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Measure Low Level and High Frequency Ultrasonic Power by Self-Reciprocity Technique

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Summary

Radiation force balance (RFB) method, a widely accepted method to measure ultrasonic power, suffers poor performance at low level power (<10 mW) and high frequency range (>15 MHz) because of the medium attenuation, thermal drift and target imperfections. In this article, considering the diffraction and attenuation effects, we derived the power formula for both plan piston transducers and focusing transducers based on reciprocity theorem, turned power measurement to the measurement of first reflected echo voltage and short-circuit current. The diffraction effect for focusing transducers was evaluated using numerical computation of the Rayleigh integral. One way to estimate the reflection coefficient of focusing beams on heterogeneous interface was also depicted. The sensitivity can be improved and the high frequency ultrasonic power is extended to 0.1 mW and 25 MHz. Comparison experiment with RFB method illustrates that ultrasonic power measurement by self-reciprocity technique is sound in theory and feasible in practice, and can be extended to high frequency ultrasound measurement.

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1. Introduction

To an increasing extent, high frequency ultrasound is used in diverse applications. The shift of the operating frequency to tens of megahertz can improve the performance of devices in many cases. High-frequency diagnostic ultrasound (>10 MHz) has drawn wide interest in areas such as small animal imaging [1], intravascular ultrasound (IVUS) [2] and ocular diagnostics [3, 4]. The improved spatial resolution at higher frequencies allows for imaging smaller pathologic and anatomic structures. In the nondestructive testing area, it can also benefit from the shorter pulse lengths [5, 6] and higher spatial resolution of imaging systems [7]. In the Consultative Committee for Acoustics, Ultrasound and Vibraiton (CCAUV) organized international comparison, the upper limit of the frequency has increased from 10.5 MHz in 2002 to almost 16 MHz in 2010 [8, 9].

The RFB (Radiation Force Balance) method has been widely accepted and used to determine ultrasonic power generated by an ultrasonic transducer, whose upper frequency limit is 25 MHz in the latest IEC standard [10]. The great advantage of RFB is that a value for the total radiated power is obtained without the need to integrate field data over the cross-section of the radiated sound beam. Nevertheless, this method can only get the time-averaged ultrasonic power. Affected by the thermal drifts of the balance, radiation force balances method has its limit in milli-watts level measurement. To overcome these problems, an expensive electronic, self-compensating microbalance has to be used. In the case of very low level power, measurements below 10 mW by RFB are considered less reliable and have less confidence. While in the high frequency case, poor performance mainly attributes to the attenuation correction and target imperfections [10, 11]. As for another alternative method – planar scanning technique, it is sophisticated and time consuming. Thus, how to measure the low level and high frequency ultrasonic power fast and conveniently is meaningful.

In this paper, based on the reciprocity theorem [12, 13, 14, 15, 16], the self-reciprocity technique has been extended to the ultrasonic power measurement both for plane piston and focusing transducers. Through the measurement of the reflected echo voltage and short-circuit current, together with the diffraction and attenuation correction, the output power generated by the transducer can be measured conveniently. Further experiments demonstrate the self-reciprocity technique is advantageous over traditional RFB both in the milli-watts level and high frequency power measurement.

2. Principle of Self-reciprocity technique

2.1. Plane piston transducers

The experiment setup of reciprocity method is shown in Figure 1. According to the electromechanical reciprocity

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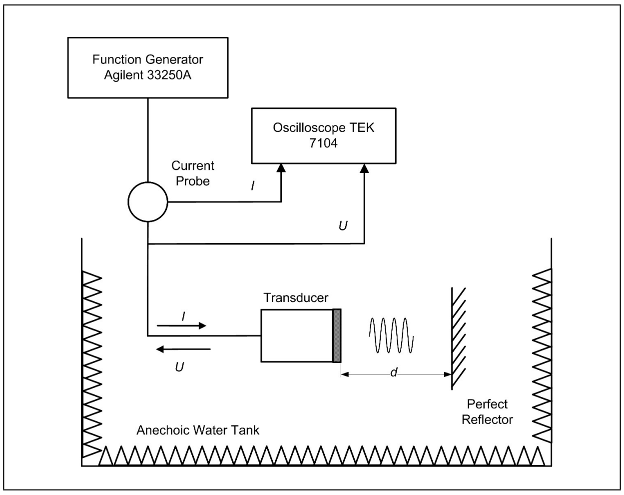

Figure 1. Experiment setup of self-reciprocity technique.

principle, a reciprocal plane piston transducer has the properties[12, 13]

$$\frac{|V|}{|I|} = \frac{|U|}{|F|}, \tag{1}$$

where V is the uniform velocity of the radiating surface of the projector for an input current I and U is the open circuit voltage of the transducer when a force F acting on the transducer, assuming the transducer is rigid.

Defining the free-field transmitting current response S_I and the free-field receiving voltage sensitivity M as

$$S_I = \left|\frac{P_{\mathrm{tr}}}{I}\right|, \tag{2}$$

$$M = \left|\frac{U}{P_{\mathrm{rec}}}\right|, \tag{3}$$

where P_{tr} is the free-field pressure on the surface of the transducer when the input current is I and P_{rec} is the acoustic pressure in the undisturbed free field of a plane wave in front of the receiver which gives the open circuit voltage U. In practice, it is not generally possible to produce ideal plane or spherical reciprocity conditions, an intermediate condition is used and several corrections have to be considered such as diffraction and attenuation effects. The former equation can be written as

$$P_{\mathrm{rec}} = P_{\mathrm{tr}} \exp\big(-2\alpha d\big) D(2d) r, \tag{4}$$

$$\frac{M}{S_I} = \Big(\frac{U}{P_{\mathrm{rec}}}\Big) \Big/ \Big(\frac{P_{\mathrm{tr}}}{I}\Big) = \frac{UI}{P_{\mathrm{tr}} P_{\mathrm{rec}}} = \frac{2A}{\rho c} = J_p, \tag{5}$$

Where α is the amplitude attenuation coefficient for sound in water, d is the distance between the projector and the reflector, r is the amplitude reflection coefficient of the water-steel interface, A is the area of the transducer radiating surface and $D(x)$ characterizes the diffraction loss in sound propagation in case no attenuation exists [17, 18, 19, 20, 21, 22], x defines the distance between the surface of the projector and the point in interest. Thus we can get

$$p_{\mathrm{tr}}^2 = \frac{UI\rho c \mathrm{e}^{2ad}}{2ArD(2d)}. \tag{6}$$

Actually the ultrasonic transducer has internal resistance, the open circuit voltage can not be measured directly. According to Thevenin law,

$$\frac{U}{U_I} = \frac{I_k}{I}, \tag{7}$$

Where U_I is the measured first echo voltage with the transducer connected, I_k is the measured current through the transducer replaced by a short-circuit link. Considering the relationship of ultrasonic pressure and power, the average output power of the projector P_{out} can be derived.

$$p_{\mathrm{out}} = \frac{p_{\mathrm{tr}}^2}{2\rho c} A = \frac{U_I I_k \mathrm{e}^{2ad}}{4rD(2d)}. \tag{8}$$

To evaluate the experimental results, the radiation conductance G_r is defined as

$$G_r = \frac{p_{\mathrm{out}}}{U_{\mathrm{in}}^2}, \tag{9}$$

where U_{in} is the root mean square of the driving voltage.

The self-reciprocity technique thus turns the acoustic measurement to electrical parameters measurement. Owing to the modern oscilloscopes having wide bandwidth and high resolution, it can be easily extended to higher frequencies and rather low level ultrasonic power measurement. Also, in the self-reciprocity technique, pulsed-mode instead of continuous-mode measurement can minimize the transducer heating which is advantageous over RFB.

2.2. Focusing transducers

While for the focusing transducers, the described self-reciprocity technique can also be applied. The reciprocity theorem of convergent spherical transducer is expressed as [23]

$$\frac{M}{S_I} = \frac{2A}{\rho c} = J_F, \tag{10}$$

Where J_F is the convergent spherical wave reciprocity coefficient for the focusing transducer, M is the free field voltage sensitivity for the focusing transducer with a spherical shape defined as the ratio of the open-circuit voltage U to the average acoustic pressure P_{rec}. S_I is the free-field transmitting current response for the focusing transducer. Similar to the reciprocity described for the plane piston transducers, the equations for the calculation of ultrasonic power for focusing transducers can also be derived. Only the differences are described here. A is the radiating surface and $A = 2\pi l_f^2(1 - \cos\beta)$ for the concave spherical focusing transducers, a is the half-aperture of the transducer and l_f the focal length respectively, $\beta = \sin^{-1}(a/l_f)$ is the beam convergence angle.

As shown in Figure 2, to derive the ultrasonic power, the diffraction loss associated with the curved ultrasonic transducers has to be corrected. Unlike the correction method using in plane piston transducers, the Rayleigh integral is used to calculate the ultrasonic pressure on the receiving area A'.

$$p = -\mathrm{j}\frac{\rho c V \mathrm{e}^{-\mathrm{j}\omega t}}{\lambda} \cdot \int_{-a}^{a}\int_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}} \frac{\mathrm{e}^{\mathrm{j}k\xi}}{\xi} \frac{l_f}{\sqrt{l_f^2 - x^2 - y^2}} \,\mathrm{d}y\,\mathrm{d}x, \tag{11}$$

$$p_{\mathrm{rec}} = \frac{\iint_{A'} p\,\mathrm{d}S'}{A'} = \frac{\int_{-a}^{a}\int_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}} p \frac{l_f}{\sqrt{l_f^2-x^2-y^2}}\,\mathrm{d}y'\,\mathrm{d}x'}{A'}, \tag{12}$$

where ω and λ are the angular frequency and wave length of the ultrasound respectively, k is the wave number, $\mathrm{d}S'$ is the area element on A',

$\xi = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}$

is the distance from the field point (x', y', z') to the point (x, y, z) on the area element $\mathrm{d}S$,

$z = -\sqrt{l_f^2 - x^2 - y^2}$ and $z' = -\sqrt{l_f^2 - x'^2 - y'^2}$.

Thus the diffraction coefficient can be derived as

$$D(2l_f) = \frac{P_{\mathrm{rec}}}{P_{\mathrm{tr}}} = \frac{\mathrm{e}^{-\mathrm{j}\omega t} \iint_{A'} \left[\iint_A \frac{\mathrm{e}^{\mathrm{j}k\xi}}{\xi}\,\mathrm{d}S'\right]\mathrm{d}S'}{\lambda A'} = \frac{\int_{-a}^{a}\int_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}} p \frac{l_f}{\sqrt{l_f^2-x^2-y^2}}\,\mathrm{d}y'\,\mathrm{d}x'}{A'}. \tag{13}$$

Using the coordinate transformation, changing equation (13) to polar coordinate, the diffraction can be numerically calculated and the curves versus transducer radius with several focal lengths is shown in Figure 3. To be noted, the flattening for focal length 0.04 m mainly comes from the transducer radius is becoming comparatively large to the focal length.

Another factor needs to be considered is the refection coefficient of the water-steel interface. From the point of ray-acoustic, the incident angles of the focusing beam on the interface are different. While the reflection coefficient $r(\theta_i)$ is the function of the incident angle θ_i when θ_i is smaller than the critical angle.

$$r(\theta_i) = \frac{m\cos\theta_i - \sqrt{n^2 - \sin^2\theta_i}}{m\cos\theta_i + \sqrt{n^2 - \sin^2\theta_i}}, \tag{14}$$

where $m = \rho_2/\rho_1$, $n = c_1/c_2$, ρ_1, c_1 and ρ_2, c_2 are the density and sound velocity in water and the steel reflector respectively. Thus the average reflection coefficient for the convergent spherical beam can be derived as

$$r_{\mathrm{av}}(\beta) = \frac{1}{A}\iint_A r(\theta_i)\,\mathrm{d}S = \frac{1}{1-\cos\beta}\int_0^{\beta} r(\theta_i)\sin\theta_i\,\mathrm{d}\theta_i. \tag{15}$$

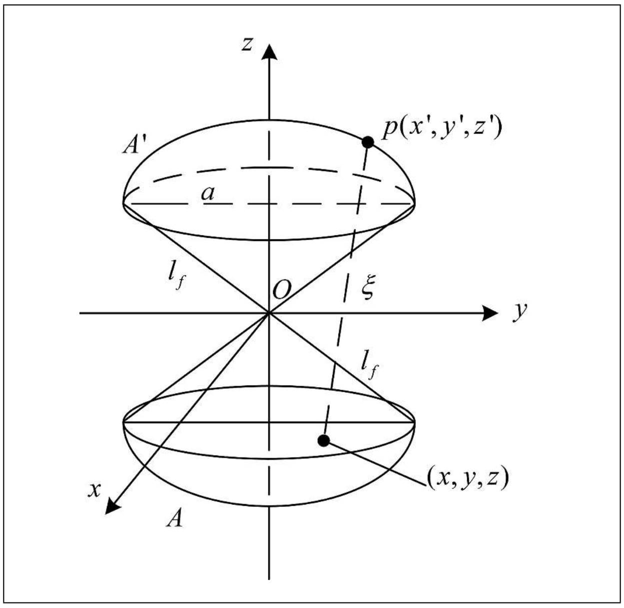

Figure 2. Geometry of the diffraction integration.

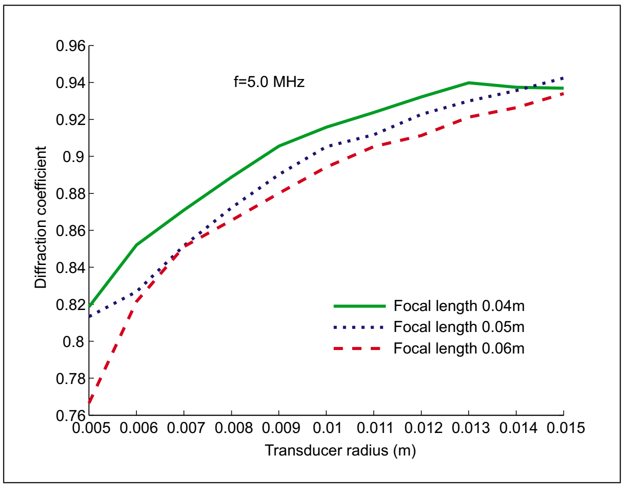

Figure 3. Diffraction coefficient versus transducer radius, depending on Focal length.

The average output power of the focusing transducer can be depicted as

$$p_{\mathrm{out}} = \frac{p_{\mathrm{tr}}^2}{2\rho c}A = \frac{U_I I_k \mathrm{e}^{2al_f}}{4r_{\mathrm{av}}D(2l_f)}. \tag{16}$$

3. Comparison experiment with RFB method

The RFB schematically diagramed in Figure 4 is used in our laboratory [10]. It has an absorbing target (HAM A, National Physical Laboratory, UK) connected to a commercial balance (UMX5, Mettler Toledo). The ultrasonic beam directs vertically upwards on the target and the output of balance is transferred to the computer. The ultrasonic power will be determined through the difference between the force measured with and without the ultrasonic radiation.

3.1. For plane piston transducers

The measurements were conducted at room temperature (20 °C), in degassed and demonized water as shown in Figure 1. The temperature of the bath was measured by Fluke F52-2 (Everett, WA), with a precision of ±0.1°C. Firstly we employ the water immersion plane piston transducer as the projector. Careful alignment of the transducer is a key part of the measurement procedure. At least five degrees of freedom have to be adjusted, two angular settings and three displacements. The transducer was driven by a pulse generator (33250A, Agilent Technologies, Palo Alto, CA). Pulsed-mode are used and duty cycles should be well chosen to avoid interference between incident and reflected waves. The interference between incident and reflected waves can be avoided as long as $n < 2df/c$, where n is the duty cycles, d is the distance between transducer and reflector, f is ultrasonic frequency and c is sound velocity. Excitation voltage and reflected echo was sampled and digitized by a digital oscilloscope (DPO7104, Tektronix, Portland, OR) . Short-circuit current was measured by TCP0030 current probe (Tektronix, Portland, OR).

As a comparison approach, the ultrasonic power was also measured by RFB method. Figure 5 shows two different transducers measurement result, (a) is for 1 MHz (Olympus A302S, Panametrics Inc., Waltham, MA; center frequency 1 MHz with a radius of 0.5 inch) and (b) for 25 MHz (Olympus V324, Panametrics Inc., Waltham, MA; with a radius of 0.25 inch). The lower limit of ultrasonic power determined using self-reciprocity is 0.1 mW in Figure 5a, much lower than 4.62 mW for the RFB. The radiation conductance in both technique is around 1.571 mS, the maximum derivation for self-reciprocity is 3.7% while 7.2% for RFB at 1MHz. For the 25 MHz ultrasonic power measurement, the lower limit using self-reciprocity is 1 mW while 4.18 mW for RFB. The radiation conductance is around 1.02 mS, the maximum derivation for self-reciprocity is 1.9% while 8.4% for RFB. The measurement uncertainty mainly attributes to the accuracy of the diffraction coefficient, it needs the effective area of the transducer to be used [24]. Other uncertainty sources include the determination of reflection coefficient and the indication error of the oscilloscope which are relatively small. Overall, the measurement uncertainty in self-reciprocity technique is estimated to be within with a careful alignment of the transducers. As an example, Table I ithe measured data of ultrasonic power at 1 MHz for plane piston transducer.

3.2. For spherically focusing transducers

For the ultrasonic power measurement using RFB for focusing transducers, the radiation force of a normal, incident, and focused beam is related to ultrasonic power P_{out} as [25]

$$P_{\text{out}} = \frac{2Fc}{1+\cos\beta}\exp\left(2\alpha d\right), \tag{17}$$

where β is the beam convergence angle, d is the distance between the transducer and the absorbing target and α is the attenuation coefficient of water. In this study a focusing transducer operating at 5 MHz was used (Olympus V308, Panametrics Inc., Waltham, MA; with a diameter of 0.75 inch). The comparison result with self-reciprocity technique is shown in Figure 6. The radiation conductance for the measurement is around 1.39 mS, the maximum deviation for self-reciprocity is 4.9% while 5.4% for RFB. The diffraction correction is also the main uncertainty source for focusing transducers in self-reciprocity technique. The overall uncertainty in self-reciprocity is estimated to be within ±8%.

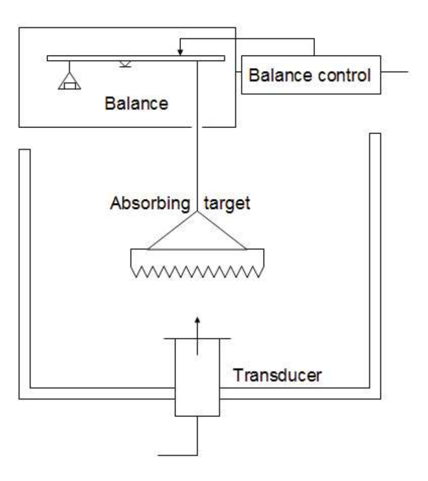

Figure 4. Schematic diagram of the Radiation Force Balance system.

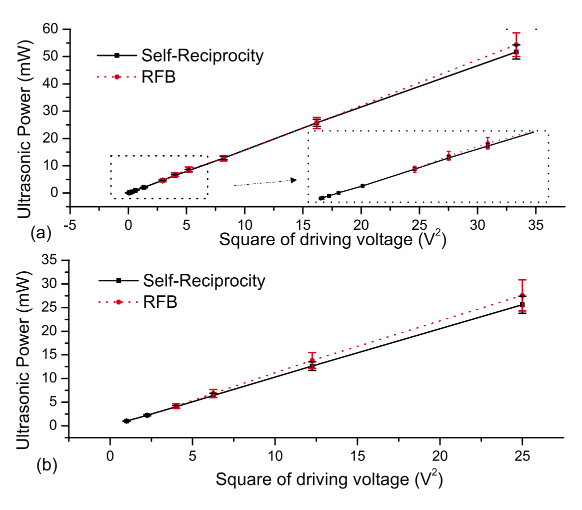

Figure 5. Comparison of RFB and Self-Reciprocity, (a) 1 MHz transducer (b) 25 MHz transducer.

4. Discussion and conclusion

One common way to validate a measurement method is to compare with another, preferably one based on a different physical principle. Thus, we applied the reciprocity theorem to the measurement of ultrasonic power and achieved

Table I. Output Power Measurement by Self-reciprocity and RFB Method. U_{in}: Driving voltage, U_I: Reflected loaded voltage, I_k: Short-circuit current, P_r: Power by reciprocity, Unc.: Uncertainty ($k = 2$), P_R: Power by RFB. Note: 1. / means not available; Frequency is 1 MHz. 2. For the RFB method, the uncertainty between (10–100) mW is 8% ($k = 2$), between (3–10) mW is 10% ($k = 2$). 3. The driving voltage is RMS value while the U_I and I_k are peak-to-peak values.

U_{in} [V]	U_I [mV]	I_k [mA]	P_r [mW]	Unc. [mW]	P_R [mW]	Unc. [mW]
0.254	74.735	17.000	0.10	0.005	/	/
0.355	104.931	23.983	0.20	0.010	/	/
0.568	162.498	37.742	0.49	0.025	/	/
0.785	229.599	53.317	0.98	0.049	/	/
1.162	329.440	77.391	2.04	0.102	/	/
1.717	499.127	116.200	4.65	0.232	4.62	0.462
1.998	582.987	136.937	6.39	0.320	6.72	0.672
2.278	662.487	154.776	8.21	0.411	8.68	0.868
2.862	829.160	193.390	12.84	0.642	12.73	1.018
4.023	1178.167	272.573	25.72	1.286	25.70	2.056
5.774	1655.500	389.755	51.68	2.584	54.37	4.350

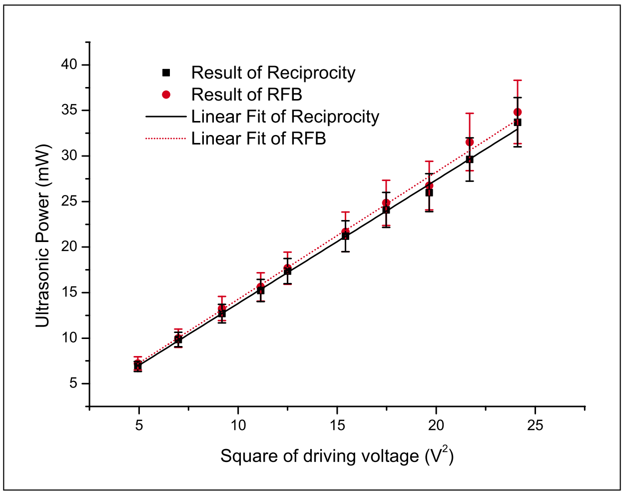

Figure 6. Comparison of RFB and Self-Reciprocity for focusing transducer.

a good agreement with RFB method. From the above experiment and analysis, the self-reciprocity technique is valid and has advantages over the traditional RFB methods: better performance at low level power and satisfactory performance in high frequency range. It can reach a lower ultrasonic power as 0.1 mW and has a better capability of anti-environmental interference. It is simple and inexpensive which should make it a wide usage in the application of ultrasonic measurement.

To be noted, this technique requires the transducer be linear, passive and reversible. The transducer cannot have both electromagnetic and electrostatic couplings. This restriction has been included in the proof [13] and a combination system is not reciprocal [26, 27]. In a word, the ultrasonic power determination using self-reciprocity technique requires the system to be reciprocal. Thus, it is necessary to check the applicability of the ultrasonic transducer to reciprocity calibration. Two transducers are checked in pairs, one being the projector and the other the receiver. A comparison is conducted between the ratios of the open-circuit output voltage of the receiver to the input current of the projector when the functions of the receiver and projector are interchanged without changing their positions. These two values should not differ by more than 10%. Comparison with a third reversible transducer will tell which one is fault. In case of nonlinearities begin to come into play, where the cavitation effect comes and the ultrasonic transducer behaves non-reciprocally, the driving voltage has to be decreased down to fulfill the measurement conditions.

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