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An impedance tube submerged in a liquid for the low-frequency transmission-loss measurement of a porous material☆,☆☆

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ABSTRACT

According to the standard ASTM E2611 an impedance tube can be used to measure the sound transmission and reflection losses in an absorption material. However, application in a liquid medium in the low-frequency range presents difficulties with respect to the size of the structure and the waveguide-related distortion of the plane-wave propagation. In this paper a four-microphone impedance tube for use in liquids in the low-frequency range, complying with the transfer-matrix method for transmission-loss measurements, is presented. The impedance tube is validated on the basis of research on an underwater, two-microphone impedance tube. It is demonstrated that in the low-frequency range the loudspeaker couples well into the plane-wave propagation. Furthermore, existing methods for measuring the group velocity and the complex wavenumber, applicable to the impedance tube, were investigated and compared to the new methods developed in this article. The results showed the best fits for the cross-correlation and the new approach of amplitude matching, respectively, for the cases of the velocity and the wavenumber measurements. Thus, the validated impedance tube was used for acoustic measurements of metal-foam samples. Problem-specific equations for calculating the dissipation coefficients of cavity-backed samples were derived from the transfer matrix and the scattering matrix. Stable results in agreement with the expected low absorption were obtained.

1. Introduction

For the effective use of absorption materials to dampen the noise in acoustic systems it is necessary to determine their ability to absorb sound energy. Wang [1] investigated the underwater sound-absorption properties of a porous metal impregnated with a viscous fluid, Sun and Hou [2] measured the sound absorption of a rubber material with an underwater pulse tube, and Xu et al. [3] studied the underwater performance of an air-saturated SiC foam and presented improvements in later work [4]. Impedance-tube-based methods, together with other standardized test methods, offer the possibility of absorption measurements in liquids. Implementation in the low-frequency range is particularly demanding, especially in the liquid environment. While the market offers commercial impedance-tube designs for use in a gaseous medium, the scope of use in liquids is to a large extent still unexplored. The fluid-structure interaction can distort the plane-wave propagation, which is the fundamental requirement for the impedance-tube measurement methods. Research on a water-filled impedance tube was conducted by Wilson et al. [5]. They investigated an impedance tube based on ASTM E1050 [6], which is a two-microphone method with a rigidly backed sample. Their work was concentrated on the pressure sensor's design, an analysis of waveguide effects and the corresponding restrictions due to the wavefront curvature and the dispersion of the sound velocity.

Porous materials, like metal foams, have inferior absorption properties in the low-frequency range, especially when backed by a rigid plate, as reported by Han et al. [7] and Navacerrada et al. [8]. Therefore, measurements based on the two-microphone impedance-tube design cannot provide useful results. Furthermore, the two-microphone method does not permit transmission-loss measurements, as only reflection can be observed. Accordingly, the four-microphone method for a normal incidence, sound-transmission measurement with a cavity-backed sample, as stated in ASTM E2611 [9], is more appropriate for this application.

Several methods for the evaluation of acoustic properties using a four-microphone impedance tube can be found in literature. The standard ASTM E2611 [9] specifies the transfer-matrix method by Song and Bolton [10]. The transfer matrix correlates the sound pressure and the

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particle velocity on each side of the sample, and can be freely multiplied to evaluate the characteristics of multiple absorption layers in series. The reflection and the transmission coefficient are presented implicitly with four elements of the transfer matrix. Similarly, the scattering-matrix method presented by Åbom [11] correlates the pressure amplitudes of the incident and reflected waves using the reflection and transmission coefficients. The procedure for extracting the scattering-matrix elements is analogous to the transfer-matrix method. Due to the explicitly written coefficients it is convenient for analysing a single layer of the test sample, but a transfer-matrix implementation is required for a further study of multiple layers, as reported by Feng [12]. In addition, Salissou and Penneton [13] revised the wave-field decomposition method from Ho et al. [14] to avoid the corresponding assumptions of sample symmetry. Like with the scattering matrix, the reflection coefficients for both directions of the wave propagation and the transmission coefficient are obtained explicitly, again causing a limitation with respect to the use for a measured layer of porous material. The previously mentioned methods are all two-load methods, requiring measurements of two different boundary conditions of the wave termination. However, this is not the case for the method described by Bonfiglio and Pompoli [15], who combined the transfer matrix and wave-field decomposition into a single measurement approach. Salissou and Panneton [13] observed that the results of a single measurement approach match with the two-load methods, but only when the acoustic load is relatively absorbing. Looking at the presented methods, the transfer-matrix method is the only one to characterize the general material-absorption properties with ease of use for multiple layers and different impedance-tube configurations.

The objective of this paper is to develop a four-microphone impedance tube for low-frequency sound-absorption measurements in liquid media. Although the standard ASTM E2611 [9] specifies a recommended design for the four-microphone impedance tube, it is mainly intended for use in gaseous media. No appropriate design for such a tube submerged in liquid was reported in the literature. Therefore, based on an underwater impedance tube, a new four-microphone instrument was developed, specifically for transmission-loss measurements in a liquid medium in the frequency range 70–560 Hz. For reasons of practicality, the transfer-matrix method is employed to evaluate the absorption properties. The calculation of the problem-specific absorption of a cavity-backed configuration under study in this paper requires a new approach for the reflection and transmission coefficients. This new approach consists of equations for sound absorption, obtained using a correlation of the transfer matrix [10] and the scattering matrix [12].

The pivotal acoustic parameters for the transmission-loss calculation include the sound velocity and the complex wavenumber; therefore, it is best to measure them on-site. For the case of the group sound velocity two new methods based on the first mode of an open-end column and the cross-correlation are introduced and compared to the basic method of the signal travel time and the minimum-difference method adapted from the work of Wang et al. [16]. For the case of the wavenumber, both numerical and analytical solutions are available. The latter was adapted from Wilson et al. [5]. On the other hand, the numerical evaluation of the wavenumber with the established methods of Peters et al. [17], Hou et al. [18] and Han et al. [19] did not produce valid results. For the needs of the new approach, amplitude-matching method is developed.

In Section 2 a short overview of the transfer-matrix method is followed by a derivation of the coefficients for the cavity-backed configuration. The design of the developed impedance tube is described and the operation of the experimental setup is explained. For the purposes of the impedance tube's validation (Section 3) a further investigation of the acoustic phenomena, such as the tube attenuation and the wave-guide effect, is performed. This includes an overview of the methods for the measurements of the group sound velocity and the complex wavenumber. Finally, a validated impedance tube is used for the acoustic testing of the open-porous metal-foam samples, as presented in Section 4, and the corresponding results are discussed in Section 5.

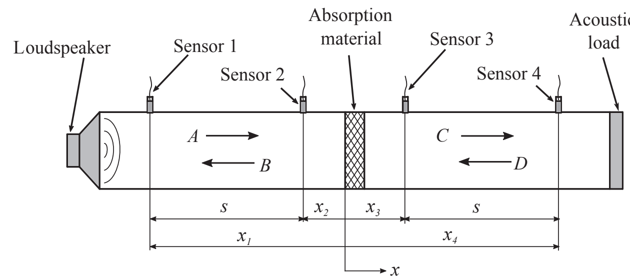

Fig. 1. Impedance tube based on ASTM E2611.

2. Transfer matrix method

The impedance tube based on the transfer-matrix method is presented in the standard ASTM E2611 [9]. It is designed to measure the change in the pressure field with a four-point measuring system and extract the acoustic absorption. A simplified model of such a measuring system is shown in Fig. 1. The sound waves are excited with a transducer on the left-hand side of the tube and the waves, transmitted to the other side, are met with the boundary condition in the form of an acoustic load. The sample of the absorption material divides the propagated waves into two different pressure fields and the corresponding amplitudes of the incident (A and C) and outbound waves (B and D):

$$p(x<0) = A\,e^{-jkx} + B\,e^{+jkx}, \tag{1}$$

$$p(x>d) = C\,e^{-jkx} + D\,e^{+jkx}, \tag{2}$$

where d is the sample thickness and the wavenumber $k = k_r - jk_i$ is a complex number, with j being the imaginary unit. The real component $k_r = \frac{\omega}{c}$ describes the ratio of the angular frequency ω and the sound velocity c. The imaginary component k_i represents the attenuation constant, which includes the viscosity and the thermal dissipation in the tube.

The pressure amplitudes are calculated from the transfer functions $H_{n,\mathrm{ref}}$ measured at the position of the sensors with the numbers $n = 1,2,3,4$ [9]:

$$A = j\frac{H_{1,\mathrm{ref}}\,e^{+jkx_2} - H_{2,\mathrm{ref}}\,e^{+jkx_1}}{2\sin[k(x_1-x_2)]}, \tag{3}$$

$$B = j\frac{H_{2,\mathrm{ref}}\,e^{-jkx_1} - H_{1,\mathrm{ref}}\,e^{-jkx_2}}{2\sin[k(x_1-x_2)]}, \tag{4}$$

$$C = j\frac{H_{3,\mathrm{ref}}\,e^{+jkx_4} - H_{4,\mathrm{ref}}\,e^{+jkx_3}}{2\sin[k(x_3-x_4)]}, \tag{5}$$

$$D = j\frac{H_{4,\mathrm{ref}}\,e^{-jkx_3} - H_{3,\mathrm{ref}}\,e^{-jkx_4}}{2\sin[k(x_3-x_4)]}. \tag{6}$$

The amplitudes obtained with Eqs. (3)–(6) are used for the derivation of the transfer-matrix elements, as described in ASTM E2611 [9]. The transfer matrix relates the acoustic pressure p and the particle velocity u on each side of the sample:

$$\begin{bmatrix} p_1 & p_2 \\ u_1 & u_2 \end{bmatrix}_{x=0} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p_1 & p_2 \\ u_1 & u_2 \end{bmatrix}_{x=d}, \tag{7}$$

where the indices 1 and 2 mark two different acoustic loads: the partially anechoic and the rigid termination. In this way no assumptions are made regarding the sample symmetry. On the basis of the transfer matrix, the transmission coefficient t and the reflection coefficient r can be predicted for multiple tube termination configurations and the corresponding transmission loss TL_n and the absorption coefficient α can be calculated using the following equations: