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# A METHOD OF MEASURING THE ACOUSTIC ABSORPTION COEFFICIENT OF A MATERIAL SPECIMEN AT ONE END OF A TUBE USING A DYNAMIC MICROPHONE AT THE OTHER END

Shih-Fu Ling* and Jin Xie

*School of Mechanical & Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Email: msfling@ntu.edu.sg*

**Abstract**

This paper reports the development of a method for measuring the absorption coefficient of a material specimen mounted at one end of a planar wave tube using a dynamic microphone at the other end. In the proposed method, the dynamic microphone mounted is used as an actuator (loudspeaker) to generate sound waves and simultaneously performs as a probe to sense acoustic impedance at the same point. For the electro-mechanical acoustical system formed by the dynamic microphone and the tube, a "transduction matrix" is introduced to relate the input electrical variables (voltage and current) and the output acoustical variables (pressure and particle velocity). Measurements of fully-reflected end, anechoic end and a porous material specimen are carried out and compared to the results obtained by the conventional transfer function method. It is found that the results match well with each other in a frequency depending on the length of the tube. In addition to the obvious medical application – in-situ and non-invasive detecting health conditions of eardrum, the method can be utilized in industrial applications where simple and portable apparatus are needed to characterize acoustic materials in-situ and on site.

## I. Introduction

To achieve the sound absorption coefficient of the material there are basically two methodologies known respectively as "standing wave ratio" and "transfer function method" [1, 2]. In the standing wave method, a single microphone is moved along the standing wave tube to find the minima and the maxima of the sound pressure of the standing wave and the procedure has to be repeated for each pure tone of interest. Compared to it, the transfer function method (also called two-microphone method) is much faster and algorithms are easily implemented by FFT analyzers. In this method, the sound pressures of the standing wave at two different locations are picked up and fed into a dynamic signal analyzer to identify the transfer function which in turn is used to derive the absorption coefficient. In [3], particle velocity sensors were employed to replace microphones in transfer function method. One important issue in transfer function method is that it requires very precise transfer function measurement, which implies accurate amplitude and phase calibrations for each of the two microphones or particle velocity sensors. To avoid this requirement, using a single microphone at two sequential positions was also proposed [4].

In the cases such as monitoring the health condition of eardrum, it is practically impossible to insert microphones into the tube either through tube wall or from the end of the test specimen. Peng and Ling [5] introduced a method of microphone-free to measure absorption. Their method probes the input voltage and current of the excitation loudspeaker to obtain the absorption coefficient. In another words, the actuator is used as a sensor simultaneously in the approach. Ling and Xie [6, 7] reported a method for measuring mechanical impedance of structures exploiting a shaker as both sensor and actuator simultaneously. In their approach, a “transduction matrix” was defined to relate the electrical impedance at the input port and the mechanical impedance at the output port of the electro-magnetic transducer. Being a characteristic of the shaker, the transduction matrix was first calibrated through tests of numerical calculations. Once the transduction matrix is calibrated, the mechanical impedance experienced at the output port can then be calculated from the measured electrical impedance at the input port of the shaker. Because of the introduction of the transduction matrix, this approach is relatively more generic than others and can be applied to many other electromechanical transducers [8].

## II. Proposed method

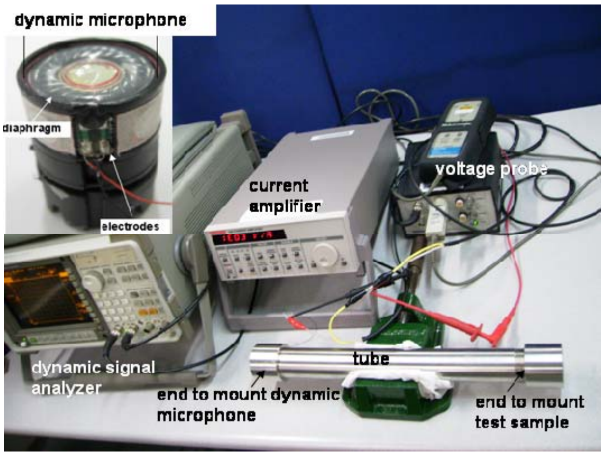



Fig. 1 shows the experimental set-up used for this investigation. A one-inch dynamic microphone is fixed at the one end of a tube in diameter of 27 mm and length of 320 mm. The material specimen under testing is mounted at the other end. The surface of specimen should be perpendicular to the propagation direction of acoustic wave. In testing, swept sinusoidal signals from dynamic signal analyzer (HP35670A) are sent to activate the dynamic microphone. The signal of voltage is measured by voltage probe (Tektronix P5205) and the current is measured by the current amplifier (Keithley 428). A two-port model is built to describe the relationship between the electrical port and acoustical port of the microphone-tube system, as shown in Fig. 2. In this model the input electrical port is referred to the two electrodes of dynamic microphone, and the output acoustical port is at the terminal of the tube, where the surface of the testing material is installed. The dynamic microphone transfers energy from electrical to acoustical domain, and the tube plays a role of relating the acoustical variables at the two ends of tube.

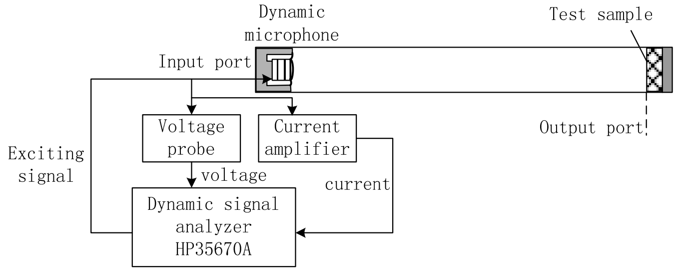



**Figure 1.** (a) Photo and (b) schematic view of experimental setup

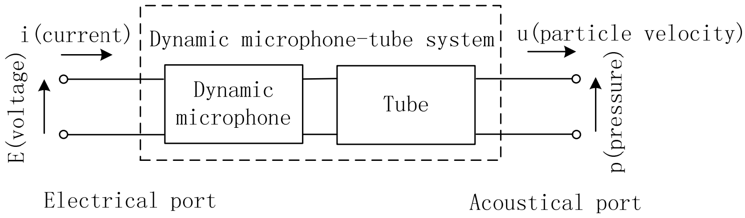



**Figure 2.** Two-port model of dynamic microphone-tube system

Since the dynamic microphone-tube system is linear and reciprocal, the input electrical port and output acoustical port are related by a transduction matrix:

$$\begin{Bmatrix} E \\ i \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} p \\ u \end{Bmatrix} \tag{1}$$

where $E$ voltage and $i$ current are power conjugate variables in electrical domain, and $p$ pressure and $u$ particle velocity in acoustical domain. The four elements of the transduction matrix are defined as and can be obtained in theory by:

$$a_{11} = E/p\big|_{u=0}; \quad a_{21} = i/p\big|_{u=0}; \quad a_{12} = E/u\big|_{p=0}; \quad a_{22} = i/u\big|_{p=0}$$

The particle velocity being zero ($u = 0$) is called clamp boundary condition, which means that the acoustic particle possesses no velocity. Generally, when a normally incident wave is totally reflected back on a rigid wall, the particle velocities in positive and negative traveling directions have equal magnitude but are $180^{o}$ out of phase, so that the superposed particle velocity is zero. The pressure being zero ($p = 0$) is called free condition or pressure release, which is impossible to be realized in laboratory.

From Eq. (1), the acoustic impedance at the output port can be calculated from the measured input electrical impedance:

$$Z_a = \frac{p}{u} = -\frac{a_{22}Z_e - a_{12}}{a_{21}Z_e - a_{11}} \tag{2}$$

where $Z_a = \dfrac{p}{u}$ is the acoustic impedance, $Z_e = \dfrac{E}{i}$ is the electrical impedance. To get $a_{ij}(i, j = 1, 2)$ of the transduction matrix through experiment using their definition in the above, we must impose free and clamp conditions to the output port of the tube. Clamp condition of acoustic is easy to realize by making the output port be rigid wall. However, free boundary condition of acoustic ( $p=0$ ) is impossible to realize in laboratory. Furthermore, calibrations of $a_{12}$ and $a_{22}$ require measurement of acoustic particle velocity. Unfortunately, so far a reliable acoustic particle velocity sensor of small size suitable for our purpose is not available in market. To overcome the above experimental difficulties, an alternative calibration method is developed to characterize the system. Three conditional impedances are defined as:

$$Z_{ao}=\left.\frac{p}{u}\right|_{i=0}\;;\quad Z_{ef}=\left.\frac{E}{i}\right|_{p=0}\;;\quad Z_{ec}=\left.\frac{E}{i}\right|_{u=0} \tag{3}$$

where $Z_{ao}$ is the acoustic impedance when the transducer is electrically open-circuited; $Z_{ef}$ is the electrical impedance of the transducer when the pressure at the output port is zero;. $Z_{ec}$ is the electrical impedance of the transducer when the particle velocity at the output port is zero. From Eq. (1), if we let $i$ , $p$ , $u$ equal to zero respectively, the following equations can be derived

$$Z_{ao}=-\frac{a_{22}}{a_{21}};\quad Z_{ef}=\frac{a_{12}}{a_{22}};\quad Z_{ec}=\frac{a_{11}}{a_{21}} \tag{4}$$

Considering Eqs. (2) and (4), the acoustic impedance at the tube end can be expressed as:

$$Z_a=Z_{ao}\frac{Z_e-Z_{ef}}{Z_e-Z_{ec}} \tag{5}$$

However, the same difficulties in measurement of $a_{ij}(i,j=1,2)$ still exist in calibration of $Z_{ao}$ and $Z_{ef}$ . Here, $Z_{ao}$ and $Z_{ef}$ are indirectly identified from a set of measured $Z_{ec}$ and $Z_e$ of the dynamic microphone when various calibration materials with known $Z_{ao}$ are applied to the output port. We can rewrite Eq. (5) as follows:

$$a\frac{1}{Z_{ao}}+bZ_{ef}=c \tag{6}$$

where $a=Z_a(Z_e-Z_{ec})$ ; $b=1$; $c=Z_e$ .

For a given absorbing material, its acoustic impedance $Z_a$ is first measured by transfer function method conducted in a commercial impedance tube. Subsequently, corresponding $Z_e$ for this material is measured by mounting it at the output port of the dynamic microphone-tube system. $Z_{ec}$ is the electrical impedance for the boundary condition of rigid wall at output port and is easily obtained. Thus, $a$ and $c$ in Eq. (6) can be calculated or measured. Repeating the same procedure over a group of simultaneous equations based on a set of $Z_e$ and $Z_a$ obtained by applying various absorbing materials to the acoustical output port of the dynamic microphone-tube system. This group of equations is written as matrix form:

$$\begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \\ \cdots & \cdots \\ a_n & b_n \end{bmatrix} \cdot \begin{bmatrix} \dfrac{1}{Z_{ao}} \\ Z_{ef} \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ \cdots \\ c_n \end{bmatrix} \tag{7}$$

where $a_{(k)} = Z_{a(k)}(Z_{e(k)} - Z_{ec})$; $b_{(k)} = 1$; $c_{(k)} = Z_{e(k)}$; $k = 1, 2, ..., n$. $n$ is the number of experiment times of applying different absorbing materials to the acoustical output port of the dynamic microphone-tube system. $\dfrac{1}{Z_{ao}}$ and $Z_{ef}$ can be identified by solving these over-determined simultaneous equations. The least square solution of the above mentioned equations can be derived as follows:

$$Z = [A^T A]^{-1} A^T C \tag{8}$$

where

$$Z = \begin{bmatrix} \dfrac{1}{Z_{ao}} \\ Z_{ef} \end{bmatrix}; \qquad A = \begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \\ \cdots & \cdots \\ a_n & b_n \end{bmatrix}; \qquad C = \begin{bmatrix} c_1 \\ c_2 \\ \cdots \\ c_n \end{bmatrix}.$$

With the calibrated $Z_{ao}$ and $Z_{ef}$, we can mount arbitrary specimen at the output port of the tube, by measuring the input electrical impedance $Z_e$ of the dynamic microphone, acoustic impedance $Z_a$ of the specimen can be calculated according Eq. (5). Finally, the acoustic reflection coefficient $R(\omega)$ or absorption coefficient $\alpha(\omega) = 1 - |R(\omega)|^2$ can be calculated according to the following equations:

$$R(\omega) = \frac{Z_a - \rho_0 c_0}{Z_a + \rho_0 c_0} \tag{9}$$

$$\alpha(\omega) = 1 - \left| \frac{Z_a / \rho_0 c_0 - 1}{Z_a / \rho_0 c_0 + 1} \right|^2 \tag{10}$$

where $\rho_0$ is the density of air, $c_0$ is the undisturbed speed of sound.

## III. Calibration of conditional impedances $Z_{ec}$, $Z_{ao}$ and $Z_{ef}$

Calibration of $Z_{ec}$ requires the particle velocity at output port be zero. This condition can be realized by mounting a steel block at the output port of the tube using the same experimental set up shown in Figure 1. The steel block functions as a rigid wall to totally reflect the acoustic wave so that the particle velocity on the surface of steel is zero. The magnitude of electrical impedance for clamp boundary condition was measured and shown in Fig. 3. The first peak at 130 Hz is the resonance of the dynamic microphone, and the other peaks are caused by the standing wave pattern in the tube. The electrical impedance varies cyclically in the frequency domain, which reflects the fact that the acoustic impedance on the surface of microphone diaphragm reaches a maximum value at the frequencies where the length of the tube is an integer multiple of the half wavelength of the sound.

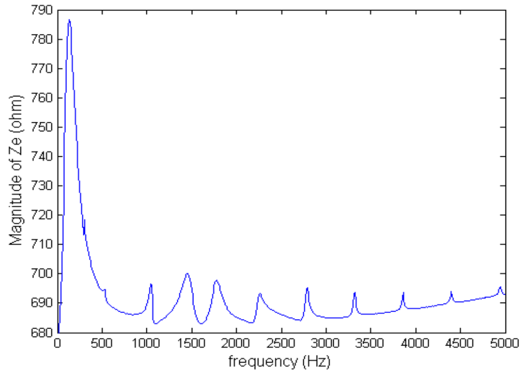
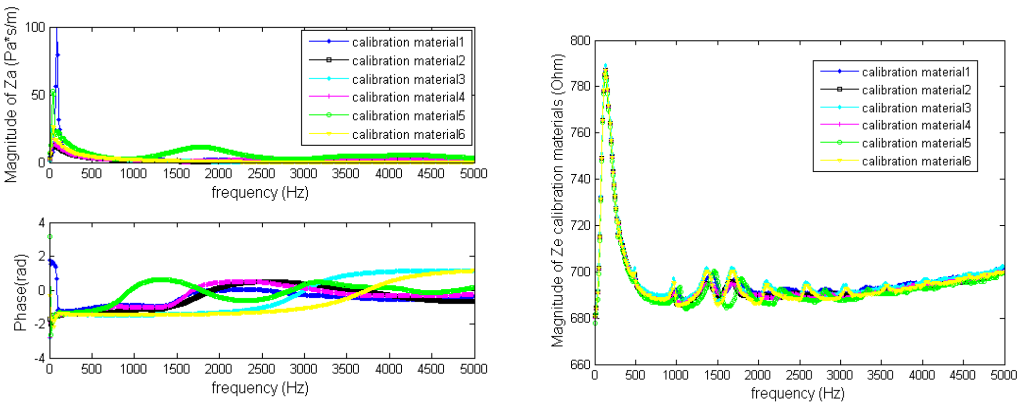



**Figure 3. Magnitude of electrical impedance for clamp boundary condition**




(a) (b)

**Figure 4. (a) Acoustic and (b) electrical impedance for the calibration materials**

Six materials with different absorption coefficients were then utilized for calibration of conditional impedances $Z_{ao}$ and $Z_{ef}$. Acoustic impedance of these materials was measured by transfer function method conducted in the B&K 4206 impedance tube. The results are shown in Fig. 4(a), from which we can observe that different calibration materials have different acoustic impedance. In general, a material with high acoustic impedance has high refection coefficient. Subsequently, these 6 calibration materials are mounted at the output of the dynamic microphone-tube system, respectively. The magnitude of electrical impedance for these calibration materials were measured and shown in Fig. 4(b). It is observed that the standing wave peaks are much weaker than those in the case of rigid wall.

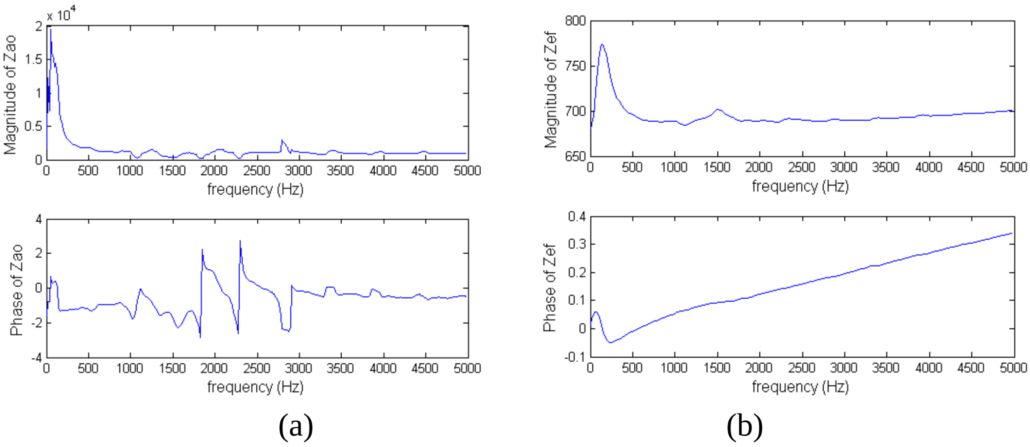
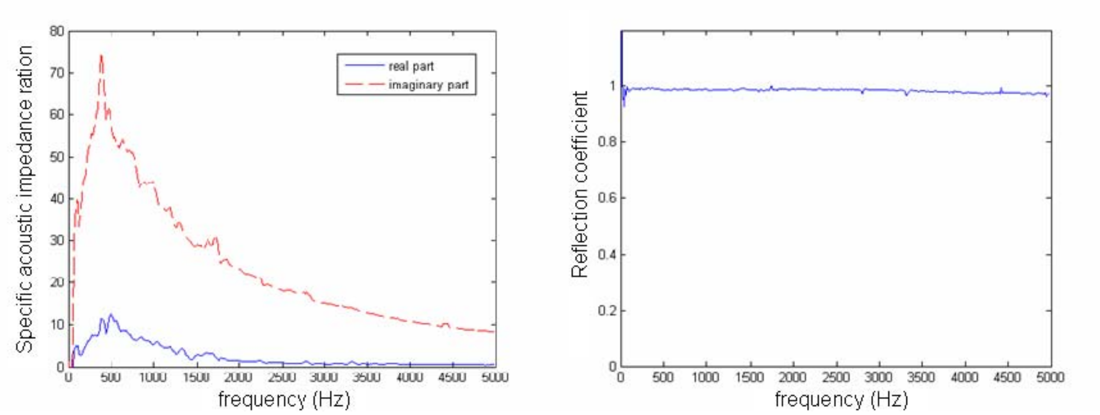



**Figure 5.** Calibrated (a) $Z_{ao}$ and (b) $Z_{ef}$

## IV. Validation of the method

With $Z_{ec}$, $Z_{ao}$ and $Z_{ef}$, we can install a material specimen to measure the acoustical absorption coefficient by probing the corresponding electrical impedance. According to Eq. (8), the specific acoustic impedance ratio was calculated from the measured electrical impedance, as shown in Fig. 6(a). The real part and imaginary part of acoustic impedance are the acoustic resistance and acoustic reactance of the material respectively. As can be seen from the result, the acoustic resistance is close to zero at the frequency range above 1500 Hz, which demonstrates that little energy dissipation happens at the aluminum sample. Furthermore, acoustic reactance and acoustic resistance discloses are different in magnitude is up to 10 times, which means that the acoustic reactance makes the active role of the mass and stiffness of aluminum sample. After calculating the reflection coefficient, we can observe from Fig. 6(b) that the reflection coefficient of aluminum is very close to unity as expected in a wide frequency range.

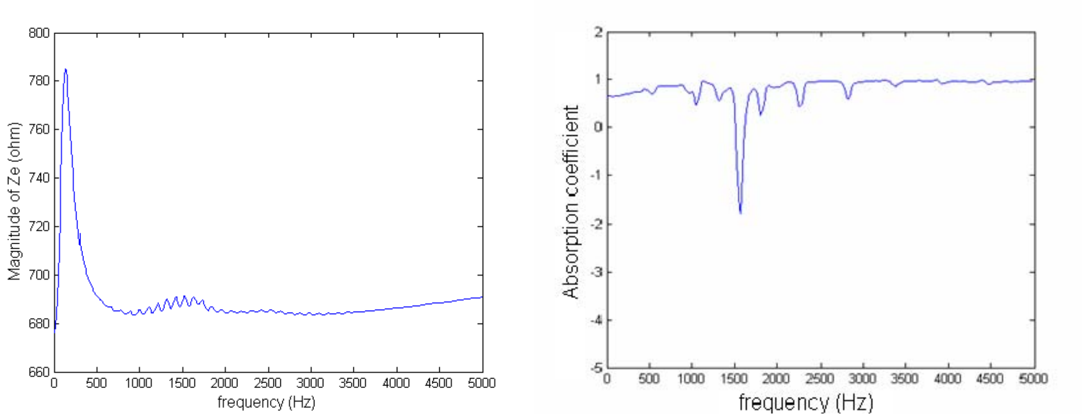
If we connect a long pipe to the experimental tube, and plug some high absorptive material at the terminal end of the long pipe, the sound energy will not be reflected back because all the acoustic energy are absorbed in its way to the end of the whole pipe, which is actually an anechoic acoustic terminal. In this case, the acoustic impedance is equal to the characteristic impedance $Z_{anechoic} = \rho_0 c_0$. Replacing $Z_a = Z_{anechoic}$ into Eq. (10), the absorption coefficient was calculated and $\alpha = 1$. The experimental realization of this boundary condition was difficult. In our experiment, a long PVC pipe of 1.3 meter in length is used to connect to the experimental tube. The PVC pipe is about four times longer than the experimental tube. Anechoic terminal condition was created by inserting some cotton at the further end of the long pipe.




(a) (b)

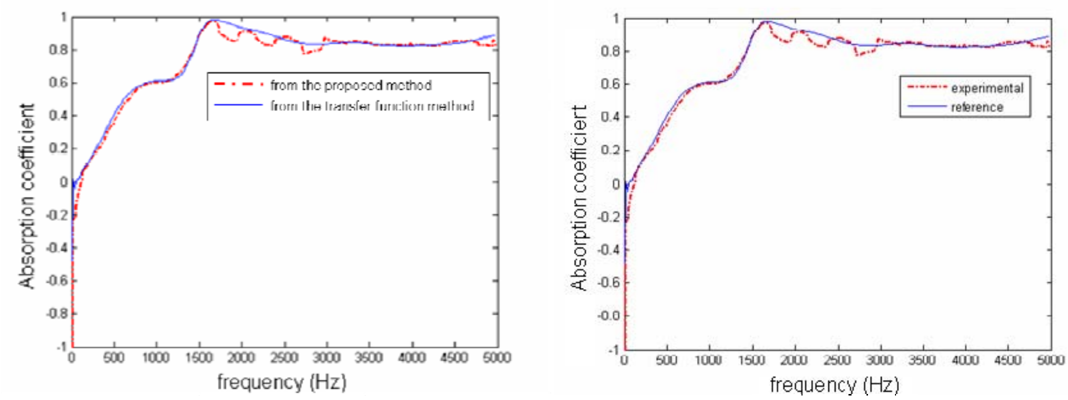
**Figure 6. (a) Specific acoustic impedance ratio and (b) reflection coefficient of aluminum**

The electrical impedance for this condition is shown in Fig. 7(a). Due to the imperfect anechoic condition, a small part of acoustic wave was reflected back and formed a weak standing wave pattern. Therefore, some resonance peaks of standing wave can still be observed when the length of the tube plus PVC pipe is an integer multiple of the half wavelength of the sound. The absorption coefficient for the anechoic condition were calculated and shown in Fig. 7(b). We next applied the proposed method to a porous material, such as a sponge sample. The experimental results from the sponge sample show that the calculated absorption coefficient agrees with the result from the transfer function method by B&K 4206 impedance tube in the frequency range of interest.




**(a) (b)**

**Figure 8. (a) Electrical impedance and (b) absorption coefficient for anechoic condition**




**(a) (b)**

**Figure 9. (a) Electrical impedance and (b) absorption coefficient for a sponge sample**

## v. Conclusion

A method for measuring acoustic impedance or absorption coefficient of materials is developed and presented. Measurement results for fully-reflected end, anechoic end and a porous material specimen Goh, Edwina (RR Energy Systems) [edwina.goh@rolls-royce.com] show that the method can correctly identify the absorption coefficient of acoustic materials in a frequency range from 100 to 5000 Hz. The microphone-free feature of the method is of particular use in situations where the transfer function method is impractical to implement, such as measurement in a tube with small diameter.

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