DEVELOPMENT OF A SMALL-SCALE REVERBERATION CHAMBER AND VALIDATION OF THE DIFFUSE FIELD

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Abstract: Noise absorbers are in a growing demand in the automotive, aerospace and building construction industries. Testing acoustic properties of materials is mandatory for developing an efficient acoustic-controlling product design. Two main methods available to measure acoustic properties of materials are impedance tube method and reverberation room method. Impedance tube method uses small test specimens (usually less than 10 cm in diameter) and measures only normal incidence sound absorption, whereas reverberation room method is a relatively expensive setup which usually requires a large space (100-200 m^3) and allows large samples (10-12 m^2). To overcome the drawbacks of the current test methods and to make a comparative analysis of the test samples, a small-scale reverberation room was designed. A chamber with 2.06 m^3 volume was constructed. All the inner surfaces including the door were lined with highly reflective ceramic tiles to obtain maximum reflectivity. The randomness of the incident angles was achieved by an asymmetric shaped room with an inclined roof to obtain all walls non-parallel. A modal analysis was performed to validate the small-scale reverberation chamber for acoustic measurements. The pressure variations inside the enclosure within resonance frequencies are too small. Even though the cut-off frequency of a purely rectangular chamber with the same volume is 270 Hz, the new design of the reverberation room allows taking measurements below 270 Hz.

Keywords: noise, acoustic, reverberation room, cut-off frequency

I. INTRODUCTION

Unwanted sound waves are called as noise and noise pollution causes adverse health effects like cardiovascular diseases, anti-social behavior, increased aggression, hypertension, tinnitus and vasoconstriction [1], [2].
Furthermore, long term exposure to a noise level higher than 85 dB leads to permanent hearing loss [3], [4]. Therefore, room acoustics deals with reducing noise levels and improving the quality of sound within an enclosed space such as a workstation, lecture hall, office,

theatre, recording studio or a concert hall.

Methods of acoustic control can be broadly classified in to two groups as active control and passive control [3]. While passive mediums dissipate acoustic energy through various damping mechanisms, active mediums need the application of external energy in the noise reducing process by destructive interference. Due to complex and expensive electro-acoustic and electronic design, active acoustic controllers are used for low frequency sound control in very limited applications, for example in headsets for helicopter pilots [5]. In room acoustics passive sound absorbers made from porous materials or resonant structures are applied in room space or on the boundaries to reduce sound pressure level or to adjust reverberation time [3]. To develop an efficient passive sound absorber, the knowledge of sound absorption coefficients of materials is mandatory [6].

The two main concepts practiced in laboratory setups for measuring the sound absorption coefficient of materials are the impedance tube method and the reverberation room method [7]. Impedance tube method uses very small test specimens (usually less than 10 cm in diameter) and measures only normal incidence sound absorption, whereas the reverberation room method is an expensive setup which requires a large space (> 125 m^3) and large samples (> 5.5 m^2). To overcome the drawbacks of the current test methods and to make a comparative analysis of the test samples, a small-scale reverberation room was designed and developed. Even though several researchers have developed small scale reverberation chambers with different dimensions, they haven't analyzed the modal behavior inside the room to validate for spatial distribution of the sound field [8],[9],[10],[11],[12],[13]. Therefore, this work is aimed at validating the proposed design using a computational approach.

II. LITERATURE REVIEW

The reverberation room method is an indirect method of measuring random incidence sound absorption coefficient of samples using reverberation time. European regulation ISO 354 and its American equivalent ASTM C432-09 have described the methodology of reverberation room method in detail [14]. A band of random noise is used as a test signal and when the signal is turned off, the reverberation time is measured for each frequency band, before and after placing the test specimen. From the two reverberation times, sound absorptions of each two cases are calculated using a formula (Eq. 1) called as Sabine's formula which was found by Wallace Clement Sabine in 1898 [15].

$$A = \frac{0.16\,V}{T_{60}} \qquad \text{.... (1)}$$

Where, A is the total absorption of the specimen in Sabins, V is the volume of the reverberation room in m^3 and T_{60} is the reverberation time in seconds. The difference of two absorptions divided by sample area is attributed to the sound absorption coefficient of the test sample α,

$$\alpha = \frac{A_{2} - A_{1}}{S} \qquad \text{.... (2)}$$

Where, A_1 is the absorption of the empty reverberation chamber, A_2 is the absorption of the reverberation room after the specimen has been installed and S is the area of the test specimen in m^2.

Sabine's formula is derived based on the following two assumptions.

1. Incident sound field is diffuse before and during decay.
2. No additional energy enters the room during decay [16].

Therefore, the sound field within the reverberation room should fulfill these assumptions to utilize Sabine's formula. The proper functionality of a reverberation room relies on the proper dimensions and the shape of the room. An acoustic field is considered to be perfectly diffuse when sound energy is uniformly distributed at every point and the angle of incidence is random [17]. In order to use Sabine's formula, the sound field inside the room should be diffuse and Sabine's formulation should be applied when the mean absorption within the room is less than 0.4 [7]. Furthermore, changes in temperature and relative humidity during the measurement period may have a large effect on the reverberation time. The average temperature shall not be less than 10 ℃ and deviations from the average temperature of the room shall not exceed 5 ℃. The average relative humidity in the room shall not be less than 40% and deviations from the average relative humidity shall not exceed 5% in the measured relative humidity [18].

The Reverberation room method is preferable for acoustic measurements as sound absorption coefficients of any type of absorber can be tested in realistic conditions. But, for research purposes, it is not economically viable to build such large rooms and large samples with a sample area of at least 10 m^2. So, several researchers have proven that small scale reverberation chambers are adequate for qualitatively distinguish the acoustical behavior of structural panels with repeatable and reproducible measurements [8],[9],[10],[11],[12],[13].

However, achieving a diffuse sound field within a small-scale reverberation room at low frequencies is complicated. When sound waves are reproduced in an enclosed space the room dimensions encourage certain frequencies for resonance behaviors. These resonances are known as room modes or standing waves which introduce irregularities in the frequency domain response of a room by modifying the pressure values of specific points in the chamber. In small spaces, the number of room modes per unit volume (modal density) for low frequencies is low and it results in individual modes being clearly audible. But in mid and high frequencies the modal density is so high and the adjacent modes sum together to give a broad frequency independent response [19]. Therefore, the volume of the chamber (V) determines the cutoff frequency which room modes start to cluster very closely together that they are no longer seen as resonant peaks; this point is known as the Schroeder frequency (F_c) and calculated using the equation 3 [20].

$$F_c = \frac{C}{\sqrt[3]{V}} \qquad \text{.... (3)}$$

Where C is the speed of sound in air. At higher frequencies, number of room resonance modes increases rapidly and tends to fill both the frequency spectrum and angle of incidence uniformly [21]. But in low frequencies poor diffusion happens due to the low number of possible resonance modes. In order to obtain an adequate diffusion, the least number of permissible room modes in the measurement bandwidth should be 20 according to previous research [22].

The most straightforward way of achieving a diffuse sound field is using large rooms with a volume of at least 100 m^3 whose walls are uniform, smooth, and rigid as possible. But there are some drawbacks when using large rooms like high cost and increase of contribution of air absorption to the total room absorption violating Sabine's necessary assumption of negligible energy loss during a mean free path transit for the validity of the reverberation equation. Therefore, this study is focused on developing a small-scale reverberation room with the use of special techniques such as using non-parallel walls made out from special materials to achieve a diffuse field.

III. MATERIALS AND METHODS

A small-scale reverberation chamber was designed according to the dimensions shown in figure 1. The volume of the reverberation room is 2.06 m^3. The outer walls were made out from 15 mm plywood to comply with weight constraints. Steel box bar frames were used to strengthen the structure. All the inner surfaces including the door were lined with highly reflective ceramic tiles to obtain maximum reflectivity. Ceramic tiles ensure repeated reflections and increase the time of sound decay. The randomness of the incident angles was achieved by an asymmetric-shaped room with an inclined roof to obtain all walls non-parallel.

The positions of the sound source, microphone and test specimen were determined according to the specifications mentioned in standards. A speaker was placed facing into trihedral corners of the room to achieve adequate diffusion. microphone with switchable polar patterns was used to measure reverberation times inside the chamber. Omni directional polar pattern and flat random incidence amplitude response were used over the range of frequencies.

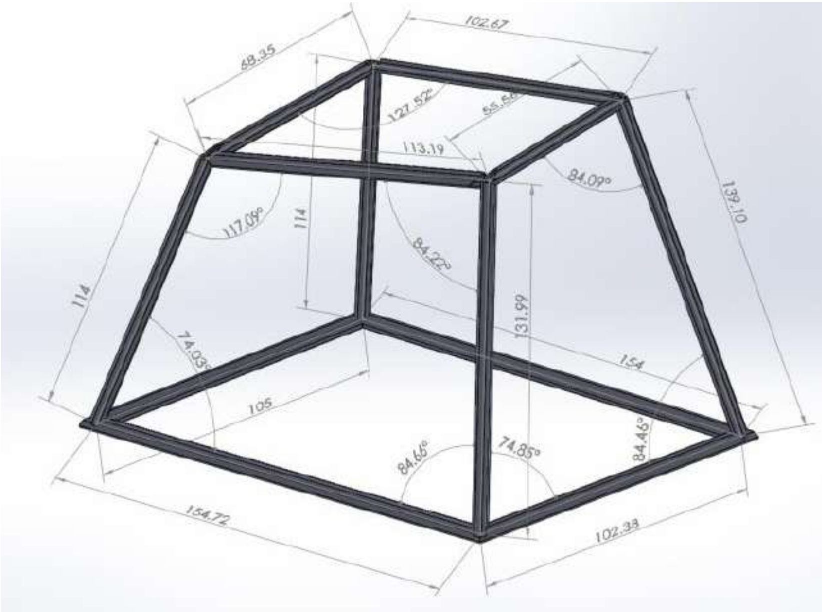

Figure 1. Dimensions of the reverberation chamber

A band of random noise with a continuous spectrum covering the frequency range of the measurements from 100 Hz to 10000 Hz was used as test signal. Test signal generation and reverberation time measurements were made with a one third octave band real-time analyzer, 'Room EQ Wizard software'. AT-2050

The axial, tangential and oblique room modes (eigenmodes) for rectangular rooms can be calculated using equation 4 [23].

$$f = \frac{c}{2}\sqrt{\left(\frac{n_x}{L}\right)^2 + \left(\frac{n_y}{B}\right)^2 + \left(\frac{n_z}{H}\right)^2} \text{ .... (4)}$$

f = Frequency of the mode in Hz
c = Speed of sound (343 m/s at 20 °C)
n_x = Order of the mode of the room length
n_y = Order of the mode of the room width
n_z = Order of the mode of the room height
L, B, H = Length, width, and height of the room in meters [24].

For rooms of more irregular shapes, it is not as easy to compute the resonances as it is for a rectangular chamber of rigid boundaries. However, using computational techniques such as finite element method, the resonance frequencies and eigenfunctions of nonrectangular rooms can be determined numerically.

To validate the required diffuse field inside the empty reverberation chamber, a finite element model shown in figure 2 was developed and simulated using COMSOL Multiphysics software. The finite element mesh consists of 1316 tetrahedral elements. All walls were defined as acoustically hard.

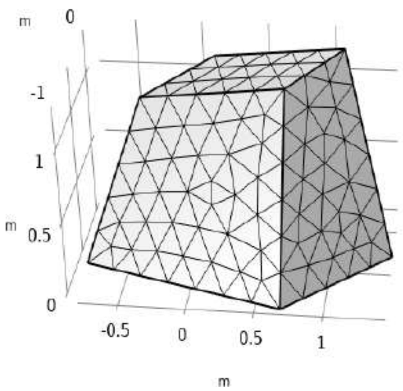

Figure 2. The finite element mesh of the reverberation room

IV. RESULTS AND DISCUSSION

Modelling sound pressure distribution within the reverberation chamber is important to test the accuracy of the experimental results. The highest-pressure variations within an enclosure happen in natural resonance frequencies which are called as eigen frequencies. Therefore, the modal analysis must be performed to validate the small-scale reverberation chamber for acoustic measurements. Three-dimensional model with same dimensions and materials discussed earlier was built. A wide range of equations were used to specify subdomains, boundaries, edges and points including Givoli and Neta's reformulation of the Higdon conditions for plane waves [25]. The theories behind this model are based on basic equations of fluid dynamics.

Figure 3. Developed small scale reverberation room

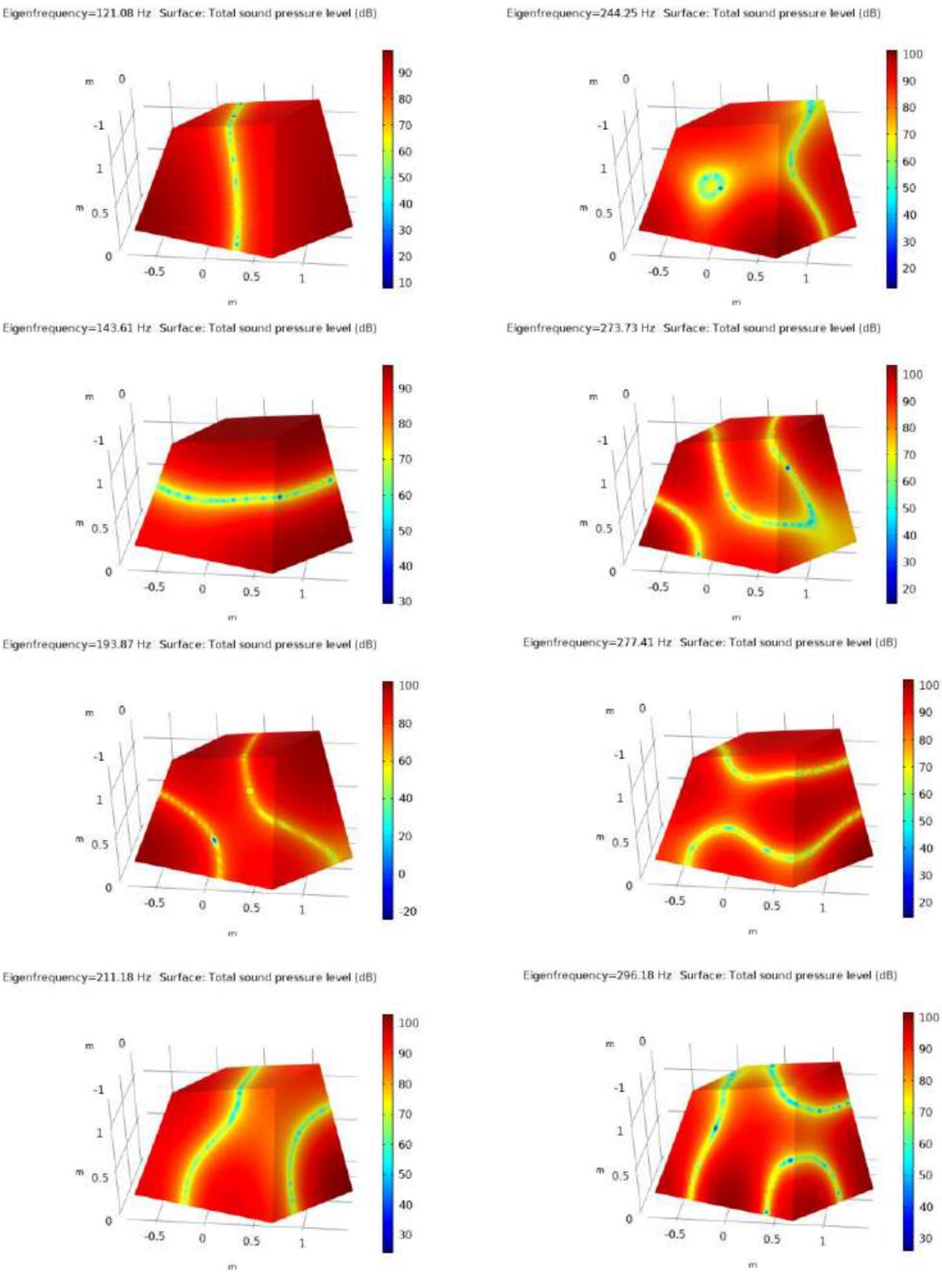

Figure 4. Acoustic eigen modes 1 to 8. A): mode 1, 121.08 Hz, B): mode 2, 143.61 Hz, C): mode 3, 193.87 Hz, D): mode 4, 211.18 Hz, E): mode 5, 244.25 Hz, F): mode 6, 273.73 Hz, G): mode 7, 277.41 Hz, H): mode 8, 296.18 Hz.

Using the eigenfrequency analysis, the pressure variations inside the chamber during first 8 eigenmodes are depicted in figure 4. The lowest eigenfrequency of the room is 143.61 Hz. The pressure variations inside the enclosure during resonance frequencies are too small. Therefore, we can conclude that, even though the theoretical cut-off frequency of the room is approximately 270 Hz, the new design of the reverberation room allows taking measurements below 270 Hz.

The reason is, in rooms of more arbitrary shape, a more randomized distribution will automatically be obtained.

V. CONCLUSIONS

The results of the simulated model indicate the superiority of the small-scale reverberation chamber to the regular large reverberation room, concerning the distribution of resonance frequencies and the spatial distribution of the sound field. By developing a small-scale reverberation chamber using the dimensions and materials mentioned in this paper, scientists, researchers, or sound engineers can accurately measure acoustic properties and calibrate acoustical instruments.

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