Proceedings of the Institute of Acoustics

INVESTIGATION INTO THE REFLECTION AND RADIATION OF SOUND FROM DUCT OPENINGS

R J Peters, C J McCambridge

NESCOT, Surrey

1. INTRODUCTION

At NESCOT we have started a line of research into the methods used to predict noise from HVAC systems. In particular we have begun to examine the end reflection effect.

At the termination of a duct the acoustic impedance radically alters due to the change from the enclosed environment of the duct to the much larger space of a room. This change causes a proportion of the sound energy to be reflected back down the duct thus reducing the noise emitted from the duct opening. This "end-reflection" effect is related to the wavelength and is greater the smaller the dimension of the duct. So the greatest reflection occurs with small ducts and at low frequencies. This can be a great boon to designers of air ventilation systems as it gives valuable attenuation in a range which is generally difficult to control and would need large passive silencers to make much of a reduction.

2. SUGGESTED END REFLECTION CORRECTIONS

As for other types of natural attenuation the design standards available take account of the end effect by subtracting set amounts, dependent on the width of the duct, from each octave bandwidth. Table 1 shows examples of these reductions using figures for a 150mm round duct from ASHRAE[1] , AMCA[2] , CIBSE[3] and BS878[4]

End Reflection Corrections for 150mm Round Duct (in dB)

	ASHRAE	AMCA	CIBSE	BS878
63	18	18	15	>20
125	12	12.5	11	15
250	8	7.5	7	9.5
500	4	3.5	3	5
1000	1	1	1	1.5

Table 1

As the table shows there is some disparity particularly between the British and the American figures. There is also a difference in the British figures between standards used for the calculation of sound power transmitted into a room and the calculation of fan sound power. This may be accounted for by CIBSE assuming a flanged duct.

Another difference between ASHRAE and CIBSE is the advice given as to when these corrections should be applied. ASHRAE recommends their application only when the duct is of length greater than 3 to 5 times its cross-sectional dimension and recommend that if a diffuser is used the correction should be reduced by 6dB - virtually eliminating the end-reflection effect for most duct dimensions.

CIBSE's advice is to halve the attenuation values if a grille or diffuser is used and immediately proceeded by a bend although the actual distance is not defined.

3. PREVIOUS RESEARCH

We have attempted to find the source of this data. From a review of the ASHRAE prediction methods by Reynolds and Bledsoe[5] it was found that both the American sets of figures were based on work by Sandbakken[6] in 1983. This work was conducted using round ducts of length 2.6m. Both kinetic and static end reflection "loss" were measured.

Although not credited, BS878's figures would seem to be based on Levine and Schwinger's theoretical paper[7] investigating the radiation of sound from a pipe termination. From their equation for the reflection coefficient of an open, unflanged pipe the end reflection loss in decibels could be taken as:

$$ER = 10\log(1-r^2) \qquad (1)$$

Where ER: End Reflection loss
r: Amplitude Reflection Coefficient

Figure 1 shows Levine and Schwinger's curve for the reflection coefficient of a round duct of 150mm diameter. Also shown on the graph is the corresponding end reflection.

The CIBSE Guide does not give any information about the sources on which their prediction methods are based.

Reynolds and Bledsoe's paper commented that there is very little experimental data of end reflection effects apart from the Sandbakken paper. They felt that his empirically derived results would presumably be applicable to ducts terminated with a diffuser of low aspect ratio (length/width) but that it is not known whether they are accurate for, say, slot diffusers which have high aspect ratios. They also remarked on the lack of data relating to short duct sections which are commonly used before a termination into a room.

It would seem that further research into end reflection is justified especially on the effect of:

- the use of grilles and diffusers
- large aspect ratios
- duct length
- flow conditions

4 MEASUREMENT OF THE REFLECTION COEFFICIENT

4.1 Methodology

The simplest method to investigate the end reflection effect is to measure the reflection coefficient and then convert into a decibel reduction using equation (1). The traditional method to find this is using the standing wave ratio. A pure tone is used and the duct is traversed by a travelling microphone which locates the pressure maximums and minimums along the standing wave. Although accurate, the technique is time-consuming and the size of duct that can be investigated is limited as a minimum length is needed, depending on the phase angle, of between half a wavelength and a wavelength .

More recently developed techniques use two fixed, wall-mounted, microphones.[8,9] Chung and Blaser's method measures the transfer function between the two positions and from this the reflection coefficient can be calculated. This has the advantage that (i) a shorter length of duct can be tested and (ii) a broad band signal can be used which decreases the time taken considerably. This technique is now the standard method for measuring reflection coefficients and impedance with Brüel and Kjær equipment[10]

One of the problems associated with the two-microphone technique is that the spacing of the microphones becomes critical at certain frequencies. Chu[11] remarks that errors associated with the method are greatest when the spacing is half a wavelength and accuracy can be maximised by keeping the spacing to a quarter of a wavelength. The one-microphone technique takes advantage of this and simplifies the equipment that is needed. Both Chu and Fahy[12] developed methods using only one microphone, in each case a constant reference signal is used with respect to which the transfer function is found sequentially at each point. The calculations are then identical to Chung and Blaser's.

4.2. Comparing Methodologies

Our preliminary experiments were comparisons of the different methods of measuring the reflection coefficient. In order to measure a large reflection effect, a small duct was used (100mm by 100mm) constructed from melamine-faced chip board, 12mm thick that was stiff enough to minimalize absorption and duct breakout. It was of length 2m. A loudspeaker from the Brüel and Kjær standing wave kit type 4002 was used as a noise source.

The standing wave ratio method results are shown in Figure 2. The greatest diversion from theory occurs at the lower frequency range when the reflection coefficient is expected to tend to unity. This may have been because the true standing wave ratio was higher than the signal-to-noise ratio.

The two and one microphone transfer function methods require a dual-channel FFT to measure the magnitude and phase of the required function. The results from these experiments are compared along side Levine and Schwinger's theoretical reflection coefficients in Figure 3. Pure tones were used in the one microphone experiment so the results are shown in third octaves for the sake of comparison, although as the two-microphone method uses broad band noise results are found aright across the frequency range investigated. Figure 4 gives the data in the form of differences between the experimental results and the theoretical reflection coefficient. This shows that the two microphone technique has a lower error at least below 1000Hz. This may be because the fixed microphone spacing can be measured more accurately than the distance moved by the travelling microphone. Due to this and also the methods greater speed, the two microphone technique has been used in subsequent experiments.

4.3 Initial Investigations

The reflection coefficient of ducts of various lengths have been investigated. The ducts compared were 0.1m, 0.2m, 0.5m, 1m, and 2m and made, as before, of stiff, smooth-faced chipboard. Figure 5 shows that the results are close and no relationship between length and reflection coefficient could be made. If these were converted to decibel reductions even very short lengths of duct could apparently give sizeable reductions in power radiated as Figure 6 shows. This would seem to argue against ASHRAE's case that end reflection reduction should not be applied to ducts shorter that 3 to 5 duct diameters.

5. THE REFLECTED ENERGY

The main problem of the above method is that only the reflection coefficient is measured rather than the true end reflection "loss". This could be defined as the difference between the in-duct power and the radiated power. Calculating the loss directly from the reflection coefficient does not tackle the rather crucial question of what happens to the reflected energy. It assumes that it is all carried back down the duct and has no influence on any other part of the system. However, the conditions opposite the duct opening must dictate what occurs to this energy and so effect the total energy radiation from the termination. Compare the cases of a silencer or a bend just preceding the outlet as shown in Figure 7.

In (b) the silencer may absorb much of the reflected energy and so the system acts almost as the infinitely long duct (a). However, for condition (c) much of the energy reflected at the outlet will be reflected again at the bend back towards the outlet and a proportion of this will be radiated from the duct opening. In the extreme case the end reflection effect could be seen as only a way of increasing the effective length of the duct and so increase absorption as the energy bounces from one side to another.

5.1 Measuring The End Reflection Effect Directly

To directly measure the end reflection loss a comparison must be made between the sound power in the duct approaching the termination, ie the power that would have been radiated if no end reflection occurred, and the power that is radiated. This is not so simple to measure as one might think. The reflected energy produces standing waves which complicates the measurement of in-duct sound power. Sandbakken resolved this problem by using an anechoic termination to measure sound power level in the duct but there is a further complication that arises. The use of such a termination will alter the acoustic load presented to the loudspeaker or fan and so change its output. Indeed, even varying the length of the duct could change the power output. We are currently working on this problem and the viability of methods monitoring the voltage and current across the loudspeaker/fan or using a high impedance source.

Another possible, if not highly feasible, method would be to use a horn of such proportions that the change in impedance from duct to the outside environment is gradual enough to eliminate end reflections. We have had some success in at least reducing the reflection at particular frequencies. Figure 8 shows the reflected pure tone in a 100mm x 100mm duct with and without a horn (0.5m in length and of outlet dimension 350mm x 350mm) on the outlet. However, to work satisfactorily the size of the horn would have to be impractically large.

5.2 Implications For Other Parts Of The Systems

Exisiting prediction methods simply aggregate various components of system attenuation without considering any interaction between them. The models of energy distribution assume the sound pressure level along a duct lenth reduces at a constant steady rate due to attenuation mechanisms. If, however, end reflections occur, as Figure 8 shows, the standing waved produced will result in a very non-uniform distribution of sound pressure level and will affect, for example calculation of duct breakout and duct attenuation.

6. DISCUSSION

The cost of noise control can be great in terms of both money and energy so design practices should exploit to the full the natural attenuation of duct systems to which end reflections can make a major contribution. It would seem to be of great importance, therefore, that the effect's wider implications are better understood. The actual reduction in sound power radiated due to reflection at the termination of a duct will depend on more than merely the duct dimensions. The length of the straight section before the termination and its acoustic properties are also of relevance as well as the conditions at the outlet, ie whether a diffuser is used and its type of configuration.

There are many gaps in the published research on end reflection and, we think, a need for a greater appreciation of its effects.

7. REFERENCES

1 HVAC Handbook (1987), American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Chapter 52: Sound and Vibration Control.

2 Air Movement and Control Association (1985), Standard 300-85, Reverberant Room Method for Sound Testing of Fans

3 Chartered Institution of Building Services Engineers. (1973) Design Guide, Section B12: Sound Control.

4 BS 848: Part 2, (1985), Fans for general purposes, Methods of Noise Testing.

5 D. D. Reynolds, J. M. Bledsoe, (1991) Algorithms for HVAC Acoustics. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Research Project 556-RP.

6 M. Sandbakken, L. Pandy, M. J. Crocker, (1983), The effecot of slow end orifice plates on the determination of end-duct fan sound power from reverberant room measurements, ASHRAE Technical paper, no. 2172.

7 H. Levine, J. Schwinger, (1948), On the Radiation of Sound From an Unflanged Circular Pipe. Physics Review , pp 383-406.

8 A. F. Seybert, D. F. Ross, (1977), Experimental determination of acoustic properties using a two-microphone random-excitation technique, Journal of the Acoustical Society of America, 61(5), pp 1362-1370.

9 J. Y. Chung, D. A. Blaser, (1980), Transfer function method of measuring in-duct acoustic properties, I Theory, II Experimental, Journal of the Acoustical Society of America, 68(3), pp 907-921.

10 Brüel and Kjær, Two-microphone Impedance Measurement Tube, Type 4206

11 W. T. Chu, (1986) Transfer function technique for impedance and absorption measurements in an impedance tube using a single microphone, Journal of the Acoustical Society of America, 80(2), pp 555-560.

12 F. J. Fahy, (1984) Rapid method for the measurement of sample acoustic impedance in a standard wave tube, Journal of Sound and Vibration, 97(1), pp 168-170

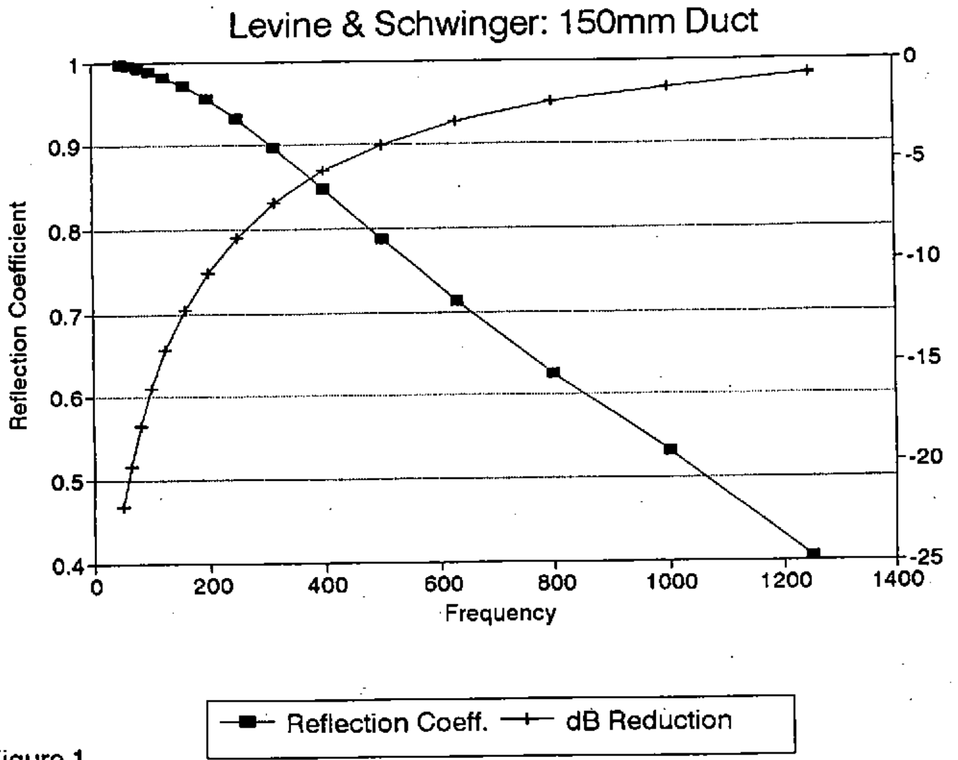

Levine & Schwinger: 150mm Duct
Reflection Coefficient
1
0.9
0.8
0.7
0.6
0.5
0.4
dB Reduction
0
-5
-10
-15
-20
-25
0
200
400
600
800
1000
1200
1400
Frequency
Reflection Coeff.
dB Reduction

Figure 1

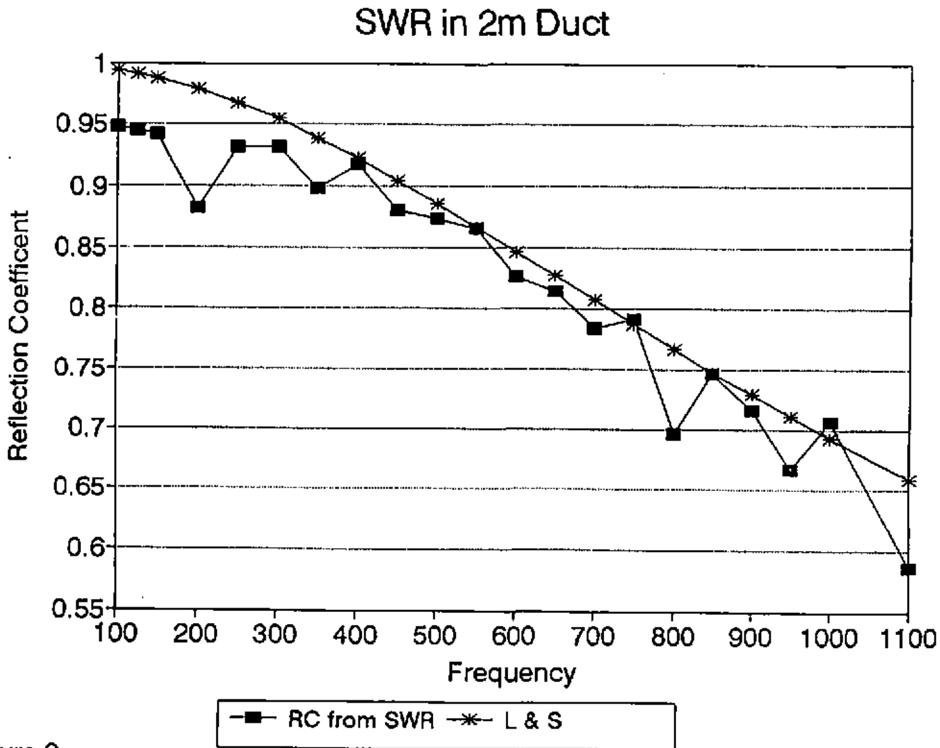

SWR in 2m Duct
Reflection Coefficent
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
100
200
300
400
500
600
700
800
900
1000
1100
Frequency
RC from SWR
L & S

Figure 2

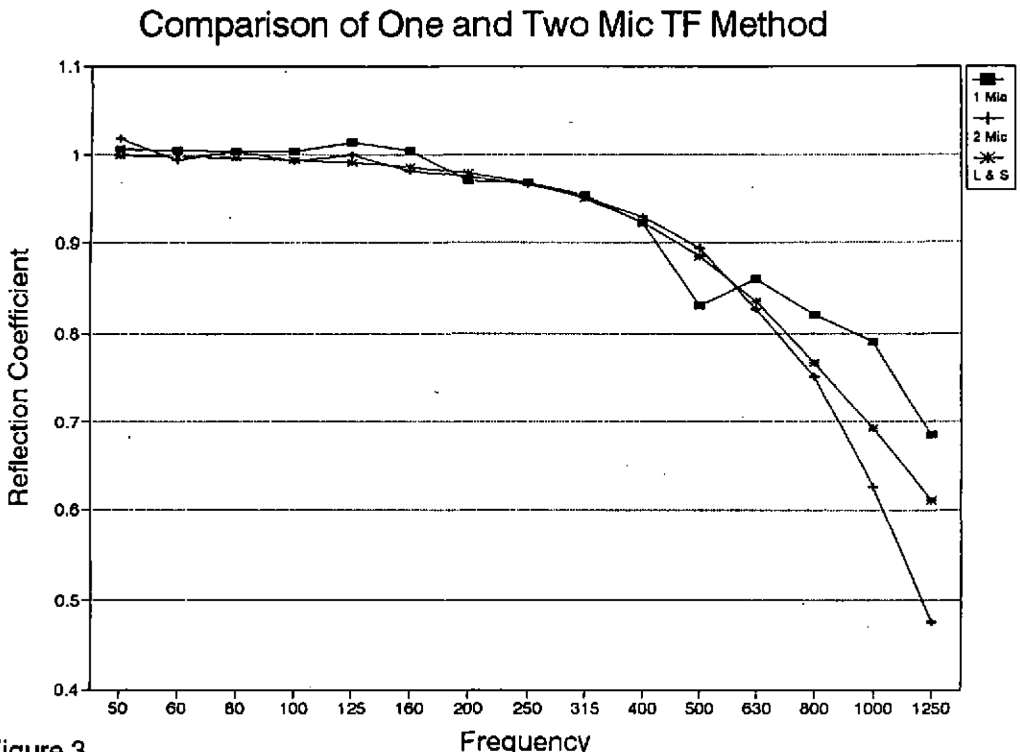

Comparison of One and Two Mic TF Method
Reflection Coefficient
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
50
60
80
100
125
160
200
250
315
400
500
630
800
1000
1250
Frequency
1 Mic
2 Mic
L & S

Figure 3

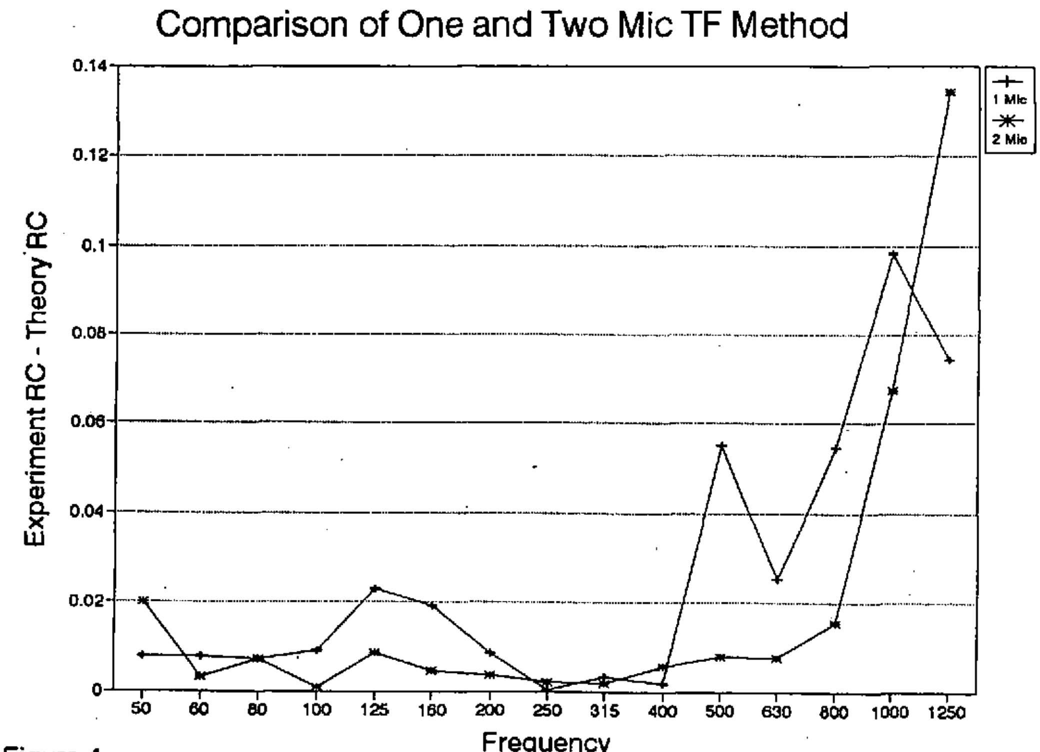
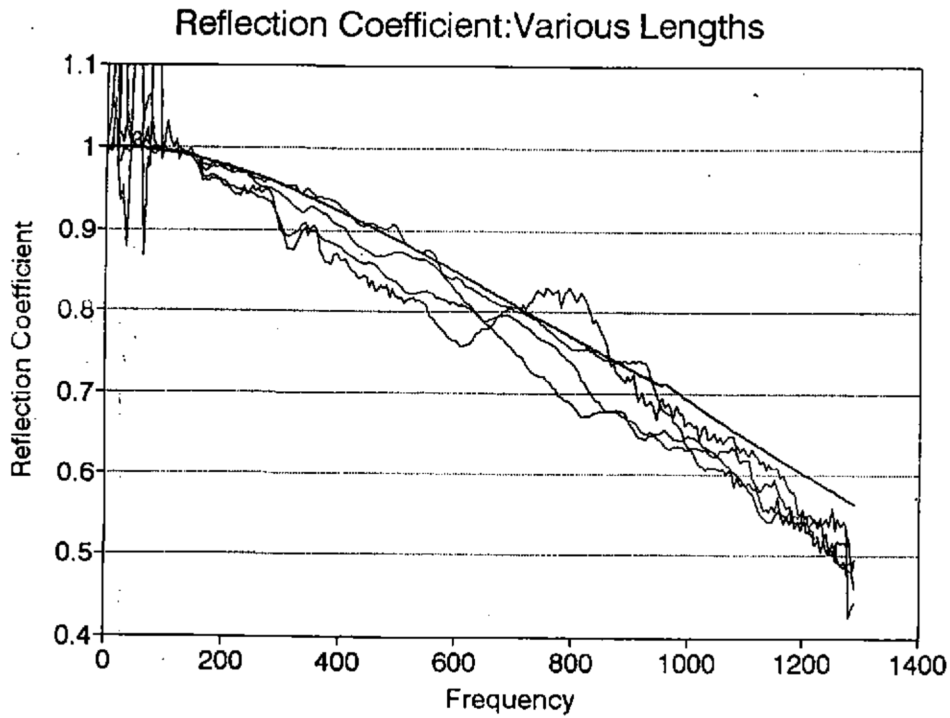

Comparison of One and Two Mic TF Method
Experiment RC - Theory RC
Frequency
1 Mic
2 Mic
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
50
60
80
100
125
160
200
250
315
400
500
630
800
1000
1250

Figure 4



Reflection Coefficient:Various Lengths
Reflection Coefficient
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
200
400
600
800
1000
1200
1400
Frequency

Figure 5

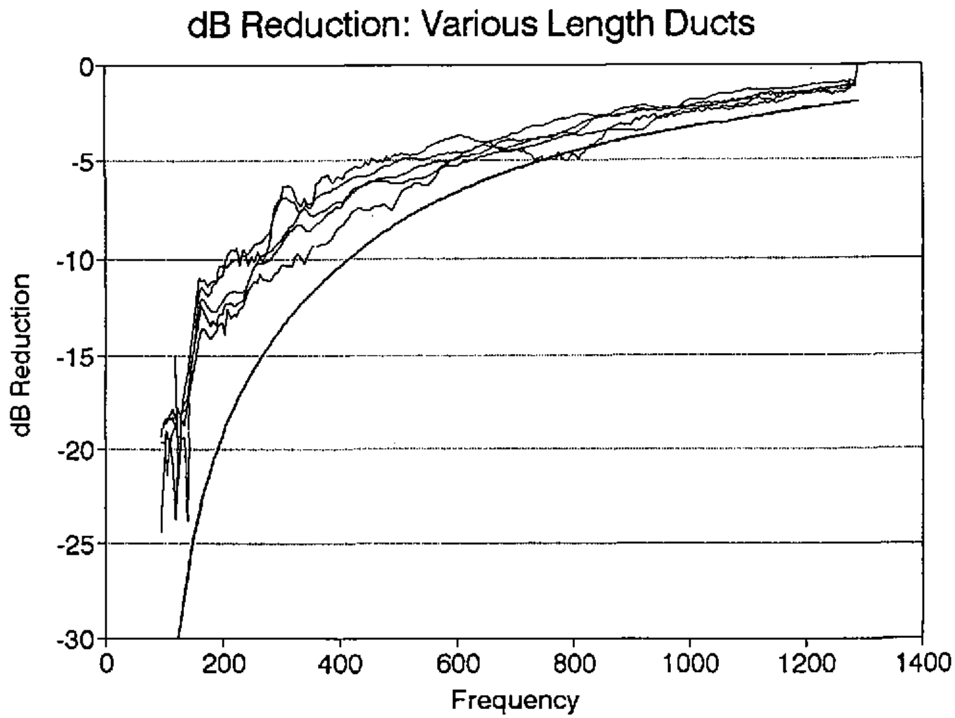

dB Reduction: Various Length Ducts
0
-5
-10
-15
-20
-25
-30
dB Reduction
0
200
400
600
800
1000
1200
1400
Frequency

Figure 6

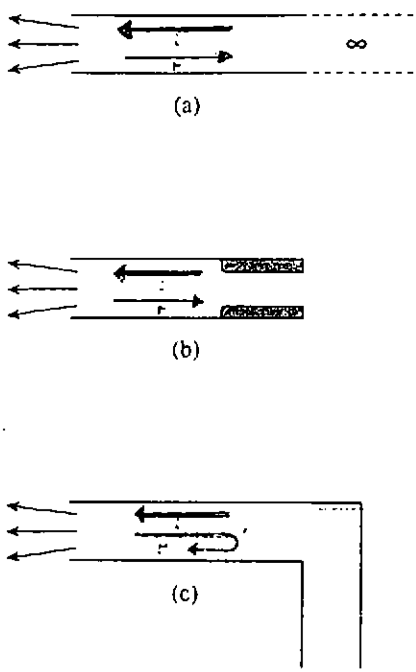


Figure 7

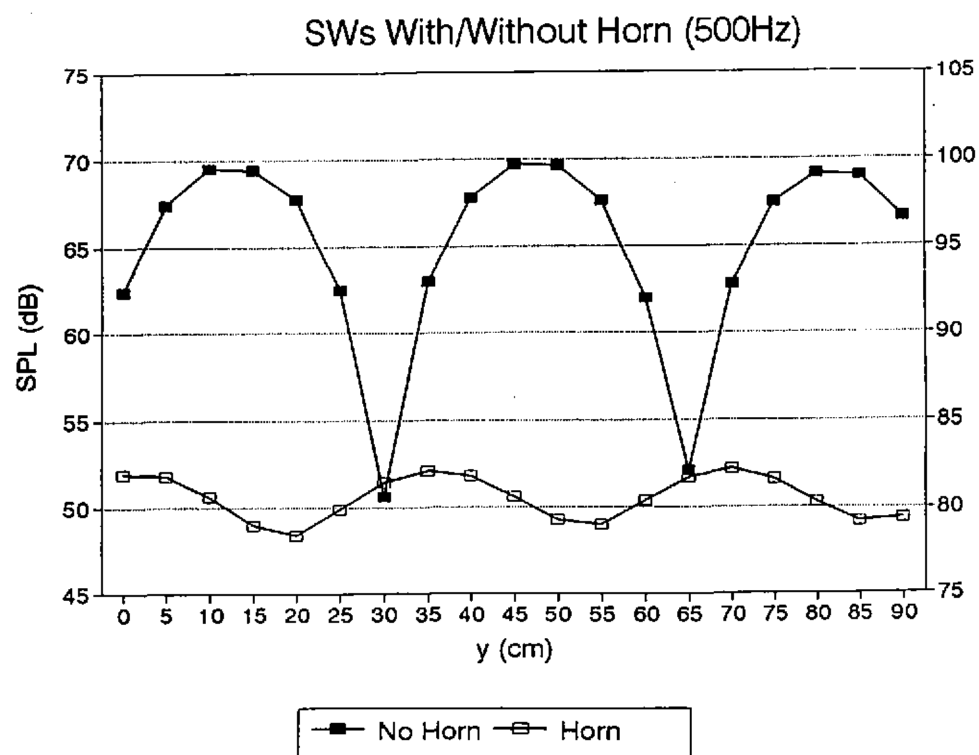

SWs With/Without Horn (500Hz)
SPL (dB)
75
70
65
60
55
50
45
105
100
95
90
85
80
75
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
y (cm)
No Horn
Horn

Figure 8