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DEVELOPMENT OF A LOW COST IMPEDANCE TUBE TO MEASURE ACOUSTIC ABSORPTION AND TRANSMISSION LOSS OF MATERIALS

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Abstract

Traditional methods of measuring sound absorption coefficient and sound transmission loss of acoustic materials and treatments are time-consuming and expensive. To overcome this limitation, normal incidence sound absorption and transmission loss measurement technique using an impedance tube was developed. Unfortunately this equipment is equally expensive. This paper presents an effort made to develop a cost-effective impedance tube for wider use especially for educational use in emerging countries. An impedance tube capable of measuring absorption coefficient and transmission loss is designed and built under a budget of $1500 suitable for educational institutions in developing countries. The design, development and fabrication of the low-cost impedance tube along with measurement results demonstrating its accuracy is presented. Using a calibrated acoustic sample, data obtained from the low-cost impedance tube were compared with those from a standard commercial tube with encouraging results. A parametric study was conducted showing the effects of various parameters on the accuracy of the measured results. These include tube material, tube dimensions, frequency range, source transducer, pressure-microphones, sample and microphone holder, data acquisition and reduction technique. Based on these, design options were generated to meet the cost and functionality targets pre-assigned. A list of suggested parts and vendors is also included for anyone interested to custom-build the tube.

1.0 Introduction

Sound absorption is defined as the amount of acoustic energy dissipated in a material as a sound wave passes through it. The sound absorption coefficient (α) of a material is a dimensionless number valued between zero and one, over a range of frequencies, that represents a percentage of sound energy absorbed based on a unit area exposed to the sound.   Figure 1 illustrates how an acoustic material reacts to impinging sound waves.

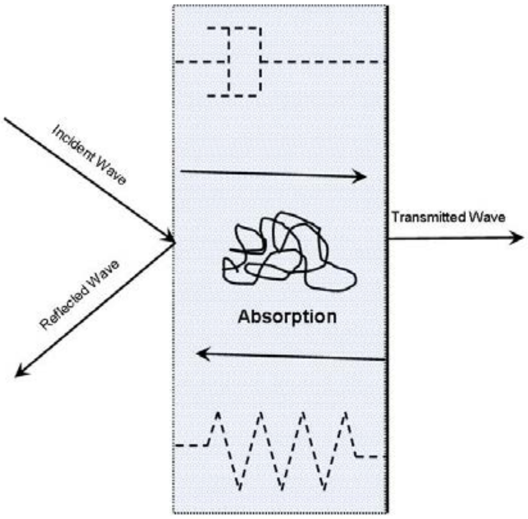

Figure 1: Representation of porous sound absorption material

The incident wave impacts the face of the material, reflecting some of its energy and sending the rest into the material. The energy sent into the material is either transmitted through the material, or absorbed within the porous structure of the material. The sound absorption coefficient is the sum of the percentages of sound that were not reflected. From Figures 1, the sound transmission coefficient, τ, is simply the ratio of the sound power transmitted through the material sample into another space to the sound power incident on one side of a material sample. Since some sound energy will be lost when waves travel through the material's structure, it is evident that the sound transmission coefficient will always be valued between zero and one.   Equation 1 below is the conversion of sound transmission coefficient to sound transmission loss (TL) expressed in decibels.

$$TL = 10\log_{10}\left(\frac{1}{\tau}\right) \quad dB \qquad (1)$$

The specification of sound transmission loss in decibels is not only easier to visualize than the transmission coefficient, but it provides for direct measurement techniques.

Materials used for passive noise control can be classified as absorbers or barriers. Acoustic absorbers (e.g. polyurethane foams, fiberglass , glass wool, etc.) absorb the acoustic energy through intermolecular friction, the effectiveness of which is measured by using the sound absorption coefficient (α) of the material or acoustic absorption (a) in m^2 which is the product of (α) and the surface area of the material (A). One type of acoustic absorber can be made from a number of materials, such as cotton or polyurethane foam. Their structures are open-celled, allowing sound waves to travel through them while they dissipate the acoustic energy. Barriers on the other hand are used to reflect the sound energy; the effectiveness is measured by its TL. Acoustic barriers are made from heavy and/or dense materials that block sound energy passage through their structures. Examples of barriers include concrete highway barriers, plexiglass, sheet metal, lead sheet, wooden barriers, etc.

To measure absorption coefficient and TL values, engineers and researchers use well documented, time tested methods. These are documented in SAE, ISO and ASTM standards [1-5]. These methods are getting updated as technology progresses. Most of these methods can be broadly classified based upon the nature of incident sound energy: random incident sound or normal incident sound energy. A reverberation room in conjunction with an anechoic room are the two most important pieces of equipment that are needed to measure absorption coefficient as well as transmission loss of materials. These methods many times are termed as traditional methods. Facilities required for traditional material testing involves expensive instrumentation, floor space, large testing time and most importantly big sized test samples. Producing oversized prototypes may not be possible each time. Hence efforts were made to develop a method for smaller sample size using smaller floor space and testing time required. This led to the development of theory of the so-called impedance tube method [6-8]. The method of testing materials using impedance tube is called as normal incident sound absorption or transmission loss testing because of the normally incident sound waves on to the surface of test sample in the tube. Several standards were later developed based on this method for measuring both acoustic absorption and sound transmission loss [9-11].

A simple schematic of the impedance tube is shown in Figure 2. It essentially consists of a straight tube with one end connected to a sound source and the other end with the capability to hold a material sample whose properties are to be measured. Pair of microphones separated by finite distance is connected to this tube with the help of microphone holders. These microphones are connected to a digital signal analyzer via signal conditioners (pre-amplifiers) and a data acquisition system. A function generator with equalizer and amplifier is used to power the sound source in the impedance tube. Based on whether to measure absorption or transmission loss, the termination conditions are different. For absorption coefficient measurements a rigid backing is used. For transmission loss measurement, a hollow tube of the same diameter as the upstream tube with pair of microphone holders is used on the downstream of the test sample. Two different termination (anechoic and rigid backing) conditions are used during transmission loss measurements.

Several commercial impedance tubes are currently available for measuring the acoustic properties including absorption coefficient and transmission loss of materials based on current standards. The most widely used is the Bruel & Kjaer (B&K) impedance tube Type 4206 [12]. This tube has become almost the industry standard in acoustic applications. It is well-built with quality materials and has proven to produce consistent results for industrial and other applications. The objective of this work was to develop a low-cost alternative to this tube for educational use especially in developing countries where cost is a primary issue for promoting hands-on educational activities. We wanted to use a PVC tube, an inexpensive speaker, studio microphones and off-the-shelf materials for the construction of the tube. A low-end laptop with integrated sound card was used for data acquisition and custom developed MATLAB software with a Graphical User Interface (GUI) for data analysis and presentation. Some details of the equipment developed along with its validation are presented below.

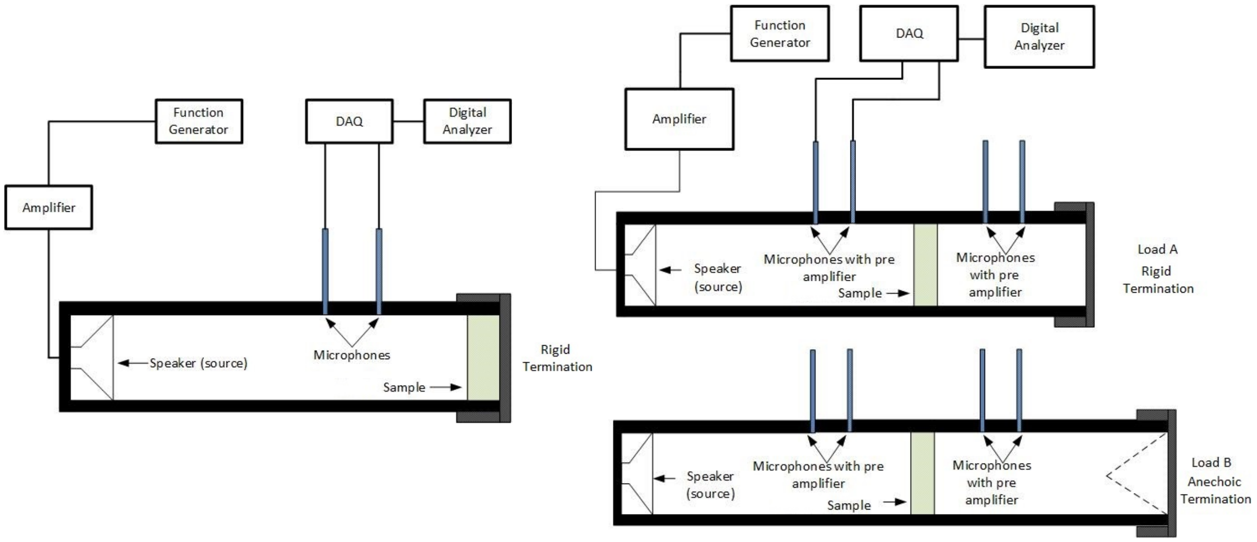

Figure 2: Schematic of the impedance tube set up for acoustic absorption and transmission loss.

2.0 Development of the Low-cost Impedance Tube

2.1 Tube Diameter and Microphone Spacing

The tube is the most important functional as well as structural part of the apparatus. It supports the source at one end and supports a sample along with the sample holder at opposite end. Besides this, it governs the operating frequency range of the apparatus. For wider range of frequencies to be included for measurements, multiple size (diameter and length) tubes are required. The frequency range is defined as $f_l < f < f_u$, where f_l is lower working frequency limit and f_u is upper working frequency limit. The lower frequency limit is dependent on the spacing between the pair of microphones and accuracy of the measurement/analysis system. The rule of thumb suggests microphone spacing should be more than one percent of the wavelength of the lowest frequency of interest. The upper and lower limits of frequencies are defined as in equations below.

$$f_u < \frac{K\,c}{d} \qquad or \qquad d < \frac{K\,c}{f_u} \tag{2}$$

$$f_l > 0.01\frac{c}{s} \qquad or \qquad s > 0.01\frac{c}{f_l} \quad . \tag{3}$$

Here K is tube factor. K = 0.586 for circular tube or K =0.5 for rectangular /square tube. The term c is speed of sound (m/s) in air. The term d is the inside diameter of the tube in meters while s is the distance between pair of microphones in meters. In many applications, frequency range from 100 Hz to 8000 Hz is usually considered for any material to be assessed based upon acoustical performance. The microphone spacing plays critical role in determining the lower cut off frequency of the tube as well. In this case, the microphone spacing is fixed by the lower usable frequency of a sound source. The speaker supports 80 Hz as the lowest frequency. Hence 50 mm of microphone spacing is generally used in large tubes (up to 100 mm diameter), while 20 millimeter spacing is used in smaller tubes having a diameter less than about 30 mm.

In this case, to keep the cost minimum, the standard PVC plastic pipes that area available in various diameters and wall thickness combinations were selected. One (1) inch nominal (1.048 inch actual i.e. 26.5 millimeter) and three (3) inch nominal (3.068 inch actual i.e. 77 millimeter) diameter with schedule 40 type PVC tubes available at hardware store with minimum conditioning required were used to produce a useful frequency range of 68-2595Hz for the large tube and 170-6864 Hz for the smaller diameter tube.

2.2 Test Sample Holder

Sample holder plays critical role of aligning test piece in normal position to the direction of traveling planer wave. It is also made up of same cross sectional dimensions as the PVC pipe used in building the impedance tube on the source side. There are different ways to attach the sample holder to the main tube. Many ways including threading, quick release coupling require special machining adding to the cost of the apparatus. Connecting the tubes with standard flanges reduced the cost significantly. The standard flanges are readily available in the market with minimum conditioning required to be used for the desired purpose. Flanges provide easy way to secure the sample into place and make the assembly / disassembly simpler without adding more cost to the apparatus. The similar design and approach is implemented for both the tube sizes (large and small impedance tube with sample holders).

For sound absorption measurements, a rigid backing plate is required to reflect the incident sound wave. An end flange is used as a rigid backing. For sound transmission loss measurements, the sample is placed at the center of the same sample holder and edges are sealed with petroleum jelly for avoiding flanking paths. Flanges were used for quick release and easy access to sample in the test holder. Wing nuts and bolts were used to tighten the flanges.

2.3 Sound Source and Microphones

Sound source is nothing but a speaker able to produce a planer wave of broadband noise in the interested frequency range. A full range cone driver (Dayton Audio ND65-8) with a flat frequency response over the desired frequency range was selected for the sound source. An anechoic backing is required on the back side of the source in order to avoid any reflected wave to interfere with the forward progressing plane wave. For measuring the incident and reflected waves, microphones are required to be positioned in such a way as to not disturb the plane wave generated, and be able to measure the sound pressure levels inside the tube. For this purpose, the microphones are mounted flush with the inner wall of the tube. The microphones should be removable, and the microphone holder should not allow any sound wave to leak into sounding environment in order not to degrade the quality of planer wave. The microphone selected was the low-cost Radio Shack Clip-on Omnidirectional studio microphone. Special care must be taken while selecting material and building the holder. To comply with all these conditions, a simple solution was to use nylon or metal reinforced nylon cable glands (traps used to secure cables in electrical devices).

2.4 Assembly

Various sections of tubes were cut to desired length and fixed with flanges using PVC sealant for air tight joints. It was made sure to flush mount all the mating parts in order to avoid any breakage in the tube continuity. Schematics and actual photographs of the complete apparatus and various sections can be seen in Figure 3.

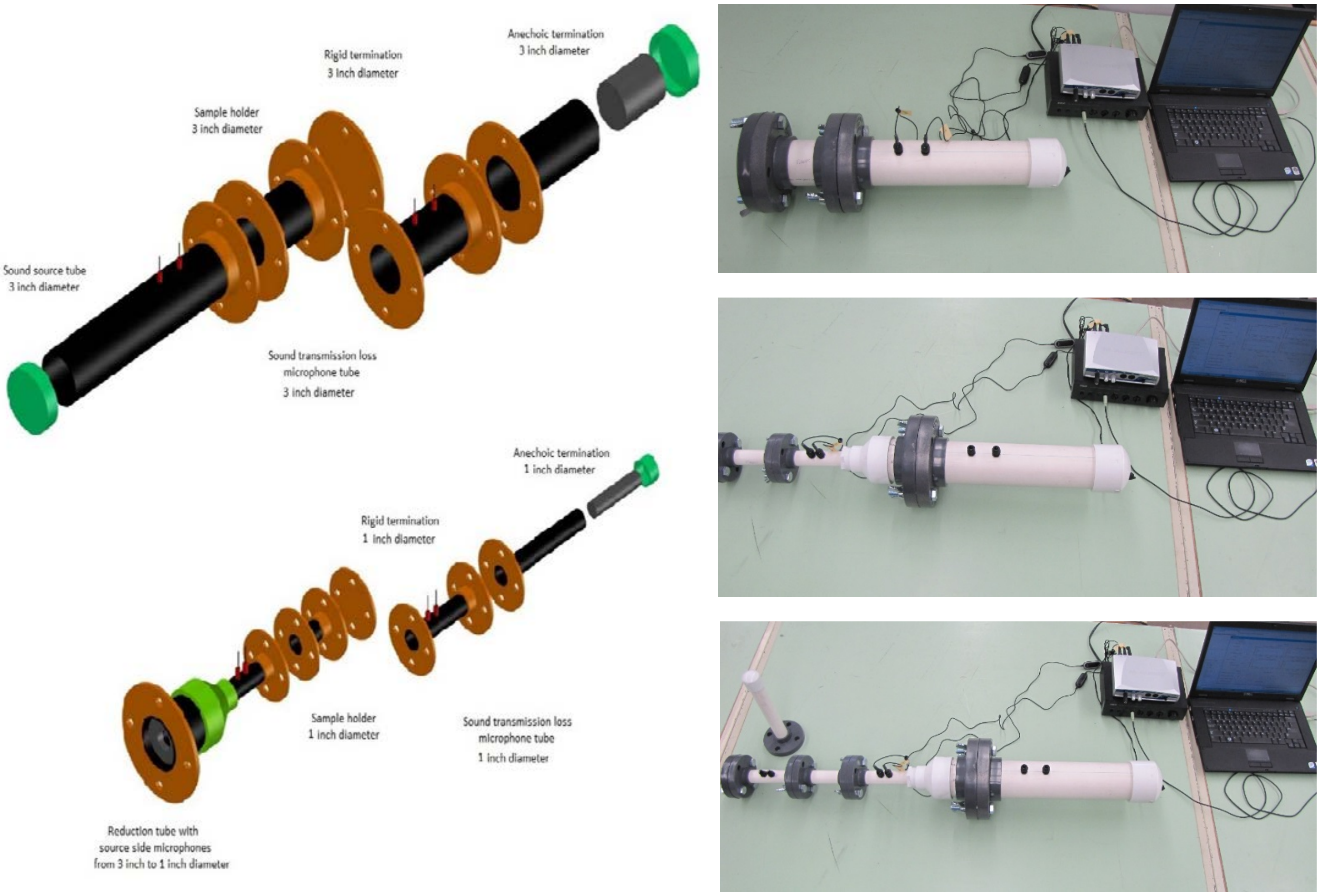

Figure 3: Assembled tubes: large and small tube for alpha; assembled TL tube

3.0 Measurement System

The measurements system consists of the newly built impedance tube (large and small tube) along with a sound card of a laptop computer (external 2 channel; left and right channel of stereo signal) and general purpose low cost ¼ in (6.5 mm) diameter pressure microphones from Radio Shack. These microphones have $^{1}/_{8}$ in (3.5 mm) TRS connectors so they can be easily plugged into convectional sound cards. A function generator applet with custom-developed Matlab code was used to generate broadband random noise needed for input and previously developed custom MATLAB GUI software was used for data acquisition and analysis. A list of parts used in the construction of the apparatus is given in Table 1.

Table 1: Part list

Impedance Tube Part	Part Description	Source & Catalog No.	Quantity (No.)
Source (Speaker)	Dayton Audio ND65-8, 2.5” AL Full Range Driver	290-206 (**P***)	1
Microphones	Radio Shack Clip-on Omnidirectional Microphone	33-3013 (**R***)	2
PVC Tubes	Standard PVC Unthreaded Pipe (Size φ1’’ & Size φ3”) Schedule 40	48925K95 (**M***)	5’ Each
PVC Flanges	PVC Unthreaded Pipe Fitting Flange (Size 1 and Size 3) Schedule 80	4881K233 (**M***)	6 Each
PVC End Caps	Standard PVC Pipe Fitting Cap (Size 1 and Size 3) Schedule 40	4880K57 (**M***)	2 Each
Cable Glands	PVC Cable Glands	PG-7 (**G***)	8
Fasteners	Bolts, Wing nuts, PVC cement	**G***	-
Sound Card	External High Definition 2 Channel I/O Audio Card	Audiophile 192 (**A***)	1

Where, **M**: McMaster-Carr Supply Company (www.mcmaster.com)
R: RadioShack Corporation (www.RadioShack.com); **G**: General Hardware Store ; **P**: Parts Express (www.parts-express.com) ; **A**: M-Audio (inMusic Brands, Inc.) (www.m-audio.com)

The actual cost involved in development of this test set-up is much less as compared to the commercial set-ups. In the current study, the overall cost is around 75% less than a commercial impedance tube. The most expensive component in the measurement chain is the laptop. We believe the reduced cost gives an added advantage in the education sector in the demonstration of acoustics concepts in undergraduate and graduate course.

4.0 Validation Study

The custom built impedance tube and the measurement system chain is validated by comparing measured results with those measured from a commercial impedance tube using standard samples. The commercial reference tube used is the industry standard Brüel & Kjær impedance tube type 4206. This apparatus uses two different tubes of 100 mm and 29 mm respectively for low and high frequency ranges. Four different types of acoustic materials as shown in Figure 4 (two fibrous, one cellular absorption pads, and one limped barrier) were used to validate the results.

Figure 4: Test specimens used during the validation (From Left to Right: EVA Barrier, Fiberglass insulation, cotton shoddy and Ether Foam)

Figures 5 and 6 show the results from sound absorption testing while the TL test results are presented in Figure 7. A comparison of sound absorption coefficient measured using the large tube for all samples show excellent agreement as indicated in Figure 5. These are for the low frequency range from 50-1500 Hz. The lower performing ether foam shows comparatively higher absorption performance. Highly absorptive samples do not show much variation in the performance.

Figure 6 shows a similar comparison study of the same samples in the small tube. For the low-cost tube, the absorption measured is significantly higher than empty reference tube. This is attributed to the rougher surface finish the schedule 40 PVC pipes use that causes disturbance in planer wave. For higher performing samples i.e. fiberglass and cotton shoddy, the agreement in performance is acceptable.

We believe the tube is very useful for instructional purpose as well as conducting relative comparisons among various acoustic materials in order to rank order the test materials without requirement of expensive laboratory testing or similar test practices. It appears that the relative rank ordering is the same for results from the reference tube as well as for low-cost tube.

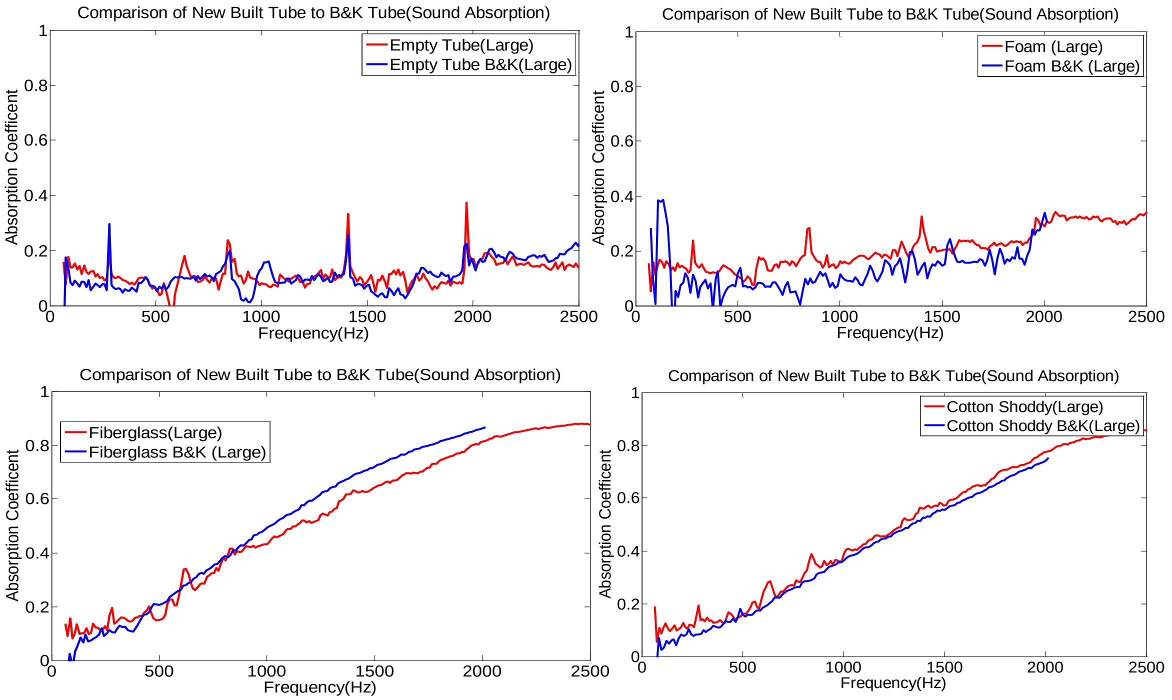

Figure 5: Comparison of B&K vs developed large tube – top left: Empty large tube, top right: ether foam, bottom left: fiberglass and bottom right: cotton shoddy

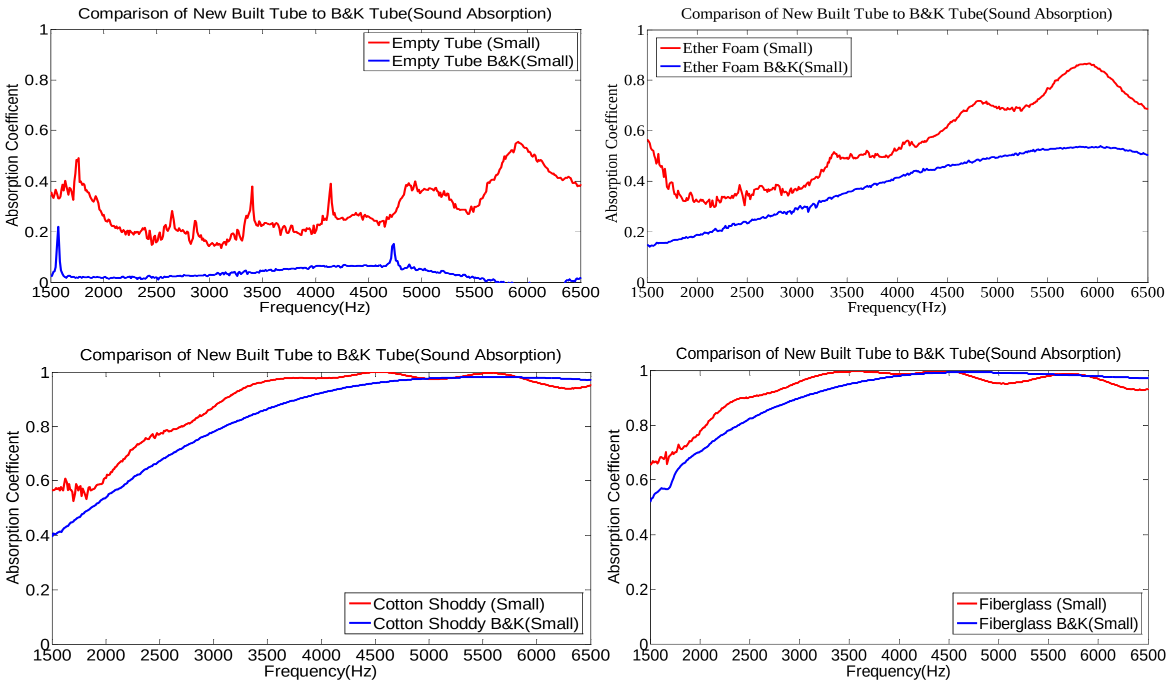

Figure 6: Comparison of B&K vs developed small tube – top left: Empty small tube, top right: ether foam, bottom left: fiberglass and bottom right: cotton shoddy

Figure 7 shows the rank ordering and comparison of the measured TL of various barriers tested in small tube. The lighter EVA barrier has lower TL of all materials whereas the heaviest EVA has the best transmission loss among all. For lightweight samples, the performance is comparable over the broad frequency range. As the sample becomes more massive, the signal to noise ratio on the receiving side dominates. Hence the data shows high level of inconsistencies at higher frequencies.

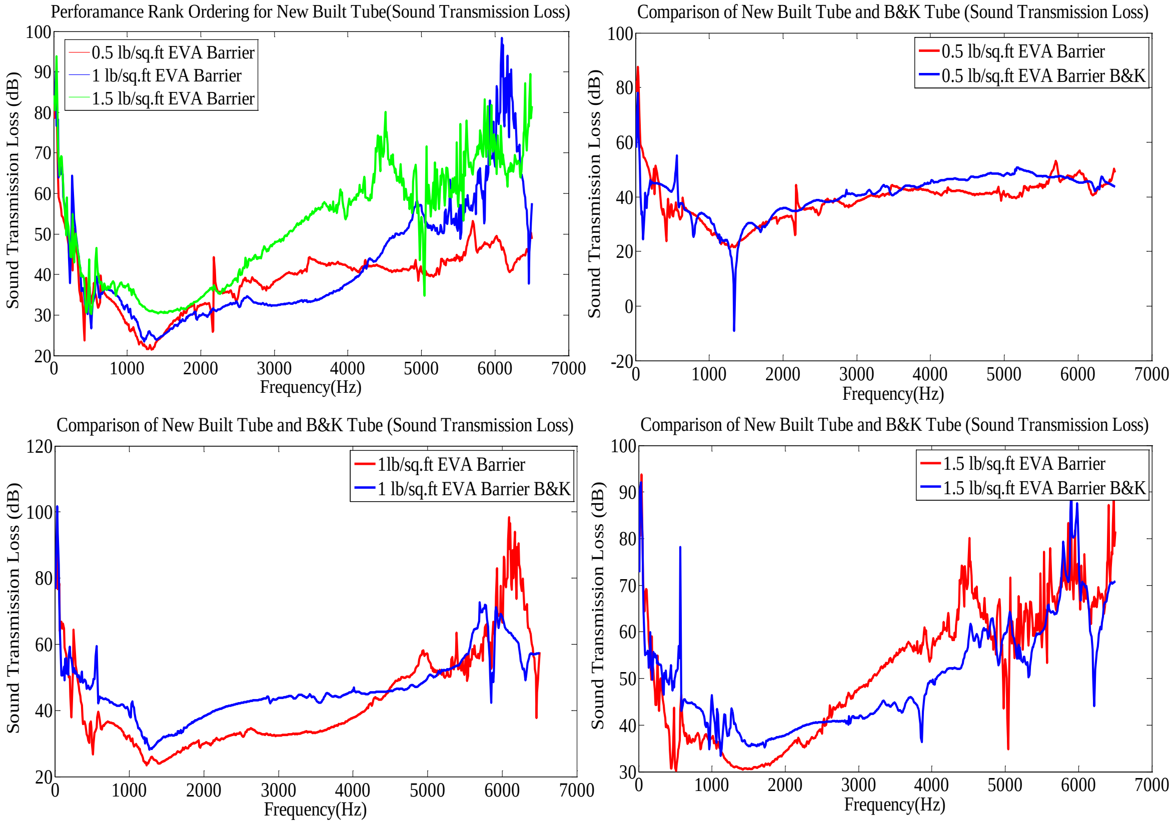

Figure 7: Top left: rank order of barriers in developed small tube, comparison of TL results for B&K vs developed small tube – top right: ½ lb/sq.ft barrier, bottom left: 1 lb/sq.ft barrier and bottom right: 1½ lb/sq.ft barrier

5.0 Educational Use

Many universities in the emerging countries in Asia, South America or East Europe may not be able to afford expensive acoustic laboratories to encourage students to actively pursue education in experimental acoustics, noise and vibration. One of the reasons for this is the cost involved in setting up labs and purchasing instrumentation. The impedance tube developed in this study can be duplicated with limited resources. The demonstration, experimentation sessions will allow students to explore further studies in this field. This tube will help the school, colleges and universities to start new programs in acoustic and NVH (noise, vibration and harshness). Over the period of time, we believe the impedance tube can be modified further with laboratory standard microphones and measurements system to improve accuracy.

6.0 Conclusions

A low-cost impedance tube intended primarily for educational use was designed and built using standard parts whenever possible. The objective was to develop an apparatus to demonstrate the measurement of sound absorption and sound transmission loss to college engineering students at a minimum cost. The impedance tube includes a source tube containing a speaker, sample holder, and other necessary termination to conduct both absorption and TL experiments. A laptop soundcard was used instead of expensive data acquisition systems to acquire data from the low cost microphones. Results from the low-cost impedance tube agree well with those obtained from a commercial impedance tube for calibrated samples.

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