Using Simulation to Determine Attenuation of HVAC Ductwork

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Overview

• Unlined and Lined Duct Insertion Loss
• Elbow Insertion Loss
• Plenum Insertion Loss
• Duct Breakout Noise
Prior ASHRAE Sponsored Work


Limitation Measurement-based studies based on a limited number of duct cross-sectional areas and lining lengths.
RP-1408 Campaign

ASTM E477

Source Room with Loudspeaker Array

Test Duct

Receiving Room (Reverberant Room)

Source Room

Receiving Room

Vibro-Acoustics Consortium
Modeling Approach

20 Monopoles

Automatically Matched Layer

Structural FEM

Rigid Ductwork

Acoustic FEM

Poroelastic FEM

Automatically Matched Layer

Automatically Matched Layer

Automatically Matched Layer

Automatically Matched Layer
Modeling Approach

- Acoustic Mesh
- Structural Mesh
- Poroelastic Mesh
Sound Absorptive Material Properties

- Johnson-Champoux-Allard model (Allard and Atalla 2009)
- Curve fit (using ESI Foam-X software) used to identify the flow resistivity, characteristic viscous length, characteristic thermal length, and mass density for the fiber.
- Alternative sound absorbing models can be used with little impact.
Metrics for Duct Attenuation

Insertion Loss – Difference in sound pressure level in receiving room without and with absorbing lining.
Noise Reduction – Difference in sound pressure level between source and termination (independent of source).
Transmission Loss – Difference between incident and transmitted sound power (independent of source and termination).
Noise Reduction – Unlined Duct

24 in x 24 in (0.61 m x 0.61 m), 10 ft (3.05 m) Length Square Duct

![Noise Reduction Graph]

- FEM (Rectangular)
- ASHRAE Handbook (Rectangular)
Noise Reduction – Unlined Duct

24 in (0.61 m) Diameter, 20 ft (6.10 m) Length Circular Duct

Noise Reduction (dB) vs. Frequency (Hz)

- FEM (Circular)
- ASHRAE Handbook (Circular)
Insertion Loss – Lined Duct

24 in x 24 in (0.61 m x 0.61 m), 10 ft (3.05 m) Length Square Duct
2 in (5 cm) fiber lining)

![Graph showing insertion loss vs frequency for FEM and Measurement (RP-1408).](image)
Insertion Loss – Lined Duct

\[ f_{\text{max att}} \approx \frac{c}{d} \]

\[ f_{\text{cutoff}} = \frac{c}{2d} \]

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Insertion Loss – Lined Duct

24 in x 24 in (0.61 m x 0.61 m), 30 ft (9.15 m) Length Square Duct
2 in (5 cm) fiber lining

![Graph showing Insertion Loss vs Frequency for FEM and Measurement (RP-1408) for lined ducts. The graph indicates a peak in insertion loss around 800 Hz for both methods.]
Likely Flanking Path

Source Room with Loudspeaker Array

Receiving Room (Reverberant Room)
Insertion Loss – Lined Duct

24 in (0.61 m) Diameter, 20 ft (6.10 m) Length Circular Duct
2 in (5 cm) fiber lining)
\[ \lambda_a = \frac{c}{f} \]
Overview

- Unlined and Lined Duct Insertion Loss
- Elbow Insertion Loss
- Plenum Insertion Loss
- Duct Breakout Noise
Introduction

HVAC Building Equipment

Airborne direct path
Airborne indirect path or duct breakout
Structure-borne path
Prior Elbow Work


Limitation Studies limited to certain duct sizes, bend angles, and specific sound absorptive linings.
Modeling Approach

- 20 Monopoles
- Rigid Ductwork
- Acoustic FEM
- Poroelastic FEM
- Structural FEM
- Automatically Matched Layer
Modeling Approach

Acoustic Mesh with Automatically Matched Layers

Structural Mesh

Poroelastic Mesh
Elbow Insertion Loss

\[ IL = L_{W,\text{without}} - L_{W,\text{with}} \]
Insertion Loss – Unlined Elbow

24 in x 24 in (0.61 m x 0.61 m)

![Graph showing insertion loss vs. frequency for a 24 in x 24 in unlined elbow. The graph includes data points for FEM and ASHRAE Handbook.]
Insertion Loss – Lined Elbow

24 in x 24 in (0.61 m x 0.61 m)
1 in (2.5 cm) fiber lining

Frequency (Hz)

Insertion Loss (dB)

FEM
ASHRAE Handbook
Lined Elbow Insertion Loss

\[ IL = L_{W,\text{straight}} - L_{W,\text{elbow}} \]
Insertion Loss – Lined Elbow

24 in x 24 in (0.61 m x 0.61 m)
1 in (2.5 cm) fiber lining

![Graph showing insertion loss in dB against frequency in Hz. The graph compares FEM and ASHRAE Handbook results.]

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Overview

• Lined Duct Insertion Loss
• Elbow Insertion Loss
• Plenum Insertion Loss
• Duct Breakout Noise
Unlined and Lined Plenums

Wells, 1958

Above the cutoff frequency

\[ IL = 10 \log_{10} \left( S_{out} \left( \frac{\cos \theta}{2\pi d^2} + \frac{1}{R} \right) \right)^{-1} \]

\[ S_{out} = lw \]

\[ R = S\alpha/(1 - \alpha) \]

\[ d = \sqrt{(L - l)^2 + H^2} \]

\[ \cos \theta = H/d \]
Unlined and Lined Plenums

Mouratides and Becker, 2003

Below the cutoff frequency

\[ IL = A_f S + W_e + E_{oa} \]

\( A_f \sim \) empirically defined surface area coefficient
\( S \sim \) total inside surface area of plenum less the inlet and outlet areas
\( W_e \sim \) wall effect (dB)
\( E_{oa} \sim \) offset angle effect (dB)
Unlined and Lined Plenums

Mouratides and Becker, 2003

Above the cutoff frequency

\[ IL = b \left( \frac{S_{out}Q}{4\pi r^2} + \frac{S_{out}(1 - \alpha_a)}{S\alpha_a} \right)^n + E_{oa} \]

\( S_{out} \sim \) outlet cross-sectional area
\( S \sim \) surface area of the plenum
\( r \sim \) distance between the centers of the inlet and outlet sections
\( Q \sim \) directivity factor, and \( \alpha_a \) is the average absorption coefficient in the plenum
\( b, n \sim \) empirically determined constants (3.505 and -0.359)
\( E_{oa} \sim \) offset angle effect (dB)
Finite Element Model

Acoustic Mesh

Automatically Matched Layers

Structural Mesh

Poroelastic Mesh
Insertion Loss – Unlined Plenum

4 ft x 6 ft x 5 ft
unlined plenum
Insertion Loss – Lined Plenum

4 ft x 6 ft x 5 ft lined (2 in fiber) plenum

- Measurement (RP-1026)
- FEM
- Wells (1958)
Insertion Loss – Lined Plenum with Right Angle

Measurement (RP-1026)
FEM
Mouratidis and Becker (2004)
Wells (1958)

4 ft x 6 ft x 5 ft lined
(2 in fiber) plenum
Inlet and outlet ducts at right angles
Overview

• Lined Duct Insertion Loss
• Elbow Insertion Loss
• Plenum Insertion Loss
• Duct Breakout Noise
Prior Breakout TL Work


**Limitation** Studies limited to certain duct sizes and specific sound absorptive linings.
Measurement (Cummings, 1985)

Method 1 (low frequencies)

\[ TL_{out} = L_{W(in)} - L_{W(out)} + 10 \log_{10} \left( \frac{S_{rad}}{S} \right) \]

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Measurement (Cummings, 1985)

Method 2 (high frequencies)

Measure sound pressure in reverberation room with cap as on prior slide then measure again with horn.

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Modeling Approach

- 20 Monopoles
- Rigid Ductwork
- Automatically Matched Layer
- Acoustic FEM
- Poroelastic FEM
- Automatically Matched Layer
- Structural FEM
Structural FEM Models

30 ft (9.15 m) Rectangular Duct

20 ft (6.10 m) Circular Duct
Damping Properties

Rectangular Duct

Accelerometers

Data Acquisition
# Measured Damping

## Measured Damping Loss Factors

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<th>Frequency (Hz)</th>
<th>Circular</th>
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<th>Rectangular</th>
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<td>10 in Diameter (25.4 cm)</td>
<td>10 in × 10 in (25.4 cm × 25.4 cm)</td>
<td>16 in × 16 in (40.6 cm × 40.6 cm)</td>
<td>32 in × 32 in (81 cm × 81 cm)</td>
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Rectangular Duct Breakout TL Curve

From Vér, I.L. 1983
Breakout TL – Rectangular Duct

16 in x 48 in (0.4 m x 1.2 m) Rectangular Duct; 10 ft (3.1 m) Length
2 in (5 cm) Fiber Lining

Breakout Transmission Loss (dB)

Frequency (Hz)

FEM (Unlined)
FEM (Lined)
ASHRAE Handbook (Unlined)
Cummings (1983)
Circular Duct Breakout TL Curve

From Vér, I.L. 1983
Breakout TL – Circular Duct

24 in (0.61 m) Diameter Duct; 20 ft (6.1 m) Length
2 in (5 cm) Fiber Lining

Breakout Transmission Loss (dB) vs. Frequency (Hz)

- FEM (Unlined)
- FEM (Lined)
- ASHRAE Handbook (Unlined)
- ASHRAE Handbook (Lined)
- Cummings (1983)
Importance of Breakout TL

- Insertion Loss
- Breakout Transmission Loss (Unlined)
- Breakout Transmission Loss (Lined)
Summary

• FEA approach qualified for predicting insertion loss of unlined and lined ducts, elbows, and plenums.
• FEA approach qualified for predicting breakout transmission loss.
• Approach can be used for design purposes and to fill in the gaps in the ASHRAE Handbook.
References

