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# IMPLEMENTATION OF TWO-CAVITY METHOD FOR MEASURING THE FLOW RESISTIVITY OF ACOUSTIC MATERIAL

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***Abstract*—Acoustic materials are characterized according to their macroscopic and microscopic properties. The sound absorption co-efficient and the air-flow resistivity are of paramount importance among those used to describe the acoustic behaviour of materials. There are several methods developed for measuring the air-flow resistivity of acoustic material. The aim of this paper is to study the existing static flow resistivity measurement methods and then accordingly implement a suitable indirect method based on standard impedance tube. The flow resistivity measurements are carried out for additive manufactured ABS (Acrylonitrile butadiene styrene) sample, foam and glass fibre using the two-cavity method. There are certain similarities observed in their results. Further analysis of the raw impedance data is carried out and conclusions are drawn pertaining to the performance and feasibility of the implemented method.**

***Keywords—flow resistivity; two-cavity method***

## I. INTRODUCTION

Flow resistivity (specific airflow resistance per unit thickness) is one of the most important non-acoustic parameter which is needed to calculate the intrinsic properties, e.g. the complex wave number and the characteristic impedance of a sound absorbing homogenous material. The specific airflow resistance determines the sound-absorptive and sound-transmitting properties of an acoustic material and its measurement is useful for specification purposes [1]. The air-flow resistivity is defined as the ratio of the pressure drop across a specimen to the linear velocity of airflow through a unit thickness of specimen.

Methods for measuring the flow resistivity can be categorized as the direct or steady airflow method [1-2], the alternating airflow method [2-3], the comparative method [4] and the acoustic method [5-8]. The direct airflow method measures the pressure drop across the test specimen and the volume velocity through the test specimen for a steady air flow and then calculates the ratio to obtain the flow resistance. In contrast to the two parameters measured in case of direct airflow methods, the alternating airflow method requires only the measurement of pressure drop across the test specimen for a known volume velocity. The pressure drop in case of ISO 9053 alternating method is measured at a low frequency of 2 Hz. Dragonetti et al. [3] proposed an alternating method based on the ratio of sound pressures measured inside two cavities coupled through a conventional loudspeaker. The imaginary part of the sound pressure ratio is useful in the evaluation of air-flow resistance. This method eliminates the need of special instrumentation and calibration required in case of ASTM C522 and ISO 9053 standards. Also, pressure measurements can be performed at frequencies greater than 2 Hz. Stinson and Daigle [4] developed an electronic system for the measurement of flow resistance. The setup basically involves two resistive elements placed in series, one with calibrated resistance and the other with unknown resistance. Since the volumetric flow of air across the elements is constant, the ratio of the pressure drops across each element is the same as the ratio of the values of flow resistance.

The acoustic methods normally carried out in impedance tubes can be broadly classified as indirect and inverse methods. While the inverse method uses a surface acoustic property, e.g. sound absorption coefficient to operate, the indirect method relies on the evaluation of two intrinsic acoustic properties of the material. The indirect acoustic methods can further be classified as two-microphone [5-7] or three-microphone [8] methods. Ingard and Dear [5] proposed that at low frequencies the ratio of the sound pressures measured at both sides of the test specimen yielded the normalized flow resistance. The pressure measurements are carried out at the front surface of the test specimen and close to the rigid termination. Woodcock et al. [6] adopted the two-cavity [10] and two-thickness [11] methods for measuring the propagation constant and the characteristic impedance of fibrous materials and then calculated the effective flow resistivity using the inverse equation of the Delany and Bazley empirical formulae [12].

Tao et al. [7] proposed a new acoustic method based on the impedance transfer function to determine the static airflow resistivity with a standard impedance tube that complies with ISO 10534.2. In this method, the static flow resistivity is expressed as a function of the intrinsic properties of the test specimen and the resistivity values are acceptable in the frequency range from 63 Hz up to a few hundred Hz. Doutres et al. [8] presented a three-microphone impedance tube method to evaluate the non-acoustic properties of sound absorbing materials. This straightforward method only requires a direct measurement of the open porosity of the material and an impedance tube setup. Berardi and Ramakrishnan [9] investigated the difference between two-microphone and three-microphone impedance tube method employed to assess the flow resistivity and sound absorption coefficient of materials in both compressed as well as uncompressed state. In this paper, an indirect acoustic method proposed by Tao et al. [7] is implemented for measuring the static flow resistivity of additive manufactured ABS sample, foam and glass fibre. The feasibility and performance of the method are discussed.

## II. THEORY

Flow resistivity can basically be classified as dynamic flow resistivity and static flow resistivity. The dynamic flow resistivity is frequency dependent and varies with it. But when the frequency tends to zero, flow resistivity varies little with frequency and is usually called as “static flow resistivity” [13]. The static flow resistivity is of more importance as it plays a critical role in the calculation of many acoustic intrinsic properties. It can also be defined as the real part of the low frequency limit of the dynamic resistivity [14]. The dynamic resistivity is expressed as a function of the material’s intrinsic properties, i.e. the propagation constant (complex wave number) and characteristic impedance. Thus the static flow resistivity can be calculated as,

$$\sigma = \mathrm{Re}\left[\lim_{(\omega \to 0)} (j k_p \mathrm{Y_p})\right]$$

where $k_p$ and $\mathrm{Y_p}$ are the complex wave number and the characteristic impedance of acoustic material respectively.

Woodcock et al. [6] adopted the two-cavity [10] method for measuring the propagation constant and characteristic impedance of fibrous materials. In this method the test specimen is backed by infinite and finite impedance by placing the specimen in contact with rigid termination and then employing a quarter wavelength back cavity respectively. But for every frequency of interest, employing a different back cavity would prove to be tedious and time consuming. Tao et al. [7] improvised on the same and implemented the two-cavity method by choosing any arbitrary back cavity for 63-500 Hz frequency range and evaluated the intrinsic properties as follows,

$$k_p = \pm(1 / 2l)\tan^{-1}([\mathrm{Z_{22}} / \mathrm{Z_{11}} - (\mathrm{Z_{12}}[\mathrm{Z_{22}}+\mathrm{Z_{11}}]) / (\mathrm{Z_{11}})^2]^{0.5})$$

$$\mathrm{Y_p} = j\mathrm{Z_{11}}\tan(2k_p l)$$

where $\mathrm{Z_{11}}$ and $\mathrm{Z_{12}}$ are respectively the specific acoustic impedance on the front surface of the specimen when the specimen is backed by rigid termination and any non-zero back cavity. On the other hand, $\mathrm{Z_{22}}$ is the acoustic impedance at the back surface of the test specimen when backed by the non-zero back cavity and is obtained as,

$$\mathrm{Z_{22}} = -j\rho c\cot(kL)$$

where $\rho$ is the air density, c is the speed of sound, $L$ is the non-zero back cavity and $k$ is the wave number defined as $k = 2\pi f/c$, where f is the frequency. The specific acoustic impedances $\mathrm{Z_{11}}$ and $\mathrm{Z_{12}}$ on the front surface of the specimen can be measured using the ISO 10534.2 standard impedance tube. A diagram of standard impedance tube design according to ISO 10534.2 is shown in Fig. 1.

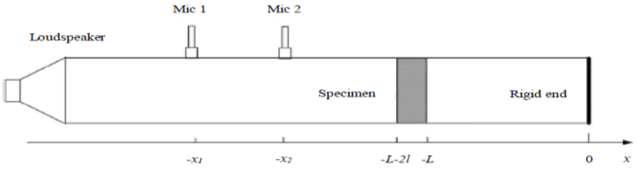
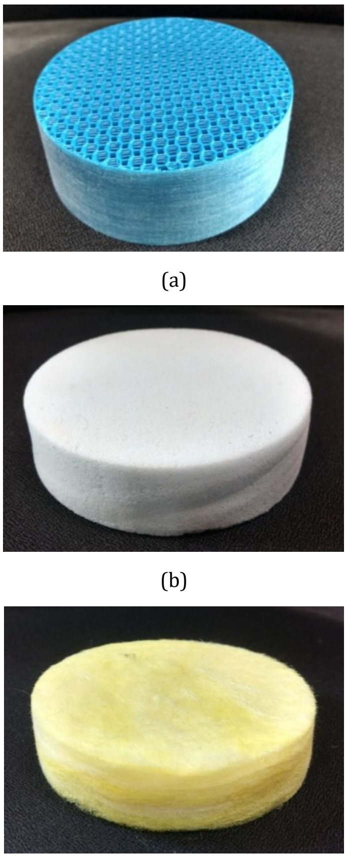


Fig. 1. A diagram of the impedance tube designed for ISO 10534.2 implementation [7]

A loudspeaker at one end generates the required random signal over a frequency range and the transfer function is measured utilizing the microphone switching procedure. The reflection coefficient and hence impedance can be evaluated from the transfer function conveniently by a programmable digital spectral analyzer.

## III. EXPERIMENTS

Initially, the two cavity method was implemented and the impedance measurements were carried out for ABS sample and foam. The two-cavity method [7] relies on measuring the surface impedances at both sides of the specimen when backed by rigid termination and back cavity of depth ‘$L$’. The impedances are measured in a large impedance tube using transfer function method. The frequency range considered is 63-500 Hz by setting the microphones at wide spacing.



(a)

(b)

(c)

Fig. 2. Impedance tube samples of 100 mm diameter (a) Additive manufactured ABS, 80 mm thick (b) Foam, 25 mm thick (c) Glass Fibre, 24 mm thick

With the help of additive manufacturing technology, a 100 mm diameter and 80 mm thick ABS sample of hexagonal periodicity was prepared. The dynamic flow resistivity as a function of frequency plot for 80 mm thick ABS sample backed by arbitrarily chosen 35 mm back cavity is depicted in Fig. 3.

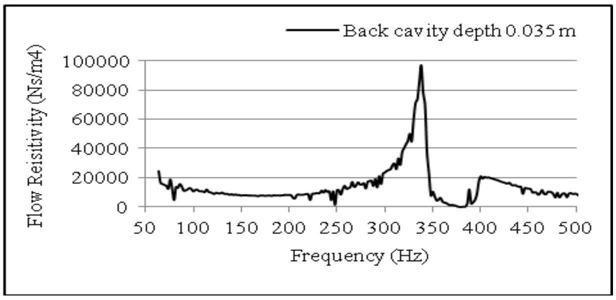


Fig. 3. Flow resistivity as a function of Frequency for 80 mm thick ABS subjected to 35 mm back cavity depth

The foam sample is extracted from a sheet which is 25 mm thick. The diameter of the foam sample is maintained 100 mm as per the impedance tube compliance. The dynamic flow resistivity as a function of frequency plot for 25 mm thick foam sample backed by arbitrarily chosen 50 mm back cavity is depicted in Fig. 4.

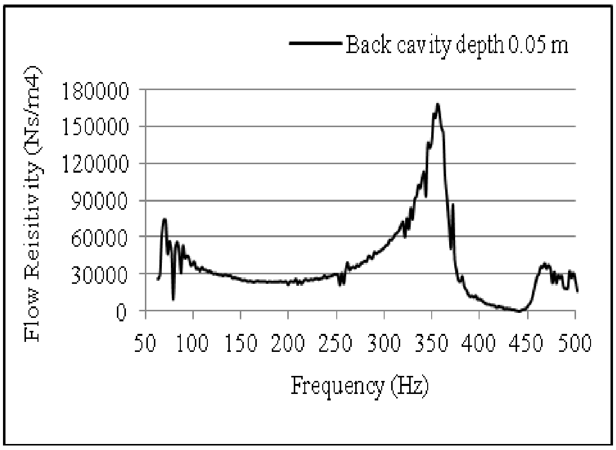


Fig. 4. Flow resistivity as a function of Frequency for 25 mm thick foam subjected to 50 mm back cavity depth

The static flow resistivity should be constant with respect to frequency. From the Fig. 3-4 it can be seen, that the flow resistivity tends to be constant in the frequency range from 150-200 Hz. The static flow resistivity value in this range for both ABS sample and foam is listed in Table 1. It is clear from Table 1 that flow resistivity values vary little in the 150-200 Hz frequency range. Also, the plots for both ABS sample and foam depict similar trend.

TABLE I. STATIC FLOW RESISTIVITY FOR ABS SAMPLE AND FOAM

| **Static Flow Resistivity (Ns/m4) in 150-200 Hz frequency range** | | | |
|---|---|---|---|
| ***Acoustic Material*** | ***Mean*** | ***Std. Deviation*** | ***% Deviation*** |
| ABS sample | 7940 | 187 | 2.35 |
| Foam | 24442 | 772 | 3.16 |

In order to check the repeatability of the experiment, three glass fibre samples of 100 mm diameter were extracted from the same sheet. The thickness ranged around 24±1 mm. The measurements were performed similarly as done in the case of foam and results obtained were as follows,

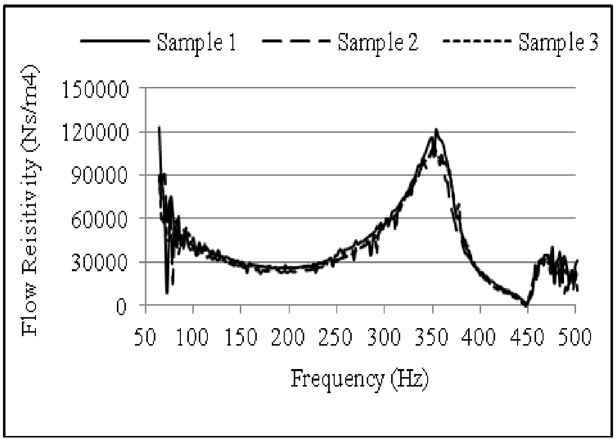


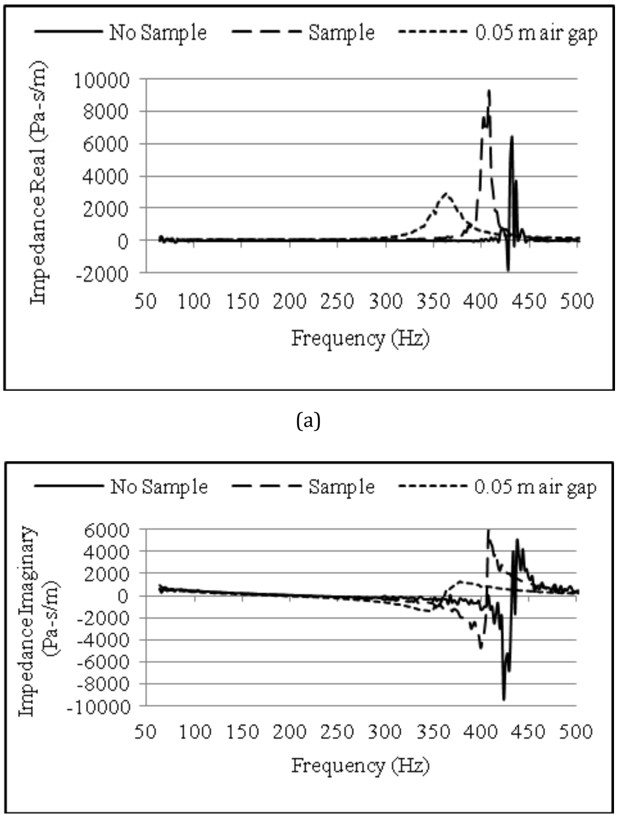
Fig. 5. Flow resistivity as a function of Frequency for 24 mm thick Glass Fibre subjected to 50 mm back cavity depth

It can be seen that the graphs for the three glass fibre samples are in good agreement, thus indicating a good experimental repeatability. The same can be proved by measuring the static flow resistivity in the 150-200 Hz range.

TABLE II. STATIC FLOW RESISTIVITY FOR GLASS FIBRE SAMPLES

| **Static Flow Resistivity (Ns/m4) in 150-200 Hz frequency range** | | | |
|---|---|---|---|
| ***Glass Fibre*** | ***Mean*** | ***Std. Deviation*** | ***% Deviation*** |
| Sample 1 | 26431 | 1440.10 | 5.40 |
| Sample 2 | 24542 | 1408.30 | 5.75 |
| Sample 3 | 26112 | 1200.40 | 4.50 |

The flow resistivity values for the three samples are found to be in good agreement. The maximum variation in static flow resistivity between samples is around ±8%. The graphs for the three materials tested, i.e. ABS sample, foam and glass fibre depict certain similarities in their trend, which are as follows – peak is observed around 350 Hz, rapid fluctuations below 100 Hz and flow resistivity tends to be constant in the 150-200 Hz region. In order to investigate the reasons for these similarities, further tests are conducted. The impedance values of the rigid termination are measured in the absence of the sample. Further the impedance values are plotted with respect to frequency for with and without sample conditions.

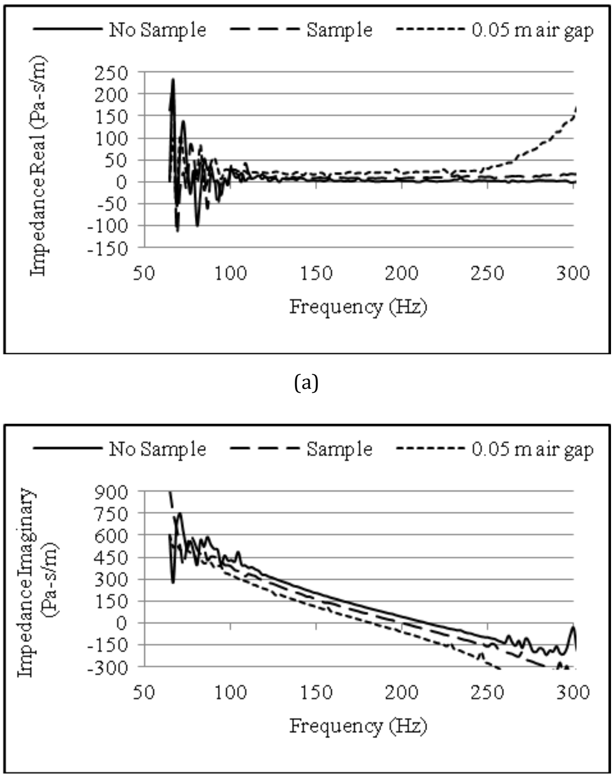


(a)

(b)

Fig. 6. (a) Real part and (b) Imaginary part of measured impedance values for 24 mm thick Glass Fibre sample in the 63-500 Hz frequency range

The imaginary part of impedance shifts from minimum to a maximum at around 432 Hz for the without sample condition. This frequency is referred to as the natural frequency and the corresponding imaginary part of impedance is zero. With the presence of the sample and air gap, the length of the standing wave tube increases, and the natural frequency shifts. Thus from Fig. 6, it could be seen that with the presence of glass fibre sample and air gap, the peak associated with the natural frequency of the tube shifts towards left at around 350-400 Hz. Since the flow resistivity value is evaluated from surface impedance, the same peak is carried forward in flow resistivity plots depicted in Fig. 3-5. Further the results depicted in Fig. 6 are reconsidered excluding the peak data.



(a)

(b)

Fig. 7. (a) Real part and (b) Imaginary part of measured impedance values for 24 mm thick Glass Fibre sample in the 63-300 Hz frequency range

It is observed from Fig. 7 that there are rapid fluctuations in the real and imaginary part of impedance below 100 Hz, that too in the absence of the sample. This means, that the experimental setup itself drives these fluctuations. One of the equipment responsible for this could be the microphones. Generally, microphones do not produce stable readings at very low frequencies and hence the effect is seen in impedance measurements and thus flow resistivity. Even with the presence of the sample and air gap, these fluctuations are seen. So, the impedance data in the frequency range of 150-200 Hz is considered for flow resistivity estimation.

## IV. CONCLUSION

The indirect acoustic method proposed by Tao was implemented for additive manufactured ABS sample, foam and glass fibre. The flow resistivity as a function of frequency plots for ABS sample, foam and glass fibre depict similar trends. There are rapid fluctuations below 100 Hz due to the inability of microphones to perform accurate measurements at low frequencies. A peak is observed in flow resistivity chart which is associated with the natural frequency of the standing wave tube. With the presence of the sample and air gap the peak shifts towards lower frequency. The flow resistivity tends to be constant in the frequency range of 150-200 Hz with maximum std. deviation of 5% and hence could be termed as static in this range. The repeatability of experiments was 8% which was acceptable.

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