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Measurement methods of ultrasonic transducer sensitivity

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ABSTRACT

Sensitivity is an important parameter to describe the electro-acoustic energy conversion efficiency of ultrasonic transducer. In this paper, the definition of sensitivity and reciprocity of ultrasonic transducer is studied. The frequency response function of a transducer is the spectrum of its sensitivity, which reflects the response sensitivity of the transducer for input signals at different frequencies. Four common methods which are used to measure the disc-vibrator transducer sensitivity are discussed in current investigation. The reciprocity method and the pulse-echo method are based on the reciprocity of the transducer. In the laser vibrometer method measurement, the normal velocity on the transducer radiating surface is directly measured by a laser vibrometer. In the measurement process of the hydrophone method, a calibrated hydrophone is used to measure the transmitted field. The validity of these methods is checked by experimental test. All of the four methods described are sufficiently accurate for transducer sensitivity measurement, while each method has its advantages and limitations. In practical applications, the appropriate method to measure transducer sensitivity should be selected based on actual conditions.

1. Introduction

Ultrasonic transducer is a critical component that used for the transformation of acoustic energy and electric energy in ultrasonic non destructive detection system [1]. Sensitivity is an important parameter to describe the electro-acoustic transducer energy conversion efficiency, and is a key indicator of transducer performance.

As discussed in the following reports, there are several common methods used for measuring the ultrasonic transducer sensitivity. In the early 1940s, Maclean and Cook developed a method of measuring electro-acoustic transducer sensitivity based on the reciprocity principle. In the process, a reciprocal transducer is used [2]. Van Buren (1980) has proposed an improved reciprocal method. During the measurement, three transducers were arranged in a straight line along a calibrated support. The measured transducer is placed in the middle of the transmitter and the reciprocity transducer. [3]. Zhang Tao et al. (2011) developed a free field comparison technique based on the reciprocity principle. The transducer sensitivity is achieved by comparing with the standard hydrophone or standard acoustic source [4]. Schmerr (2006) proposes a pulse-echo technique. The transducer was excited by electrical pulses, and the ultrasonic waves were reflected by the reflector and received by the measured transducer [5]. The British national physical laboratory (NPL) established a standard device to calibrate the ultrasonic hydrophone sensitivity. A laser interferometer was used to measure the particle vibration displacement in the acoustic field [6]. Huang Yongjun (2005) puts forward the laser vibrometer method. The particle vibration velocity in the acoustic field is measured by the laser vibrometer [7]. S.J. Everitt (2000) measures the transducer sensitivity by using a calibrated hydrophone [8].

In this paper, the definition of sensitivity and reciprocity of the transducer is studied. Four general methods of measuring the disc-vibrator ultrasonic transducer sensitivity are discussed. The validity of the four methods is also checked by experiments.

2. Theory

Ultrasonic transducer is an electro-acoustic energy conversion component. It can be used as an acoustic transmitter which converts the electrical energy that converts its electrical terminal into the mechanical energy in the form of the surface vibration. The mechanical energy propagates in the coupling medium in the form of wave. In this case, the sensitivity of the transducer is defined as transmitting sensitivity. The ultrasonic transducer can also convert the displacements that received by its surface into the electrical

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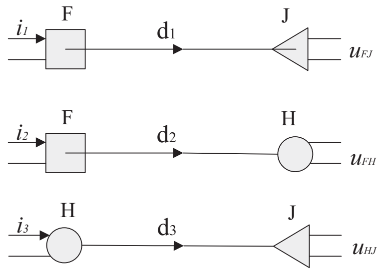


Fig. 1. Diagram of reciprocity method measuring process.

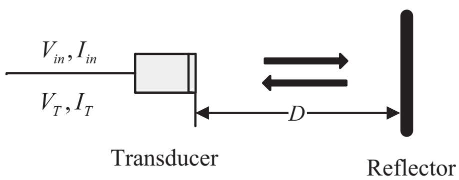


Fig. 2. Measuring principle diagram the pulse-echo method.

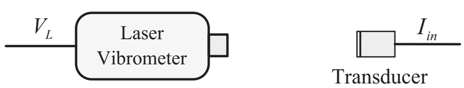


Fig. 3. Measuring principle diagram of the laser vibrometer method.

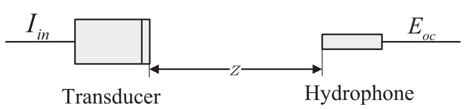


Fig. 4. Measuring principle diagram of the hydrophone method.

signals output from its electrical terminal. The sensitivity of the transducer is referred to receiving sensitivity. According to system theory, sensitivity is the output increment caused by per unit input increment, namely, the differential of the function relation between the input and output under the condition of specific input values. The relation between the input of the system $x(t)$, the output $y(t)$, and the impulse response function $h(t)$ is $y(t) = x(t)h(t)$. Then the sensitivity is defined as

$$S(t) = dy(t)/dx(t) = h(t) \tag{1}$$

The frequency-domain expression of the sensitivity is

$$S(\omega) = Y(\omega)/X(\omega) = H(\omega) \tag{2}$$

Meanwhile, the frequency response function of a system is the spectrum of its sensitivity, which reflects the response sensitivity of the system for input signals of different frequencies. The current approaches for the test of ultrasonic transducer sensitivity are the measurement of the sensitivity spectrum, and the frequency response function. Therefore it's more rigorous that the definition of ultrasonic transducer sensitivity is given in the form of the sensitivity spectrum.

2.1. Transmitting sensitivity

In the transmitting process, the input signal through the electrical terminal of the transducer is the current I_{in}, while the output of its mechanical terminal is the normal velocity v_t on the transducer surface or the acoustical point pressure p_z at an axial distance z of the transducer [9]. The transmitting sensitivity of ultrasonic transducer is defined to be [10,11]

$$S_{vI}(\omega) = v_t(\omega)/I_{in}(\omega) \tag{3}$$

$$\text{or } S(\omega) = p_z(\omega)/I_{in}(\omega) \tag{4}$$

The distribution of the acoustic pressure along the axis of the disc wave source is

$$p_z = 2p_0 \sin\frac{\pi}{\lambda}\left(\sqrt{R^2+z^2} - z\right) \tag{5}$$

where p_0 is the acoustic pressure on the surface of the transducer, λ the wavelength of the ultrasonic wave in the medium, R the radius of the transducer.

The acoustic pressure p_0 and the normal velocity v_t on the transducer surface are represented by

$$p_0 = v_t \rho c \tag{6}$$

where ρ, c are the density and the acoustic wave speed of the medium in which the transducer is inserted, respectively [9].

The correlation between S_{vI} and S is obtained by combining Eqs. (3)–(6),

$$S_{vI}(\omega) = \frac{S(\omega)}{2\rho c \sin\frac{\pi}{\lambda}\left(\sqrt{R^2+z^2} - z\right)} \tag{7}$$

2.2. Receiving sensitivity

In the receiving process, the input of the mechanical terminal of the transducer is the blocked force F_B acting on the transducer or the received pressure p_f at the sensitive area of the transducer [1], while the output of the electrical terminal is the open circuit output voltage E_{oc} over the transducer [9]. Thus the receiving sensitivity is generally defined as [11]

$$M_{EF_B}(\omega) = E_{oc}(\omega)/F_B(\omega) \tag{8}$$

$$\text{or } M(\omega) = E_{oc}(\omega)/p_f(\omega) \tag{9}$$

2.3. Reciprocity

According to the acoustic principle of reciprocity, reciprocal transducer has the features as:

$$M(\omega)/S(\omega) = J \tag{10}$$

where J is the reciprocity parameter. For the plane wave:

$$J = \frac{2A}{\rho c} \tag{11}$$

where A is the transducer surface area, ρ is the density of the medium in which the transducer is inserted, c is the acoustic wave speed of the medium in which the transducer is inserted.

If the transducer is reciprocal, the open-circuit, blocked force, receiving sensitivity is identical to the transmitting sensitivity

$$M_{EF_B}(\omega) = S_{vI}(\omega) \tag{12}$$

$$|v_t(\omega)/I_{in}(\omega)| = |E_{oc}(\omega)/F_B(\omega)| \tag{13}$$

Thus, we can apply the condition (12) and (13) into transducer reciprocity [10].

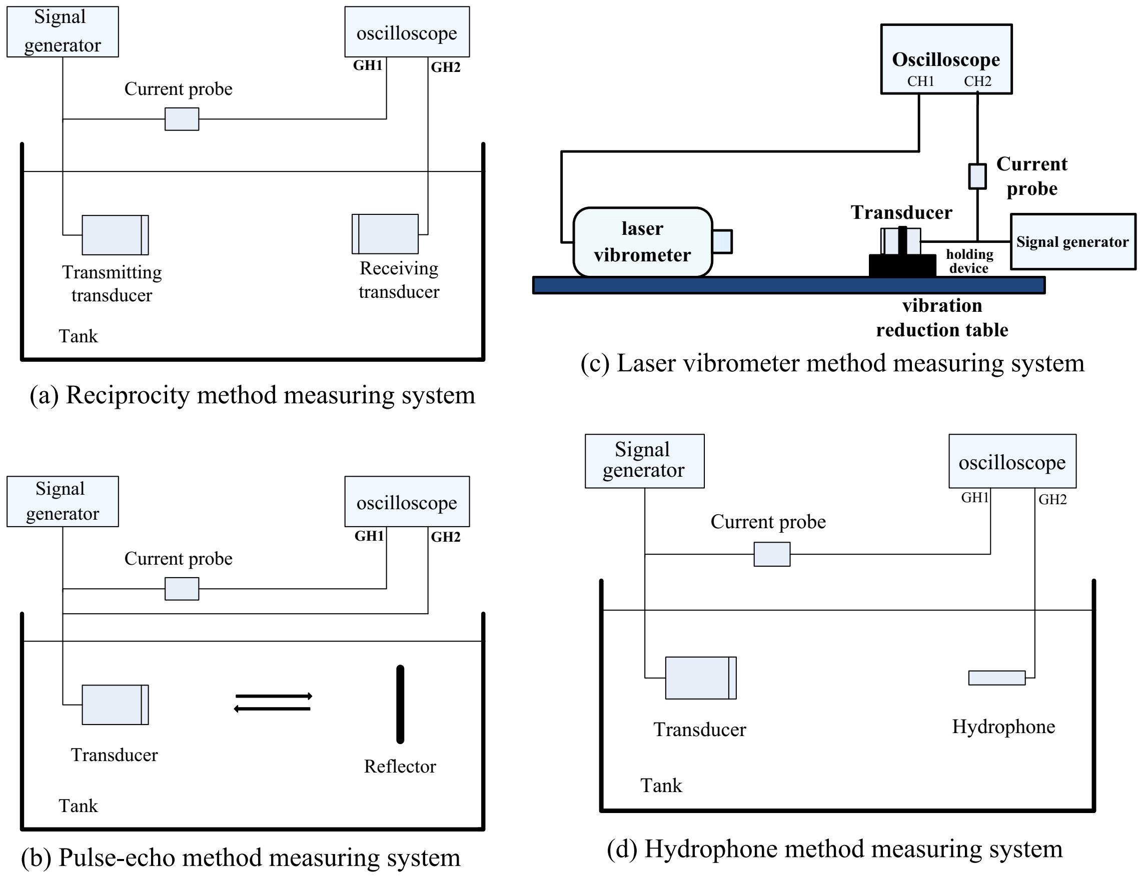


Fig. 5. Block diagrams of ultrasonic transducer sensitivity measurement experiments.

3. Methods

3.1. Reciprocity method

Reciprocity method requires three transducers in the measurement process, at least one of them is reciprocal transducer H, and the other two are transmitting transducer F and receiving transducer J, respectively. The receiving transducer is located in the far-field of the transmitting transducer. Three measuring combinations are shown in Fig. 1. In each process, the input current of the transmitting transducer and the output open circuit voltage of the receiving transducer are measured.

Based on the principle of reciprocity, under the condition of far field the reciprocity transducer H meet the following equation,

$$M_H(\omega)/S_H(\omega) = 2A/\rho c = J \tag{14}$$

The receiving sensitivity of the measured transducer is calculated by

$$M(\omega) = [(Z_{FJ}(\omega)\cdot Z_{HJ}(\omega)/Z_{FH}(\omega))\cdot(d_1 d_3/d_2)\cdot J]^{\frac{1}{2}} \tag{15}$$

where $Z_{FJ}(\omega) = \frac{u_{FJ}(\omega)}{i_1(\omega)}$, $Z_{HJ}(\omega) = \frac{u_{HJ}(\omega)}{i_3(\omega)}$, $Z_{FH}(\omega) = \frac{u_{FH}(\omega)}{i_2(\omega)}$ respectively are the complex transfer impedance of the transducer pairs (F–J), (F–H) and (H–J) [4].

After $M(\omega)$ is obtained, the transmitting sensitivity of the measured transducer can be calculated based on the principle of reciprocity,

$$S(\omega) = M(\omega)/J \tag{16}$$

3.2. Pulse-echo method

The measuring principle diagram of the pulse-echo method is shown in Fig. 2. The measured transducer is excited by electrical pulses. The ultrasonic waves which transmit into water are reflected from the solid block at normal incidence. The reflected waves are received by the measured transducer and convert to electrical signal output. The input voltage and current of the transducer respectively are V_{in}, I_{in}, the output voltage and current are V_T, I_T, respectively.

The received open-circle voltage of the transducer is

$$E_{oc}(\omega) = Z_{in}(\omega)I_T(\omega) + V_T(\omega) \tag{17}$$

where $Z_{in}(\omega)$ is the electrical impedance.

Based on the transducer reciprocity $M_{EF_B}(\omega) = S_{vI}(\omega)$ or $\frac{E_{oc}(\omega)}{F_B(\omega)} = \frac{v_t(\omega)}{I_{in}(\omega)}$, a relation between $E_{oc}(\omega)$ and $S_{vI}(\omega)$ is obtained

$$E_{oc}(\omega) = S_{vI}(\omega)F_B(\omega) \tag{18}$$

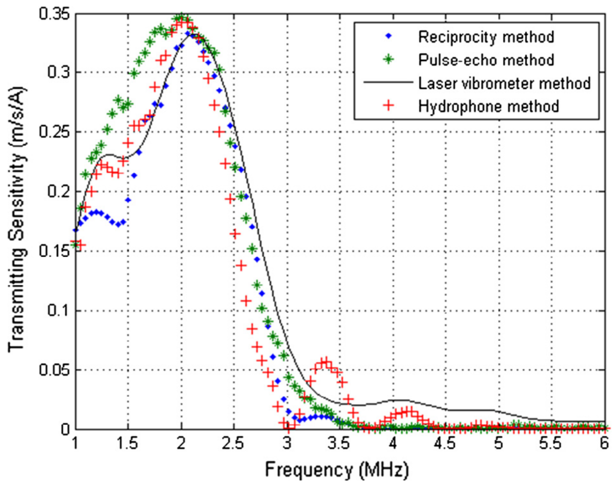
Combine (17) and (18) produces

$$S_{vI}(\omega)F_B(\omega) = Z_{in}(\omega)I_T(\omega) + V_T(\omega) \tag{19}$$

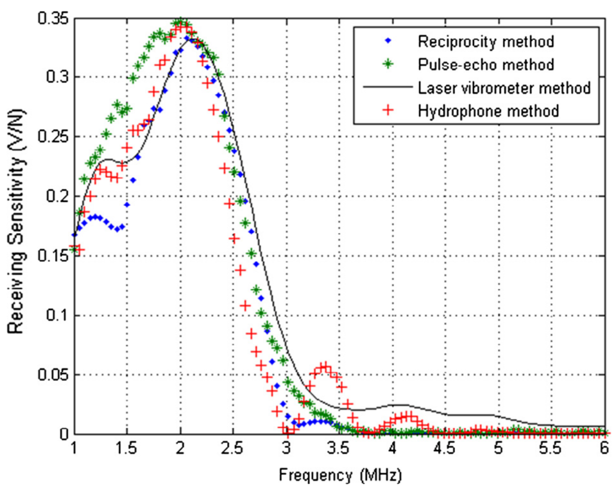
and also:

$$F_B(\omega) = \frac{F_B(\omega)}{F_t(\omega)}\frac{F_t(\omega)}{v_t(\omega)}\frac{v_t(\omega)}{I_{in}(\omega)}I_{in}(\omega) = t_A(\omega)Z_r S_{vI}(\omega)I_{in}(\omega) \tag{20}$$

where $F_t(\omega)$, $v_t(\omega)$ are the compressive force and uniform outward normal velocity of ultrasonic transducer surface, respectively. $t_A(\omega)$ is the acoustic/elastic transfer function.

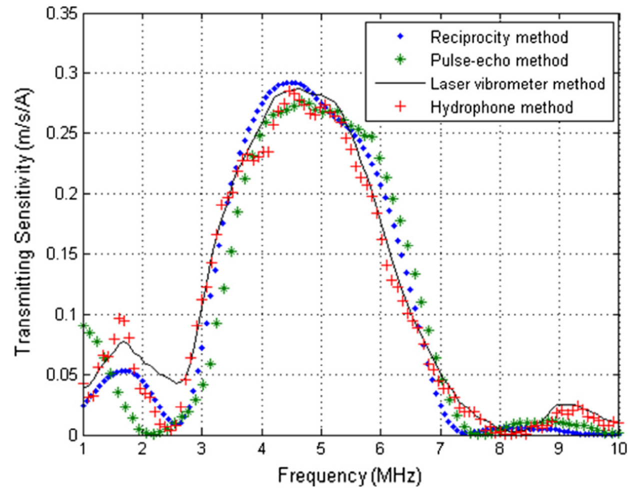


(a) Transmitting sensitivity

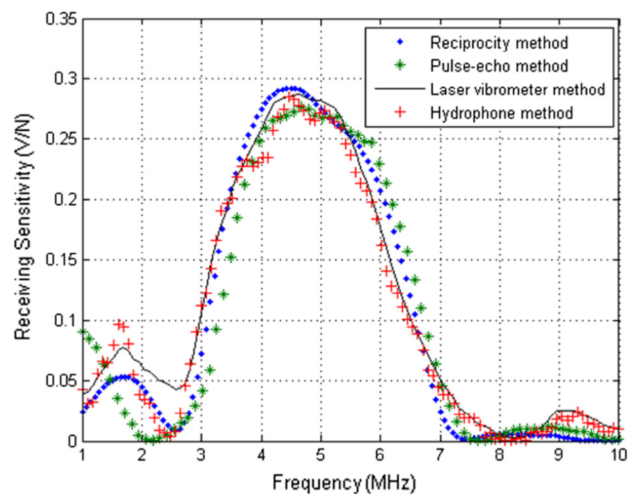


(b) Receiving sensitivity

Fig. 6. Transmitting and receiving sensitivity of the 2.25 MHz ultrasonic transducer.



(a) Transmitting sensitivity



(b) Receiving sensitivity

Fig. 7. Transmitting and receiving sensitivity of the 5 MHz ultrasonic transducer.

The transmitting sensitivity of the transducer is obtained by combining (19), (20) and $Z_{in}(\omega) = V_{in}(\omega)/I_{in}(\omega)$,

$$S_{vI}(\omega) = \sqrt{\frac{V_{in}(\omega)I_T(\omega) + V_T(\omega)I_{in}(\omega)}{t_A(\omega)Z_r I_{in}^2(\omega)}} \quad (21)$$

where the sound radiate impedance Z_r can be calculated as:

$$Z_r = \rho_1 c_{p1} A$$

where ρ_1 is the density of water, c_{p1} is the wave speed of signal in the water, A is the transducer surface area [5].

Based on the principle of reciprocity, the receiving sensitivity of the measured transducer can be calculated by

$$M_{EF_B}(\omega) = S_{vI}(\omega)$$

3.3. Laser vibrometer method

The principle diagram of the laser vibrometer method is shown in Fig. 3. The measured transducer is excited by electrical pulses. The transducer emits ultrasonic waves and causes vibration of the transducer radiating surface. The normal velocity on the transducer radiating surface is directly measured by the laser vibrometer. The input current through the transducer is I_{in}, and the output voltage of the laser vibrometer is V_L.

Since the conversion coefficient M_L of laser vibration is known, the normal velocity on the transducer radiating surface can be calculated by

$$v_t(\omega) = \frac{V_L(\omega)}{M_L} \quad (22)$$

Based on the definition of sensitivity, the transmitting sensitivity of the measured transducer can be calculated by

$$S_{vI}(\omega) = \frac{v_t(\omega)}{I_{in}(\omega)} = \frac{V_L(\omega)}{I_{in}(\omega)M_L} \quad (23)$$

If the measured transducer is reciprocal, based on the principle of reciprocity, the receiving sensitivity of the measured transducer can be calculated by

$$M_{EF_B}(\omega) = S_{vI}(\omega) \quad (24)$$

3.4. Hydrophone method

The principle diagram of the hydrophone method is shown in Fig. 4 [1]. The measured transducer is excited by electrical pulses and the input current is I_{in}. The measured transducer and the calibrated hydrophone are placed coaxially. The hydrophone is located in the far-field region of the measured transducer and the distance between them is z. The output open circle voltage of the hydrophone is E_{oc}.

Since the hydrophone sensitivity $M_H(\omega)$ is known, the sound pressure received by the hydrophone is calculated by

$$p_z(\omega) = \frac{E_{oc}(\omega)}{M_H(\omega)} \tag{25}$$

Combining (4) and (25) produces

$$S(\omega) = \frac{p_z(\omega)}{I_{in}(\omega)} = \frac{E_{oc}(\omega)}{M_H(\omega) \cdot I_{in}(\omega)} \tag{26}$$

If the measured transducer is reciprocal, the receiving sensitivity of the measured transducer can be calculated by

$$M(\omega) = \frac{S(\omega)}{J} \tag{27}$$

4. Experimental results

4.1. Experimental setup

The block diagrams of ultrasonic transducer sensitivity measurement experiments are shown in Fig. 5. Two ultrasonic transducers were investigated, both of them are in planar type. The central frequency of one of them is 2.25 MHz with 13 mm diameter, the other one is 5 MHz central frequency and 19.05 mm diameter. The signal generator (American BNC Company's MODEL 645 arbitrary waveform generator) emits electrical pulses to excite the measured transducer. The excitation current or receiving current is measured by the current probe (Tektronix P6022 current probe). The oscilloscope (Tektronix DPO4104 oscilloscope) is used to acquire signals. The receiving transducer and the transmitting transducer are coaxially arranged in the measuring process of reciprocity method and the receiving transducers are located in the far field of the transmitting transducers (Fig. 5(a)). The laser vibrometer (Germany Polytec Company's OFV5000 laser vibrometer) and the measured transducer are placed coaxially to measure the vibration velocity of transducer surface directly in the process of laser vibrometer method (Fig. 5(c)). In the process of the hydrophone method, the measured transducer and the hydrophone (American Precision Acoustics Company's needle hydrophone whose effective aperture is 0.5 mm) are placed coaxially and the hydrophone is placed in the far-field of the measured transducer (Fig. 5(d)).

4.2. Experimental results

The measurement results of the four methods are shown in Figs. 6 and 7.

The sensitivity of the 2.25 MHz transducer is shown in Fig. 6, where Fig. 6(a) shows the transmitting sensitivity and Fig. 6(b) presents the receiving sensitivity.

The sensitivity of the 5 MHz transducer is shown in Fig. 7, where Fig. 7(a) shows the transmitting sensitivity and Fig. 7(b) presents the receiving sensitivity.

The sensitivity measured by the four methods are almost the same. Thus, it can be concluded that all these methods are correct and can be applied practically.

5. Conclusion

Analysis and experiment show that all methods described are sufficiently accurate for transducer sensitivity measurement, while each method has its advantages and limitations. The reciprocity method is a direct measurement method and the measurement process is complicated. It is susceptible to the impact of transducer nonlinearity and non-reciprocity. The pulse-echo method is a direct measurement method which requires the measured transducer to be reciprocal, while the measurement devices are simple, and it's easy to operate. For the laser vibrometer method measurement, the normal velocity on the transducer radiating surface is directly measured and it can only measure transmitting sensitivity. The measuring process is in the air and does not involve acoustic propagation characteristics, so as not to introduce corresponding error. The hydrophone method is an indirect measurement method which can only measure transmitting sensitivity. It is simple and practical, while a calibrated hydrophone is needed. The reciprocity method, the pulse echo method and the hydrophone method are carried out in the water far field and involve acoustic propagation characteristics so as to introduce corresponding error. In specific applications, the particular choice of method is based on practical considerations.

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