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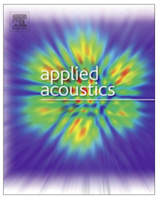

A modified electro-acoustical reciprocity method for measuring low-frequency sound source in arbitrary surroundings

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ABSTRACT

The reciprocity principle provides a possible means of measuring the low-frequency volume velocity of a sound source in arbitrary surroundings; however, the auxiliary transducer in the reciprocity experiment is required to be absolutely reciprocal, which means that the radiation property and the receiving property of the transducer are identical. However, it is not always easy to obtain such a low-frequency reciprocal transducer, because some issues like nonlinearity would lead the transducer to be non-reciprocal. In this study, a modified method is proposed to conduct the reciprocity measurement using an ordinary loudspeaker instead of a strictly reciprocal one as the auxiliary transducer. Firstly, the relationship is established between the measurement error and the inconsistency of auxiliary loudspeaker's radiation property and receiving property. Furthermore, a modified reciprocity method is proposed to compensate the inconsistency. Finally, experiments are carried out with the modified reciprocity method in both an anechoic room and a reverberation room with two different auxiliary loudspeakers. The experimental results of the modified reciprocity method agree with the results obtained with the free field method very well.

1. Introduction

Volume velocity is a useful parameter required in sound source evaluation and application [1,2]. Measurement of this parameter is usually carried out in special test rooms, such as the anechoic room and the reverberation room. Some scholars put forward several designs for sources with known volume velocity [3–5], such as the Salava's method, the internal pressure measurement method, the compression chamber method, and the blocked pipe method. In these methods, an additional transducer is used to produce a signal which is related to the volume velocity of the tested sound source according to a known theoretical or empirical formula. Such a signal may be proportional to the velocity, acceleration or volume displacement of loudspeaker membrane or coil. These methods are excellent at creating a new volume-velocity source, but they may be stranded when measuring some ready-made loudspeakers. For example, if a loudspeaker has a fixed back cavity and the back cavity cannot be destroyed, then the internal pressure measurement method, the compression chamber method and the blocked pipe method are not applicable because it is impossible to install a microphone in the back cavity.

Several alternative approaches have been proposed to estimate the free-field response functions with signal processing techniques, such as the impulse Fast Fourier Transform technique (impulse FFT), the time delay spectrometry technique (TDS), the maximum-length sequence technology (MLS), and the coherent averaging method [6–8]. The critical step in these approaches is extracting the direct wave radiated by the sound source. These approaches could be applied to test the volume velocity of sound source in some complex surroundings, but not for low-frequency source when the experiment is carried out in a small room.

The principle of reciprocity provides a possible means of measuring the volume velocity of a low-frequency sound source in arbitrary surroundings. In acoustics, this principle was first formulated by Helmholtz in 1860. Then Rayleigh proposed the generalized reciprocity principle and demonstrated that this principle exists in all linear, passive, and stable dynamic systems [9–12]. As early as 1970s, Ten Wolde proposed an electro-acoustical reciprocity method for measuring the volume velocity of a monopole sound source [2]. Later, Kim also estimated the volume velocity of a sound source in an enclosure using the principle of vibroacoustic reciprocity [1]. Ten Wolde was the pioneer of applying the reciprocity principle in many engineering problems. In a review article, he summarized the advantages of the electro-acoustical reciprocity method: (1) applicability in any reciprocal

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surroundings; (2) capability of determining of the intensity of sound source in situ; (3) good accuracy because electrical quantities and sound pressure can be measured precisely [2].

The authors of this paper followed Ten Wolde's method to establish a convenient, low-cost, and practical approach for testing the low-frequency properties of loudspeakers. An electro-acoustical reciprocity testing system was set up to measure the volume velocity response function of a sound source [13]. Large local peaks and dips were observed at some frequencies in the curve of the volume velocity response function, and they occurred at low coherence value. Polynomial fitting was used to remove the local peaks and dips; as a consequence, the results of reciprocity method agreed with the result of reference method (the free field method) very well.

However, later comparison with the free-field data showed that the results are not accurate in the low-frequency band. The possible causes were analyzed and ruled out one by one, and at last it was found that the auxiliary transducer (an electrodynamic loudspeaker) is not absolutely reciprocal in the low-frequency band. The term "absolutely reciprocal" means that the radiation property is equal to the receiving property. Finding an absolutely reciprocal transducer seems to be the only solution, but such an electrodynamic loudspeaker is not always easy to obtain. It is well known that a loudspeaker becomes nonlinear when operating at large displacement. The poor radiation efficiency of electrodynamic loudspeaker at low frequencies makes it almost impossible to increase the driving current under the condition of keeping the loudspeaker linear and reciprocal.

In this study, the influence of a non-reciprocal auxiliary loudspeaker on the reciprocity method is analyzed and a modified method is proposed to correct this influence. In Section 2.1, the principles of electro-acoustical reciprocity and electro-acoustical-electro reciprocity are introduced briefly, and a typical result of electro-acoustical-electro reciprocity experiment is given to illustrate the behavior of a non-reciprocal system. Then the influence of a non-reciprocal auxiliary loudspeaker is analyzed and the solution is proposed in Section 2.2. In Section 3, experiments are carried out to examine the modified method.

2. Method

2.1. The principles of reciprocity

In this section, the basic theory of the electro-acoustical reciprocity principle and the electro-acoustic-electro reciprocity principle are briefly introduced.

2.1.1. Electro-acoustical reciprocity

A classical electro-acoustical reciprocity system is shown in Fig. 1 [2,9,10]. The box stands for the entire electro-acoustical system, which contains four poles. Q_1 and P_1 stand for the volume velocity and the sound pressure of the acoustical port, respectively.

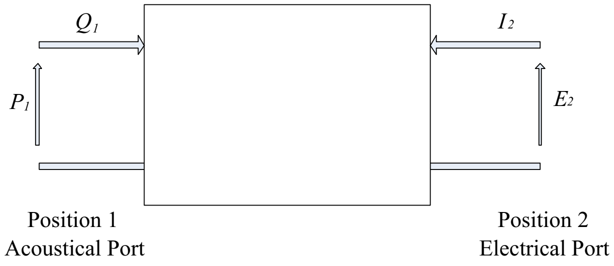

Fig. 1. A classical electro-acoustical system.

I_2 and E_2 stand for the electric current and the open output voltage of the electrical port, respectively.

If the system is reciprocal, the transfer function from position 1 to position 2 is equal to the transfer function from position 2 to position 1. Hence the signals coming in or out of the four poles are related:

$$\left.\frac{E_2'}{Q_1'}\right|_{I_2'=0} = \frac{P_1''}{I_2''}\bigg|Q_1''=0 \tag{1}$$

The prime ("′") in Eq. (1) indicates that the variable is measured in the direct experiment, and the double prime ("″") indicates that the variable is measured in the reciprocal experiment. According to Eq. (1), the volume velocity of a sound source can be obtained by measuring E_2', I_2'' and P_1'':

$$Q_1' = E_2' \cdot \frac{I_2''}{P_1''} \tag{2}$$

It should be pointed out that several conditions must be satisfied in Eq. (2) [10]: (1) the testing environment must be linear, passive, and stable, or in other words, reciprocal; (2) the auxiliary loudspeaker must be absolutely reciprocal; (3) the sound source is an omni-directional point sound source; (4) the directivity of the microphone should be consistent with that of the sound source; (5) the voltage should be measured under the condition that the electrical port is open.

In the low frequency range, an electrodynamic loudspeaker with a back cavity could be regarded as a point sound source, and the directivity of a microphone is omni-directional, so the third and fourth conditions are satisfied. The fifth condition could also be satisfied by disconnecting the electrical port in the reciprocity experiment. In order to check the first and second conditions, the principle of electro-acoustic-electro reciprocity is required [10].

2.1.2. Electro-acoustic-electro reciprocity

Similar to the electro-acoustical reciprocity system, an electro-acoustic-electro reciprocity system consists of an electrical system, an acoustical system and another electrical system connected in series. A similar relationship also exists between the signals coming in and out of the system:

$$\left.\frac{E_2'}{I_1'}\right|_{I_2'=0} = \left.\frac{E_1''}{I_2''}\right|_{I_1''=0} \tag{3}$$

From Eq. (3), it can be known that if the transfer functions in the direct and reciprocal experiments are equal, the acoustical system and the two electrical systems are reciprocal.

An electrodynamic loudspeaker is reciprocal theoretically [9,10,13]. However, it has very poor low-frequency radiation efficiency, so the amplitude of input signal of the loudspeaker has to be large enough to ensure sufficient signal-to-noise ratio (SNR) in the response signals (E_2', E_1''). However, large current in the loudspeaker may lead to nonlinearity or different system properties in the transmitting and the receiving modes, breaking the precondition of Eq. (2).

In an anechoic room, an electro-acoustic-electro reciprocity experiment is carried out with two different electrodynamic loudspeakers, which are described in Section 3.1. Fig. 2 shows the ratio of the transfer function in the direct experiment over the transfer function in the reciprocal experiment. If the two transfer functions are equal, the amplitude ratio should be 0 dB in Fig. 2(a) and the phase difference should be 0 degree in the full frequency band in Fig. 2(b). However, the curves significantly deviate from 0 dB and 0 degree in the low frequency band, suggesting that the system is non-reciprocal. The acoustical environment is a free field, which