XXVII Congresso Nacional de Estudantes de Engenharia Mecânica
08 a 12 de fevereiro de 2021, Curitiba, PR, Brasil

USE OF SMARTPHONES AS SIGNAL GENERATOR AND DATA ACQUISITION SYSTEM IN A LOW-COST IMPEDANCE TUBE: A PRELIMINARY FEASIBILITY STUDY

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Abstract. *The cost of a typical commercial impedance tube is around a few thousand dollars. Given this scenario, this contribution deals with a proposal of a low-cost solution in order to overcome this roadblock, especially in low budget educational institutions. Thus, the main intention of this work is to investigate the feasibility of using smartphones with specific apps playing the role of signal generator and data acquisition system (DAQ), respectively, to be applied to a low-cost impedance tube. Therefore, a low-cost impedance tube system was designed and built from scrap steel tubes and profiles in addition to ordinary components and accessories. It follows that the measuring of sound absorption coefficients is performed based on Transfer Function Method using two microphones according to ISO 10534-2. From the measured signals, all post-processing were carried out in a free scientific language so-called Scilab. Finally, considering the whole context, the results revealed that the measured coefficients were reasonably promising when compared to the values reported by the manufacturer of the commercial sound absorption material used in this work.*

Keywords: *low-cost impedance tube, sound absorption coefficient, Acoustics, transfer function method, Scilab*

Resumo. *O custo de um tubo de impedância comercial típico é em torno de mil dólares. Neste cenário, esta contribuição propõe uma solução de baixo custo para contornar este problema, sobretudo em instituições educacionais de baixo orçamento. Assim, o principal objetivo deste trabalho é investigar a viabilidade do uso de smartphones com aplicativos dedicados que cumpram a função de gerador de sinais e sistema de aquisição de dados, respectivamente, para serem empregados em um tubo de impedância de baixo custo. Portanto, este sistema foi projetado e construído a partir de sucatas de tubo e perfis com acessórios e componentes comuns. Em seguida a medição do coeficiente de absorção é feita pelo método da função de transferência sonora usando dois microfones de acordo com a norma ISO 10534-2. A partir dos sinais medidos, todo o pós-processamento foi realizado usando um software livre de programação científica chamado Scilab. Finalmente, considerando todo o contexto, os resultados revelaram que os coeficientes medidos foram razoavelmente promissores quando comparados com os valores reportados pelo fabricante do material acústico comercial utilizado neste trabalho.*

Palavras-Chaves: *tubo de impedância de baixo custo, coeficiente de absorção sonora, Acústica, método da função de transferência, Scilab*

1. INTRODUCTION

In the recent years several acoustic absorbers materials has been developed to improve the enviromental acoustic comfort, especially in the industry and civil construction. Aiming in the consequences of noisy enviroment (Stansfeld *et al.*, 2000) found the impact of this scenario on cognitive health in children. In order to contribute to technological development of this class of material, some specific standards regulates how the material evaluation should be performed. Just this way to classify the acoustic materials performance in terms of sound absorption. However, to accomplish this task sofisticated equipments and large roominess to provide whole infra-structure are required, as so-called reverberant chamber. Experimental campaigns for material evaluation in this kind of room is very expensive with low availability around our country territory. Moreover, there is another option to evaluate acoustic materials by using impedance tubes. In comparison with the cost of using a reverberant chamber, the operation of impedance tube is less expensive, however its acquisition and operation are still expensive for most technological education institutions. Given this scenario, there is an research effort to develop low-cost equipments as an alternative solution to measure sound absorption coefficients of the materials under development. (Deshpande and Rao, 2014), developed an impedance tube capable to measuring absorption coefficient from a budget of $US\$\ 1500,00$ using a DAQ system using a laptop, where the results revealed a good agreement with ones measured by a commercial tube. (Palella and Binkley, 2018), also built a low-cost tube to be used in a school, however the results were discouraging due to difficulties on modeling and convertion of wav files into sound pressure in a open source software. Here in Brazil (Salvo *et al.*, 2015) built a tube made of PVC with wooden connections whose the cost is around 20 times lower than a average commercial system.

The goal of this paper relies on the development of a low-cost impedance tube respecting the ISO 10534-2. To verify its performance, a commercial acoustic insulation will be used as a baseline. The biggest challenge for the authors is to use smartphones as the platform to generate the signals and record them for post-processing in Scilab. It is expected from this to extrapolate the concept of low-cost to the entire system, since the scraped materials will be used in the tube construction.

The paper is organized as follows: after this introductory section, the basics of sound absorption computing is presented. Then, the methodology presents some expressions from the standard in addition to presentation of the concepts on the impedance tube designed with its instrumentation. After, the results are presented and discussed, ending with the conclusions.

2. THEORETICAL BACKGROUND

The design of the impedance tube is according to ISO 10534-2 that in turn is based on Transfer Function Method. The specimen to be tested in locate inside the speciment holder and sealed by a rigid termination. The tube is designed to guarantee plane waves propagating, even when excited by a random noise, specifically white noise. During the measuring process the sound pressure is measured in two different positions. Thus, the sound absorption coefficient is computed using a acoustic complex transfer function from each microphone (Chu, 1986). This function is responsible for interpreting the sound pressure data, resulting in reflection factor, as following expressed

$$r = |r|e^{j\Phi_r} = \left(\frac{H_{12} - H_I}{H_R - H_{12}}\right) e^{2jkx_1} \tag{1}$$

where r is the reflection factor for normal incidence; x_1 is the distance between the specimen and furthest microphone; $j = \sqrt{-1}$; $k = 2\pi f/c$; Φ_r is the phase reflection angle; H_{12} is the transfer function of microphone 1 relative to the microphone 2 being defined by complex ratio p_2/p_1; $H_R = e^{-jks}$ and $H_I = e^{-jks}$ are the transfer function of incident and reflected waves, respectively; α is the sound absorption coefficient and can be calculated as follows

$$\alpha = 1 - |r|^2 \tag{2}$$

The reader can find more details regarding to this formulation in Chu (1986); Suhanek *et al.* (2008); Palella and Binkley (2018); Raj *et al.* (2020).

3. MATERIALS AND METHODS

The purpose of this section is to present the main steps within the impedance tube design from the geometrical perspective besides the aspects related to the instrumentation and work principle of the whole system.

3.1 Design of impedance tube

According to ISO 10534-2, the initial parameters to design an impedance tube are: tube inner diameter, tube length, microphones positions, specimen inner face position and frequency operation range. As the inner diameter defines the rest of geometrical dimensions, it is the first parameter to be chosen. How for this article it was selected a galvanized steel tube 1 1/4" Schedule 10, the inner diameter is $d = 36.8\ mm$. Therefore, from this value in addition to speed of sound c_0 the upper frequency f_u can be computed by the following expression

$$d < 0.58c_0/f_u \tag{3}$$

Consequently, $f_u = 5348\ Hz$. On the other hand, the lower frequency f_l depends on the distance between the microphones s as expressed below

$$f_l s < 0.45c_0 \tag{4}$$

However, the maximum distance between the microphones must be calculated using the following relationship

$$s_{max} < 0.05c_0/f_l \tag{5}$$

Hence, from "Eq.(4)" and "Eq.(5)" the lower frequency is $f_l = 576\ Hz$ and $s_{max} = 120\ mm$ can be computed, respectively. As the intention is provide conditions for plane waves propagating inside the tube, some requirements should be met. Before this, key geometrical parameters are defined and depicted in "Fig. 1".

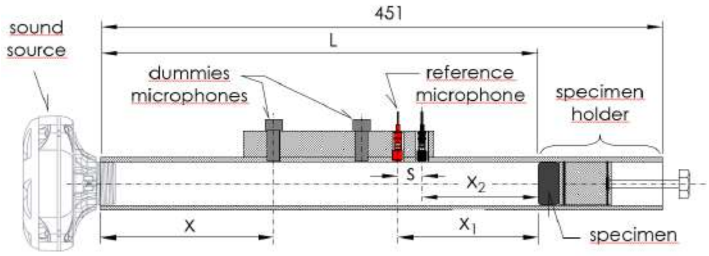

Figure 1. Impedance Tube: parameters assignments. Source: Authors

Despite of using of two microphones positions, the microphone holder will be ready to four diferent positions as will be emphasized later on the text. Anyway, the distance between the sound source and nearest microphone, and the distance between the inner face of the scpecimen should met, respectively, $x > 3d$ and $x_2 > 2d$. Hence, for safety and convenience reasons $x = 133\ mm$ and $x_2 = 93\ mm$ were chosen. Then, the operational tube lenght is give by $L = x + x_2 + s_{max}$, resulting in $L = 346\ mm$.

Aiming to enlarge the frequency range of using of impedance tube, it was decided to provide four diferent positions in the microphones holder, where the holes location choosing is made respecting the procedure previously described. As recommended by ISO 10534-2, structurally the whole system should be rigid enough to avoid dynamic deformations due to its own operation besides vibratory excitation from surrounding enviroment. That is why the authors decided for use a tube made of galvanized steel (specifically $1\ 1/4$" Schedule 10 with $2.7\ mm$ of wall thickness) and carbon steel profiles for the rest, where all these material is a scrap bought in a junkyard.

Now, in terms of instrumentation, the authors, in an attempt to persevere in the low-cost concept, decided to use ordinary components and devices. As the signal generator a smartphone with an specific free app so-called *Signal Generator* connected to a quite handcrafted amplifier send the amplified signal to a compression driver (sound source). For the sound measuring two ordinary lapel microphones were used connected to another smartphone with a free app so-called *iNVH Bosch* in order to work as data acquisiton system (DAQ), where all measurements over the time were recorded in CSV files. Just for information, both apps are avaiable in *Google Play Store*. "Figure 2" shows a simplified schematics with the signal flow throughout the system besides the microphones positions assignments. For this paper, the position 2 and 3 in michophones holder were selected, where the signal for each microphone is captured individually (not simultaneously) for approximately for $30\ s$ at a rate of $44.1\ kHz$. Therefore, the sound absorption coefficients was computed twice: the first time using only the black microphone and the other using the red microphone. The commercial acoustic absorption material to be tested is manufactured by *Trisoft* and its specification is *Tech Felt* with thickness $50\ mm$. From this material (in $1200 \times 600\ mm$ plate) some disk-shaped specimens were cut. For the reader information, the absorption coeeficients reported by the datashet was measured in a reverberant chamber, which according to Drabek (2017) is the most accurate resource for this purpose.

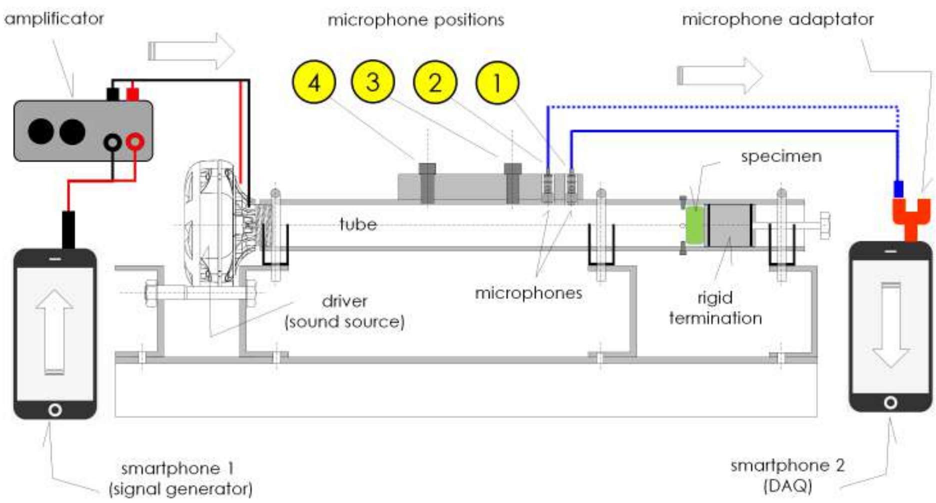

Figure 2. Schematics of Impedance Tube System. Source: Authors

The calibration is an essential to guarantee successfull results. From the raw signal captured by the microphones besides the sound pressure level measured by using the app *iNVH Bosch* not simultaneously, a table is created wilth the RMS gain of the signal in mV and the sound pressure level (SPL) in dB. Then, a curve fitting by using linear regression is made. Just for remembering, the signal flow since the signal generator was already presented in "Fig. 2". "Figure 3(a)" shows the screen of app *Signal Generator* with the white noise mode selected. Now, the screen of app *iNVH Bosch* presenting the option for sound pressure level (SPL) measuring is depicted in "Fig. 3(b)", where the focus relied on instantaneous value L_{inst}. Finally, still in the same app, "Fig. 3(c)" show the screen for raw data from microphones over time.

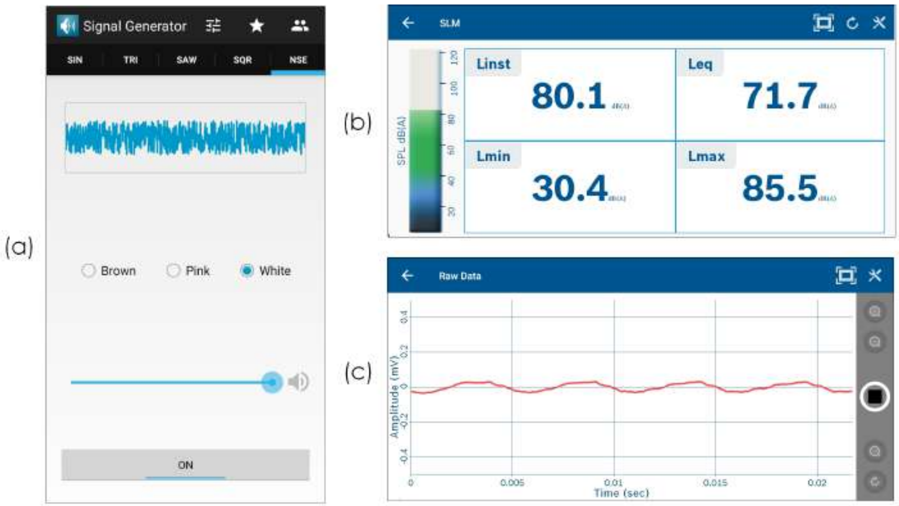

Figure 3. Apps Screens: (a) app *Signal Generator* with white noise mode selected; (b) app *iNVH Bosch* wiht SPL mode selected; (c) app *iNVH Bosch* with raw data over time selected. Source: Authors

All post-processing was carried out in Scilab by using a code with the basics of theory as presented in section 2.as well as in Chu (1986); Suhanek *et al.* (2008); Palella and Binkley (2018). It is noteworthy to inform the reader that, at this early stage of the research, the signals will not be filtered. All the signal convertion chain is shown in "Fig. 6" where this last one is essential for sound absorption coefficient computing purposes.

3.2 Key constructive aspects

"Figure 4" presents the actual photo of experimental apparatus composed by the impedance tube and its instrumentation with items descriptions.

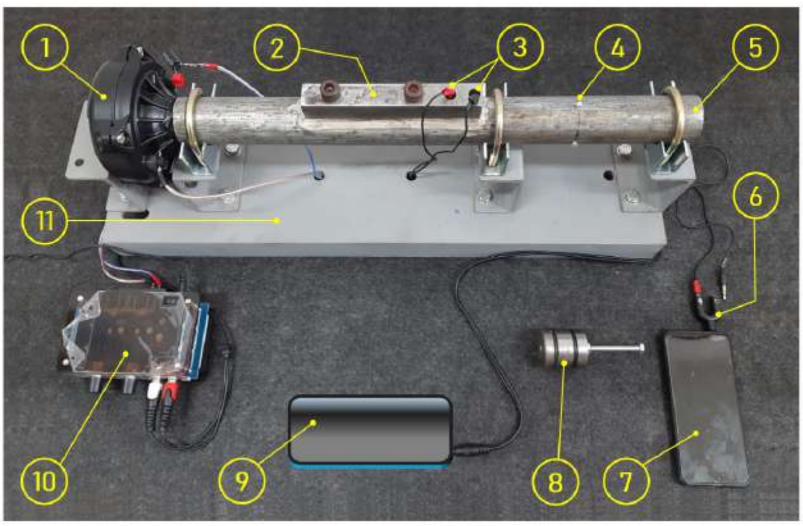

Figure 4. Experimental apparatus: (1) compression driver; (2) mics holder; (3) mics; (4) specimen limiter; (5) tube; (6) mic adaptor; (7) smartphone/DAQ; (8) rigid terminator; (9) smartphone/signal generator; (10) amplifier; (11) base. Source: Authors

One of most essential item in the proposed system is this quite cheap ordinary lapel microphone with *not declared brand* as shown in "Fig. 5", whose the frequency range is not reported by the seller due to a lack of its datasheet; its tip diameter is around $9\ mm$. The compression driver is a *JBL D260 Pro* with $150\ W$ RMS and its response frequency range is between $400\ Hz$ to $9\ kHz$. The mini-amplifier is the model *AP 40* from the manufacturer *MBORG* with total power of $20W$ RMS ($10W$ per channel). the rest of the connection items (e.g. cables, wires and adapters) are also ordinary and very cheap. Finally, in terms of instrumentation and aplication to an low-cost impedance tube, the most remarkable and unusual item is doubtedly the smartphone, especially as it is a relatively inexpensive and highly available device. The overall cost was around $R\$\ 900,00$ (or approximately $US\$\ 180,00$), then breaking down it, 57% is due to structural parts (including cutting, drilling and welding services) and 43% is due to instrumentation (excluding the two smartphones).

Figure 5. Ordinary lapel microphone. Source: Authors

In order to minimize the amount of errors source, the authors opted for emphasize four characteristics, as follows: firstly, as afforementioned, the design was based on the structural robustness both in terms of rigidity and weight ; secondly, the tube was integrated with the specimen holder in a unique piece, avoiding relative vibratory motion; then, the rigid termination in addition to hermetically sealing the tube because of the o-rings and keeping the sample stable and supported, its thick piston-like concept strongly suppresses any chance of deformation or relative motion between parts; finally, a rigid microphones holder welded to tube, for the same reason previously commented, isolates the mics from vibration.

4. RESULTS AND DISCUSSIONS

This section is devoted to present the results from the experimental verification. "Figure 6(a)" shows the calibrated microphone signal for the black microphone at positions 2 and 3 whereas "Fig. 6(b)" depicts this signal converted into sound pressure level (SPL). Lastly, "Figure 6(c)" shows the signal converted from SPL into sound pressure, that will really be used to calculate the sound absorption coefficient. Although computed, the same signal conversion chain is not shown for the red microphone.

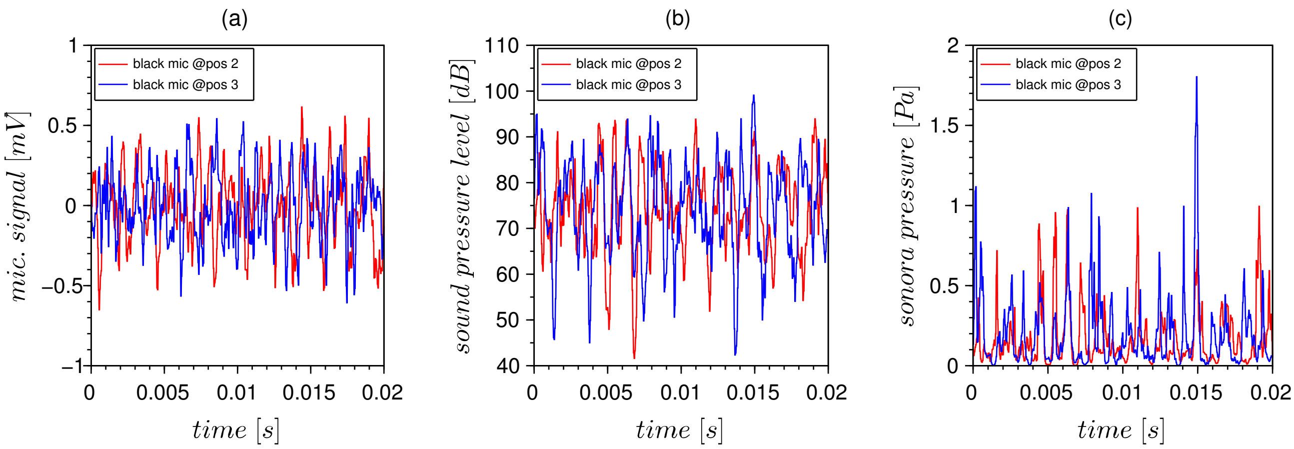

Figure 6. Signal conversion chain (black mics at position 2 and 3): (a) microphones signals; (b) converted signals into sound pressure level; (c) converted signals into sound pressure. Source: Authors

It is important to say that before calculating the absorption coefficient, it were calculated a average H_{21} from 128 signals because these ones contains a lot of noise in the form of outliers that needs to be smoothened out (Raj *et al.*, 2020). It is noteworthy that the signals considered so far have not been filtered yet. Finally, "Fig. 7" presents the comparison between the commercial acoustic material (measured in a reverberatn chamber according to its datasheet) and the measured absorption coefficient from the proposed low-cost system.

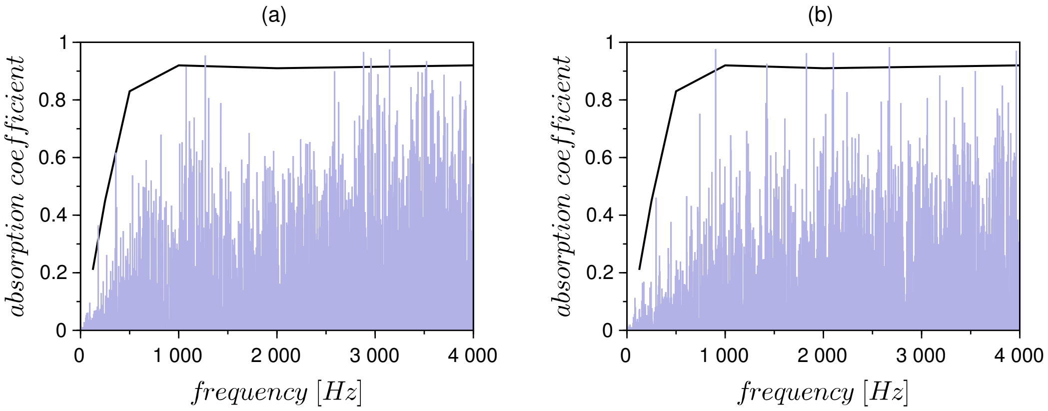

Figure 7. sound absorption coefficient: (a) using black microphone at position 2 and 3; (b) using red microphone at position 2 and 3. [black solid line - from commercial material datasheet]. Source: Authors

Obviously, the initial intention was not compete with a industry-ready impedance tube nor with a reverberation chamber, whose results are the most accurate (Drabek, 2017). Even so, the results was revealed a intersting shape in terms of silhouete. As Raj *et al.* (2020), there are several sources of error involved in the system such as power amplifier clipping, microphone channel overload, the air gap between the specimen holder and tube. In the specific case of this work, the authors had some difficulty in identifying the cut-off limit in the amplitude of the signal coming from the microphone in the acquisition system on the smartphone via the *iNVH Bosch* app. Also, the authors believe that the numbers of signals used to compute the average signal was relatively small that in turn motivates increase this number later on to check the trend. Other point to be considered is regarding to the ordinary lapel microphone because its response in frequency range can be narrow enough to distort the results.

5. CONCLUDING REMARKS

This work was dedicated to propose a low-cost impedance tube system (tube and instrumentation). Scrap material and ordinary items were employed to do it however the remarkable solution is the smartphones using with the apps emulating a signal generator and a DAQ system, respectively. The absorption coefficients for a commercial material was computed and compared with the specifications reported in its datasheet. The authors assumed the results as satisfactory and promissing, even though it was reasonably far from the baseline. Therefore, a new campaign to improve this results will be led. Thus, as a preliminary feasibility study, this contribution accomplished its objective.

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7. AUTHOR'S RESPONSIBILITIES

Authors are solely responsible for the information included in this work.