EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THE ACOUSTIC ABSORPTION COEFFICIENT AT VERY LOW FREQUENCY

DAVID W.Y.K., YOUSIF A.A.
Department of Mechanical, Manufacturing and Materials Engineering
The University of Nottingham Malaysia Campus, Jalan Broga, 43500 Semenyih, Selangor Darul Ehsan, Malaysia
Corresponding author e-mail: yousif.abakr@nottingham.edu.my

Abstract: Sound attenuation had always been an interesting topic of investigation. The low frequency range investigated by researchers is usually from few hundreds to few thousands of Hz, still far away from the interesting zone for a low frequency thermoacoustic engine which operates in only 30-150 Hz. An acrylic straight tube configuration is used to investigate the effectiveness of different absorbing materials by using multi-microphone impedance tube technique. Results show the elastic termination has better attenuation characteristics compared to other alternatives. The results were also compared with the DeltaEC simulation.

Keywords: Thermoacoustic, Low frequency, Impedance tube, Attenuation, DeltaEC

1. Introduction

The thermoacoustic engine is a device that converts heat to sound energy. Thermoacoustic engines work according to Rayleigh's criterion [1]. The SCORE^{TM} thermoacoustic engine is a waste-heat driven travelling-wave engine utilises the waste heat from a cooking stove to create travelling acoustic oscillations through a closed loop at an operating frequency of 30-150 Hz [2]. To simulate the engine a speaker is used to generate sound waves at one of the termination ends in a straight tube, passive attenuation can be used to experimentally obtain a travelling wave using suitable absorbing material in an open loop, simulating the conditions of the engine while being able to control the frequency and amplitude of the wave. The sound absorption coefficient is an important indicator to determine how much sound energy is dissipated and reflected. There are several methods to determine the acoustic properties of a material with the aid of a commercial impedance tube setup. The standing wave impedance tube method makes use of the measured standing wave ratio (SWR) for a specific frequency in the tube to determine the acoustic properties by means of a microphone. The advantage of this method is that it is not necessary to calibrate the microphone. The disadvantages to this method are the complex setup with a movable probe and the time needed to find the location of the maximum and minimum pressures [3].

Seybert and Ross [4] proposed a different method for impedance tube measurements of sound absorption using the pressure readings at two positions, called the two-microphone method, which was faster than the SWR method. The acoustic wave response is separated into its reflection and incident components using a transfer function between the microphones. Chu [5] improved this method by including the tube-attenuation effect, allowing the microphones to be placed far away from the sample. Boden and Abom [6] found that the two-microphone method has its lowest sensitivity when the two microphones are separated by a quarter wavelength. The influence of errors in the two-microphone method has been investigated [7]. Chu [8] has proven in order to obtain accurate results, one of the microphones has to be placed close to the minimum pressure. The drawbacks are that its accuracy significantly degrades at large wavelengths and at microphone separations near one-half wavelength [9]. Jones and Parrot [10] described the multiple-microphone method on the pressure measurements at more than three positions. The multi-microphone method has no restriction on microphones separation relative to wavelength and allows results to be plotted with a single line based on the transfer function of a few microphone combinations. Another improved method uses least squares curve fitting to optimize the response of all the microphone positions to produce results with minimum error [11]. This paper focuses on measuring the acoustic properties using the least squares technique with the aid of multi-microphone impedance tube system. The current study also includes the comparison with the numerical results produced by the DeltaEC predictions [12].

2. Least Squares Technique

The formulation of this method was developed based of an imaginary source equidistant from the specimen in an impedance tube but in the negative x-direction as depicted in fig 1.

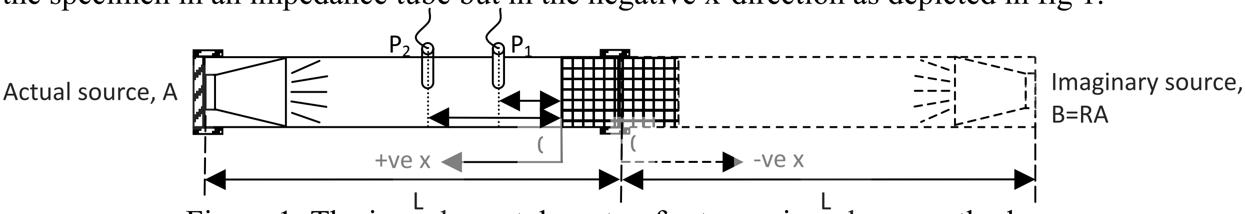

Figure 1: The impedance tube setup for two-microphone method.

The imaginary region is symmetrically mirrored at the end of the specimen from the actual source region. The amplitude of the imaginary source is given by

$$B = RA, \tag{1}$$

R is the complex reflection factor and A represents the amplitude of the actual source in Eq. (1). The relationship between the measured pressure from each microphone and both of the sources can be deduced with the aid of Green's function as shown in Eq. (2):

$$P_1 = Ag_{1A} + Bg_{1B} = A(g_{1A} + Rg_{1B}) \qquad P_2 = Ag_{2A} + Bg_{2B} = A(g_{2A} + Rg_{2B}) \tag{2}$$

where P_1 and P_2 are the pressure readings from the microphone 1 and 2 respectively. g_{1A} is the Green's function that relates the output of microphone 1 to the input of the actual source, A where g_{1B} is the Green function that relates the output of microphone 2 to the input of the imaginary source, B. Same relationship apply for Green functions, g_{2A} and g_{2B} with respect to microphone 2. Considering a plane wave is propagating in the tube, the Green functions can be expressed by Eq. (3):

$$g_{1A} = \frac{\rho_o c}{2s} e^{-jk(L-dx1)} \qquad g_{1B} = \frac{\rho_o c}{2s} e^{-jk(L+dx1)}$$

$$g_{2A} = \frac{\rho_o c}{2s} e^{-jk(L-dx1)} \qquad g_{2B} = \frac{\rho_o c}{2s} e^{-jk(L-dx2)} \tag{3}$$

where ρ_o is the air density, c is the speed of sound, s is the cross-sectional area of the tube, L is the total length of the system, dx1 and dx2 are the distances between the sample and the microphone 1 and 2 respectively. k represents the wave number which is defined as $2\pi f/c$. The transfer function, H_{12} is the pressure ratio between microphone 1 and 2 which can be rearranged to give the complex reflection coefficient, R as shown in Eq. (4) and (5). An optimised reflection coefficient, R_{opt} can be obtained by using a least squares solution with the aid of multi-microphone method. Eq. (6) can be used for any number of microphones M, where m indicates number of each microphone in the tube. The absorption coefficient, α of the sample can therefore be determined by Eq. (7):

$$H_{12} = \frac{P_2}{P_1} = \frac{g_{2A} + g_{2B}R}{g_{1A} + g_{1B}R} \tag{4}$$

$$R = \frac{g_{2A} - g_{1A}H_{12}}{g_{1B}H_{12} - g_{2B}} \tag{5}$$

$$R_{opt} = -\frac{\sum_{m=2}^{M}(g_{1A}H_{1m} - g_{mA})(g_{1B}H_{1m} - g_{mB})^*}{\sum_{m=2}^{M}|g_{1B}H_{1m} - g_{mB}|^2} \tag{6}$$

$$\alpha = 1 - |R_{opt}|^2 \tag{7}$$

3. Experimental Setup

The experimental apparatus is composed of straight tubes and tapers which are made out of transparent acrylic plates. The total length of the system is 2.85 m and the wall thickness is 5mm. The straight tubes have internal square cross-sectional area of 0.0081 m^3 and the tapers have internal rectangular cross-sectional area of 0.0122 m^2 respectively. Tapers are used at two ends of the tube to smoothen the acoustic flow. The working fluid is air at atmospheric pressure. One extremity of the tube is attached to a loudspeaker while the tested sample is placed inside a wooden speaker box at the other end. Three different types of excitation signals were examined namely: Uniform white noise, Gaussian white noise, and Swept sine signal. A total of six microphones are used to measure the sound pressure along the length of the tube with the aid of a data acquisition system. There are basically three different types of absorbing materials, sponge, honeycomb and egg tray as shown in fig 2.

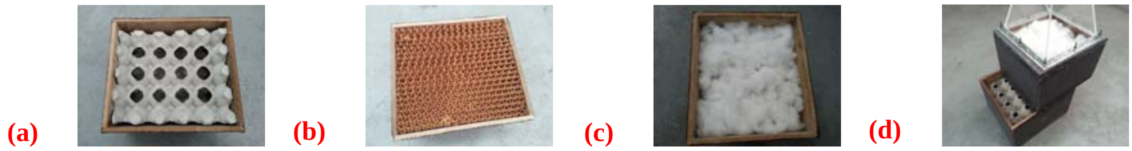

Figure 2: The four different types of materials that are under investigation: (a) Egg tray, (b) Honeycomb, (c) Sponge and (d) Egg tray and sponge combination.

4. DeltaEC^{TM} Modelling and Simulation

The Design Environment for Low-Amplitude ThermoAcoustic Energy Conversion (DeltaEC) model for the experimental setup is constructed by eighty three segments including the six Reverse Polish Notation (RPN) segments which are used to indicate the microphone locations and sixty three RPN segments after the HARDEND for the calculations of least squares technique. The impedance tube system is made out of six CONE segments and six DUCT segments. A total number of two GUESSes and two TARGETs are chosen. The first segment has always been a BEGIN segment and will be used as a loudspeaker that generates a sinusoidal wave in this case. Calculations have been done using a mean pressure P_m = 1 bar, a mean temperature T_m = 300 K and an acoustic pressure of 50 Pa. Air is used as working gas. Perspex is selected as the material for the components in the model with the aid of User Defined Function (UDF). The HARDEND acts as a rigid backing to reflect the acoustic wave. The GUESS vector, which has two components in this case, shows what variables

DeltaEC targets for a solution: the frequency and the volume flow rate. The initial guess of the frequency is 20 Hz and the initial value of the volume flow rate is 0.005 ms^{-1}.

5. Results and Discussion

In the range of the tested frequency, the type of input signal was found to be of small effect on the reflection and absorption coefficients, which is a good evidence of the validity of the experimental setup. Fig 3 presents the reflection and absorption coefficients of the rigid plate for different types of excitation signal from the source. The aluminium plate was found not to be a perfect rigid backing, but the reflection coefficient was close to unity in the tested frequency range. Moreover, the swept sine signal has shown deviation from all other signals and the numerical simulation in the low frequency range up to about 65 Hz, but the reflection coefficients for all types of signals behave in a similar manner elsewhere. The DeltaEC results were found to be in an good agreement with the experimental results. However the coefficients were slightly overestimated by the numerical simulation at the frequency above 120 Hz, this is due to nonlinear effects not taken into consideration by DeltaEC simulation.

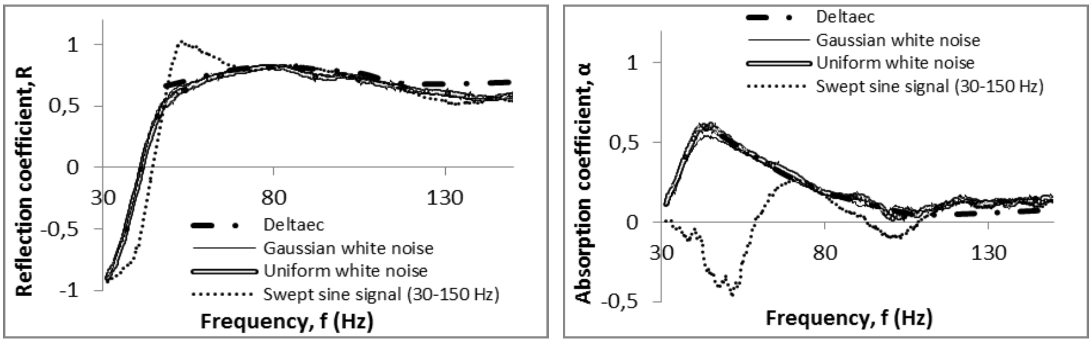

Figure 3: The results for reflection and absorption coefficients as a function of frequency when aluminium plate is used as the rigid backing.

The performance of the different material combinations was also under investigation. The elastic end shows the highest absorption coefficient relative to the other attenuation alternatives. The elastic end is essentially an acrylic plate with a thickness of 0.5 mm. Other attenuation arrangements work better at higher frequency range (few kHz) but for low frequency range, the elastic end was found to be better as shown in Fig 5. A general trend can be clearly observed that all the tested materials show a maximum absorption coefficient at the frequency of approximately 50 Hz. The absorption coefficient is gradually decreased after the peak value with increasing frequency. A compliance volume (empty box) gives a rather low absorption coefficient as compared to the rigid end (aluminium plate) at the frequency below 100 Hz. Whereas the absorption coefficient obtained for the rest of the absorbing material arrangements were higher than the rigid plate regardless of the frequency, which gives confidence in the validity of the results. Noting that the aluminium plate is approximately a rigid end and should reflect back most of the incident acoustic waves. Besides that, the sponge was found to have lower absorption coefficient compared to the elastic end, but it has a better absorption coefficient compared to all other materials or combinations of materials used in the frequency range above 50 Hz. All combinations of two materials performed better in the frequency range below 50Hz. With the inclusion of the sponge, all materials investigated exhibited a higher absorption coefficient when used in a combination of a pair of two materials together, compared with the case when each one is used separately. The sponge and honeycomb combination was found to have a better absorption coefficient than the egg tray and sponge combination.

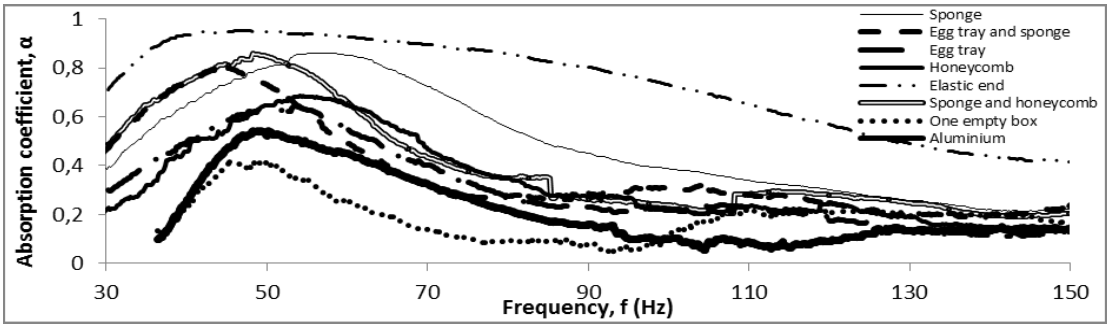

Figure 5: The responses of absorption coefficient as a function of frequency for all the tested materials when uniform white noise is used as the excitation signal.

6. Conclusions

The experimental setup for a low frequency travelling wave thermoacoustic engine was successfully modelled and simulated with DeltaEC and the comparison of the two results showed a very good agreement for a rigid end situation. Eight materials and combinations were investigated to realise that using an elastic end will work better for low frequency attenuation applications. The selection of the attenuation material or combination of material should be done very carefully and is strongly dependent on the target frequency. The outcomes of this work will be used for further ongoing investigations on loss assessments of the low frequency thermoacoustic engine. The validated DeltaEC model will be used to investigate a wider range of alternative for better optimisation.

References

[1] Swift, G., W.: A unifying perspective for some engines and refrigerators; USA; Acoustic Society of America; 2002.

[2] Chen, B., M.; Abakr, Y., A.; Goh, J., H.; Riley, P., H.; Hann, D., B.: Development and assessment of a SCORE Demo2.1 thermoacoustic engine; International Conference on Low-Cost, Electricity Generating Heat Engines For rural Areas; Nottingham; Uk; 2012.

[3] Fahy, F., J.: A simple method for measuring loudspeaker cabinet impedance; J. Audio Engineering Society; 41 (1993) 154-156.

[4] Seybert, A., F.; Ross, D., F.: Experimental determination of acoustic properties using a two-microphone technique; J. the Acoustical Society of America; 61 (1977) 1362-1370.

[5] Chu, W., T.: Extension of the two-microphone transfer-function method for impedance tube measurements; J. the Acoustical Society of America; 80 (1986) 347-348.

[6] Hans, B., Mats, A.: Influence of errors on the two-microphone method for measuring acoustic properties in ducts; J. the Acoustical Society of America; 79 (1986) 541-549.

[7] Mats, A.; Hans, B.: Error analysis of two-microphone measurements in ducts with flow; J. the Acoustical Society of America; 83 (1988) 2429-2438.

[8] Chu, W., T.: Further experimental studies on the transfer-function technique for impedance tube measurements; J. the Acoustical Society of America; 83 (1988) 2255-2260.

[9] Michael, G., J.; Patricia, E., S.: Comparison of methods for determining specific acoustic impedance; J. the Acoustical Society of America; 101 (1997) 2694-2704.

[10] Jones, M., G.; Parrott, T., L.: Evaluation of a multi-point method for determining acoustic impedance; Mechanical Systems and Signal Processing; 3 (1989) 15-35.

[11] Cho, Y., Nelson, P., A.: Least squares estimation of acoustic reflection coefficient" Institute of Acoustic Spring Conference; Salford; UK; 2002.

[12] Ward, B.; Clark, J.; Swift, G., W.: Design environmental for low amplitude thermoacoustic energy conversion; USA; Los Alamos National Laboratory; version 6.2; 2008.