2015

Development and Validation of Finite Element Approaches to Determine the Insertion Loss of Louvered Terminations including Parametric Investigations

Huangxing Chen
University of Kentucky, hch249@g.uky.edu

STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained needed written permission statement(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine) which will be submitted to UKnowledge as Additional File.

I hereby grant to The University of Kentucky and its agents the irrevocable, non-exclusive, and royalty-free license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless an embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student's advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student's thesis including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

Huangxing Chen, Student

Dr. David W. Herrin, Major Professor

Dr. Haluk E. Karaca, Director of Graduate Studies

Development and Validation of Finite Element Approaches to Determine the Insertion Loss of Louvered Terminations including Parametric Investigations

Thesis

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science
in Mechanical Engineering in the College of Engineering
at the University of Kentucky

By

Huangxing Chen

Lexington, Kentucky

Director: Dr. David.W.Herrin, Professor of Mechanical Engineering

Lexington, Kentucky

2015

ABSTRACT OF THESIS

Development and Validation of Finite Element Approaches to Determine the Insertion Loss of Louvered Terminations including Parametric Investigations

Louvers are employed at the ends of HVAC ducts to direct airflow, provide weather protection, and attenuate noise. This details two finite element approaches that can be used to assess the acoustic attenuation from a louvered termination. In the first approach, plane wave propagation is assumed inside of a duct with a non-reflective source. On the receiver side, a baffled termination is assumed and the radiation condition is simulated using a non-reflective boundary condition called an automatically matched layer. In the second approach, a short aperture is placed between two infinite acoustic spaces. On the source side, a diffuse acoustic field is simulated using 20 monopole sources having random phase. The receiver side is modeled as before. For both approaches, the insertion loss is defined as the difference in sound power on the receiving side with and without the louver array. The second approach is compared with measurement with good agreement. The effect of different louver parameters including angle, length, and spacing, and the presence of sound absorptive lining is investigated using both approaches.

KEYWORDS: Louvers, Insertion Loss, HVAC duct noise, sound absorbing material, perfectly matched layer

Huangxing Chen
Student's Signature

1th December, 2015

Development and Validation of Finite Element Approaches to Determine the Insertion Loss of Louvered Terminations including Parametric Investigations

By

Huangxing Chen

Dr. Haluk.E.Karaca

Director of Graduate Studies

Dr. David W. Herrin

Director of Thesis

1th December, 2015

Date

ACKNOWLEDGEMENTS

I would like to convey my deepest gratitude to my advisor Professor David Herrin for his priceless advice and concern during my graduate study at University of Kentucky. His knowledgeable suggestions have made my M.S life very colorful. I am grateful to Professor Tingwen Wu for my committee and for his invaluable acoustic course and research assistance during my time at UK. I would also like to thank Professor Nelson Akafuah for being my committee members and providing valuable suggestions.

My life at Lexington, KY has been enjoyable with the friends and colleagues I have. I would like to thank all my colleagues who working for the Wanlu Li, Gong Cheng, Rui He, Quentin Hunsucker, Jiazhu Li, Shujian He, Nan Zhang, Chaoyang Li, Weiyun Liu, Keyu Cheng, Jundong Li, Ruimeng Wu, Kangping Ruan, Shishuo Sun, Peng Wang, Yitian Zhang, and Limin Zhou.

In the end, I appreciate my parents and my older sister and her husband living in Houston, TX for their support and love all my life.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

Chapter 1 Louver Termination

1.1 Introduction

Louvers or grilles are commonly employed at the ends of heating, ventilation, and air conditioning (HVAC) ducts to screen or cover supply air outlets and return air inlets. There are many different louver configurations (a few are shown in Figure 1.1), but they normally consist of equally spaced blades in parallel with each other. They serve to direct airflow and act as a rain jacket, but also provide a secondary acoustic benefit, reflecting sound back towards the source and absorbing noise when lined with acoustic materials.

Figure 1.1 Louver configuration (From C-S Louvers Website and Price HVAC Website)

For acoustic purposes, louvers serve as barriers between the duct air space and the room blocking the sound transmission. This attenuation is typically small since louvers need to be relatively open to allow airflow. Nevertheless, louvers do provide some needed attenuation, particularly at higher frequencies, and engineers can augment that attenuation using sound absorbing materials.

As pressures mount to decrease HVAC noise in buildings, engineers endeavor to design for noise prior to building construction. The primary reference that HVAC engineers utilize is the American Society for Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Handbook – Applications (2014). ASHRAE has sponsored a number of experimental studies to measure the attenuation of commonly used HVAC components (Mouratidis and Becker, 2004; Well, 1958; Cummings, 1983; Reynolds and Bledsoe, 1989a; Reynolds and Bledsoe, 1989b; Kuntz and Hoover, 1987; Ver, 1978). This work has been used to develop a number of tables and simple equations for the prediction of the attenuation of built-up HVAC systems. Moreover, ASHRAE continuously improves this information. Commonly used HVAC components include unlined and lined ducts, plena, and elbows.

However, the information on duct terminations in the ASHRAE Handbook is very limited. At the present, the Handbook provides a table for the end reflection loss of flush mounted or flanged ducts. End reflection loss (ERL) is defined as the attenuation in decibels at the duct termination. If the termination is conservative (i.e. non-absorbing), the sound power into the room can also be determined. However, the usefulness of ERL is limited when the termination is dissipative since ERL does not differentiate between the sound radiated into the room or absorbed by the termination.

In the work that is most relevant to this thesis, Michaud and Cunefare (2008) measured the end reflection loss for a variety of different sized square and circular duct terminations including a few samples fitted with a slot diffuser and return grille. The weaknesses of that work include the limited number of cases investigated and the choice of metric if the termination is dissipative.

It can be observed that there is a great need for a measurement campaign to acquire data for a wide variety of louver systems. In addition, a metric should be selected that directly relates to the radiated power into the receiving room since that is of greater interest to engineers. Unfortunately, measurement campaigns are costly because they require the manufacture and installation of each configuration, experienced technicians to perform the measurements, and specialized acoustic facilities.

Alternatively, measurement campaigns can be performed using a simulation approach if the approach has been suitably verified. The current research aims to address these concerns by developing a simulation approach to determine the attenuation of louvered terminations.

1.2 Overview

The primary objective of this work is to develop a finite element modeling approach to assess the attenuation of louvered terminations. Two approaches are developed.

1. A <u>plane wave approach</u> that is suitable at lower frequencies up to the first cut-on mode in the duct. A velocity source is placed on one end of a duct with a flanged termination. The louver is modeled at the termination. The source is non-reflective so that longitudinal duct modes are not included. Hence, results are independent of the duct length.
2. A <u>two-room approach</u> that can be used at both low and high frequencies. Source and receiving rooms are simulated as large acoustic spaces with a short length of duct connecting the two rooms. A diffuse acoustic field is simulated on the source side and the louvered termination is placed at the end of the short duct. This approach will depend on the length of the duct and is likely more appropriate at high frequencies.

In both approaches, the metric selected is insertion loss which is defined as the difference in radiated sound power at the termination without and with the louvered system. Insertion loss can be thought of as the increment in attenuation with the louvered system in place and directly relates to the sound power radiated from the termination regardless of whether the termination is non-dissipative of dissipative.

Follow-on objectives include validating the approach, and demonstrating the suitability for parametric investigations. The finite element approach is validated by determining the termination impedance of flanged and unflanged circular ducts for which analytical solutions were readily available. After which, the two-room approach was validated via measurement to demonstrate that the approach could predict the relative difference between two louver configurations.

Parametric investigations were then undertaken to examine the effect of changing the blade length, spacing, and angle. In addition, the impact of adding sound absorptive lining to the louvers is also examined.

1.3 Outline of Thesis

Chapter 2 summarizes the prior work dealing with determining the impedance and end reflection loss of flanged and unflanged terminations, bellmouths, and annular steps. The measurement campaign by Michaud and Cunefare (2008) is also reviewed and some representative results are shown. Following this, measurement and simulation studies that have examined the attenuation of louvers are reviewed. In addition, the acoustic finite element approach is reviewed including technical details about the automatically matched layer used to model a non-reflecting boundary.

In chapter 3, the plane wave approach is described. The method for applying an anechoic source and a baffled termination is emphasized. This is followed by a parametric study using the method examining the effect of blade length, spacing, and angle for both unlined and lined blades.

In chapter 4, the similar two-room approach is detailed. The boundary conditions are selected for both source and termination are detailed. The approach is compared with measurement for two louver configurations. Following this, sensitivity studies are performed to assess the effect of louver angle, length, spacing, and the presence of sound absorptive lining.

In chapter 5, the research is summarized and some conclusions are made. This is followed by some recommendations for further work.

Chapter 2 Background

In this chapter, the subject of termination impedance is first reviewed. First, termination impedance is defined. Following this, the two-microphone method to measure termination impedance is reviewed. Then, analytical solutions for determining the impedance of circular and rectangular ducts are detailed.

After this introductory material, the research by Michaud and Cunefare (2008) is reviewed in some detail. They performed a measurement campaign to characterize the terminations of a number of standard sized heating, ventilation, and air conditioning (HVAC) ducts. Specifically, they measured the end reflection loss (ERL) which can be related to the termination impedance.

The final section examines the measurement and simulation of louver attenuation. Several researchers have measured the attenuation of louvers acting as barriers or used to cover the opening of an enclosure.

2.1 Acoustic Impedance

Impedance is defined as the ratio of an effort to a flow variable. The specific acoustic impedance is defined as the ratio of the acoustic pressure (p) to the acoustic particle velocity (u). This can be expressed as

$$z = \frac{p}{u} \tag{2.1}$$

Impedance is used in acoustics to characterize sound absorbing materials, the acoustic load within ducts, the reflection of a source, and the radiation condition at the end of a duct. The latter is often referred to as a Termination impedance is illustrated in Figure 2.1

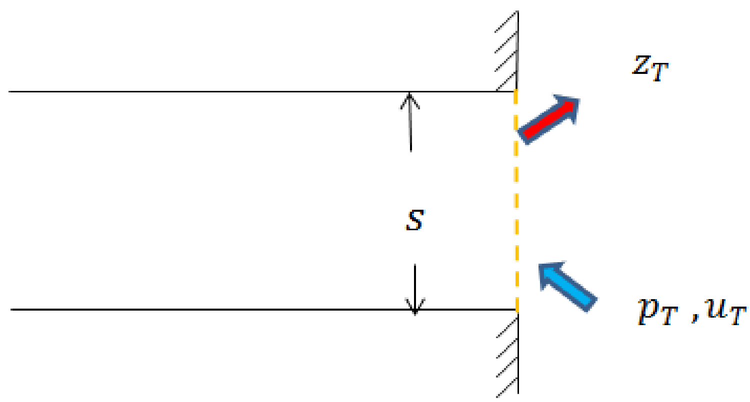

Figure 2.1 Schematic of termination impedance

2.2 Two microphone method

The two-microphone method to measure impedance was first developed by Seybert and Ross (1977) used the measured cross-spectral density function to determine the normal incident impedance of sound absorbing materials. The normal incidence impedance (z_n) can be defined as

$$Z_n = \frac{p_s}{u_n} \qquad (2.2)$$

u_n is the normal velocity and p_s is the surface sound pressure.

The method was improved by Chung and Blaser (1980) who measured the reflection coefficient to determine the impedance and the corresponding normal incident sound absorption coefficient (α_n). Boden (1986) examined the effects of microphone spacing, microphone distance from the sample, and the total duct length. The method has been standardized in ASTM E1050 (ASTM, 1998) and the measurement approach is detailed in the discussion which follows.

A specimen of sound absorbing material is placed at one end of an impedance tube as shown in Figure 2.2. A loudwspeaker is placed on the other side of the tube and is used as a source. Normally, white noise is used though sometimes a swept or stepped sine source is used. Two microphones are placed just upstream of the sample. It is assumed that there is plane wave propagation, no mean flow, and that losses in the tube can be neglected. This implies that the sound absorption of the specimen is much greater than that of the tube wall.

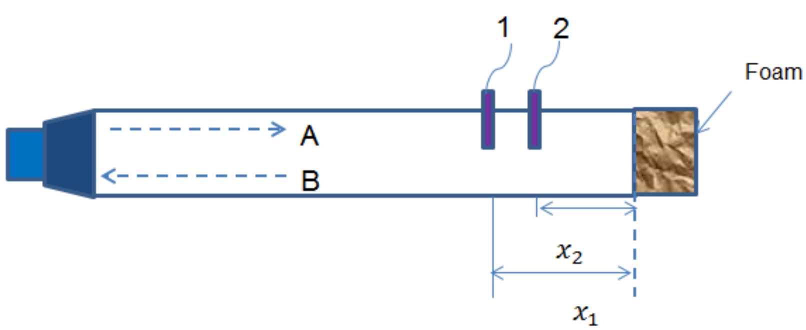

Figure 2.2 Schematic measurement of transfer impedance and reflection coefficient

Below the plane wave cutoff frequency, sound travels as a plane wave and is composed of incident and reflected waves. The sound pressure can be expressed as

$$p(x) = p_+ e^{-ikx} + p_- e^{ikx} \quad (2.3)$$

where p_+ and p_- are the complex amplitudes of the propogating and reflected waves. The corresponding particle velocity can be developed from the equation of motion and is expressed as

$$u(x) = \frac{p_+}{\rho c} e^{-ikx} - \frac{p_-}{pc} e^{ikx} \quad (2.4)$$

where ρ and c are the mass density and speed of sound of air respectively.

The specific acoustic impedance for the material can be expressed as

$$Z(x) = \frac{p(x)}{u(x)} \quad (2.5)$$

where x is the position at the surface of the sound absorbing material.

When measuring impedance, the sound pressure reflection coefficient (R) is measured as a first step. It can be expressed as

$$R = \frac{p_-}{p_+} \quad (2.6)$$

and is normally complex.

As shown in Figure 2.2, two microphones are placed close to the duct termination; one at position $x = x_1$ and the other at $x = x_2$. The surface of the material corresponds to $x = 0$. The reflection coefficient (R) can be expressed in terms of the measured transfer function (H_{12}) between the two microphones. This can be written as

$$R = \frac{e^{-ikx_2} - H_{12}e^{-ikx_1}}{H_{12}e^{ikx_1} - e^{ikx_2}} \tag{2.7}$$

where the transfer function is written as

$$H_{12} = \frac{p(x_{1)}}{p(x_2)} \tag{2.8}$$

The sound absorption coefficient (α), which can be expressed as

$$a = 1 - |R|^2 \tag{2.9}$$

is the ratio of the absorbed and incident sound powers.

In general, impedance can be expressed at any x along a duct. In which case, it is normally termed acoustic load impedance. In the case of a duct, it is normally more convenient to define impedance as the ratio of the sound pressure and volume velocity. Accordingly,

$$Z(x) = \frac{p(x)}{su(x)} \tag{2.10}$$

When the position x is at the end of a duct, the impedance is commonly referred to as a termination or radiation impedance.

2.3 Radiation impedance

2.3.1 *Circular duct free space termination*

The most notable work on termination impedance is that of Levine and Schwinger (1947) who developed an explicit solution for the termination impedance of a circular unflanged duct below the plane wave cutoff.

For a circular unflanged duct neglecting flow,

$$R = 1 + 0.013(ka) - 0.591(ka)^2 + 0.336(ka)^3 - 0.064(ka)\text{^}4 \qquad (2.11)$$

where k is the wavenumber and a is the radius at the termination.

The termination impedance (z_t) can then be expressed as

$$Z_t = \frac{\rho c(1+R)}{S(1-R)} \qquad (2.12)$$

Where S is cross section area of circular duct.

2.3.2 ***Circular duct baffle termination***

For a circular duct baffled termination, Pierce (1981) expressed the termination impedance as

$$Z_t = \frac{\rho c}{S}(R_1(2ka) - iX_1(2ka)) \qquad (2.13)$$

Where

$$R_1 = 1 - \frac{J_1(2ka)}{ka} \qquad (2.14)$$

And

$$X_1 = \frac{H_1(2ka)}{ka} \qquad (2.15)$$

where J_1 and H_1 are are the Bessel and Struve function of the first order, respectively.

2.3.3 ***Rectangular duct baffle termination***

For a rectangular duct in a baffle, Lindemann (1968) showed that

$$Z_t = \frac{1}{(ab)^2}(\frac{-i\rho c}{2\pi}k(ab)^{\frac{3}{2}}f\left(\frac{a}{b}\right) + \frac{\rho c}{2\pi}k^2(ab)^2 \tag{2.16}$$

Where a and b are the dimensions of the duct outlet end and

$$f\left(\frac{a}{b}\right) = 2\left(\frac{a}{b}\right)^{\mathbf{1/2}} sinh^{-1}\left(\frac{a}{b}\right)^{-1} + 2\left(\frac{a}{b}\right)^{-1/2} sinh^{-1}\left(\frac{a}{b}\right) + \frac{2}{3}\left(\frac{a}{b}\right)^{3/2} + \frac{2}{3}\left(\frac{a}{b}\right)^{-3/2} - \frac{2}{3}\left(\left(\frac{a}{b}\right) - \left(\frac{a}{b}\right)^{-1}\right)^{3/2} \tag{2.17}$$

2.4 Simulation of Terminations

For the general case, simulation of the termination is desirable since closed form solutions are not readily available. However, this requires an infinite acoustic domain or a reflection free boundary condition. An infinite acoustic domain is automatically satisfied if the boundary element method is used [Wu's Boundary Element Acoustics]. If the finite element is used the infinite domain must be meshed, which is infeasible, or a special boundary condition should be applied. For example, the finite element mesh can be extended several wavelengths into the domain and the characteristic impedance (ρc) of the medium can be applied as a boundary condition. There is some error with this approximation since it depends on waves being normal incident to the boundary.

Alternatively, special non-reflecting elements or boundary conditions are now commonly used for finite element analysis. Some of the many schemes for modeling unbounded domains are provided by Astley et al. (2000) and Givoli and Harari (1998).

Infinite elements (Astley and Coyette, 2000; Burnett and Holford, 1998) are often used to model acoustic radiation. In that case, a layer of elements is placed around a conventional finite element mesh of the acoustic domain. Normally, the conventional finite element mesh should be spheroidal or ellipsoidal in shape. Infinite elements utilize special shape functions to extend an element to infinity. However, simulation of the radiation is not exact and depends on the using a series of increasingly higher order polynomial terms in the element shape functions to reduce the error. The polynomial order can be adjusted and the effect of adding terms can be assessed using most commercial codes. Less polynomial terms are required if the mesh is extended from the radiating boundary. Accordingly, a compromise is normally made between the size of the mesh and the order of the infinite elements.

In recent years, perfectly matched layers (PML) (Berenger, 1994; Tam et al., 1998; Bermudez et al., 2007; Casalino and Genito, 2008) have been preferred to infite elements. The algorithms used normally replace oscillating waves with exponentially decaying waves. The advantage of the approach is that a conventional finite element mesh is only required to extend several elements from a termination or radiating boundary. Waves at all angles of incidence are absorbed and not reflected.

Different meshes for a PML are recommended depending on the analysis frequency. More recently, the automatically matched layer or AML (Siemens LMS, 2015) implementation has been used. It is advantageous because the PML is automatically generated. Figure 2.3 illustrates how the AML can be applied to model both an unflanged and baffled or flanged termination.

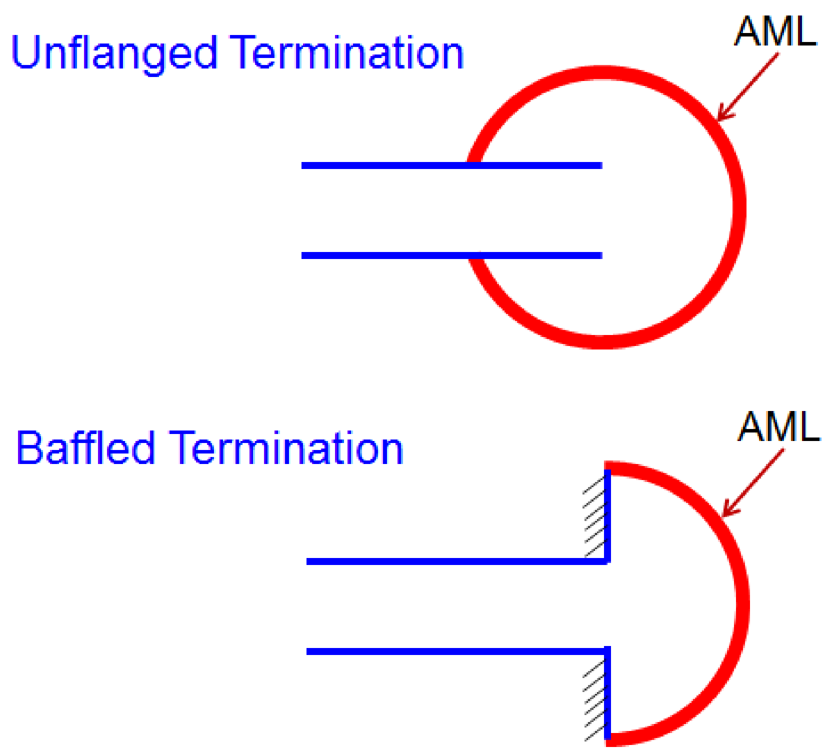

Figure 2.3 Schematic of circular baffle and free space termination

2.5 End Reflection Loss

2.5.1 *Definition of End Reflection Loss*

A number of authors including Kinsler et al. (1982) and Blackstock (2000) have used the end reflection loss (ERL) to characterize the termination of ducts. ERL

can be thought of as the logarithmic sound absorption of the termination (See Equation 2.9) and is expressed as

$$ERL = -10\log(1 - |R|)^2 \tag{2.18}$$

It is representative of the sound power that is by the termination compared to the incident power.

Selamet et al. (2001) developed equations for the reflection coefficient of several conservative duct terminations including bellmouths and annular steps. Boundary element analysis was used to validate the analytical results. Though certainly interesting, geometries considered were of more academic interest and were not representative of those used in industry.

2.5.2 *ASHRAE Research of Michaud and Cunefare*

Perhaps the most relevant applied research is that by Michaud and Cunefare (2008) who measured the ERL of several standard duct terminations of various sizes. They measured the ERL using the two-microphone method described earlier. This approach assumed plane wave propogation in the duct. Hence, sound pressure was assumed constant across the cross-section. Hence, the methodology was only appropriate up to the plane wave cutoff of the duct. Stepped sine excitation was used.

Severial duct configurations were tested. These included various rectangular and cylindrical duct sizes. For instance, they considered the effect of extending the duct past the baffle so that neither the flanged or unflanged assumptions were entirely appropriate. In addition, they considered flex duct leading up to the termination. In which case, a substantial portion of the energy will break out through the flex duct before reaching the opening. Moreover, they also looked at a case with a slot diffuser and with a return grille. Such examples are the most similar to the cases examined in this thesis.

Some of the major findings by Michaud and Cunefare are surveyed in the discussion that follows. First, they found that the measured and analytically determined ERL compare closely for cylindrical and rectangular ducts. The study confirmed that assertion in the ASHRAE Handbook (2008) that the ERL for a rectangular duct is equivalent to that of a circular duct with the same flow area, Figure 2.8 shows the analytical ERL for rectangular and circular ducts with the same cross-sectional area or effective diameter. The effective diameter of a rectangular cross-section can be expressed as

$$D = \sqrt{\frac{4ab}{\pi}} \tag{2.19}$$

where a and b are the width and height of the duct. For the example in Figure 2.4, the the effective radius was 6.77 in (17.196 cm). The results demonstate that ERL correlates with the open area at the termination up to the plane wave cutoff.

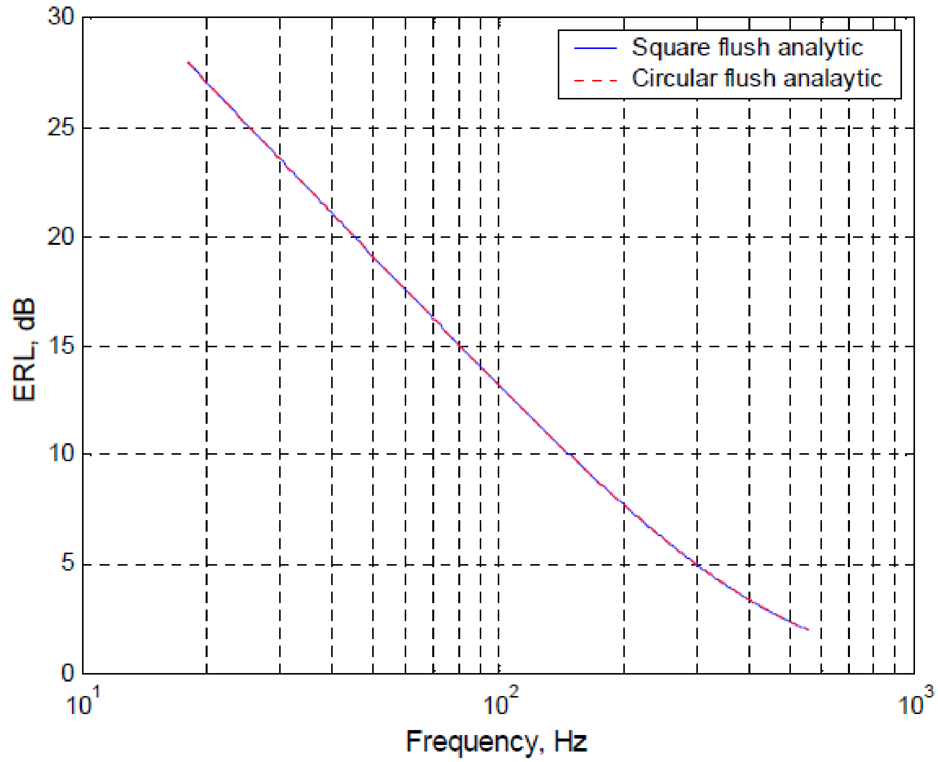

Figure 2.4 Analytic circular and rectangular duct ERL for D = 6.77 in. (17.196 cm) from Michaud and Cunefare (2008)

In Figure 2.5, Michaud and Cunefare plotted the analytical and measured ERL for several different rectangular duct sizes. The ERL is plotted versus kD which normalizes the frequency scale so the analytical curves for various duct sizes are the same. Results demonstrate the good agreement between analytical results and measurement.

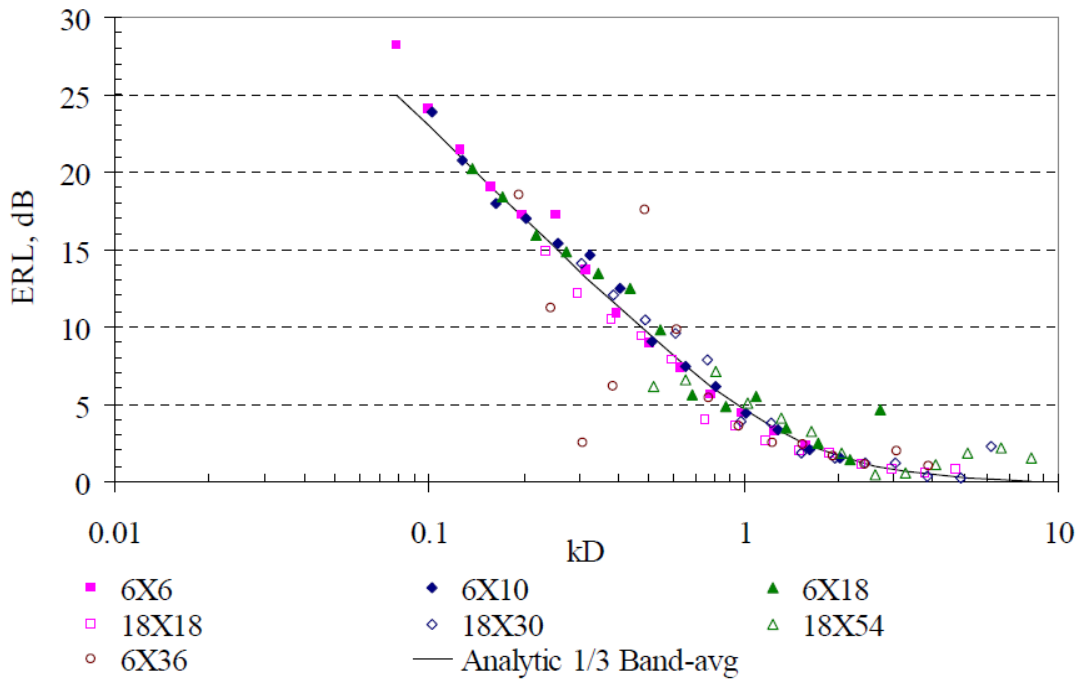

Figure 2.5 Experimental and analytic third-octave band-averaged ERL with a baffled termination

Michaud and Cunefare also investigated effect of baffle hardness. Plywood was used for the hard wall case and furred ceiling tiles were used for the soft case. Figure 2.6 compares the hard and soft wall cases and shows that the ERL is only marginally affected by the baffle hardness. The average ERL difference was less than 0.6 dB.

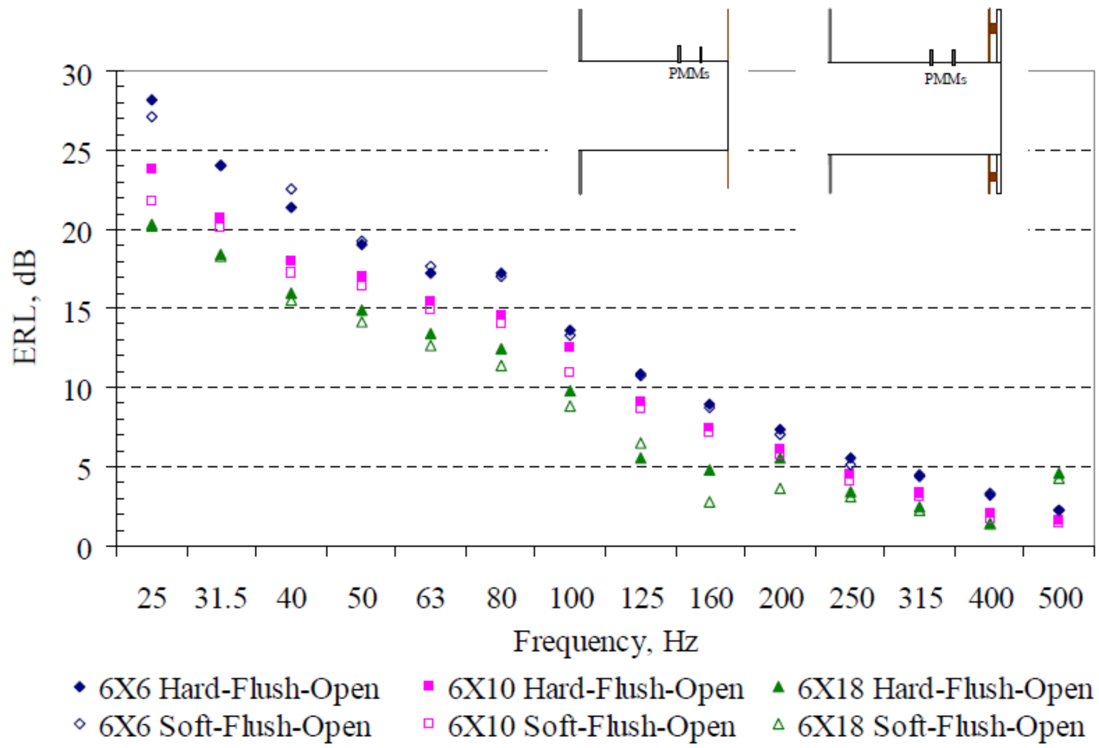

Figure 2.6 Impact of baffle hardness variation on ERL

Furthermore, Michaud and Cunefare developed a simplified analytical expression for ERL prediction for flanged and unflanged ducts. It is written as

$$ERL = log_{10}(1 + (\frac{a_1 c}{\pi f D})^{a_2} \quad (2.20)$$

where a_1 and a_2 are coefficients defined in Table 2.1 that should be selected for given termination, bandwidth, and spectrum shape. The values computed via Equation (2.20) are within 0.1 dB of the analytical ERL.

Table 2.1 Coefficients for flanged and unflanged terminations (Michaud and Cunefare, 2008)

Termination	Bandwidth	Spectrum	a_1	a_2
Flush	continuous	NA	0.6966	2.0126
	Full Octave	Pink	0.6747	2.0088
		White	0.6513	1.9945
	Third Octave	Pink	0.6938	2.0141
		White	0.6912	2.0117
Free Space	continuous	NA	1.0207	1.9869
	Full Octave	Pink	0.9868	1.9828
		White	0.9544	1.9692
	Third Octave	Pink	1.0155	1.9888
		White	1.0120	1.9866

Michaud and Cunefare found that slot diffusers significantly affected the ERL whereas grille style diffusors were largely unaffected. Figure 2.7 shows a plot of the ERL for a Titus ML-39 slot diffuser that is flush mounted and extended by $0.5D$ and D from hard and soft surfaces. Notice that the results are consistent regardless of the extension or baffle surface. Results indicate that the low frequency ERL is greatly reduced whereas the ERL is higher close to 500 Hz.

Figure 2.8 shows similar results for a Titus 350 return grille. Results are compared to analytical and measurement without the grille. It can be seen that the grille impacts the results at very low frequencies.

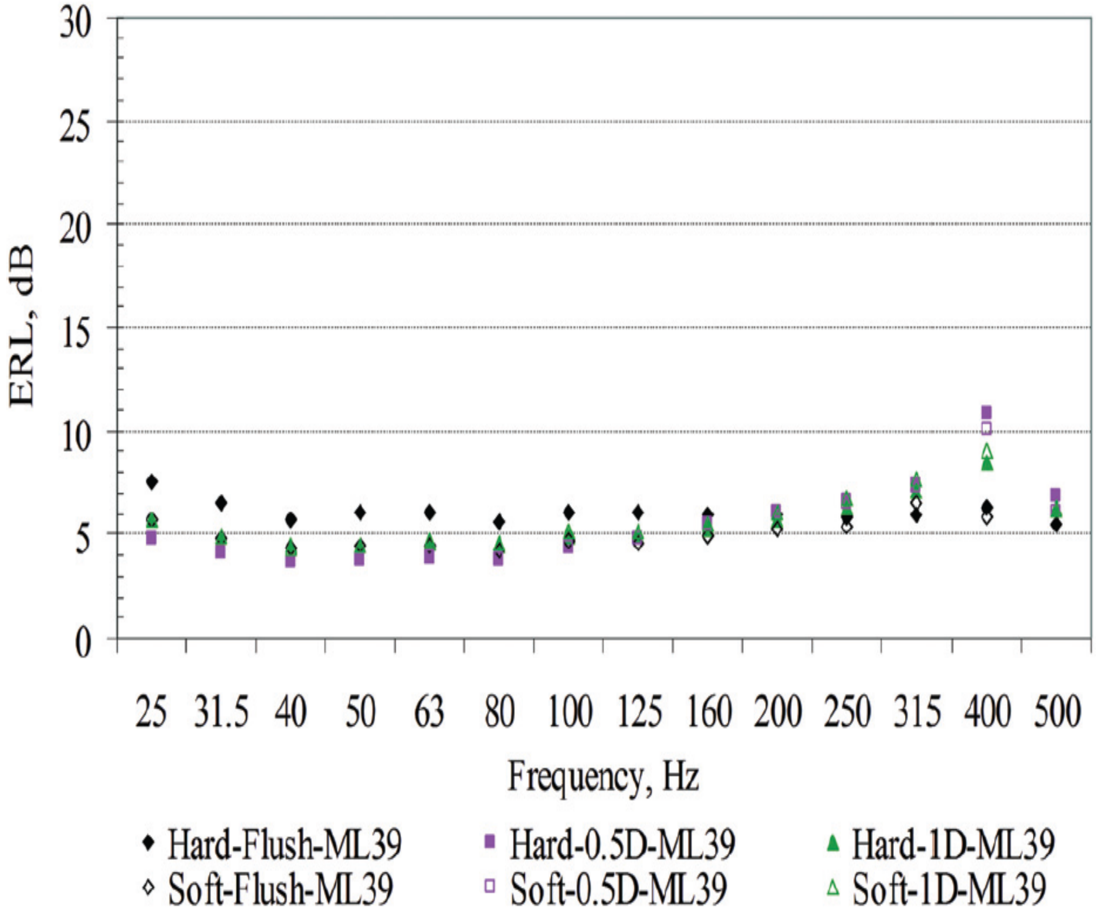

Figure 2.7 $\boldsymbol{ERL}$ for a Titus ML39 slot diffuser

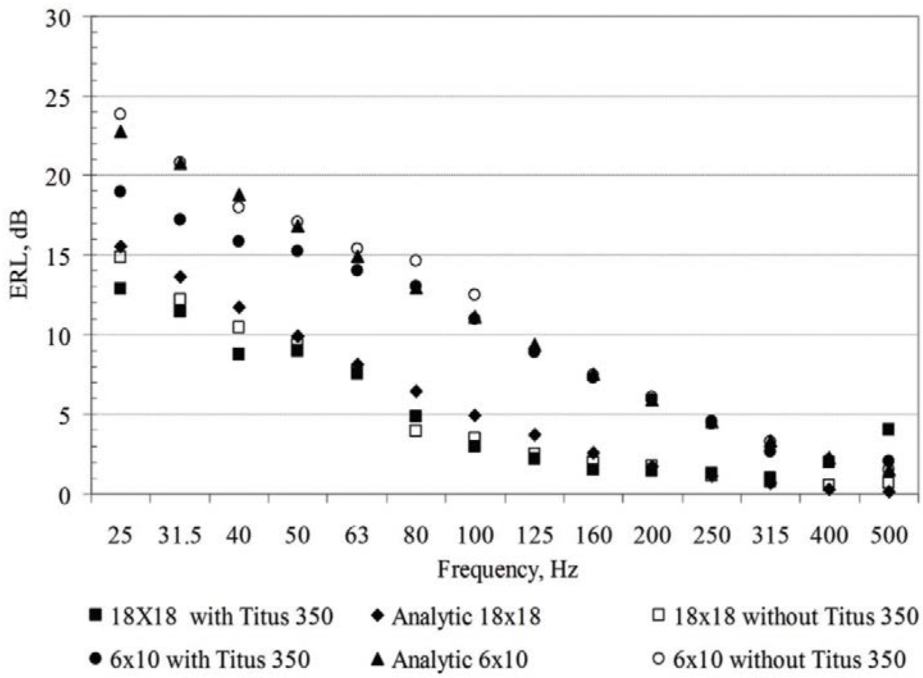

Figure 2.8 ERL for a Titus 350 return grille compared to measured and analytical results without grille.

While the study by Michaud and Cunefare (2008) was important, there were some important limitations. First, the cases examined were limited for louvered terminations. Secondly, ERL can only be used to determine the radiated sound power if the termination is conservative. That is not the case if sound absorption is used in the termination. In that case, ERL is only characteristic of the attenuation at the end of the duct and does not differentiate between the sound absorbed and the sound radiated. Thirdly, the frequency was limited by the plane wave approximation. The present work improves upon the work of Michaud and Cunefare (2008) by detailing an approach that can be used beyond the plane wave cutoff frequency. Moroever, the developed procedure is used to determine the insertion which is the preferred metric since it directly relates to the radiated sound power and results can be extended beyond the plane wave cutoff frequency.

Chapter 3 A Parametric Investigation of Louvered Terminations for Rectangular Ducts

3.1 Introduction

Louvers often cover the openings of enclosures or ends of ducts as a rain jacket or for safety reasons. They also have an acoustic function acting as a partial barrier while also introducing a reactive effect due to the area change through the louvered opening. Placing sound absorbing material on the louvers can further augment the attenuation.

The most suitable metric for gaging the acoustic performance of a louver is insertion loss. Insertion loss depends on other factors besides the louver geometry. For example, it also is contingent on the nature of the source (plane wave, diffuse field). If louvers are installed at the ends of a duct, insertion loss will also be affected by whether the termination is baffled or unbaffled.

The transmission loss of panels is normally measured using the method detailed in ASTM E90 (2009). The panel is placed between a source and a receiving room. The source room is a reverberant room and the receiving room may either be a reverberant or anechoic room. However, reverberant room methods are inappropriate for low insertion loss devices like louvers due to coupling between the source and receiver rooms. Accordingly, Viveiros et al (2002). developed an alternative impulse method for determining the transmission loss of louvers. In follow up work, Viveiros and Gibbs (2003) demonstrated that results from impulse response tests could be used to predict the insertion loss of louvers mounted between two rooms.

Watts et al (2001). Measured and predicted the insertion loss of louvered road barriers using two-dimensional boundary element analysis (BEA). Insertion loss measurements were performed using a scale model approach with and without a strip of sound absorption plugging the gap between louvers. Boundary element results were compared to experimentation with good agreement.

Martinus et al (2001). used BEA to determine the transmission loss of a partial enclosure with a louvered opening. A loudspeaker was connected to the enclosures via an impedance tube and the incident sound power in the tube was determined using wave decomposition. The sound power escaping from the opening was measured and subtracted from the incident sound power. Martinus et al. investigated changing the angle of the louvers and adding sound absorptive lining to one or both sides of the blades. The BEA transmission loss results compared well with measurement. Though the results had limited application because they were dependent on the size and shape of the enclosure, the research validated that numerical analysis could be used to assess the acoustics of a partial enclosure with louvered opening.

The aim of the current work is to determine the effect of louvers at the termination of a duct using acoustic finite element analysis. Plane wave propagation is assumed in the duct. This research will especially interest the heating, ventilating, and air conditioning (HVAC) industry. However, the same approach could be used to determine the acoustic effect of a louvered termination for the HVAC duct attached to the passenger compartment of an automobile or construction vehicle.

3.2 Termination Impedance

There has been considerable research on terminations and the determination of termination impedance. Probably the most notable work is that of Levine and Schwinger (1948) who developed an equation for the termination impedance of a circular unflanged duct below the plane wave cutoff. Pierce (1981) did the same for a flanged circular duct later considering rectangular cross-sections. Selamet et al (2001). determined the reflection coefficient of several duct termination configurations using BEA. Configurations included ducts extending past a baffle, ducts at an angle to a baffle, bellmouths, and stepped annular terminations.

In work for ASHRAE, Michaud and Cunefare (2008) measured the end reflection loss (ERL) for different HVAC duct terminations. ERL was defined as

$$ERL = -10\log(1 - |R|^2) \tag{3.1}$$

Where R is the reflection coefficient. The sound pressure reflection coefficient can be expressed as

$$R = \frac{Z_r + \rho c}{Z_r - \rho c} \tag{3.2}$$

Where Z_r is the termination or radiation impedance, ρ is the mass density of the fluid, and c is the speed of sound. Several rectangular duct sizes typical of HVAC applications were tested with a couple configurations including commercial diffusers placed at the duct end, which are a type of louvered termination.

The current paper details an acoustic finite element analysis approach to determine the insertion loss of louvered terminations. Insertion loss is defined as the difference in sound power without and with louvers installed. As such, the reported insertion loss would add directly to the ERL of a termination without louvers. Several louvered terminations were analyzed and empirical equations were developed.

3.2.1 *Methodology*

Acoustic finite element analysis (FEA) was performed using the LMS Virtual.Lab software (LMS Siemens; 2015). Finite element models were created both without and with louvers and insertion loss was defined as the difference in sound power at the termination.

Special consideration was given to insure that the source was reflection free. If not, there will be resonances in the duct that depend on the duct length. In the model, the source was a sound pressure boundary condition of $p_S = 1$ Pa with a source impedance Z_s equal to the characteristic impedance of the medium. Accordingly,

$$Z_s = \rho c \tag{3.3}$$

where ρ is the mass density of the fluid and c is the speed of sound.

Source impedance can be thought of as a special case of a series or transfer impedance. Transfer impedance is defined as shown in Fig. 1a according to the equation

$$Z_{tr} = \frac{p_1 - p_2}{u} \tag{3.4}$$

where p_1 and p_2 are the sound pressures on either side of the impedance and u is the particle velocity of the source. Note that it is assumed that the source velocity is the same on both sides of the impedance. For the special case of a source impedance, Equation (3.4) can be rewrote as

$$Z_s = \frac{p_S - p_L}{u_L} \tag{3.5}$$

where p_L and u_L are the load pressure and particle velocity respectively. This concept is illustrated using the electrical analogy shown in Fig. 3.1.

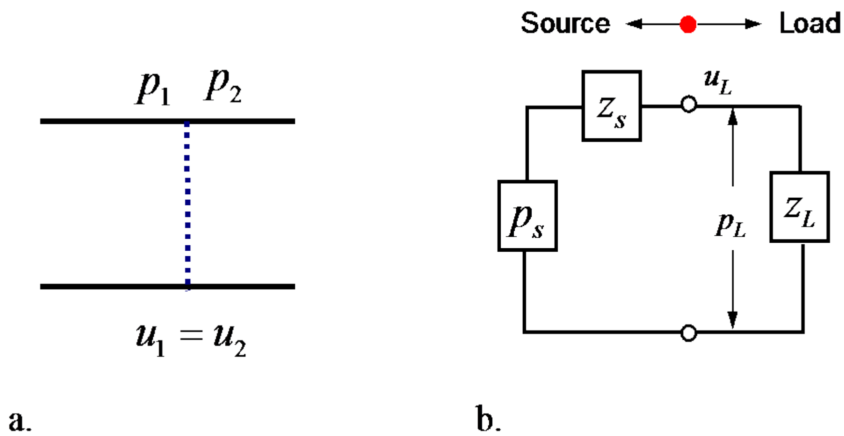

Figure 3.1 a) Schematic illustrating transfer impedance. b) Schematic showing electrical analogy for acoustic source impedance

The way this is implemented in the FEA is illustrated in Fig3.2. A transfer relation is used to define the constraint equations between element face Sides 1 and 2. In LMS Virtual.Lab, a transfer relationship is defined using the convention

$$\begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} = \begin{bmatrix} a_1 & a_2 \\ a_4 & a_5 \end{bmatrix} \begin{Bmatrix} p_1 \\ p_2 \end{Bmatrix} + \begin{Bmatrix} a_3 \\ a_6 \end{Bmatrix} \quad (3.6)$$

where u_1, u_2, p_1, and p_2 are defined in Fig. 1a. $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$ and α_6 are complex constants. For the particular case of a source impedance, $\alpha_3 = \alpha_6 = 0$, $\alpha_1 = \alpha_5 = \frac{1}{z_s}$, and $\alpha_2 = \alpha_4 = -\frac{1}{z_s}$.

Fig. 3.2 is a schematic showing the modeling approach and the boundary conditions. Note that the source side consists of two separate meshes (shown in Fig3.2), which are linked together using the aforementioned constraint equations.

The leftmost mesh can be arbitrary in length. The source pressure boundary condition of $p_S = 1$ is specified on Side 1 as shown in Fig3.2. The particle velocity can be assumed to be zero on the left hand side of the mesh. The baffled termination is modeled using a hemispherical mesh with an automatically matched layer (AML) to deal with the radiation boundary condition. The AML is a non-reflective boundary that will function properly even for high angles of incidence. The AML permits a conformal mesh to be used and is mathematically equivalent to a perfectly matched layer (PML). However, an AML automatically adjusts the thickness and resolution of the mesh at the boundary so that that the boundary is non-reflecting at both low and high frequencies. Berenger, et al [1994] includes a thorough summary of PML theory for acoustics and readers are encouraged to look there for more information.

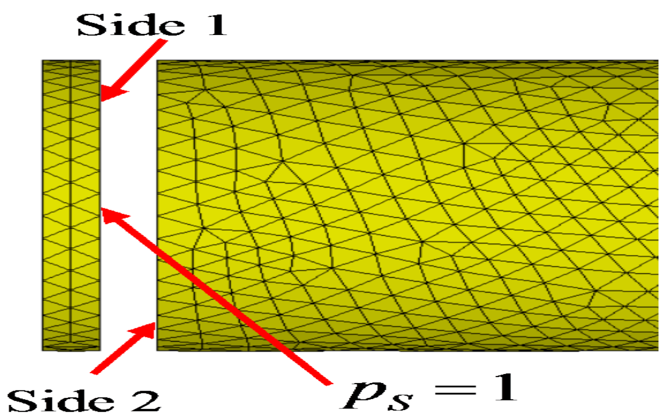

Figure 3.2 Finite element mesh of the source side

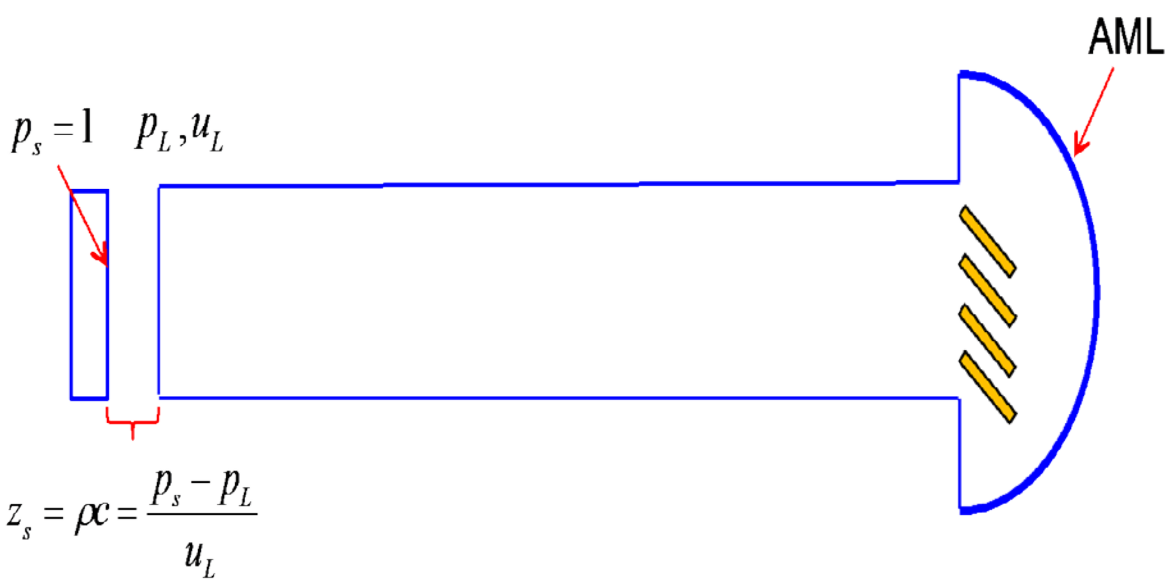

Figure 3.3 Schematic showing FEA boundary conditions

In order to validate the methodology for modeling the termination using an AML, termination impedance results were compared to the equations developed by

Levine and Schwinger (1948) and Pierce (1981) for unflanged and flanged terminations respectively with good agreement. Real and imaginary parts of the termination impedance are compared in Figs3.4a and 3.4b respectively for a circular unlined flanged duct that is 0.1 meter in diameter.

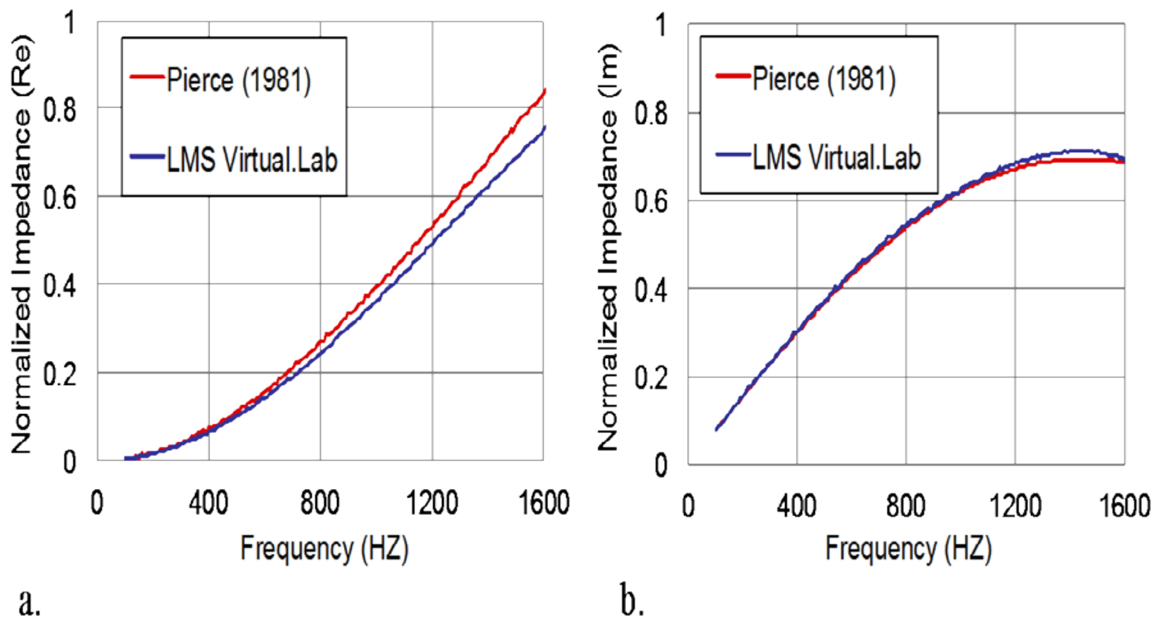

Figure 3.4 Theoretical and predicted termination impedance for a flanged 0.1 m diameter circular duct. a) real and b) imaginary part

3.2.2 ***Lined Louvers***

The approach used for lined louvers was identical to that described above for the unlined case. For the lined case, the lining was modeled using poroelastic elements. The poroelastic properties are shown below in Table 1.

Table 3.1 Biot parameters selected for lined cases

Static Flow Resistivity	5000, 10000, and 15000 Rayls
Porosity	0.926
Tortuosity	1
Characteristic Viscous Length	0.252 mm
Characteristic Thermal Length	0.504 mm

3.2.3 *Sensitivity Studies*

The approach detailed above was then applied to a number of cases. The unlined louvered cases were selected so that there was some overlap between a louver and its neighbor. Accordingly, there was no direct line of sight from the source through the louvered arrangement. In each case, 12×12 in^2 cross-sectional area ducts were examined. For the unlined case, the geometrical parameters selected and varied are shown in Fig. 3.5a. Similarly, the parameters selected for the lined cases are shown in Fig. 3.5b. The unlined and lined cases analyzed are listed in Tables 2 and 3. For the lined case, the effect of both changing the sound absorber lining thickness and the flow resistivity was also considered.

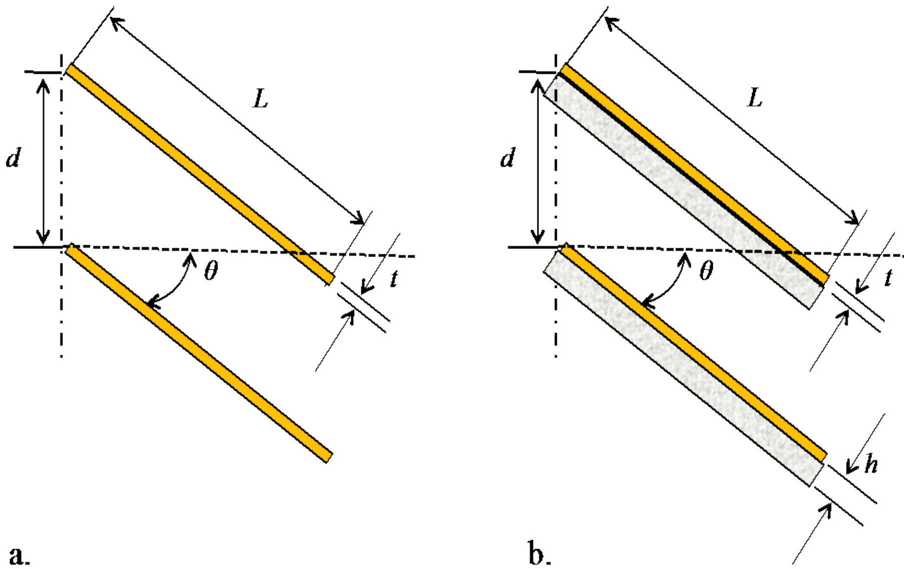

Figure 3.5 Geometrical parameters selected to describe the louvered terminations a) without and b) with sound absorptive

Table 3.2 listing of cases for unlined sensitivity

Case	θ (degrees)	L (inches)	d (inches)
1	45	3	2
2	60	3	2
3	75	3	2
4	60	2	2
5	60	4	2
6	60	3	2.4
7	60	3	3.2

Table 3.3 Listing of cases for lined sensitivity studies

Case	θ(deg.)	L (in)	d (in)	h (in)	σ(rayls)
1	0	3.0	2.4	0.4	15,000
2	45	3.0	2.4	0.4	15,000
3	60	3.0	2.4	0.4	15,000
4	60	2.0	2.4	0.4	15,000
5	60	4.0	2.4	0.4	15,000
6	60	3.0	2.0	0.4	15,000
7	60	3.0	3.2	0.4	15,000
8	60	3.0	3.2	0.0	15,000
9	60	3.0	3.2	0.8	15,000
10	60	3.0	3.2	0.8	5000
11	60	3.0	3.2	0.8	10,000

3.3 Unlined Louver Results

Sample results for unlined case 1, 2, and 3 are shown in Fig. 3.6. The result shown is typical. The results show that the insertion loss will increase as the louvers are closed (the angle θ is increased from 45° to 75°). The curve is smooth for each case and is roughly linear up to the plane wave cutoff frequency. The geometry and boundary conditions are symmetric, so that the plane wave cutoff frequency is twice what would be predicted for a duct having these cross-sectional dimensions.

There are no resonances in the insertion loss since the source is anechoic. Notice also that the insertion loss is only a few dB and is less than 1.0 dB below

200 Hz. The insertion loss results indicate that louvers will only have appreciable acoustic attenuation at higher frequencies.

Fig. 3.7 shows the effect of changing the cross-sectional area size for Case 2. It can be seen that the insertion loss is unaffected by the change in the duct size and will be similar regardless of the size of the duct up to twice the cutoff frequency.

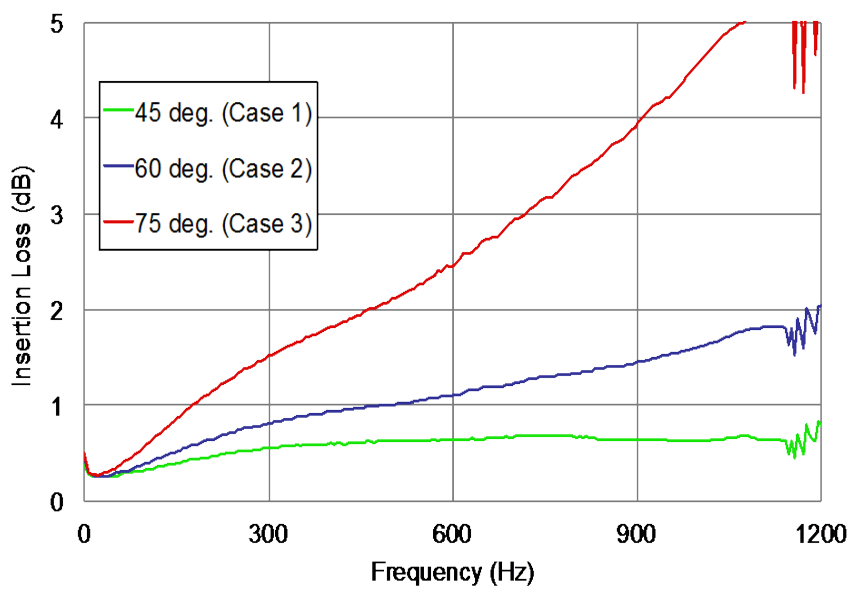

Figure 3.6 Insertion loss comparisons for unlined Cases 1, 2 and 3

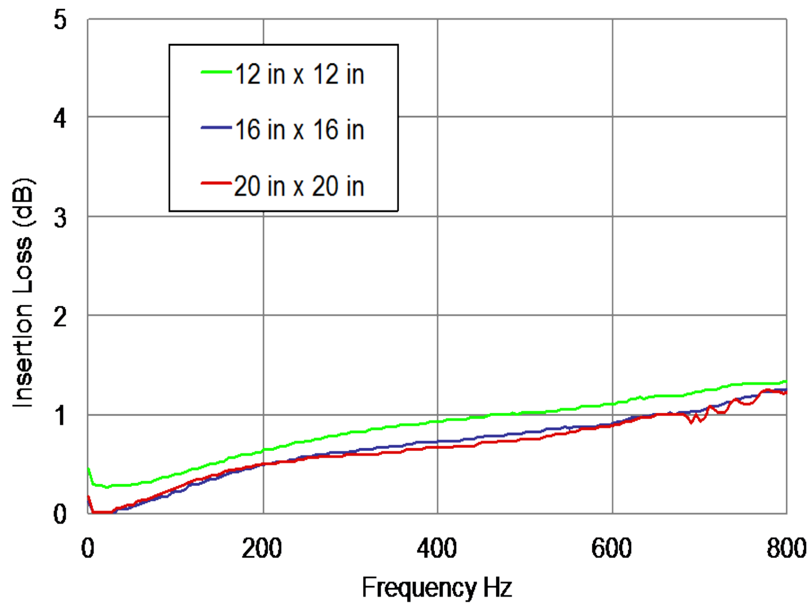

Figure 3.7 Insertion loss comparison for Case 2 with different duct cross-sectional areas.

3.4 **Lined Louver Results**

Results for lined Cases 1, 2, and 3 are shown in Fig. 3.8. Results are very similar to the unlined cases. Notice that the insertion loss is improved with lining. The insertion loss is nearly doubled comparing lined Case 3 to the similar unlined Case 2 (Fig. 3.6). The lining improves the sound absorption at higher frequencies and also partially obstructs the opening improving the low frequency attenuation.

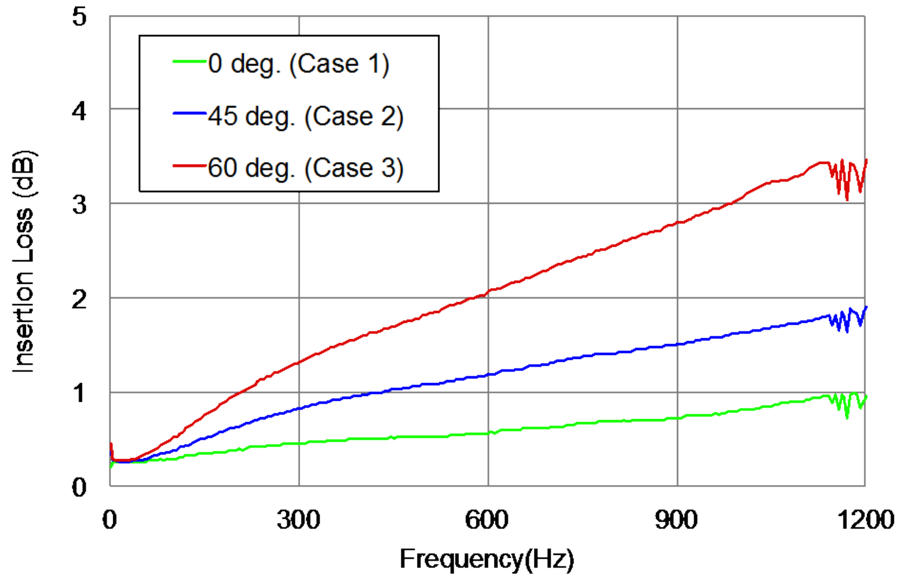

Figure 3.8 Insertion loss comparison for lined Cases 1, 2, and 3

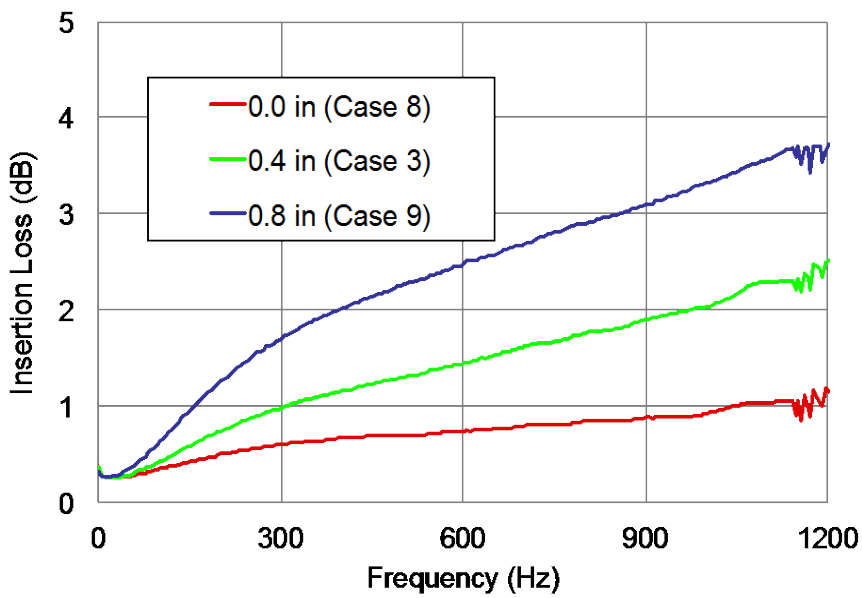

Figure 3.9 Insertion loss comparisons for different sound absorbe lining thickness

The effect of varying the liner thickness is shown in Fig. 3.9. It can be seen that the thickness of the liner has a sizeable effect at higher frequencies. The effect of varying the flow resistivity of the lining is shown in Fig. 3.10. The effect is negligible below 300 Hz and is on the order of 1 dB or less at higher frequencies. The results indicate that the selection of sound absorbing material may not be as important as the liner thickness

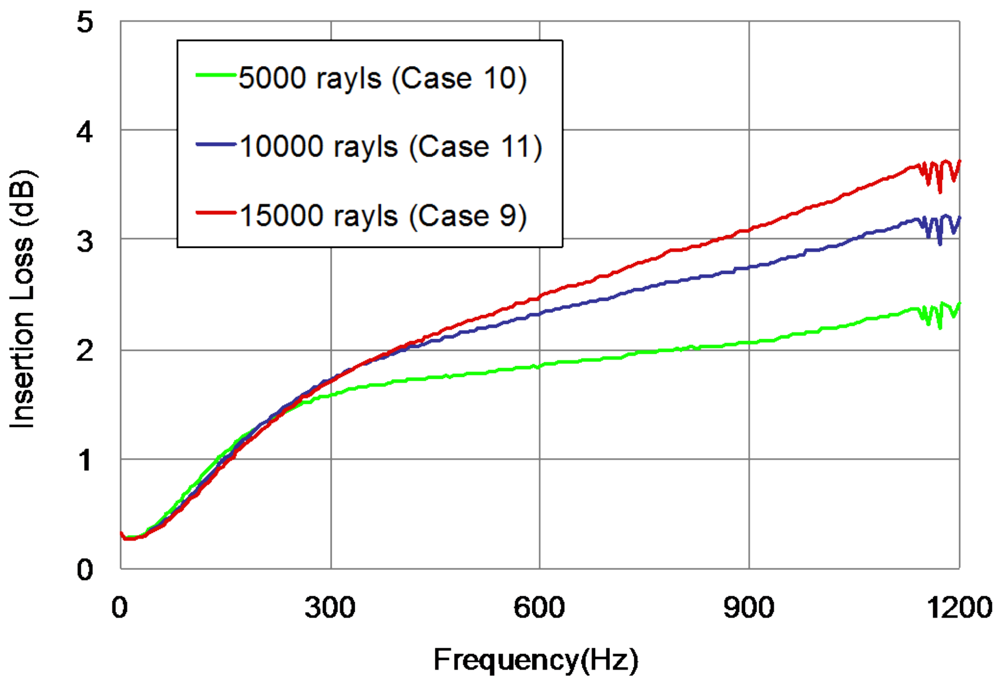

Figure 3.10 Insertion loss comparisons for different flow resistivities

3.5 Empirical Equations

Based on the sensitivity studies for unlined and lined louvers, equations were developed for the insertion loss. The equations were developed using a simple curve fitting approach. The terms selected in the equation included Lsin(theta)-d which corresponds to the amount of coverage that the louvers offer at the end of the duct. dcos (theta) - t corresponds to the spacing between louvers. These two variables seem to relate most clearly to the attenuation at the termination.

The insertion loss is expressed in terms of a louver overlap factor and the spacing between louvers which are defined as $L\sin\theta - d$ and $d\cos\theta - t$ respectively.

For the unlined case,

$$IL = (4.5(L\,sin\,\theta - d) - 40.78(d\,cos\,\theta - t) + 1.294) * \frac{f}{c} + 0.5 \qquad (3.10)$$

where f is the frequency in Hz. It should be recognized that this equation is limited in applicability since it relies on the cases summarized in Table 3.2. A similar equation for lined louvers was found to be difficult to develop due to the increased number of variables.

3.5.1 ***Summary***

Several louvered terminations have been modeled using acoustic FEA. The source impedance is anechoic so the source is reflection free and the longitudinal modes inside the duct are ignored. Sensitivity studies were performed for both unlined and lined louvers. Based on these studies, empirical equations for the insertion loss were developed for the unlined case. It can be concluded that louvers will only attenuate the sound pressure level by a few dB if they are unlined. However, more substantial attenuation may be achieved by lining the louvers.

Chapter 4 Finite Element Approach to Determine the Insertion Loss through Louvered Terminations

4.1 Introduction

One of the primary advantages of numerical acoustics is that experiments can be simulated that require 1) special equipment and high skilled technicians and 2) substantial setup and measurement effort. This is certainly the case for determining the acoustic properties of duct terminations or inlets especially if they are louvered. Louvers or grilles are commonly used to cover supply air outlets and return air inlets directing flow. They also provide a secondary acoustic benefit by reflecting sound back towards the source or absorbing sound. Assessing this acoustic attenuation is difficult to accomplish experimentally.

In ASHRAE sponsored research (RP-1314), Michaud and Cunefare (2008) measured the end reflection of standard duct terminations of various sizes including a few cases of commercial slot diffusers and return grilles. The end reflection loss (ERL) was expressed as

$$ERL = -10\log\left(1 - \frac{W_{ref}}{W_{inc}}\right) = -10\log(1 - |R|^2) \tag{4.1}$$

where W_{ref} and W_{inc} are the reflected and incident power and R is the reflection coefficient. Plane wave propagation was assumed meaning that the sound pressure is assumed to be constant across the cross-section. Hence, the approach used was appropriate at frequencies below the plane wave cutoff. The cutoff frequency for a square or rectangular duct is $c/2L$ where L is the largest cross-sectional dimension. For a circular duct, the cutoff frequency occurs at $c/1.71d$ where d is the diameter of the duct (Eriksson, 1980).

Designers are commonly most interested in knowing the transmitted power (W_{tr}) into the room. However, ERL can only be used to assess the transmitted power (W_{tr}) if the termination is conservative (i.e., non-dissipative). Hence, there are two important limitations of ERL. It 1) assumes plane wave propagation and 2) is most useful if the termination is conservative.

Viveiros et al. (2002) used an impulse method to measure the transmission loss of a louver introduced between two rooms. The setup for the test was comparable to that for the measurement of panel transmission loss used in ASTM E90-09 (2009) or ISO 10140-2 (2010) where a test panel is placed between a source and a receiving room. Normally, two reverberation rooms are used for the test but there are some standards which use an anechoic cell on the receiving side such as ISO 15186-3 (2002). Viveiros et al. (2002) noted that the typical method for determining the transmission loss according to the standard is flawed when the transmission loss of the specimen is low. In that case, there is too much communication between rooms for the reverberant fields in each room to be considered separately.

In a follow-on paper, Viveiros and Gibbs (2003) argued compellingly that insertion loss is a more relevant metric than transmission loss for the case of louvers. Transmission loss includes the effect of the aperture and louvers whereas insertion loss isolates the increment in attenuation due to the addition of the louvers. They developed an analytical image model, and then validated the model by comparison to measured insertion loss. Insertion loss was measured by introducing an aperture into a large enclosure with loudspeaker source. Sound power was measured without and with the louvered specimen installed in the aperture. Using this metric, no differentiation is made between the sound power reflected or dissipated by the aperture. However, the transmitted power is of greater interest to designers and the attenuation mechanism is of less consequence.

There have also been a few simulation studies of louvered systems. Watts et al. (2001) measured and used the boundary element method to determine the insertion loss of a louvered barrier. Two-dimensional boundary element analysis and measurement compared well. However, the barrier was intended for roadside applications so results are not conveyable to typical HVAC terminations.

Martinus et al. (2001) determined the transmission loss of a small enclosure with a louvered opening. A tube instrumented with microphones (known as an impedance tube) was attached to the small enclosure and used as the sound source. The incident sound power was measured in the impedance tube and the transmitted power was determined at the louvered opening using a sound intensity scan. Simulated and measured attenuation agreed well. The results demonstrated that boundary element methods could be used to determine attenuation but the results were restricted to a single enclosure configuration and were not transferrable to more general cases.

Selamet et al. (2001) developed equations to determine the reflection coefficient of several conservative duct terminations of varying geometry. Cases included bellmouths and annular steps, and boundary element analysis was used to validate the analytical approach. However, cases were not typical of those used in HVAC duct applications and reported results were limited to end corrections.

In prior work at the University of Kentucky (See Chapter 3), the insertion loss of different terminations was determined using an approach valid below the plane wave cutoff. This approach is certainly of interest for HVAC applications at low frequencies and is reviewed in this chapter. In addition, a second procedure is suggested which is appropriate at both low and high frequencies, but is most suitable for use above the plane wave cutoff.

All analyses are performed using acoustic finite element analysis. The airspace from the source to termination is modeled. For the first method, the louver assembly is positioned at the end of the duct. A plane wave source is imposed and is non-reflecting in order to avoid any acoustic resonances in the duct. Insertion loss is defined as the difference in sound power without and with the louvered specimen in position. Since the source is non-reflective, insertion loss is independent of the length of the duct. This approach is most suitable below the plane wave cutoff and thus for ducts of smaller cross-section.

The second approach is similar. The louver is positioned at the end of a short aperture connecting two infinite spaces. A diffuse acoustic field is applied on one side using 20 monopole sources of random phase. On the other, the louver is positioned in an infinite baffle and the transmitted power is determined. This procedure is more appropriate for ducts of large cross-section. Simulation results were validated with measurement for the second approach.

Sensitivity studies were performed to primarily demonstrate the usage of the approach. The effects of louver angle, length, spacing, and the presence of sound absorptive lining were assessed.

4.2 Two Room Procedure

The geometry is selected to be similar to the ASTM E90 (2009) standard for determining the transmission loss of a panel that calls for placing a sample in an aperture between two reverberation rooms. For the simulation, the reverberation rooms are instead assumed to be infinite acoustic spaces. This insures that interconnected room modes will not affect the measurement, which is a concern. Accordingly, the louver system is positioned at the end of a short aperture between the two acoustic spaces as shown in Figure 4.1. A diffuse acoustic field is applied on the source side. This parallels using a reverberation room with several loudspeakers. The sound power radiated into the receiving room is determined and insertion loss is defined as the difference in transmitted power without and with the louver system in place.

The geometry and boundary conditions are illustrated in Figure 4.1. Twenty sources having the same volume velocity amplitude but random phase are applied to the hemispherical surface on the source side in an effort to simulate a diffuse field boundary condition. Care is taken so that the source definition is consistent between untreated and treated cases. Insertion loss results were within 1 dB of each other as long as over 15 sources were used.

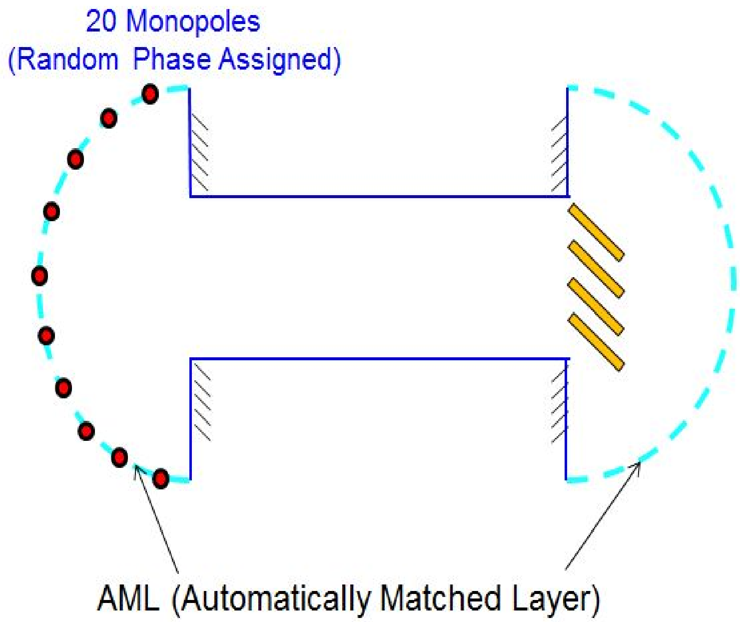

Figure 4.1 Schematic showing simulation setup and boundary conditions for the two room procedure

In the simulation, the source and receiver sides are infinite in dimension so that room modes can be neglected. One advantage of simulation is that the ideal case can be studied.

Sound absorbing lining was assumed to be fiber and was modeled using poroelastic finite elements which include sound pressure degrees of freedom plus degrees of freedom for the displacement of the elastic frame (Atalla et al., 1998). Though poroelastic properties are difficult to measure directly, they can be estimated from the measured sound absorption coefficient using the ESI Foam-X software (ESI, 2014). The algorithm divides the sound absorption into different frequency regimes and uses a curve fit to identify the poroelastic properties. Using this procedure, the flow resistivity, characteristic viscous length, characteristic thermal length, and mass density for glass fiber was determined to be 0.0017 lbf-s/in^4 (17,700 N-s/m^4), 0.0099 in (0.25 mm), 0.020 in (0.504 mm), and 0.00072 lbf/in^3 (20 kg/m^3) respectively. The porosity was determined to be 0.93. For the results that follow, the flow resistivity was assumed to be 0.0014 lbf-s/in^4 (15,000 rayls/m).

4.3 Geometric Parameters

HVAC louvers come in a variety of configurations and it is accordingly impracticable to arrive at a set of geometric parameters that will encapsulate all geometries. Often, a louvered plate will include groups of blades that are at right angles to each other. In this work, blades are assumed to be in one direction, uniformly spaced, and identical to each other. Moreover, slats running perpendicular to the blades are not considered.

The geometric parameters for the louver systems are shown for unlined and lined cases in Figure 4. For the unlined case, the important parameters are louver spacing (d), angle (θ), and blade length (L). For the lined case, fiber thickness (t) and flow resistivity are also considered.

Since the geometric cases are incomplete, the sensitivity studies detailed later demonstrate the feasibility of the approach for parametric studies and are not intended to provide a comprehensive understanding of HVAC terminations. With that in mind, it is recommended that a more exhaustive measurement study be undertaken in consort with simulation work.

In the simulation, the source and receiver sides are infinite in dimension so that room modes can be neglected. One advantage of simulation is that the ideal case can be studied.

4.4 Experimental Validation

The geometric parameters for the louver systems are shown for unlined and lined cases in Figure 4.2 For the unlined case, the important parameters are louver spacing (d), angle (θ), and blade length (L). For the lined case, fiber thickness (t) and flow resistivity are also important.

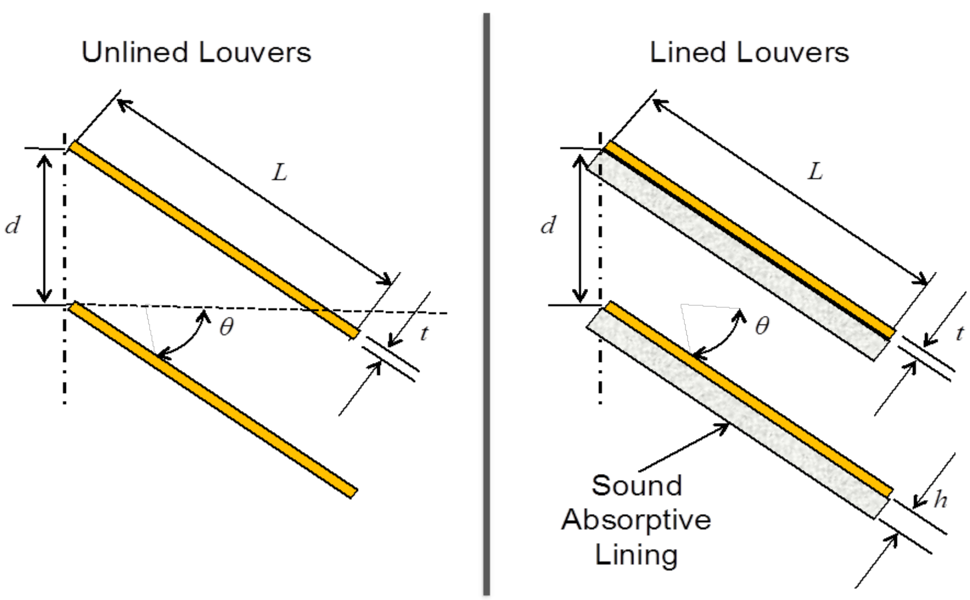

Figure 4.2 Geometric parameters for unlined (left) and lined (right) louvers

The model was corroborated experimentally. A 40 in x 40 in x 100 in (1.02 m x 1.02 m x 2.54 m) enclosure was constructed from particle board and was open on one side. Two loudspeakers were used as sources on the closed end of the enclosure. The loudspeakers were directed towards the rear of the enclosure. 4 inch (10 cm) fiber was placed as shown in Figure 4.3 in the enclosure. Fiber was added in order to reduce the effect of the first several acoustic modes. The enclosure was placed in a hemi-anechoic chamber and the sound power was measured at the opening with and without the louvers installed.

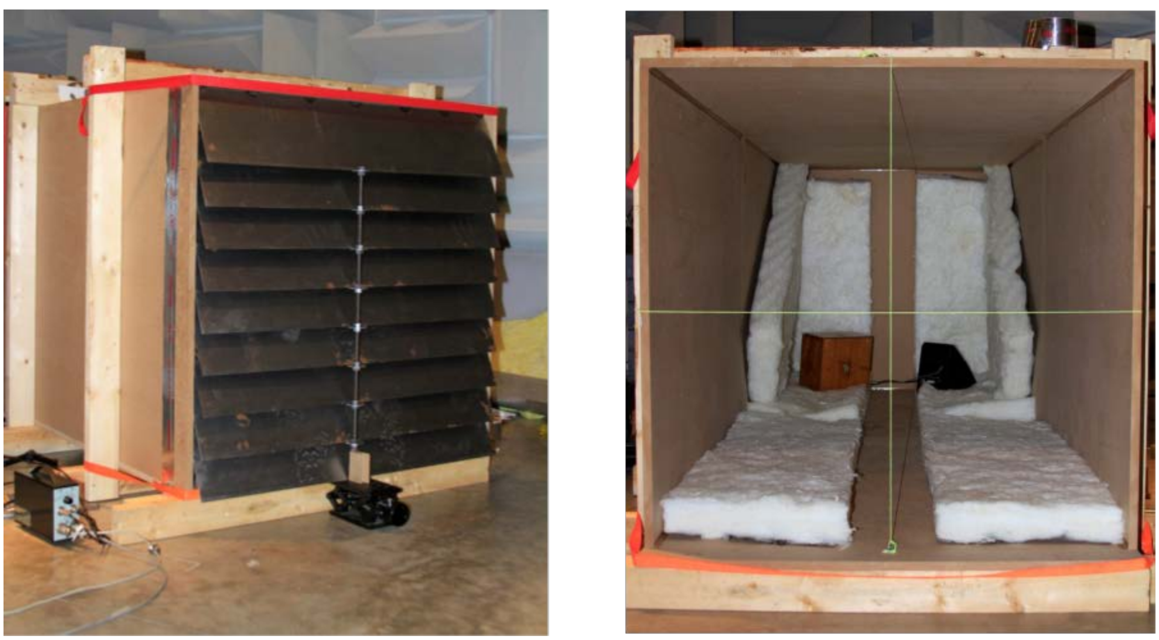

Figure 4.3 Photographs showing louvered termination and interior of enclosure with fiber lining and loudspeakers

It should be recognized that the measurement does not replicate the ASTM-E90 approach much less the simulation approach. The sound field inside the enclosure is likely semi-diffuse but is not as ideal as that produced in a reverberation room. Moreover, the termination is not a baffled termination. However, there was no access to a reverberation room. With that in mind, it was judged that the measurement procedure should approximate a diffuse field at the termination and would approximate the ideal case that was simulation. Hence, the analysis could, at the very least, be used in a relative sense.

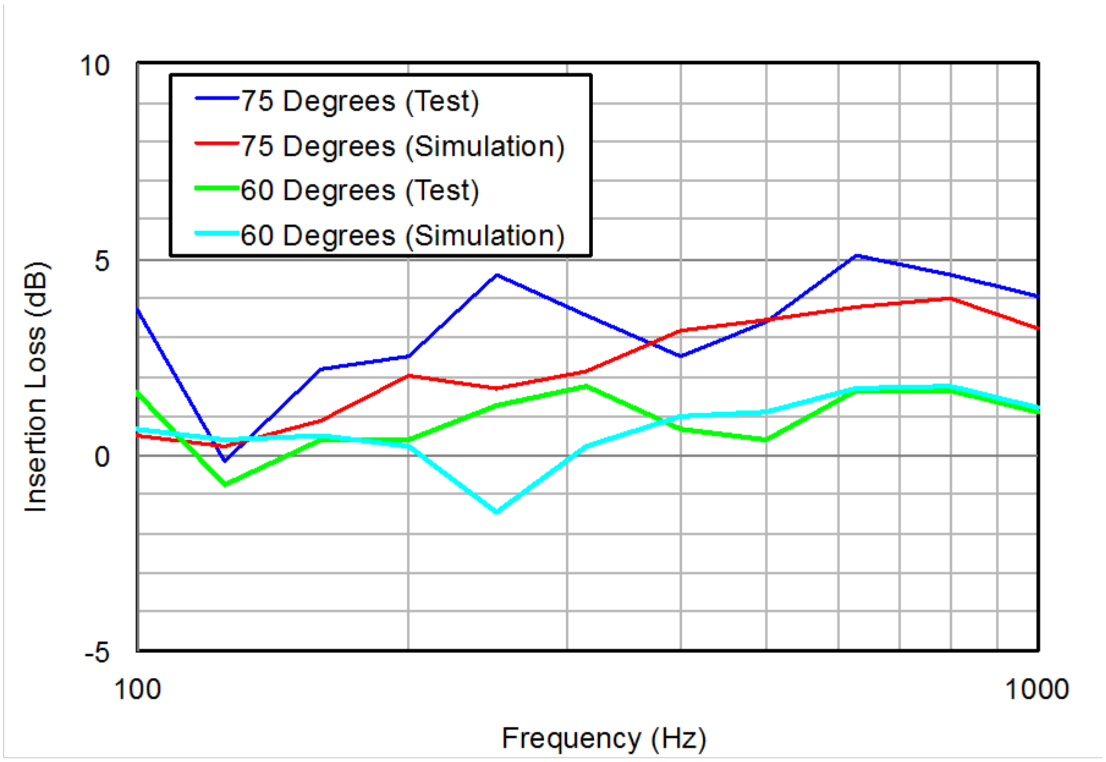

Figure 4.4 Comparison of measured and simulated insertion loss for louver angles of $60°$ and $75°$

Figure 4.4 are compares the results for two unlined cases. The louver parameters selected were 8 in (20.3 cm) and 4 in (10.2 cm) for the louver length (L) and spacing (d) respectively. Louver angles (θ) of $60°$ and $75°$ were considered. Simulation and measurement of insertion loss agree well. Moreover, the effect of changing the louver angle was accurately predicted using simulation. Though the experimental validation is not as rigorous as would be desired, the agreement of the approximate procedure with simulation lends support to the analysis procedure.

4.5 Two-Room Results

A similar to tha in Chapter 3 was performed using the two-room procedure. The aperture considered has a 39.4 in (1.0 m) x 39.4 in (1.0 m) cross-section with a length of 19.7 in (0.5 m). The louvered system is placed at the opening closest to the receiving room.

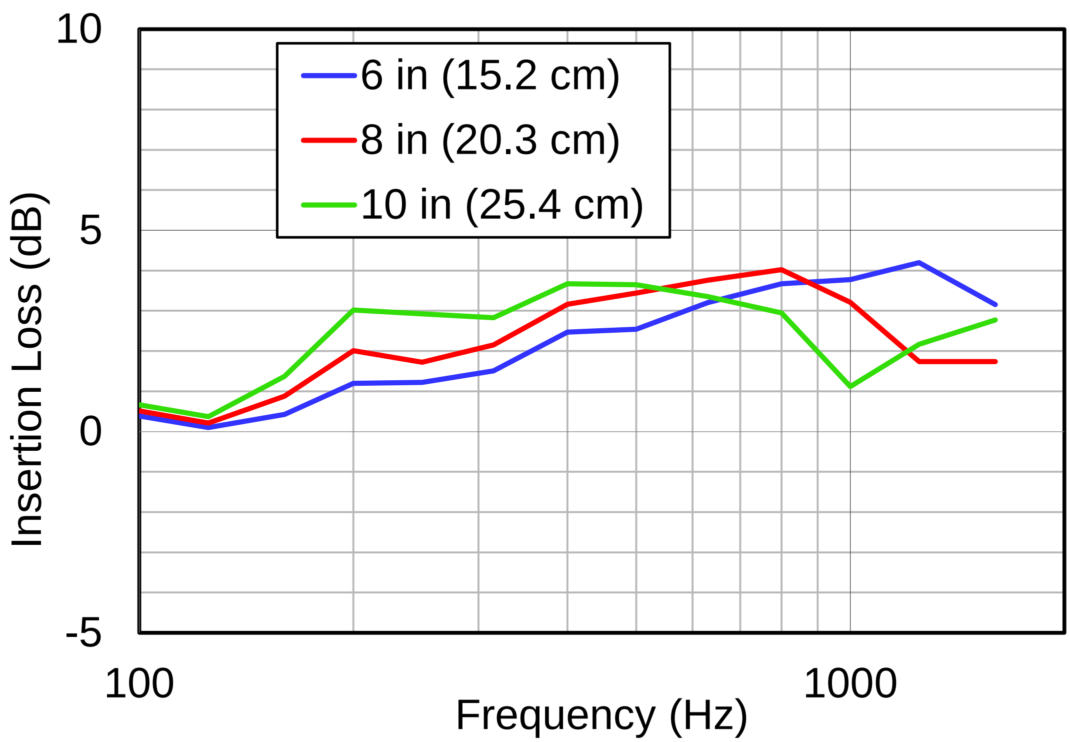

Figure 4.5 Comparison of insertion loss for different louver lengths using the two room procedure. Results are shown for unlined louvers with a spacing (d) of 4.0 in (10.2 cm) and a louver angle of $75°$

The effect of varying the louver length is shown in Figure 4.5 for unlined louvers with a spacing (d) of 4.0 in (10.2 cm) and a louver angle of $75°$. Notice that curves are not as smooth as those determined using the plane wave procedure. This is likely due to longitudinal resonances in the aperture. The results indicate that longer louver lengths appear to have some benefit at lower frequencies. At frequencies close to 1000 Hz, acoustic resonances between the louver slats begin to compromise the performance.

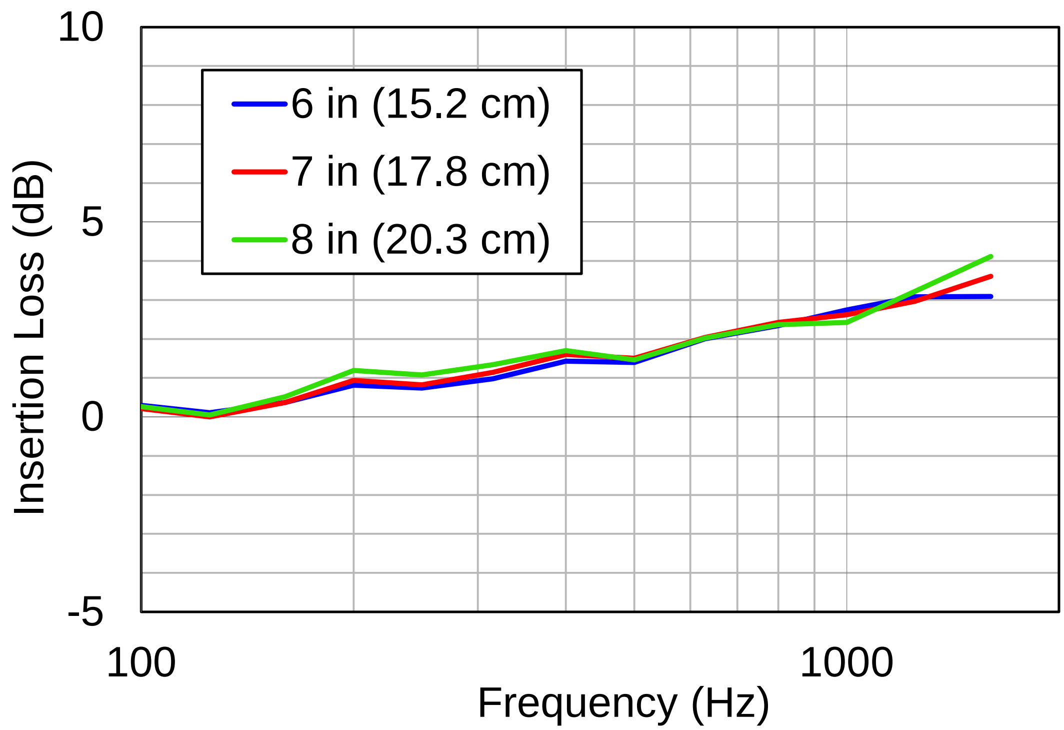

Figure 4.6 Comparison of insertion loss for different louver lengths using the two room procedure. Results are shown for lined louvers (0.4 in or 1 cm fiber) with a spacing (d) of 4.0 in (10.2 cm) and a louver angle of $60°$

Figure 4.6 shows a similar plot for the lined louver case. The louvers angle is $60°$ and the spacing is 4 in (10.2 cm). The fiber is assumed to have a flow resistivity of 0.0014 lbf-s/in^4 (15,000 rayls/m) and a thickness of 0.4 in (1.0 cm). The insertion loss is similar regardless of the louver length. In addition, there are no obvious acoustic resonances. This suggests that the added fiber is sufficient to attenuate the acoustic modes. In addition, the insertion loss is generally lower than for the unlined case with a louver angle of $75°$. Once again, results suggest that closing the louvers rather than adding sound absorption more effectively increases attenuation.

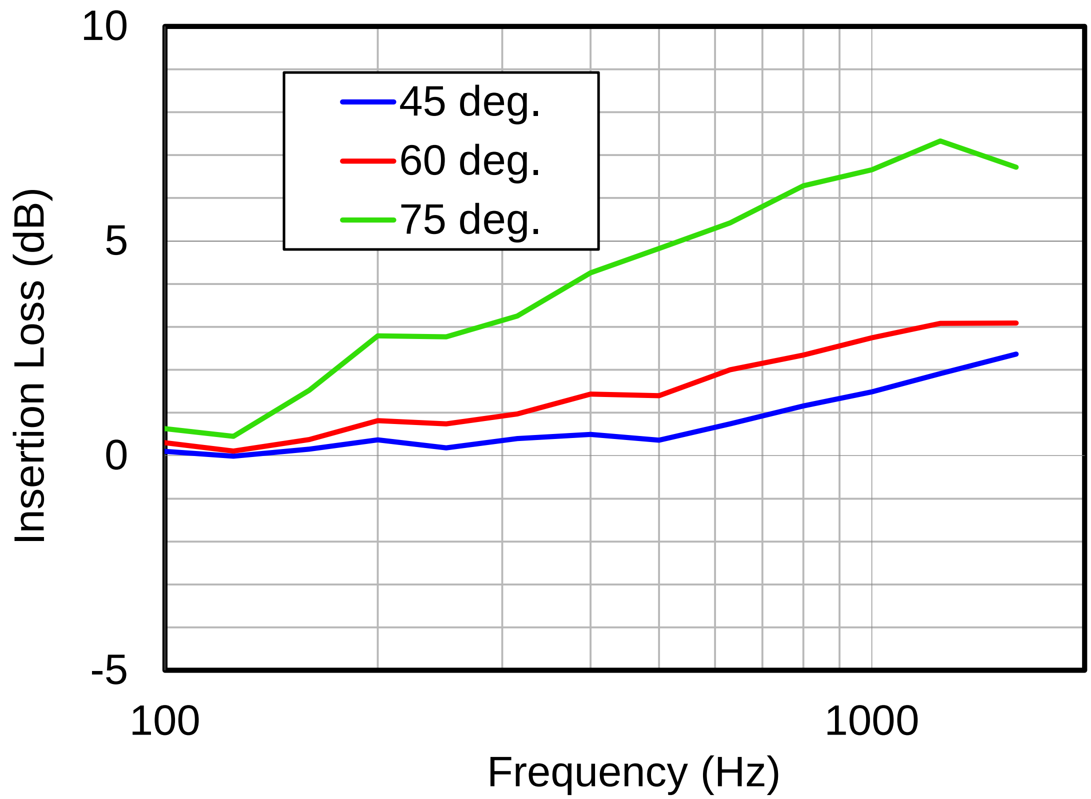

Figure 4.7 Comparison of insertion loss for different blade angles using the two room procedure. Results are shown for lined louvers (0.4 in or 1 cm fiber) with a spacing (d) of 4.0 in (10.2 cm) and a blade length of 6 in (15.2 cm)

Figure 4.7 shows the effect of louver angle. In this case, the spacing is 4 in (10.2 cm), length is 6 in (15.2 cm), and the fiber thickness is 0.4 in (1.0 cm). The insertion loss increases with frequency and is much greater for higher louver angles. The results are intuitive since closing the louver provides a more effective barrier and reflects sound back towards the source. At low frequencies, diffraction effects render the louvers ineffective.

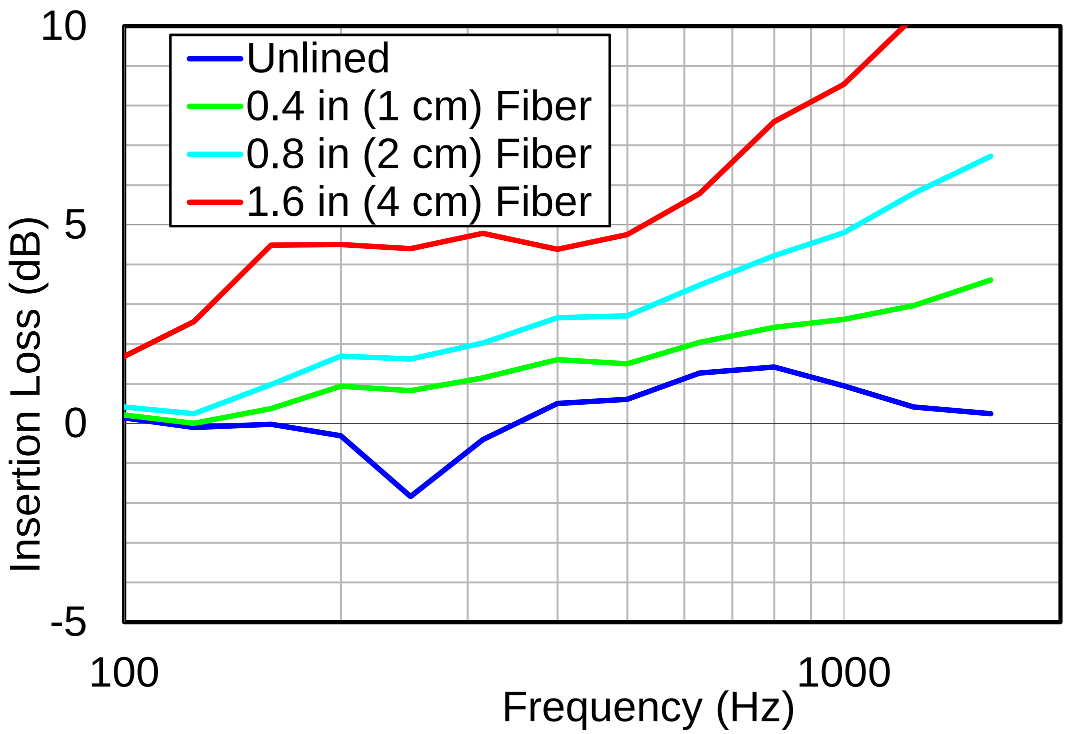

Figure 4.8 Comparison of insertion loss for different lining thicknesses using the two room procedure. Results are shown for a blade spacing (d) of 4.0 in (10.2 cm), a blade length of 7 in (17.8 cm), and blade angle of $60°$

Figure 4.8 shows the effect of increasing the thickness of the liner. The louver spacing is 4 in (10.2 cm), length is 7 in (17.8 cm), and the angle is $60°$. Increasing the fiber thickness both increases the sound absorption and fills the spacing between louvers. For 1.6 in (4.0 cm) fiber, the louver insertion loss exceeds 5 dB at higher frequencies. Results demonstrate that resistive terminations may be more effective if the lining thickness is increased.

4.6 **Conclusions**

In this paper, two acoustic finite element strategies have been described for determining the insertion loss of louvered terminations. In the first approach, plane wave propagation is assumed with a non-reflecting source. The approach has some advantages since the length of the test duct does not affect the results. In the second approach, a louver sample is placed at one end of an aperture connecting two infinite acoustic spaces. A diffuse field is simulated on the source side using monopole sources having random phase. The second approach was experimentally corroborated by measuring the insertion loss of two sample louvered terminations installed at the end of a large enclosure. The relative difference in attenuation between terminations was correctly assessed.

Following this, sensitivity studies were performed where the louver angle, blade length, blade spacing, and sound absorber liner thickness were varied. Results suggested that reducing the open area of the louver assembly most effectively increased the attenuation.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

Louvers are often introduced at the inlets or outlets of ducts or enclosures for flow and protective purposes. Conventional louvers (grilles and diffusers) also provide a modest amount of acoustic attenuation. As the public demands further reduction of noise in building environments, engineers are pursuing adding sound absorptive or reactive elements at the ends of ducts. Accordingly, methods for analyzing and assessing novel duct attenuations are in need.

In this thesis, two simulation approaches have been developed for assessing the performance of louvered terminations in a systematic manner. For each approach, the metric used to quantify attenuation is insertion loss. Insertion loss is defined as the increment in attenuation due to adding the louvers to the termination.

The first simulation approach is a plane wave method where the louvered termination is placed at the end of a duct. The source is simulated as being non-reflective (i.e., anechoic). Hence, longitudinal resonances in the duct are eliminated. This approach is more appropriate at requencies below the plane wave cutoff frequency of the duct.

The second simulation approach is a two-room method. In this case, a source room is attached to a receiving room through a short duct. The louver system is positioned at the end of the short duct. This approach roughly corresponds to ASTM E90 (1998), which is normally used to determine the sound transmission loss through a panel. A reverberant room is typically used as the receiving room in ASTM E90. However, the two-room simulation method models the receiving room as being infinite in dimension. Both the inlet and outlet sides of the short duct are assumed to terminate in a rigid baffle. The two-room method will be more appropriate at frequencies above the plane wave cutoff.

For both methods, acoustic finite elements are used to model the air space, and an automatically matched layer is used to model the reflection free boundary. The two methods differ in the manner that the source is modeled. For the plane wave method, a uniform sound pressure is prescribed on the source side and an anechoic source impedance is simulated using a transfer impedance boundary condition. For the two-room method, 20 monopole sources with random phase were positioned on a hemisphere. An automatically matched layer is applied to the surface of the hemisphere so that it is non-reflective.

The plane wave method could not be validated using measurement since it is difficult to prescribe an anechoic source in the lab. However, the insertion loss of a system of louvers affixed to the end of a large enclosure was determined experimentally and results were compared with analysis. Simulation correlated well with measurement.

Several sensitivity studies were then performed using both approaches. Geometric parameters were varied for simple parallel, evenly spaced louver arrangements. Factors investigated included louver angle, louver length, spacing between louvers, and the effect of adding sound absorption. It was demonstrated that the acoustic attenuation could be greatly increased by adding sound absorption to the louvers and that the louver angle is the most important geometric consideration.

5.2 Recommendations

It is recommended that simulation and measurement research on louvers continue.

1. It would be beneficial to conduct a measurement campaign to determine the insertion loss of a large number of standard louver systems. Measurements could be compared with the simulated insertion loss in an effort to more thoroughly vailidate the simulation.
2. Results from Recommendation 1 should be used to develop insertion loss tables or semi-empirical equations for the ASHRAE Handbook.
3. Analysis and measurement should be perfomed on more complicated louver arrangements than were considered in this thesis.
4. After further validation, the simulation strategies developed should be used to examine novel louver or termination arrangements. These could include perforated blades and blades with sound absorption added.

References

ASTEM E1050, "Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones and a Digital Frequency Analysis System." (1998).

ASTM E90-09, "Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements." ASTM International. (2009).

Berenger, J.P. "A perfectly matched layer for the absorption of electromagnetic waves." Journal of Computational Physics 114(2):185–200(1994).

Bermudez, A., L. Hervella-Nieto, A. Prieto, and R. Rodriguez. "An optimal perfectly matched layer with unbounded absorbing function for time-harmonic acoustic scattering problems." Journal of Computational Physics 223(2):469–488. (2007).

Boden,H, and M. Abom. "Influence of errors on the two-microphone method for measuring acoustic properties in ducts." The Journal of the Acoustical Society of America 79(2):541-49(1986).

Casalino, D. and M. Genito. "Achievements in the numerical modeling of fan noise radiation from aero-engines." Aerospace Science and Technology 12(1):105–113. (2008).

Chen, H. and Herrin, D. W. "A parametric investigation of louvered terminations for rectangular ducts." SAE International Journal of Passenger Cars – Mechanical Systems 8(3). (2015)

Chung, J.Y. and D.A. Blaser. "Transfer function method of measuring in-duct acoustic properties." The Journal of the Acoustical society of America68 (3):907-13(1980).

Cummings, A. “Acoustic noise transmission through the walls of Air conditioning ducts.” Final Report. Department of Mechanical and Aero-space Engineering. University of Missouri- Rolla (1983).

Eriksson, L. J. “Higher order mode effects in circular ducts and expansion chambers.” Journal of the Acoustical Society of America 68(2): 545-550, (1980).

ISO Standard 10140-2. Laboratory measurement of sound insulation of building elements – Part 2: measurement of airborne sound insulation. The International Organization for Standardization. ISO (2010).

ISO Standard 15186-3. “Measurement of sound insulation in buildings and of building elements using sound intensity.” – Part 3: laboratory measurements at low frequencies. The International Organization for Standardization. ISO. (2002).

Istvan L. Ver, “A Review of the Attenuation of Sound in Straight Lined and Unlined Ductwork of Rectangular Cross Section.” (RP-196), ASHRAE Transactions, Vol. 84, Pt. 1, (1978).

J. Liu and D. Herrin, “Load Effect on Source Impedance Measurement Accuracy,” Proceedings of SAE 2009 Noise and Vibration Conference and Exhibition, St. Charles, IL. (2009).

Kinsler, L.Eand Blackstock, D,T(2000),”Fundamentals of Acoustics”, New York:John Wiley&Sons. (1982)

Kuntz, H.L. and R.M. Hoover. “The interrelationships between the physical properties and acoustical properties of fibrous duct liner materials and lined duct sound attenuation.” ASHRAE Transactions 93, (1987).

Levine, H. and Schwinger, J., “On the Radiation of Sound from an Un-Flanged Circular Pipe,” Physical Review, Vol. 73, pp. 383-406, (19480.

Lindemann, JASA Vol. 44 “Radiation Impedance of a Rectangular Piston at very low frequencies.” (1968).

Martinus, F., Quabili, Z., and Seybert, A. F., “Sound through Partial Enclosures with Louvers,” SAE Noise and Vibration Conference, Paper No. 2001-01-1525, Traverse City, MI, (2001).

Michaud, A. P., and Cunefare, K. A., “Experimental Investigation of Reflection of Airborne Noise at Duct Terminations,” ASHRAE Transactions, Vol. 114, Part 2, pp. 3-16, (2008).

Mouratidis, E., and Becker, J., "The Acoustic Properties of Common HVAC Plenum," ASHRAE Transactions. Vol. 110, No. 2, pp. 597-606 (2004).

Pierce, A. D., (Acoustics, an Introduction to Its Physical Principles and Applications,” McGraw-Hill, (1981).

Pierce, A.D., Cleveland, R.O., and Zampoli, M., “Radiation Impedance Matrices for Rectangular Interfaces within Rigid Baffles: Calculation Methodology and Applications,” Journal of the Acoustical Society of America, Vol. 111, No. 2, pp. 672–684, (2002).

Reynolds, D.D. and J.M. Bledsoe. “Sound attenuation of acoustically lined circular ducts and radiuses elbows.” ASHRAE Transactions 95, (1989b).

Reynolds, D.D. and J.M. Bledsoe. “Sound attenuation of unlined and acoustically lined rectangular ducts.” ASHRAE Transactions 95, (1989a).

Selamet, A., Ji, Z. L., and Kach, R. A., “Wave Reflections from Duct Terminations,” The Journal of the Acoustical Society of America, Vol. 109, No. 4, pp. 1304–1311, (2001).

Seybert,A.F,and D.F.Ross. “Experimental determination of acoustic properties using two-microphone random-excitation technique.” The Journal of the Acoustical society of America 61(5):1362-70(1977).

Siemens. LMS Virtual.Lab Online Help. (2015).

Tam, C.K., L. Auriault, and F. Cambuli. “Perfectly matched layer as an absorbing boundary condition for the linearized Euler equations in open and ducted domains.” Journal of Computational Physics 144(1): 213–234(1998).

Viveiros, E. B., and Gibbs, B. M., "An Image Model for Predicting the Field Performance of Acoustic Louvres from Impulse Measurements," Applied Acoustics, Vol. 64, pp. 713-730, pp. 713-730, (2003).

Viveiros, E. B., Gibbs, B. M., and Gerges, S. N. Y., “Measurement of Sound Insulation of Acoustic Louvres by an Impulse Method,” Applied Acoustics, Vol. 63, pp. 1301-1313, (2002).

Watts, G. R., Hothersall, D. C., and Horoshenkov, K. V., “Measured and Predicted Acoustic Performance of Vertically Louvred Noise Barriers.” Applied Acoustics, Vol. 62, pp. 1287-1311, (2001).

VITA

Huangxing Chen was born in Xiamen, China in 1988. He graduated from Shuangshi Hight School in Xiamen. He received the B.S in Automation Engineering from University of Eletctronic Science and Technology, China in 2008. In August 2012, he enrolled in the Department of Mechanical Engineering, University of Kentucky. During his three years graduate studies at University of Kentucky, he has published 1 “SAE Noise and Vibration” conference paper and been rewarded as an “SAE Journal article”. The second paper has been done and will be submitted to “ASHRAE” by his Advisor D.W.Herrin.

Huangxing Chen