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Mechanical Duct Designs to Provide Speech Privacy

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Mechanical Duct Designs to Provide Speech Privacy
Part 3: Design and Evaluation Procedure

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1. Introduction

This report presents a design procedure to predict speech privacy between two rooms when sound is transmitted via an air-handling duct system.

Extensive experiments were required to establish the basis for this design procedure. The measurements have clearly established the factors relevant for sound transmission along a duct between two rooms comparable to private offices, and it is believed the results can reasonably be extrapolated to larger rooms. The experimental studies were presented in two preceding reports.

The first report (CR-5763.1) presented a study of sound transmission through a duct system installed between two reverberation rooms. This laboratory setup provided an ideal environment for accurate comparison of sound transmission with different duct treatments. However, these results must be related to the performance of a duct system between typical rooms.

The second report (CR-5763.2) examined the effect of room characteristics and of source and receiver position in those rooms, using a two-room facility to simulate a pair of adjacent offices. A simple duct system was installed with outlets to both rooms, and the sound transmission via the duct was measured with room conditions representative of the range of acoustical conditions likely in typical offices.

This third report presents a step-by-step design procedure based on the results of the experimental studies and published data from other sources. This problem has three main aspects, each of which is presented in one section of this report:

- How much sound power enters the duct from a typical person speaking in the source room?
- How much of that sound power is transmitted through the duct system?
- How does intelligibility of the sound reaching the receiving room depend on receiver location and room characteristics?

Report Layout

The presentation in the report was structured in an unusual form, to facilitate its use as a reference for actually performing the necessary calculations to predict the speech intelligibility for a given case.

Each page presents one step of the calculation method. The page is set up with three main parts:

1) The first part presents any general information needed to explain the concept involved.
2) The calculation instruction is presented (in italic print).
3) In most cases, the instruction is followed by a table of values needed to carry out the procedure.

After the final step, a summary section discusses the basis of the evaluation proceedure and its relation to other work, and identifies sources for additional information and more detailed evaluation methods.

The report finishes with an appendix containing worked examples and a worksheet form.

2. The Source Room

The preceding experimental studies established that the sound power entering the duct depends on a number of factors. The key issues are:

- loudness of speech,
- position and orientation of the speaker,
- sound reflection from room surfaces, and
- the duct opening(s).

The effect of these variables are inter-related, but the following steps provide a simple method for estimating their combined effects.

2.1 Typical Speech Sound Levels

Although there is some variation among individuals, the loudness of most people's speech falls within a rather small range. The loudness may be roughly characterized in terms of "normal voice effort" (which would be used in normal conversation in a quiet environment) or "raised voice effort". The latter is common in speaking to a large group or in heated discussion.

Typical peak speech levels are presented in Table 2.1. These are octave band equivalents of the standard speech spectra in ASTM standard E1130-88.

Step 1: Select the initial speech levels from Table 2.1. The use of the "raised voice" levels is strongly recommended, to provide a reasonable margin of safety in estimating speech privacy.

Speech Effort	Octave Band Frequency, Hz 250	500	1 k	2 k	4 k
Normal Voice	67	70	63	59	55
Raised Voice	71	76	71	66	61

Table 2.1: Peak speech levels at 1 m, for typical males.

2.2 The Source Room

The sound energy entering the duct includes both the sound energy going directly from the speaker to the duct inlet, and also sound reflected from nearby room surfaces. Reflections arriving within about 80 ms contribute to intelligibility, which means that reflected sound travelling up to 25 m farther than the direct sound tends to make speech clearer. For small rooms, this would include reflections from most surfaces. For office-sized rooms, the effect can be conservatively estimated by including all reflections.

The strength of reflections depends on the sound absorption characteristic of all room surfaces. Table 2.2 can be used to estimate the absorption.

Step 2: Determine total absorption of room surfaces and furnishings by multiplying the room's floor area (in m²) by the appropriate absorption factors given in Table 2.2. These values are needed in Step 3.

Room Type	Octave Band Frequency, Hz				
	250	500	1 k	2 k	4 k
Dead (has acoustical ceiling, plush carpet upholstered furniture)	1.0	1.2	1.3	1.4	1.5
Medium Dead (acoustical ceiling, commercial carpet, hard furniture)	0.5	0.7	0.9	1.1	1.2
Average (has acoustical ceiling or commercial carpet, hard furniture)	0.5	0.6	0.7	0.8	0.9
Medium Live (hard room finishes, some carpet or soft furniture)	0.5	0.5	0.5	0.6	0.7
Very Live (tile and/or concrete surfaces with sparse furniture)	0.4	0.3	0.3	0.3	0.4

Table 2.2: Absorption factor for typical room categories.

2.3 Sound Pressure at Duct Entry

The room absorption calculated in Step 2 is one factor that determines the combined strength of direct and reflected sound pressure at the duct entry.

The location and orientation of the speaker are also important. The direct sound becomes stronger if the speaker moves closer to the duct inlet. The sound levels in the high-frequency bands become stronger if the speaker faces toward the duct inlet. The values in Table 2.3 apply to the rather conservative case where the speaker is facing horizontally in the general direction of the duct opening and at least 1 m from the opening. (In the absurd case of speaking directly into the duct opening, speech privacy would be less than that predicted using Table 2.3.)

Step 3: For each frequency band, add the correction in dB given in Table 2.3, to allow for room absorption and expected location of the speaker. Use absorption values closest to those determined in Step 2.

Expected Speaker Location	Room Absorption (m sabins)	Octave Band Frequency, Hz				
		250	500	1 k	2 k	4 k
Near duct opening (within 2 m)	5	8	8	7	6	5
	6	6	6	6	5	4
	8	5	5	5	4	3
	10	4	4	4	3	2
	12	3	3	3	2	1
	16	2	2	2	1	0
	20	1	1	1	0	-1
	25	0	0	0	-1	-2
Distant from duct opening (over 2 m)	5	7	7	6	5	4
	6	6	6	5	4	3
	8	5	5	4	3	2
	10	3	3	3	2	1
	12	2	2	2	1	0
	16	0	0	1	0	-1
	20	-1	-1	-1	-1	-2
	25	-2	-2	-2	-2	-3

Table 2.3: Correction (in dB) for expected speaker location and absorption by room surfaces and furnishings.

2.4 Sound Power Entering Duct

The sound power entering the duct system depends on the total open area of the duct inlet(s) or diffuser(s).

For multiple diffusers with similar connections to the duct system, simply adding the areas of the diffusers is acceptable. If there are several different duct systems connecting the source and receiving rooms, the calculation should be performed separately for each system.

The sound power entering the duct is lower than the effective sound pressure level in the room (determined at step 3) by 6 dB - 10.log(A), where A is the open area in m^2. Values of this correction are presented in Table 2.4 for the expected range of area.

Step 4: For each frequency band, subtract the correction in dB given in Table 2.4, to allow for total open area (in m^2) of duct openings in the source room. Note that this correction is the same for all bands.

Duct Inlet Area in m^2	Octave Band Frequency, Hz 250	500	1 k	2 k	4 k
0.05	19	19	19	19	19
0.06	18	18	18	18	18
0.08	17	17	17	17	17
0.10	16	16	16	16	16
0.13	15	15	15	15	15
0.16	14	14	14	14	14
0.20	13	13	13	13	13
0.25	12	12	12	12	12
0.32	11	11	11	11	11
0.40	10	10	10	10	10
0.50	9	9	9	9	9
0.63	8	8	8	8	8
0.80	7	7	7	7	7
1.00	6	6	6	6	6

Table 2.4: Correction (in dB) for total open area (in m^2) of duct inlets or diffusers in the source room. These values should be subtracted from result of Step 3.

3. Duct Transmission

There are a number of empirical design procedures for calculating sound transmission through a duct system. By far the most widely used is the method in the ASHRAE Systems and Applications Handbook, but many textbooks have similar methods. Unfortunately, the details of these models differ appreciably, and experimental studies to validate the models are incomplete and far from consistent.

To ameliorate this problem, ASHRAE Technical Committee 2.6 recently commissioned studies to assemble and evaluate the available technical data, to provide the basis for more reliable evaluation of sound transmission. The results were published in May 1991 in the ASHRAE book "Algorithms for HVAC Acoustics". Given the extensive literature survey and data synthesis on which the algorithms are based, and the review of this material by the ASHRAE Technical Committee, this is clearly the most authoritative data source currently available.

A subset of the algorithms and tables in "Algorithms for HVAC Acoustics" has been used as the basis for the procedure presented in this chapter. Low-frequency data and aspects not pertinent to the problem of speech privacy were omitted. The data were converted to a consistent tabular form to simplify use by a non-technical audience.

For those interested in more detail, the references include computer programs, analytical expressions, and data pertinent to other duct noise issues.

Note 1: Most duct systems include several elements between the rooms occupied by the speaker and potential listener, and the transmitted sound will be reduced slightly by each. The correction for each duct element should be determined separately (Steps 5 - 12), and subtracted from the levels obtained at Step 4.

Note 2: If sound power can be transmitted along several paths between the rooms of interest, each duct path must be evaluated separately, and the results must be combined at Step 13, to calculate the sound pressure in the receiving room.

3.1 Unlined Straight Duct

Straight unlined ducts provide a small amount of sound attenuation, mainly at low frequencies. The sound attenuation depends on the size of the duct, and also on its shape (round vs rectangular cross-section).

Table 3.1 gives attenuation per unit length for ducts whose sheet metal thickness conforms to normal practice for HVAC duct construction. These values apply to ducts *without* internal absorptive lining.

Step 5: For each section of unlined straight duct, subtract the product of the length in metres of that duct section, multiplied by the correction in dB given in Table 3.1 for each frequency band.

Duct Shape	Duct Size in mm	Octave Band Frequency, Hz 250	500	1 k	2 k	4 k
Rectangular Duct	150 x 150	.33	.33	.33	.33	.33
	300 x 300	.33	.22	.22	.22	.22
	300 x 600	.33	.16	.16	.16	.16
	600 x 600	.33	.10	.10	.10	.10
	1200 x 1200	.22	.07	.07	.07	.07
	1800 x 1800	.16	.07	.07	.07	.07
Circular Duct	(Diameter)					
	150	.16	.16	.33	.33	.33
	250	.10	.16	.22	.22	.22
	500	.07	.10	.16	.16	.16
	750	.06	.09	.13	.13	.13
	1000	.05	.08	.10	.10	.10
	1500	.03	.07	.07	.07	.07

Table 3.1: Reduction in sound level along a section of unlined straight duct, in dB per metre of duct length.

3.2 Straight Duct with Absorptive Lining

Internal duct lining is commonly added to reduce transmitted sound. The most common material is glass fiber with a special surface. For effective sound control, the lining thickness should be at least 25 mm.

The values listed in Table 3.2 are appropriate for duct sections several times longer than the duct width. Because of structure-borne sound, the total attenuation along a lined sheet metal duct will not usually exceed 40 dB.

Dependence on lining thickness and duct cross-section dimension varies slightly with shape of the duct.

Step 6: For each section of lined straight duct, subtract the product of the length in metres of that duct section, multiplied by the correction in dB given in Table 3.2 for each frequency band. The maximum correction at this step is 40 dB.

Duct Shape	Duct Size in mm	Octave Band Frequency, Hz 250	500	1 k	2 k	4 k
Rectangular Duct	150 x 150	5.0	9.5	24.8	24.3	12.8
	300 x 300	2.8	6.7	15.3	14.0	9.4
	300 x 600	2.2	5.8	12.5	11.1	8.2
	600 x 600	1.6	4.7	9.5	8.0	6.8
	1200 x 1200	0.9	3.3	5.8	4.6	5.0
	1800 x 1800	0.7	2.8	4.6	3.5	4.3
Circular Duct	(Diameter)					
	150	3.1	5.1	7.2	7.6	6.8
	250	2.8	4.9	7.3	6.8	5.5
	500	2.2	4.4	6.4	4.8	3.3
	750	1.5	3.9	4.5	3.2	2.3
	1000	1.0	3.1	2.4	1.9	1.9
	1500	0.3	0.4	0.3	0.5	0.4

Table 3.2: Reduction in sound level along a section of lined straight duct, in dB per metre of duct length.

3.3 Unlined Elbows

Where a duct changes direction, only part of the sound energy goes around the bend. The attenuation depends on both the shape of the bend and the duct size, especially for low frequencies and small duct cross-section.

As evident from comparison of the data for three elbow shape categories in Table 3.3, less sound reduction is provided by a smoother and more gradual bend.

Step 7: For each unlined elbow, subtract the correction in dB given in Table 3.3 for each frequency band.

Bend Shape	Duct Width in mm	Octave Band Frequency, Hz				
		250	500	1 k	2 k	4 k
Plain Square Elbow	150	0	1	5	8	4
	350	1	5	8	5	3
	700	5	8	4	3	3
	1000	8	4	3	3	3
Square Elbow with Turning Vanes	150	0	1	4	6	4
	350	1	4	6	4	3
	700	4	6	4	3	3
	1000	6	4	3	3	3
Round Elbow	150	0	1	2	3	3
	350	1	2	3	3	3
	700	2	3	3	3	3
	1000	3	3	3	3	3

Table 3.3: Reduction of transmitted sound level, in dB, for unlined duct elbows.

Step 7: Unlined elbow

3.4 Lined Elbows

Typically, a lined elbow will occur between lined straight sections. The values listed here are appropriate for that situation.

The added attenuation due to absorptive lining of a bend in the duct depends on the shape of the bend or elbow. Note that the *additional* attenuation due to absorptive lining is given by the *difference* between values in Table 3.3 and Table 3.4. In general, the change due to an absorptive lining is greatest for a square elbow without turning vanes, and negligible for a round or radiused elbow.

Step 8: For each lined elbow, subtract the correction in dB given in Table 3.4 for each frequency band. Unless the lining extends along the duct for at least two duct widths from the bend, use the (smaller) correction for an unlined bend.

Bend Shape	Duct Width in mm	Octave Band Frequency, Hz 250	500	1 k	2 k	4 k
Plain Square Elbow	150	0	1	6	11	10
	350	1	6	11	10	10
	700	6	11	10	10	10
	1000	11	10	10	10	10
Square Elbow with Turning Vanes	150	0	1	4	7	7
	350	1	4	7	7	7
	700	4	7	7	7	7
	1000	7	7	7	7	7
Round Elbow	150	0	1	2	3	3
	350	1	2	3	3	3
	700	2	3	3	3	3
	1000	3	3	3	3	3

Table 3.4: Reduction of transmitted sound level, in dB, for lined duct elbows.

Step 8: Lined elbow

3.5 Branches

Sound travelling along a duct system is distributed between the branches encountered at a junction.

At low frequencies, reflection back along the original duct is significant, but for speech frequencies (250 Hz band and higher) almost all sound is transmitted into the other branches. The sound power is divided between the branches in proportion to branch cross-section area. To calculate the sound power transferred into a specific branch of the duct system, one must know its cross-section and the combined cross-section of all the ducts leading from the junction.

Step 9: For the specific branch of interest, subtract the correction in dB given in Table 3.5 for the case closest to the area of the branch as a percentage of combined area of all branches leading from the junction. Note the correction is the same for all frequency bands.

Duct Area, % of combined branch areas	Octave Band Frequency, Hz				
	250	500	1 k	2 k	4 k
5 %	13	13	13	13	13
6 %	12	12	12	12	12
8 %	11	11	11	11	11
10 %	10	10	10	10	10
13 %	9	9	9	9	9
16 %	8	8	8	8	8
20 %	7	7	7	7	7
25 %	6	6	6	6	6
31 %	5	5	5	5	5
40 %	4	4	4	4	4
50 %	3	3	3	3	3
63 %	2	2	2	2	2
80 %	1	1	1	1	1
100 %	0	0	0	0	0

Table 3.5: Correction, in dB, for area of duct branch as a percentage of total area of all branches leading from this junction.

Step 9: Duct branch

3.6 Silencers

Factory-produced duct silencers are often used to attenuate unwanted sound in HVAC duct systems. The attenuation is highly dependent on manufacturer's design, but also depends on silencer location in the duct system.

It is not practical to present data for a complete range of silencers, but their performance is commonly determined by standard laboratory testing (in accordance with ASTM standard E477) and presented as part of the manufacturer's literature.

Unfortunately, the standard test method verifies attenuation in the optimum situation, with the silencer installed in a long straight duct. Measurements presented previously (in report CR5763-1) demonstrated attenuation substantially lower than the rated performance when the silencer was adjacent to a bend or other discontinuity. Estimates of the reduced effectiveness in realistic installation situations are presented in Table 3.6.

Step 10: For each commercial duct silencer, multiply the manufacturer's rated attenuation in each frequency band by the appropriate factor from Table 3.6, and subtract the product from the result obtained in Step 9.

Silencer Location	Octave Band Frequency, Hz				
	250	500	1 k	2 k	4 k
Long straight duct (3 or more duct diameters from discontinuity)	1.0	1.0	1.0	1.0	1.0
Near discontinuity (within 3 duct diameters)	1.0	0.9	0.7	0.8	0.9
Adjacent to another silencer or lined duct (within 1 duct diameter)	0.9	0.7	0.5	0.5	0.7

Table 3.6: Factor by which manufacturer's rating of silencer attenuation should be multiplied to obtain estimated performance in typical installation. "Discontinuity" in the duct system means a bend, a branch, or other deviation from straight unlined duct.

Step 10: Commercial silencer

3.7 Duct Outlet / Diffuser

When sound waves transmitted along a duct reach the outlet or diffuser discharging the air into the (much larger) room, some of the sound energy is reflected back along the duct.

More reflection occurs for small diffuser areas than for large ones. For the lower speech frequencies this effect can be significant, but the effect tends to be small at high frequencies.

Diffusers can vary widely in shape (from circular to narrow slots), but no data are available on the effect of diffuser shape on the end reflection. The values presented in Table 3.7 were calculated using the new ASHRAE algorithm which was based on available data.

Step 11: Subtract the corrections in dB given in Table 3.7 for each frequency band from the result obtained in Step 10.

Duct Outlet Area	Octave Band Frequency, Hz				
in m^2	250	500	1 k	2 k	4 k
0.04	5	2	1	0	0
0.05	5	2	1	0	0
0.06	4	2	1	0	0
0.08	3	1	0	0	0
0.10	3	1	0	0	0
0.13	3	1	0	0	0
0.16	2	1	0	0	0
0.20	2	1	0	0	0
0.25	2	1	0	0	0
0.32	1	0	0	0	0
0.40	1	0	0	0	0
0.50	0	0	0	0	0

Table 3.7: Correction, in dB, for total open area, in m^2, of duct outlet or diffuser into the receiving room. These values should be subtracted from result of Step 10.

Step 11: Duct outlet

4. In The Receiving Room

This part of the procedure deals first with the loudness of sound reaching a receiver (below), and then with whether that sound can be understood (in part 4.3).

4.1 Sound Reaching Receiver's Ear

The sound received at a listening position depends on the sound power emitted (determined in the preceding steps) and the listener's position relative to the duct outlet:

> Adjacent to the duct outlet, the transmitted speech is loudest. At this location, the sound level is essentially independent of the room characteristics.
>
> For normal listener positions (over 1 m from the outlet) sound absorption by surfaces and furnishing of the receiving room will affect the received sound level.

Step 12 (listener at duct outlet):
Add 12 dB to the value obtained at Step 11, to obtain the highest expected speech level. Use of this correction is recommended where speech security is of critical concern.

Alternate Step 12 (at normal listening positions):
(a) Multiply receiving room floor area in m^2 by appropriate values from Table 2.2 to determine room absorption for each frequency band.
(b) Subtract the correction in dB given in Table 4.1 from the value obtained at Step 11, to obtain the sound reaching the receiver from a duct outlet.

Expected Speaker Location	Room Absorption (m sabins)	Octave Band Frequency, Hz				
		250	500	1 k	2 k	4 k
Distant from duct opening (over 1 m)	5	0	0	0	0	0
	6	1	1	1	1	1
	8	2	2	2	2	2
	10	3	3	3	3	3
	12	4	4	4	4	4
	16	5	5	5	5	5
	20	6	6	6	6	6
	25	7	7	7	7	7
	32	8	8	8	8	8
	40	9	9	9	9	9

Table 4.1: Correction, in dB, for expected receiver location and absorption by room's surfaces and furnishings.

Step 12: Listener location & room

4.2 Multiple Paths

If there is more than one duct outlet in the receiving room, the sound energy transmitted by these paths must be combined, to determine the overall speech signal.

This requires that the preceding calculation (steps 1 to 12) be performed for each duct path.

Combining the sound arriving by two paths is not simply the addition of the sound pressure levels; to handle the combination of values expressed in decibels requires rather complicated arithmetic. However, by handling the combination for two levels at a time, Table 4.2 can be used to simplify the process. If there are more than two duct outlets, combine the lowest two levels first, then the result with the next lowest level, and so on.

Step 13: For normal listener positions, if sound reaches the listener via several duct outlets in the receiving room, calculate the transmitted sound level (Steps 1 to 12) for each path separately, and then combine the sound levels. This step is not needed for a location immediately adjacent to an outlet.

If higher level exceeds lower level by	Add this correction to larger level
0 to 1 dB	3 dB
2 to 4 dB	2 dB
5 to 9 dB	1 dB
over 10 dB	0 dB

Table 4.2: To combine two levels expressed in decibels, first determine the difference between the two levels. Using that value in the left column, determine the corresponding correction in the right column, and add this correction to the higher of the two levels.

4.3 Background Sound

The basic approach for determining speech intelligibility depends on the speech signal at the receiver relative to the background noise. The preceding sections of this report provide a step-by-step method for determining the loudness of speech levels reaching the receiver through a duct system.

The next step is to select appropriate background sound levels for the speech intelligibility calculation. Wherever possible, actual measured background sound levels should be used. If that is impossible, levels from comparable space provide the next best estimate. If no such data exist, use the estimates on the next page.

Step 14: If possible, measure the background sound pressure levels in the room(s) where speech might be overheard. Care should be taken to measure only the steady noise present in the absence of conversations and other transitory sounds that might be absent at the time privacy is desired.

The background sound levels in Table 4.3 are based on the Room Criterion (RC) curves from the ASHRAE Handbook, which are intended to sound "neutral" with no obvious hiss or rumble. Sound from a building ventilation system is unlikely to match this shape exactly, but this provides a basis for approximate AI calculations.

Note: In some cases masking noise may be used to improve speech privacy. Typical masking noise is close to the RC-35 contour, with an overall level of about 45 to 50 dBA; higher levels tend to annoy office occupants.

Alternate Step 14: If measurements are not feasible, rough estimates can be made using the appropriate noise spectrum from Table 4.3.

Room Type	Octave Band Frequency, Hz				
	250	500	1 k	2 k	4 k
Very quiet (RC-20)	30	25	20	15	10
Quiet private office (RC-25)	35	30	25	20	15
Quiet large office (RC-30)	40	35	30	25	20
Average office (RC-35)	45	40	35	30	25
Noisy office (RC-40)	50	45	40	35	30

Table 4.3: Approximate background sound levels for some common cases. If possible, measured background levels should be used rather than this table. The descriptions relate to the sound in the absence of speech or other noise from building occupants.

4.4 Calculate Speech Intelligibility

Given the speech level and the background noise, the next step is to assess how well the speech can be understood.

This procedure is based on the Articulation Index calculation, following the procedure defined in ANSI Standard S3.5.

The Articulation Index ranges from 0.00 (where speech is unintelligible) to 1.00 (where all individual words can be understood by a listener with normal hearing), with lower values indicating speech that is harder to understand.

Step 15: Calculate the Articulation Index by inserting the speech levels and background levels in the appropriate columns of Table 4.4, and performing the indicated operations.

	Octave Band Frequency, Hz				
	250	500	1 k	2 k	4 k
A. Speech Signal(Step 12 or 13)					
B. Ambient Level (Step 14)					
C. Signal-to-Noise in dB(A-B)					
D. Weighting Factor	.0024	.0048	.0074	.0109	.0078
E. Contribution to AI (D x C)					
F. Articulation Index	Sum of row E =				

Table 4.4: Worksheet for calculating Articulation Index. Enter into Row A the speech levels for each frequency band (from Step 13). Enter into Row B the ambient or background sound levels (from Step 14). The difference between these is the signal-to-noise for each frequency band. Each of these must be multiplied by the appropriate weighting factor (given in Row D) and the sum of these products is the Articulation Index.

4.5 Evaluate Privacy

Although the precise value of Articulation Index (AI) corresponding to confidential privacy depends on the spoken material (and to some degree on acuity of the listener), approximate criteria for privacy have been developed:

- Confidential speech privacy is indicated by AI values of about 0.05 or lower.
- Normal speech privacy is indicated by AI values between 0.05 and 0.20. In this range, concentrated effort is required to understand speech.

To allow some margin of safety, slightly more restrictive criteria are proposed in this design procedure. These are discussed further in the Summary.

The greatest margin of safety can be obtained by requiring AI of 0.05 or lower at the duct outlet. This will provide speech privacy even in the worst location, and will ensure that AI is well below 0.01 in most of the room.

Step 16: Compare the AI values calculated in Step 15 versus the following criteria:

Confidential privacy should exist if:

Articulation Index in mid-room is less than 0.02
Articulation Index at duct outlet is less than 0.05

Step 16: Compare with criteria

5. Summary

The Articulation Index (AI) was chosen as the basis for evaluating speech privacy in this design procedure because it offers a reasonable balance between ease of calculation and validated application to speech clarity evaluations.

However, it should be remembered that (as ASTM Standard E1130 cautions) this index is based on evaluation of speech quality where communication is fair to good. It has not been extensively calibrated as a measure of speech privacy where communication is very poor.

In view of the above cautions about precision of the AI in evaluating confidential speech privacy, the criterion used in Step 16 is slightly more restrictive than the conventional wisdom, to provide a margin of safety.

Other factors such as reverberation time of the receiving room should also be included in a state-of-the-art calculation of speech intelligibility, but were ignored here in the interest of simplicity. Overall, the simplifications inherent in Steps 2 to 14 should provide an additional small margin of safety.

The relationship between AI and the Speech Security Rating (SSR) was examined in an earlier case-study evaluation of the SSR. That study indicated that an Articulation Index of 0.02 would correspond to a Speech Security Rating of about 75, barely meeting the criterion for a Secure Discussion Area.

Ensuring that Articulation Index is less than 0.05 in the worst case (right at the duct outlet) would provide a comfortable margin of safety for normal listener positions in the room.

Thus, the procedure here should yield designs compatible with the federal government's Standard Practice for Verifying the Acoustical Security of Special Discussion Areas.

6. References

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- Mechanical Duct Designs to Provide Speech Privacy, Part 2: Source and Receiving Room Effects, J.D. Quirt, IRC/NRC Report CR-5763.2 (1991).
- Standard Practice for Verifying the Acoustical Security of Special Discussion Areas.
- Evaluation of "Standard Practice for Verifying the Acoustical Security of Special Discussion Areas", R.E. Halliwell and J.D. Quirt, IRC/NRC Report CR-5682.1 (19 April 1988).
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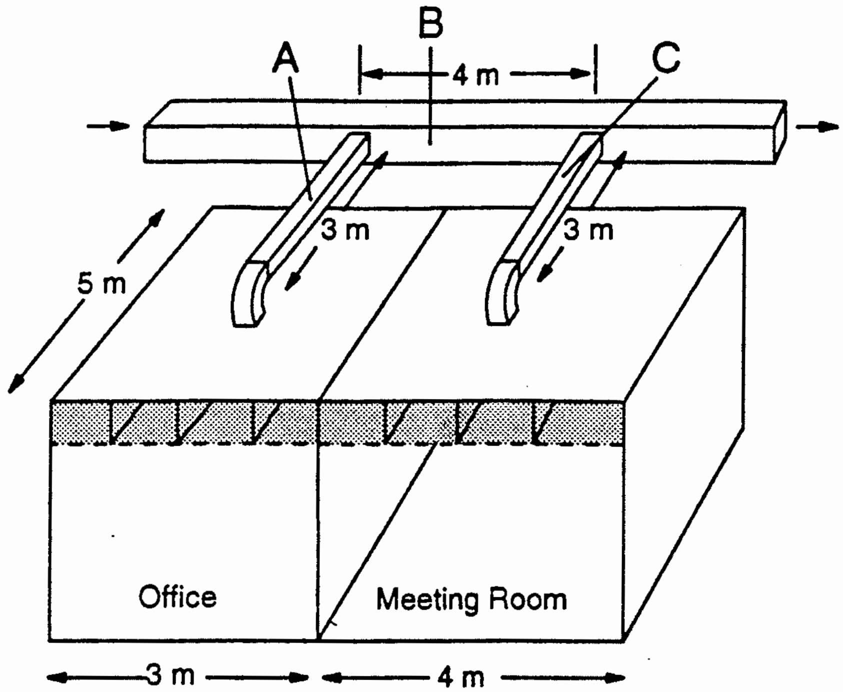
- ANSI Standard S3.5, "Methods for the Calculation of the Articulation Index", American National Standards Institute, 1430 Broadway, New York, NY 10018 (1973).
- Handbook of Acoustical Measurement and Noise Control, 3rd edition, Cyril M. Harris (Editor) McGraw-Hill (1991). See Chapter 16, "Effects of Noise and Reverberation on Speech".
- Algorithms for HVAC Acoustics, by D.D. Reynolds and J.M. Bledsoe, Publication 90334 of American Society of Heating Refrigerating & Air-Conditioning Engineers (May 1991).
- "Sound and Vibration Control", Chapter 52, ASHRAE 1987 HVAC Systems and Applications Handbook.

Example 1:

A private office used for discussions needing confidential privacy is adjacent to a small meeting room where the conversations might be overheard. Both have air supplied by ducts branching from the same main duct. The general configuration is shown in the diagram. Details of the rooms and duct system are as follows:



Source room:
- executive office
- 3 x 5 m floor area
- absorptive suspended ceiling
- deep carpet
- upholstered furniture in area near diffuser

Quiet meeting room
- 5 m by 5 m floor area
- part-absorptive suspended ceiling (hard surface in mid-room)
- commercial carpet
- hard furniture
- low background sound (RC-25)

Duct A:
- Receiving room:
- diffuser with 2 openings 40 x 1250 mm
- short transition (ignore)
- curved elbow, 300 x 300 mm
- 300 x 300 mm duct, 3 m long

Duct B:
- main duct, 500 x 500 mm
- 4 m between branch A & C
- no acoustic lining

Duct C:
- 300 x 300 mm duct, 3 m long
- curved elbow, 300 x 300 mm
- short transition (ignore)
- diffuser with 2 openings 40 x 1250 mm

Because the meeting room is designed for effective communication (low background sound and reflective ceiling), the possibility of understanding speech is rather good. For the case when conversation in the private office is in a raised voice, data above were used to calculate the speech privacy as shown on the following worksheet. The calculated Articulation Index of 0.251 indicates that speech would be intelligible with concentration, everywhere in the room, especially near the duct outlet.

Example 1 (continued):

2. Source Room	
Floor area	$15 m^2$
Room type	dead
Absorption:	
250 Hz	15
500 Hz	18
1 kHz	20
2 kHz	21
4 kHz	23

Source Room	Octave-Band Frequency, Hz 250	500	1 k	2 k	4 k
1. Speech level	71	76	71	66	61
3. Room & location	+2	+1	+1	+0	-2
4. Duct opening $0.10 m^2$	-16	-16	-16	-16	-16
A. Entry sound power	57	61	56	50	43
Along Duct (Steps 5 to 11)					
5. 3m duct A	1.0	.7	.7	.7	.7
4m duct B	1.3	.4	.4	.4	.4
3m duct C	1.0	.7	.7	.7	.7
7. elbow duct A	1	2	3	3	3
elbow duct C	1	2	3	3	3
9. branch A→B (50%)	3	3	3	3	3
branch B→C (26%)	6	6	6	6	6
11. Duct opening $0.10 m^2$	3	1	0	0	0
B. Total duct attenuation	17	16	17	17	17
C. Exit sound power (A-B)	40	45	39	33	26
Receiving room:					
12. Position & Room	-3	-4	-5	-5	-6
13. Combine if needed					
D. Speech Level	37	41	34	28	20
E. Background level	35	30	25	20	15
F. Signal-to-noise (D-E)	2	11	9	8	5
G. Weighting factor	.0024	.0048	.0074	.0109	.0078
H. AI Contrib. (F x G)	.005	.053	.067	.087	.039
J. Articulation Index	Sum of Row H: .251				

← As Speak near duct

List nea midd of r

12(a). Receiving Room	
Floor area	$20 m^2$
Room type	average
Absorption:	
250 Hz	10
500 Hz	12
1 kHz	14
2 kHz	16
4 kHz	18

The Articulation Index of 0.251 in the middle of the room is significantly higher than the criterion value of 0.02. Speech privacy is not provided. A modification of the duct system to reduce the transmitted sound is presented in Example 2, following.

Example 2(a): Same case with duct lining added

One way to reduce sound transmission is to line the inside of the duct with acoustically absorbing material, discussed as Step 6 on page 9. For the same duct configuration and room details considered in Example 1, lining duct A (see figure on page 23) would change the transmitted sound as follows:

2. Source Room	
Floor area	15m²
Room type	dead
Absorption:	
250 Hz	15
500 Hz	18
1 kHz	20
2 kHz	21
4 kHz	23

Source Room	Octave-Band Frequency, Hz 250	500	1 k	2 k	4 k
1. Speech level	71	76	71	66	61
3. Room & location	+2	+1	+1	0	-2
4. Duct opening ______	-16	-16	-16	-16	-16
A. Entry sound power	57	61	56	50	43
Along Duct (Steps 5 to 11)					
5. 4m duct B	1.3	.4	.4	.4	.4
3m duct C	1.0	.7	.7	.7	.7
6. 3m lined duct A	8	20	40	40	28
7. elbow duct C	1	2	3	3	3
8. lined elbow duct A	1	2	3	3	3
9. branch A→B	3	3	3	3	3
branch B→C	6	6	6	6	6
11. Duct opening 0.1 m²	3	1	0	0	0
B. Total duct attenuation	24	35	56	56	44
C. Exit sound power (A-B)	33	26	0	-6	-1
Receiving room:					
12. Position & Room	-3	-4	-5	-5	-6
13. Combine if needed					
D. Speech Level	30	22	–	–	–
E. Background level	35	30	25	20	15
F. Signal-to-noise (D-E)	–	–	–	–	–
G. Weighting factor	.0024	.0048	.0074	.0109	.0078
H. AI Contrib. (F x G)	0	0	0	0	0
J. Articulation Index	Sum of Row H: 0				

Assume speaker near duct (row 3)

Middle of Room (row 12)

12(a). Receiving Room	
Floor area	20m²
Room type	average
Absorption:	
250 Hz	10
500 Hz	12
1 kHz	14
2 kHz	16
4 kHz	18

In the middle of the room, the Articulation index is below 0.02, indicating confidential speech privacy. Very near the duct outlet, the speech would be clearer, as shown in Example 2(b).

Example 2(b): Near the duct outlet

The transmitted speech signal is loudest immediately adjacent to the duct outlet (and it is there that someone deliberately eavesdropping would listen). Most of the calculation to evaluate privacy at the duct outlet is the same as in Example 2(a), but the calculation is different from Step 12, as shown:

	Same as previous example				
C. Exit sound power (A-B)	33	26	0	-6	-1
Receiving room:					
12. Position & Room	+12	+12	+12	+12	+12
13. Combine if needed					
D. Speech Level	45	38	12	6	11
E. Background level	35	30	25	20	15
F. Signal-to-noise (D-E)	10	8	—	—	—
G. Weighting factor	.0024	.0048	.0074	.0109	.0078
H. AI Contrib. (F x G)	.024	.038	0	0	0
J. Articulation Index	Sum of Row H: .06				

The Articulation Index of 0.06 near the outlet is slightly above the criterion value of 0.05, so confidential privacy is not quite achieved at this position. With concentration, some of the speech from the adjoining office would be intelligible, although conversations at normal voice levels would not be.

If absolute privacy were critical for this installation, it could be achieved by adding masking noise near the duct outlet (not desirable for communication within the meeting room, but only a slight increase in ambient levels would be needed) or by adding absorptive lining to all or part of the duct to the meeting room (Duct C).

Worksheet

2. Source Room

Floor area ______
Room type ______

Absorption:
250 Hz ______
500 Hz ______
1 kHz ______
2 kHz ______
4 kHz ______

Source Room	Octave-Band Frequency, Hz 250	500	1 k	2 k	4 k
1. Speech level					
3. Room & location					
4. Duct opening ______					
A. Entry sound power					
Along Duct (Steps 5 to 11)					
11. Duct opening ______					
B. Total duct attenuation					
C. Exit sound power (A-B)					
Receiving room:					
12. Position & Room					
13. Combine if needed					
D. Speech Level					
E. Background level					
F. Signal-to-noise (D-E)					
G. Weighting factor	.0024	.0048	.0074	.0109	.0078
H. AI Contrib. (F x G)					
J. Articulation Index	Sum of Row H:				

12(a). Receiving Room

Floor area ______
Room type ______

Absorption:
250 Hz ______
500 Hz ______
1 kHz ______
2 kHz ______
4 kHz ______

Confidential privacy if
Articulation Index in mid-room is less than 0.02
Articulation Index at duct outlet is less than 0.05

National Research Council Canada | Conseil national de recherches Canada

Institute for Research in Construction | Institut de recherche en construction

CLIENT REPORT

for

Royal Canadian Mounted Police
Security Engineering Branch
810 Belfast Road
Ottawa, Ontario K1A 0R2

Mechanical Duct Designs to Provide Speech Privacy
Part 1: Effect of Duct Elements

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Report No. CR-5763.1
Report Date: 13 October 1990
Contract No. CR-5763
Reference: Application for test dated 14 September 1988
Section: Acoustics

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1. Summary

This is the first of three reports dealing with design of duct systems to ensure sound transmission through the ducts does not eliminate speech privacy.

This part deals with the effect of specific details of the duct system on the sound attenuation achieved. The second report will deal with room effects - primarily the significance of speaker and listener positions on the transmitted sound. The final report will present basic rules for design of a suitable system to ensure speeech privacy with an adequate margin of safety.

It is well established that locating noise control elements such as silencers close to bends or other duct discontinuities can significantly alter their effectiveness in controlling noise. The purpose of this study was to quantify such effects to provide a rational basis for system design for speech privacy.

Significant details identified in this part of the study include:

- The sound reduction by a commercial duct silencer tends to be significantly below the rated performance if the silencer is located close to a bend, branch, or other duct discontinuity;

- Lining several metres of duct with absorptive material can provide essentially the same effect as commercial duct silencers;

- A simple prediction model provides adequate prediction of sound attenuation by untreated duct systems and by lined sections.

After a brief discussion of the duct mockup and the measurement procedures, the report presents a discussion of trends in the measured sound reduction. Appendices present both tabulated data for all the configurations tested and a prediction method which compared quite closely with the measured performance.

2. Measurement Approach

The schematic drawing in Figure 2.1 illustrates the basic concept of the experimental setup for these measurements. The duct system was installed between two reverberation rooms in the laboratory of the Institute for Research in Construction, to simulate the situation where cross-talk commonly occurs - an air supply duct with connections to two adjacent rooms.

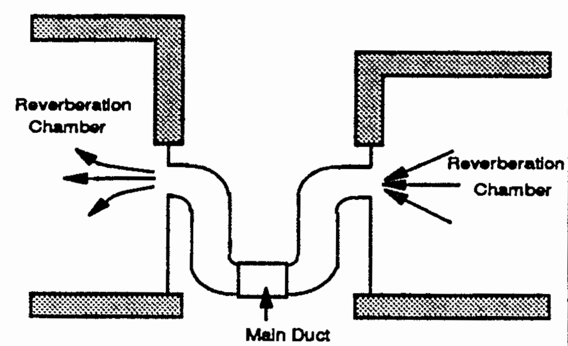


Figure 2.1

The intent of this phase of the measurement program was to assess how changing various details of the duct system altered the sound power transmitted from a duct outlet in one room to an outlet in another room. It is well established that placing silencers or absorptive linings near bends or other duct discontinuities significantly alters the sound attenuation achieved. The intent of these measurements was to quantify those effects, to provide a rational basis for system design for speech privacy.

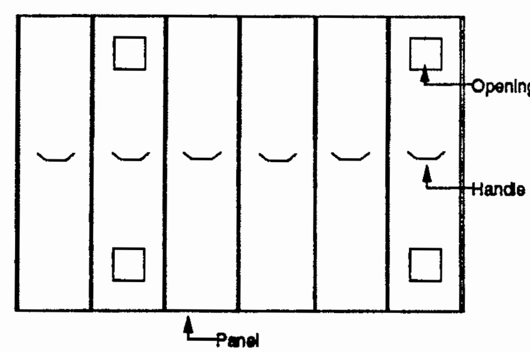


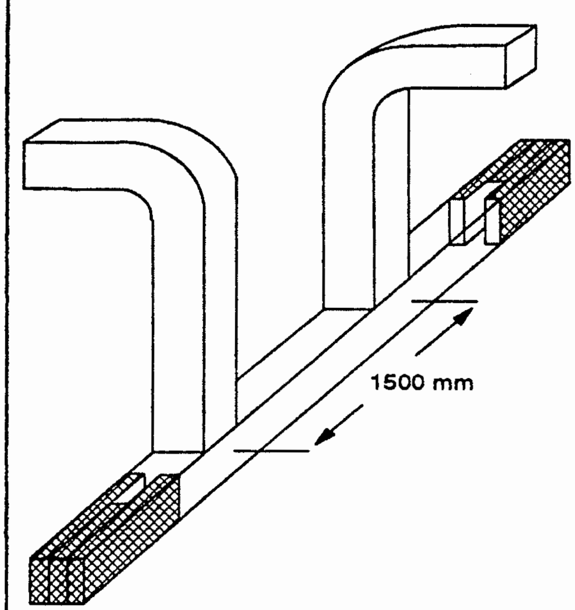
Figure 2.2

The mockup for these measurements used the opening between the reverberation rooms where wall specimens are normally mounted for sound transmission measurements. A modular wall panel system (as illustrated in Figure 2.2) was installed in each reverberation room. This provided a barrier between the two rooms that transmitted very little sound. Sound transmission performance of the panels is given in the graphs in the following section for those cases where duct attenuation approached performance of the wall panels.

As shown in Figure 2.1, the duct system was installed in the space between these two modular walls. The wall panels had 310 x 310 mm ports which could be removed to provide an opening for the duct system at one of 12 positions in each room. The positions used depended on the duct configuration.

One of the reverberation rooms served as a source for sound power. Loudspeakers in that room generated sound, and measurement of the resulting sound pressure level in the room permitted accurate determination of the sound power striking the room boundaries, including the opening into the duct system. Part of that sound energy was transmitted through the duct system and emitted into the second reverberation room. The sound power emitted could be accurately determined by measuring the sound field in that room. Comparison of the incident sound power in the source room with that radiated into the receiving room provided an accurate measurement of sound attenuation in the duct (which was systematically modified to include silencers, absorptive linings, etc.).

Figure 2.3



As illustrated in Figure 2.3., the basic duct system had two sidebranches (one connecting to each reverberation room) and a main duct. The ducts were made in sections to permit insertion of treated sections at many positions. To facilitate comparison of many silencer locations, all the ducts had the same internal cross-section of 305 x 305 mm, so the same silencer could be placed in the main duct or sidebranches.

The walls of the sidebranches were 22 guage galvanized sheet steel, covered with a liner of adhesive-backed damping material (TEC Damping Sheet from Eckel Industries) weighing 5 kg/m^2. The main duct was 4.9 m long, with provision for inserting silencers in the central part and for connecting the sidebranches either to the top or side of the main duct. The walls of this duct were 19 mm plywood. At each end of the main duct was a 1.2 m long anechoic termination of absorptive fiberglass material. These prevented sound reflections from the duct ends, so performance would simulate that in a real building where the duct typically extends for long distances.

A set of nominally identical IAC "Quiet-DUCT Type S" commercial duct silencers were purchased; manufacturers' test data for these was available. These had the same 305 x 305 mm cross-section as the ducts and were 914 mm long. They were installed at various positions in the duct system to evaluate the effect of silencer location on the sound attenuation achieved.

Some additional tests were made to evaluate the effect of absorptive lining of part of the sidebranch duct, by lining duct sections with absorptive foam. The material used to line the duct was 25 mm thick Conaflex F-100 foam manufactured by H.L. Blatchford Ltd., but fiberglass duct liner material of the same thickness would provide similar added attenuation; their expected performance is compared in Appendix B. The foam was used for this research study because it is easier to handle.

The laboratory reverberation chambers, instrumentation and testing procedures all meet or exceed the requirements of ASTM Standard E90-85 for laboratory measurement of sound transmission. The sound field in each room was measured using nine GenRad 1961 electret condenser microphones (25 mm diameter, random incidence response). These were mounted on GenRad 1972 preamplifiers, whose output signals were selected in sequence by a GenRad 1560 multiplexer/amplifier. The output from this multiplexer was connected to a Norwegian Electronics 830 real time analyzer. The multiplexer, analyzer, and sound sources were all controlled by an IBM/PC compatible computer, running custom software to perform the measurement.

The sound transmission loss for a partition is calculated from the expression:

$$\text{Transmission Loss} = L_1 - L_2 + 10\log(S/A)$$

where:

L_1 is the average sound pressure level in the source room,
L_2 is the average sound pressure level in the receiving room,
S is the surface area of the specimen, in m^2,
A is the absorption in the receiving room, in metric Sabins.

Presenting the results for sound transmission through a duct using the above equation, one would use the area of the duct opening (0.093 m^2) as the surface area S. Although this would be technically acceptable, it does not present the results in a way that makes transmission through the duct obviously comparable to other transmission paths, such as the separating partition.

The same problem applies to the corresponding expression for the ASTM and AMA standard measurements of sound transmission between adjacent offices via a suspended ceiling. To provide more intuitive presentation, those standards use a nominal area $S = 12\ m^2$, which corresponds to the area of the partition between the two rooms of the laboratory facility used for suspended ceiling tests. When this is done, the ceiling attenuation can be compared directly with transmission loss for a partition to determine the limiting path, or combined with partition transmission loss to obtain the overall inter-office noise reduction.

The same practice is followed in this report, to relate performance of the duct system more obviously to noise reduction. Thus, data are expressed using the equation:

$$\text{Normalized Attenuation} = L_1 - L_2 + 10 \log(12/A)$$

where:

L_1 is the average sound pressure level in the source room,
L_2 is the average sound pressure level in the receiving room,
12 is a normalization constant (12 metric Sabins),
A is the absorption in the receiving room, in metric Sabins.

Results calculated in this way correspond to the noise reduction that would be observed if the absorption in the receiving room were 12 metric Sabins (which is a reasonable value for a typical modern private office). Most of the following graphs use this form of presentation.

The benefit of this form of presentation, is that the stated attenuations can be compared directly with partition STC values, to assess whether the duct transmission is a problem. If the normalized duct attenuation is significantly larger than partition STC, the duct is not a problem. How much larger is necessary will be established in subsequent reports.

For applying these results to cases where the receiving room absorption (A) differs markedly from the arbitrary normalization, the expected attenuation can be obtained by adding the correction 10 log (A/12) to the results shown here.

3. Experimental Results

Results for each configuration tested are presented in Appendix A, with diagrams to illustrate duct configuration and silencer location.

This report focuses primarily on transmission through the duct system itself; some consideration of room acoustics is needed to assess how much attenuation is *needed*, but that is postponed to subsequent reports.

This section summarizes the main trends of attenuation within the duct system, first for an untreated duct system and then for a system with added attenuators. Where possible, the measurements are compared with expectations from existing design guidelines.

There are several factors expected to reduce sound transmission through the duct system according to available prediction models:

1) Energy losses at branch connections: the duct system had two T-junctions, where only part of the sound energy will go towards the outlet duct.

2) Energy losses at bends: the sidebranches each had one or more bends at which part of the sound energy might be reflected back.

3) End reflections: at the outlet into the receiving room, the discontinuity is expected to reduce the low frequency sound energy transmission.

4) Sound energy losses by transmission through duct walls: for the measurements reported here, the ducts are sufficiently short and duct walls were sufficiently heavy so that negligible sound energy should be lost in transmission along straight untreated duct segments.

5) Deliberate attenuation from lining ducts with absorptive material or adding a silencer.

There are also several factors which are mentioned only qualitatively in prediction models, such as spacing between sidebranches or proximity of bends and junctions to one another or to absorptive treatment. These factors are of considerable concern because practical installations often require small distances between duct elements, which may significantly alter the effect of silencers or duct linings. In addition, there may be resonances associated with the duct dimensions.

The measurement series was deliberately designed to examine the performance of untreated ducts and the addition of silencers or duct lining in configurations with worst-case spacing among elements.

3.1 Untreated Duct System

Figure 3.1 shows the measured normalized attenuation for duct systems that differ in the number of bends in the sidebranches. The solid curve is for a system with only one bend in each sidebranch; the dashed curve is for a system with two bends in each sidebranch. In both cases, there is a 2.5 m separation between the sidebranch openings to the main duct. At frequencies below 500 Hz, there are minor differences between the two curves, but on average they provide similar low-frequency attenuation. At higher frequencies, the dashed curve is consistently higher by a few decibels - the expected effect due to the added gradual bends. Overall, the two have quite similar performance.

Figure 3.1

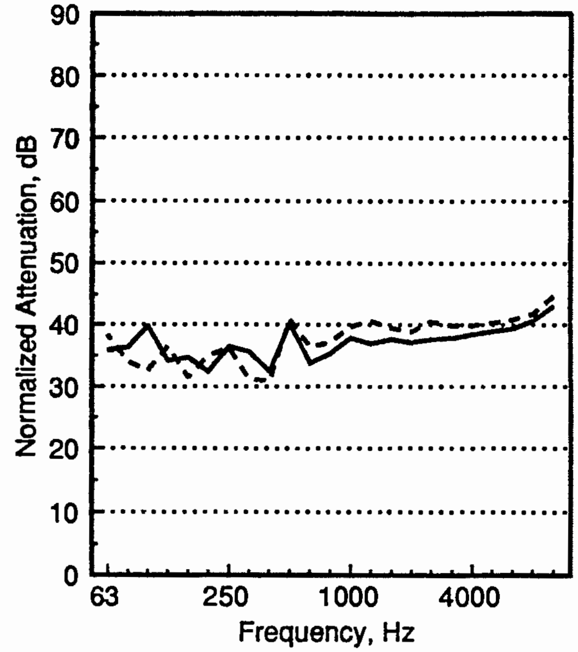
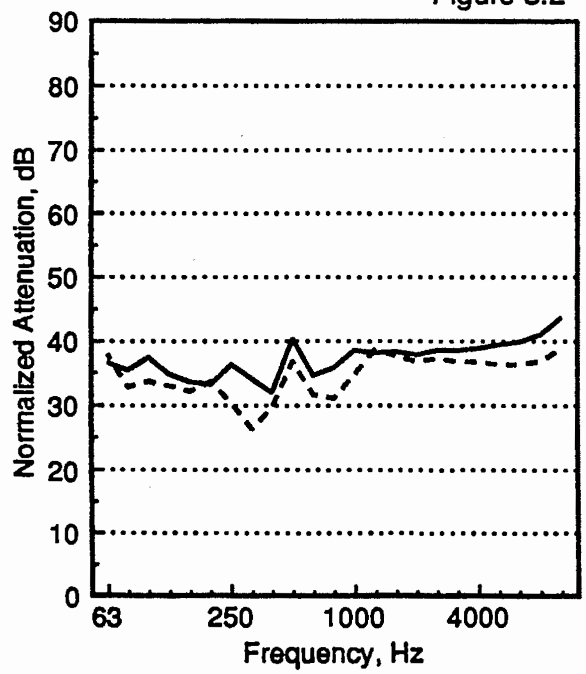


Figure 3.2 shows the measured attenuation for duct systems with different spacing between the two sidebranches. The solid curve is the average of several results with centers of the sidebranches 2.5 m apart; the dashed curve is an average of results where sidebranch separation was only 0.5 m. Note that the latter has only 200 mm between the near edges of the sidebranches. With the smaller spacing, the attenuation is generally lower by a few decibels.

Figure 3.2



Below 1000 Hz, there are several quite obvious peaks and dips in the attenuation curves in Figures 3.1 and 3.2. These are tentatively ascribed to specific resonances due to the 300 mm width of the ducts. The peak at 500 Hz, which is evident in all these curves, corresponds to the frequency where duct width equals 1/2 wavelength. Note in Figure 3.2 that these resonances are considerably stronger in the case with smaller spacing between branch ducts. In general, these resonances should not be a serious problem for speech privacy, because most speech intelligibility information is in the higher frequency bands, but it is clearly preferable to locate sidebranch connections to the main duct several metres apart.

Figure 3.3

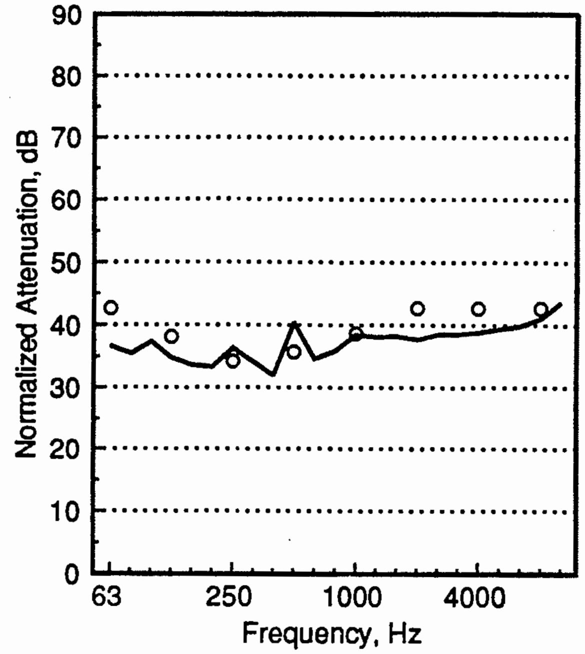
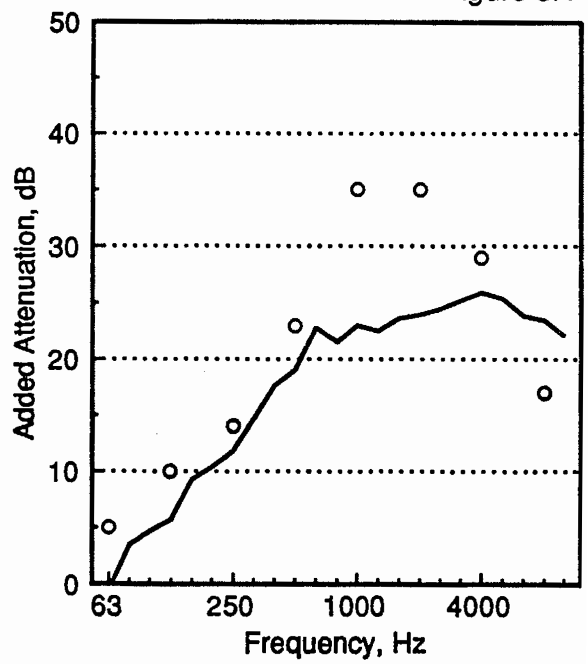


Figure 3.3 presents a comparison between measured attenuation (solid line) and that predicted (circles) by the method given in Reference 2, which appears to provide the best correlation with the results in this study. Tabulated corrections and the details of the prediction presented in Figure 3.3 are discussed in Appendix B. The key point is that this simple prediction method does give a rather good estimate of attenuation through the duct system.

3.2 Performance of Duct Silencers

Commercially manufactured duct silencers were obtained and were installed in various locations in the duct system to assess deviation of their performance from the manufacturers' specifications.

Figure 3.4



Testing of duct silencers is normally performed according to ASTM standard test method E-477, which requires the silencer to be installed between long straight inlet and outlet ducts whose cross-section matches that of the silencer. In practical installations, the silencer is often close to bends, outlets, or other discontinuities; these tend to reduce the effectiveness of the silencer. A major purpose of these measurements was to assess how much the silencer performance was degraded when located in "worst-case" situations.

Figure 3.4 presents the increase in attenuation through the duct system when one silencer was added in the main duct (Case R). The silencer was midway between the sidebranches, approximately 600 mm from their openings into the main duct. The circles in Figure 3.4 are the manufacturer's rating for this product installed in the ideal case, conforming to the standard test method. The attenuation measured in the present study was less than that predicted in the frequency bands at 1000 and 2000 Hz (which are unfortunately of great importance for speech privacy).

Test results presented in the following figures were for cases with two silencers in the duct system. In these cases, the nominal attenuation for a single silencer (in dB) would be half the attenuation shown for a pair of silencers. These tests do not give a fair assessment of the silencer relative to its rated performance because interactions due to the presence of the two units might be expected. However, these tests should give a reasonable basis for estimating worst case performance because in all cases the silencers were adjacent to bends or branches in the duct system.

Figure 3.5

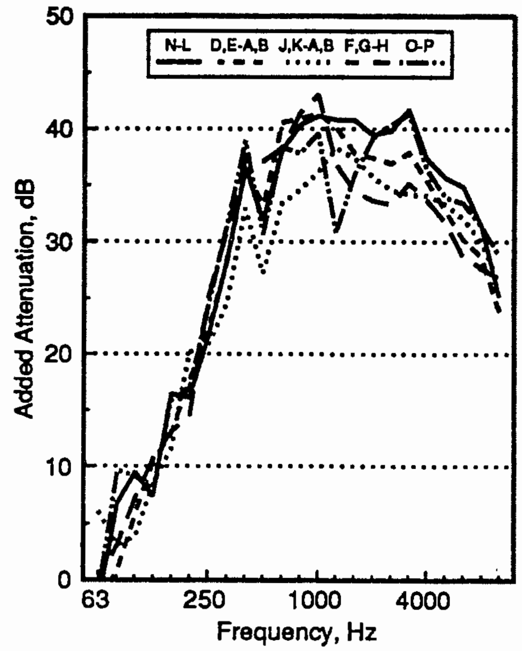
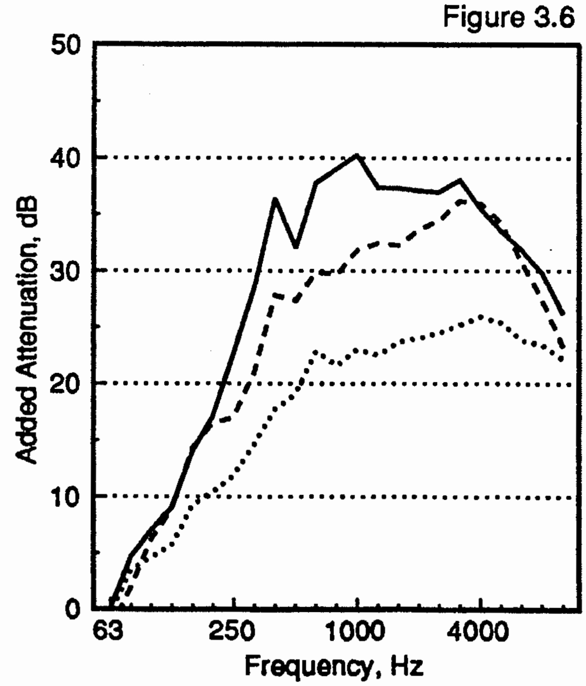


Figure 3.5 presents the increase in attenuation for all configurations tested with a silencer in each sidebranch. Some curves are a mean of two nominally equivalent cases; cases are identified in Appendix A. These included configurations with one to three bends in each sidebranch and different spacing between sidebranches. Although there are minor differences, the results were quite similar for all the configurations.

Figure 3.6

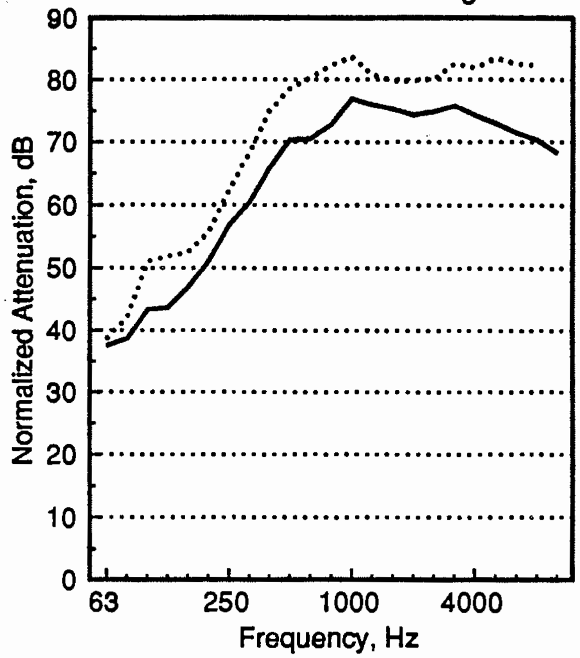


The solid curve in Figure 3.6 is the mean of the five results from Figure 3.5. The dashed line is the attenuation added by two silencers (end to end) in the main duct; obviously, this provides less attenuation than the same two silencers farther apart, with one in each sidebranch. Thus, if two silencers are to be used, they should be kept well separated. The dotted curve is the result for a single silencer. Clearly the two silencers provide more attenuation than a single silencer, but less than double the attenuation.

Below about 250 Hz, the solid curve in Figure 3.6 indicates that two silencers in the sidebranches give about double the attenuation for the single silencer, but at higher frequencies the increase is less than double. This is probably at least in part due to flanking transmission - either vibration transmission along the duct walls or break-out/break-in transmission. The latter is caused by sound energy transmitted through the duct walls into the surrounding airspace (primarily from the part nearest the source room where sound power inside the duct is highest) and subsequent transmission of some of that sound energy back into the duct near its exit (after the second silencer).

These limiting results are significant as a reminder of the need for suitable duct construction. An unusually heavy and highly damped duct system was used in this study; this limited duct vibration and hence break-out and break-in to minimal effects, but the problem could be significant if lightweight ducts were used adjacent to vents to a room where secure discussions are occurring.

Figure 3.7

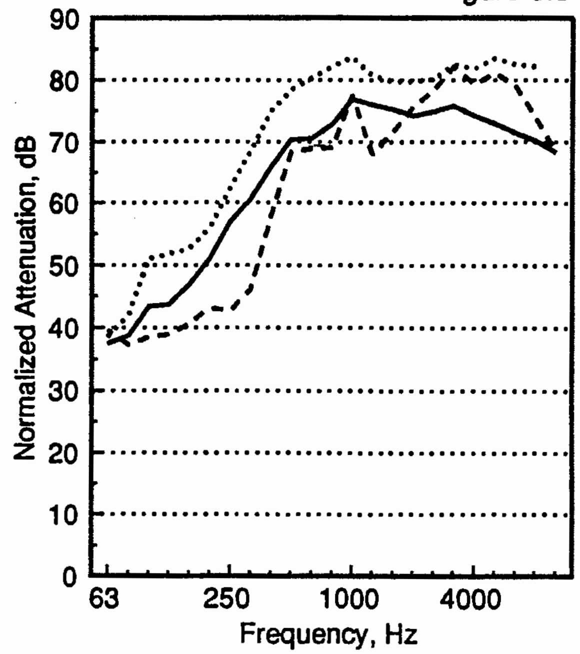


At the high attenuations involved here, little vibrational energy is required to limit the performance. To put this in perspective, the solid curve in Figure 3.7 presents the overall normalized average attenuation for two silencers in the sidebranches (the same case for which added attenuation is given by the solid curve in Figure 3.6). At the frequencies above 250 Hz, where these flanking effects appear to marginally limit silencer performance, the overall attenuation is over 70 dB, which is far above what would be required to achieve speech privacy. Thus, it is clear that commercial duct silencers can reliably provide enough attenuation to more than satisfy practical needs for speech privacy.

The dotted curve in Figure 3.7 shows the limiting attenuation for airborne transmission through the blocking walls between the two reverberation chambers; this should not have affected the apparent silencer attenuation results by more than about 1 dB (except at frequencies near 63 Hz, which are insignificant for speech).

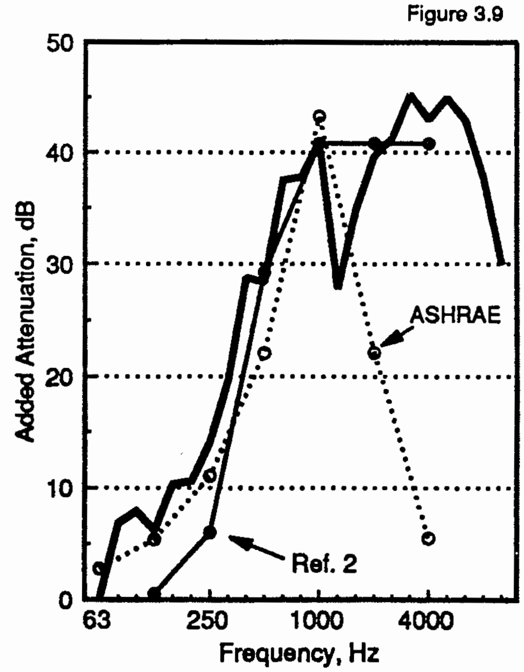
3.3 Performance of Absorptive Duct Lining

Figure 3.8



Absorptive lining can provide substantial attenuation of sound transmitted through the duct system. The dashed curve in Figure 3.8 is the overall attenuation observed when a 1.5 m long section of both sidebranches was lined with absorptive foam. The overall attenuation was very similar to that with silencers in both sidebranches (the solid curve). Below about 500 Hz, the absorptive lining provided less noise reduction than the silencers, but this would have little effect on speech intelligibility. At the highest frequencies, the absorptive lining provided higher attenuation that the silencers. How much better is not known because the attenuation reached the limit of airborne flanking through the partition walls (dotted curve), but the important issue is that duct lining can clearly provide more than enough attenuation to assure speech privacy.

Figure 3.9



The expected attenuation for added absorptive lining depends on thickness and absorption coefficient of the lining material and on duct size. Different design guides predict quite different performance. Figure 3.9 compares the added attenuation due to the absorptive lining in this study with predictions from the ASHRAE Handbook and from Reference 2 (discussed in more detail in Appendix B). The experimental result is shown by the solid curve. The ASHRAE procedure (open circles) does not seem to agree with the data as well as that presented in Appendix B. However, the ASHRAE guide mentions an unspecified additional increase in high-frequency absorption when the absorptive lining is close to bends or other discontinuities; this might explain part of the discrepancy.

The added attenuation with absorptive lining exhibits a noticeable dip around 1000 Hz. Similar irregularities in the attenuation for untreated ducts were tentatively explained in terms of duct width matching a half wavelength. Adding absorptive lining would change boundary conditions and hence resonant frequencies for such resonances, and thus offer a likely explanation for this effect. Although the resonance is quite noticeable, it is not of great significance for overall reduction of speech intelligibility.

Overall, the present study confirms the general expectation that absorptive linings can provide significant added attenuation, and the procedure in Appendix B gives a reasonable, but slightly conservative estimate of that attenuation.

4. Discussion and Conclusions

This study has clearly demonstrated that either commercial duct silencers or lined duct sections can provide enough sound attenuation to ensure that transmission through the duct does not compromise speech security.

Further details about speaker and receiver location relative to duct vents are needed to assess how much attenuation the duct system must provide. However, this part of the study has established some conservative rules of thumb about the performance of sound attenuating elements:

- In general, the sound attenuating device(s) should be placed in the branch(es) to ventilation outlets into a Secure Discussion Area. A commercial duct silencer should not be located immediately adjacent to the duct outlet, but absorptive lining should begin at the outlet.

- if commercial duct silencers are located within a few duct diameters of branches or other duct discontinuities, design values equal to 2/3 of the rated attenuation should be used;

- if two silencer units are located within one duct diameter of each other, the rated attenuation for one silencer should be used to estimate the combined attenuation of the two silencers;

- the effect of absorptive lining of duct sections can be predicted with adequate accuracy by the procedure given in Appendix B;

- Fairly simple duct construction is adequate to control sound breakout from ducts, but damping and/or lagging treatment is strongly recommended for duct elements between a Secure Discussion Area and the sound attenuating elements.

5. References

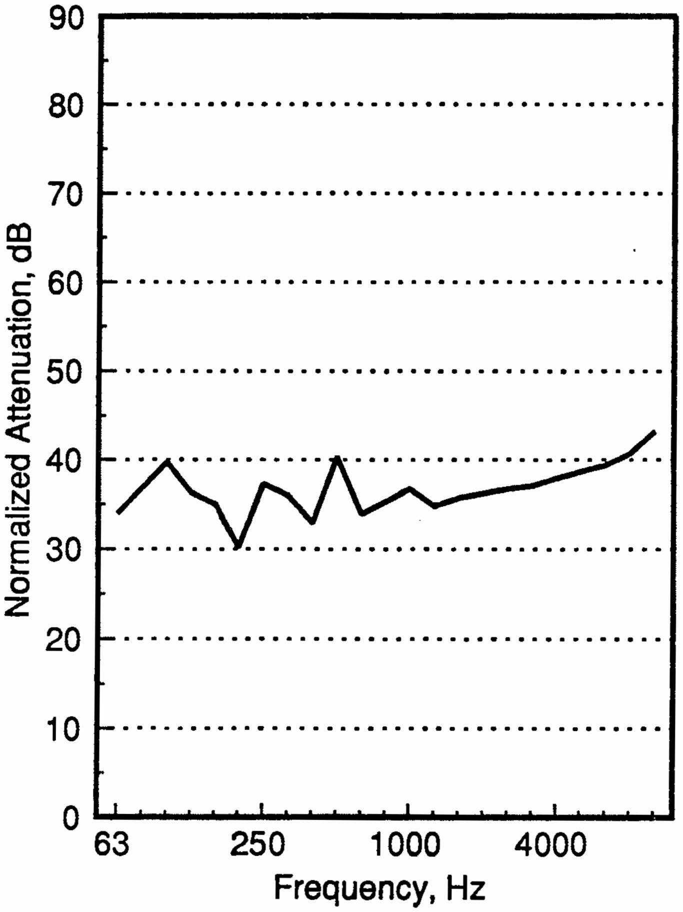
1. ASHRAE 1984 Systems Handbook, Chapter 32: Sound and Vibration Control, p. 32.1-32.38.

2. Noise Control in Building Services, Sound Research Laboratories Ltd., Alan Fry (Ed.), Pergamon Press (1988).

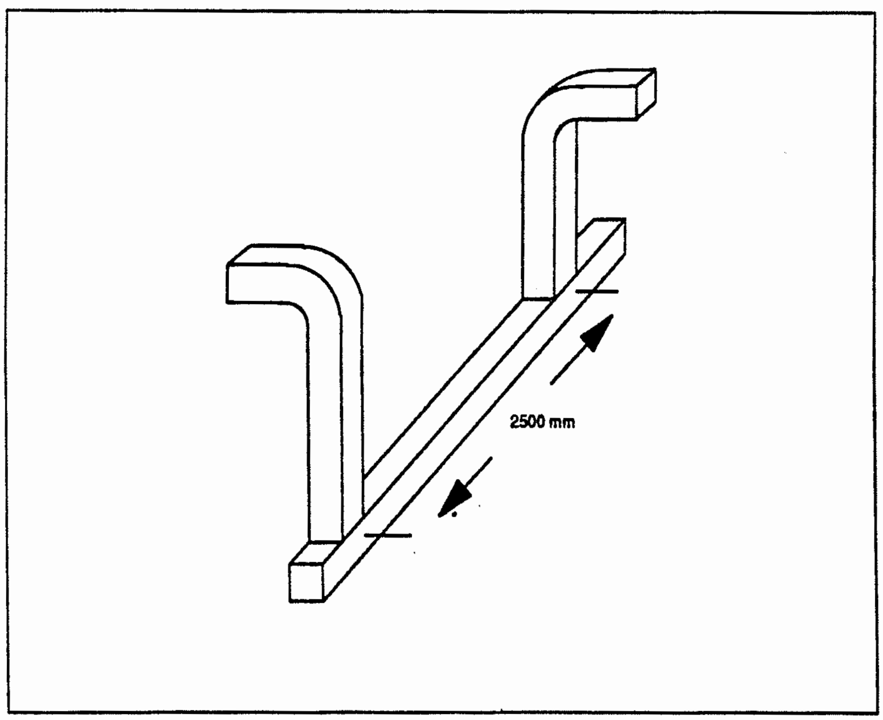
3. Handbook of Noise Control, Second Edition, Cyril M. Harris (Ed.), McGraw-Hill Book Company (1979).

APPENDIX A. SOUND ATTENUATION BY SPECIFIC DUCT CONFIGURATIONS TESTED

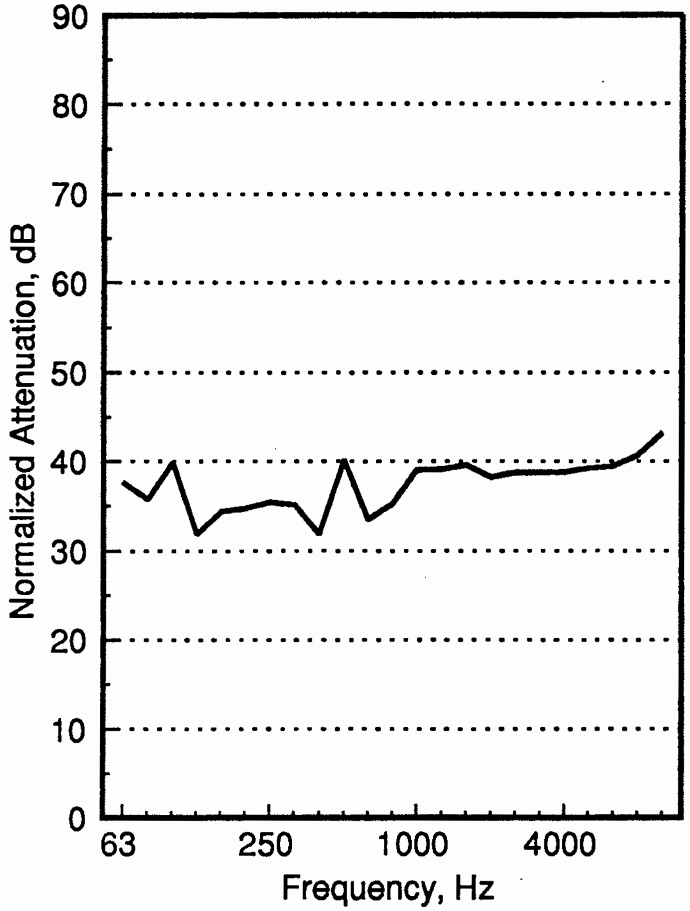
CASE A: Normalized attenuation for duct system A (two sidebranches joined to common duct at top, one bend in each sidebranch, no attenuators, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



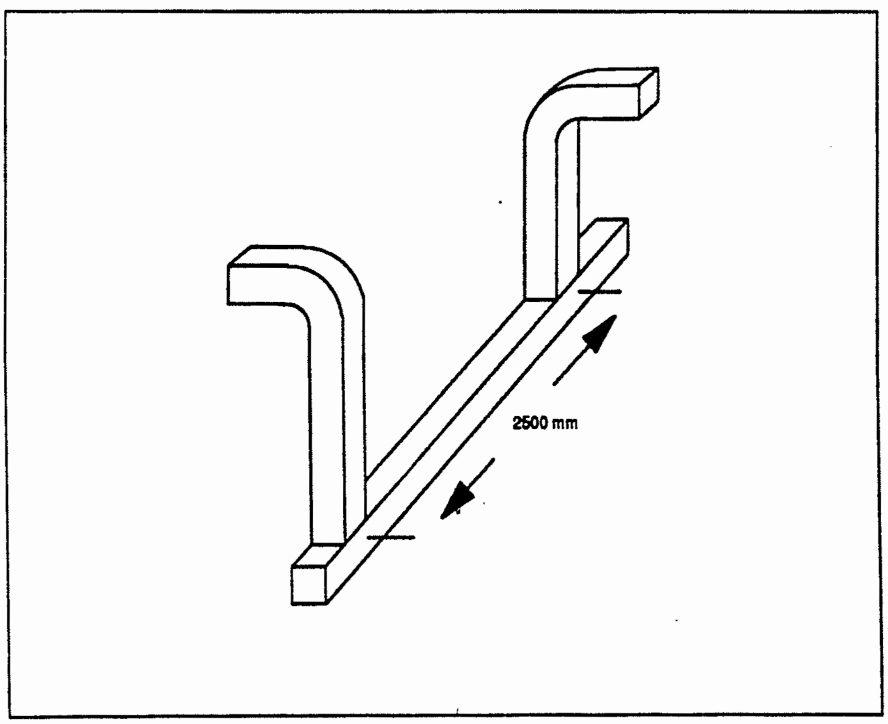
Frequency (Hz)	Normalized Attenuation (dB)
63	34.0
80	36.8
100	39.7
125	36.3
160	35.0
200	30.2
250	37.3
315	36.0
400	32.9
500	40.3
630	33.9
800	35.3
1000	36.7
1250	34.8
1600	35.7
2000	36.2
2500	36.7
3150	37.1
4000	37.9
5000	38.7
6300	39.3
8000	40.6
10000	43.1



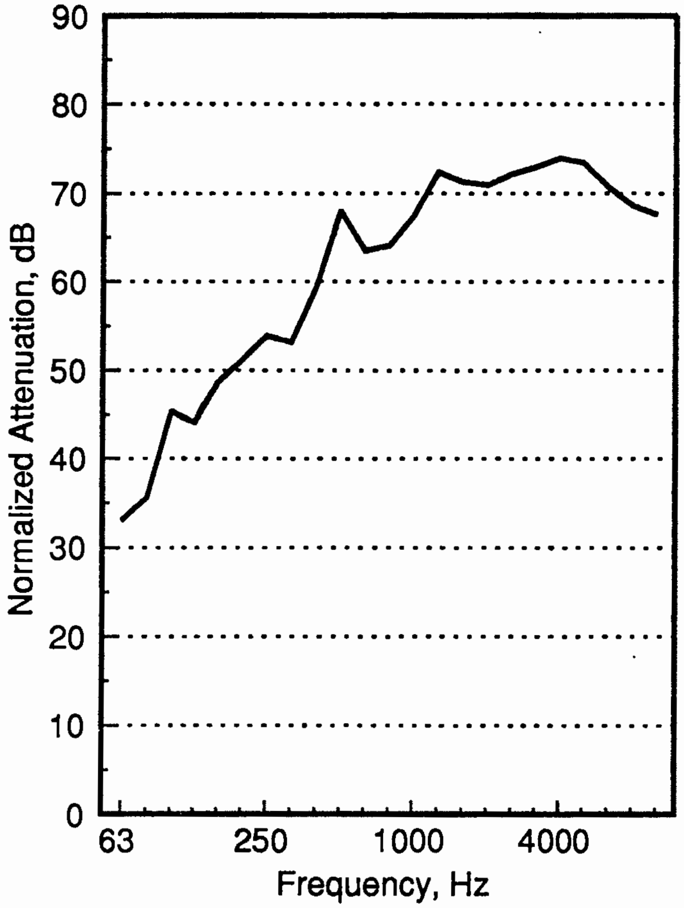
CASE B: Normalized attenuation for duct system B (two sidebranches joined to common duct at top, one bend in each sidebranch, no attenuators, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



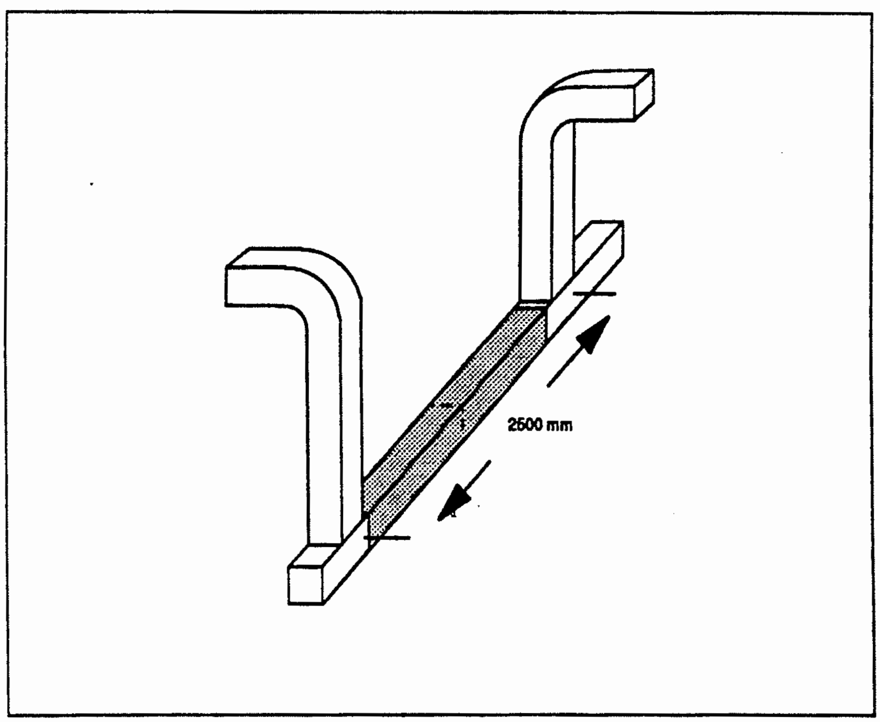
Frequency (Hz)	Normalized Attenuation (dB)
63	37.6
80	35.7
100	39.9
125	31.8
160	34.3
200	34.7
250	35.4
315	35.1
400	31.8
500	40.1
630	33.5
800	35.2
1000	39.0
1250	39.1
1600	39.6
2000	38.2
2500	38.7
3150	38.7
4000	38.8
5000	39.2
6300	39.4
8000	40.6
10000	43.1



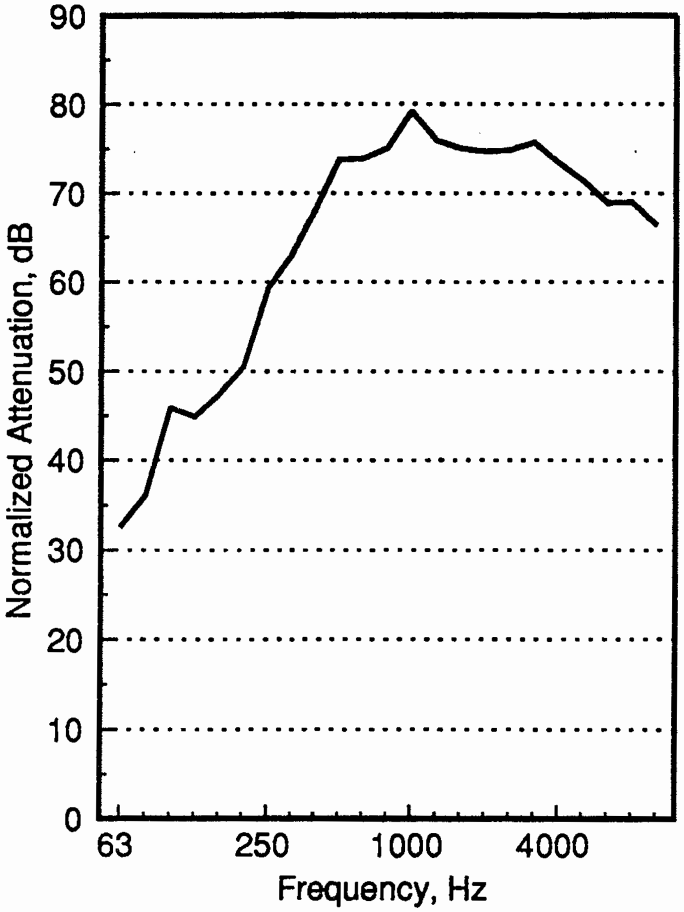
CASE C: Normalized attenuation for duct system C (two sidebranches joined to common duct at top, one bend in each sidebranch, two attenuators in common duct, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



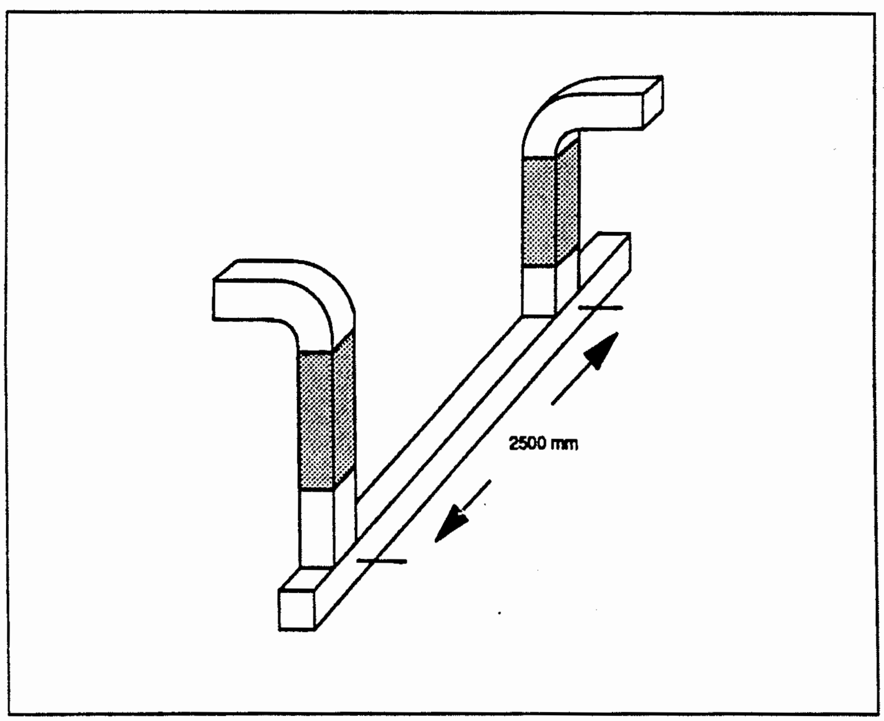
Frequency (Hz)	Normalized Attenuation (dB)
63	33.0
80	35.5
100	45.4
125	44.1
160	48.6
200	51.1
250	53.9
315	53.2
400	59.3
500	68.0
630	63.5
800	64.1
1000	67.4
1250	72.3
1600	71.3
2000	70.9
2500	72.1
3150	72.9
4000	73.9
5000	73.4
6300	70.7
8000	68.6
10000	67.6



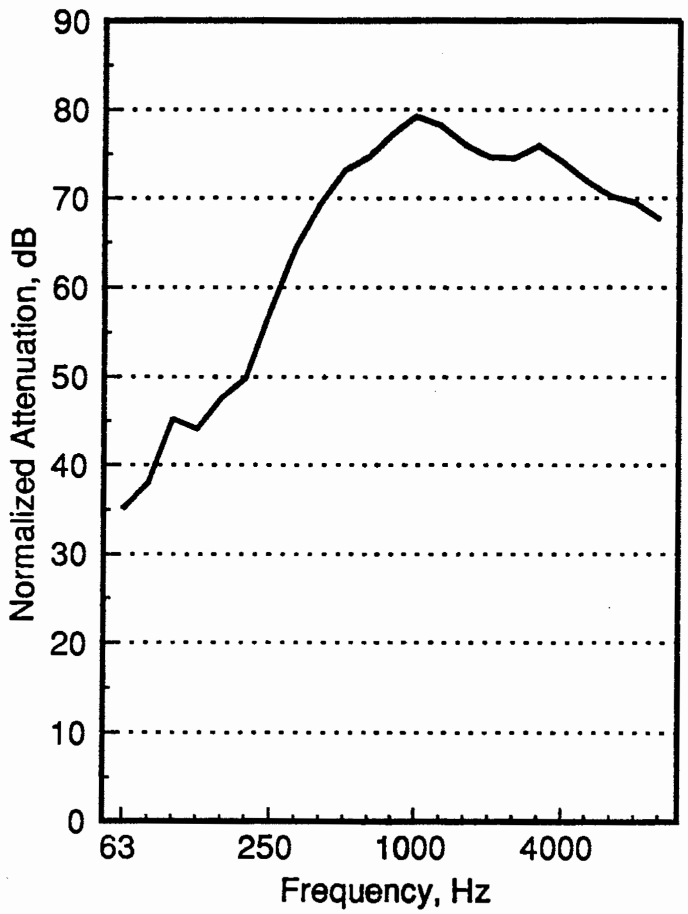
CASE D: Normalized attenuation for duct system D (two sidebranches joined to common duct at top, one bend in each sidebranch, one attenuator in each sidebranch, just below bend, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



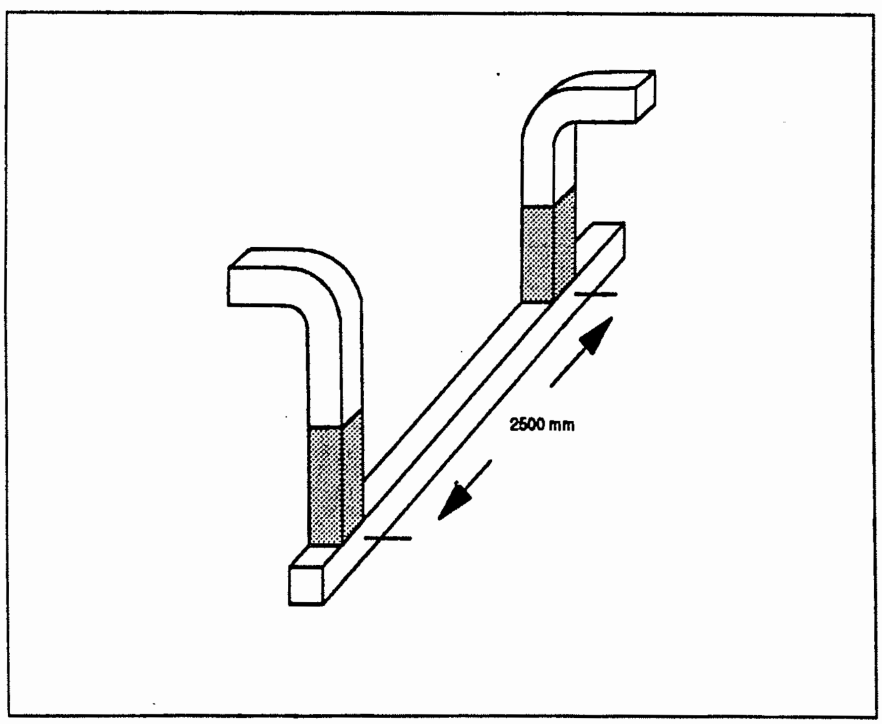
Frequency (Hz)	Normalized Attenuation (dB)
63	32.6
80	36.1
100	45.9
125	44.9
160	47.4
200	50.4
250	59.3
315	63.0
400	68.1
500	73.8
630	73.9
800	75.1
1000	79.2
1250	75.9
1600	75.1
2000	74.7
2500	74.8
3150	75.7
4000	73.4
5000	71.5
6300	68.9
8000	69.0
10000	66.4



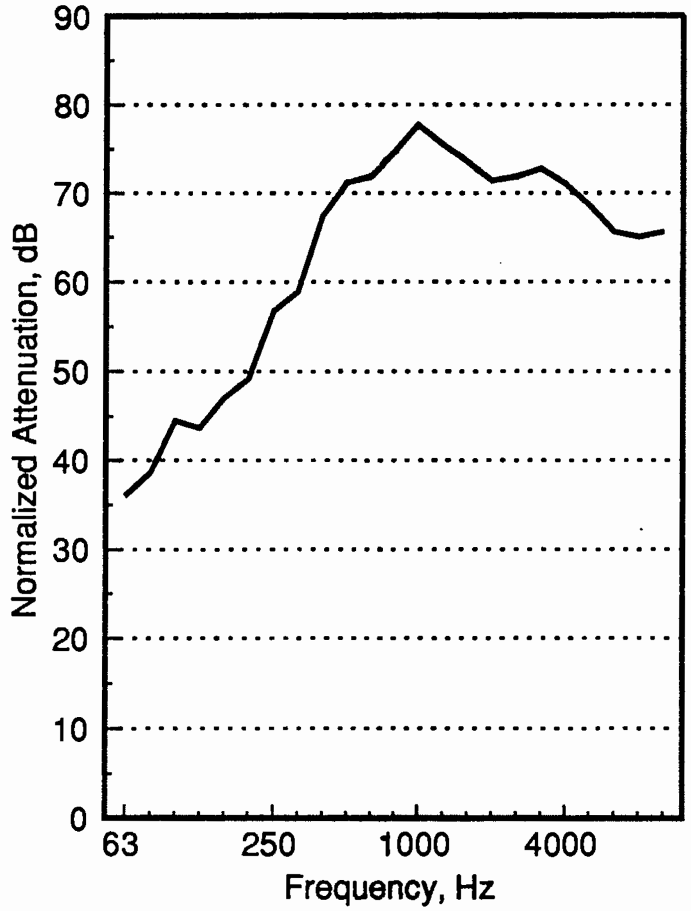
CASE E: Normalized attenuation for duct system E (two sidebranches joined to common duct at top, one bend in each sidebranch, one attenuator in each sidebranch at juncture with common duct, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



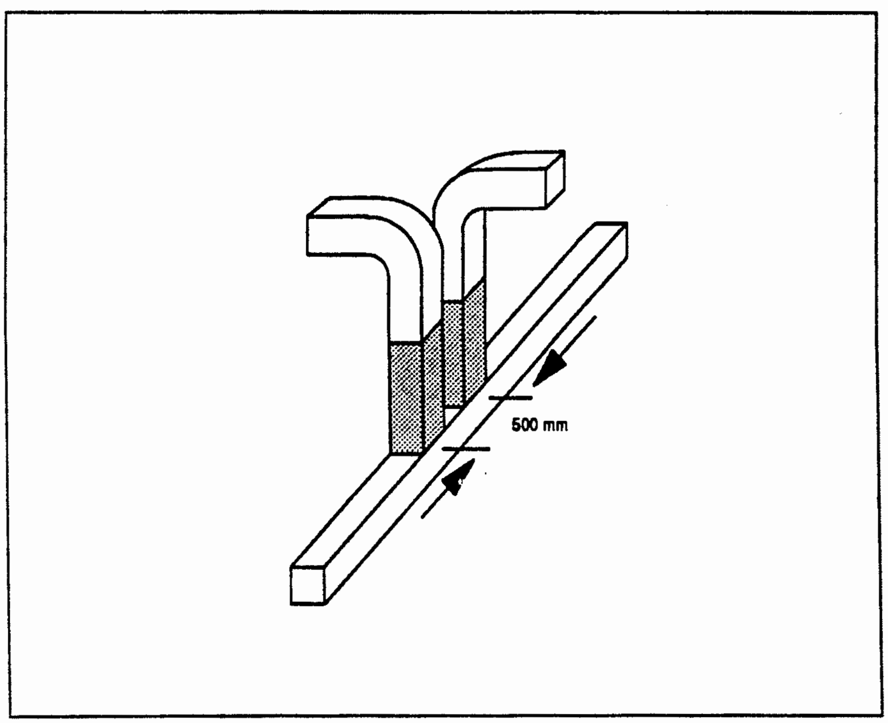
Frequency (Hz)	Normalized Attenuation (dB)
63	35.1
80	38.0
100	45.2
125	44.1
160	47.6
200	49.8
250	57.6
315	64.4
400	69.3
500	73.1
630	74.6
800	77.2
1000	79.2
1250	78.2
1600	76.0
2000	74.6
2500	74.5
3150	75.9
4000	74.1
5000	71.9
6300	70.2
8000	69.5
10000	67.6



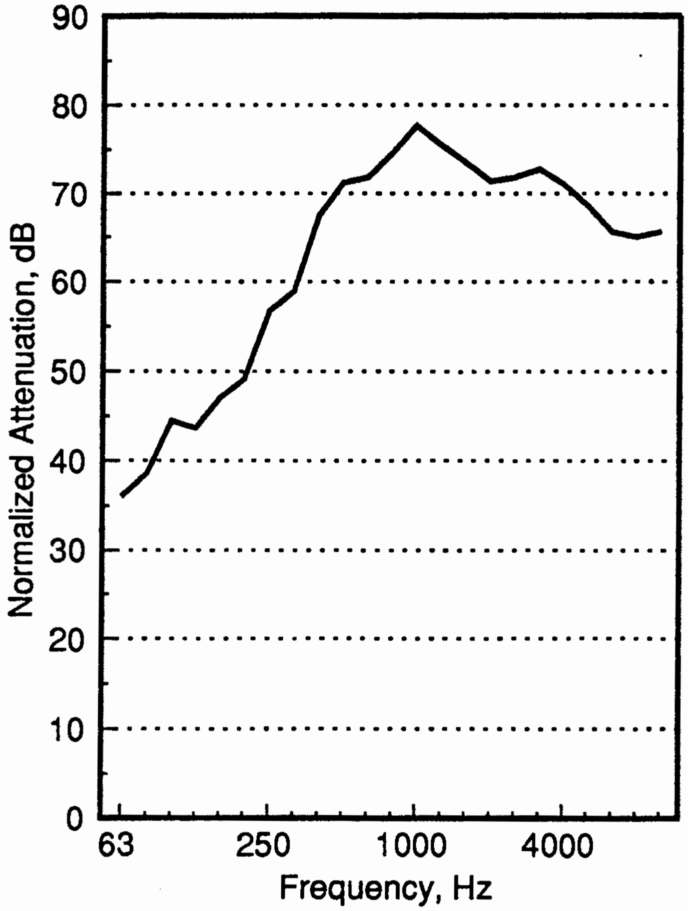
CASE F: Normalized attenuation for duct system F (two sidebranches joined to common duct at top, one bend in each sidebranch, one attenuator in each sidebranch at juncture with common duct, sidebranch separation .5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



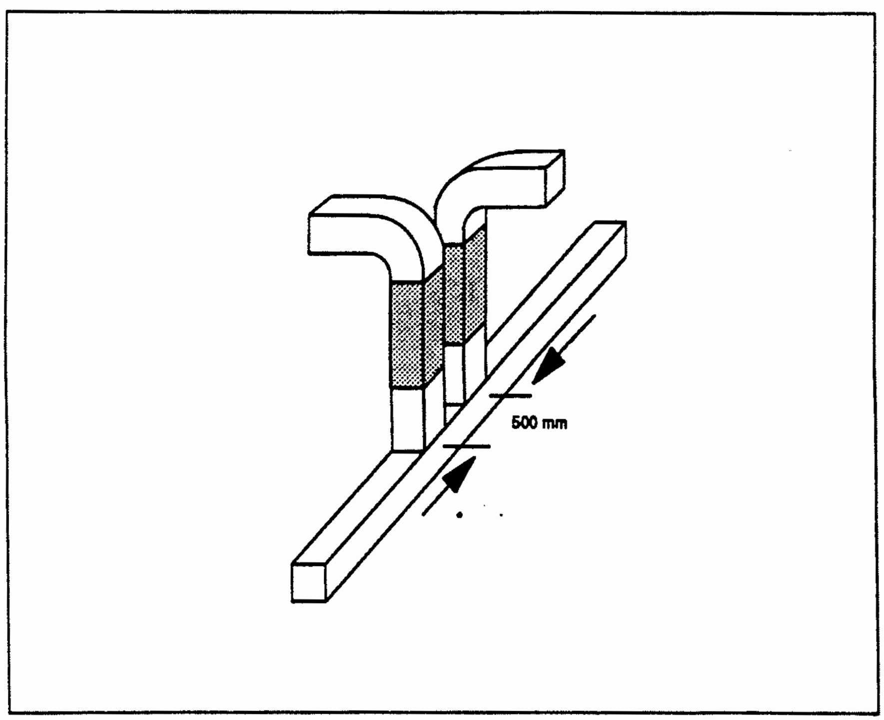
Frequency (Hz)	Normalized Attenuation (dB)
63	36.1
80	38.7
100	44.4
125	43.7
160	47.0
200	49.1
250	56.7
315	58.9
400	67.4
500	71.2
630	71.8
800	74.6
1000	77.7
1250	75.5
1600	73.5
2000	71.4
2500	71.8
3150	72.8
4000	71.0
5000	68.6
6300	65.6
8000	65.0
10000	65.6



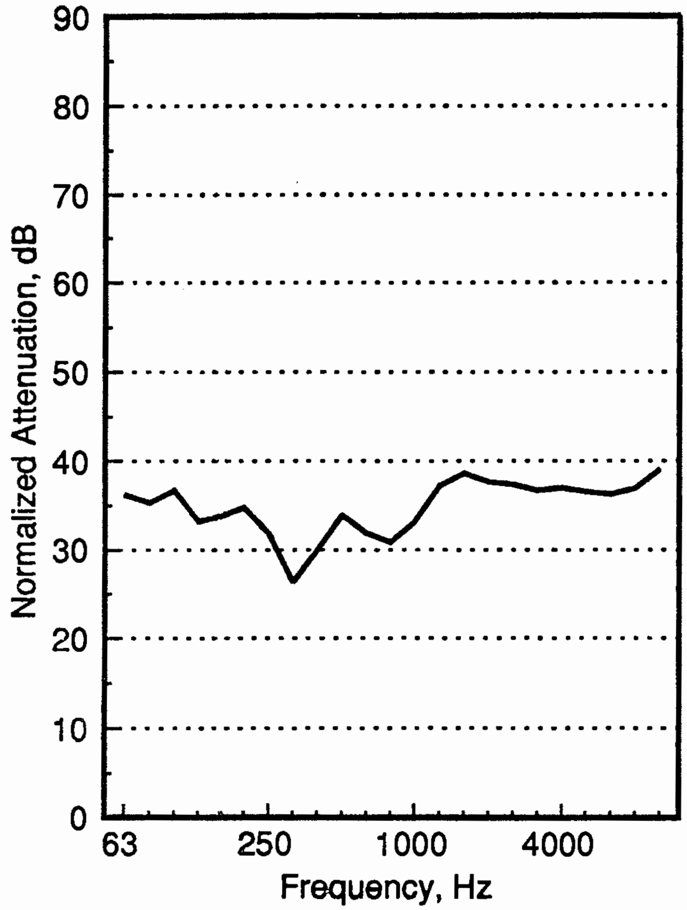
CASE G: Normalized attenuation for duct system G (two sidebranches joined to common duct at top, one bend in each sidebranch, one attenuator in each sidebranch just below bend, sidebranch separation .5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



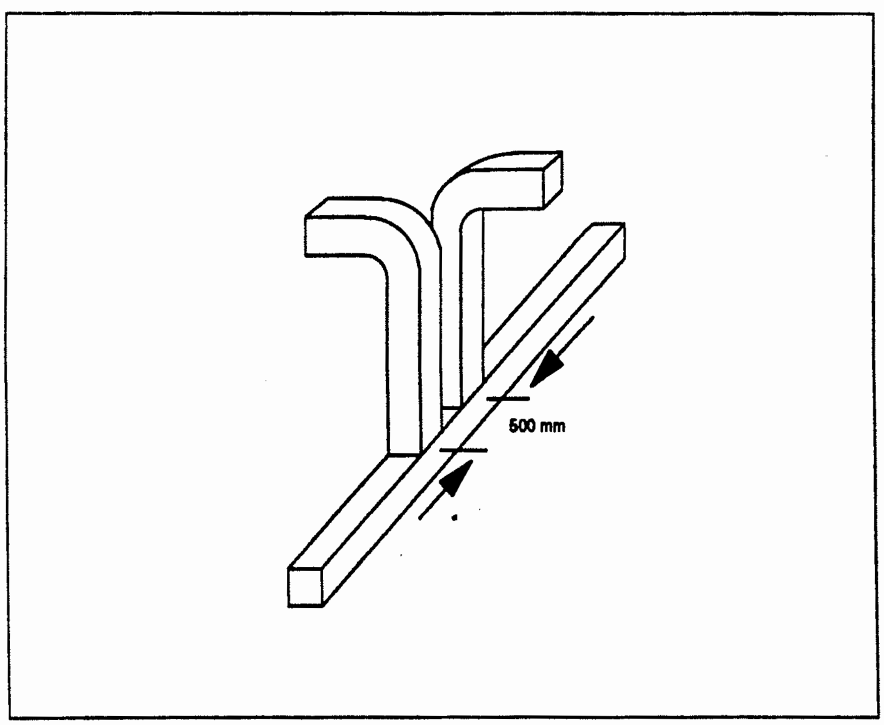
Frequency (Hz)	Normalized Attenuation (dB)
63	35.8
80	38.1
100	43.5
125	44.1
160	46.8
200	49.1
250	56.7
315	55.8
400	67.2
500	70.9
630	68.7
800	69.8
1000	74.5
1250	72.6
1600	73.0
2000	71.0
2500	69.6
3150	71.0
4000	70.4
5000	68.0
6300	64.4
8000	64.2
10000	66.3



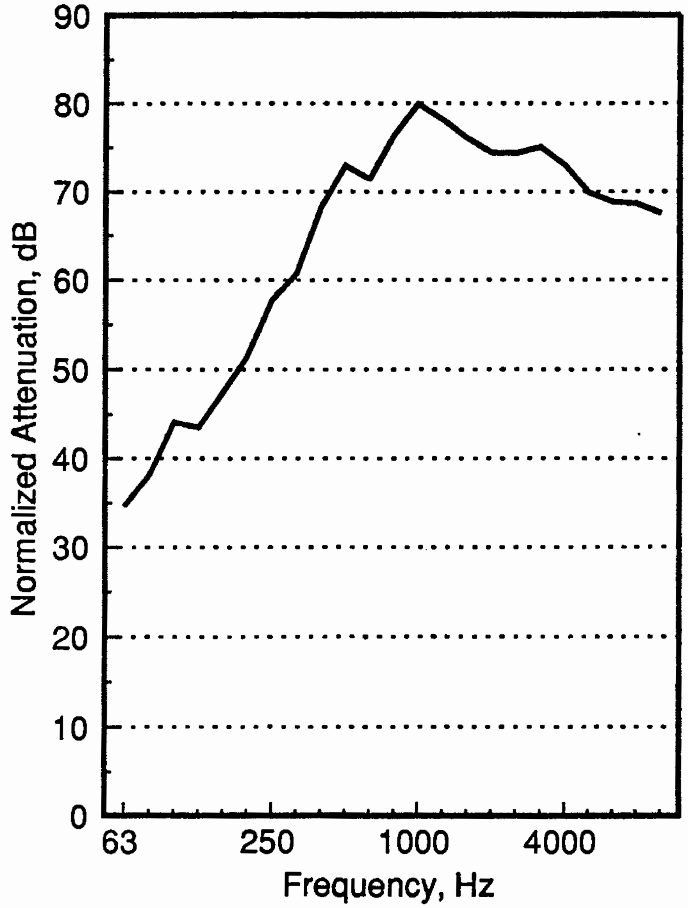
CASE H: Normalized attenuation for duct system H (two sidebranches joined to common duct at top, one bend in each sidebranch, no attenuators, sidebranch separation .5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



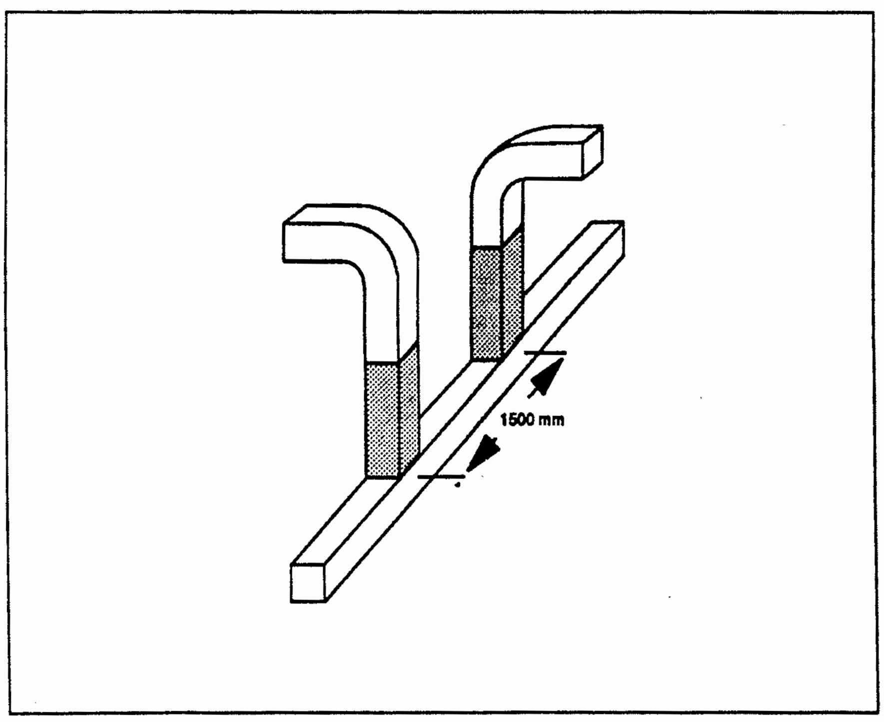
Frequency (Hz)	Normalized Attenuation (dB)
63	36.2
80	35.3
100	36.7
125	33.2
160	33.8
200	34.8
250	31.8
315	26.3
400	30.0
500	33.9
630	31.9
800	30.8
1000	33.1
1250	37.2
1600	38.7
2000	37.6
2500	37.4
3150	36.7
4000	37.0
5000	36.6
6300	36.3
8000	36.9
10000	39.1



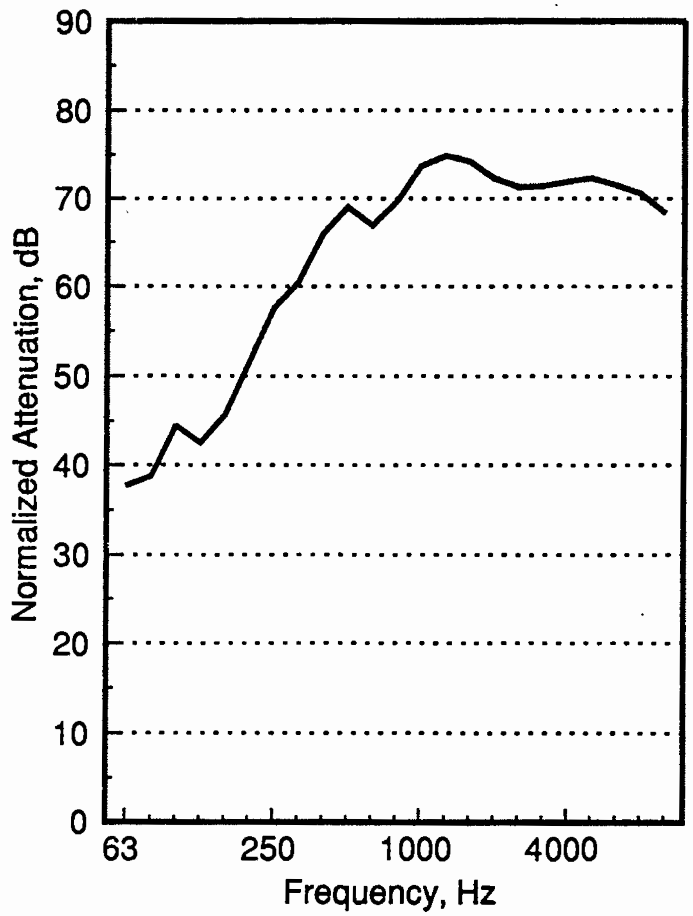
CASE I: Normalized attenuation for duct system I (two sidebranches joined to common duct at top, one bend in each sidebranch, one attenuator in each sidebranch at juncture with common duct, sidebranch separation 1.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



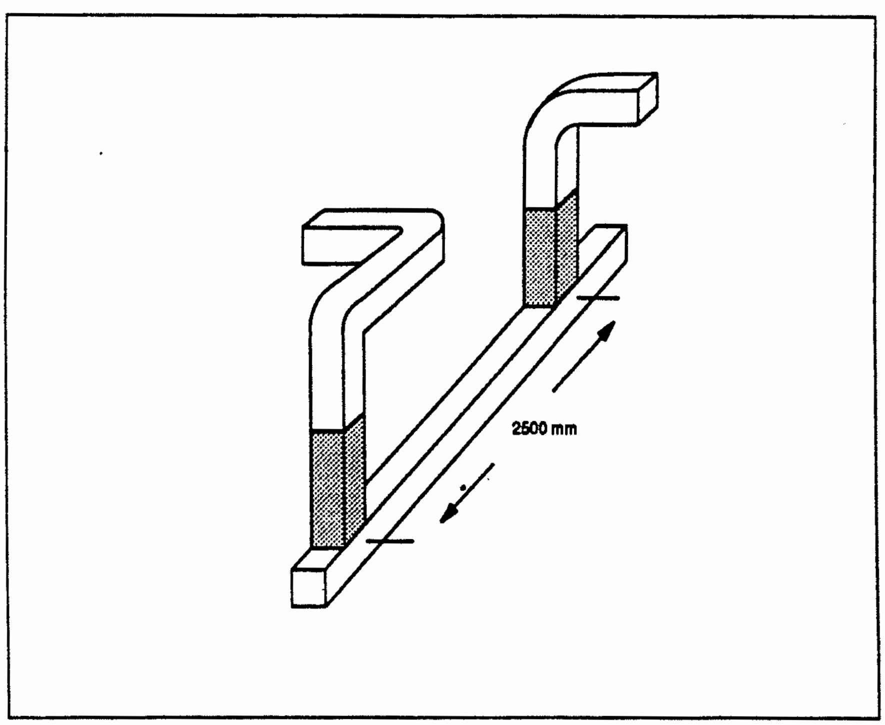
Frequency (Hz)	Normalized Attenuation (dB)
63	34.6
80	38.1
100	44.1
125	43.5
160	47.5
200	51.4
250	57.8
315	60.7
400	68.2
500	72.9
630	71.4
800	76.4
1000	79.9
1250	78.1
1600	76.0
2000	74.4
2500	74.3
3150	75.1
4000	73.0
5000	69.9
6300	68.8
8000	68.6
10000	67.5



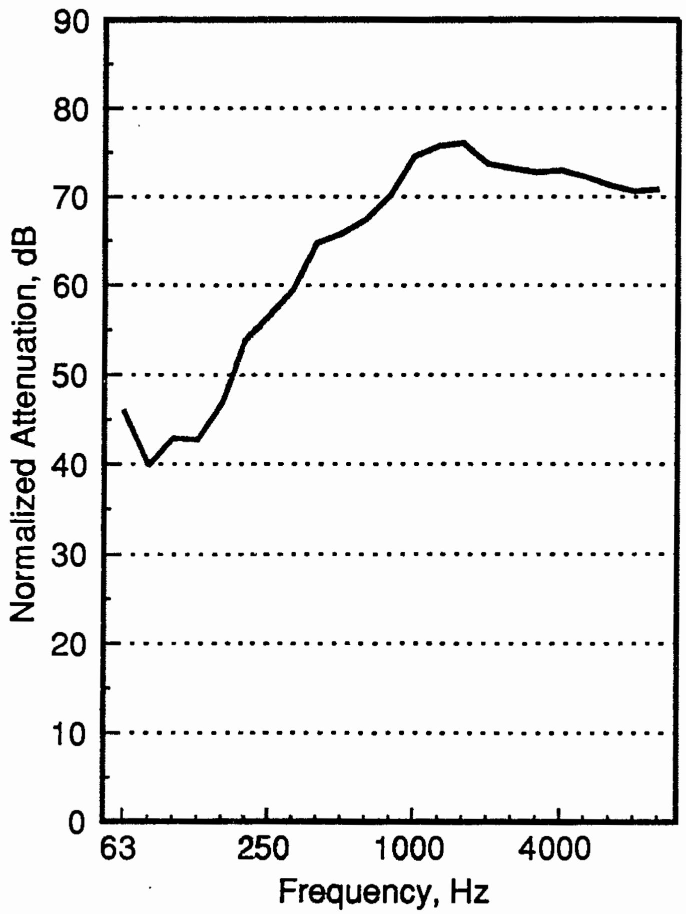
CASE J: Normalized attenuation for duct system J (two sidebranches joined to common duct at top, one bend in one sidebranch, two bends in the second sidebranch, one attenuator in each sidebranch at the juncture with the common duct, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



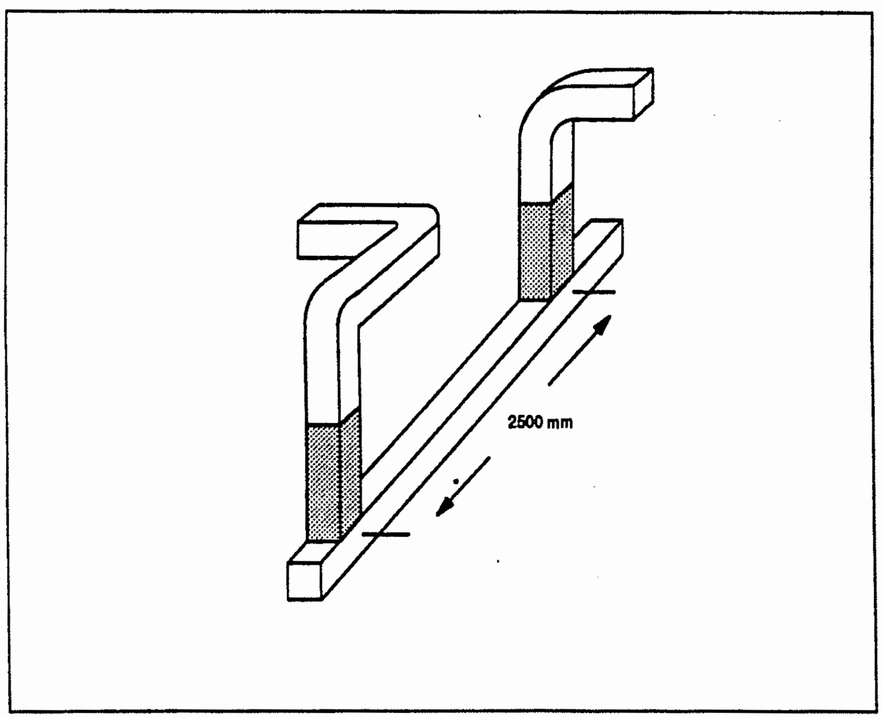
Frequency (Hz)	Normalized Attenuation (dB)
63	37.7
80	38.8
100	44.4
125	42.5
160	45.6
200	51.4
250	57.6
315	60.5
400	65.9
500	69.0
630	66.9
800	69.6
1000	73.6
1250	74.8
1600	74.2
2000	72.2
2500	71.3
3150	71.4
4000	71.9
5000	72.3
6300	71.5
8000	70.5
10000	68.3



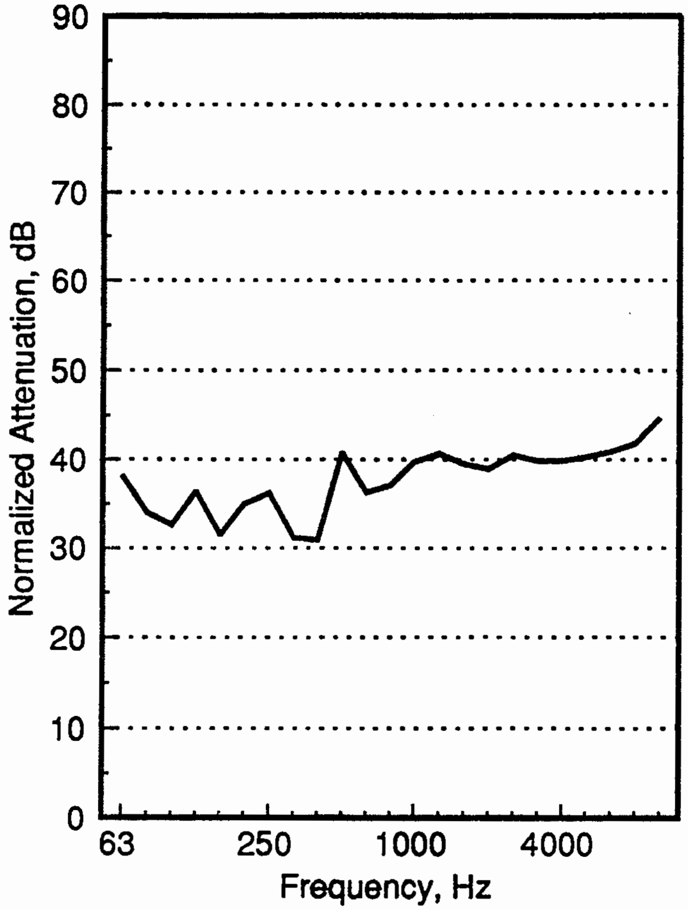
CASE K: Normalized attenuation for duct system K (two sidebranches joined to common duct at top, one bend in one sidebranch, two bends in the second sidebranch, one attenuator in each sidebranch at the juncture with the common duct, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



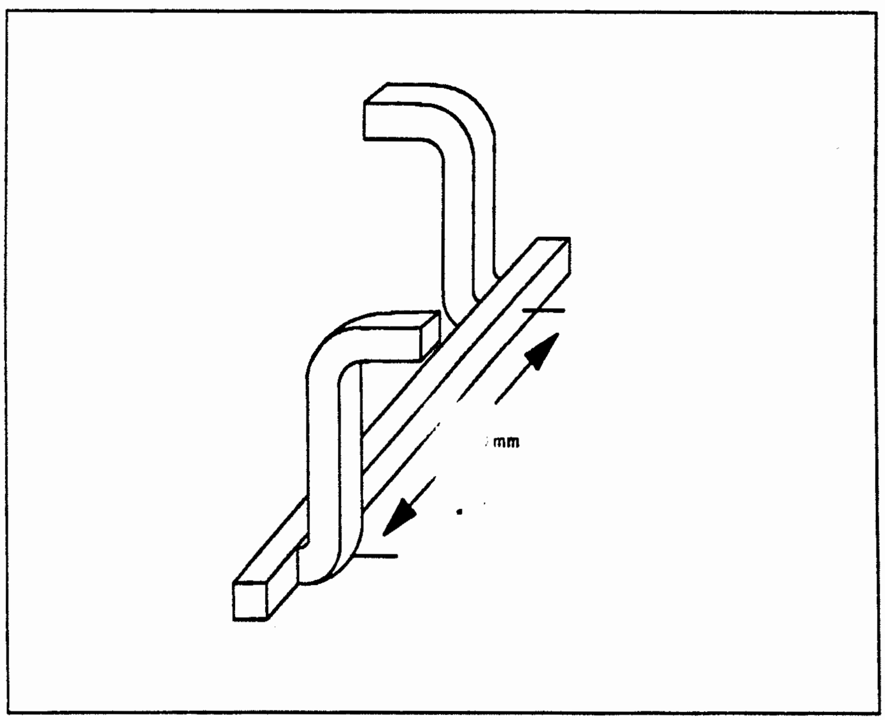
Frequency (Hz)	Normalized Attenuation (dB)
63	46.0
80	39.9
100	42.9
125	42.7
160	46.8
200	53.8
250	56.5
315	59.5
400	64.7
500	65.8
630	67.4
800	70.1
1000	74.5
1250	75.7
1600	76.0
2000	73.7
2500	73.2
3150	72.8
4000	73.0
5000	72.2
6300	71.3
8000	70.6
10000	70.8



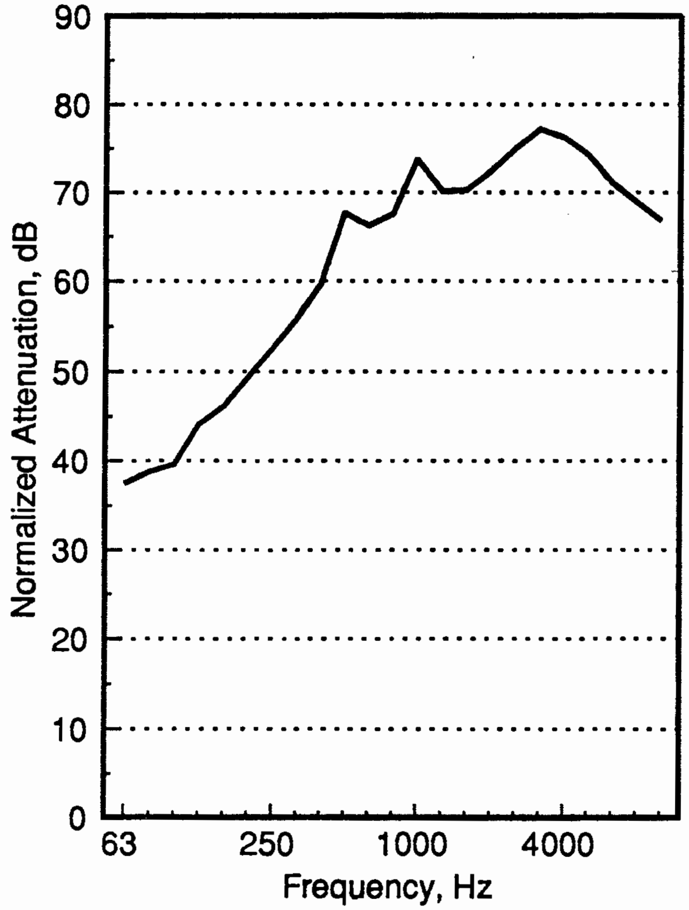
CASE L: Normalized attenuation for duct system L (two sidebranches joined to common duct at sides, two bends in each sidebranch, no attenuators, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



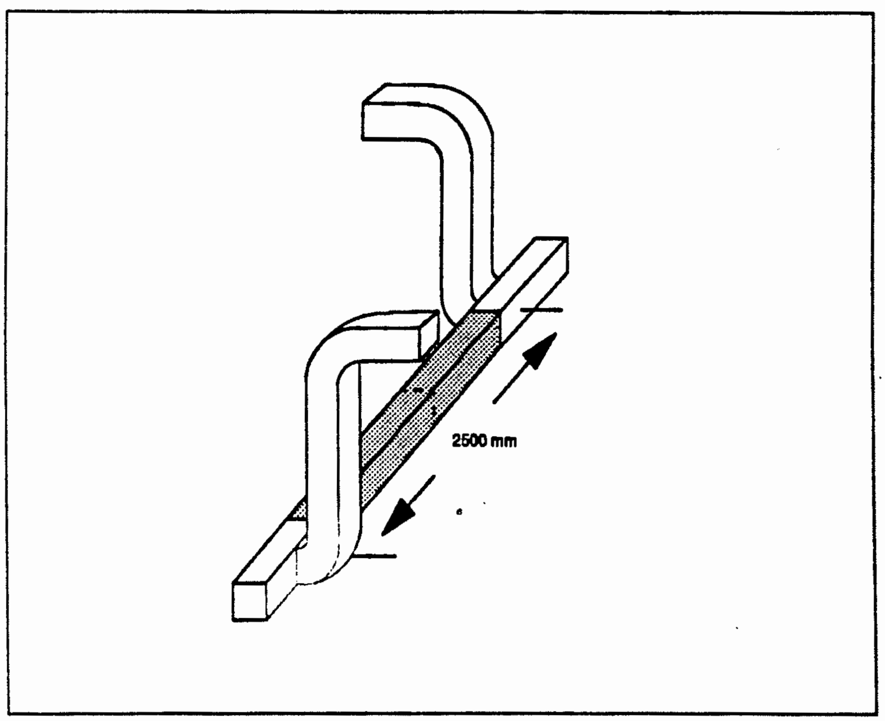
Frequency (Hz)	Normalized Attenuation (dB)
63	38.2
80	34.0
100	32.6
125	36.4
160	31.5
200	35.0
250	36.2
315	31.2
400	30.9
500	40.8
630	36.3
800	37.1
1000	39.7
1250	40.6
1600	39.5
2000	38.9
2500	40.5
3150	39.9
4000	39.9
5000	40.3
6300	40.9
8000	41.8
10000	44.7



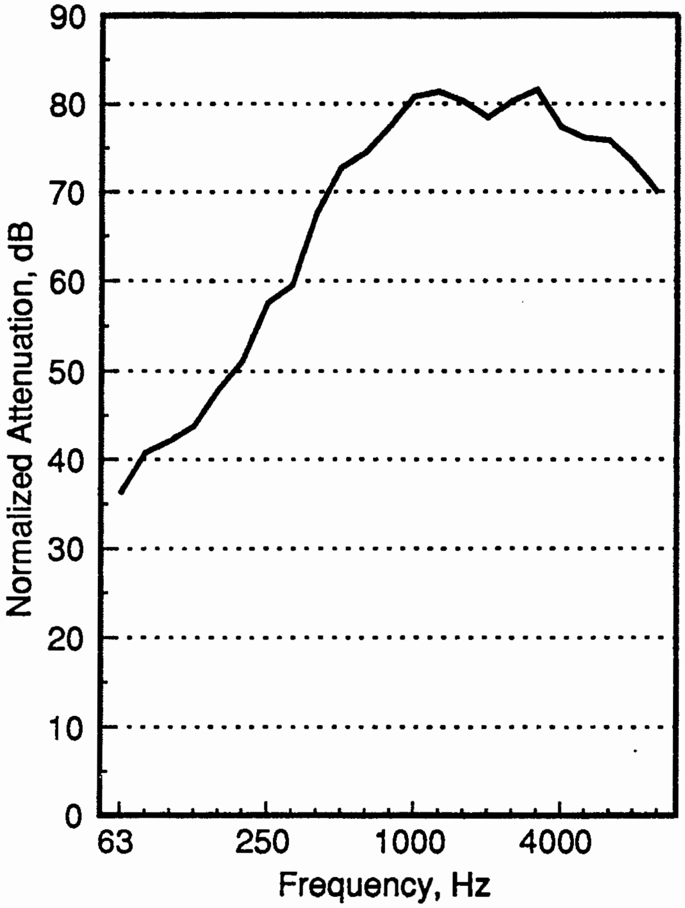
CASE M: Normalized attenuation for duct system M (two sidebranches joined to common duct at sides, two bends in each sidebranch, two attenuators in common duct, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



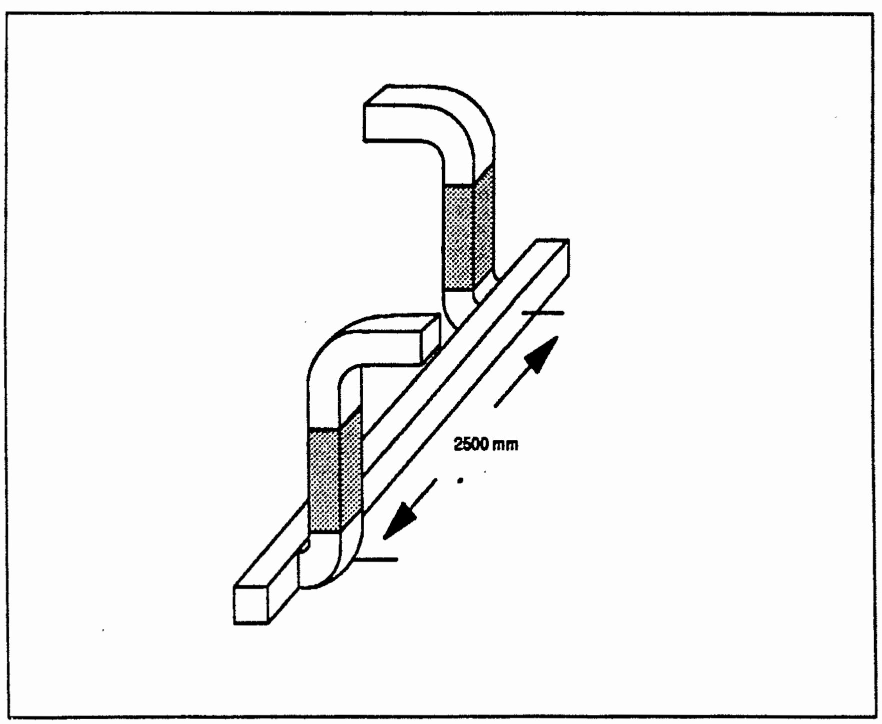
Frequency (Hz)	Normalized Attenuation (dB)
63	37.5
80	38.8
100	39.6
125	44.1
160	46.1
200	49.3
250	52.6
315	55.9
400	59.6
500	67.7
630	66.2
800	67.6
1000	73.8
1250	70.1
1600	70.3
2000	72.4
2500	75.0
3150	77.2
4000	76.3
5000	74.3
6300	71.0
8000	68.9
10000	66.8



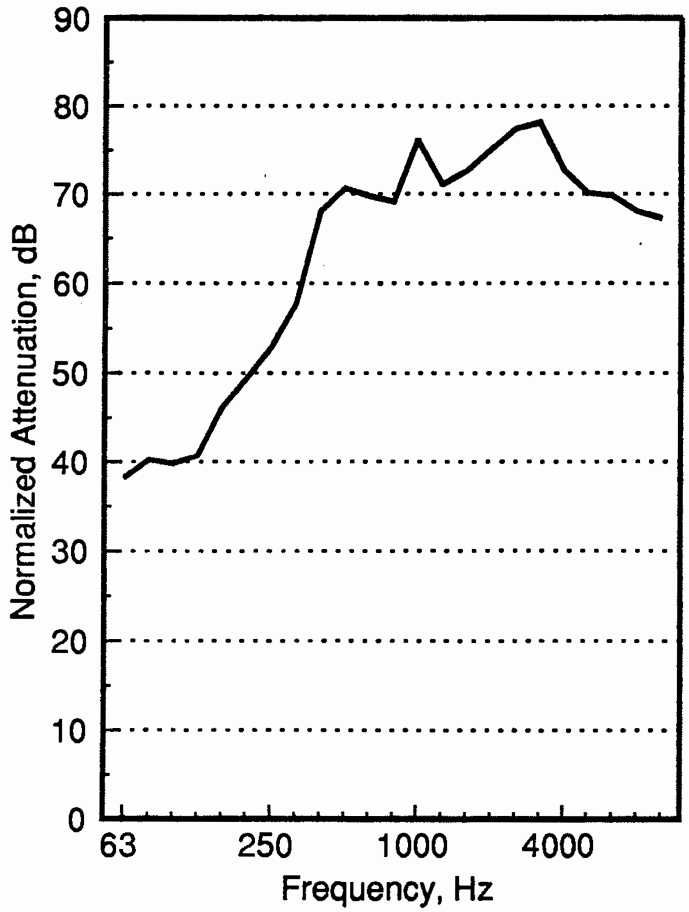
CASE N: Normalized attenuation for duct system N (two sidebranches joined to common duct at sides, two bends in each sidebranch, one attenuator in each sidebranch above juncture with common duct, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



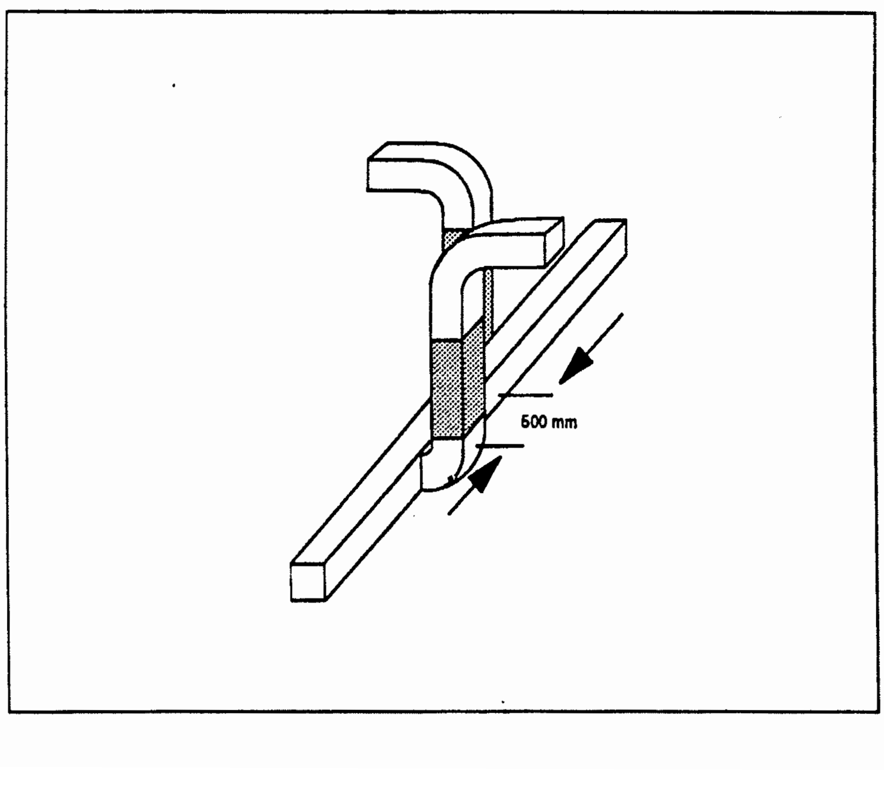
Frequency (Hz)	Normalized Attenuation (dB)
63	36.2
80	40.8
100	42.1
125	43.8
160	47.9
200	51.1
250	57.6
315	59.5
400	67.5
500	72.7
630	74.4
800	77.4
1000	80.8
1250	81.4
1600	80.3
2000	78.4
2500	80.3
3150	81.6
4000	77.3
5000	76.0
6300	75.8
8000	73.2
10000	69.9



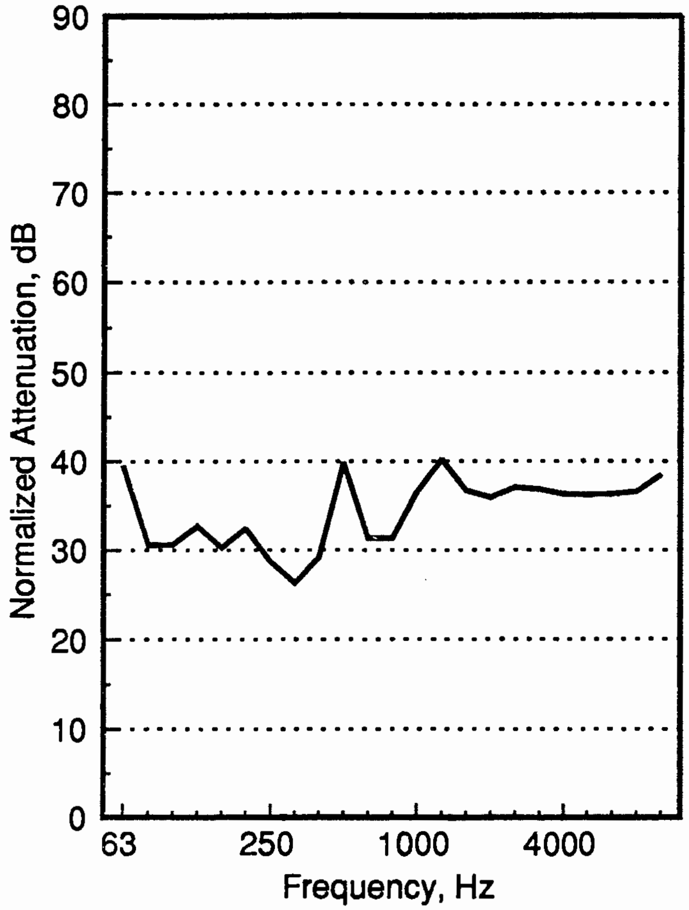
CASE O: Normalized attenuation for duct system O (two sidebranches joined to common duct at sides, two bends in each sidebranch, one attenuator in each sidebranch above juncture with common duct, sidebranch separation .5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



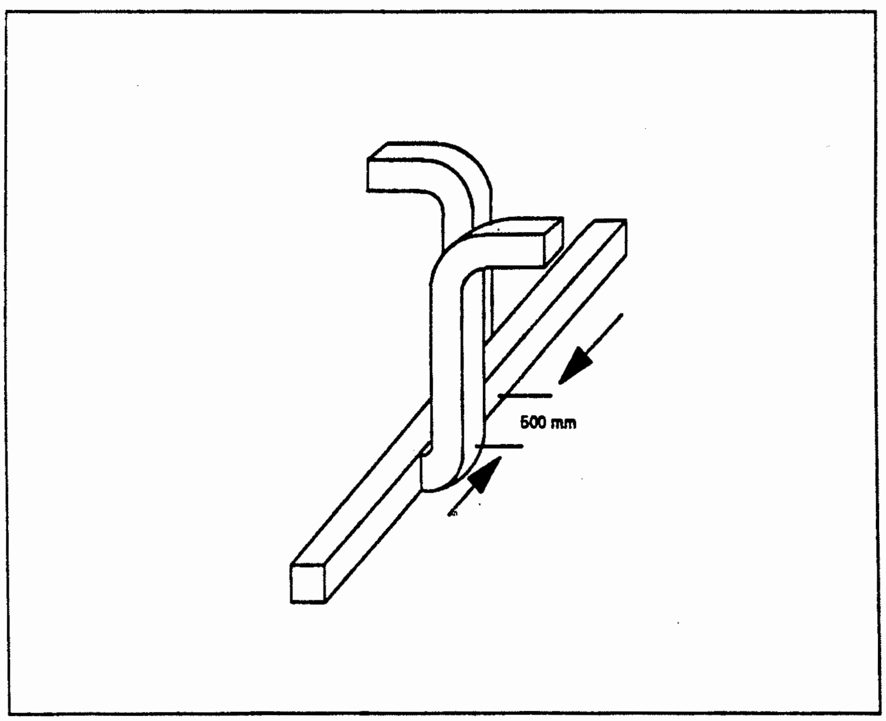
Frequency (Hz)	Normalized Attenuation (dB)
63	38.2
80	40.2
100	39.8
125	40.7
160	46.1
200	49.3
250	52.8
315	57.8
400	68.0
500	70.6
630	69.7
800	69.1
1000	76.1
1250	71.0
1600	72.6
2000	75.1
2500	77.4
3150	78.1
4000	72.7
5000	70.1
6300	69.7
8000	68.0
10000	67.2



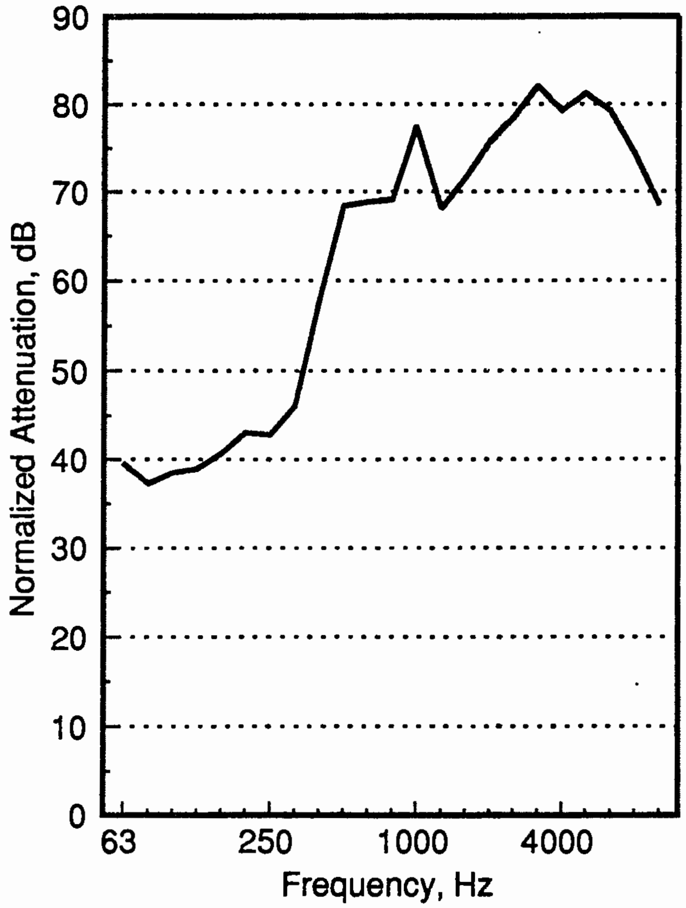
CASE P: Normalized attenuation for duct system P (two sidebranches joined to common duct at sides, two bends in each sidebranch, no attenuators, sidebranch separation .5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



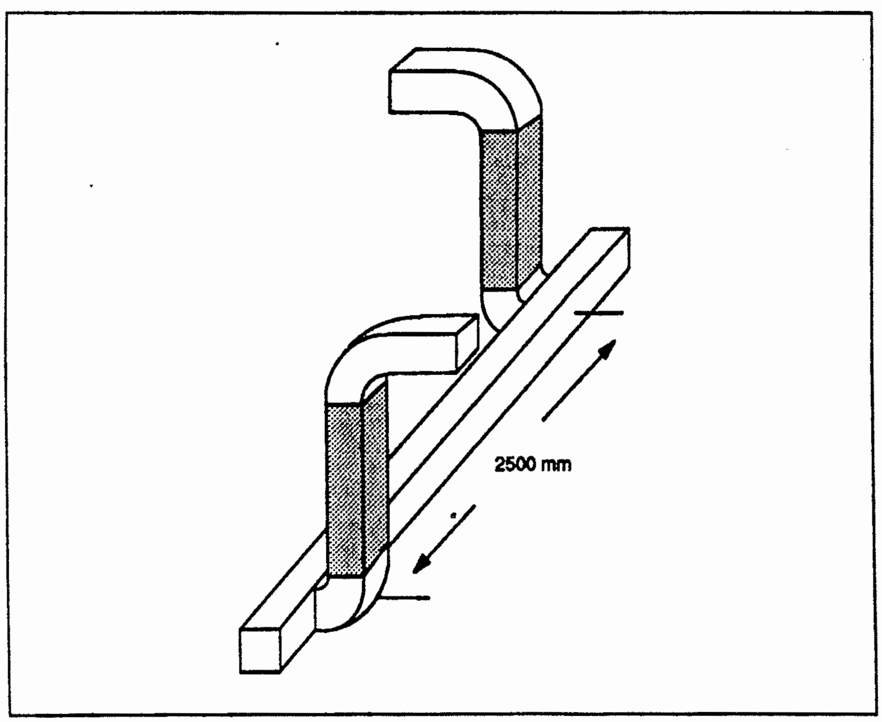
Frequency (Hz)	Normalized Attenuation (dB)
63	39.5
80	30.5
100	30.6
125	32.7
160	30.3
200	32.4
250	28.7
315	26.3
400	29.1
500	39.9
630	31.3
800	31.3
1000	36.5
1250	40.2
1600	36.7
2000	35.9
2500	37.1
3150	36.8
4000	36.3
5000	36.2
6300	36.3
8000	36.6
10000	38.4



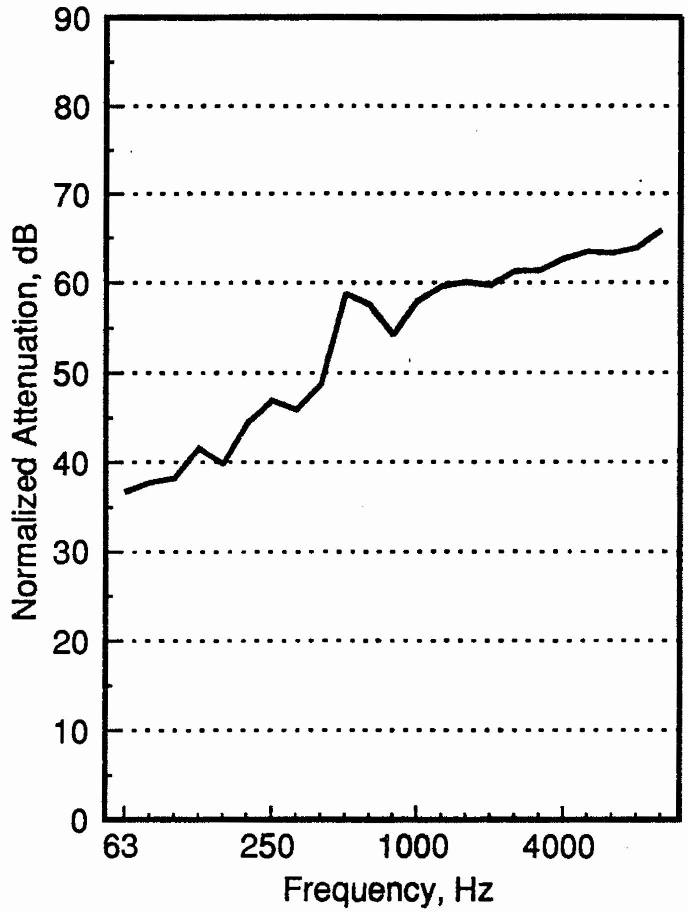
CASE Q: Normalized attenuation for duct system Q (two sidebranches joined to common duct at sides, one bend in each sidebranch, foam in each sidebranch between bends, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



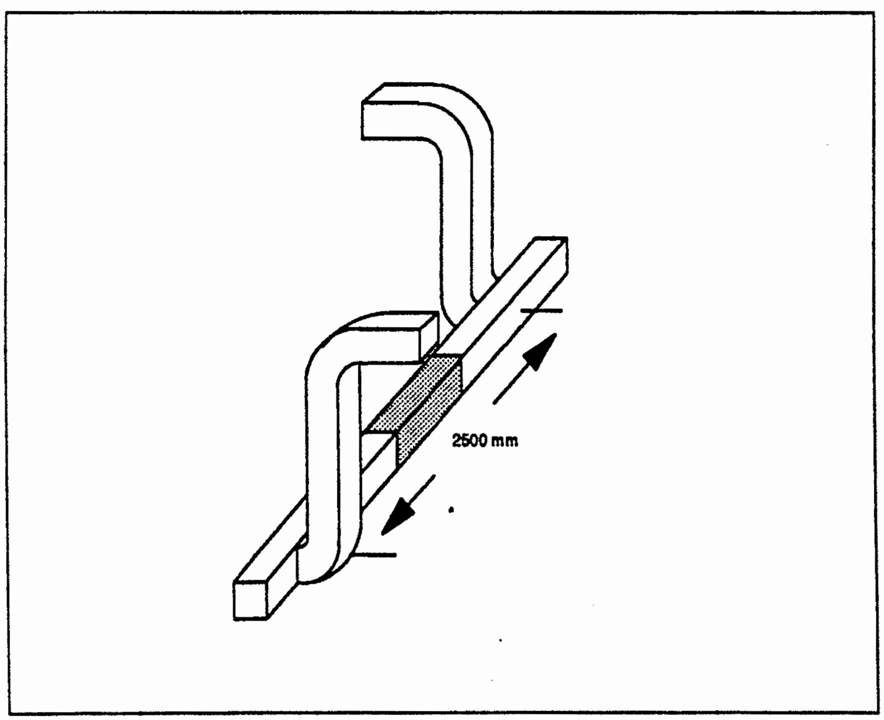
Frequency (Hz)	Normalized Attenuation (dB)
63	39.6
80	37.3
100	38.5
125	38.9
160	40.6
200	43.0
250	42.8
315	46.0
400	57.9
500	68.3
630	68.8
800	69.1
1000	77.5
1250	68.0
1600	71.6
2000	75.6
2500	78.4
3150	82.1
4000	79.3
5000	81.2
6300	79.2
8000	74.3
10000	68.4



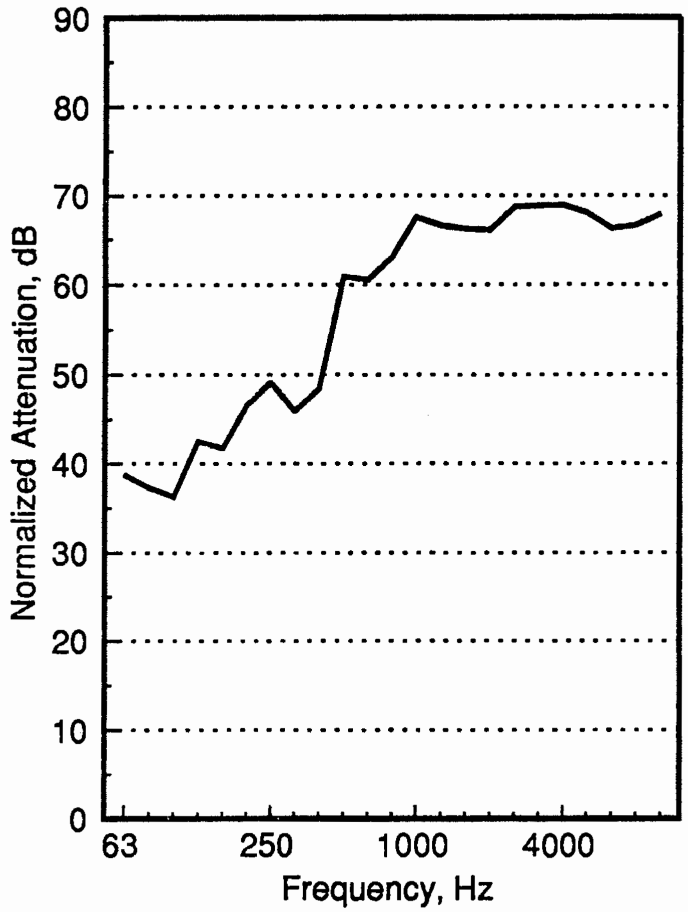
CASE R: Normalized attenuation for duct system R (two sidebranches joined to common duct at sides, two bends in each sidebranch, one attenuator in common duct, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



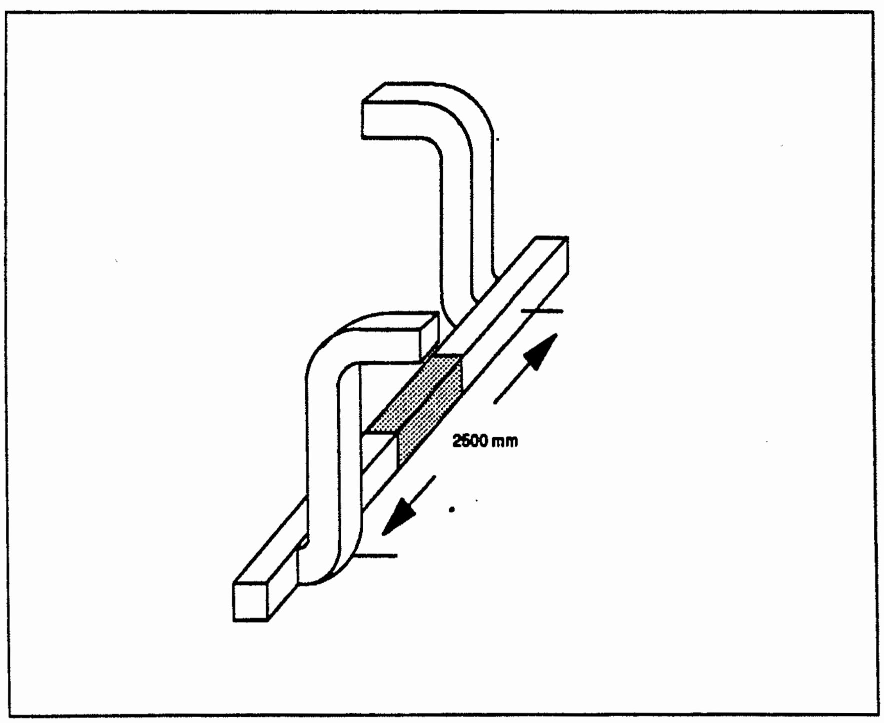
Frequency (Hz)	Normalized Attenuation (dB)
63	36.7
80	37.7
100	38.2
125	41.6
160	39.8
200	44.3
250	46.9
315	45.9
400	48.7
500	58.8
630	57.6
800	54.2
1000	57.9
1250	59.6
1600	60.1
2000	59.7
2500	61.3
3150	61.4
4000	62.7
5000	63.4
6300	63.3
8000	63.9
10000	65.8



CASE S: Normalized attenuation for duct system S (two sidebranches joined to common duct at sides, two bends in each sidebranch, one attenuator in common duct, sidebranch separation 2.5 m). Attenuation normalized to attenuation expected for receiving room absorption of 12 metric sabins.



Frequency (Hz)	Normalized Attenuation (dB)
63	38.8
80	37.3
100	36.3
125	42.5
160	41.7
200	46.5
250	49.1
315	45.9
400	48.4
500	60.9
630	60.6
800	63.1
1000	67.5
1250	66.6
1600	66.2
2000	66.1
2500	68.7
3150	68.8
4000	68.9
5000	68.0
6300	66.2
8000	66.6
10000	67.9



Appendix B. Calculation of duct attenuation

There are a number of empirical design procedures for calculating sound transmission through duct systems. By far the most widely used is the ASHRAE method, but many textbooks have similar models. Unfortunately, the details of the predictions by various models differ significantly in some important cases.

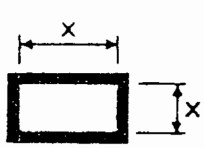
No extensive controlled experimental studies to validate the models appear to be available. The data on which these predictions are based appear to be from many sources, and of dubious precision. Presumably, this accounts for the differences among the many prediction models.

Validating a design method was a central goal of this study, and the ASHRAE model (and others) were therefore compared with the data from this study. Three models are listed as references below, and parts of the model from Reference 2 are reproduced here to illustrate the basic concepts.

The Design Method

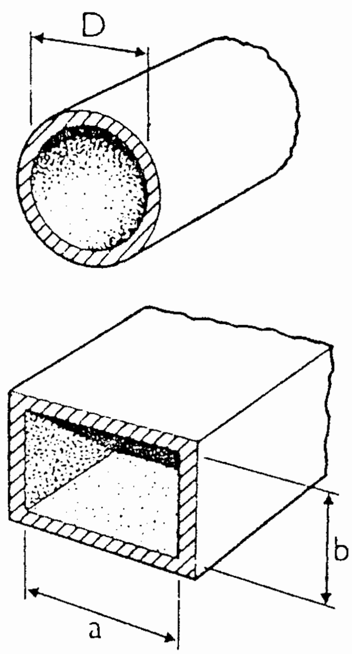
Sound transmission along a straight unlined section of duct is slightly attenuated, primarily by transmission of sound energy through the duct walls. This attenuation is greater for rectangular ducts than for round ones, but is unlikely to introduce significant sound reduction in the short distances pertinent for cross-talk. Table B1 presents values of the attenuation per metre (in dB/m) for typical cross-sections. For rectangular ductwork, the attenuation for each dimension should be calculated separately, and then added.

Table B1

Circular/oval	x (mm)	Octave Band Centre Frequency (Hz)						
		63	125	250	500	1k	2k	4k
	75–200	0.14	0.20	0.20	0.32	0.33	0.33	0.33
	200 – 400	0.14	0.20	0.20	0.32	0.23	0.23	0.23
	400–800	0.14	0.14	0.14	0.20	0.16	0.16	0.16
	800–1500	0.06	0.06	0.06	0.14	0.07	0.07	0.07
Rectangular	x (mm) side dimension	Octave Band Centre Frequency (Hz)						
		63	125	250	500	1k	2k	4k
	75–200	0.33	0.66	1.00	0.66	0.33	0.33	0.33
	200–400	1.00	1.32	1.00	0.66	0.23	0.23	0.23
	400–800	1.64	1.32	0.66	0.32	0.16	0.16	0.16
	800–1500	1.32	0.66	0.32	0.20	0.07	0.07	0.07

Sound attenuation by ductwork lined with absorptive material depends on the thickness and sound absorption properties of the material, the dimensions of the clear cross-section, and the sound frequency. The attenuation at low frequency is significantly less than that at higher frequencies (1000 to 4000 Hz). Figure B.1 presents an expression for calculating the attenuation per metre of lining. Examples applying this are given later.

Figure B.1



$$\text{Attenuation} = 1.07 \left(\frac{P}{S} \right) \alpha^{1.4} \text{ dB/metre} \ldots\ldots\ldots\ldots$$

where P = perimeter (inside) of lining, m
S = cross sectional area of duct, m^2
α = absorption coefficient

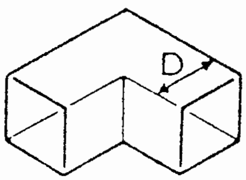
Constraints:

accuracy $\pm$ 10%
frequency range 250 to 2000 Hz
$\alpha \leq 0.8$
for circular duct $D > 0.15$ m
for rectangular ducts a or b $\leq$ 900 mm
and $0.5 < \frac{a}{b} < 2$

For this calculation, S is presumably the clear cross-section of the duct (i.e. - the part not occupied by the duct liner material). The constraints listed are a problem. Calculations for speech privacy will require consideration of the 4 kHz octave band, and duct liner materials often have absorption coefficients exceeding 0.8. In the examples below, the constraints were largely ignored.

Where a duct changes direction, some sound energy will be reflected back along the duct. This provides mainly medium and high frequency attenuation, which is useful in reducing speech intelligibility. The sound attenuation depends on the duct cross-section and sharpness of the bend. For right angle ("mitre") bends, the attenuation is significantly greater than that for rounded bends. Table B2 presents typical attenuation for two classes of bends: right angle mitre bends, or bends with rounded corners and/or turning vanes to smooth flow.

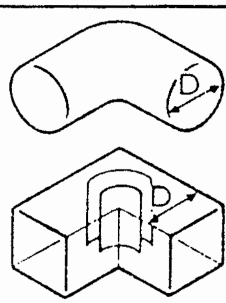
Table B2



Duct Width D mm	63	125	250	500	1k	2k	4k	Hz
75–100	–	–	–	–	1	7	7	dB
100–150	–	–	--	–	5	8	4	
150–200	–	–	–	1	7	7	4	
200–250	–	–	–	5	8	4	3	
250–300	–	–	1	7	7	4	3	
300–400	–	–	2	8	5	3	3	
400–500	–	–	5	8	4	3	3	
500–600	–	–	6	8	4	3	3	
600–700	–	1	7	7	4	3	3	
700–800	–	2	8	5	3	3	3	
800–900	--	3	8	5	3	3	3	
900–1000	–	5	8	4	3	3	3	
1000–1100	1	6	8	4	3	3	3	
1100–1200	1	7	7	4	3	3	3	
1200–1300	1	7	7	4	3	3	3	
1300–1400	2	8	7	3	3	3	3	
1400–1500	2	8	6	3	3	3	3	
1500–1600	3	8	5	3	3	3	3	
1600–1800	5	8	4	3	3	3	3	
1800–2000	6	8	4	3	3	3	3	

Octave Band Centre Frequency

(a)

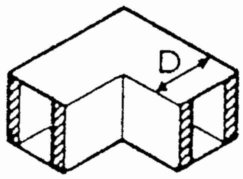


Duct Width/ Diameter D mm	63	125	250	500	1k	2k	4k	Hz
150–250	–	–	–	–	1	2	3	dB
250–500	–	–	–	1	2	3	3	
500–1000	–	–	1	2	3	3	3	
1000–2000	–	1	2	3	3	3	3	

Octave Band Centre Frequency

The combination of a change of direction with lined sidewalls provides even greater attenuation. No estimates were found for lined round bends, but attenuations for lined square bends are given in Table B3.

Table B3



Duct Width D mm	63	125	250	500	1k	2k	4k Hz (Octave Band Centre Frequency)
75–100	–	–	–	–	2	13	18 dB
100–150	–	–	–	1	7	16	18
150–200	–	–	–	4	13	18	18
200–250	–	–	1	7	16	18	16
250–300	–	–	2	11	18	18	17
300–400	–	–	4	14	18	18	17
400–500	–	1	5	16	18	16	17
500–600	–	1	8	17	18	16	17
600–700	–	2	13	18	18	17	18
700–800	–	3	14	18	17	16	18
800–900	–	4	15	18	18	17	18
900–1000	–	5	16	18	17	17	18
1000–1100	1	7	17	18	16	17	18
1100–1200	1	8	17	18	16	17	18
1200–1300	1	10	17	18	16	18	18
1300–1400	2	11	18	18	16	18	18
1400–1500	2	12	18	18	16	18	18
1500–1600	3	14	18	18	17	18	18
1600–1800	4	15	18	18	17	18	18
1800–2000	5	16	18	17	17	18	18

Lining thickness = $\frac{D}{10}$

Lining to extend distance 2D or greater

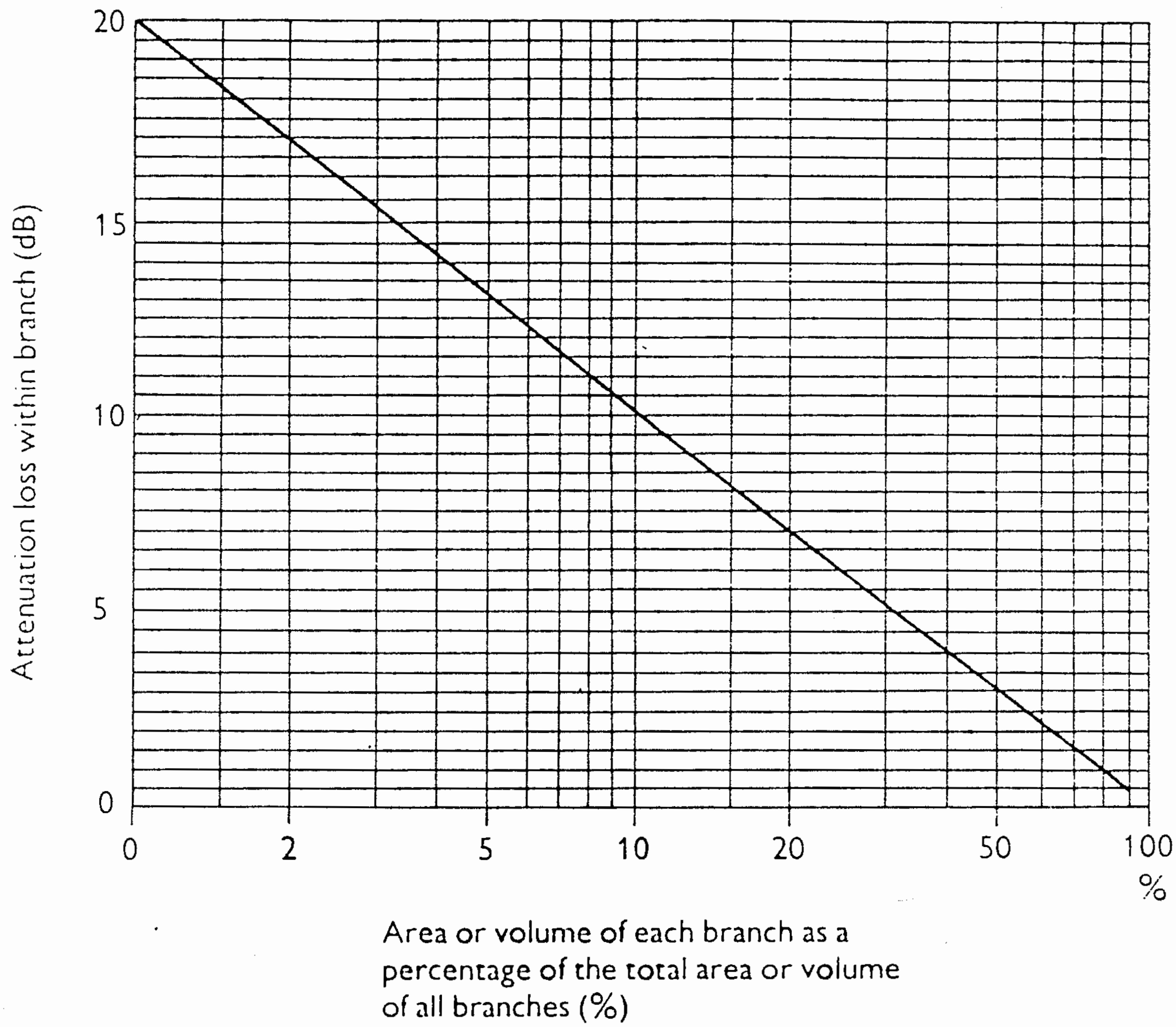
Rapid changes in duct cross section also reflect sound energy back along the duct, attenuating the transmitted signal. This occurs not just for changes in cross-section of a straight duct, but also where a branch duct enters a larger main duct, or where a smaller branch leaves a main duct. Table B4 presents typical attenuation values as a function of the change in cross-section area.

Table B4

Ratio of areas A1/A2	5	4	3	2.5	2	1	0.5	0.4	0.33	0.25	0.20
Attenuation dB	2.6	1.9	1.3	0.9	0.5	0	0.5	0.9	1.3	1.9	2.6

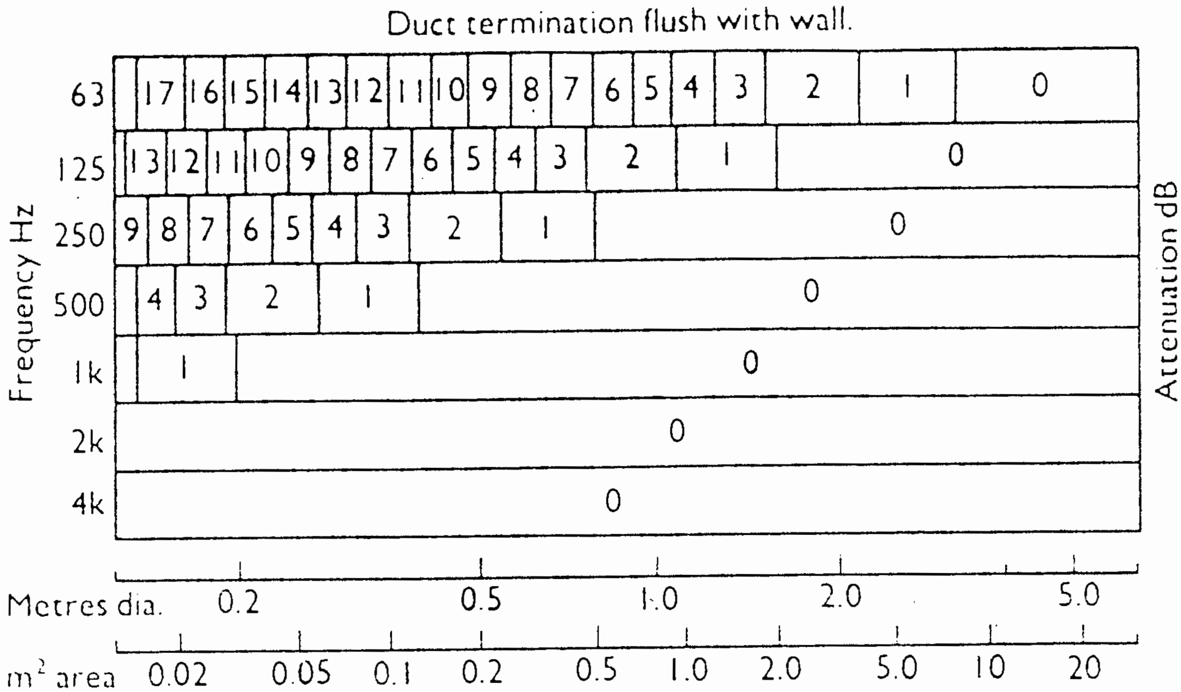
In addition to attenuation due to change in cross section (as given in Table B4), there is attenuation where sound energy reaching a branch is divided among the outlets from the branch. The attenuation of the transmission along a given branch is given in Figure B.2, as a function of branch area relative to total area of all duct openings comprising that junction.

Figure B.2



The final element of concern is the outlet from the duct into the receiving room. Because this involves a drastic change in duct cross-section, there is reflection at the end of the duct. In principle, this depends on whether the termination is flush with a hard susrface or extends out into the middle of the room, but the latter is obviously rare in practical installations. The expected attenuation at the duct end is presented in Figure B.3. Note that most of this attenuation is at low frequency (of little effect for speech intelligibility) and that the attenuation increases for smaller outlet area.

Figure B3



In principle, the effect of a rated duct silencer could be included simply by adding the rated attenuation to that for the other elements, just as the attenuation for other elements are simply added. Obviously, this presents a rather simplistic model of sound transmission through a duct system. For example, there is no allowance for the effect of having bends or branch T's close to the silencer. Further, there are appreciable differences between the effects of given linings, bends, or other discontinuities according to various models.

However, the agreement between the measured and predicted results in Section 3 shows that the model does give a reasonable first approximation. The intent of this study was to provide additional rules of thumb to improve that approximation.

B2. Example for a Plain Duct System

The plain duct system of Case L is illustrated in Figure B.4; this configuration has no added silencer or absorptive treatment. There are T-junctions at each of two sidebranches, and each sidebranch has two bends. The appropriate corrections are presented in Table B5, from the first end to the outlet, and Figure B.5 compares the measured result (solid line) with the prediction (circles).

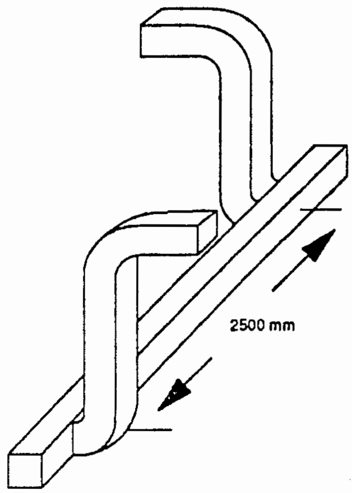


Figure B.4

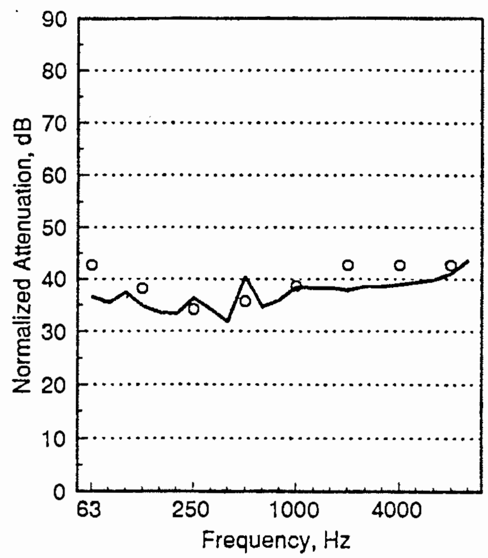


Figure B.5

Table B5: Predicted Attenuation for Case L

	63	125	250	500	1k	2k	4k
10 log(12/S)	21	21	21	21	21	21	21
T-branch	5	5	5	5	5	5	5
2 round bends	0	0	0	2	4	6	6
T-branch	5	5	5	5	5	5	5
2 round bends	0	0	0	2	4	6	6
end loss	12	7	3	1	0	0	0
Total	43	38	34	36	39	43	43

The first term, 10 log(12/S), is the attenuation that would be observed for a simple hole (with 0 dB attenuation) of area S (S = .305 x .305 m^2) in a 12 m^2 partition. This term was discussed at the end of Section 2, in explaining the normalization of sound transmission results. A T-branch correction is added for each of the two T's the sound must pass through; in each case, the cross-section area of the continuing duct is 1/3 of the total area. The effect of two rounded bends is added for each sidebranch. Finally, the end reflection loss for a duct opening of 0.093 m^2 is added.

It appears that the low-frequency correction for end reflection and the high-frequency correction for bends are both slightly larger than the measured effect. This is expected because some elements are so close together (for example, there is a bend right next to the outlet) that the overall attenuation is less than the sum of attenuations for well-spaced elements.

B3. Example for a Lined Duct Section

It is well established that absorptive lining of a duct provides considerable attenuation of the transmitted sound. However, the availabel guidelines give quite different results (and consider slightly different descriptors for the material.

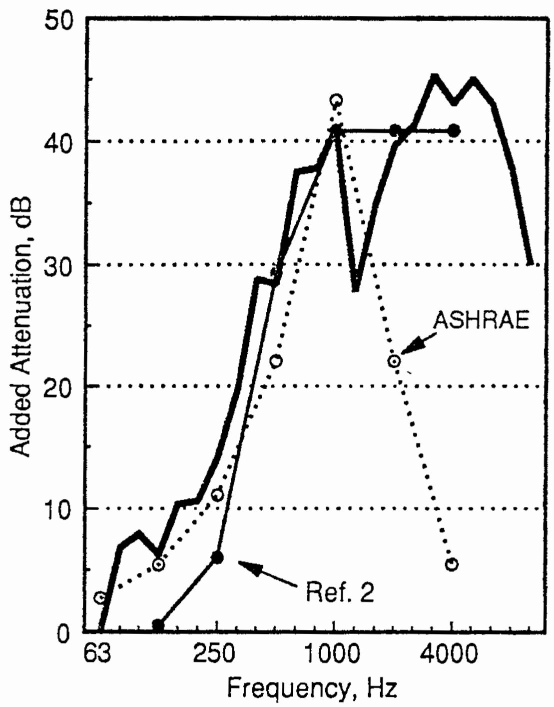


Figure B.6 compares the attenuation measured in this study (solid line) with predictions by the ASHRAE method and the method given in Figure B.1. The configuration studied had two lined sections (one in each sidebranch, each 4.5 ft long). Total length of lining was 2.8 m, and there was an adjacent bend at each end of the lined section. The detailed calculation is given in the table below.

The ASHRAE calculation procedure is probably most widely used. It is presented both in equation form and in tables for common duct dimensions. It does not use the absorption coefficient for the lining material, but is presumably based on an average result for typical materials. The prediction differs significantly from the measured results for the 2000 and 4000 Hz octave bands, which are unfortunately of major importance for speech.

Table B6: Predicted Attenuation for Lined Section

	63	125	250	500	1k	2k	4k
Method of Reference 2 for Conaflex foam							
Absorp. Coeff.		.04	.23	.71	1.00	.95	1.00
dB/m (see Fig. B.1)		.2	2.2	10.6	14.8	14.8	14.8
dB in 2.8 m		.5	6	29	41	41	41
Method of Reference 2 for Fiberglass Duct Liner							
Absorp. Coeff.		.26	.49	.63	.85	.95	.94
dB/m (see Fig B.1)		2.6	6.3	9.0	13.6	14.8	14.8
dB in 2.8 m		7	17	25	38	41	41
ASHRAE method (ASHRAE System Handbook p32.6 Table 8)							
dB/m	.3	.59	1.2	2.4	4.7	2.4	.60
dB in 2.8 m	2.8	5.4	11	22	43	22	5.5

It is possible that having bends in the duct at each end of the lined section was the source of some high-frequency attenuation. There is evidence to support this for right angle bends, but no data on this effect have been found for gradual bends such as were used here. This doubtless warrants some further investigation.

The method extracted from Reference 2 and presented above in Figure B.1 gives much closer agreement with the measurements. The calculation details are given in the table, using the absorption coefficients for the foam lining measured according to ASTM standard method C423. Because the calculation is nominally restricted to absorption coefficients under 0.8, absorption coefficient values for the calculation were limited at 0.90 if measured absorption was higher. Using the measured absorption coefficients would slightly improve agreement with experiment, but tends to over-predict the attenuation.

A corresponding calculation is presented for the expected performance of fiberglass duct lining material with a treated glass cloth surface. This was calculated from the average of five manufacturers' published data for this type of product. In general, manufacturers' data are readily available for duct lining material. It should be noted that the fiberglass materials appear to give slightly more attenuation below 500 Hz than was obtained with the Conaflex foam used in this study.

Overall, the use of absorptive lining appears to be at least as effective as a commercial silencer. The prediction method appears to provide adequate accuracy, and by starting the lined section with a right angle bend (at the outlet to the room) a considerable margin of safety can be added.

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Institut de recherche en construction

CLIENT REPORT

for

Royal Canadian Mounted Police
Security Engineering Branch
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Mechanical Duct Designs to Provide Speech Privacy
Part 2: Source and Receiving Room Effects

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Report No. CR-5763.2
Report Date: 1 February 1991
Contract No. CR-5763
Reference: Application for test dated 14 September 1988
Section: Acoustics

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1. Introduction

The problem to be considered in this report is speech privacy between two rooms when sound is transmitted via an air-handling duct system. This problem has three main aspects, each of which is presented in one section of the following report:

1) How much sound power enters the duct from a typical person speaking in the source room?
2) How much is that sound power reduced by transmission through the duct system itself, and how can this be related to the laboratory tests presented in the preceding report CR-5763.1 on the effect of duct lining and silencers?
3) How does the sound observed in the receiving room depend on receiver location and room characteristics?

Quite extensive experiments were required to establish the basic trends in the sound transmission. These measurements have clearly shown the factors relevant for sound transmission between two rooms comparable to private offices, and it is believed the results can reasonably be extrapolated to larger rooms.

The purpose of this report is to present the results of the experimental study, and to indicate how they could be applied in a method to predict the overall speech privacy. A step-by step design procedure based on these results will be presented in the third report of this series.

The three problems listed above follow the obvious sequence from speaker to listener, but this report follows a different order which is better suited to explaining the physical effects observed. Inter-room sound transmission is presented first because it provides the foundation, which can then be adjusted for effects at both ends. The effects observed in the receiving room are then discussed, to provide a basis for understanding what happens in the source room. The final part of the data concerns effects due to the source room and the source itself. Some details needed for application of the results are presented in appendices.

2. Inter-room Sound Transmission by a Duct

The preceding report (CR-5763.1) presented an analysis of sound transmission through a duct system installed between two reverberation rooms. This laboratory setup provided an ideal environment for accurate comparison of sound transmission with different duct treatments. However, these results must be related to the performance of a duct system between typical rooms.

This relationship was demonstrated using an office mockup facility intended to simulate two adjacent offices. A simple duct system was installed with outlets to both rooms, and the sound transmission was measured with room conditions representative of the range of acoustical conditions likely in typical offices.

2.1 Basic Concept

Conventional sound transmission measurements are based on finding what fraction of the sound power generated in one room is transmitted into a second room. Standard measurement procedures normally determine this from the difference between the average sound pressure levels in the source room and the receiving room. This approach is used both for laboratory measurements between reverberation rooms (as in the preceding report CR-5763.1) and for field measurements between adjacent rooms in a building.

Some adjustments for room characteristics are needed to provide the results in a standard form suitable for comparison. Absorption in the receiving room affects the sound pressure level, so an adjustment to allow for this is needed.

In the case of a wall or floor between two rooms, the surface area affects how much sound power is transmitted; results are commonly normalized to surface area so the values characterize the construction, independent of its size. For small elements such as duct openings, it is more common to adjust the results to give values of sound attenuation normalized to a reference absorption situation.

This approach was followed in report CR-5763.1, which presented results in terms of the Normalized Sound Attenuation:

$$\text{Normalized Attenuation} = L_s - L_r - 10\log(A_r / A_0) \quad (1)$$

where:

L_s is average sound pressure level in the source room,

L_r is average sound pressure level in the receiving room,

A_r is absorption in the receiving room, and

A_0 is the reference absorption area, equal to 12 metric Sabins.

The intent is to measure sound transmission from one room to the other via the duct system, in a facility designed to mimic typical offices. The term $- 10.\log(A_r/A_0)$ normalizes the result to the level difference that would be observed if the receiving room absorption were equal to A_0 (i.e., equal to 12 metric Sabins). Since 12 m^2 is also the area of the separating partition (and a reasonable approximation of typical office partition areas), this provides the sound attenuation rating in a form directly comparable with the partition's transmission loss. This approach permits designers to combine the duct attenuation data directly with partition transmission loss data using the usual process for decibel combination and (after an adjustment for actual receiving room absorption) to estimate overall inter-office noise reduction.

2.2 Experimental Approach

The laboratory facility used for this study is a hard-walled rectangular chamber 9.1 m long, 4.85 m wide, and 3.6 m high. A suspended ceiling is installed 2.8 m above the floor, as shown in Figure 1. A duct system was installed above the test rooms, with a branch duct opening through the suspended ceiling in each room. Both the main duct and the branch ducts were of square (300 mm x 300 mm) cross-section. Anechoic terminations at both ends of the main duct eliminated sound reflections from the ends, simulating the typical situation with a long duct supplying air to many rooms in a large building.

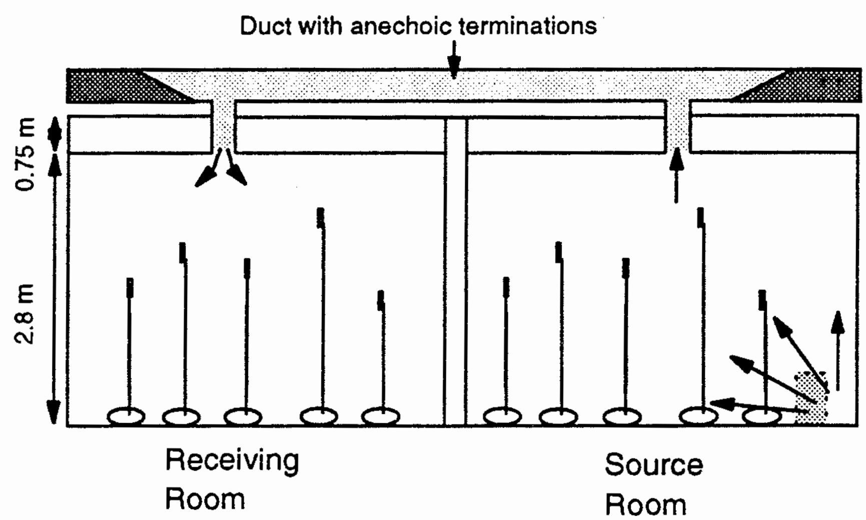


Figure 1: Vertical cross-section through the test facility used for this study.

A partition divides the space into two rooms whose length (and volume) differ by 10%. This partition extends through the suspended ceiling, up to the top of the test rooms. Sound attenuation by this partition and structural paths is sufficient to ensure negligible sound transmission between the rooms by paths other than the duct. This was verified by measurements with the duct openings blocked.

The sound pressure level in each room was sampled by five Bruel & Kjaer 4149 (13 mm) microphones on B&K 2619 preamplifiers, connected via B&K 2811 microphone multiplexers to a Norwegian Electronics NE-830 real time analyzer. This data acquisition system was controlled by a minicomputer, which also controlled the sound sources in both rooms. Each room had two loudspeakers driven simultaneously by independent amplifiers with separate (incoherent) noise generators. The loudspeakers pointed into the room corners, to minimize direct radiation to nearby microphones.

Each measurement was the average result from two subtests. Each subtest included a series of measurements:

- background sound levels were measured;
- white noise was generated through the loudspeakers in one room;
- energy average L_s was determined from 30-second equivalent sound pressure levels measured at the five microphones in the source room;
- energy average L_r was determined from 30-second equivalent sound pressure levels measured at the five microphones in the receiving room; and
- absorption A_r was calculated from the average reverberation time measured from five decays at each of the five microphones in the receiving room.

All 10 microphones were then moved to different positions, and the subtest was repeated. The microphone positions are shown in Figure 2 (and tabulated later in the report); where two numbers are indicated at the same floor position, the microphone heights were different.

This extensive sampling of the sound fields ensured good precision despite the significant variation in sound pressure levels within these rather small and non-reverberant rooms.

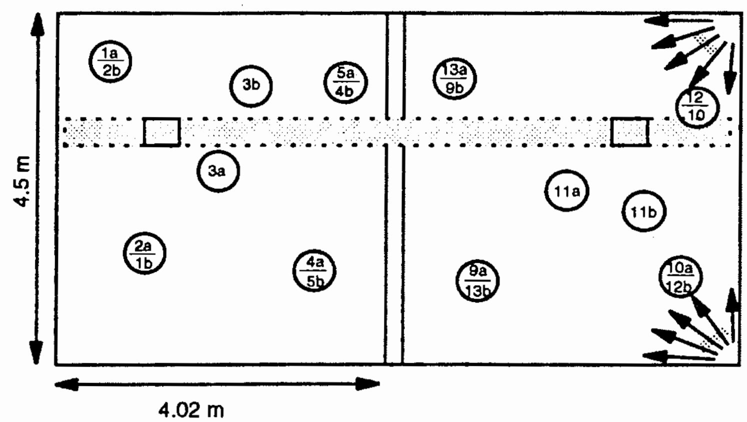


Figure 2: Position of the microphones for measurements of average sound pressure level in the two rooms.

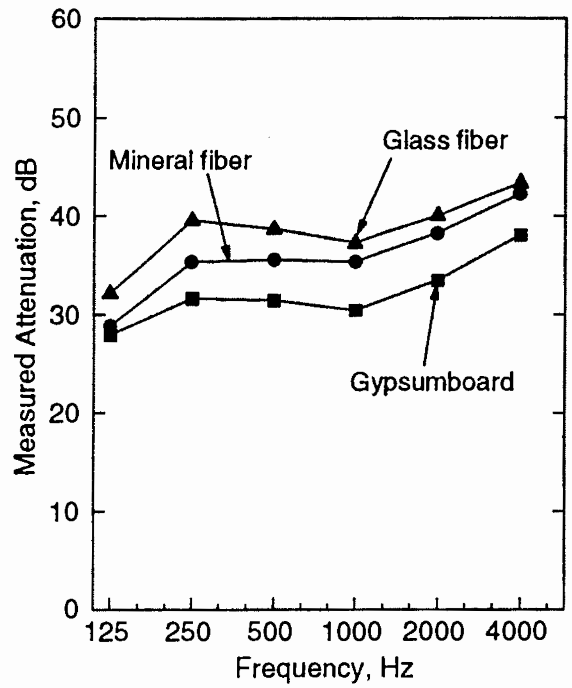
All measurements in this study were made for 1/3-octave bands from 100 Hz to 5000 Hz. In most cases, these results were then combined into octave-band form, to illustrate the trends in a more concise form. This use of octave bands is consistent with all major prediction schemes for sound transmission through ducts.

2.3 Data and Discussion

The first series of measurements examined the effect of absorptive treatment of the receiving room. Measurements were made with three different types of panels in the suspended ceiling: vinyl-faced gypsum board (very reflective), mineral fiber panels (intermediate), and glass fiber panels (highly absorptive). The resulting acoustical absorption in the room spanned the range of conditions likely in typical offices.

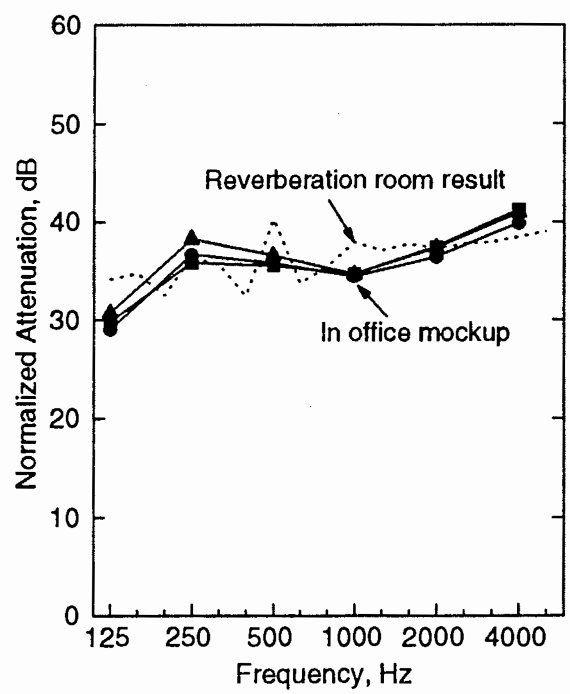
Figure 3 shows the measured difference (L_s - L_r) between the average sound pressure levels in the source and receiving rooms with these three receiving room ceilings. Increasing the absorption in the receiving room causes lower sound levels there, and hence more attenuation.

Figure 3: Measured inter-room attenuation (L_s - L_r) with no normalization to allow for receiving room absorption.



Adding the correction -10.log(A_r/A_0) to convert these level differences to Normalized Attenuation eliminates most of the difference between the three results, as shown in Figure 4. For comparison, the dotted curve in Figure 4 is the attenuation measured for a similar duct system in the laboratory tests reported previously.

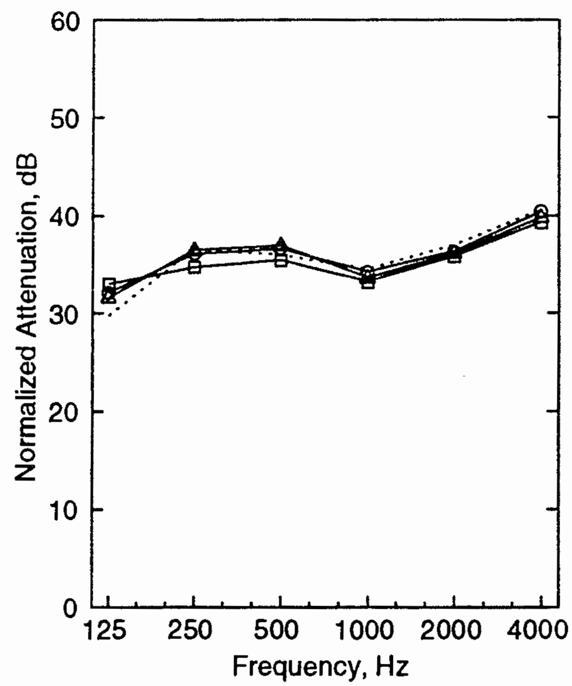
Figure 4: Measured normalized attenuation with three receiving room ceilings. Squares are with suspended ceiling panels of gypsumboard, circles with mineral fiber, and triangles with glass fiber, as in Figure 3. The dashed curve is for a similar duct system measured between two reverberation rooms.



The laboratory result exhibits more peaks and dips (which may be attributed to the shorter distance between branch ducts as discussed in the earlier report), but the overall attenuation is very similar. Since the Normalized Attenuation should measure performance of the duct system (which was the same for all four cases), the consistent results in Figure 4 are a good indication that the normalization works properly.

A second series of measurements was made to evaluate the effect of absorption in the source room on the normalized attenuation. To ensure the results were representative of the practical problem, these measurements were made with a loudspeaker whose directionality is comparable with a human speaker; characteristics of this source are discussed in the evaluation of source effects later in this report. The tests were performed with the same three suspended ceiling systems previously used to evaluate the effect of absorption in the receiving room. For each ceiling, the normalized attenuation was measured with the loudspeaker placed successively at 10 locations in the source room.

Figure 5: Measured normalized attenuation with three source room ceilings. Squares are with suspended ceiling panels of gypsumboard, circles with mineral fiber, and triangles with glass fiber. The dashed curve is the average of results in Figure 4 for the same duct system with different receiving room ceilings.



The average results for each of the three source room ceilings are presented in Figure 5. The dotted line is the average of the three results with different receiving room ceilings. All the results agree very closely, showing that variations in source room absorption have negligible effects on the normalized attenuation.

Even with a rather directional sound source in a highly absorptive room, the average sound level in the source room provides a good measure of the sound power entering the duct. For all cases, the consistency of the measured results shows that the normalized attenuation is a consistent measure of sound transmission through the duct system.

3. The Receiving End

The purpose of this section is to evaluate how receiving room conditions and listener location can affect the sound level at the listener.

3.1 Basic Concept

The preceding section establishes that the normalized attenuation provides a repeatable measure of sound transmission through the duct system. This predicts the average sound pressure level in the central part of the adjacent (receiving) room, if the receiving room absorption is 12 metric Sabins. However, what is heard at any given point in the adjacent room is expected to differ systematically from this for two main reasons:

- the average sound level in the receiving room depends on the actual absorption (which depends on room furnishings and absorptive surfaces such as carpet or suspended ceiling), and
- near the duct opening, the sound pressure level tends to be higher than this average level.

3.2 Experimental Approach

With a constant sound signal coming from the source room via the duct, sound pressure was measured at many locations in the receiving room. This sequence of measurements was repeated with three different types of panels in the suspended ceiling, to examine how changing room absorption alters the results.

The measurements of sound pressure level as a function of receiver location were made in two ways:

1) ten standard microphone locations in each room were used for the measurements of normalized attenuation described in the preceding section. These were distributed through the room, at heights from 1 to 2 m above the floor; distance to the duct opening ranged from 1.5 to 3.0 m. Examining the sound received at these locations versus distance to the duct provided a first measure of sound levels expected at "normal listening positions";
2) a single microphone moved to specific positions along a traverse was also used, to obtain more precise results and measure the sound closer to the duct opening. This evaluates the worst case for speech privacy.

The latter measurement was inherently more precise because it eliminated uncertainty due to calibration differences among the multiple microphones in the first method. However, both provided useful data.

All microphone sensitivities were checked with a Bruel & Kjaer calibrator at the beginning and end of measurements with each ceiling, to ensure accurate calibration.

The experimental setup for the measurements with the traversing single microphone is shown in Figure 6. The microphone was positioned at distances from 0.10 to 1.90 m from the center of the duct opening. The traverse frame was rotated to five different angles (shown in Figure 6) for each opening-to-microphone distance. These measurements were repeated with the three suspended ceiling systems.

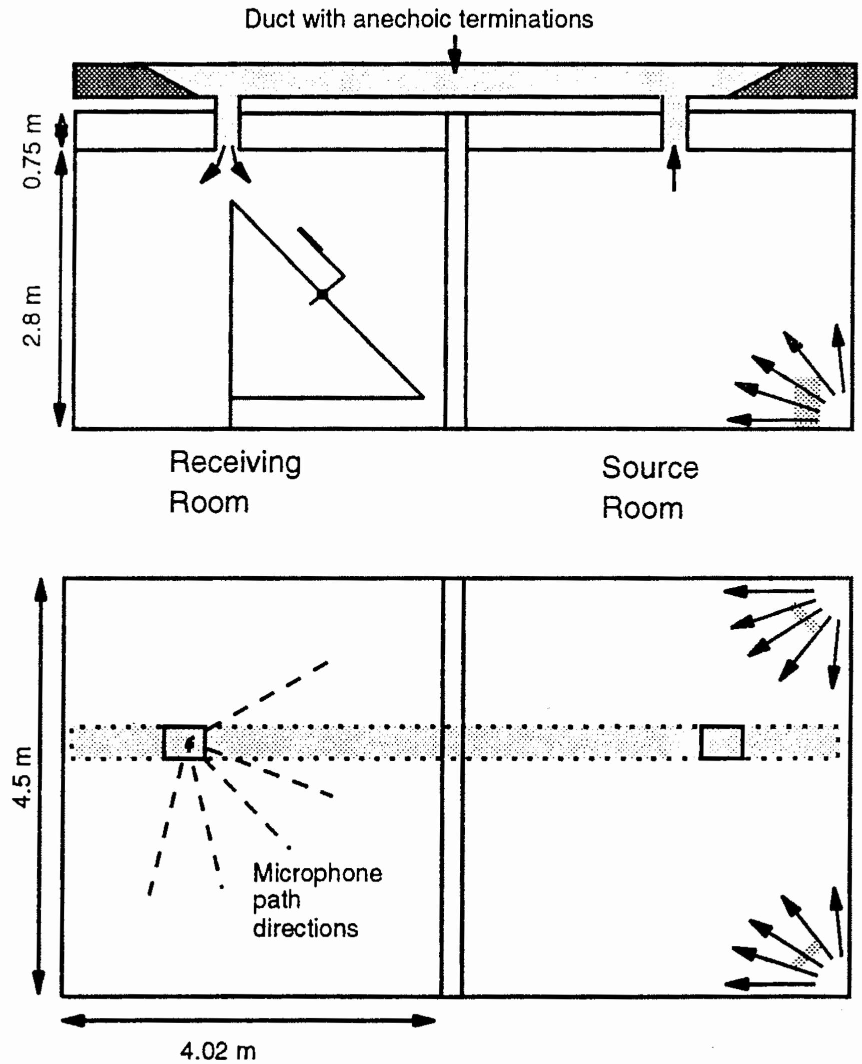


Figure 6: Schematic indication of microphone positions traverse for measurements near duct opening in receiving room. The upper drawing is a vertical cross-section; the lower is a floor plan. Loudspeakers facing the corners of the source room provided the sound.

The main sound pressure level measurement was a determination of level versus distance from the duct opening. For each of the three ceilings, these measurements were made in five directions, at ten distances (0.10, 0.15, 0.25, 0.40, 0.55, 0.70, 0.90, 1.15, 1.50, and 1.90 m) from the center of the duct opening. The sound pressure level measurements were made in one-third-octave bands using a Norwegian Electronics NE-830 analyzer with a 13 mm diameter condenser microphone (B&K 4165 on type 2619 preamplifier).

The sound power coming from the duct was also measured directly, using a Norwegian Electronics Model 216 acoustic intensity probe with the NE-830 analyzer. These measurements were made in the plane of the duct outlet through the suspended ceiling. The square opening was treated as two rectangular sub-surfaces (each comprising half of the opening) so the complete probe could be inserted with nominal probe location in the plane of the opening. For each of the sub-surfaces, the acoustic intensity was determined by a 30-second scan with the intensity probe. The probe was oriented to measure intensity perpendicular to the surface, and each scan was repeated with the probe direction reversed (which should give the same intensity level but reversed direction). If the overall A-weighted acoustic intensity magnitudes for the two probe directions did not agree within 0.2 dB, the measurement was repeated. In most cases, agreement was within 0.1 dB or better.

The sound power from the two sub-surfaces was calculated from the measured intensity and the surface area, and these partial sound powers were combined to give the overall sound power level.

No standard procedures for assessing precision or validity of scanned acoustic intensity measurements have been developed yet, and obtaining reliable acoustic intensity measurements in a reverberant space is not trivial. Several precautions were taken to permit subsequent evaluation of measurement quality. The equivalent sound pressure level at the probe was also recorded, to permit subsequent checks that the reactivity index (the difference between sound pressure level and intensity level) was within acceptable limits. Repeating each measurement with the probe reversed is the most reliable way to check measurement validity, and this was done for each measurement surface.

Finally, the acoustical absorption was determined for each 1/3-octave band from measurement of sound decay rate at the ten standard microphone positions for each suspended ceiling system. The ensemble average of 10 decays at each position was used.

3.3 Data and Discussion

The 1/3-octave results were combined into octave bands, to show the trends more clearly and present them more concisely. Results for the 1000 Hz octave are presented in Figure 7(a)-(c) to illustrate the basic features.

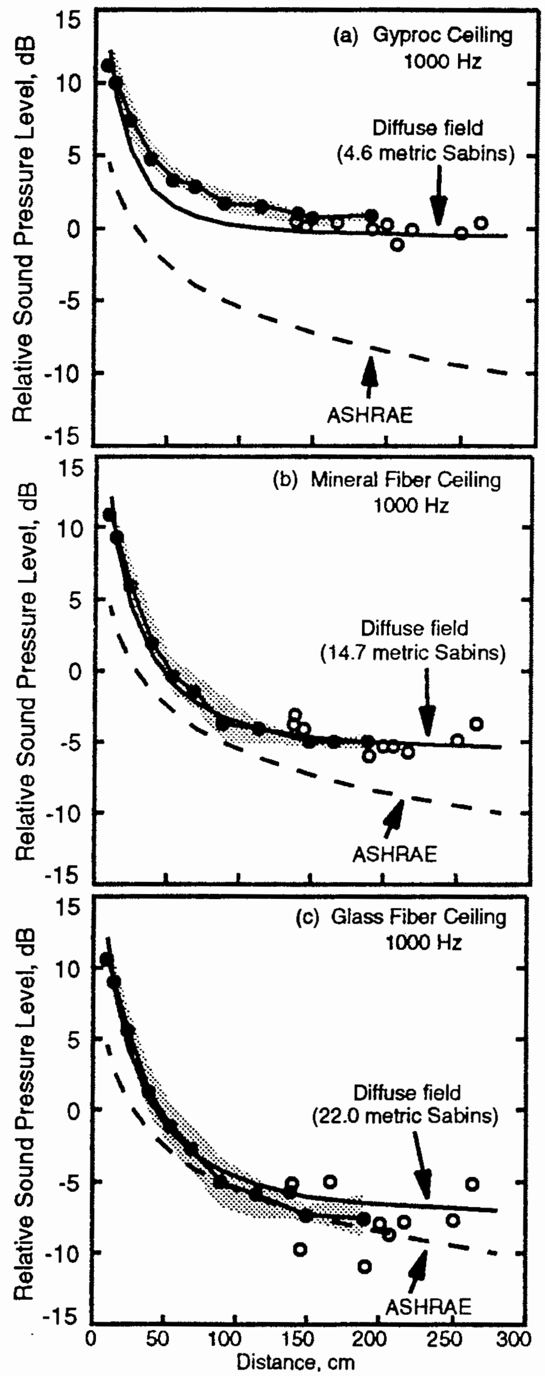


Figure 7: Relative sound pressure level for 1 kHz band versus distance from the source. Each graph presents data for one ceiling case; ceiling type (and corresponding total room absorption) are indicated on each graph. Each graph shows sound pressure level relative to sound power emitted from the duct opening. The joined solid circles are means of levels measured along the five traverse directions; the gray area shows the range in results along these paths. The open circles are measured results for the ten microphone positions distributed through the room. The heavy solid curve and dashed curve are the diffuse field and ASHRAE predictions, respectively, as discussed in the text.

The results for all octave bands (125 Hz to 4000 Hz) are given in Appendix A.

With all three ceilings, the sound pressure level decreases appreciably with increasing distance from the duct opening, but changes more slowly at larger distances. Very close to the opening, the level is essentially independent of acoustical absorption in the room.

The level at larger distances depends on the type of ceiling panels, showing the effect of adding acoustical absorption to the room. This effect can be predicted quite well by traditional diffuse field theory, given the measured sound decay rates.

Traditional diffuse sound field theory predicts the sound pressure level in a reverberant room will exceed the corresponding sound power level by:

$$10 \log [Q / 4 \pi r^2 + 4 / R] \qquad (2)$$

where:

- Q is source directivity factor,
- r is distance from the source, m, and
- R is the "room factor", approximately equal to room absorption, in metric Sabins.

The source directivity factor Q can depend on the specific source in rather complicated ways, but for simple sources is primarily determined by the number of sound reflecting surfaces adjacent to the source. For a source near one surface, such as the ceiling, Q is about $2^1 = 2$. For a source near the junction of one wall and the ceiling (two surfaces), Q is about $2^2 = 4$. For a source near a corner (three surfaces), Q is approximately $2^3 = 8$.

Approximating R by the room absorption A, the term 4/R can be calculated from the measured sound decay rate in each room using the traditional Sabine expression:

$$A = 0.161 V / T_{60} \qquad (3)$$

where:

- A is absorption, in metric Sabins,
- V is room volume, in m^3, and
- T_{60} is reverberation time, in seconds.

For the case illustrated in Figure 7, the source is adjacent to the ceiling but far from the walls (one surface, so Q = 2) and the diffuse field curves were calculated using measured absorption A as an estimate of R. Agreement is quite good for all three absorption cases (and also good for most frequency bands presented in the Appendix).

There are some noticeable deviations from the predictions. Especially for the lower frequencies, there is noticeable scatter at larger distances, which is attributed to reflections from room boundaries. With the glass fiber ceiling, the measured results tend to be slightly below the diffuse field prediction both in Figure 7(c) and in the corresponding figures in Appendix A for lower frequencies. This can be explained by the acoustical transparency of the glass fiber ceiling at lower frequencies, which changes the effective room volume. Aside from these rather minor deviations, the diffuse field prediction works well, especially close to the source.

Figures 7(a)-(c), and the similar figures in Appendix A, have a dashed line labelled "ASHRAE", calculated using Eq. 15 from Chapter 32 of the ASHRAE Systems Handbook. This expression is intended to predict sound pressure level in typical offices due to the sound power radiated from a ventilating duct outlet. The ASHRAE expression predicts the sound pressure level in a room will exceed the corresponding sound power level by:

$$- 5 \log(V) - 3 \log(f) - 10 \log(r) + 12 \qquad (4)$$

where:

- V is room volume, in m^2;
- f is octave-band frequency, in Hz;
- r is distance from the source, in m.

This equation was derived from a regression analysis of measurements at distances greater than 1 m from sound sources in "typically furnished" rooms. Note that the ASHRAE prediction ignores the effect of room absorption, which is clearly significant in the present study.

The ASHRAE expression clearly predicts lower sound pressure levels than were observed in Figure 7 with the gypsumboard and mineral fiber ceilings. This deviation is to be expected, because the room absorption conditions are significantly different here from the ASHRAE assumptions. For the most absorptive case, the results come close to the ASHRAE prediction (which is identical for the three absorption cases).

Very close to the source, the ASHRAE expression consistently predicts sound pressure levels more than 5 dB below those observed. In contrast, the diffuse field prediction is consistently close to the observed level near the opening. In this region, the relative sound pressure level is almost independent of room absorption and of frequency.

Figure 7 presents the difference between the measured sound pressure level and the sound power emitted from the duct opening. The values presented could be converted to levels relative to the normalized average sound pressure level in the receiving room (the case predicted in Part 2, with 12 metric Sabins of absorption), by adding 4.8 dB to the values in the graphs (Figure 7 and Appendix A).

4. Effects at the Source Room End

At the source room end of the duct, the problem is to predict the sound power entering a duct when a typical person is speaking.

Sound power entering the duct could depend on source characteristics (strength and directivity), location and orientation of the source relative to the duct entry, and the strength of reflections from room surfaces. The experiment was structured to examine these factors.

4.1 Basic Concept

In practical terms, the problem is to get from what we know, to what we need for predicting sound transmission through the duct:

- What we know: The loudness and directivity of typical human speech is well established (in terms of sound pressure level in an anechoic environment).
- What we need: The average sound pressure level in the central part of the source room is needed to apply the normalized duct attenuation discussed earlier in the report.

The experiments and analysis were devised to establish the relation between the anechoic sound pressure level and the resulting effective average sound level in the source room. This is complicated by source directionality and by dependence on source location (which was glossed over by using the average of many loudspeaker positions in the earlier analysis).

The approach had several steps:

1) Establish directivity and on-axis sound pressure level for the loudspeaker (to permit comparison with human speech data).
2) Using this loudspeaker with the same input signal, measure sound transmitted into the receiving room through the duct for a realistic range of loudspeaker locations and source room absorption conditions.
3) Calculate the mean normalized attenuation from all these measurements to characterize duct transmission.
4) For each case, combine the sound level actually observed in the receiving room with the mean attenuation to find the "effective average source room level" for that source case.
5) Find the difference between these effective levels and anechoic levels (the result we need).

For these measurements, the only factors changing are the source position and the source room ceiling panels. Because the measuring system, the receiving room, sound transmission through the duct, and sound emission from the loudspeaker should not be changing, any differences in the transmitted sound must be due to changes in the sound energy transfer from the loudspeaker into the duct.

4.2 Experimental Details

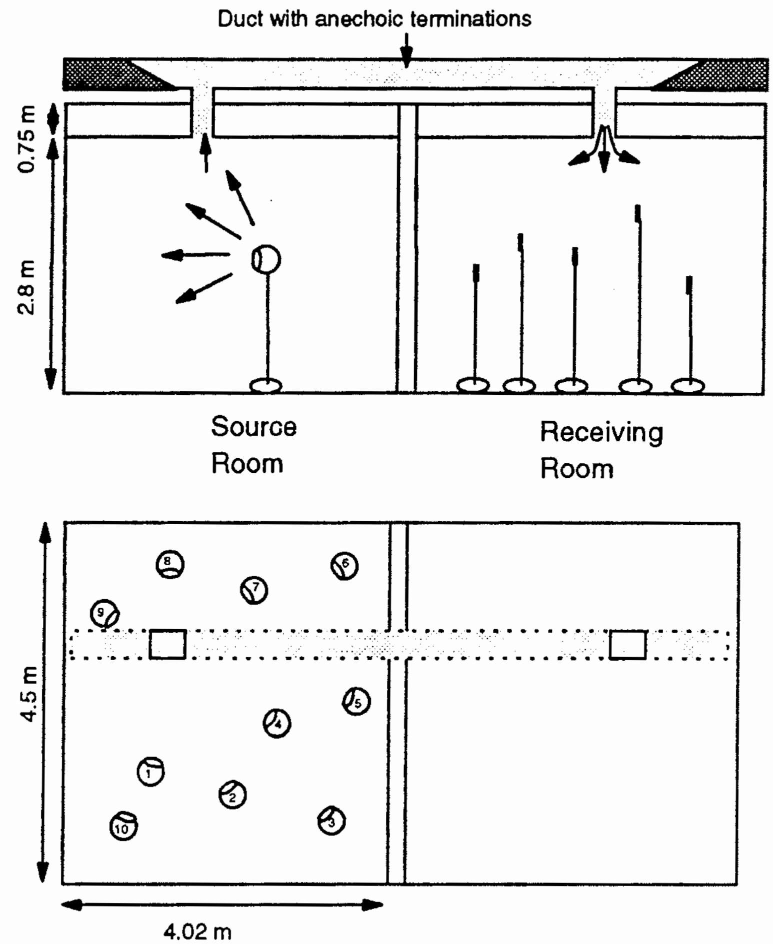
The source effect measurements were performed using a loudspeaker system with a single driver mounted on the face of a spherical enclosure of 250 mm radius (comparable to a head). The characteristics of this source were measured in the IRC anechoic chamber, to provide data directly comparable with that from the literature on human speech. Both sound pressure level (on-axis at 1 m from the loudspeaker surface) and directivity around the source were measured using a 13 mm diameter B&K 4165 condenser microphone with a Norwegian Electronics NE-830 analyzer.

Sound transmission measurements were made using this loudspeaker at various positions in the two-room office mockup. The signal supplied to the loudspeaker was maintained constant and monitored repeatedly. This procedure should provide essentially constant sound power output, which can be accurately related to the on-axis sound pressure level from the anechoic room tests. Given human speech data for the anechoic environment, this provides a convenient way to relate measured sound pressure levels in the room to expected sound from human speech.

The laboratory setup is shown in Figure 8. Measurements were made as described in Section 2.2, except that the special loudspeaker was used as the sound source. Measurements were repeated with this loudspeaker at each of the 10 source positions shown schematically in Figure 8; exact positions are tabulated in Appendix C.

This series of tests was repeated with three suspended ceiling systems in the source room, to establish the effect of absorption. The receiving room absorption and microphone locations were constant throughout these measurements.

Figure 8: Schematic drawing of setup for measurements of source effects. The upper drawing is a vertical cross-section. The lower drawing indicates the source positions used. In all cases, the source was aimed horizontally but turned toward the opening.



For all the measurements with the special source, the loudspeaker was 1.5 m above the floor. The distances to the duct opening cover the range likely in normal use of an office - it is unlikely that someone conducting a confidential discussion would climb up to talk directly into a duct outlet in the ceiling. The loudspeaker was aimed horizontally but turned towards the duct opening, to simulate the worst reasonable case, where a speaker is talking in the general direction of the duct - it is not reasonable to assume that someone immediately under the duct outlet would talk up towards the ceiling.

4.3 Data and Discussion

(Source Directivity)

Ideally, one would prefer to perform this sort of study using a loudspeaker whose characteristics precisely match the typical human source. Unfortunately, no such loudspeaker system was available.

However, for practical engineering purposes, one can obtain adequate results with any loudspeaker whose directionality is reasonably similar. From room acoustics measurements for a series of frequency bands using a loudspeaker source, the effects expected for human speech in each octave band can be predicted, if the loudspeaker directivity in each band is known.

The first step was to measure the directivity of the loudspeaker in the IRC anechoic chamber. The full results of these loudspeaker directivity measurements are presented in Appendix B, together with data from the literature for directivity of typical human speakers. These results provide a basis for relating the effective source level results discussed later in this section to effects expected with human speech.

As an example, the range of directivity observed in the 250 Hz band with human speakers is compared in Figure 9 with the loudspeaker directivity for the 250 Hz and 500 Hz bands. For the design procedure to be presented in the third report in this series, the average of loudspeaker effective source level results measured for the 250 and 500 Hz bands would be used to predict the corresponding effect for speech at 250 Hz.

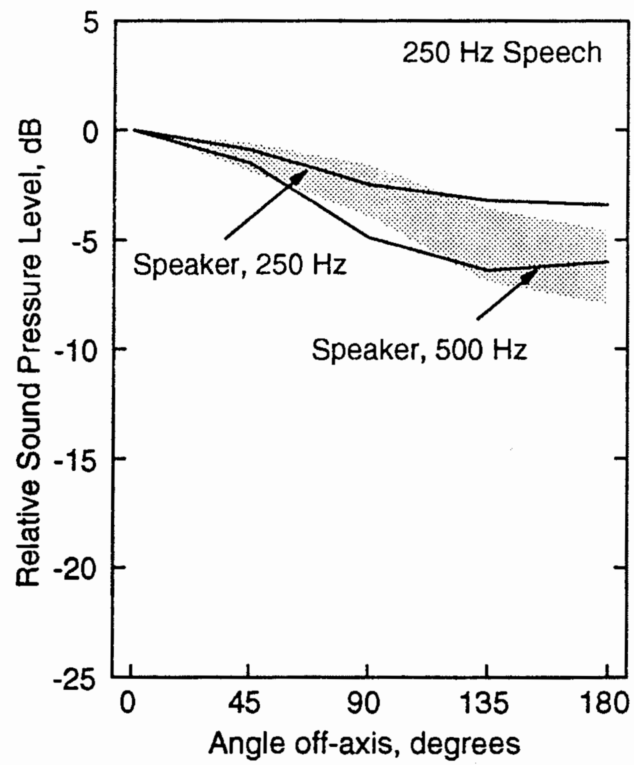
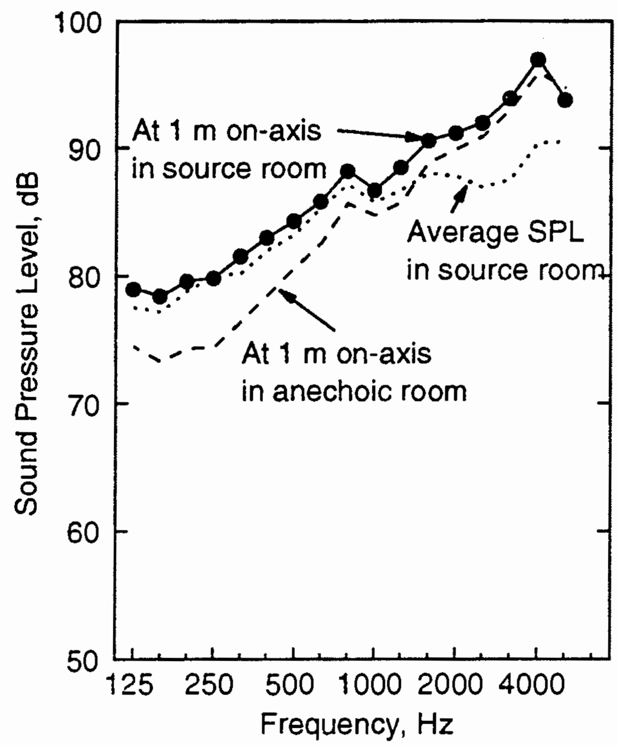


Figure 9: Directivity of typical human speech and of the loudspeaker used in this study. The gray region is the range reported for human speech as discussed in Appendix B. The solid curves are the measured directivity of the loudspeaker for the most comparable octave bands.

The sound pressure level in a room includes both sound coming directly from the source (comparable to the on-axis sound in an anechoic room) plus sound reflected from room surfaces. For the lower frequency bands (such as the 250 Hz case illustrated in Figure 9), the loudspeaker is only slightly directional. At higher frequencies, the loudspeaker increasingly beams sound to the front. This results in a changing relation between the sound pressure level immediately in front of the loudspeaker and the resulting average sound pressure level in the room, as shown in Figure 10.

Figure 10: Sound pressure level produced by the directional loudspeaker in different environments, with a constant input signal of white noise. The source room measurements were for the intermediate case with a mineral fiber ceiling.



In Figure 10, at low frequencies the reflected sound dominates in the source room: thus, the room average sound pressure and that observed 1 m from the loudspeaker are nearly identical, and are higher than the corresponding anechoic level. The relative strength of the room-average sound level decreases with increasing absorption and/or increasing loudspeaker directivity. Hence, in Figure 10, at high frequencies the reflected sound energy is much less important; the level in the source room is only slightly higher than the anechoic result, and the room average level is considerably lower.

4.4 Data and Discussion

(Room Effects)

The purpose of this analysis is to establish the difference between the direct sound (at 1 m on-axis in an anechoic environment) and the room-average level in the source room for the range of source directivity and absorption expected for human speech in offices.

A "Relative Effective Source Level" corresponding to this difference was calculated from the experimental results by:

1) subtracting the mean normalized attenuation from the normalized sound level in the receiving room for each of 30 cases (10 source positions x 3 source room ceilings) to obtain the effective source room level;
2) presenting this relative to the anechoic sound pressure level (at 1 m on-axis, like published human speech levels) obtained with the same loudspeaker and input signal.

Subtracting the anechoic level makes the results independent of the specific source signal spectrum (so the graphs could be used directly with standard speech spectra).

The 1/3-octave results were combined into octave bands, to show the trends more clearly and present them more concisely. The results for all octave bands (125 Hz to 4000 Hz) are given in Appendix C.

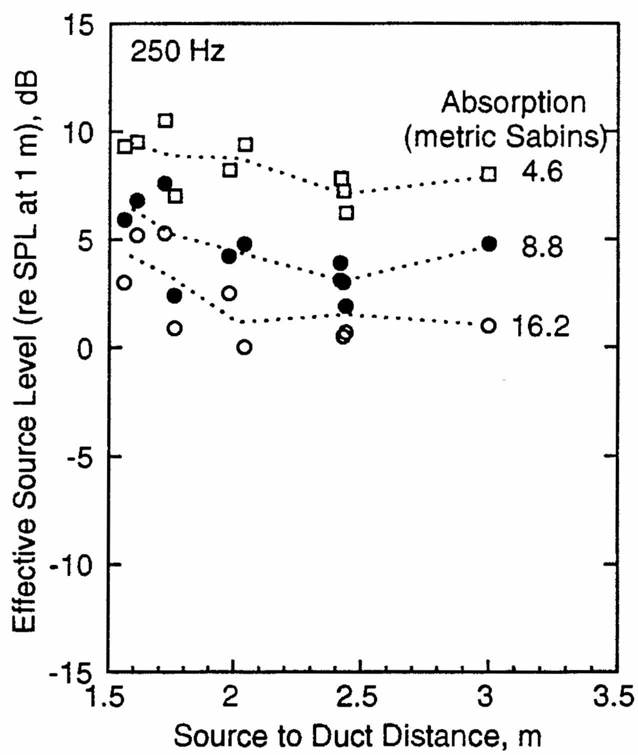
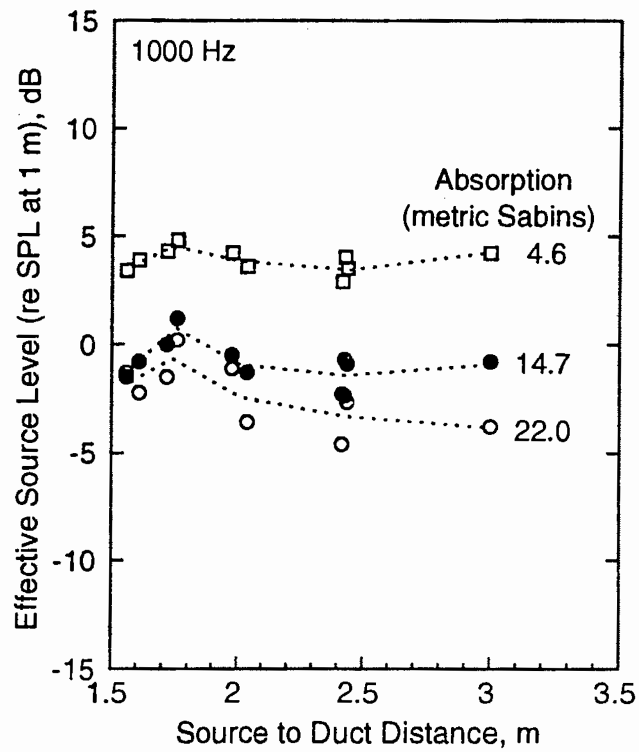


Figure 11: Effective source room level for 250 Hz octave, relative to the sound pressure level at 1 m on-axis in the anechoic room with equivalent input to the same loudspeaker. Results are for three types of suspended ceiling panels: squares are for gypsum board, closed circles are for mineral fiber, and open circles are for glass fiber panels. To highlight trends, dotted lines join each group of two or three data points. The measured octave band absorption for each ceiling case is listed at the right.

Relative effective source room levels for the 250 Hz and 1000 Hz octaves are presented in Figures 11 and 12, to illustrate the basic features. Each graph presents data for the three ceiling cases, labelled by the absorption for each.

Figure 12: Effective source room level for 1000 Hz octave, relative to the sound pressure level at 1 m on-axis in the anechoic room with equivalent input to the same loudspeaker. Results are for three suspended ceiling systems: squares are for gypsum board, closed circles are for mineral fiber, and open circles are for glass fiber panels. To highlight trends, dotted lines join each group of two or three data points at similar distance. The measured octave band absorption for each ceiling case is listed at the right.



Obviously, there are some fluctuations (presumably due to both experimental errors and wave interference effects) but grouping the data into sets of two or three points with similar speaker-to-duct distances makes the trends fairly clear:

- the relative effective source room level decreases with increasing absorption. The change is about 3 dB for each doubling of the absorption when the source is far from the duct, and smaller for nearby positions;
- lower relative levels are observed for higher frequency bands, presumably due to increasing source directivity;
- variation with source position is rather weak.

Given that dependence on source-to-duct distance is comparable to the experimental scatter, discussing the trends is rather tenuous. However, some explainable features were observed. In general, the dependence on position was stronger when room absorption was largest, which would be expected due to the decrease in the reflected sound which is expected to be fairly independent of source position.

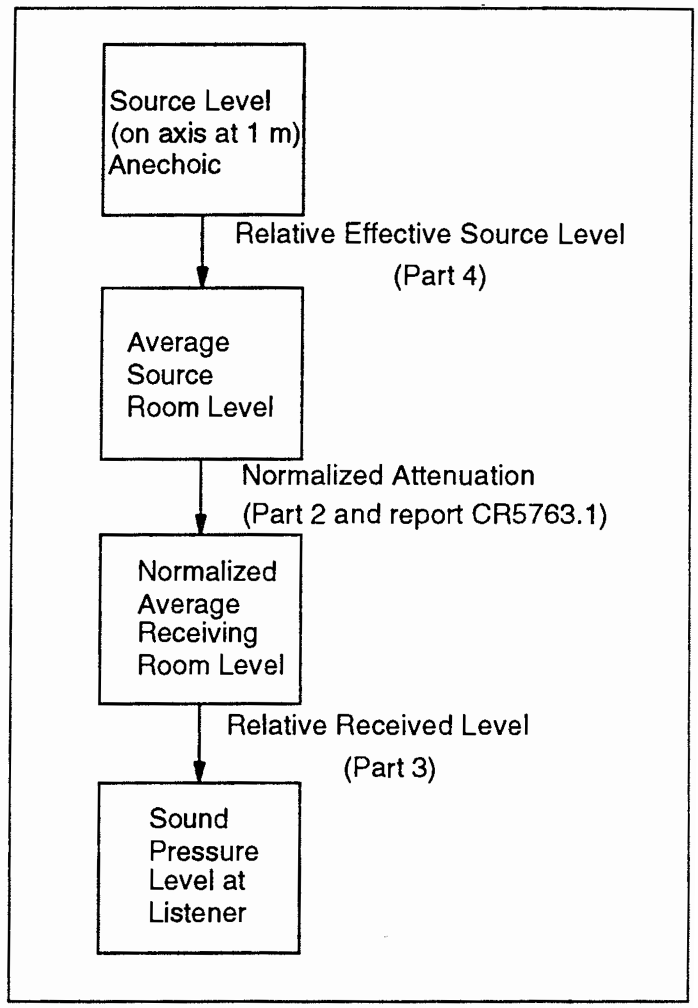
The 250 Hz data in Figure 11 show increasing levels when the source is closer to the duct; this is similar to trends observed in the receiving room (as in Figure 7), as expected when the source is nearly omnidirectional.

At higher frequencies as shown in Figure 12, the data exhibit a weak peak around 1.8 m probably because at closer distances (angles farther off-axis) the direct sound from the horizontally aimed loudspeaker is lower.

Summary

The prediction of sound reaching a receiver in an adjacent room via a duct system involves the transition through four stages from typical speech levels to sound at any point in the receiving room. This process is illustrated in the chart on the following page.

Each of the steps in this process has been examined in this study, and numerical corrections suitable for a simple design procedure can be extracted from the results presented.



In the source room, the position of the source is not very important for reasonable cases. Absorptive treatment of the room and allowance for source directivity are the key concerns.

Normalized attenuation provides a consistent basis for measurement and prediction of attenuation through the duct system. The effect of duct treatments such as silencers or linings can be readily added, as discussed previously in report CR-5763.1.

Very near the duct outlet (the worst case for speech security), the sound pressure level is almost independent of room absorption and can be accurately predicted. In the central part of the room, the level can also be predicted, given a reasonable estimate of absorption from room surfaces and furnishings.

Appendix A: Receiving Room Sound Pressure Levels

Graphs on the following pages show relative sound pressure level versus distance from the source (the duct opening in the receiving room). Relative sound pressure level is measured sound pressure level minus the sound power level measured at the duct opening.

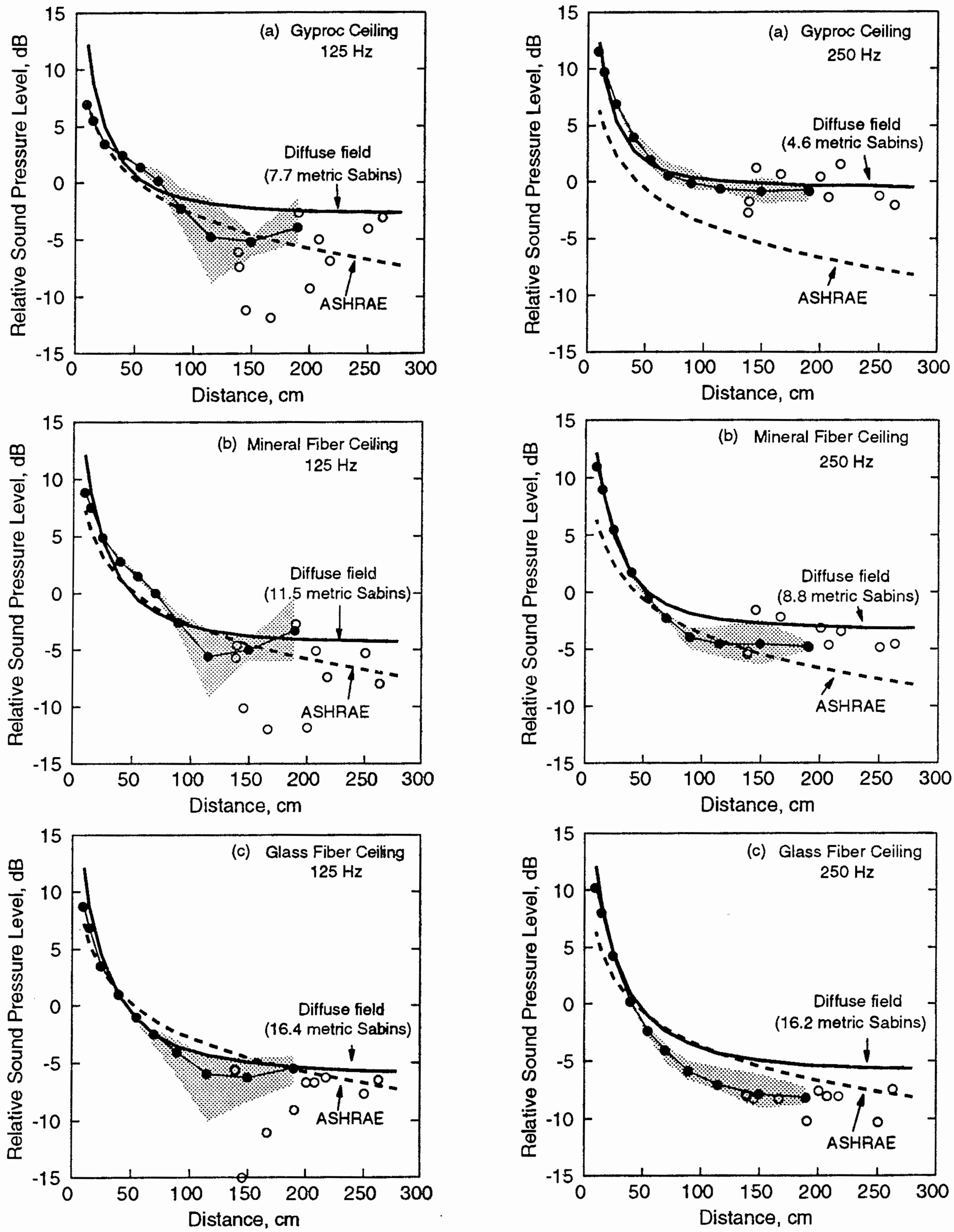
Each graph presents data for one octave band with a specific receiving room ceiling. Ceiling type (and corresponding total room absorption) are indicated on each graph.

The joined solid circles are means of levels measured along the five traverse directions shown in Figure 6; the grey area shows the range in results along these paths. The open circles are measured results for the 10 microphone positions distributed through the room. The heavy solid curve and dashed curve are the diffuse field and ASHRAE predictions, respectively, as discussed in Section 3.3.

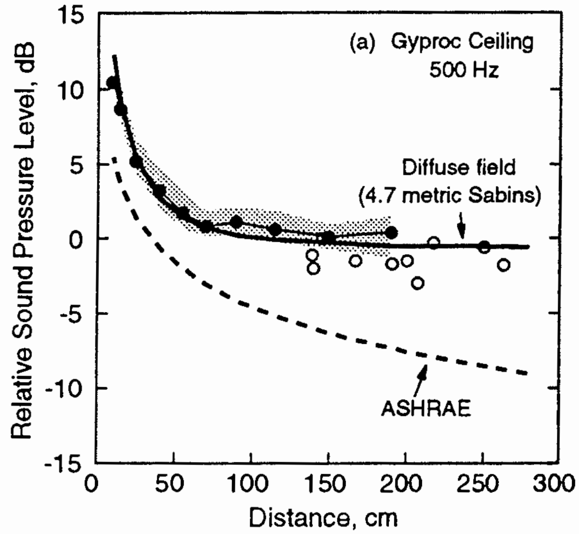
The 10 microphones distributed through the central volume of the room were at locations listed in the table. Distance X was to the side wall, distance Y to the central partition. The center of the duct opening was at X = 1.50, Y = 2.71, height = 2.80 m

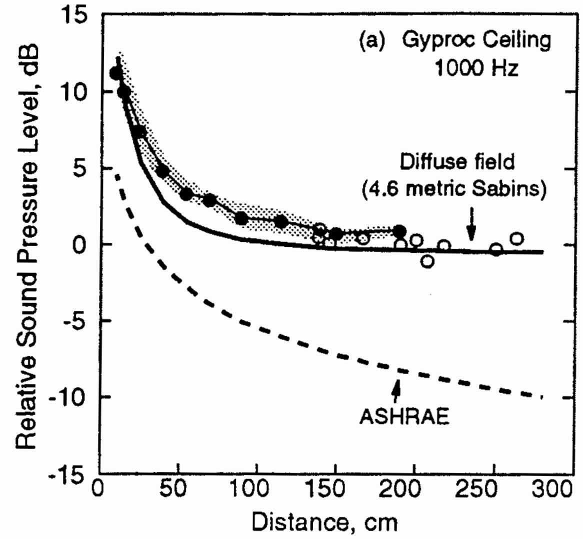
Microphone Position	X m	Y m	Height m	Distance to duct m
1a	0.90	2.97	1.26	1.67
2a	2.90	2.74	1.50	1.91
3a	1.95	2.12	1.63	1.39
4a	2.80	1.17	1.98	2.18
5a	1.25	0.89	1.09	2.51
1b	2.90	2.74	1.26	2.08
2b	0.90	2.97	1.50	1.46
3b	1.35	1.96	1.63	1.40
4b	1.25	0.89	1.98	2.01
5b	2.80	1.17	1.09	2.64

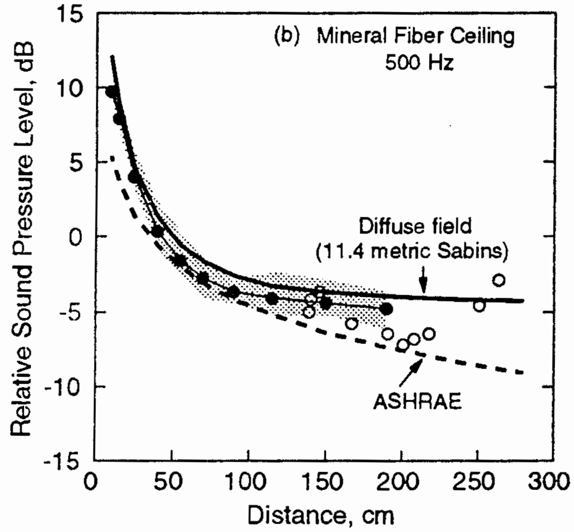
Normalized attenuation values for a duct system predict the average sound pressure level in a room, adjusted to the value expected if absorption in the receiving room matched the reference absorption (12 metric Sabins). To apply the curves in this appendix relative to average normalized receiving room level, subtract 5 db from the values in the graphs.

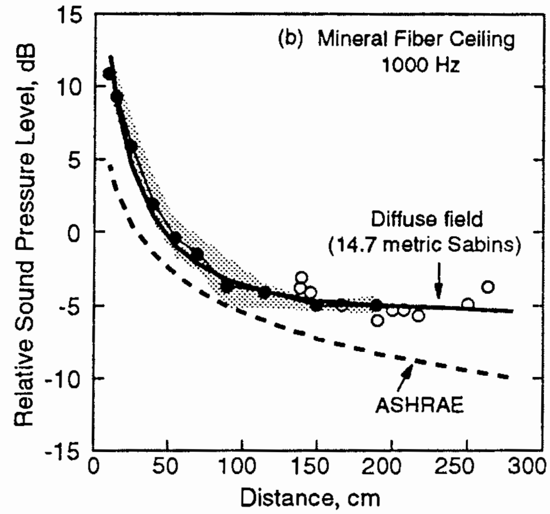


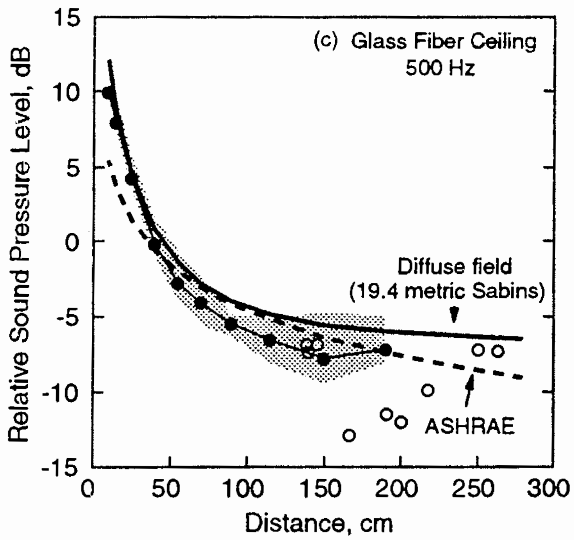
(a) Gyproc Ceiling
125 Hz
Diffuse field
(7.7 metric Sabins)
ASHRAE
(a) Gyproc Ceiling
250 Hz
Diffuse field
(4.6 metric Sabins)
ASHRAE
(b) Mineral Fiber Ceiling
125 Hz
Diffuse field
(11.5 metric Sabins)
ASHRAE
(b) Mineral Fiber Ceiling
250 Hz
Diffuse field
(8.8 metric Sabins)
ASHRAE
(c) Glass Fiber Ceiling
125 Hz
Diffuse field
(16.4 metric Sabins)
ASHRAE
(c) Glass Fiber Ceiling
250 Hz
Diffuse field
(16.2 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
15
10
5
0
-5
-10
-15
0
50
100
150
200
250
300

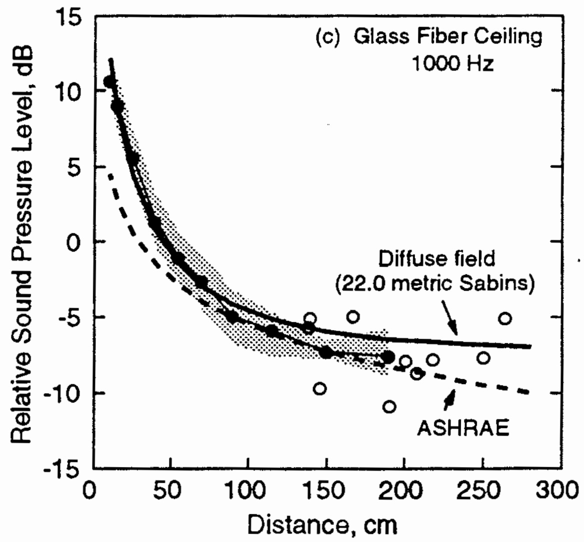

(a) Gypproc Ceiling
500 Hz
Diffuse field
(4.7 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
15
10
5
0
-5
-10
-15
0
50
100
150
200
250
300

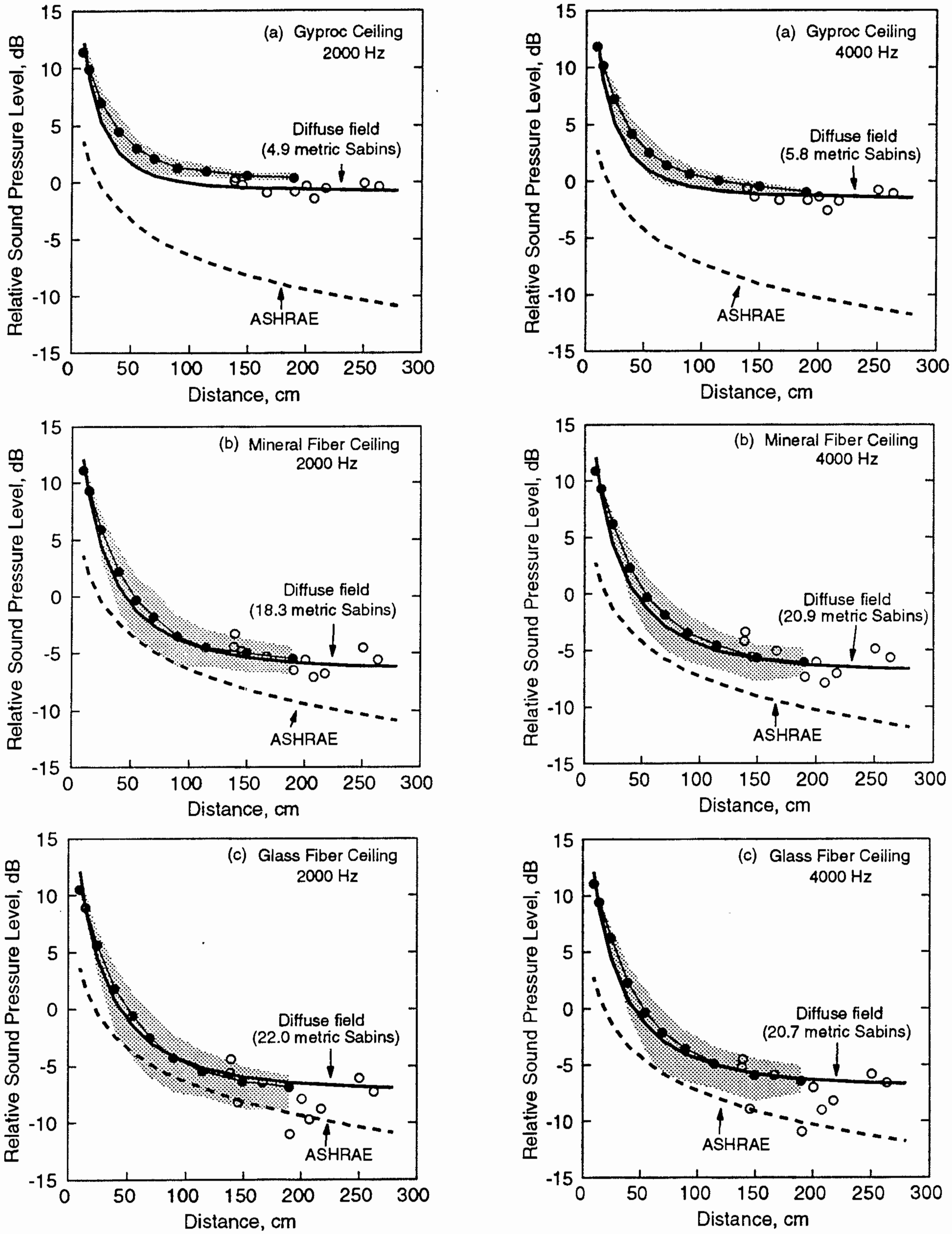

(a) Gyproc Ceiling
1000 Hz
Diffuse field
(4.6 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
15
10
5
0
-5
-10
-15
0
50
100
150
200
250
300


(b) Mineral Fiber Ceiling
500 Hz
Diffuse field
(11.4 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
15
10
5
0
-5
-10
-15
0
50
100
150
200
250
300


(b) Mineral Fiber Ceiling
1000 Hz
Diffuse field
(14.7 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
15
10
5
0
-5
-10
-15
0
50
100
150
200
250
300


(c) Glass Fiber Ceiling
500 Hz
Diffuse field
(19.4 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
15
10
5
0
-5
-10
-15
0
50
100
150
200
250
300


(c) Glass Fiber Ceiling
1000 Hz
Diffuse field
(22.0 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
15
10
5
0
-5
-10
-15
0
50
100
150
200
250
300


(a) Gyproc Ceiling
2000 Hz
Diffuse field
(4.9 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
15
10
5
0
-5
-10
-15
0
50
100
150
200
250
300
(a) Gyproc Ceiling
4000 Hz
Diffuse field
(5.8 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
(b) Mineral Fiber Ceiling
2000 Hz
Diffuse field
(18.3 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
(b) Mineral Fiber Ceiling
4000 Hz
Diffuse field
(20.9 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
(c) Glass Fiber Ceiling
2000 Hz
Diffuse field
(22.0 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm
(c) Glass Fiber Ceiling
4000 Hz
Diffuse field
(20.7 metric Sabins)
ASHRAE
Relative Sound Pressure Level, dB
Distance, cm

Appendix B: Source Characteristics

The first purpose of this appendix is to present data from the literature on strength and directionality of typical human speech. Second, the appendix shows the approximate relationship between directionality of human speech and that for the loudspeaker used in this study.

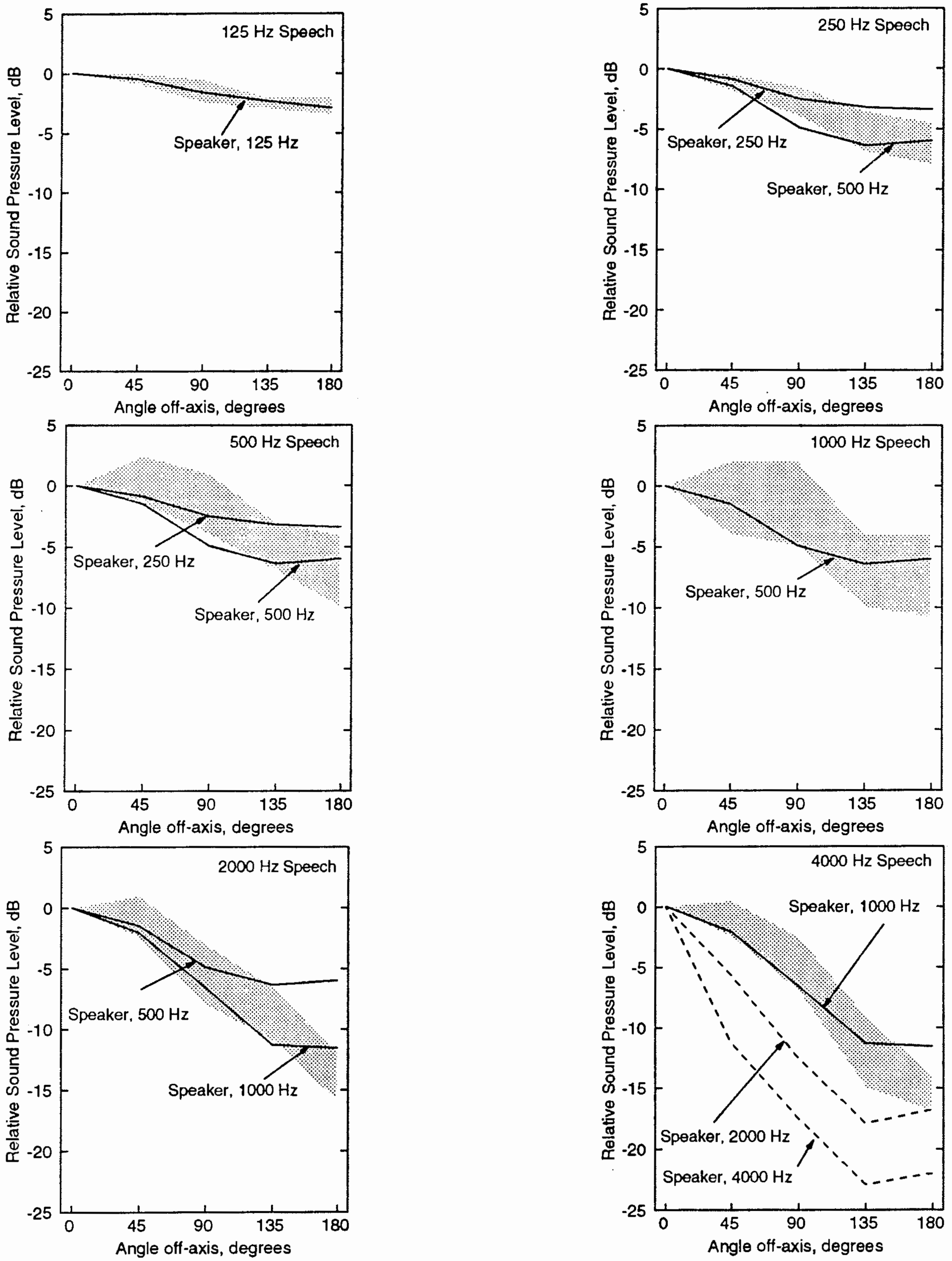
The data on directionality of human speakers was taken from a publication by A. Moreno and J. Pfretzschner in Applied Acoustics, Volume 1, p 78 (1977). The original publication presented 1/3-octave data with fine angular resolution; the octave band ranges shown by the grey area in the figures are a much simplified presentation of that data at 45 degree intervals, but convey the general trends.

Directionality of the loudspeaker is also presented in these figures. Each of the figures includes one or more solid curves - these are octave-band loudspeaker sound pressure levels, relative to the level on-axis, as measured in the IRC anechoic chamber at 1 m from the loudspeaker. In each figure, the loudspeaker results most nearly comparable to the speech directivity are presented. For the design procedure in the third report of this series, the loudspeaker effective source level results for the octave bands indicated by solid curves in each figure would be used to predict the relative effective source level for speech in that octave band.

The last figure also presents dotted curves for the loudspeaker at 2 kHz and 4 kHz; at these frequencies, the loudspeaker used is much more directional than human speech.

To apply the data in this report to calculation of speech privacy, one must also know the loudness of human speech at 1 m, on-axis. For this purpose, the use of the standard spectrum for speech peaks with raised voice effort from ASTM standard E1130-88 is recommended. These sound pressure levels are reproduced in the table here.

Frequency Hz	Standard Speech 1 m, on-Axis
200	63
250	68
315	67
400	70
500	72
630	70
800	66
1000	65
1250	67
1600	63
2000	59
2500	60
3150	58
4000	56
5000	52

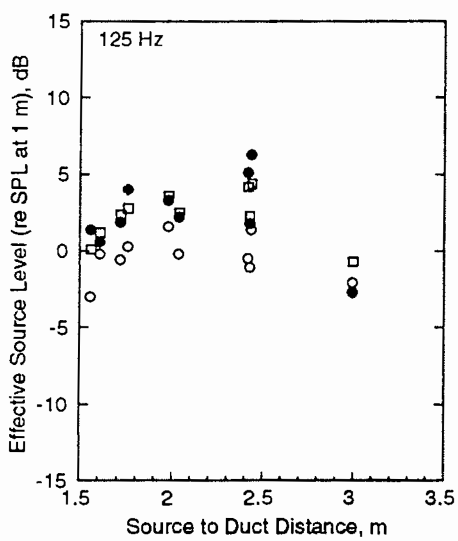

125 Hz Speech
Speaker, 125 Hz
250 Hz Speech
Speaker, 250 Hz
Speaker, 500 Hz
500 Hz Speech
Speaker, 250 Hz
Speaker, 500 Hz
1000 Hz Speech
Speaker, 500 Hz
2000 Hz Speech
Speaker, 500 Hz
Speaker, 1000 Hz
4000 Hz Speech
Speaker, 1000 Hz
Speaker, 2000 Hz
Speaker, 4000 Hz
Relative Sound Pressure Level, dB
Angle off-axis, degrees
5
0
-5
-10
-15
-20
-25
0
45
90
135
180

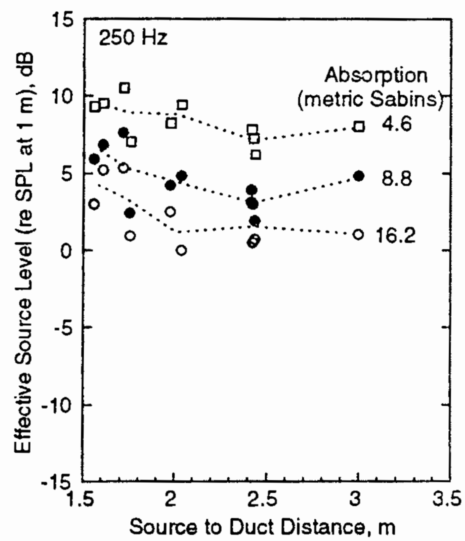
Appendix C: Source Room Sound Pressure Levels

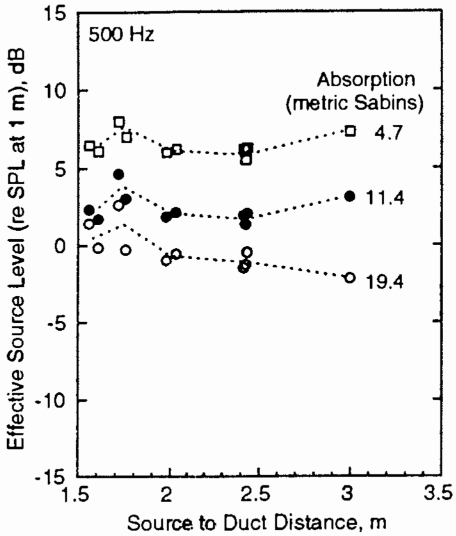
The following graphs present the effective source room sound pressure level relative to the sound pressure level at 1 m on-axis in the anechoic room with equivalent input to the same loudspeaker. The former is needed as the reference point for normalized duct attenuation, and the latter is the conventional form for expressing loudness of human speech. Thus, these graphs provide the transition from speech spectra to the resulting room-average sound pressure level.

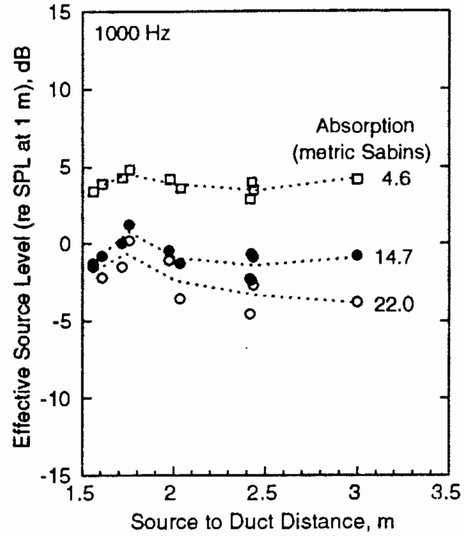
Results are for three types of suspended ceiling panels: squares are for gypsum board, closed circles are for mineral fiber, and open circles are for glass fiber panels. To highlight trends, dotted lines join each group of two or three data points.

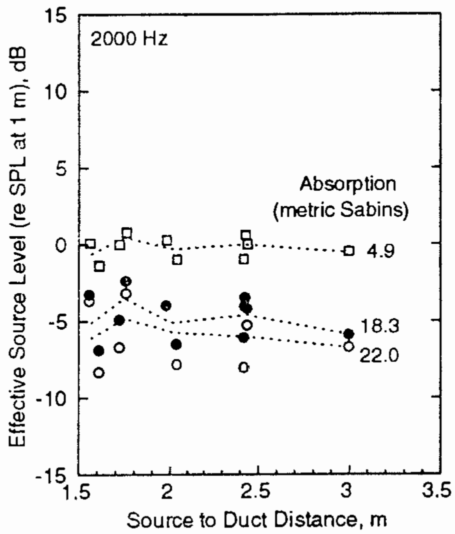
Each graph presents results for one octave-band. The measured octave band absorption for each ceiling case is listed at the right. Note that for application to speech, the directionality information in Appendix B must also be used to select the appropriate graph for each speech frequency.

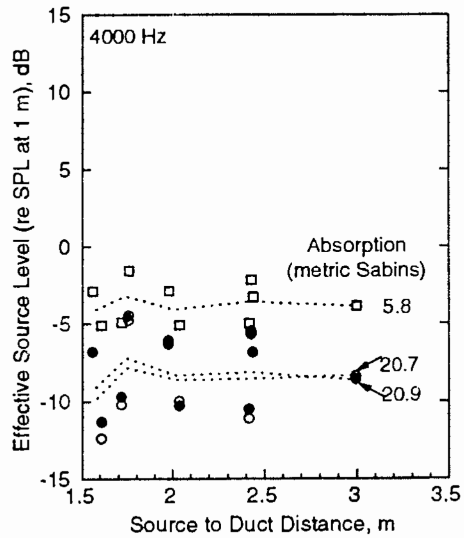





500 Hz
Absorption (metric Sabins)
4.7
11.4
19.4
Effective Source Level (re SPL at 1 m), dB
Source to Duct Distance, m


1000 Hz
Absorption (metric Sabins)
4.6
14.7
22.0
Effective Source Level (re SPL at 1 m), dB
Source to Duct Distance, m


2000 Hz
Absorption (metric Sabins)
4.9
18.3
22.0
Effective Source Level (re SPL at 1 m), dB
Source to Duct Distance, m


4000 Hz
Absorption (metric Sabins)
5.8
20.7
20.9
Effective Source Level (re SPL at 1 m), dB
Source to Duct Distance, m