largest size studied, there should be little difference in ANC effectiveness between the duct sizes. To test those suppositions, a commercially available ANC system was used to reduce random noise in rectangular and round ducts having different diameters. Results showed that insertion loss (IL) ranged from 5 dB to 29 dB in frequencies ranging from 40–1000 Hz and varied inversely with cross-sectional size as expected. There was no difference in IL below 280 Hz ($p = 0.7751$) between the different diameter ducts. There was a significant difference between duct diameters above 280 Hz ($p < 0.0001$). The same tests were conducted on a rectangular duct with one cross-sectional dimension fixed and one varied at seven different sizes. Results showed similar IL from 5 dB to 29 dB that varied inversely with size.

Keywords active noise control, duct diameter, engineering noise control, noise cancellation

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INTRODUCTION

Noise is a ubiquitous occupational and environmental hazard. Although personal protective equipment (hearing protection) can control the hazard, some researchers indicate that there are strong workplace cultural factors that preclude their proper use;^(1,2) therefore, it is more effective to devise engineering controls for noise hazards. Engineering controls for noise can be divided into active and passive methods. Passive methods reduce noise either by transmission loss through dense materials or by absorption of reflected waves, or both. Passive controls work better for frequencies at or above 1000 Hz.⁽³⁾

Active methods use a sound of equal frequency and amplitude but 180° out-of-phase to reduce the offending noise. The actual active noise control (ANC) insertion loss is defined as the difference in sound pressure levels (SPL) with and without ANC ($IL = SPL_{ANCoff} - SPL_{ANCon}$). ANC works better at frequencies below 500 Hz than for higher frequencies.⁽⁴⁾ Compared with passive controls, ANC also has the attractive feature of being less bulky and offering less additional resistance to airflow in duct applications. However, unlike passive controls, for which dimensions are not necessarily important to effectiveness, the success of ANC methods is dependent on the physical dimensions of the space in which noise is to be controlled. ANC is easiest to apply and generally produces the greatest degree of noise reduction in closed channels of limited cross-section;⁽⁴⁾ therefore, most examples of successful ANC applications are in noisy ducts.^(3–7) A very common field application is reducing noise escaping from exhaust stacks, especially for cases where the main goal is to reduce fan noise contributions to community noise.^(5,7) It is also used for cases where the goal is to reduce HVAC system noise to increase the comfort of building occupants.⁽⁶⁾ ANC may become a more attractive noise control alternative if it can be applied successfully to a broader (higher) frequency range.

The effectiveness of ANC applications depends heavily on two things: predictability of waves and bandwidth. First,

there is some processing time for the ANC system to sample a sound, analyze it, determine a control signal, and send that signal to the control speaker. For a random noise source, that calculated control signal will attenuate only the exact sound sampled at the instant of measurement. During the calculation time, the original noise wave travels down the duct at the speed of sound. Even with very fast processors, at least 3 m of distance is needed between the original source microphone and the control speaker.⁽⁴⁾ If the noise wave has changed in frequency or phase during that travel down the duct, then the addition of the control wave will not attenuate the noise but only add to the overall noise.

Also, if the noise wave is complex, more than one microphone is needed to sample the noise source for the ANC processor to determine countering waves, and more than one control speaker is needed to produce the complex attenuation sound. Therefore, the degree to which the noise wave can be sampled at the source location to accurately predict the frequency, amplitude, and phase at the later control location is directly related to the achievable IL. The second main determinant of IL is the bandwidth, or how many target frequencies are included in the range. The ability to predict waves depends on the type of wave, whereas the bandwidth is dependent on the noise source.

Type of Wave: Plane Waves vs. Higher Order Modes

The reason for the relative effectiveness of ANC methods inside ducts can be better appreciated with an understanding of the different types of sound waves inside a duct. Noise inside a duct is physically limited in its direction of propagation. Waves can either travel straight down the duct (plane waves) or bounce back and forth between the walls (higher order modes).⁽⁸⁻¹⁰⁾ Plane waves are easy to attenuate with ANC; higher order modes are more difficult. The cross-sectional dimensions of the duct determine where in the frequency spectrum the plane waves will be the dominant contributor to the overall noise and where the shorter wavelength, higher order modes will become the dominant noise contributor.

Plane waves have a uniform pressure distribution over the cross-section of the duct and propagate down the center of the duct for wavelengths at least twice the cross-sectional diameter of the duct (or hydraulic diameter for noncircular ducts).⁽¹¹⁾ Using ANC methods, these plane waves can be analyzed at one location in the duct and attenuated at some distance away (to allow for ANC processor time) in the same duct with high accuracy and, thus, with high effectiveness because their frequency spectra do not change rapidly as they move down the duct.

Shorter wavelengths do not exhibit propagation parallel to the axis of the duct as seen with the lowest order mode and longer wavelengths. Instead of moving longitudinally in the duct, they bounce back and forth between the duct walls and excite higher order modes. A higher order mode represents a solution of the wave equation that is unique for the geometry of the particular duct cross-section.

The boundary or “cut-on” frequency (f_{co}) at which higher order modes begin in round ducts of various diameters can be estimated using Eq. 1:⁽¹¹⁾

$$N = \left(\frac{f_{co}D}{c} \right)^2 + 1.5 \left(\frac{f_{co}D}{c} \right) \quad (1)$$

where

- N = positive integer mode number
- f_{co} = cut on frequency (Hz)
- D = duct diameter
- c = speed of sound in air

As can be inferred from Eq. 1 and is plotted in Figure 1, the cut-on frequency for a given mode number above which that higher order mode will be excited is inversely related to the duct diameter (D). This suggests that modes become increasingly important at larger diameters. As one continues up the frequency spectrum for a given diameter, higher order modes will increasingly dominate the noise content. The dominant frequency below which plane waves will still dominate the higher order modes (f_d) can be estimated for round ducts by Eq. 2:^(8,10,11)

$$f_d = \left(\frac{0.5861}{D} \right) c \quad (2)$$

where

- f_d = frequency (Hz) where higher order modes will begin to dominate the noise content
- D = duct diameter
- c = speed of sound in air

The estimated cut-on frequencies for the first higher order modes of the five duct sizes used in the experiment were calculated from Eq. 1 and presented in Table I, along with the estimated dominant frequencies below which plane waves will dominate the noise signal calculated from Eq. 2. As duct diameter increases, the upper boundary of plane wave domination decreases and ANC IL at higher frequencies should correspondingly decrease.

For rectangular ducts, the cut-on frequency can be estimated by considering both the vertical (height) and horizontal (width)

TABLE I. Estimated First Higher Order Mode Cut-On Frequencies and Maximum Frequency of Plane Wave Dominance by Round Duct Diameter

| Diameter (cm) | Cut-On Frequency (Hz) | Maximum Frequency (Hz) of Plane Wave Dominance |
|---------------|-----------------------|--|
| 10 | 1695 | 1987 |
| 15 | 1130 | 1325 |
| 20 | 847 | 993 |
| 30 | 565 | 662 |
| 46 | 377 | 442 |

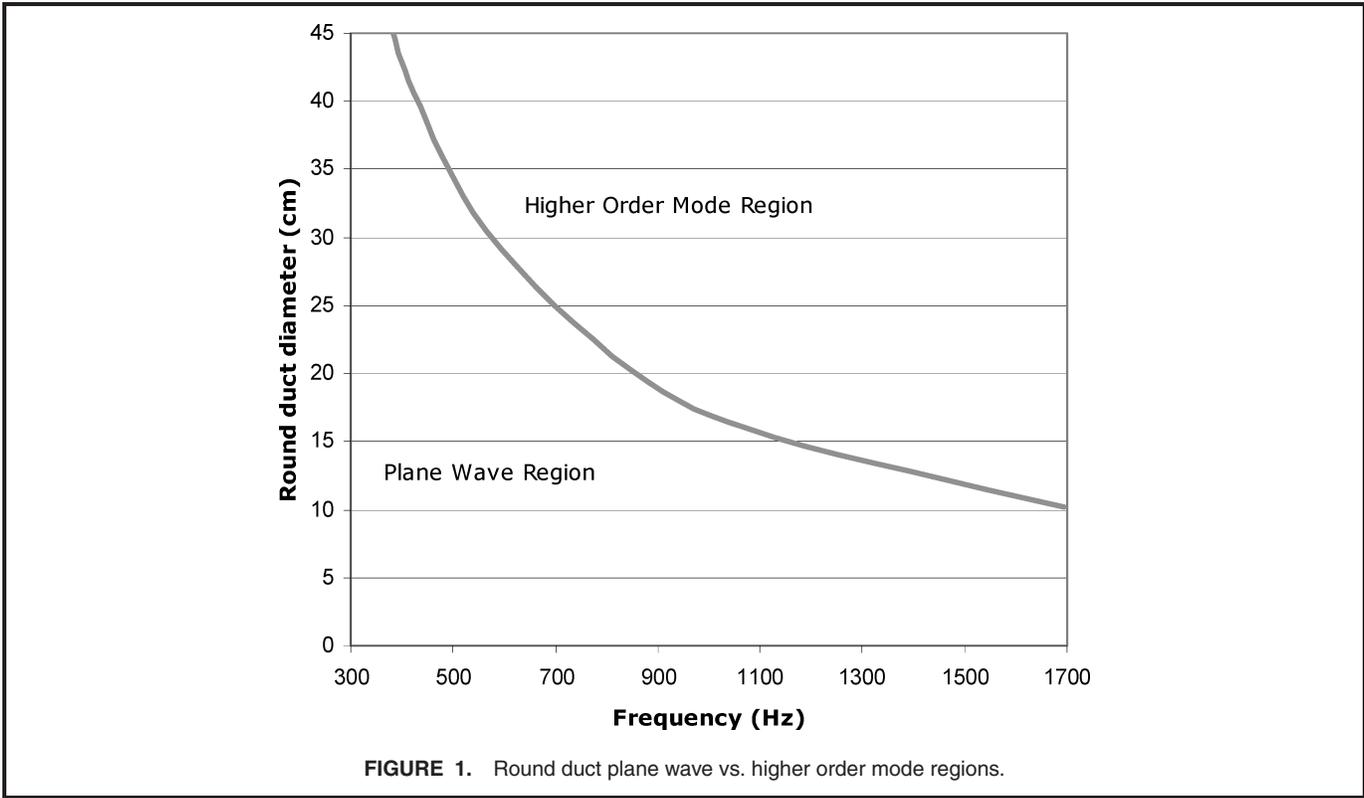


FIGURE 1. Round duct plane wave vs. higher order mode regions.

cross-sectional dimensions (Eq. 3):⁽¹⁰⁾

$$f_{co} = \left(\frac{c}{2\pi}\right) \left[\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 \right]^{1/2} \quad (3)$$

where

- f_{co} = cut on frequency (Hz)
- c = speed of sound in air
- a = width of duct
- b = height of duct
- m = integer number of pressure nodal lines along width
- n = integer number of pressure nodal lines along height

The modes can be described as (m,n). For example, mode (0,1) is the first lowest mode associated with the duct height, with no contribution from the duct width. If the height, for example, were held constant at a large value relative to the width, the first higher order mode (the lowest cut-on frequency) would depend on the larger cross-sectional height (0,1), which in this set of experiments was fixed at 61 cm. This mode would appear above 282 Hz. There would be different cut-on frequencies for the second, third, etc., modes based on the contribution from both dimensions and following Eq. 3.

Above 282 Hz, the first mode (0,1) would begin, and the second mode (1,0), tied to the cross-sectional width, would begin at different frequencies depending on the width (Table II). In this experiment, other higher order modes, such as (3,1), (2,2), (4,1), would have f_{co} greater than or equal to the f_{co} for (0,1), so mode (0,1) is most relevant.

Because the cut-on frequency for the second higher order mode (1,0) decreases with increasing cross-sectional width, the range of frequencies with only plane waves and the first mode also decreases with increasing width; therefore, the IL above 282 Hz should be smaller with increasing cross-sectional width.

Because higher order mode waves bounce back and forth in the duct space as the wave front moves down the duct, the frequency content and phase of the wavefront is difficult to predict at a distant position in the duct to allow ANC processor time; therefore, higher order modes are more difficult to attenuate than plane waves.

Also, because higher order mode cut-on frequencies are inversely related to the cross-sectional dimensions of the

TABLE II. Second Higher Order Mode (1,0) Cut-On Frequency for the Rectangular Duct with Constant Height of 61 cm While Varying Width

| Cross-Sectional Width (cm) | Second Higher Order Mode (1,0) Cut-On Frequency (Hz) |
|----------------------------|--|
| 7 | 2460 |
| 15 | 1148 |
| 23 | 749 |
| 31 | 556 |
| 39 | 442 |
| 47 | 366 |
| 55 | 313 |

duct, smaller ducts have a larger frequency range that is dominated by plane waves and can be more readily controlled by ANC methods. Hence, one could reasonably expect that values of IL achieved at a given frequency at one diameter will fall with larger diameters or rectangular dimensions as planar waves become progressively less important than higher order modes. This is widely assumed to be true by ANC practitioners.⁽¹¹⁾ However, no research has been published relating duct diameter to ANC performance.

Plane waves are more simple to control because the sample of the uniform wavefront at the reference point should still represent the wavefront at the control speaker point later in the duct. Higher order modes require more effort to predict and are difficult to control with a simple ANC system. As a result, many sensors and control speakers are needed to sample and counter higher order modes.^(6,7,12-14) If the frequencies involved are largely limited to those producing plane waves by selecting the appropriate cross-sectional duct dimensions, ANC is more likely to produce substantial insertion losses.

Bandwidth of Noise Source

Noise problems in the occupational and environmental health (OEH) field are typically broadband (i.e., a broad range of frequencies) and are seldom narrow band (tonal). Pure tones (single frequency) are rare. Noises in OEH practice are also typically random in that amplitudes at each frequency fluctuate separately without following a cyclical or other pattern. Narrow band noise tends to vary nonrandomly, and pure tones may be quasiconstant. Hence, although the bandwidth of typical noises may be constant, the amplitude of the frequencies inside the band changes constantly. A commonly encountered source of narrow band noise comes from the repetitive passage of fan blades as a fan wheel rotates. Because of the repetitive, easily predicted nature of rotational noise, ANC can be effective in reducing it. In applying ANC to actual industrial duct noise problems, Hansen reports that: "Typical results achieved are 15–20 dB over two octaves of random noise and 20–30 dB for tonal noise. Typical frequencies which are controlled range from 40 Hz to 400 Hz."^(4,p.112)

For a given broadband noise, each ANC system uses an algorithm to determine the most important (i.e., highest amplitude) frequencies. The amount of insertion loss is limited by the size of the target frequency range. ANC systems can be optimized for only a narrow range of frequencies at a time.⁽⁴⁾ The smaller the range of frequencies and the fewer individual high amplitude frequencies of concern, the more accurately the ANC system can predict the waveform and phase at the downstream control point later in the duct, and attenuate those frequencies.

Even if insertion loss is desired across a wide range of frequencies, it is generally more effective to focus on a single two-octave band (as suggested by the excerpt from Hansen⁽⁴⁾ within the range where ANC has the potential to be effective. If the ANC system can handle several channels independently, the adjacent two-octave bands can be controlled independently. Because broadband random noise is much more often encountered than pure tones or narrow bands, this study focused on control of broadband random noise only.

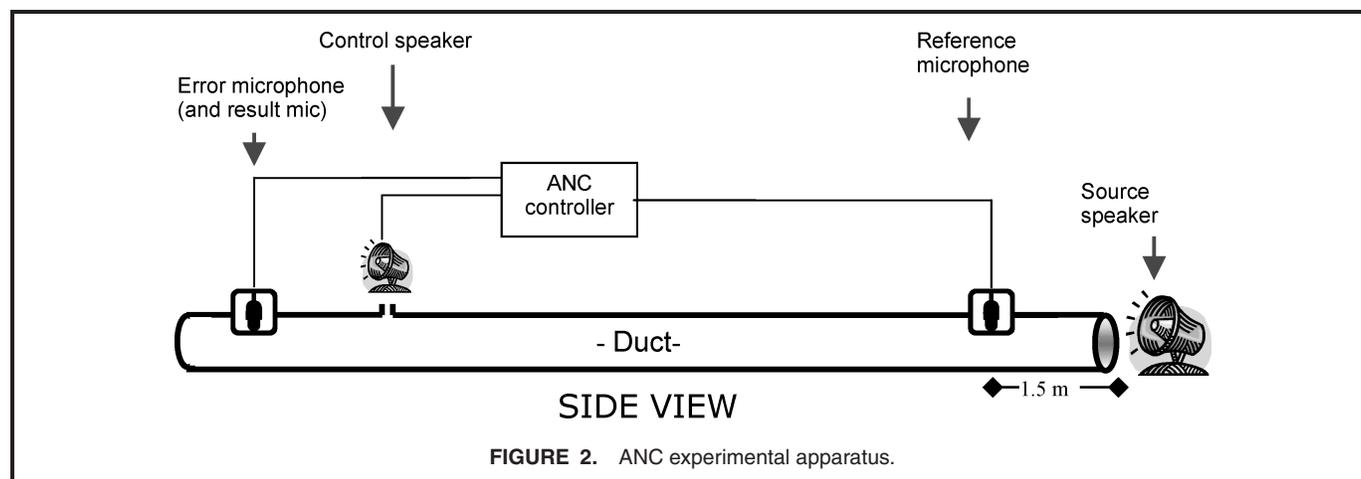
Problem Statement

This article reports the effectiveness of ANC in large ducts through the systematic variance of the cross-sectional dimensions for round and rectangular ducts. The rectangular duct study explored the effect of varying the duct width while holding the height constant. The second study examined the effect of changing the radius of a round duct.

METHODS AND MATERIALS

The active noise control test device was common throughout all studies. The difference in the studies was in the ducts used, which are described in the individual sections pertaining to those studies.

The simple feed forward ANC system sketched in Figure 2 was used for the experiments described here. The components consisted of a source speaker attached tightly to one end of the various ducts with a coaxial directional reference microphone



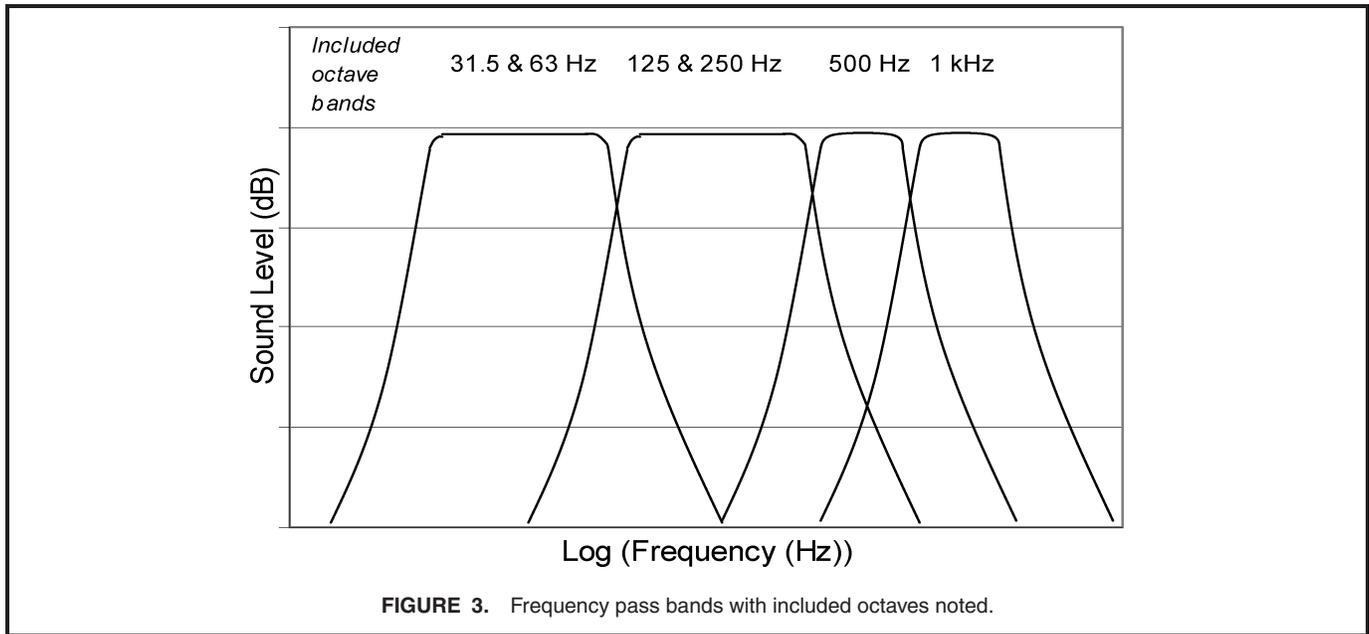


FIGURE 3. Frequency pass bands with included octaves noted.

next to the source speaker in the tube. The 1/4-inch array microphone with 1/2-inch pre-amplifier (PCB Piezotronics, Depew, N.Y.) was made directional by inserting it into a 1/2-inch ID 4-ft-long X5305 microporous tube (Porex, Atlanta, Ga.). This method results in a relatively low-cost directional microphone as explained in Hansen.⁽⁴⁾ The directional reference microphone preferentially senses the source speaker wave impinging at the tip and was necessary to prevent feedback from the control speaker noise broadcast at the other end of the duct reaching the reference microphone.

The source speaker signal was a random broadband white noise source driven by a signal generator on an OR-38 (OROS, Falls Church, Va.) real-time analyzer (RTA). The reference microphone signal was fed into the EZ-ANC II active noise controller (Causal Systems, Inc., Rundle Mall, South Australia) that used a “filtered-x” least mean squares (LMS) digital control algorithm to determine the signal it generated for the control speaker to counter the noise coming down the duct, according to the user’s manual.

Another 1/4-inch array microphone (PCB Piezotronics) mounted coaxially was used as the “error” microphone (Figure 2) to detect the residual sound after control (i.e., the sound not canceled by the downstream speaker). The active noise controller dynamically adjusted the signal sent to the control speaker to minimize the residual sound. Note that the control speaker must be capable of producing enough sound energy in the volume of the duct to cancel the noise wave. As duct dimensions increase, more sound energy is demanded of the control speakers. For the experiments, the error microphone signal was split off to the real-time analyzer to provide a result reading (SPL with and without ANC). In both the rectangular and round ducts, the duct was acoustically closed at the source speaker end, and the other end was open with acoustically absorbent foam placed across the opening.

Frequency Pass Bands and Maximum IL Determination

As indicated previously, pass bands of frequencies aided in comparing the best ANC insertion loss achievable for different frequency regions. Pass bands two octaves wide were developed to use in the experiments (Figure 3). The pass band encompassing the 500 Hz and 1000 Hz octave bands was split into single octave widths (500 Hz and 1000 Hz separately) because of the wider frequency ranges in higher frequency octaves. Figure 3 provides a visual representation of the width of the frequency pass bands with included octave bands noted. To illustrate the frequency pass bands, examples of both round and rectangular duct sound pressure level data measured at the error microphone position are provided. Figure 4 is an example of the sound pressure levels by 1/3 octave bands with ANC off and ANC on during a test of the 10 cm diameter round duct at the 500 Hz pass band. Figure 5 is a similar example of sound

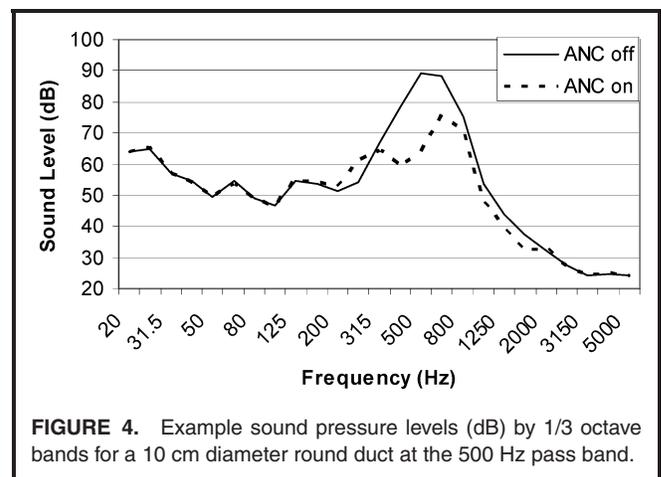


FIGURE 4. Example sound pressure levels (dB) by 1/3 octave bands for a 10 cm diameter round duct at the 500 Hz pass band.

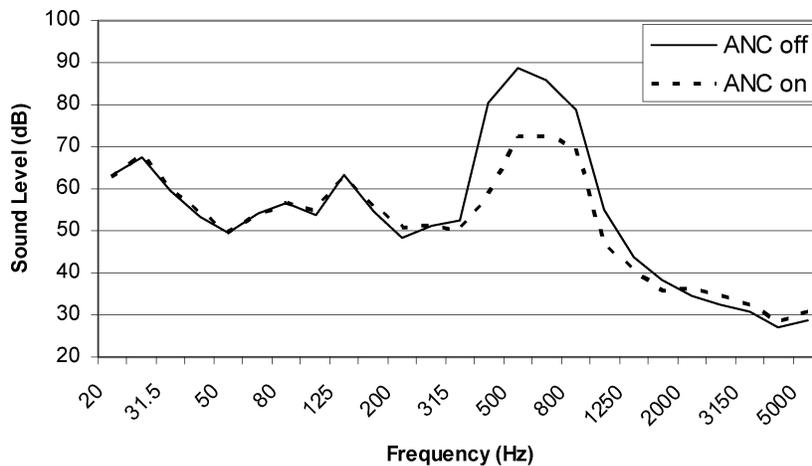


FIGURE 5. Example sound pressure levels (dB) by 1/3 octave bands for a 15 cm wide by 61 cm high rectangular duct at the 500 Hz pass band.

pressure levels at 1/3 octave bands with ANC off and ANC on during a test of the 15 cm wide by 61 cm high rectangular duct at the 500 Hz pass band.

Insertion loss estimates from 1/3 octave band sound pressure levels (SPLs) on various duct sizes were compared between pass bands. In some cases the maximum IL for a 1/3 octave band occurred for a 1/3 octave band outside the pass band. For example, the highest IL for the 500 Hz 1/3 octave band may be when using the 125 and 250 Hz pass bands that did not nominally include the 500 Hz 1/3 band.

The insertion loss ($SPL_{ANCoff} - SPL_{ANCon}$) values from all pass bands at each 1/3 octave frequency band were recorded and the highest IL estimate taken. This maximum insertion loss (IL_{max}) method was selected because, in practice, the ANC system would be tuned to reduce the noise of greatest concern for attenuation. For those reasons, the IL_{max} method was used as the “best achievable result” when presenting results in this investigation.

A further concern was how to best summarize the results. Because the thrust of all the experiments was to determine the difference in ANC IL above a certain frequency where higher order modes would begin and compare interventions, a common frequency breakpoint was chosen. The first higher order mode from the rectangular duct experiments was 282 Hz due to the fixed 61 cm duct height. The lowest higher order mode frequency for the round ducts (associated with the 46 cm diameter duct) was 377 Hz; therefore, the lower breakpoint frequency of 280 Hz was selected for ease of comparison. The different duct size treatments should have no effect on the ANC IL below 280 Hz, but there should be increasing ANC IL above 280 Hz with decreasing duct dimensions. The 1/3 octave bands of 20–250 Hz (upper bound of 280 Hz) were summed by decibel addition as a low frequency IL_{max} value. The 1/3 octave bands of 315–5,000 Hz (lower bound of 280 Hz) were summed as a middle frequency IL_{max} value.

Because the plane wave region can be described in rectangular and round ducts by Eqs. 1 and 3 as dependent on the

cross-sectional dimensions of the duct, a study was designed to ascertain how well these independent variables correlated with the dependent variables of middle and low frequency ANC insertion loss. The first study was designed to examine the effect of varying the width of a rectangular duct with constant height to change the cut-on frequency of the second higher order mode ($n = 2$ trials of each of $a = 7$ treatments).

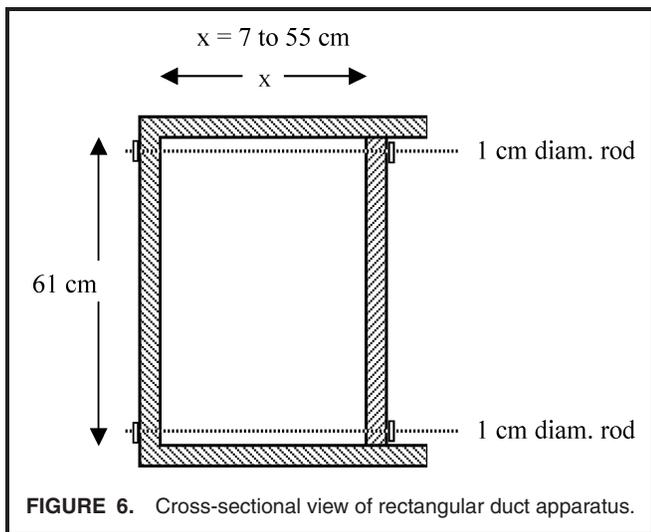
The second study was designed to examine the effect of different round duct diameters used to change the cut-on frequency of the first higher order mode ($n = 3$ trials of each of $a = 5$ treatments). These effects on the higher order mode cut-on frequency should directly affect the ANC insertion loss that could be achieved. Within each study, the order of trial runs was randomized. Independent variables with potential to affect IL_{max} were controlled, including bandwidth, ANC controller operation, and software settings. Microphone position was held constant during each individual study. The remaining independent variables were rectangular dimension and round diameter. IL_{max} data was evaluated using JMP Intro software (SAS Institute, Inc.).

Specific Test Apparatuses

Rectangular Duct

The rectangular duct study was performed with a 7.3-m-long rectangular duct constructed of 1 cm thick plywood. The duct was constructed of three 2.4-m lengths connected end to end and sealed with foam. The cross-sectional height of the duct was fixed at 61 cm, whereas the width was variable from 7 to 55 cm (Figure 6). One side wall was movable with threaded 1 cm diameter steel rods used to fix the side wall at certain widths for the experiments.

The steel rods spanned the cross-section 3.8 cm from the top and bottom of the duct. Although these obstructions could disrupt development of modes, they were thin relative to the cross section and the wavelengths considered. The reference microphone (inside a 1.2-m microporous tube) was suspended by nylon thread in the center of the cross section 30 cm inside



the source end of the duct so that the actual microphone was 1.5 m inside the duct. The error microphone was insulated from vibration inside a foam holder and placed on a wire stand 30 cm inside the far end of the duct, centered in the cross section (Figure 7).

Round Duct

The round duct study tested for the effects of diameter in round ducts using tight-fitting, laser-welded, center-seam galvanized steel duct (Nordfab, Inc., Thomasville, Ga.) with diameters 10, 15, 20, 30, and 46 cm (standard available 4, 6, 8, 12, and 18 inches). The ducts were selected based on availability and space constraints.

Five round ducts each 1.5 m long were clamped together and tightly sealed at the junctions to form a 7.5-m-long duct. The source speaker was joined to one end of the run of ducts, and the control speaker joined to a 20-cm length of duct connected to the straight duct with a 60–90° junction fitting at the point 6 m from the source speaker at the far end of the run of duct from the source speaker (Figure 2) Given the 1.2-m microporous plastic tube needed to make the reference

microphone directional, the actual duct length between the reference microphone and the control speaker was actually 4.9 m. Preliminary testing confirmed recommendations from Hansen⁽⁴⁾ that 3 m was sufficient length to allow travel time for the active noise controller processor to determine a counter signal for the noise as the plane wave traveled down the length of the duct.

Study I—Rectangular Duct

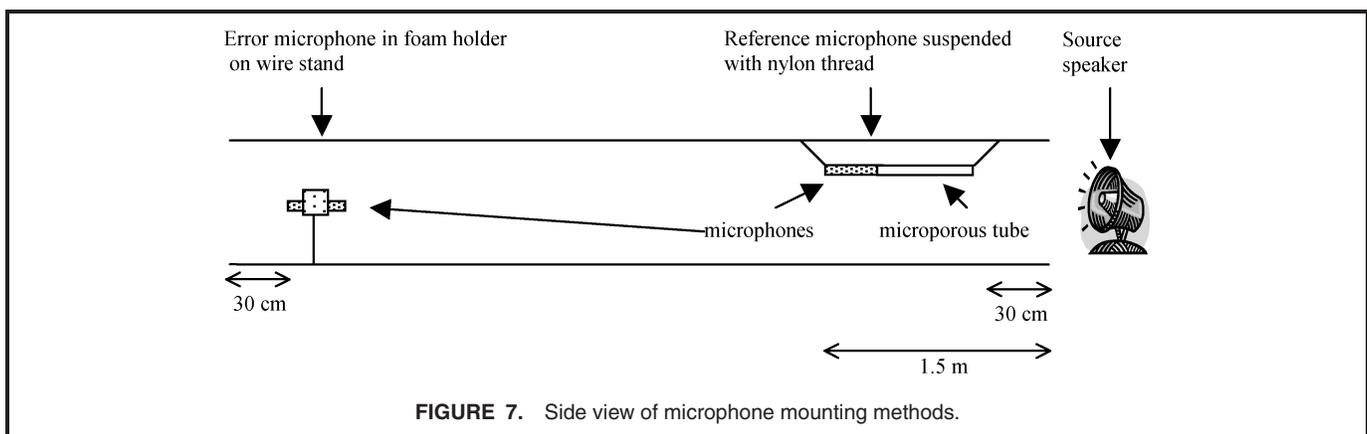
Rectangular Duct Results

The results of the rectangular duct study are shown in Figure 8. The IL_{max} values in decibels for the two dependent variables (low and middle frequency) are plotted against the independent variable of cross-sectional width in centimeters. The open diamonds represent the low frequency data, and the plus signs represent the middle frequency data. Regression lines were added to the figure to help analyze the data.

Low frequency. For the low frequency data, the best fit line does not describe the data well, with an associated R^2 of only 0.1453. However, it appears that the dependent variable does not have a very large effect on the low frequency IL_{max} result. In other words, the IL_{max} is constant at low frequency with regard to cross-sectional width.

Middle frequency. The middle frequency data were certainly affected by the cross-sectional width. As the width increases, the cut-on frequency of the second higher order mode decreases so that the overall IL_{max} at the middle frequencies also should decrease. That is reflected in the data in Figure 8. A linear regression line fit to the middle frequency data had an R^2 of 0.8279 and does describe the data relationship somewhat. An exponential line fit to the data increased the value of R^2 to only 0.8401. However, the middle frequency data seemed to reach a cut-off point with a change of slope between 23 cm and 31 cm; therefore, multivariate regression was used to determine a fit for the data in the case of a breakpoint between two slopes. The regression was fit using Eq. 4:

$$\hat{Y} = b_0 + b_1 X_1 + b_2 (X_1 - 31 \text{ cm}) X_2 \quad (4)$$



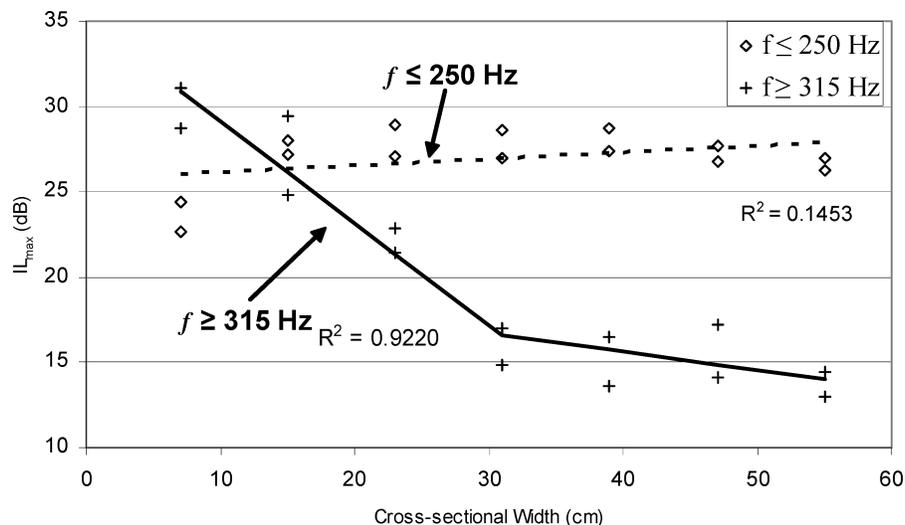


FIGURE 8. Rectangular duct results, IL_{\max} by rectangular cross-sectional width with fixed height of 61 cm.

where

$$\hat{Y} = IL_{\max} \text{ (dB)}$$

$b_0, b_1,$ and b_2 = regression coefficients

X_1 = cross-sectional width of the rectangular duct (cm)

$X_2 = 1,$ when $X_1 > 31$ cm, otherwise $X_2 = 0$

The R^2 value for the multivariate regression line from Eq. 4 was 0.922, which described the data well.

Rectangular Duct Discussion

The results of the rectangular duct study support the logic based on the higher order mode cut-on frequency expressed in Eq. 3. For low frequencies, there was no effect of changing the cross-sectional width apparent via regression. There may be a systematic effect in that the low frequency data appear to form a parabola, and a more complicated model may describe the effect better. However, the IL_{\max} values of the different treatment groups overlapped for all but the narrowest width (7 cm did not overlap the other treatments). In effect, the variability of the data is large enough that the possible systematic effects are obscured. In the end, the regression model indicated no discernible effect for this set of low frequency data, which was expected from the study design. For middle frequencies, there was a significant effect of changing the cross-sectional width so that IL_{\max} decreased with increasing width. There is a limit in the effect somewhere between 23 cm and 31 cm as the slope of the data changed from negative to flat.

Because the cut-on frequency for the second higher order mode decreases with increasing cross-sectional width, the range of frequencies with only plane waves and the first mode (due to height) also decreases with increasing width; therefore, the IL_{\max} for the middle frequency range should be smaller with increasing cross-sectional width, which was seen in the data. The flattening of the middle frequency data above 23 cm in horizontal width may have to do with the difference in

effectiveness of the control speaker to create a signal in the larger volume of air required at larger cross sections.

Rectangular Duct Conclusion

For the middle frequency IL_{\max} data, there was a 6 dB to 14 dB average increase in insertion loss for successively smaller cross-sectional widths (23, 15, and 7 cm) compared with the 31 cm treatment. There is a significant effect of cross-sectional width on middle frequency IL_{\max} for rectangular ducts, and the effect follows the logic of the underlying equation.

Study II—Round Duct

Round Duct Results

The results of the round duct study are shown in Figure 9. The IL_{\max} values in decibels for the two dependent variables (low and middle frequency) are plotted against the independent variable of duct diameter in centimeters. The open diamonds represent the low frequency data, and the “plus” signs represent the middle frequency data. Linear regression lines were added to the figure to help analyze the data.

Low frequency. For the low frequency data, the best fit line does not describe the data well, with an associated R^2 of only 0.0825. However, the dependent variable does not have a very large effect on the low frequency IL_{\max} result ($p = 0.4328$, no effect per ANOVA). Again, the low frequency IL_{\max} appears constant with regard to diameter.

Middle frequency. The middle frequency data were certainly affected by the diameter. As the diameter increases, the cut-on frequency of the first higher order mode decreases, so that the overall IL_{\max} at the middle frequencies should decrease as well. The effect of diameter on IL_{\max} ($p = 0.0024$) is reflected in the data in Figure 9. A linear regression line fit to the data has an R^2 of 0.6872 and does describe the data relationship somewhat.

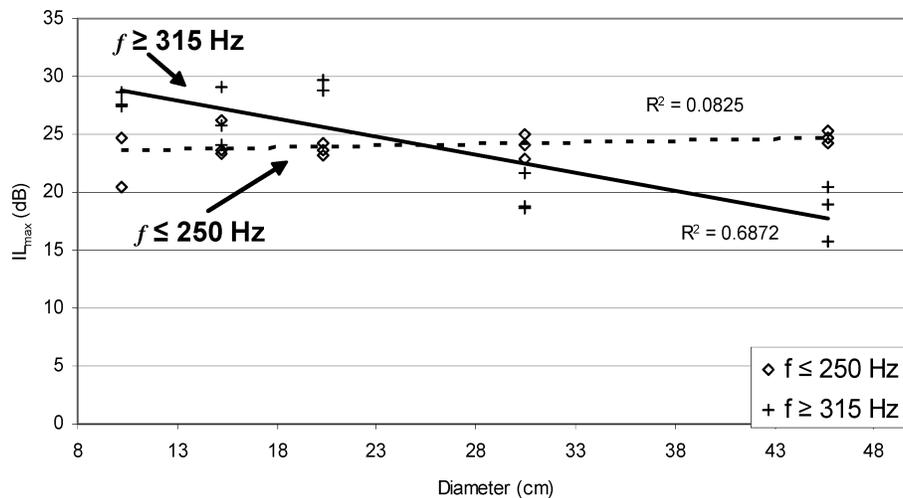


FIGURE 9. Round duct results, IL_{max} by round duct diameter.

Round Duct Discussion

The results of the round duct study support the logic based on the higher order mode cut-on frequency Eq. 1. For low frequencies below the first higher order mode cut-on frequency of the largest diameter (377 Hz), there was no effect of changing the diameter. In effect, all diameter systems operated on plane waves for the low frequency IL_{max} data. For middle frequencies, there was a significant effect of changing the diameter so that IL_{max} decreased with increasing diameter.

Round Duct Conclusion

For the middle frequency IL_{max} data, there was a 1.4 dB to 11.1 dB average increase in insertion loss for successively smaller diameters (30, 20, 15, and 10 cm) compared with the 46 cm diameter duct. There is a significant effect of diameter on middle frequency IL_{max} for round ducts that follows the logic of the underlying equation.

DISCUSSION

Reducing the cross-sectional dimensions of both rectangular and round ducts increases the frequency range of effective ANC IL. The overall ANC IL levels were higher for round ducts (18 dB to 29 dB for middle frequency) than for the rectangular ducts (13 dB to 29 dB for middle frequency). However, the main reason for the lower ANC IL values in the rectangular ducts could probably be that one dimension remained fixed at 61 cm, which would mean that the first higher order mode would cut-on for all the variable width sizes at the beginning of the middle frequency range (282 Hz) for the rectangular ducts.

The application of this research to industrial noise control problems would be most useful for environmental noise from exhaust stack situations, but decreasing duct size to improve insertion loss at higher frequencies may bring up other problems. One concern would be the increase in pressure requirements to the exhaust fan. For instance, if a 46 cm

diameter duct were to be replaced with smaller ducts of equal total cross-sectional area, the number of ducts would increase quickly. The cross-sectional area of a single 46 cm diameter duct is equal to the area of twenty 10 cm diameter ducts, nine 15 cm diameter ducts, five 20 cm diameter ducts, or two 30 cm diameter ducts. The increase in fan pressure from one 46 cm to twenty 10 cm diameter ducts would be large (about $[D_1/D_2]^{1.22} = [46\text{ cm}/10\text{ cm}]^{1.22} = 6.26$ times the initial pressure for each duct).⁽¹⁵⁾ There is also the increase in cost to purchase and install 20 ducts to consider. Further, the ANC hardware costs would become considerable to have a separate control channel for each duct.

CONCLUSION

Active noise control has long been an area of interest for acousticians and noise control engineers. Hardware limitations and the need for expertise in implementation have limited the industrial applications of ANC technology. One application to which ANC is particularly well suited is noise control on exhaust stacks. ANC works well to reduce the low frequency “rumble” that can travel great distances and annoy neighboring communities. However, for broadband noise sources, even a combination of active and passive controls may fall short of complete broadband noise control. This research indicated that the use of smaller ducts can extend the frequency range of control of ANC methods to higher frequencies. By providing up to 26–28 dB of insertion loss at the 500 Hz 1/3 octave band, ANC may become more viable as an option for industrial noise control issues.

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