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THE USE OF AN IMPEDANCE TUBE FOR MEASURING ACOUSTIC IMPEDANCE AT LOW FREQUENCIES

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1. INTRODUCTION

As progress is made toward environmental protection and the development of lightweight vehicles, noise control in automobiles is becoming increasingly important. For designing a quieter vehicle, the knowledge of acoustic impedance of the trim materials is crucial to the prediction of the interior noise level in the passenger compartment. Automobile noise is usually dominated by low frequencies, 50 to 300 Hz[1,2]. A technique is required to measure the acoustic impedance of the trim materials at that frequency range.

The impedance tube method is well known for measuring specific impedance of material surfaces. Traditionally, impedance was estimated from the measurement of the location of maximum and minimum pressures of the standing wave propagated in the tube. This has been standardised by American Society of Testing Materials ASTM C 384[3]. A number of alternatives to the standing wave method have been proposed, such as sine sweep[4], pure tone and broad-band excitation methods[5, 6].

Seybert and Ross[7] (1977) introduced the two-microphone transfer function method which was then developed by Chung and Blaser[8,9]. The acoustic impedance of the tested materials is evaluated from the measured transfer function of the sound pressure between two microphones. In 1986 this method was standardised as ASTM E1050[10]. It has been used in measuring acoustic properties of automotive carpet materials[11] and extended to include the effect of mean flow in tube by Chung and Blaser[12] and Åbom and Bodén[13], and the effect of tube attenuation by Chu[14] and Mills and Spiekermann[15, 16].

For designing an impedance tube, ASTM E1050 recommended that the microphone spacing has to be much less than a half wavelength of the highest frequency of the interest. Chu (1988) [17] showed that one of the microphone positions has to be close to a minimum pressure point. Error analysis by Bodén and Åbom (1986)[18] and Bank-Lee and Peng[19] showed that the error in impedance measurement will be small if the microphone spacing is approximately a quarter wavelength and will be large if it is about a half wavelength.

In this paper, we describe the analysis of the accuracy of impedance evaluation using the two-microphone technique and the use of such an impedance tube to measure trim materials at low frequencies.

2. THEORETICAL ANALYSIS

An impedance tube is schematically represented Fig. 1. For a rigid tube wall and plane wave propagation in the tube, the transfer function of the sound pressure between two is given as

$$H = \frac{e^{jk(h_s - h_t)} + R\,e^{jk(h_s + h_t)}}{e^{jk(h_s - h_b)} + R\,e^{jk(h_s + h_b)}} \qquad (1)$$

where k is the wave number, defined as

$$k = \frac{2\pi f}{c} \qquad (2)$$

f the frequency, c the sound speed in the air.

The reflection coefficient R is a function of the specific impedance z and is given as

$$R = \frac{z-1}{z+1} \qquad (3)$$

From the measured value of the transfer function H, the impedance of tested specimen can be evaluated through the estimation of the reflection coefficient R

$$R = e^{-j2kh_b} \cdot \frac{e^{-jkT} - H}{H - e^{jkT}} \qquad (4)$$

Thus the impedance of the testing specimen is given by

$$z = \frac{1+R}{1-R} \qquad (5)$$

Taking first order approximation, the error in the estimation of reflection coefficient R due to the change in the measured transfer function H can be written as

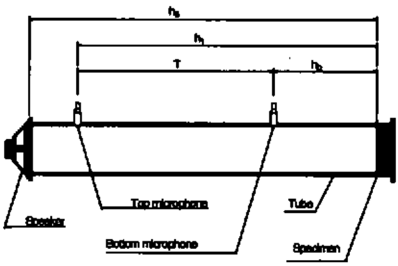

Fig. 1 Schematic diagram of an impedance tube.

$$\Delta R = \frac{dR}{dH} \cdot \Delta H \qquad (6)$$

where the evaluation sensitivity of the reflection coefficient R to the estimation of transfer function H is given as the derivative

$$\frac{dR}{dH} = e^{-j2kh_b} \cdot \frac{e^{jkT} - e^{-jkT}}{(H - e^{jkT})^2} \qquad (7)$$

Substitute equation (1) into above equation, we obtain the derivative

$$\frac{dR}{dH} = e^{-j2kh_b} \cdot \frac{1 + R\,e^{j2kh_b}}{2\sin(kT)} \qquad (8)$$

For an accurate estimate of the impedance, the derivative should be as small as possible. It should be noted that both the transfer function H and reflection coefficient R are complex numbers, and so is the derivative. The location of the microphone should make the modulus of the derivative as small as possible, since the modulus of the derivative represents the projecting magnitude, that is

$$\left|\frac{dR}{dH}\right| = \left|e^{-j2kh_b} \cdot \frac{1 + R\,e^{j2kh_b}}{2\sin(kT)}\right| \rightarrow 0 \qquad (9)$$

The optimum microphone spacing T is then given as

$$kT = \frac{\pi}{2} + n\pi, \qquad n = 0,1,2,\ldots\ldots \qquad (10)$$

i.e.

$$T = \frac{c}{4f} + \frac{c}{2f}n, \qquad n = 0,1,2,...... \tag{11}$$

This shows that the microphone spacing has to be a quarter of the wavelength or quarter plus n times of half wavelength. The worst condition is the microphone spacing close to a half wavelength where the sensitivity takes a value of infinity.

The bottom microphone height h_b could be adjusted such that the modulus of $(1 + R_e{}^{j2kh_b})$ is kept small. Representing θ as the phase angle of the reflection coefficient, the bottom microphone height h_b is defined as

$$2kh_b + \theta = \pi + 2\,n\pi \;=\; 0,1,2,...... \tag{12}$$

or

$$h_b = \frac{c}{4f} + \frac{c}{2f}n - \frac{\theta\,c}{4\pi f}\; n = 0,1,2,...... \tag{13}$$

In most of cases, at low frequency the specific impedance of the materials is very large, $|z| \gg 1$, the phase angle of the reflection coefficient approaches zero, therefore h_b is taken as

$$h_b = \frac{c}{4f} + \frac{c}{2f}n \;\; n = 0,1,2,...... \tag{14}$$

From the above analysis we could conclude that for measuring the impedance at low frequency, both the microphone spacing and bottom microphone height should be a quarter wavelength.

3. EXPERIMENTAL RESULTS

An impedance tube was designed to measure the impedance at the lowest frequency of 100 Hz. It was built from gas pressure pipe, 180 mm outside diameter, 1600 mm long and 11 mm wall thickness. A sound source is at one end of the tube and a specimen of test material at the other end. Two microphones are 857 mm apart (a quarter wavelength of 100 Hz), and located flush with the inside surface of the tube. The construction of the tube, in general, is governed by ASTM E1050. An FFT analyser generates a sinusoidal signal which drives a piston sound source and measures the transfer function of the sound pressure between two microphones. The measured transfer function is then transferred to a PC to calculate the value of the impedance. The results of repetition tests show that whole system was very stable with 0.2% of repetition error over 8 repeated tests.

Three samples of acoustic materials, acoustic foam, car seat foam, car floor carpet/underlay, were tested at the frequencies 100, 150, 200, 250, 300 and 350 Hz. Each test repeated 4 times and the averaged values of the transfer function were used for the impedance estimate.

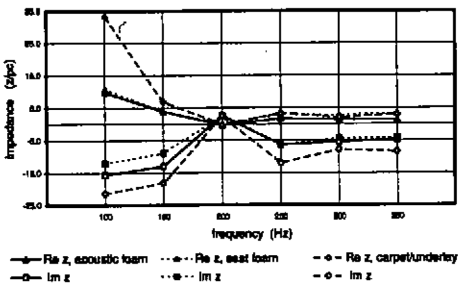

Fig. 2 Measured impedance of trim materials

The tube was designed for the lowest frequency match at 100 Hz, i.e. the microphone spacing was a quarter wavelength of 100 Hz. An accurate evaluation of impedance was expected at 100 and 300 Hz. It was also expected that an inaccurate estimate of the impedance would occur at 200 Hz. Fig. 2 shows consistent impedance at frequency 100, 250, 300 and 350 Hz, and poor evaluation of the impedance at 200 Hz which resulted in a negative absorption coefficient. The results of the experimental measurement proved the accuracy analysis of the impedance estimate in section 2. It validated that, for an accurate impedance measurement using the two-microphone method the microphone spacing and the distance of the specimen to the nearest microphone has to be a quarter wavelength. The worst condition for the impedance tube is that the microphone spacing is close to a half wavelength.

4. CONCLUSION

The lack of the knowledge of the acoustic impedance of trim materials at low frequency limits the ability to accurately predict the interior noise level in automobiles. The work reported in this paper presents an improved two-microphone method for measuring the impedance at low frequency. The analytical and experimental results show that the microphone locations are critical to the measurement accuracy. It is recommended that both the microphone spacing and the distance between the tèst specimen and the nearest microphone should be close to a quarter wavelength. The evaluated impedance would be unreliable if the microphone spacing was close to a half wavelength.

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