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Influence of White Noise in the Measurementof Acoustic Impedance of Some Industrial Insulating Materials

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Abstract:*This study presents theInfluence of White Noise in the Measurement of Acoustic Impedance and Absorption Coefficients of some Industrial Insulating Materials using white noise generator instead of one-third of octave or sine wave and impedance tube with single moveable microphone. The standing wave method is used to measure the acoustic properties (absorption coefficient and acoustic impedance) of sound absorbing materials. A burst of white noise and a signal processing technique was used. The algorithm is based on the equation of simple harmonic motion, however,distance was used as a variable, instead of time. This measurement allows frequency resolutions as low as 5 Hz in a reasonably short amount of time. Although the frequency resolution of 5 Hz and distance of 1cm may not have affected the sampling rate for each time of measurement, but these features of the frequency resolution and distances used does affect the results by the responses of the signals that is produced.*

Keywords:*Absorption coefficient, Acoustic Impedance,Sound, white noise*

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I. Introduction

Sound is a kind of energy that produces a mechanical movement or sound wave. The energy has to travel outward away from the sound source. The medium, such as air, transfer the mechanical wave. The detector, such as an ear detects the wave [1]. It is necessary to characterize the sound insulation characteristics of materials using a less expensive and less time-consuming approach than the reverberant room method. Insulation of sound is a kind of measure to prevent the sound waves from permeating. It is expressed by the sound transmission loss which is determined by the difference of decibels between the incident sound and permeated sound. This kind of measurement may be performed with one microphone located at a specified point and level noted and recorded, making sure that suitable time averaging was used at each point[2].

Acoustic materials play an important role in noise control solutions such as machinery housings or airborne sound silencers. The strength of an industrial noise control solution in most cases lies in the acoustic materials used. The acoustic energy that is incident on the object is converted into reflected acoustic energy, energy loss, and transmitted acoustic energy. The ratio of reflected acoustic energy to incident energy is defined as the reflectivity, and the ratio of the sum of energy loss and transmitted energy to incident energy is defined as acoustic absorption. The ratio of transmitted energy to incident energy is defined as acoustic transmissibility [1].

The sound-absorbing ability of a material is given in terms of an absorption coefficient. Absorption coefficient isdefined as the ratio of the energy absorbed by the surface to the energy incident on the surface. The absorption coefficient can be anywhere betweenO and 1. When it is O, all the incident sound energy is reflected; when it is 1, all the energy is absorbed.The value of the absorption coefficient depends on the frequency[3].The standing wave method was used to measure the acoustic properties (absorptioncoefficient and acoustic impedance) of sound absorbing materials.Using algorithm that is based on the equation of simple harmonic motion, but uses distance as a variable, instead of time.This method allows measuring at frequency resolutions as low as 5 Hz in a reasonably short amount of time using an impedance tube with single moveable microphone and a white noise generator in thedevelopment on a time efficient approach to measurethe Acoustic Impedance of Industrial Insulating materials [4].

[5] investigated the influence of granules size in silica aerogels in terms of thermal and acoustic performance characteristics. The thermal conductivity (λ) is evaluated using a Hot Plate apparatus, setting up an appropriate methodology, due to the nature of the sample, whereas, the transmission loss (TL) is measured at normal incidence in a traditional impedance tube. The results obtainedindicated that performance is dependent on the granules size, that the small granules (granules size in the 0.01-1.2 mm range), have the highest density and the best performance both in terms of thermal and acoustic properties. While λ varies in 19-22

mW/mKrange at 10°C, whereas a TL equal to 13 dB at about 6400 Hz for 20 mm thickness is obtained for small granules. Also, Basalt natural fibre insulating panels were investigated for their thermal and acoustic properties due to its growing interest focused on using insulating recycled and sustainable materials.The acoustic absorption coefficient was measured by means of an impedance tube and thermal conductivity was evaluated by means of a heat flow meter apparatus: which is included in 0.030-0.034 W/mK range.The obtained results were compared to traditional solutions with similar chemical composition such as rock wool and glass wool panels, but worse mechanical resistance [6]. While, [7] examined the sound absorption coefficient of recycled polyester nonwovens for the purpose of substituting the conventionally used materials such as glass wool and rockwool.The sound absorption coefficient of the recycled polyester nonwovens wasdetermined by a two-microphone impedance measurement tube; by evaluating the absorption energy rate of the material against the incidence energy.

According to [8] the review on the progress in sound transmission properties of bio-based materials providescomprehensive account of various multi-porous bio-based materials and multi-layered structuresused in sound absorption and insulation products.This is because many bio-based materials, which have lower environmental impact than traditional syntheticmaterials, showed good sound absorbing and sound insulating performance. Whereas, [9]investigated new measurement technique of the sound absorptionproperties of materials, based on the measurements of active intensity and sound energy density. This allowed for the measurement of the absorption coefficient with a wide band excitation, to use frequencybands of any width and to make measurements both inside a tube or in situ.Transfer Function Method (as defined in the ASTM E-1050 standard) is compared with intensity techniqueby means of a complete theoretical study and of a large experimental validation.The results obtained suggested that the new method is at least as accurate and reliable as the ASTM E-1050 standard.

[10] developed a methodology to establish and define a clear relationship between the two absorption coefficients of Reverberant room method and Impedance tube transfer function method by means of measuring samples of the same type of material.28 polyester samples were tested using the two aforementioned methods and a set of variables were considered for each sample such as thickness, density, and flow resistivity.Thus, results obtained presented a multivariate linear regression study of the absorption coefficients that provides a new model to convert the normal incidence sound absorption coefficient measured in an impedance tube into a random incidence sound absorption coefficient.

Furthermore, the reflection coefficient of acoustic absorbing materials is often measured in a standing wave tube.A novel technique, that is capable of determining the reflection coefficientin a fast way in-situ, real time, oblique and without the use of a standing wave tube was presented. Using a methodthat is based on the simultaneous measurement of normal acoustical particle velocity and sound pressure at the same position. Micro flown (Titan sensor-element) and a sound pressure microphone were used for thedetermination of the values for the reflection coefficient [11].Similarly, [12] investigated the measurement of Acoustic surface impedance in free field of a sound absorbing material.Using a method which is based on the combined measurement of the instantaneous sound pressure and soundparticle velocity, in which a simultaneous measurement of the particle velocity and the pressure above the absorbing material is performed. Thus, this allows the field impedance close to the surface to be measured directly.The present study is to investigate the Influence of white noise in the measurement of acoustic impedance of some industrial insulating materials using white noise generator instead of one-third of octave or sine wave.

II. Materials and Methods

PN70, Ekla,Pladur,Black rubber/M.A.D.2,National Instrument (NI) LabVIEW and National Instrument equipment such as NI 9263, NI 9234, NI CDAQ 9174 for data acquisition and processing, one microphone, loudspeaker, Impedance tubes, Power Amplifier, computer, meter rule, developed NI LabVIEW application for white noise generation. NI LabVIEW is "a highly productive development environment for engineers and scientists need for creating custom applications that contains all the necessary tools to design and implement measurement and control systems " [13].

This information about the material’s acoustic properties can be used for calibrating and validating computational methods used to forecast the acoustic performance of multi-layer systems [4]. Standardized procedures are used for the measurementof the normal incident absorption coefficients of acoustical material. These standardized methods for evaluating the normal incident absorptioncoefficients includes the Kundt's tube, also known as standing waveor impedance tube: standing wave ratio [14], and the transfer-function methods[15].

Using the transfer function method, the microphone does not interfere with the sound field inside the tubedue to its side wall mounting. However,problems can arise as a result of the limited number of microphoneslocations and the inadequacy of spacing distance between the microphones(according to [14] the distance between microphones should be more than five times the diameter of the microphone). The optimal spacing distance between the microphones, that produces good quality measurements, is also dependent on thefrequency (that is it decrease with an increase in frequency). Microphone phasemismatch and errors concerning the knowledge of the exact microphone and sample locationare other possible problems[16]. That said, the single moveable microphone method has a distinct advantage in that it avoids the somewhat complicated calibration procedure that is necessary for transfer function measurements, when compared with 2 - 3 microphones method and reverberation chamber although provides a quick broadband alternative. Impedance tubes are designed for measurement of the normal incidence absorption coefficient and normal specific impedance of a wide range of acoustic materials [4].

2.1 Samples description

Materials used in this research were sourced by Pronorma, a Portuguese company working in the field of Acoustic sampling of structures “Table 1”.

Table 1. Showing the material samples and their applications.

PN70 	**Materials:** Rock wool and Resin **Applications:** Thermal and acoustic insulation solution.
Ekla 	**Materials:** Composite material: Volcanic Rock wool and Mineral coating. **Applications:** Best suitable for those with high demands of local sound absorption, such as: • Open office • Call centre • Collective entertainment • Venues for education
Pladur 	**Materials:** Composite materials (Laminate plaster) **Applications:** A system for use in laminate plasterboard
Black rubber/M.A.D. 2 	**Materials:** Bituminous membrane **Process:** Obtained from modified bituminous to achieve better acoustic performance **Applications:** Used to improve the sound insulation of partitions at low frequencies dry, placed between the plate’s plaster-cardboard (both walls and ceiling).

The pictureof the schematic experimental setup is shown in “Fig. 1”. Measurements with impedance tube using the standing wave ratio method [15] was used having one microphone that is moveable to probe at different position points, and the samples are circular in shape placed at one end of the tube.Using the standing wave method, a white noise sound source is placed one endof the tube, and terminate at the other end containing the test sample. Once thesound is initiated a standing wave pattern develops in the tube, and the microphonemoves through the length of the tube starting at the loudspeaker end andmoving a 1 cm distance for each measurement and terminating at the sample end.

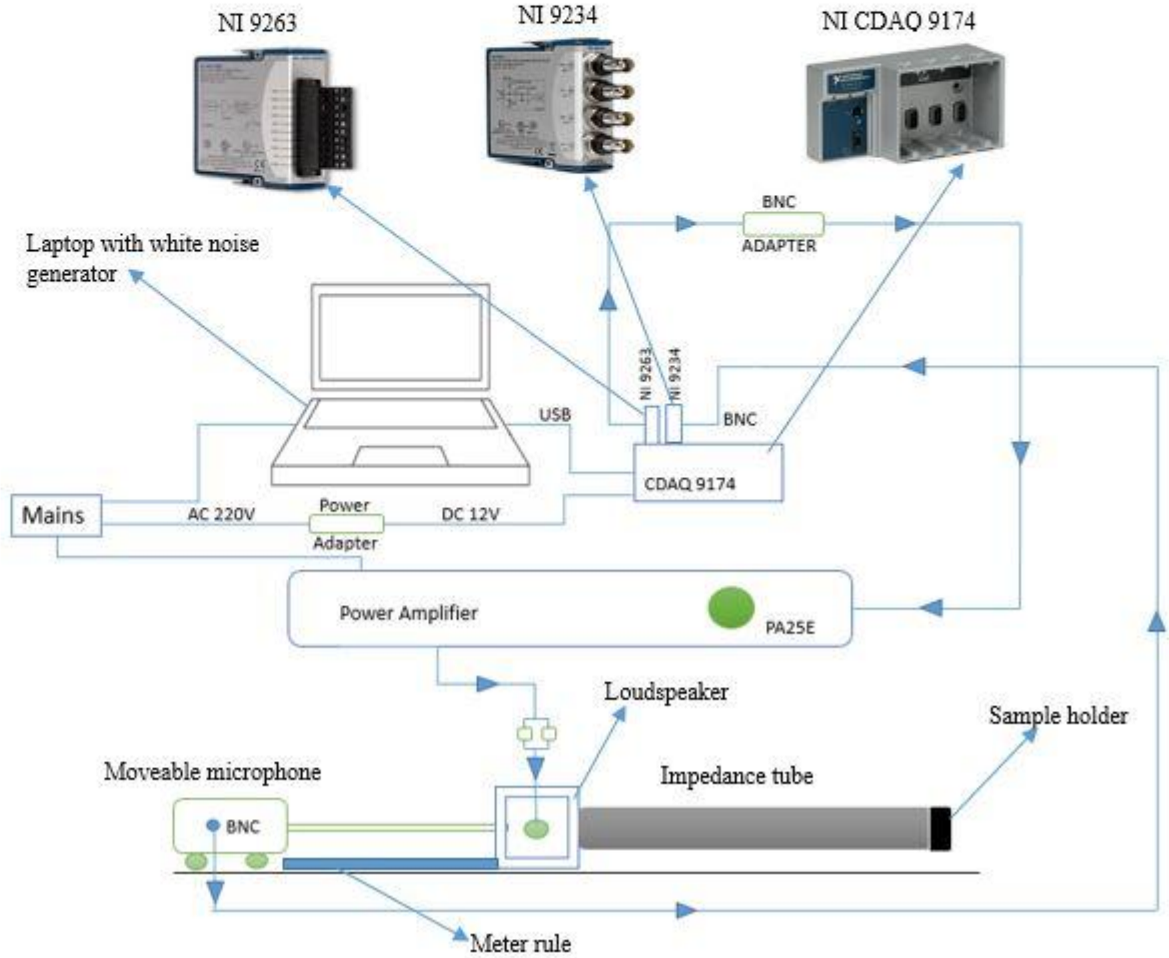

Figure 1. Schematic block representation of the Experimental Setup

The developed white noise generator records the location and level of the first extrema alongwith the following minima and maxima. From this information the sound absorptioncoefficient and specific acoustic impedance of samples can be calculated.This is done with multiple frequency of 5 Hz resolution from 0 Hz to 6500 Hz at1 cm distance at a time, with a complete scan through the entire tube distance.Frequency resolution of 5 Hz is used together with each 1 cm measurement ofthe sample testing, and a maximum frequency of 6500 Hz is specified. The 5 Hzresolution enables a measurement to be made for a multiple of 5 Hz to 6500 Hzfor each cm distance moved by the microphone.This implies that measurement can be performed for any resolution selected forthetesting sample, that is if 2 Hz resolution is selected for the program,then measurement can be taken for every 2 Hz and its increment up to themaximum frequency that is allowed.The reason for selectingthe specified cm and 5 Hz wasto reduce any form of aliasing that might influence the results.

Aliasing appears when a signal is measured at an insufficient sampling rate to encapsulate the changes of that signal. This means that there is the presence of some unwanted components in the reconstructed signal that were not present in the original signal that was sampled. Aliasing arises because signal frequencies overlap some times when the sampling frequency is too low or smaller than the signal being measured [17].

2.2 Using White Noise in the measurement of the Acoustic Impedance in a Standing Wave Tube

White noise is statistically a random signal with its power spread evenly across the signal frequency domain. This implies that, it has a flat power spectral density in which signal at any frequency has the same power within a fixed bandwidth which is the difference between frequencies of lower and upper limits in a continuous set of frequencies measured in Hertz [4].

Advanced National Instrument LabVIEW was used to developed the white noise generator in generating the sound, acquiring the data and processing the data to calculate the acoustic absorption coefficient and acoustic impedance of samples tested.Frequency spectrum presents the description of the signals in a simpler way byclearly showing these signals as harmonics. The frequency spectrum of the amplitudeversus time which is also the time-domain signal can be represented as a signal in the frequency domain through the use of

the Fast Fourier Transform (FFT). The FFT "breaks down" a cycle of random waveforms or signals into sinewave components of amplitude and frequency.
To measure the Acoustic Impedance in an Impedance tube, one starts by defining the Standing Wave Pressure Ratio SWR as:

$$SWR = \frac{P_{max}}{P_{min}} = \frac{A+B}{A-B} \qquad (1)$$

where P_{max} is the pressure maximum of the standing wave in the tube, P_{min} is the pressure minimum and:

$$R = \frac{B}{A} = \frac{SWR+1}{SWR-1} \qquad (2)$$

is the ratio coefficient between the reflected and incident wave amplitude.

In this paper, a new approach to model a standing wave in a tube was used. "Fig. 2"below shows a real example of experimental data recorded along the length of an impedance tube for an harmonic signal.

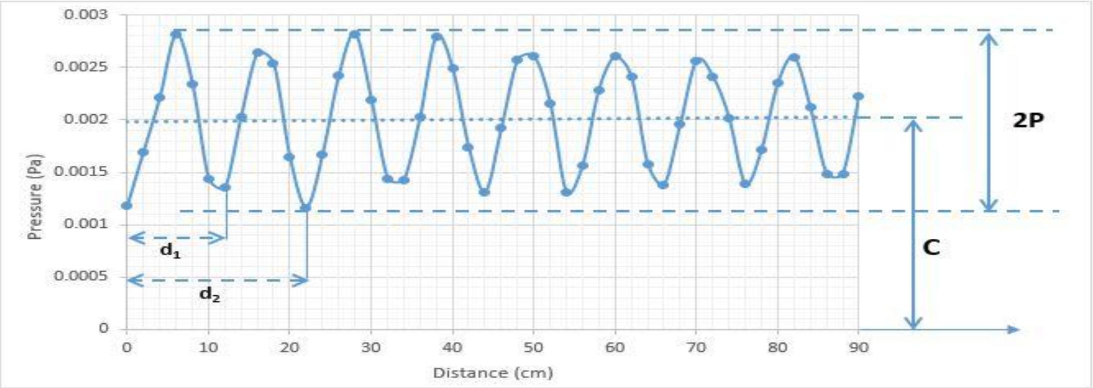

Figure 2. Plot showing the Amplitude vs distance for a standing wave with a frequency of 1700 Hz [4].

The harmonic waveform that correspond mathematically with the sine function in the time domain is:

$$P(t) = P \cdot \sin(\omega t + \alpha) + C \qquad (3) \qquad [4]$$

where ω is the angular frequency of the wave, C is the offset mean pressure and α is the phase angle, where the latter two quantities cab be obtained from:

$$C = \frac{P_{max} + P_{min}}{2} \qquad (4) \qquad [4]$$

$$\alpha = 1 - \left(\frac{SWR-1}{SWR+1}\right)^2 = 1 - R^2 \qquad (5) \qquad [4]$$

Since each spectral component of the white noise is similar in pattern to that of the harmonic waveform (after application of the FFT), and following the earlier line of thought that harmonic spectral components can be represented as a sinusoidal function of the distance d instead of time t, the waveform shown in "Fig.2" is suggested to be written as:

$$P(d) = P \cdot sin(\widehat{\omega} d + \widehat{\alpha}) \qquad (6) \qquad [4]$$

Making the analogy between equations (3) and (6), we have:

$t(s) \rightarrow d(m)$
$\omega(rad \cdot s^{-1}) \rightarrow \widehat{\omega}(rad \cdot m^{-1})$
$\alpha(rad) \rightarrow \widehat{\alpha}(rad)$

The values for $P, C, \widehat{\omega}$ and $\widehat{\alpha}$ are extracted with the help of the software developed in LabVIEW, where:

$$P = \frac{P_{max} - P_{min}}{2} \qquad (7) \qquad [4]$$

$$P_{max} = C + P \qquad (8) \qquad [4]$$

$$P_{min} = C - P \qquad (9) \qquad [4]$$

Taking into account the phase angle, the distance $d_1$of the first minimum from the sample being measured was determined from:

$$d_1 = -\frac{\hat{\alpha}}{\hat{\omega}} + \frac{3\pi}{2\hat{\omega}} \qquad (10) \qquad [4]$$

If $d_1 < 0$, then the value from equation (10) must be amended to:

$$d_1' = d_1 + \frac{2\pi}{\hat{\omega}} \qquad (11) \qquad [4]$$

since it does not make sense to have a negative distance. The distance d_2 from the sample to the second minimum can be determined from the wavelength $\lambda = 2(d_2 - d_1)$; hence:

$$d_2 = \begin{cases} d_1 + \dfrac{2\pi}{\hat{\omega}}, & d_1 > 0 \\ d_1' + \dfrac{2\pi}{\hat{\omega}}, & d_1 < 0 \end{cases} \qquad (12) \qquad [4]$$

Therefore, with the above equation producing d_1 and d_2, the real and imaginary components of the acoustic impedance $Z_n$can be calculated from:

$$\mathrm{Re}\left(\frac{Z}{\rho c}\right) = \frac{1 - R^2}{1 + R^2 - 2R\cos(\Delta)} \qquad (13) \qquad [4]$$

$$\mathrm{Im}\left(\frac{Z}{\rho c}\right) = \frac{2R\sin(\Delta)}{1 + R^2 - 2R\cos(\Delta)} \qquad (14) \qquad [4]$$

where ρ is the density of air, c is the speed of sound in the tube and Δ is the phase angle between the incident and reflected sound pressure:

$$\Delta = \left(\frac{4d_1}{\lambda} - 1\right)\pi = \left(\frac{2d_1}{d_2 - d_1} - 1\right)\pi \qquad (15) \qquad [4]$$

With the Real and Imaginary components of the Acoustic Impedance (equations 13 and 14), the Acoustic Impedance in rayls can finally be determined from:

$$Z = \rho c \sqrt{\mathrm{Re}^2\left(\frac{Z}{\rho c}\right) + \mathrm{Im}^2\left(\frac{Z}{\rho c}\right)} \qquad (16) \qquad [4]$$

The measurement was made with the impedance tube's moveable microphone which moves continuously from 90 cm to 0 cm distance from the sample, when using the white noise generator.The white noise generator developed in LabVIEW utilizes theequations presented above to post-process the data and determine the acoustic impedance of the sample materials as a function of frequency in an automatic fashion and with a much higher frequency resolution, as shown in the Results and Analysis section.

III. Results and Analysis

Impedance tube with the setup which contains a single moveable microphone was used for the acoustic measurements. This converts sound pressure into electrical signals which was captured and displayed on the developed application and was analysed to examine the effect and relationship of the materials tested and their acoustic impedance.

The white noise generator performs only one set of measurement to acquire the pressure minima and pressuremaxima for the selected frequencies from 0 Hz to 6500 Hzwith 5 Hz resolution and distances from 0 to

90 cm.Impedance is concerned with the ease with which a sound wave could be transferred between two media. The acoustic impedance at a specific frequency suggest how much of sound pressure that is generated by air vibration of the molecules of that specific acoustic medium at that frequency. This implies that, the acoustic impedance of a material determines the amount of sound that will be reflected and transmitted when the wave approaches a boundary with another material. Thus, the higher the acoustic impedance the lower the absorption coefficient of that sample.That is, a material with a high acoustic impedance will allow the passage of sound energy through the medium while a low acoustic impedance will impede the movement of sound energy.

3.1 PN70

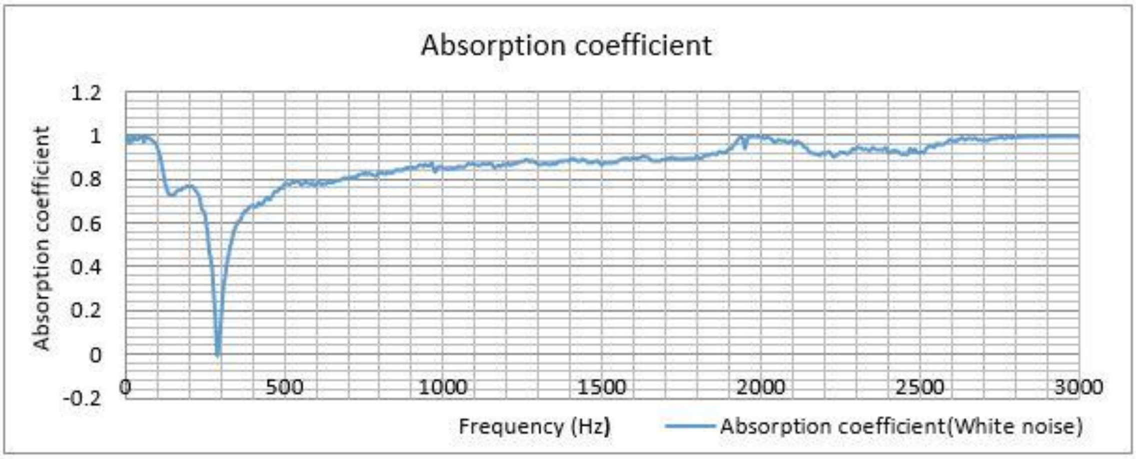

Figure 3. Absorption coefficient of PN70 sample using white noise with 5 Hz resolution

Absorption coefficient for PN70 sampleis shown in “Fig. 3” with absorption coefficient decreasing from 1 to 0 at frequencies 0 – 299 Hz, it later increased gradually from 300 Hz to 500 Hz to reach an absorption coefficient value of 0.76 then, further increased from 0.8 – 1 from 500 Hz to 2750 Hz.This sample shows good characteristics for sound absorption in that the sound wave is observed to be absorbed by the sample gradually and steadily up to the absorption coefficientvalue of 1.It can be said that density and thickness of the material is a major factor which influences the absorption performance.

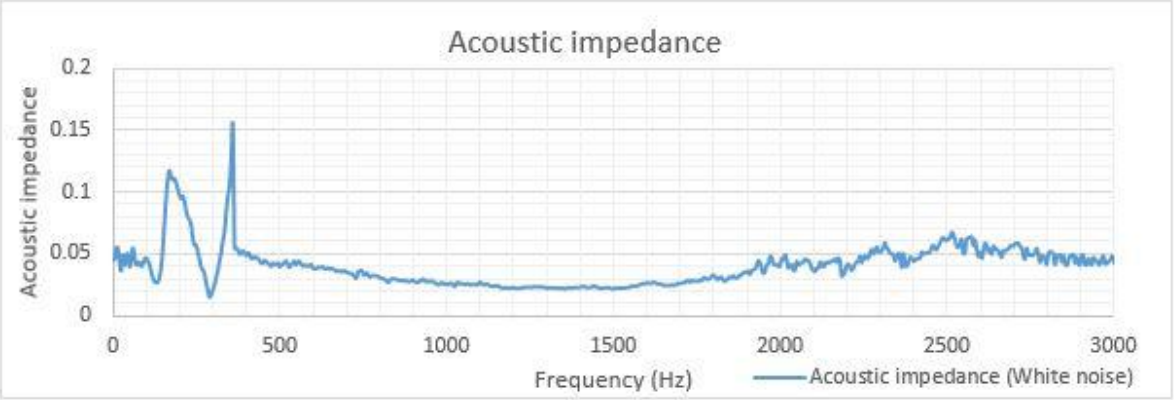

Figure 4. Acoustic Impedance of PN70 sample using white noise with 5 Hz resolution

The acoustic impedance of the PN70 sample shown in “Fig. 4” reveals a result that is the opposite of the absorption coefficient indicating thatthe sample have a low impedance to sound. Thus, allowing most of the sound energy to be transmitted through the sample.

3.2 Ekla

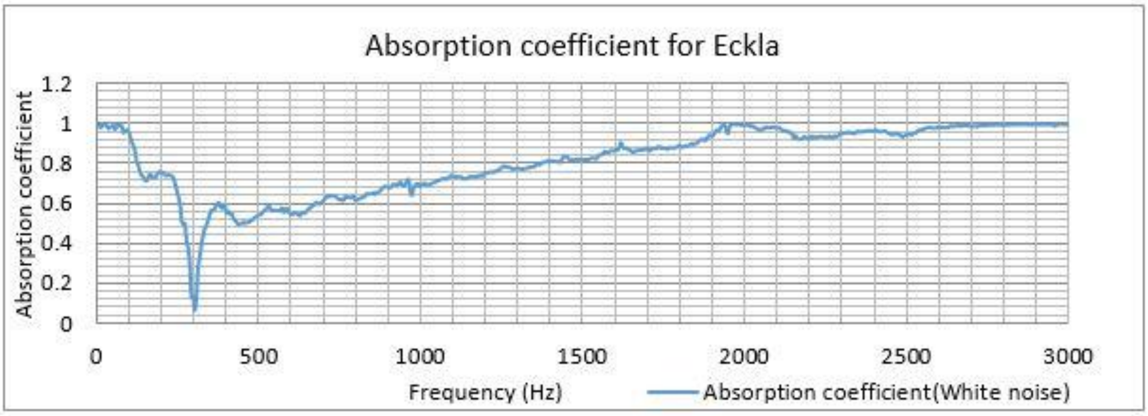

Figure 5. Absorption coefficient of Ekla sample using white noise with 5 Hz resolution

Absorption coefficient for Ekla sample is shown in "Fig. 5" with absorption coefficient decreasing from 1 to 0.4 at frequencies 0 – 300 Hz, it later increased gradually from 300 Hz to 500 Hz to reach an absorption coefficient value of 0.6 with fluctuations, it further increased from 0.6 – 1 from 650 Hz to 1950 Hz still with fluctuations. This sample shows good characteristics for sound absorption in that the sound wave is observed to absorbed by the sample, but with fluctuations up to the absorption coefficientvalue of 1. It can be said that density and thickness of the material also plays a major role in the influence of the absorption performance.

The acoustic impedance of the Ekla sample shown in "Fig. 6" belowalso shows a result that is the opposite of the absorption coefficient indicating that the sample have a low impedance to sound. Thus, allowing most of the sound energy to be transmitted through the sample, and the fluctuation was also visible.

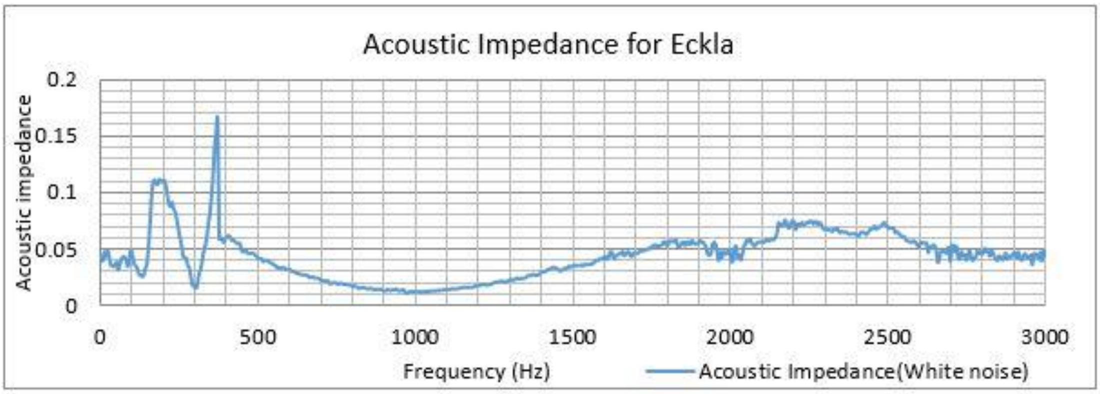

Figure 6. Acoustic Impedance of Ekla sample using white noise with 5 Hz resolution

3.3 Pladur

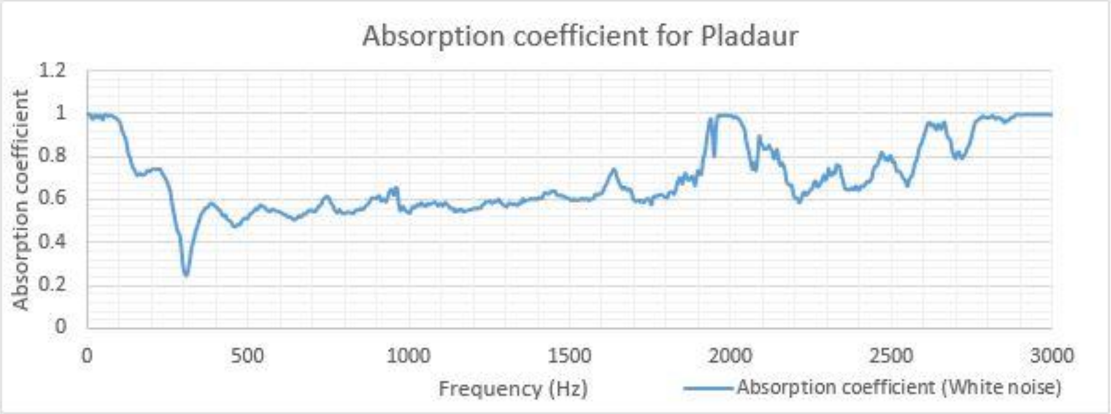

Figure 7 Absorption coefficient of Pladur sample using white noise with 5 Hz resolution

Absorption coefficient for Pladur sample shown in “Fig. 7” with absorption coefficient decreasing from 1 - 0.24 at frequencies 0 -300 Hz, but not as sharp as observed with the previous samples. It later increased from 300 Hz to 400 Hz to reach an absorption coefficient value of 0.6 with much fluctuationsvisible as waves, it further increased from 0.6at650 Hz to 1 at 2000 Hz still with large fluctuations. It then decreases inabsorption coefficient again from 1 - 0.64 at frequency of 2200 Hz before climbing again. This sample obviouslydoes not present agood characteristic for sound absorption in that the sound wave is observed to have too much fluctuations by the sample. The samplehave less thickness, but it is denser when compared with the other samples.

The acoustic impedance of the Pladur sample shown in “Fig. 8” belowalso showssimilar result that is the opposite of the absorption coefficient as other samples indicating that the sample have a low impedance to sound. It was alsoobserved that the large fluctuations did not alter in the chart pattern.Thus, allowing most of the sound energy to be transmitted through the sample. This is an indication that using the pladur sample as a backing for another sample would improve the absorption coefficient of the new sample that would be produced from the combination as investigated by [4].

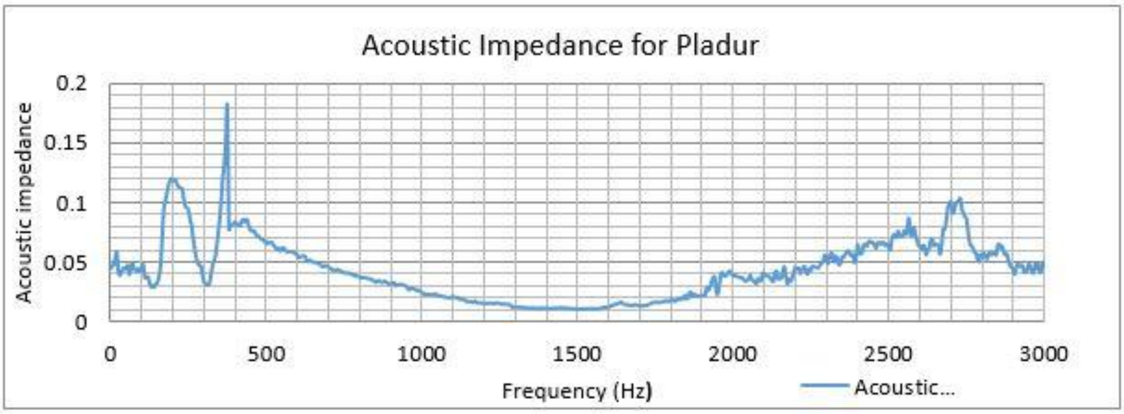

Figure 8. Acoustic Impedance of Pladur sample using white noise with 5 Hz resolution

3.4 Black rubber/M.A.D.2

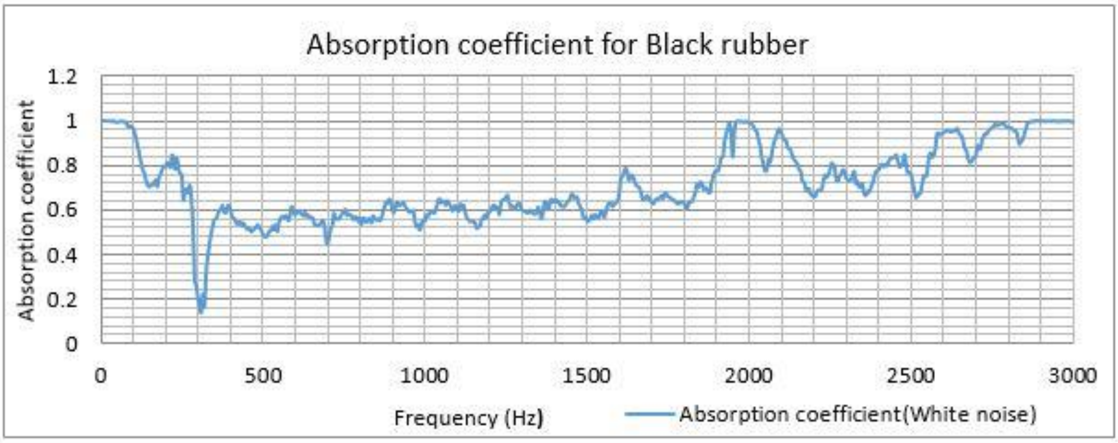

Figure 9. Absorption coefficient of M.A.D.2 sample using white noise with 5 Hz resolution

Absorption coefficient for M.A.D.2 sample shown in “Fig. 9” with absorption coefficient decreasing from 1 - 0.24 at frequencies 0 -300 Hz,with more fluctuations when compared with the previous samples at this stage. It later increased from 300 Hz to 380 Hz to reach an absorption coefficient value of 0.6 then continued with series of fluctuations toreach anabsorption coefficient of 1 at a frequency of 1750 Hz. It then decreases inabsorption coefficient again from 1 - 0.64 at frequency of 2200 Hz before climbing again with large fluctuations. This sample also does not present a good characteristic for sound absorption in that the sound wave is observed to havetoo much fluctuations by the sample. The sample is flat with thin layer of thicknesswhen compared with other samples and it is also dense like the pladur sample.

The acoustic impedance of the M.A.D.2sample shown in “Fig. 10” belowalso shows result that is the opposite of the absorption coefficient as other samples but indicating that the sample have a high impedance to sound. It was alsoobserved that the large fluctuations did alter the chart pattern. Thus, M.A.D.2sample would reflect most of the sound energy approaching the sample.

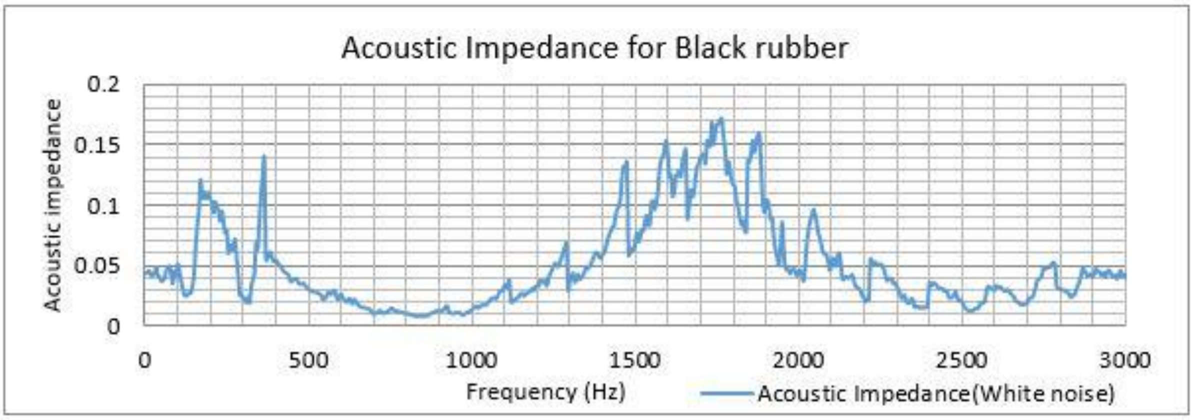

Figure 10. Acoustic Impedance of M.A.D. 2 sample using white noise with 5 Hz resolution

The white noise generator and the impedance tube reveals that the frequency range of 0 Hz to 89 Hz is measurable when compared with measurement using one-third of octave [4], and the absorption coefficient was observed to decreases from 1 - 0, at frequency from 0 Hz - 299 Hz for "Fig. 3", from 1 –0.06, at frequency from 0 Hz - 300 Hz for "Fig. 5", from 1 - 0.24, at frequency from 0 Hz - 300 Hz for "Fig. 7", from 1 - 0.14, at frequency from 0 Hz - 301 Hz for "Fig. 9". It then gradually increases back up to 1 for the absorption coefficient thus having similar characteristics with the investigation executed by [4]. While for the acoustic impedance, the measurement obtained for “Fig. 4”, “Fig. 6” and “Fig. 8” are similar which may be as a result of the thickness of the samples whereas “Fig. 10” produced a different result which couldhave resulted from the thin layer of thickness of the M.A.D.2 sample.Backing of the samples of PN70 and Ekla would produce a steady and better absorption performance.The measurements from 3000 Hz – 6500 Hz and were not included because the results were not resourceful. It produces a constant line with vibration which might be an indication of noise measurement.

IV. Conclusion

The results obtained from the measurement of the sample reveals that PN70 and Ekla respectively in their order produced better measurements for the absorption coefficient and Acoustic Impedance. For this two samples that produced better measurement havesomething in common, they both have thickness above 20 mm.Also, by their composition they are porous, density also was a major factor. While, Pladur and M.A.D.2 samples both have thickness less than 20 mm and they are denser with less porosity.

The present study that yielded these sets of results have a probe distance of about 90 cm of which the microphone can move to measure from one end to the other end of the tube, the absorption of sound which modern designed impedance tube do not have.Recent measurements carried out with the impedance tube does not use moveable single microphone, but rather a fixed single microphone or two to three microphones placed at strategic positions on the impedance tube.The present measurement has the advantage of moving with the microphone through the impedance tube to measure the sound pressure intensity at different distances.

Using one-third of octave or sine wave for measurement, only one sampling rate is being used for a single frequency that is selected, but using this white noise generator the same one sampling rate is not used for one frequency but rather a range of frequencies from 0 Hz to 6500 Hz with 5 Hz resolution.

It can be concluded that this method of measurement of the sound absorptioncoefficient and acoustic impedance using white noise produceseasier measurement andallows efficient performancedemonstration of the samples tested.

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