7 - 12 SEPTEMBER 2014, KRAKÓW
FORUM ACUSTICUM

Experimental Analysis of Dissipative Silencer Coupled with Quarter Wave Tube

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Summary
The study deals with investigation of acoustical characteristics of a hybrid silencer made up of a dissipative silencer and a quarter wave tube resonator. Experimental analyses are performed to define acoustical characteristics of a simple expansion chamber, reactive and dissipative perforated silencer. Furthermore, the experiments are extended to the hybrid silencer to determine the effect of quarter wave tube resonator on the silencer performance. Experimental results of the dissipative silencer are verified with theoretical solutions. The results found with experimental results are found to compare to analytical and numerical results favorably.

PACS no. 43.50.+y, 43.58.+z

1. Introduction

Dissipative silencer, composed of a reactive silencer and fibrous acoustical media, controls the broadband airborne noise efficiently by reacting to and absorbing sound waves. In addition, dissipative silencers can be enhanced to attenuate pure tone noise at low frequencies by reactive acoustic resonators such as quarter wave tube (QWT) tuned to the frequency of the pure tone. Transmission loss is the most important properties of a silencer to demonstrate its characteristics. Some experimental methods are available to determine the transmission loss.

Prediction of transmission loss by experimentation is surely different from analytical calculations. Recent studies present some evaluation methods to determine the transmission loss from measured data.

The standard two-microphone random excitation method including the transmission loss calculation is described by Chung and Blaser [1]. Seybert and Ross [2] present a study about an experimental method to predict the acoustic properties in a tube considering mean flow. The most common ones are the two load method and two source method. Tao and Seybert [3] present a study including the comparison of these two common methods. The main difference between these methods is expressed as the two load method is easier to measure transmission loss while both transmission loss and four pole parameters of a muffler can be measured by the two-source method. The classical method of transmission loss measurement is two room method. In this method the test specimen is placed in the opening between anechoic and a reverberant room. Two microphones located in each room are used to measure the sound generated in the reverberant room. This reliable method is well defined in previous studies, but it is very expensive. In recent years, a number of various transmission loss measurement methods are studied and two-load method is one of them. The comparison of two-load and reliable two-room method of transmission loss measurements is studied by Yousefzadeh et al. [4]. Besides different tube termination conditions are considered and the results of these different measurements are compared with those two room method.

The aim of this study is an acoustical evaluation of dissipative silencer enhanced with QWT resonator that provides the reduction of noise at specific frequencies. The study deals with the behavior of the silencer investigated experimentally and the comparison of the experimental results with analytical and numerical solutions. Firstly, transmission losses of simple expansion chamber and reactive perforated silencer are determined by experimentally in order to compare the results of analytical and computational approaches. Secondly, transmission loss of the dissipative perforated silencer is predicted. Finally, the enhancement of QWT resonator to dissipative silencer is investigated by predicting the transmission loss of the hybrid silencer experimentally.

2. Transmission Loss Measurement

2.1. Transmission Loss Measurement with Two Load Method [5]

Two-load method is based on calculation of full transfer matrix of an acoustical sample. In this study acoustic sample is the silencer whose transmission loss is measured using impedance tube with 4 microphones. Transfer matrix elements are expressed with relation between incident and reflecting waves of source part of tube and incident and reflecting waves passing through the specimen. Transfer matrix is formulated as;

$$\begin{Bmatrix} A_1 \\ B_1 \end{Bmatrix} = \begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix} \begin{Bmatrix} A_2 \\ B_2 \end{Bmatrix} \tag{1}$$

where A_1 and B_1 are incident and reflecting waves at the source part of the impedance tube, respectively. Similarly, A_2 and B_2 are incident and reflecting waves at the receive part of the impedance tube, respectively. Incident and reflecting waves of the impedance tube are shown in Figure 1.

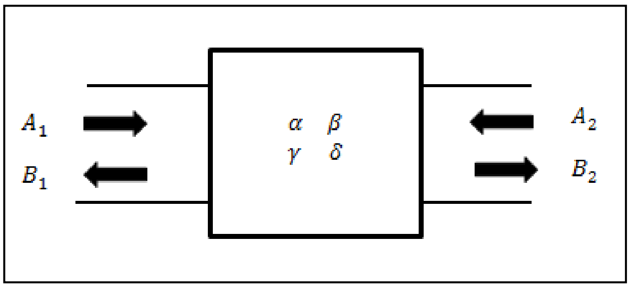

Figure 1: Transfer matrix between incident and reflecting waves

The transmission loss of the silencer is expressed as;

$$TL = 20\log|\alpha| \tag{2}$$

Two-load method should contain two solutions with variation of boundary conditions at the end of the impedance tube, i.e. open ended and close ended terminations. Therefore, incident and reflecting waves formulation is represented with including the two ended termination as;

$$\begin{Bmatrix} A_{1O} \\ B_{1O} \end{Bmatrix} = \begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix} \begin{Bmatrix} A_{2O} \\ B_{2O} \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} A_{1C} \\ B_{1C} \end{Bmatrix} = \begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix} \begin{Bmatrix} A_{2C} \\ B_{2C} \end{Bmatrix} \tag{4}$$

where "o" and "c" expressions used in subscripts denote open ended and close ended terminations, respectively. Using Eq. 3 and Eq. 4, the solution, α, is expressed as;

$$\alpha = \frac{A_{1O}B_{2C} - A_{1C}B_{2O}}{A_{2O}B_{2C} - A_{2C}B_{2O}} \tag{5}$$

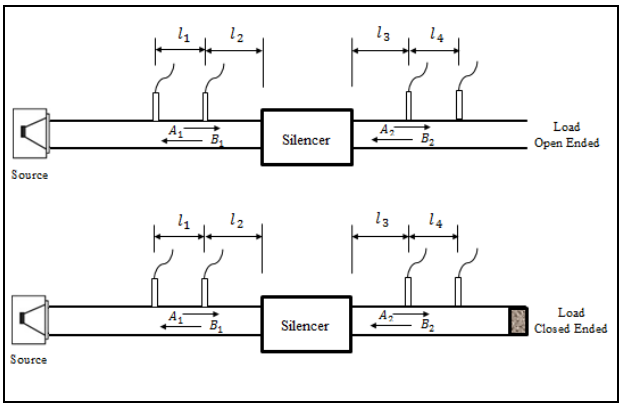

Figure 2: Schematic view of measurement setup of two load method

The sound pressures at the corresponding measurement points shown in Figure 2 are presented as follows, based on plane wave theory;

$$P_1 = A_1 e^{jk(l_1+l_2)} + B_1 e^{-jk(l_1+l_2)} \tag{6}$$

$$P_2 = A_1 e^{jkl_2} + B_1 e^{-jkl_2} \tag{7}$$

$$P_3 = A_2 e^{-jkl_3} + B_2 e^{jkl_3} \tag{8}$$

$$P_4 = A_2 e^{-jk(l_3+l_4)} + B_2 e^{jk(l_3+l_4)} \tag{9}$$

Using the Eq. 9, the incident and reflecting waves used in transmission loss calculation are represented as;

$$A_1 = \frac{-j}{2} \frac{P_1 - P_2 e^{-jkl_1}}{sin(kl_1)} e^{-jkl_2} \tag{10}$$

$$B_1 = \frac{j}{2} \frac{P_1 - P_2 e^{jkl_1}}{sin(kl_1)} e^{jkl_2} \tag{11}$$

$$A_2 = \frac{j}{2} \frac{P_4 - P_3 e^{jkl_4}}{sin(kl_4)} e^{jk3} \tag{12}$$

$$B_2 = \frac{-j}{2}\frac{P_4 - P_3 e^{-jkl_4}}{sin(kl_4)} e^{-jk3} \quad (13)$$

The incident and reflecting waves can also be expressed as auto and cross spectrum that are collected data at measurement points.

$$A_1 {P_1}^* = \frac{-j}{2}\frac{S_{11} - S_{12} e^{-jkl_1}}{sin(kl_1)} e^{-jkl_2} \quad (14)$$

$$B_1 {P_1}^* = \frac{j}{2}\frac{S_{11} - S_{12} e^{jkl_1}}{sin(kl_1)} e^{jkl_2} \quad (15)$$

$$A_2 {P_1}^* = \frac{j}{2}\frac{S_{14} - S_{13} e^{jkl_4}}{sin(kl_4)} e^{jkl_3} \quad (16)$$

$$B_2 {P_1}^* = \frac{-j}{2}\frac{S_{14} - S_{13} e^{-jkl_4}}{sin(kl_4)} e^{-jkl_3} \quad (17)$$

where ${P_1}^*$ is the conjugate of P_1. S_{11} is the auto-spectrum of measured data at first microphone location, and S_{12}, S_{13} and $S_{14}$are the cross-spectrum between measured data at first and other microphone locations. Therefore, the transmission loss of the silencer located between impedance tubes can be found from following expression;

$$TL = 20\log\left|\frac{\{A_{1O}{P_{1O}}^*\}\{B_{2C}{P_{1C}}^*\} - \{A_{1C}{P_{1C}}^*\}\{B_{2O}{P_{1O}}^*\}}{\{A_{2O}{P_{1O}}^*\}\{B_{2C}{P_{1C}}^*\} - \{A_{2C}{P_{1C}}^*\}\{B_{2O}{P_{1O}}^*\}}\right| (18)$$

where “o” and “c” denote open and close end termination.

2.2. Experimental Test Setup

An impedance tube test setup is used to measure the transmission loss of a silencer with two microphones at four different positions, a sound source and digital frequency analysis device in the absence of mean flow. Schematic of the experimental test setup is shown in Figure 3.

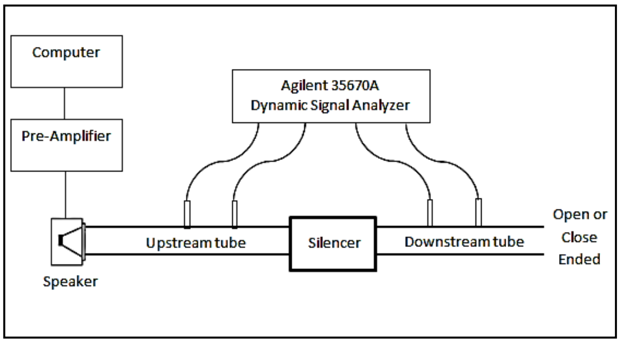

Figure 3: Schematic view of experimental test setup

Upstream and downstream tubes are located in front of a loudspeaker which is enclosed in a housing. Silencer is mounted between the upstream and downstream tubes. PCB Piezotronics 1/4 inch condenser microphones (serial numbers: 30735 and 30740) are positioned onto the tubes shown in Figure 3. Agilent 35670A four-channel Dynamic Signal Analyzer is used to collect data measured by microphones. Auto-spectrum and cross-spectrum are determined by using the signal analyzer. Pink noise is generated by a computer connected to a loudspeaker pre-amplifier card driving the speaker. The signal analyzer is adjusted to measure sound pressure spectra at 0-3200 Hz. Resolution is selected as 800 lines, so the frequency interval of measurement is 4 Hz. Record length is automatically adjusted to 250 ms by the signal analyzer because of selection of the resolution lines and span frequency. The temperature of the test room is measured to calculate the speed of sound before all measurements and is about 25±1 °C.

2.3. Transmission Loss Measurements [6]

In order to verify the test setup, transmission losses of simple expansion chamber, perforated reactive silencers with different perforated tube, dissipative silencer and hybrid silencer with indicated perforated tube are determined by using Two-Load Method described in Section 2.1. The results obtained from these experiments are compared with analytical and numerical methods.

2.3.1. Simple Expansion Chamber

First experiment of transmission loss determination is made with simple expansion chamber that is the main element of the dissipative perforated silencer and is presented inFigure 4: The schematic view of simple expansion chamber Figure 4.

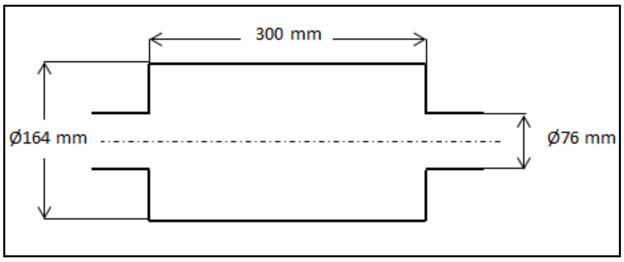

Figure 4: The schematic view of simple expansion chamber

Transmission loss of the simple expansion chamber predicted from BEM solution and analytical formulation is compared with experimental results in Figure 5. The results from both BEM solution and experiment agree with each other. On the other hand, at high frequencies, after 2000 Hz, the transmission loss characteristic calculated from 1D analytical method displays a deviation. Thus, it is demonstrated that even for a simple expansion chamber model, 1D analytical method would be inadequate.

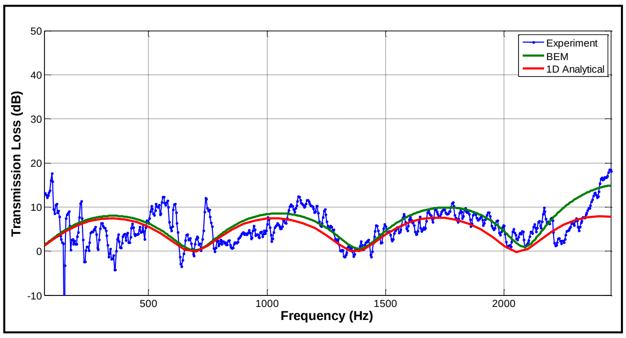

Figure 5: Transmission Loss of simple expansion chamber

2.3.2. Reactive Perforated Silencer

The schematic view of reactive perforated silencer is illustrated in Figure 6.

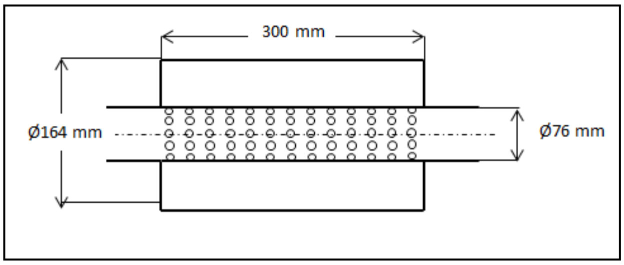

Figure 6: The schematic view of reactive perforated silencer.

In perforated tube the hole diameter, d_h is 4 mm, and the porosity, ϕ, is 28.8%. The perforation provides an increasing transmission loss after 2000 Hz. This dome can be shifted by changing the perforation parameters.

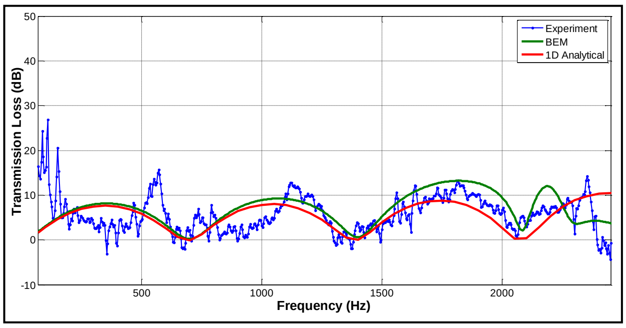

Figure 7: Transmission Loss of reactive perforated tube with d_h = 4 mm and ϕ = 28.8% (Staggered array)

2.3.3. Dissipative Perforated Silencer

Dissipative perforated silencer is configured by filling glass fiber into space between perforated tube and expansion chamber. The schematic view of dissipative perforated silencer is demonstrated in Figure 8.

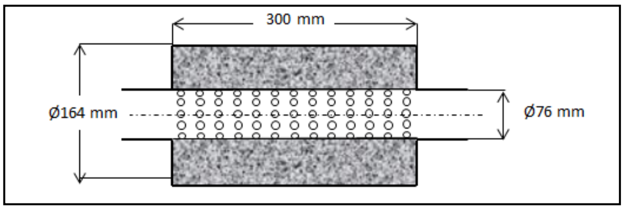

Figure 8: The schematic view of dissipative perforated silencer.

Stainless steel tube (d_h= 4 mm and ϕ = 28.8%) is used as perforated tube and predicted transmission loss is presented in Figure 9. The results found from BEM model is close to those found from experiments.

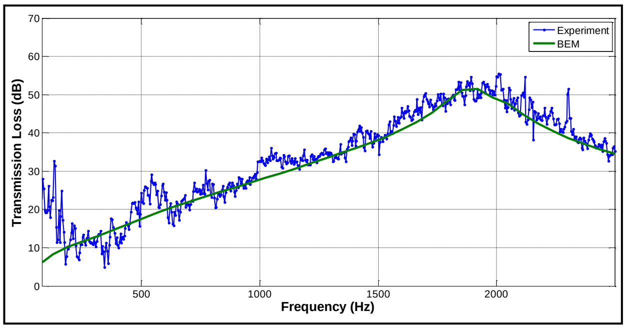

Figure 9: Transmission Loss of dissipative perforated silencer (d_h= 4 mm and ϕ = 28.8%)

2.3.4. Hybrid Silencer

Hybrid silencer is composed of dissipative perforated silencer (d_h= 4 mm and ϕ = 28.8%) and QWT which is attached to end of the dissipative silencer. QWT is a reactive element and it is used to enhance the attenuation at low frequencies, particularly at a specific frequency related to its length. In this study, transmission loss measurements of hybrid silencers with varying length (100 mm, 120 mm and 140 mm) of QWT resonator are examined. The schematic view of the hybrid silencer is presented in Figure 10.

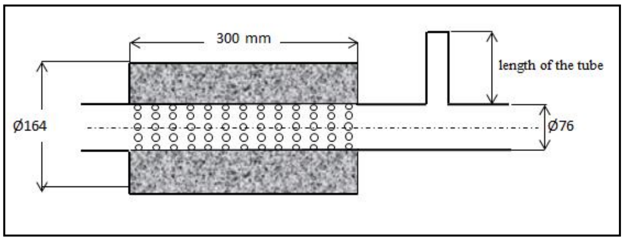

Figure 10: The schematic view of hybrid silencer

Hybrid silencers with 100, 120 and 140 mm length of QWT resonator are investigated by numerically and experimentally, and transmission loss characteristic of one of them is presented in Figure 11. The BEM solutions are shown to be in good agreement with experimental results for hybrid silencers. At high frequencies, transmission loss values increase because of dissipative perforated part of the hybrid silencer. At low frequencies, the side branch affects the sound attenuation and transmission loss has a peak at a frequency of corresponding tube length. Figure 12 indicates difference between the hybrid silencers with varying lengths of QWT. Increasing length of the QWT shifts the frequency to the left. So, the wavelength of QWT increases.

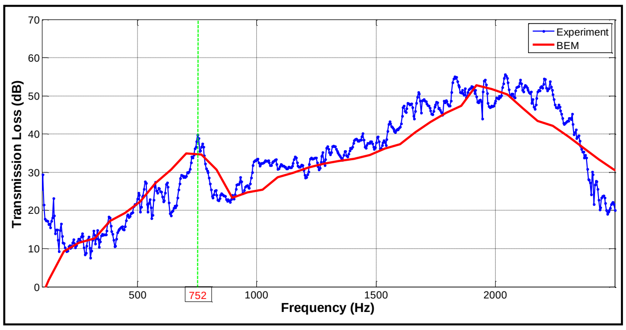

Figure 11: Transmission Loss of Hybrid Silencer with 100 mm length of QWT (d_h= 4 mm and ϕ = 28.8%)

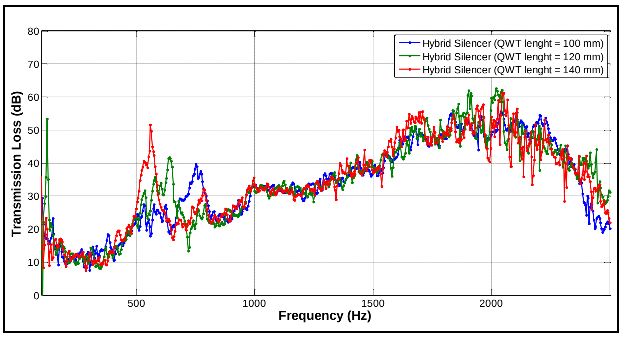

Figure 12: Transmission Loss of Hybrid Silencers (Experiment)

The resonance frequencies of QWT resonators shown in Figure 11 and Figure 12 are used to calculate effective lengths of the QWT. The calculated effective lengths are 115, 135 and 155 mm for 100, 120 and 140 mm lengths of QWT resonator, respectively. Using the effective lengths of side branch, transmission losses of QWT resonator alone are calculated. Transmission loss of hybrid silencer is actually summation of dissipative perforated silencer and QWT resonator alone. Figure 13 shows transmission loss of dissipative perforated silencer, hybrid silencer and QWT alone.

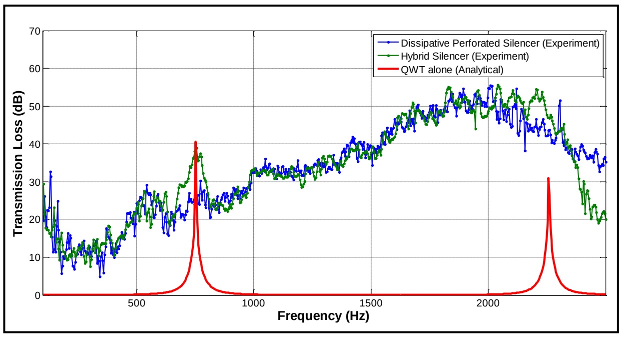

Figure 13: Transmission Loss comparison of dissipative perforated tube, hybrid silencer and QWT (QWT length = 100 mm)

3. Conclusions

Acoustical evaluation of hybrid silencer composed of a dissipative perforated silencer and quarter wave tube resonator is carried in this study. Firstly, simple expansion chamber and reactive perforated silencer are investigated to predict the transmission loss, the main performance index for acoustical characteristics of a silencer, as dissipative perforated silencer is made up of an expansion chamber and perforated tube. Transmission losses of simple expansion chamber and reactive perforated silencer are predicted analytically, numerically and experimentally. Findings for each approach are compared with each other. After comparison of these three methods, it is seen that theoretical solution is inadequate at high frequencies, whereas BEM solution is found to agree with the experimental results. Second investigation is carried to determine the transmission loss of a dissipative perforated silencer. Two experimental setup schemes are established to examine the acoustical characteristics of dissipative perforated silencer.

Acknowledgement

This study was supported by ASELSAN Inc. as a part of requirements for MSc degree in mechanical

engineering at the Middle East Technical University.

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