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Experimental investigations on the effects of coiling and bends on the sound energy losses through a resonator tube

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Abstract

In order to miniaturize the thermoacoustic engine, thereby to increase their potential applications, coiling the resonator tube is one of the solutions to make it smaller in size (rather than scaling the engine). Whether in a standing wave or travelling wave engine, a resonator is necessary to sustain the driving acoustic waves. However, the curvature of the tube may introduce losses that are not encountered by the normal straight resonator. A straight resonator tube is the easiest design and will have small losses, but it requires large space. However, there are only few studies regarding the effect of resonator coiling. This work investigates the effect of the coiling of the tubes and the bends effects on the efficiency of the sound energy transmission through the tube experimentally. This work consists of the design of an impedance tube system to measure the sound energy losses of coiled tubes of different configurations and comparing the results with the losses in a straight tube. A similar investigation is also conducted for different number of sharp turns of the tubes (u-shaped bend and 90° bend tube). The impedance tube system designed for the testing consists of an upstream tube, the test section and a downstream tube. The two load method was used to analyze the results by using the four-microphone impedance tube methodology. The results showed significant differences between the four configurations and the outcomes were found to be very useful in the future when designing thermoacoustic looped engine.

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Keywords: Thermoacoustic; impedance tube; sound energy losses; resonator tube.

Nomenclature

ρ	density (kg/m^3)
c	speed of sound (m/s)
k	wave number (1/m)
α	transmission coefficient
T_L	transmission loss (dB)
P_n	sound pressure at microphone no. n (Pa)
A_m	the pressure amplitude with respect to Ref axis m for Incident waves
B_m	the pressure amplitude with respect to Ref axis m for Reflected waves
f_L	lower frequency limit (Hz)
f_u	upper frequency limit (Hz)
f_o	fundamental frequency when open end boundary condition (Hz)
f_c	fundamental frequency when closed end boundary condition (Hz)

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s	spacing between two microphones 12 & 34 (m)
l	spacing between the resonator and the closest microphone (m)
X_{ms}	distance between the speaker and the closest microphone (m)
d	inner diameter of the tube (m)
λ	wavelength (m)
L	total length of the impedance tube and the resonator (m)

1. Introduction

Thermoacoustic engine is a device which uses a heat temperature difference to induce high-amplitude sound waves (heat Engine), or uses high amplitude sound waves to pump heat from one place to another (refrigeration). Thermoacoustic engine can be divided in standing wave and travelling wave devices. The typical thermoacoustic device consists of heat exchangers (cold and hot), a resonator, and a stack (on standing wave devices) or regenerator (on travelling wave devices). Depending on the type of engine, a driver or loudspeaker might be used as well to generate sound waves. The resonator in the thermoacoustic engine acts as a pressure vessel (tube) for the working gas that is used to sustain the acoustic wave in the tube. The function of the resonator is to store the acoustic energy to be amplified by the thermoacoustic engine. Besides that, it is also used to transfer the output power of the engine to the acoustic load which could be a heat pump or cooler as well as an alternator [1]. In order to miniaturise the thermoacoustic heat engine, thereby increase their potential applications, coiling the resonator tube is another idea to make it smaller in size. A straight resonator tube is the easiest design and will have a small transmission loss, but it requires large space. The coiling of the resonator will definitely improve the engine footprint but it may introduce losses that are not encountered by the normal straight resonator. The proposed work in coiling the resonator will certainly create more energy losses than the previous designs but the magnitude of these losses are unknown.

There are very few examples in the literature that investigate the energy loss due to resonator geometry. The most important investigation in the energy loss due to resonator geometry is the one carried by Florian et al who investigated the effect of resonator curvature on the thermoacoustic effect using CFD simulation [2]. The variation of pressure amplitude and operating frequency serve as metrics in his investigation. However, no experimental work was carried out as he only focused on the numerical simulation. He showed that the severely curved resonator will exhibit a variation in operating frequency and the amplitude of the acoustic waves. Most importantly, there was no magnitude of energy loss shown in his work.

The overall objective of this work is to investigate the effect of the coiling of the resonators on the efficiency of the sound energy transmission through the resonators thereby optimise the acoustic power transfer between the thermoacoustic engine and the acoustic load (heat pump or cooler). The energy loss (transmission loss) through a Coiled tube was first measured and the results obtained are compared with the energy loss induced in a Straight tube. A similar investigation was conducted for different geometries (U-shaped tube and 90^{o} bend tube). The impedance tube system designed for the testing consists of an upstream tube, the test section (resonator) and a downstream tube. Tang et al illustrated that the typical lengths used for resonator in thermoacoustic engine is in the range between 4-9 m [3]. Therefore, the lengths for all the resonator geometries were fixed at 4 m long with an inner diameter of 105 mm.

2. Methodology

There are various techniques in the literature used for measuring the sound transmission loss through a test specimen [4, 5, and 6]. The test specimen could be an exhaust system or simply a sound absorbent material in more common. In this work, two-load method developed by Yunseon Ryu & Man-Rim Choi is chosen to calculate the transmission loss through the resonator by using the four-microphone impedance tube technique [7]. Two-load method is the most suitable and easiest method to employ as compared to other existing methods [8, 9].

Instead of moving the sound source from one side to the other, the end boundary condition is obtained by altering the end condition as illustrate in Fig. 1. The removable end cover is adjusted to obtain different boundary conditions. Transmission loss is an important indicator which can effectively determine the how much sound energy is prevented from travelling through the resonator. The transmission loss is found by setting two measurement configurations in order to get two boundary conditions where Eq. 1 and 2 has an open boundary condition at the end of the tube, and Eq. 3 and 4 has the closed boundary condition at the end of the tube:

$$P_1 = A_1 e^{jk(dx1+dx2)} + B_1 e^{-jk(dx1+dx2)} \quad (1)$$

$$P_2 = A_1 e^{jkdx2} + B_1 e^{-jkdx2} \quad (2)$$

$$P_3 = A_2 e^{-jkdx3} + B_2 e^{jkdx3} \quad (3)$$

$$P_4 = A_2 e^{-jk(dx3+dx4)} + B_2 e^{jk(dx3+dx4)} \quad (4)$$

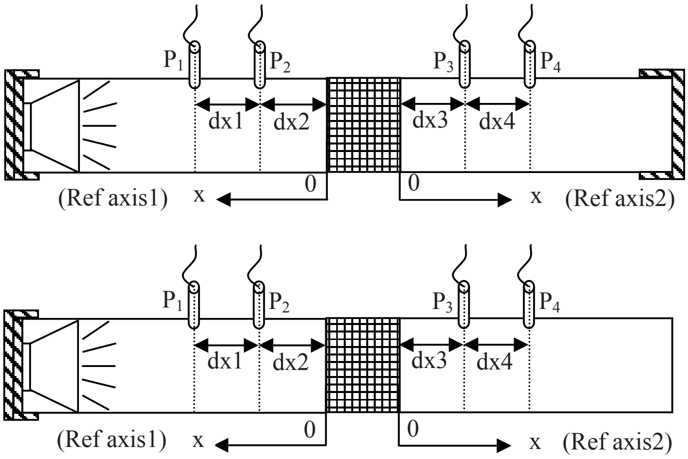


Fig. 1. The schematic diagram of the assembly of the four-microphone impedance tube for both closed and open boundary condition at the end of tube.

In one dimensional wave propagation field, the two pressure waves can be separated into incident and reflected wave respectively. The incident and reflected waves in the upstream tube could be defined as A_1 and B_1 whereas the incident and reflected waves in the downstream tube, passing through the test specimen could be defined as A_2 and B_2.Using the transfer matrix method developed by Yunseon Ryu & Man-Rim Choi [7], the relationship of the pressure amplitude in between the test specimen could be formulated as follow:

$$\begin{Bmatrix} A_1 \\ B_1 \end{Bmatrix} = \begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix} \begin{Bmatrix} A_2 \\ B_2 \end{Bmatrix} \quad (5)$$

$$T_L = 20 \log_{10}|\alpha| \quad (6)$$

3. Impedance tube system

An impedance tube also called as a standing wave tube is an acoustic measurement that provides an effective and easy way for measuring the absorption coefficient and transmission loss of acoustical material. A typical impedance tube consists of microphones, a loudspeaker and sample material. The microphones sense the sound pressure fluctuations and covert them to an analog electrical signal. The loudspeaker acts as a source that generates sinusoidal sound waves which propagate down the tube and reflect from the other end of the tube. The sample material is placed between the tubes to be investigated. In this project, different sample is the tubes with different geometry (Coiled tube, 90^o bend tube, and etc.). In this work, four-microphone impedance tube will be used to evaluate the transmission loss. The impedance tube is designed based on the ISO standard 103534 using the formulas as below [10]:

$$s \ll \frac{0.45}{f_u} c \quad (7)$$

$$l > \frac{d}{2} \quad (8)$$

$$X_{ms} > 3d \quad (9)$$

4. Experimental setup

The impedance tube and resonators have the same circular cross section with an inner diameter of 105 mm. All the tested geometries (resonators) were fixed at 4 m long. These geometries are made from the same material and assumed to have the same surface roughness. The total length of the impedance tube and the resonator is approximately 5 m. The experimental apparatus need to carry out the experiment for the four different geometries are shown clearly on Fig. 2. The sound source used in this work is a loudspeaker which is contained in a transparent sound-insulating box in order to avoid airborne flanking transmission to the microphones. The loudspeaker creates a sinusoidal pressure disturbance that propagates down the tube with the aid of an amplifier. Ring seal socket, a type of o-ring, is used between the impedance tube and the frame of the loudspeaker as well as the loudspeaker box, and also between the impedance tube and the resonator to provide sealing and avoid air leakage. Silicon grid is applied on the surface of the resonator before it is connected to the impedance tube to avoid the socket o-ring to get worn out.

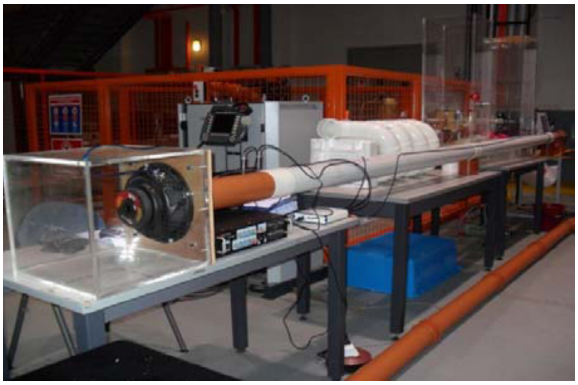
(a) 
(b) 
(c) 
(d) 

Fig. 2. The experimental apparatus for (a) Straight tube, (b) Coiled tube, (c) U-shaped tube, and. (d) 90º bend tube.

The sound pressure in the tube is collected by the microphones at different locations with the aid of data acquisition. A total of 4 microphones are used to measure the sound pressure along the length of the tube whereby 2 microphones are placed upstream of the tube and the other two are placed downstream. The microphones are sealed tightly to the mounting holes with the aid of rubber and O-ring. All the microphones have a slightly different sensitivity. These microphones are calibrated by using the sound calibrator every time before the experiment is conducted. The measured sound pressure is then used to calculate transmission loss by using both Labview SignalExpress and Matlab. In Labview SignalExpress, the experiment results are collected using filtered and non filtered method. It was found that the non filtered data gives more accurate results. The time-step used in the experiment was 0.001 which means 1000 of data will be collected at 1 second. Maximum pressure was chosen amount the data as the final result to calculate the transmission loss in Matlab.

A signal generator is used to generate a stationary signal with a flat spectral density within the frequency range of interest. The removable end cover is adjusted to obtain open and closed end boundary conditions in the experiment. A standing wave interference pattern results dues to the superposition of the incident and reflected wave. If 100% of the incident wave is reflected, then the incident and reflected waves have the same amplitude; the nodes in the pipe have zero pressure and the antinodes have double the pressure. If some of the incident sound energy is dissipated during the transmission due to the friction loss near the wall for instance, then the incident and reflected waves have different amplitudes; the nodes in the pipe no longer have zero pressure. The pressure amplitudes at the nodes and antinodes are measured with the microphones. The wavelength of the sound emitted by the source (loudspeaker) can be adjusted, but it should be kept substantially larger than the tube diameter, so that plane wave assumption holds. According to the ISO standard 10534-2, the dimensions of the experimental setup determine the working frequency range. The lower frequency limit, f_L depends on the microphone spacing whereas the upper frequency limit, f_u depends on the diameter of the tube [11]:

$$f_u < 0.58 \text{ x } \left(\frac{c}{d}\right) \tag{10}$$

$$f_L < 0.75 \text{ x } \left(\frac{c}{L-d}\right) \tag{11}$$

For the 105 mm inner diameter tube, the working frequency range is 53 Hz < f < 1895 Hz. In order to avoid the occurrence of non-planar wave mode propagation and to assure accurate phase detection, resonance frequencies or overtones are used as the operating frequency for both open and closed boundary conditions. To avoid the phase mismatch between the upstream and downstream of the impedance tube, the overtones of the tubes are used as the operating frequency which is in the range of 206-274 Hz. The overtones or harmonic frequencies are the multiple of the fundamental frequency.

5. Results and Discussion

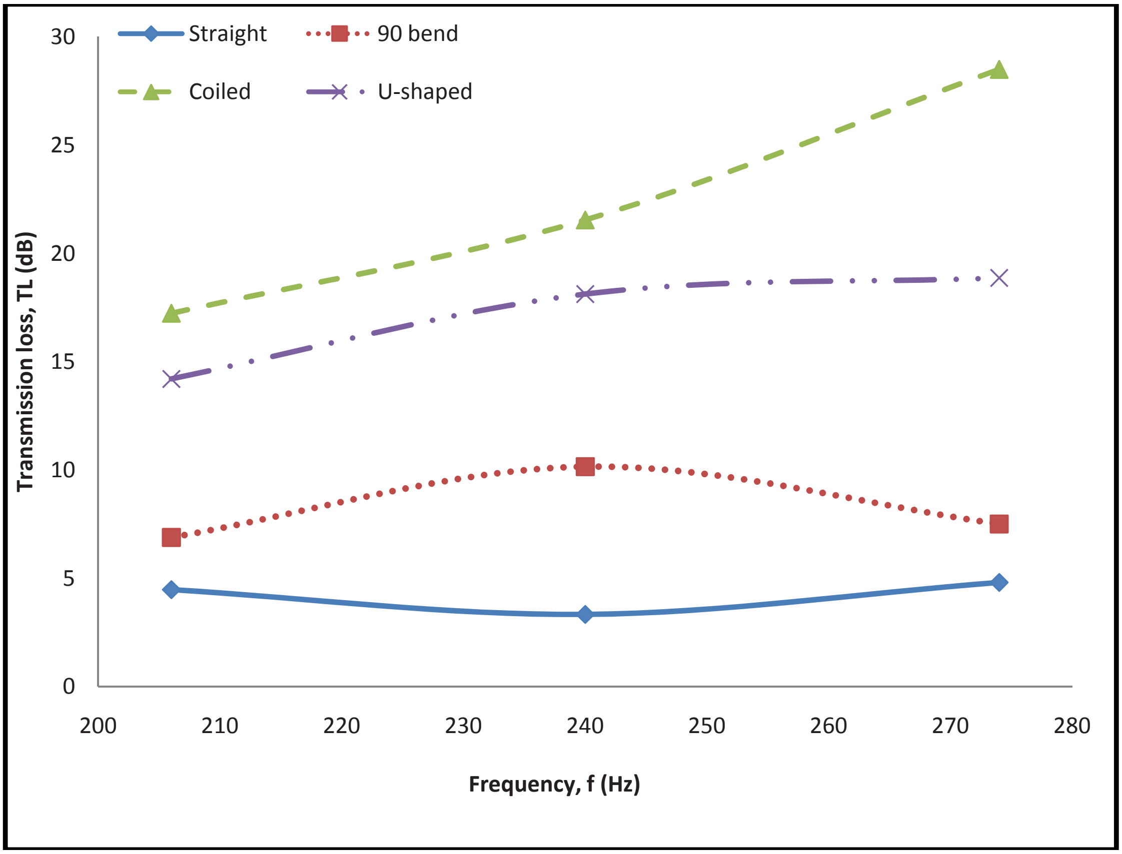


Fig. 3. Transmission loss against frequency for all the four geometries.

As shown in Fig. 3, a general trend can be seen. All the geometries show a gradual increase in transmission loss when the frequency increases except the straight tube and the 90 bends tube. 90^o bend tube gives a higher transmission loss as compared to the Straight tube. Whereas the transmission loss obtained by U-shaped tube is much higher than both Straight tube and 90^o bend tube which is approximately 14 to 19 dB. This can be explained because the U - shaped tube is constructed using two bends and this has led to more losses to be produced. Coiled tube gives the most transmission loss for the all tested frequency as compare to the other three geometries. A very obvious linear transmission loss can be seen as the tested frequency increases. Coiled tube is made up of 16 bends which the number of bends is more than the other three geometries. It is believed that most of the losses came from the air leakage due to imperfect fittings between the resonator and the down and upstream of the impedance tube. The transmission loss obtained for all the four geometries are summarised and presented by a simple flow chart in Fig. 4.

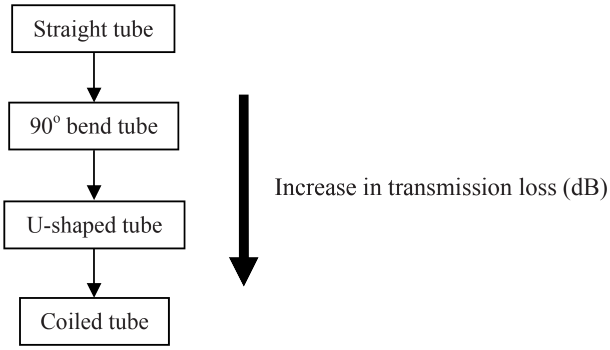


Fig. 4. Flow chart with an order of the increase in transmission loss.

There are a few important factors which lead to the inaccurate results to be collected. Although the microphones were first calibrated every time before the experiment but as time goes by the humidity and temperature in the room changes which turn out the sensitivity of the microphone also changes. Another main factor would be to obtain an exact 4 m long tube for all the geometries. As mentioned earlier in this work, the experiment was conducted using 4 different geometries with the same dimensions. However, the tubes or resonators are not exactly 4 m long as fabricating Coiled tube for instance is not a common product in the market. Therefore, it is made up of several bends instead of one whole tube like the Straight tube. Moreover, another possible error which affects the results taken will be the imperfect sealing between the resonator and the impedance tube. The resonator is connected to the impedance tube by using high force. This high amount of force applied will definitely cause the socket o-ring to get worn out easily although silicon grid was first applied on the surface of the resonator. The quality of socket o-ring will therefore affect inaccurate data to be collected as air leakage will occur. Furthermore, the idea of using overtone as the operating frequency is to avoid inaccurate phase detection. However, the slightly unequalled length of the geometries will cause phase mismatch between the incident and reflected waves in the upstream and also downstream of the tube. Eventually, data are collected at the wrong position which leads to inaccurate results to be collected. In addition, the unwanted sound or noise had propagated into the tube when the open end boundary condition was tested.

The experiment should be carried out in an anechoic room whereby the walls, floor and ceiling are treated with wedge-shaped acoustical absorbing material that absorbs the unwanted sound from surrounding. There is also a certain possibility that unwanted noise was induced when the loudspeaker vibrates and propagates into the downstream section via the tube surface. Instead of placing the loudspeaker directly on the table, a vibration absorber is placed below the loudspeaker to get rid of the vibration. Besides that, it can be seen clearly that the operate overtone would significantly affect the amount of transmission loss through the resonator.

6. Conclusion

The two load method has been used successfully to evaluate the energy loss level in different types of bends and coiled tubes. Based on the experimental results obtained, it can be proven that the Coiled tube gives the most transmission loss, followed by the U-shaped tube, 90^o tube and lastly the Straight tube. The proposed work of Coiled tube will definitely enhance the engine footprint but high transmission loss induced. Straight tube might be the recommendatory geometry as it creates the least amount of transmission loss but requires large space to be stored. Thus, it is suggested that the efficiency of the engine can be further improved by using a smoother one whole tube instead of a making up of several bends. The experiment can be carried out in an anechoic room to avoid unwanted sound in order to predict the results accurately. The future work would be to use DeltaEC, an effective tool used to simulate the thermoacoustic engine, to simulate the energy loss in the resonator.

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