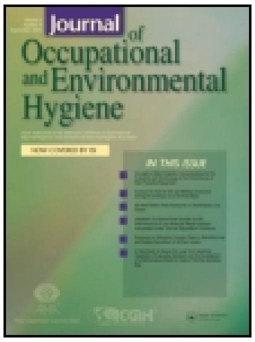

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Effects of Cross-Sectional Partitioning on Active Noise Control in Round Ducts

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Active noise control (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 diameter of the duct. The lowest frequency for higher order modes will increase 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. If smaller diameters have broader frequency ranges that can be controlled with ANC, perhaps one could extend the frequency range for a large cross section by partitioning it into smaller cross sections using axial vane splitters. This hypothesis was tested by two methods of cross-sectional partitioning. Partitioning was achieved in one design by inserting a smaller duct inside a large duct. In a second design, a cross-shaped splitter was inserted inside the large duct. Summed ANC insertion loss (IL) at low frequencies (≤250 Hz) was at least 16 dB and at least 14 dB at middle frequencies (≥315 Hz). ANC IL results were 1.7 to 2 dB better for the large duct partitioned by a smaller inner duct than the large duct alone ($p = 0.0146$ for low frequency and $p = 0.0333$ for middle frequency). ANC insertion loss was 5.6 dB better for the large duct partitioned by a cross-shaped splitter at high frequencies than the large duct alone ($p = 0.0003$). However, the cross-shaped partition system was 5.8 dB less effective at low frequencies than the large duct ANC IL alone ($p < 0.0001$).

Keywords active noise control, axial vane splitters, noise cancellation, partitioning, round ducts

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INTRODUCTION

Although some researchers have attempted to make off-the-shelf active noise control (ANC) devices available to the mainstream occupational hygienist,[1] ANC is still largely an art for acoustics experts. The complexities of acoustics and the risk of a hygienist recommending capital investment in a control strategy that may result in low, practical insertion loss if done incorrectly have combined to limit widespread enthusiasm. Recognizing that many ANC applications are used in exhaust ducts to limit broadband noise,[2,3] this study investigated the use of an off-the-shelf, commercially available ANC system to reduce broadband noise in ducts. The findings may encourage more consideration for ANC as a practical duct noise solution.

When using an active noise control system in a duct, plane waves are simple to control because the movement of the wave down the duct can be easily predicted from the length of the duct and the speed of sound. Higher order modes are more complex and therefore difficult to predict and control. As a result, many sensors (such as microphones) and control speakers are needed to sample and counter higher order modes.[3–7] Therefore, if the frequencies involved are largely limited to those producing plane waves, ANC is more likely to produce substantial insertion losses. Cross-sectional dimensions are the main determinant of frequency boundaries between plane waves and higher order modes. Smaller diameter ducts have a higher frequency range of plane wave dominance compared with larger ducts.

This article documents a case study of using an off-the-shelf active noise control system to control broadband noise in different treatments of round ducts. It is not intended to be an acoustical analysis of ANC in ducts.

Because most ANC applications are in large exhaust ducts, the frequency boundary for plane wave dominance is usually low (the first higher order mode cut-on frequency for a 46 cm diameter round duct would be 377 Hz, and the maximum frequency of plane wave dominance would be 442 Hz).[8–10] One method to increase the upper frequency bound of plane wave dominance is to reduce the cross-sectional dimensions of the duct. However, most duct dimensions are selected for a specific volumetric flow rate, and reducing the duct dimensions would increase the pressure requirements of the duct system.

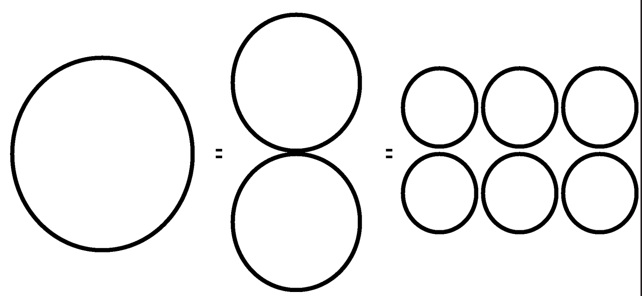

FIGURE 1. Equivalent volumetric round ducts

Two methods used to reduce duct dimensions without reducing total cross-sectional area are (1) using many smaller ducts for the same volumetric flow as in Figure 1, or (2) using axial vane splitters for cross-sectional partitioning as in Figure 2. It is not always practical to substitute several smaller diameter ducts for a larger one, since the pressure due to airflow is proportional to diameter to the 1.2 power.[11] (Note that using a single smaller duct with the same flow would change the pressure by the diameter ratio to the 4.5 power.[11] The increased flow velocity from a single smaller duct would also raise the frequency of the noise, which would make ANC more difficult.) Whereas splitters have been used to increase surface area of acoustically absorptive material in ducts for some time,[12,13] there is only one study applying them to active noise control.[14] Further, each different axial vane splitting scheme would have different modes in the ducts. The acoustics of the ducts involved were not treated in this article.

Besides recognizing that plane waves are easier to control, many researchers also mention axial vane splitters as a method to extend the range of plane wave dominance to higher frequencies. Eghtesadi et al.[14] actually split an HVAC duct to reduce higher order mode concerns. Egaña et al.[15] used an HVAC duct from a train car that was already split by design. Eriksson et al.[5] focused on higher order mode control but mentioned that axial splitters would be a common method to prevent higher order mode excitation. Earlier mention of axial vane splitters by Cullum[12] and Beranek[13] was solely to facilitate passive noise controls by increasing the absorptive surface area inside the duct.

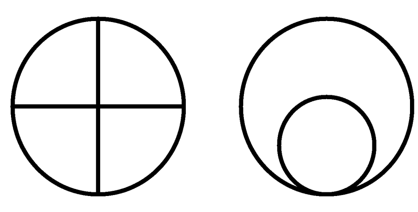

FIGURE 2. Cross-sectional partitioning schemes for round ducts

After reviewing the literature, no diameter effects studies involving cross-sectional partitioning strategies were found except Eghtesadi et al.'s study[14] on energy conservation. The data obtained from such experiments would aid in devising simple ANC solutions for large duct broadband noise problems so often encountered in industry.

Problem Statement

The research presented here attempted to extend the upper bound of frequency effectiveness of ANC in large ducts by exploring the effects of cross-sectional partitioning on ANC insertion loss in large ducts using an off-the-shelf ANC device and nonacoustician researchers. The initial information gathered from cross-sectional dimension studies in both rectangular and round ducts[16] (first part published separately) was used to help design these cross-sectional partitioning experiments that focused only on round ducts.

METHODS AND MATERIALS

A series of studies was developed to explore the effects of axial vane splitters on ANC performance against broadband noise in large ducts. The dependent variables (results) were ANC insertion loss (IL = Sound Pressure $\text{Level}_{\text{ANCoff}}$–Sound Pressure $\text{Level}_{\text{ANCon}}$) at low frequencies (between 20 Hz and 250 Hz 1/3 octave bands) and middle frequencies (between 315 Hz and 5000 Hz 1/3 octave bands). All studies used a 46 cm diameter large duct. Study I compared ANC IL in the remaining crescent-shaped area of the large duct with different diameter round ducts inserted inside. The smaller diameter ducts were acoustically blocked so that the ANC "live" area was only the remaining crescent-shaped cross section of the large duct. Study II used one of the inner duct diameter treatments from Study I as a "live" axial vane splitter, with ANC systems applied to both the inner and outer ducts. It had two components. First (IIa), two ANC systems were applied independently, one to the smaller inner duct and one to the larger outer duct. Second (IIb), a scheme was attempted with two ANC systems but one using some of the hardware of the other system to reduce cost requirements.

Lastly (Study III), a cross-shaped axial vane splitter method was attempted on the large duct. ANC was applied to one of the resulting pie-shaped, cross-sectional quadrants, with the idea that the technique could later be extended to all quadrants if worthwhile results were realized. In all studies, the axial vane splitter treatments were compared with ANC IL in the large 46 cm diameter duct by itself to see if the particular axial vane splitter was any different (better) and worth the effort to employ in broadband noise situations.

The active noise control test device and the 46 cm diameter outer duct were common throughout all studies and are discussed in this section. The apparatus difference between the studies was in the different axial vane splitters used.

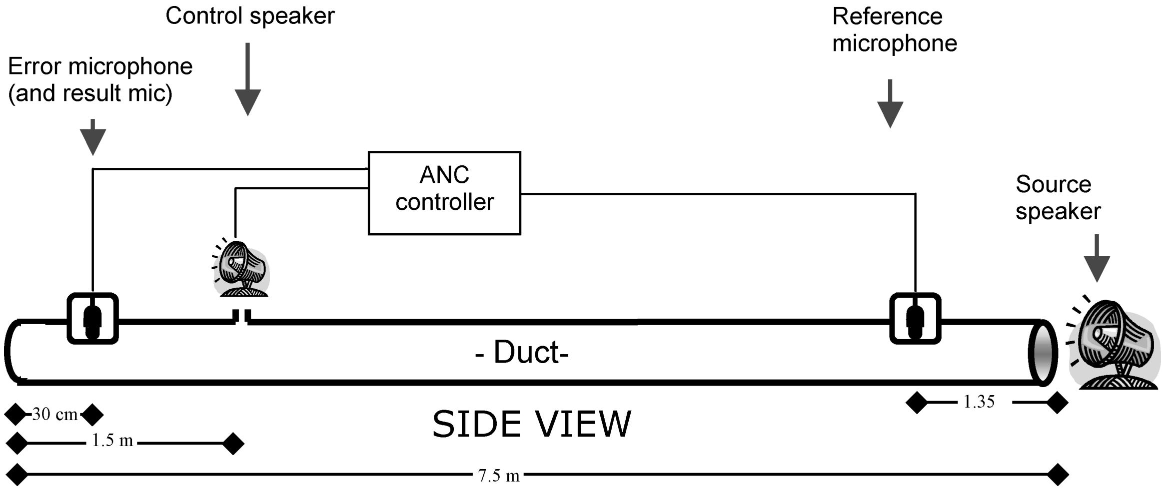

FIGURE 3. ANC experimental apparatus

The simple feed forward ANC system sketched in Figure 3 was used for the experiments described here. The components consisted of a source speaker attached tightly to one end of the 46 cm diameter duct with a coaxial directional reference microphone next to the source speaker in the tube. The $\frac{1}{4}$-inch array microphone with $\frac{1}{2}$-inch preamplifier (PCB Piezotronics, Depew, N.Y.) was made directional by inserting it into a $\frac{1}{2}$-inch i.d. 4 ft long X5305 microporous tube (Porex, Atlanta, Ga.). This method results in a relatively low-cost directional microphone as explained in Hansen.(17) 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 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 (Filtered-x 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 (Causal Systems, Inc.). Another 1/4-inch array microphone (PCB Piezotronics) mounted coaxially was used as the “error” microphone (see Figure 3) to detect the residual sound after control (i.e., the sound not “cancelled” 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), except in studies IIa and IIb where a separate result microphone was placed 10 cm past the end of the duct. The duct was acoustically closed at the source speaker end, and the other end was open with acoustically absorbent foam placed across the opening.

The round duct used in the study was tight-fitting, laser-welded, center-seam galvanized steel duct (Nordfab, Inc., Thomasville, Ga.) with diameters 15, 20, 30, 41, and 46 cm (standard available 6, 8, 12, 16, and 18 inches). The different duct diameters were normalized to the largest duct to facilitate presentation in this paper. The normalized diameters were 0.33, 0.44, 0.67, 0.89, and 1.0, respectively. The ducts were selected based on availability and space constraints. In all studies, the large 46 cm diameter outer duct served as a control, and other treatments were compared to the achievable ANC IL in the 46 cm large duct alone. 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 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 (see Figure 3). Given the 1.2-m microporous plastic tube placed 15 cm inside the source speaker end of the duct, needed to make the reference microphone directional, the actual duct length between the reference microphone and the control speaker was actually 4.65 m. Preliminary testing confirmed recommendations from Hansen(17) 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.

The reference microphone was suspended by nylon thread attached to foam holders in the center of the cross section 15 cm inside the source end of the duct. The error microphone was insulated from vibration inside a foam holder and suspended by duct tape 30 cm inside the far end of the duct, centered in the cross section (see Figure 4). For Studies IIa and IIb, a separate result microphone was placed 10 cm past the far end of the duct inside a foam holder on a ring stand.

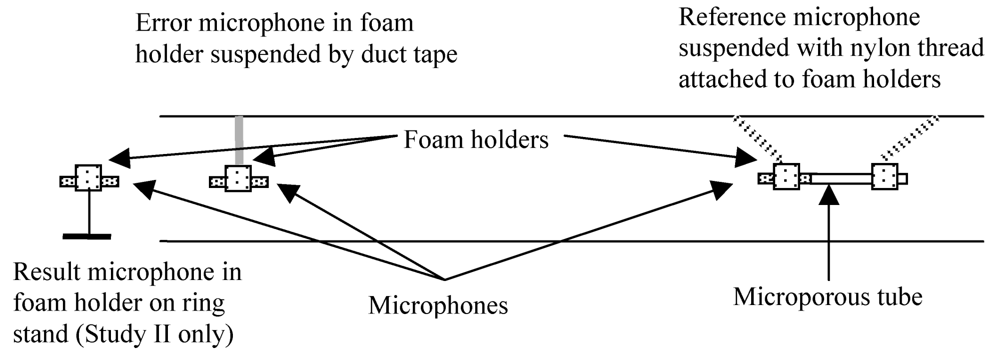

FIGURE 4. Side view of microphone mounting methods

Variables and Hypotheses

The two dependent variables monitored were the insertion loss at two different frequency ranges. As described in-depth in the first part,[16] frequency pass bands 1–2 octaves wide were selected for the experiments due to ANC limitations by bandwidth.[10] Broadband random noise was broadcast as the source noise signal within each pass band. One-third octave band sound pressure level (SPL) values, with ANC on, were subtracted from the SPLs of the same bands with ANC off to give a measure of insertion loss for each 1/3 octave band. Because of pass band roll-off overlap, the highest IL value for a particular 1/3 octave band was sometimes from a pass band experiment that did not nominally include that 1/3 octave band. Therefore, the maximum insertion loss values among the frequency pass bands were recorded for each 1/3 octave band. The insertion loss values were then summed from 20–250 Hz as a low frequency IL_{max} value, and summed from 315–5000 Hz as a middle frequency IL_{max} value. These two values, $IL_{max} \leq 250$ Hz and $IL_{max} \geq 315$ Hz, were the dependent variables.

There are numerous independent variables that affect the IL_{max} results for ANC of random noise in ducts. The independent variables of bandwidth, ANC controller operation, and software settings were held constant. Microphone position was held constant during each individual study. The remaining independent variables were: inner duct diameter for two-duct studies (Study I), simultaneous operation of two ducts (IIa), simultaneous operation with a reduced hardware configuration (IIb), and finally a cross-shaped splitter in a round duct (III). As these were too many variables to analyze in a single study, a series of studies was devised to address one independent variable at a time. The studies with variables, null hypotheses, and test type are listed in Table I. Preliminary tests were used to characterize variability so that sample size could be determined for sufficient statistical power. Study I used three replicates of each of the five treatment groups. The rest of the studies (IIa, IIb, and III) had only two treatment groups each, with four, three, and three replicates, respectively.

The series of studies was designed to describe the effects of cross-sectional partitioning on active noise control in round ducts.

STUDY-UNIQUE MATERIALS

Study I Inner Duct Diameter Unique Apparatus

Study I was designed to test the effect on ANC insertion loss efficacy of inserting a smaller diameter (0.33, 0.44, 0.67, 0.89) round duct inside a large diameter round duct. The IL_{max} was compared between different smaller duct diameters as the treatment groups and also to the large duct alone using multiple comparison techniques.

The smaller inner ducts were capped at the end facing the source speaker to reduce the sound transmitted down their interior that might radiate back into the outer duct space (see Figure 5). Because the first part[16] established the ANC IL of different diameter round ducts, Study I was not concerned with the ANC IL of the smaller inner ducts but of the outer duct space left after the smaller ducts were inserted.

The inner ducts were similar to the outer duct except they were straight runs of sealed, clamped duct 7.5 m long with no tee. The effect of the position of the duct, whether concentric to or sitting at the bottom of the outer duct (tangent), was investigated in a preliminary experiment. There was no significant difference between the IL achieved at the concentric

TABLE I. Series of Studies to Describe Independent Variables

Study	Variable	Null Hypothesis (H_0)	Test
I	Inner duct diameter	No effect of inner duct diameter	One-way ANOVA
IIa	Simultaneous operation	No difference between 1.0 duct alone and 2 ducts simultaneously	t-test
IIb	Hardware combination	No difference between 1.0 duct alone and 2 ducts with single reference microphone	t-test
III	Cross-shaped splitter	No difference between 1.0 duct alone and single quadrant area	t-test

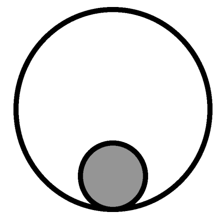

FIGURE 5. Study I Apparatus, end view of inner duct position

vs. tangent inner duct positions, so the tangent position was selected for the study as in Figure 5. The tangent inner duct position would provide an easy access for control speakers to the inner duct space in application.

Study I investigated the effect of different diameter inner ducts on the ANC IL in the remaining area of the outer duct. The empty outer duct was also tested as a treatment group with which to compare all other treatments.

Study II Simultaneous Dual-Duct Operation Unique Apparatus

Study II used the previously described outer duct, with a 0.67 (30 cm diameter) inner duct inserted. Based on the preliminary finding that coaxial was no better than the more convenient tangent placement, a 0.67 inner duct was placed tangent to the bottom of the outer duct. The inner duct was open to the same source noise and had a separate reference microphone, control speaker, and error microphone (see Figure 6). The inner duct ANC system was run by a separate set of channels on the same active noise controller as the outer duct. A 10 cm diameter, 20-cm-long piece of duct connected the control speaker to the inner duct through the wall of the outer duct at the control position 6 m down the duct away from the source speaker. The control speaker for the inner duct system was isolated inside a 0.10 m^3 (3.4 ft^3) plywood box to reduce cross-contamination of noise between the two ducts (see Figure 7). The gaps between the plywood box and the 10 cm diameter control speaker tube, as well as the outer duct wall and the 10-cm tube, were packed with acoustic foam and sealed with duct tape to reduce noise cross-contamination.

To compare the difference in overall ANC insertion loss with and without the inner duct system in place, a separate result microphone was placed at the center of the end of the outer duct, 10 cm past the end (see Figures 4 and 6. This allowed for a more realistic measurement past the end of the duct, analogous to the noise actually exiting an exhaust stack. Both stages of the study compared a simultaneous dual-duct system with a single outer duct system, as in Figure 7.

The second stage of the study (Study IIb) was to determine whether a reduced hardware system could still return better ANC insertion loss than the outer duct ANC alone. Preliminary studies attempted to eliminate hardware and then check the stability of the system. When an error microphone from either the outer or inner system was removed, the system became too unstable to measure within seconds and had to be shut down to protect the speakers. When a single control speaker signal was sent to each control speaker, there was no measurable ANC insertion loss for either system. The only viable hardware reduction scheme was determined to be eliminating the reference microphone from the outer duct system and feeding the inner duct reference microphone signal to both the inner and the outer duct control channels and algorithms.

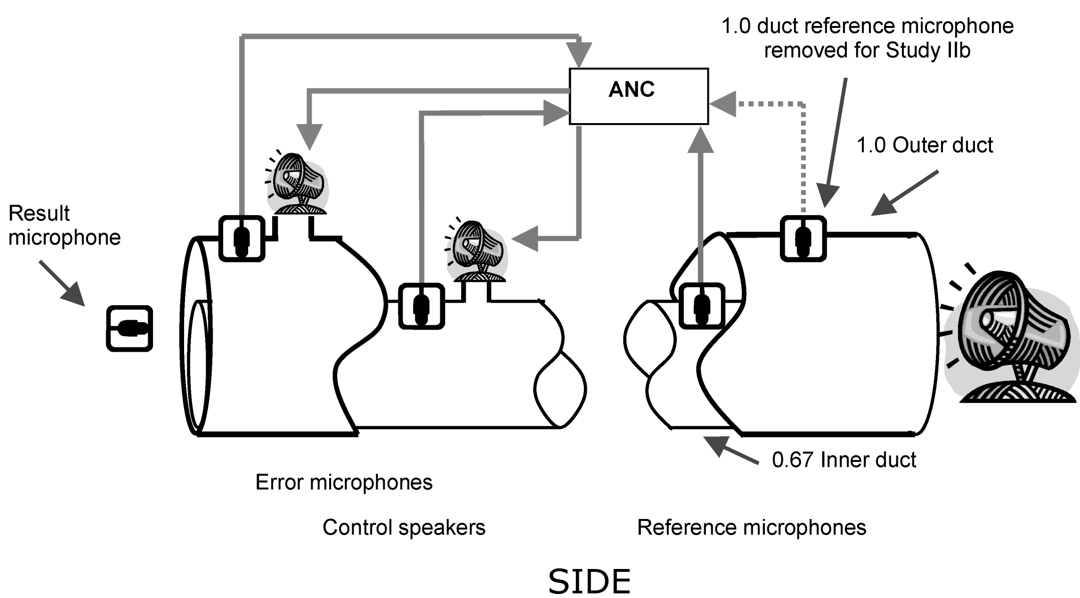

FIGURE 6. Study II Apparatus, side view

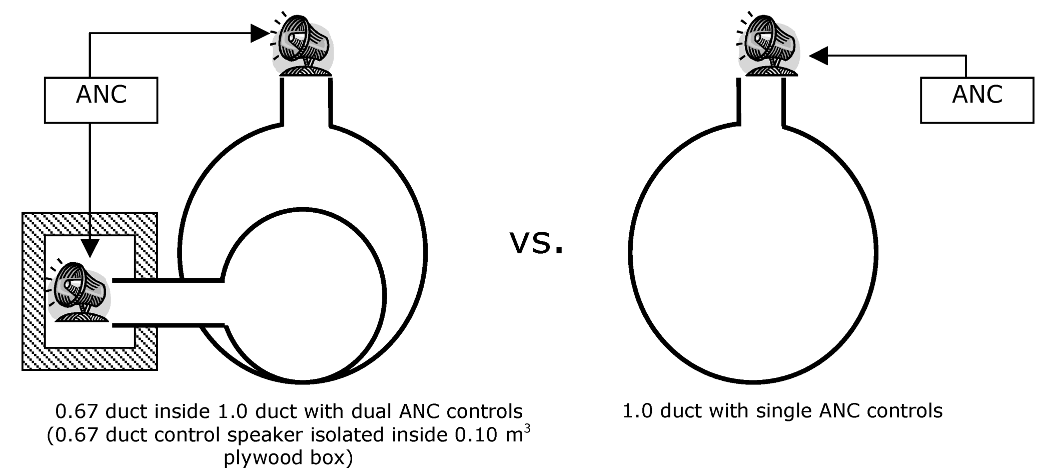

FIGURE 7. Study II Apparatus, end view of apparatus with control speakers

Study III Single Quadrant Unique Apparatus

Study III used the previously described outer duct, with a 7.3-m-long, cross-shaped plywood splitter inserted into the duct. The duct was modified in that the control speakers at the tee area were mounted directly on the side wall for Study III. Four control speakers were mounted at the 46 cm diameter tee at 6.4 m from the source speaker. Several preliminary tests kept all four quadrants live with separate ANC channels devoted to the individual quadrants. Although the cross-splitter was caulked at its center to reduce noise cross-contamination between quadrants, the ANC system was too unstable to have all four channels operating, most likely due to mutual interference. Even though the quadrants should have similar shape and noise traveling down their lengths, the single ANC controller could not adequately control the four individual quadrants. Therefore, the study was restricted to compare a single quadrant, with the other three quadrants blocked off, vs. the outer duct alone, as in Figure 8. The other three quadrants were blocked with a dense rubber sheet across the face sealed with duct tape, and acoustic foam stuffed inside the duct. The assumption was that the difficulties in having four live quadrants could be resolved later if the ANC IL results from the single quadrant were worthwhile.

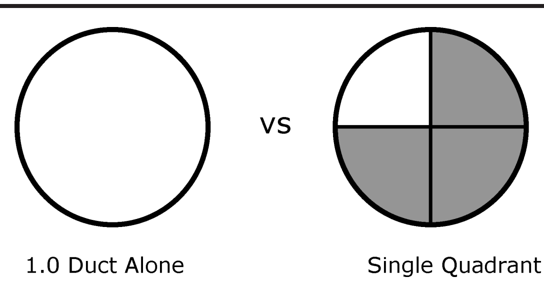

FIGURE 8. Study III Apparatus, end view of comparison treatments

Because not all quadrants had live ANC systems in place, an external result microphone would not represent the two treatments. Instead, the comparisons used the error microphone signal, which was mounted at the same position for both treatments, 7.2 m along the duct.

RESULTS

The results from the series of four experiments are presented together. Study I was a multiple comparison analysis of variance (ANOVA) to test the null hypothesis that there was no effect of inner duct diameter on ANC IL. Studies IIa, IIb, and III were simple t-tests to test the null hypotheses that there was no difference in ANC IL between the treatment groups and the untreated outer duct. In all instances, assumptions of homogeneity of variance were checked by statistical tests: For heterogeneous variance in the ANOVA, Welch's ANOVA procedure was used.[18−20] For t-tests of groups with unequal variances, the appropriate adjusted degrees of freedom were used for the test statistic. The p-values and summary results from all of the studies are presented in Table II.

Study I Results

The results by frequency region for all the inner duct diameters are displayed 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 inner duct diameter in centimeters. The open boxes represent the low frequency data, and the closed triangles represent the middle frequency data. Linear regression lines were also added to investigate trends.

Statistical testing demonstrated that for frequencies below 250 Hz the insertion loss was not dependent on inner duct diameter and above 315 Hz it was dependent. For low frequency (long wavelength) noise, the different open areas in the outer duct were not large enough to allow for cut-on of higher order modes. Therefore no significant difference in

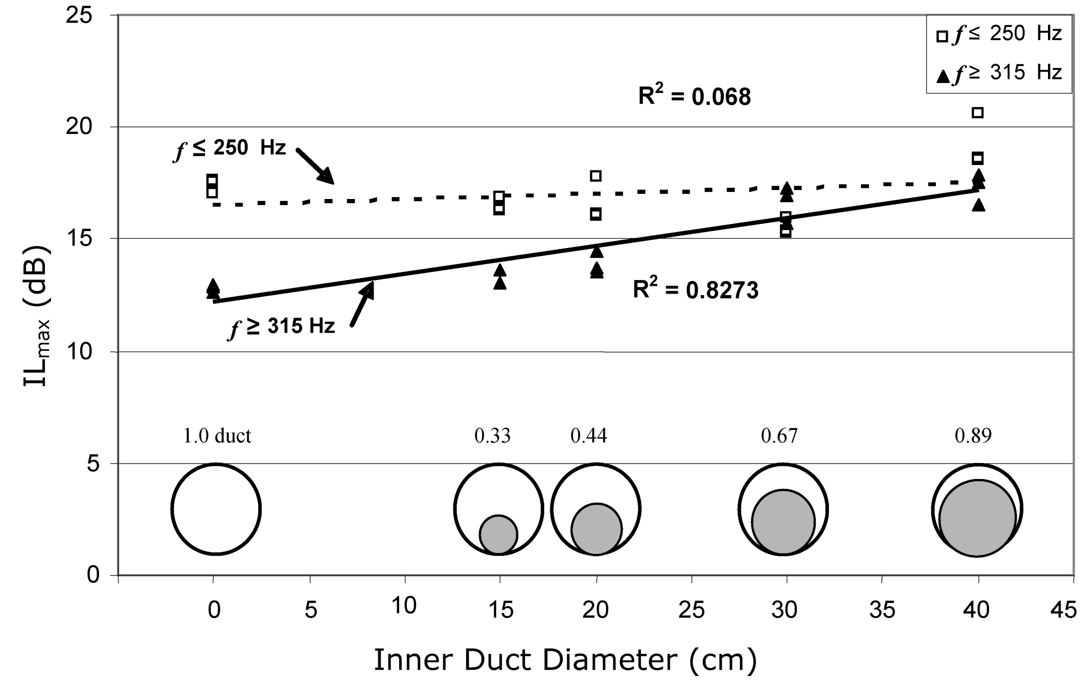

FIGURE 9. Study I Results, IL_{max} by inner duct diameter

achievable ANC IL was expected. For middle frequency noise, there was an expectation of higher ANC IL with decreasing open area (increasing inner duct diameter) as higher order modes contribute less. This was indicated in the figure and confirmed by the R^2 (0.8273) of the regression line.

ANOVA tests returned $p = 0.0157$ for the low frequency data and $p = 0.0020$ for the middle frequency data. Further, the model accounted for 81% of the sums of squares variability for the low frequency data, and 94% for the middle frequency data. There was an effect of inner duct diameter on ANC IL. Although this analysis concluded that the model was a good description of the data and that the inner diameter was important, the more important question was whether the several treatments were different from the open duct (zero cm inner diameter).

Multiple comparison tests of the several treatments indicated that there was no difference in ANC IL performance between the treatments and the untreated "open" duct for the low frequency data. Although the ANOVA revealed there was a statistically significant effect of inner duct diameter on ANC IL, the multiple comparison tests indicated that none of the treatments were statistically significantly different from the outer duct alone. For the middle frequency data, the 0.67 and 0.89 inner ducts (30 cm and 40 cm inner duct diameter) were different (higher ANC IL) from the untreated open duct. These results indicated that for the low frequency region (20–250 Hz), there was no significant advantage to inserting inner ducts for cross-sectional partitioning inside the outer duct. For the middle frequency data, inserting 0.67 or 0.89 (30 or 41 cm diameter) inner ducts resulted in an average 3.7–4.4 dB increase in ANC insertion loss above the outer duct alone.

TABLE II. p-Values and Summary Results from All Studies

		p-Values and IL_{max} Difference (Treatment–1.0 Duct)	
Study	Variable	Low Frequency	Middle Frequency
I	Inner duct diameter	$p = 0.0157$ (no effect)[A]	$p = 0.0020$ (3.7–4.4 dB)
IIa	Simultaneous operation	$p = 0.3749$ (no effect)	$p = 0.0178$ (2 dB)
IIb	Hardware reduction	$p = 0.0146$ (2 dB)	$p = 0.0333$ (1.8 dB)
III	Cross-shaped splitter	$p < 0.0001$ (−5.8 dB)	$p = 0.0003$ (5.6 dB)

[A]No treatments different from outer duct alone.

Study IIa Results

There was no statistical difference between treatments at low frequency. The average IL_{max} ≥315 Hz was 22.4 dB for the 0.67 duct system and 22.2 dB for the outer (46 cm diameter) single-duct system. At middle frequencies, the dual system achieved 2 dB better ANC insertion loss over the outer duct system on average (IL_{max} ≤ 250 Hz of 16.4 and 14.4 dB,

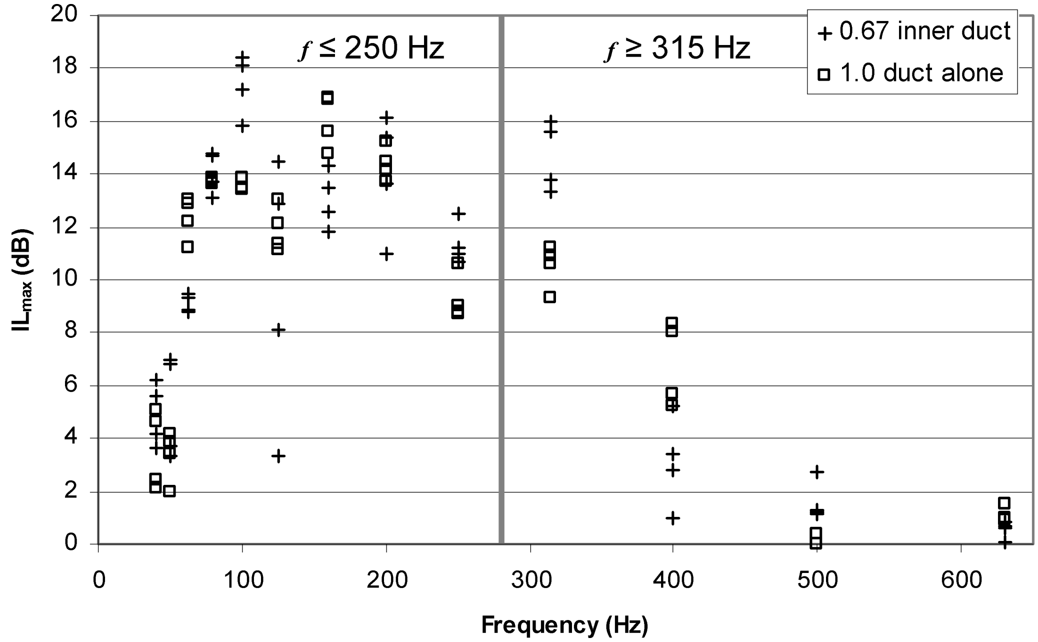

FIGURE 10. Study IIa Results, ANC insertion loss by 1/3 octave bands (dual 0.67 duct full hardware system vs. 1.0 duct single system)

respectively). Whereas that difference was statistically significant, it was not highly substantial. Substantial in this case refers to an IL of at least 3 dB, representing a halving of noise energy. However, when the 1/3 octave band insertion loss values were plotted in Figure 10, there was a substantial (>3 dB) difference between the two treatment groups for certain middle frequency third octave bands. The dual system data points were denoted by "+" signs, and the single system data points were denoted by open squares. The vertical line in the center of the figure marks the division between low and middle frequency for the experiments. The mean difference between the groups at the 315 Hz band is 4 dB. The effect is obscured somewhat from the decibel summation in the IL_{max} result because the single system had a slightly higher average insertion loss at the 400 Hz band. However, the 4 dB difference in means in this narrow range is of practical importance only if that frequency range is prominent in the source to be controlled.

Study IIb Results

Whereas Study IIa suggested some small degree of efficacy for the simultaneously-operated dual-duct system (using another round duct for the cross-sectional partitioning), reducing the hardware of the system components would decrease the cost of the intervention and perhaps make it more appealing as a control option. The only reduced hardware option for the dual-duct system was to use the reference microphone inside the 0.67 (30 cm diameter) inner duct as the reference signal for both duct systems. Each duct (1.0 and 0.67 ducts) had separate ANC controller channels and separate control speaker signals and error microphones. Other than the single reference signal, the two systems were independent but operating simultaneously.

There was a 2-dB difference between treatments at low frequency. The average $IL_{max} \geq 315$ Hz was 22.8 dB for the 0.67 duct system and 20.8 dB for the outer single-duct system. At middle frequencies, the dual system achieved less than 2 dB better ANC insertion loss over the outer duct system on average ($IL_{max} \leq 250$ Hz of 15.7 and 13.9 dB, respectively). The dual system with reduced hardware achieved 1.7 to 2 dB better ANC insertion loss over the single system on average. Although that difference was statistically significant, it was not at all substantial (<3 dB).

Further investigation of the 1/3 octave band insertion loss values (Figure 11) revealed that there was not the substantial difference between the two treatment groups for high-frequency third octave bands that there was for the full hardware dual system in Study IIa. The mean difference between the groups at the 315 Hz band was 2 dB. In effect, the summary middle and low frequency IL_{max} values used in the comparison did not seem to obscure the underlying data. Although the difference in IL_{max} for middle and low frequency between the two treatments was significant, it was not substantial, even at individual 1/3 octave bands.

Study II Noise Reduction Rating Results

To help understand the frequency dependence of the Study II treatments, the ANC IL values for the 1.0 and 0.67 treatments were also interpreted using the Noise Reduction Rating (NRR) algorithm.[21] The NRR calculation accounts for the importance of middle frequency noise to human hearing by comparing C-weighted noise with A-weighted noise after insertion loss for full octaves from 125 to 8000 Hz. This reduces the contribution of low frequency IL in the resultant single number rating of noise reduction. The NRR calculation also accounts for data variability by subtracting two standard deviations from the average IL at each frequency.

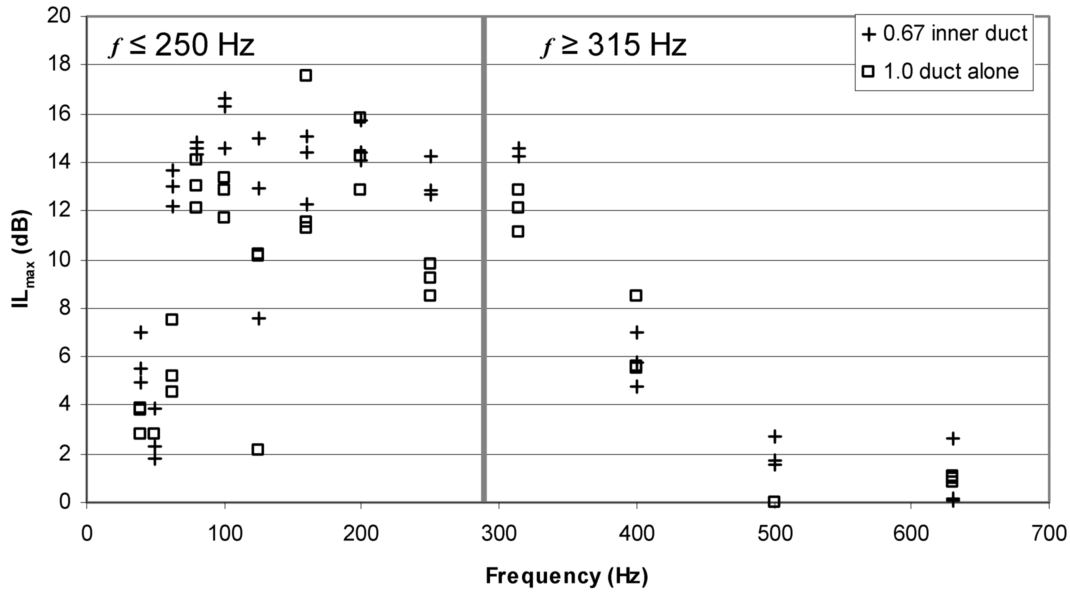

FIGURE 11. Study IIb Results, ANC insertion loss by 1/3 octave bands (dual 0.67 duct reduced hardware system vs. 1.0 duct single system)

Lastly, 3 dB is subtracted from the final value to account for the differences in the assumed pink noise spectrum compared with typical occupational noise spectra. Because the NRR in this study was not dealing with the variability in human personal protective equipment use, and since the ANC application would be used to control a given frequency range (most likely below 1000 Hz), a single standard deviation was subtracted from the average IL, and the 3 dB adjustment for occupational spectra was not subtracted, as a modified NRR_{1-sd}. The values for Studies IIa and IIb are presented in Table III.

When the NRR_{1-sd} calculation was applied to the Study II results, the 1.0 treatment (46 cm diameter duct ANC without axial vane splitters) provided 0.9 dB of IL overall, 3.7 dB of IL at 1000 Hz and below, and about 7 dB of IL at 500 Hz and below. The NRR_{1-sd} values of the 0.67 ducts for both full hardware (IIa) and reduced hardware (IIb) were less than 1 dB different from the 1.0 duct treatments except the Study IIb at and below 500 Hz. In other words, operating the ANC system, regardless of axial vane splitters, provides little reduction in noise unless the spectrum to be controlled is lower frequency. Also, there is no apparent broadband advantage to using axial vane splitters in this configuration (0.67 duct treatments), as opposed to 1.0 duct alone, unless the offending noise spectrum is at or below 500 Hz. The results reveal the frequency-dependence of ANC IL effectiveness. Also, although one treatment may have provided 4 dB better IL than the other at a particular 1/3 octave band, there is little difference between the two treatments when summed across even a narrow range of frequencies.

TABLE III. Noise Reduction Ratings for Study II Treatments

Treatment	NRR_{1-sd} (dB)	NRR_{1-sd} $\leq$ 1 kHz (dB)	NRR_{1-sd} $\leq$500 Hz (dB)
1.0 duct alone Study IIa/IIb	0.9/0.9	3.7/3.7	7.5/7.1
0.67 dual duct Study IIa/IIb	0.8/0.5	3.9/4.5	8.5/9.2

Note: Single standard deviation.

Study III Results

The single quadrant system achieved 5.6 dB higher ANC IL_{max} over the outer duct system on average at middle frequency (IL_{max} $\geq$315 Hz of 22.7 and 17.1 dB, respectively), but 5.8 dB lower ANC IL_{max} at low frequency (IL_{max} $\leq$250 Hz of 16.7 and 22.5 dB, respectively). The difference (in both directions) is both statistically significant and substantial ($>$3 dB). The 1/3 octave band insertion loss values were plotted in Figure 12. The mean difference between the groups at the 630 Hz band was 15.5 dB (17.8 dB for the single quadrant vs. 2.3 dB for the 46-cm duct system). Although some low frequency ANC insertion loss would be sacrificed by the cross-shaped splitter, the increase in high-frequency ANC insertion loss would be quite substantial. Further, the high frequency ANC insertion loss for the single quadrant treatment extended out to 1000 Hz (8.1 dB), which would help fill the frequency gap between passive and active noise control.

Using the same modified noise reduction rating as Study II, the results of Study III reveal slightly better noise control at and below 1000 Hz. The overall (summed octave bands from 125 Hz to 8000 Hz) NRR_{1-sd} for the single quadrant treatment was not much different at 1.8 dB from the Study II 0.67 duct treatments (0.8/0.5 dB). However, the NRR_{1-sd} $\leq$ 1 kHz for Study III was 9.9 dB, and 17.3 dB for NRR_{1-sd} $\leq$ 500 Hz. The single quadrant Study III results for low frequency indicated roughly twice the noise reduction of the 0.67 round duct axial vane splitter method of Studies IIa and IIb. Again,

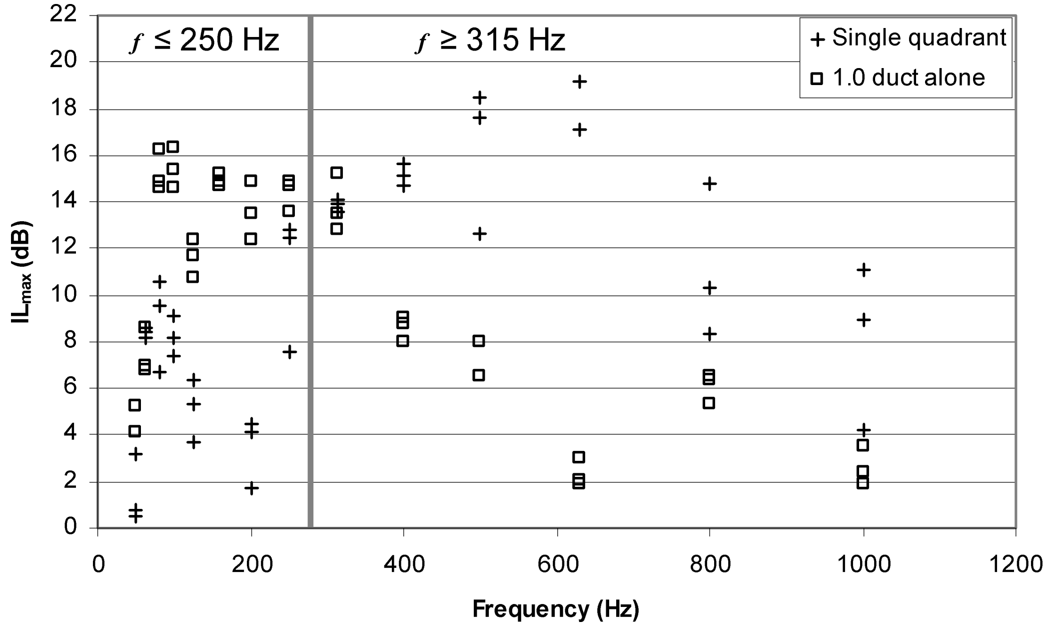

FIGURE 12. Study III Results, ANC insertion loss by 1/3 octave bands (single quadrant system vs. 1.0 duct system)

the frequency spectrum of the offending noise is essential to the viability of an ANC system.

DISCUSSION

All the studies indicated that active control of random broadband noise in ducts can be extended to higher frequencies by using either smaller duct dimensions[16] or cross-sectional partitioning (this article; Studies I, II, and III). The most impressive middle frequency partitioning results came from the cross-shaped splitter (Study III), but there was a trade-off of low frequency ANC insertion loss.

However, while there were good results at certain 1/3 octave bands for different treatments, when considering broadband noise as a whole using the NRR_{1-sd} calculation, the results were less impressive. Across the 125 Hz to 8000 Hz frequency range, the expected ANC noise reduction would amount to less than 2 dB, and there was no advantage to using axial vane splitters over a simple ANC system in the large duct by itself. If the offending noise had a spectrum with significant low frequency peaks to reduce, then ANC might be more useful, providing 3-9 dB of reduction at and below 1000 Hz, and 7-17 dB reduction at and below 500 Hz.

However, since most ANC applications are in exhaust stacks with broadband noise, how useful could these ANC interventions be against the typical application? As an example, the single-quadrant Study III average ANC IL was applied to a broad frequency, high noise level, large diameter vent exhaust noise spectrum. The blade passage frequency peak happened to be at the 250 Hz 1/3 octave band. The vent noise was A-weighted to better represent the effect on neighbors. The A-weighted vent noise and potential resultant noise after Study III ANC IL treatment is displayed in Figure 13. This example reveals the importance of frequency spectrum to potential ANC IL. Although the resultant 6 dB of IL may be significant, the noise spectrum, duct dimensions, and many other factors must be considered before investing in an ANC duct noise solution.

The application of this research to industrial noise control problems would be most useful for environmental noise from exhaust stack situations. (Although the partitioning scheme has also been successfully applied in a laboratory situation to underground coal mining equipment.[22] As discussed in the first part,[16] there would be a concern for increased pressure requirement on the fan to use either a single smaller duct (proportional to the duct diameter ratio raised to the 4.5 power) or many smaller ducts (proportional to the duct diameter ratio raised to the 1.2 power).[11] The axial vane splitter treatments of this article may also be more attractive than using smaller ducts with the same flow. Axial vane splitters would have little effect on air velocity, which would prevent the frequency spectrum shift to higher frequencies from the higher velocities in smaller ducts.

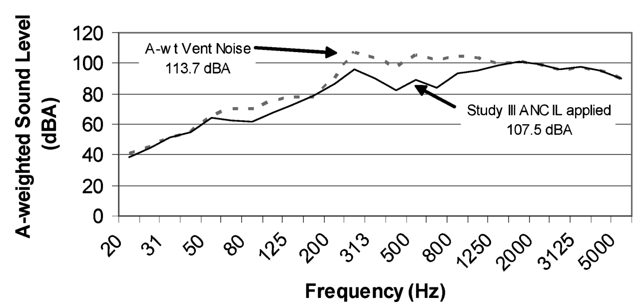

FIGURE 13. Example A-weighted large exhaust vent noise with Study III single quadrant average ANC insertion loss applied

Therefore, the more modest gains of the cross-sectional partitioning methods may be attractive if the noise control problem could be solved with the frequency-specific ANC insertion loss levels reported in this research. It should be noted that when the frequency spectrum is amenable to ANC intervention, ANC actually was highly effective in every test except when it was unstable. The modest differences between ANC IL_{max} in the outer duct alone compared with the partitioning interventions were due to the fact that the ANC on the outer duct worked well in the first place. The outer duct ANC system typically achieved 14 dB IL_{max} at middle frequencies. The partitioning treatments achieved 16 to 23 dB ANC IL_{max}. At lower frequencies, both the outer duct system and the partitioning systems achieved over 20 dB of ANC IL_{max} (except the single quadrant treatment of Study III, which had a low frequency IL_{max} of only 16 dB).

CONCLUSION

The studies presented here showed that potentially useful ANC IL levels can be achieved for duct applications via cross-sectional partitioning. Further research in this vein would be useful on the cross-shaped splitter method of partitioning. While losing some low-frequency control, the impressive insertion loss in the range of 8.1 to 17.8 dB from the particular 1/3 octave band frequencies 315 to 1000 Hz may make that method more attractive for some specific industrial applications, even after applying A-weighting. Also, it would be useful to extend the diameter size study to 61 to 122 cm (24 to 48 inches). One of the limitations of this research was that having a 46 cm (18 inch) duct did not seriously degrade the ANC performance. It would be better to start with a duct sufficiently large such that no ANC insertion loss could be achieved, then attempt partitioning strategies.

Active noise control has long been an area of interest for acousticians and noise control engineers. The hardware limitations and 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 an off-the-shelf ANC system with cross-sectional partitioning can extend the frequency range of control of ANC methods to middle frequencies. Especially for spectra with peaks below 1000 Hz where ANC could provide up to 17 dB of insertion loss (630 Hz 1/3 octave band, Study III), ANC may become more viable as an option for industrial noise control issues.

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