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A direct method for acoustic impedance measurement based on the measurement of electrical impedance of acoustic transmitter

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ABSTRACT

A simple and straight forward method for acoustic impedance measurement is presented and evaluated. In this method a speaker is used as the signal source. The relationship between the electrical impedance of the speaker and its acoustical load is developed and studied. It is shown that the electrical current and voltage of the speaker relate to the acoustical pressure and volume velocity. The mechanical and acoustical impedances are therefore easily derived by measuring the electrical current and voltage of the circuit. The proposed method yield itself to the automatic computer measurement and can be used for the field and in situ measurements.

Comparison of the measurement data with those from other methods proves the applicability and accuracy of the proposed method.

1. Introduction

Measurement of acoustical impedance is an essential task in the design of acoustical systems such as silencers, resonators, absorbent material, horns, and acoustical pipes. By definition, mechanical impedance is obtained by dividing the applied force to the particle velocity. In addition, acoustical impedance is the applied pressure divided by the volume velocity [1]. Therefore, the relationship between mechanical and acoustical impedances is derived from the force–pressure and volume velocity–velocity.

Based on the above definition, to calculate the acoustical impedance, the volume velocity needs to be measured. However, most of the present acoustical impedance measurement methods used today such as ISO-10534-1 [2], ISO-10534-2 [3], and ASTM C384-58-1972 [4] do not provide a direct measurement of the volume velocity. This is due to the lack of available and accurate volume velocity sensors. The majority of the methods that are currently used determine the acoustical impedance based on the wave reflection techniques.

The two standard wave reflection methods that are described by ISO-10534-1 [2] and ISO-10534-2 [3] are

a. Standing wave ratio (SWR) method;
b. Two microphone transfer function method.

The standing wave ratio (SWR) method is known as “Classical kundt duct” in ISO-10534-1. In this method, one end of the kundt duct is closed while a speaker is placed at the other end to generate a standing wave within the duct. A microphone is moved along the duct to measure and locate the maximum and minimum pressure amplitude points along the duct. The standing wave ratio and the acoustical impedance are then calculated [5] accordingly.

In the “Two Microphone Transfer Function Method” described in ISO-10534-2 the system transfer function and the subsequent acoustical impedance are derived using the data extracted from the two microphones placed at two fixed points along the duct. This method has mostly replaced the SWR-method because of its more convenient mechanical set up and measurement process [6]. These methods, however, suffer from the limited measurement band-width and errors due to the spacing of the microphones and their location with respect to the pressure nodes [7–9]. The calibration method based on the hard wall impedance measurement proposed by Boonen et al. [6] improves the measurement bandwidth to about two frequency decades and reduces the error by shifting the reference section and multiple measurements.

In this paper, the dependence of the electrical impedance of a speaker on its acoustical load is used as the basis of the proposed method. This method does not require acoustical pressure or volume velocity measurements. The dependency of performance to the microphones position and the need for the calibration to compensate pressure nodes due to microphones spacing is also removed.

The proposed method can also be used for in situ measurement of the acoustic properties of components in industries such as in oil and gas field or refineries. This is particularly important when the coupling of the measurement duct to the unknown acoustic system is not straight forward. In these cases of industrial applications the

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low sensitivity of the proposed technique to the environmental noise is an indispensable advantage.

In Section 2 of this paper the basic electrical and acoustical model of the measuring system and the relation between the two models is derived. Section 3 describes a computer based measurement system with its mechanical setup. Derivation of the measuring system parameters is given in Section 4. Section 5 presents the measurements and comparison of the measured data with that of simulations and other previously reported measuring techniques. Conclusions are finally given in Section 6.

2. Basic model

Fig. 1 shows a speaker with its diaphragm connected to a coil of fine wire which can move axially inside a cylindrical magnet of magnetic field strength B. Any current I in the coil generates a mechanical force F that causes the diaphragm to move along the x-axis with the instantaneous speed of $u(t)$. If the coil has n loops of wire, the total applied force on the diaphragm along the x-axis can be written as

$$F(t) = n \cdot B \cdot I(t) \cdot 2\pi r \cdot \sin\theta \tag{1}$$

where r is the coil radius, and θ is the angle between the current and magnetic field, which is 90 degrees. $F(t)$ can then be simplified as,

$$F(t) = n \cdot B \cdot I(t) \cdot 2\pi r \tag{2}$$

Consequently, the wire winding crosses the electromagnetic field when the diaphragm moves. The change in the magnetic flow, $d\varphi(t)$ for every loop is

$$d\varphi(t) = 2\pi r \cdot B \cdot dx(t) \tag{3}$$

where $dx(t)$ is the diaphragm displacement. The induced voltage in n loops of wire is

$$V(t) = n\frac{d\varphi(t)}{dt} \tag{4}$$

Using Eq. (3), and taking the particle velocity $u(t)$ as $u(t) = \frac{dx(t)}{dt}$, one can write

$$V(t) = n \cdot 2\pi r \cdot B \cdot u(t) \tag{5}$$

By definition, mechanical impedance is [1]

$$Z_{m0} = \frac{F(t)}{u(t)} \tag{6}$$

which is simply the applied force divided by the velocity of the fluid at the diaphragm interface.

It is worth noting that the speed of fluid particles varies at different locations of the fluid due to the compressibility and other mechanical properties of the fluid. This phenomenon is analogous

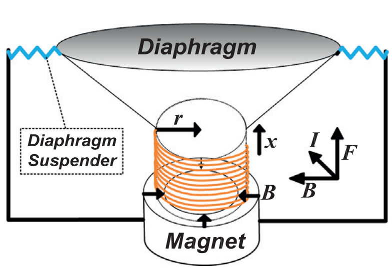

Fig. 1. Speaker structural diagram.

to variation of current through the electrical transmission lines due to distributed inductance and capacitance of the line.

The velocity of fluid at the diaphragm interface is equal to the speed of diaphragm itself. From Eqs. (2) and (5) the electrical impedance of a linear passive speaker can be written as

$$Z_{e0}(t) = \frac{n \cdot 2\pi r \cdot B \cdot u(t)}{\frac{F(t)}{n \cdot B \cdot 2\pi r}} \tag{7}$$

The relationship between mechanical and electrical impedances in the time domain can then be found by inserting Eq. (6) into Eq. (7) as

$$Z_{e0} = \frac{(n \cdot B \cdot 2\pi r)^2}{Z_{m0}} \tag{8}$$

For a constant B, Eq. (8) can be written in the frequency domain as

$$Z_{e0}(\omega) = \frac{(n \cdot B \cdot 2\pi r)^2}{Z_{m0}(\omega)} \tag{9}$$

By definition, acoustical impedance is [1]

$$Z_{a0} = \frac{p(t)}{Q(t)} \tag{10}$$

where for a speaker diaphragm area of A_s, $p(t) = \frac{F(t)}{A_s}$ is the acoustical pressure and $Q(t) = A_s u(t)$ is the volume velocity. Eq. (10) can then be written as

$$Z_{a0} = \frac{F(t)}{u(t)} \frac{1}{A_s^2} \tag{11}$$

And from Eqs. (6) and (11) can be simplified as

$$Z_{a0} = \frac{Z_{m0}}{A_s^2} \tag{12}$$

Using Eqs. (9) and (12), the relationship between acoustical impedance (seen by the speaker) and electrical impedance of the speaker can be derived as

$$Z_{e0}(\omega) = \frac{(n \cdot B \cdot 2\pi r)^2 A_s^2}{Z_{a0}(\omega)} \tag{13}$$

2.1. Electrical parasitic components

Eq. (13) is derived without considering the parasitic resistance R and inductance L of the speaker's coil. Including these parasitic components in Eq. (13) yields

$$Z_e(\omega) = R + jL\omega + \frac{(n \cdot B \cdot 2\pi r)^2}{Z_{m0}(\omega)} \tag{14}$$

where R is typically 2–8 Ohms and L is a few micro-Henrys. For a given speaker, R and L can be easily measured using conventional instruments such as an RLC meter.

2.2. Mechanical parasitic components

The mechanical parasitic components of the speakers are dependent on the elasticity, mass, and damping properties of the diaphragm, and how it is attached to the speaker body.

A mechanical model for the parasitic components is shown in Fig. 2 in which m is mass, R_m is damping, and s is spring constant.