Self-reciprocity calibration method of ultrasonic transducer as well as its application in power measurement and relation with radiation force balance method

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Abstract: The principles of electroacoustic reciprocity and self-reciprocity method (SRM) for the plane piston and the spherically focusing transducer are described. A series of definitions with uses of transmitting voltage (current) responses and voltage sensitivity are introduced. The relation of SRM with the radiation force balance (RFB) is expounded. Experiments in frequency range of 1.0~15 MHz show that the two methods are of close accuracy in calibration and output power measurement of ultrasonic transducer. The measurement by SRM is of high signal noise ratio and better stability than by RFB.

Key words: self-reciprocity method; radiation force balance; acoustic power; radiation conductance; transmitting voltage (current) response; voltage sensitivity

0 INTRODUCTION

Self-reciprocity method is an old method for calibration of underwater acoustic transducer founded in War II[1,2]. This technique was applied to the calibration for ultrasonic plane piston transducer in 1976[3] and 1987[4], for spherically focusing transducer in 2002[5] and 2006[6]. SRM was used to measure ultrasonic output power started in 1996 for piston transducer[7] and in 2005 for spherically focusing transducer[8]. The applied frequency range is up to 25 MHz for plane piston transducer[9]. Up to now, SRM has been developed into the standard method for calibrating ultrasonic focusing transducer and measuring acoustic power in China[9]. In this paper the principles and methods of SRM for the non-focusing and the focusing transducers, as well as the parameters to be measured, are described systematically. Then the relations between the results obtained by both SRM and RFB are derived. Experiments in frequency range 1.92~15 MHz demonstrate that the two methods have the close accuracy in measurements. Their advantages and defects are discussed.

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1 RECIPROCITY PRINCIPLE OF PLANE WAVE AND SPHERICALLY FOCUSED WAVE

A linear, passive, and reversible transducer generally is the one which satisfies the electromechanical reciprocity condition[4]:

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

where: (in transmission) v is the uniform velocity of the radiating surface of the transducer for an input current I and (in reception) U is the open-circuit voltage generated by a force acting on the transducer assumed in this case to be rigid.

From the definitions of the transmitting response to current S_I of a projector and the free-field sensitivity M of a receiver:

$$S_I=\frac{|p_{tr}|}{|I|} \text{ and } M=\frac{|U|}{|p_{rec}|} \tag{2}$$

where:

p_{tr} is the acoustic pressure of the sound wave just in front of the projector for an input current I in the absence of interference effects;

p_{rec} is the acoustic pressure in the undisturbed free field of a plane wave at the position of the acoustic center of the receiver, if it were removed, which gives an open-circuit voltage U; Or p_{rec} is the acoustic pressure on the receiving surface of the spherical segment-shaved transducer in the undisturbed spherical wave free field of an point source at the position of focus of the transducer, if it were removed, which gives an open-circuit voltage U.

For a plane wave or a convergent spherical wave, the pressure in front of the projector is related to the uniform surface velocity by the relationship:

$$p_{tr} = \rho c v \tag{3}$$

where:

ρ is the density of the propagation medium

c is the speed of sound in the medium

If it is now assumed that the acoustic wave propagates between transmission and reception without loss or diffraction effects, as for an example of an infinite plane wave traveling in a loss-free medium

$$p_{tr} = p_{rec} = p \tag{4}$$

The best method to make the received free field pressure p_{rec} of a transducer equal to the transmitting pressure p_{tr} of itself is to place an ideal plane reflector (pressure reflection coefficient r =1) normal to the beam axis at a proper position with a distance d from the transducer without diffraction effects in the loss-free medium. This method is named self-reciprocity method whose ideal scheme is shown in Fig.1 (a).

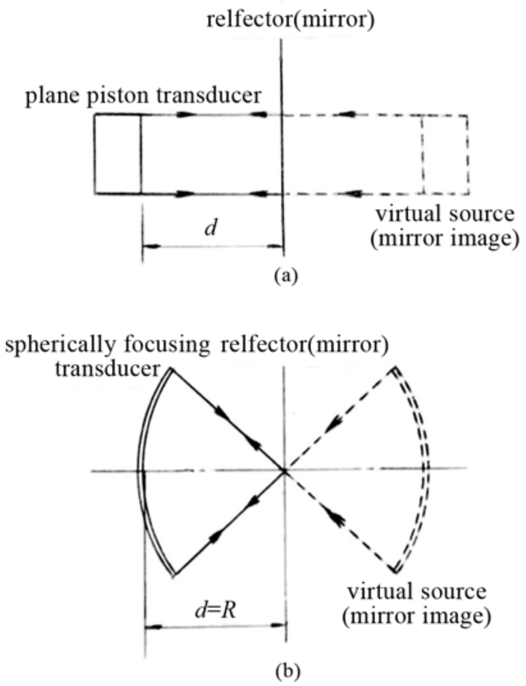

Fig.1 The ideal scheme of the self-reciprocity method for plane piston transducer (a) and spherically focusing transducer (b)

Clearly Equation (4) is valid for a plane piston transducer in ideal self-reciprocity method.

In ray acoustics, a spherically focusing transducer transmits a convergent spherical wave normal to the ideal plane reflector on the focal plane of the transducer in a loss-free medium without diffraction effects. The incident convergent spherical wave is reflected on the reflector, then the wave transfers a divergent spherical wave back to the transducer with the same pressure, so that Equation (4) is also valid due to the mirror effect of the reflector as shown in Fig.1(b).

The force exerted on the rigid surface of the receiver, area A, is therefore given by:

$$F = 2Ap \tag{5}$$

Hence, under the assumed plane wave and spherical wave boundary conditions, the ratio

$$J = \frac{M}{S_I} = \frac{UI}{p^2} = \frac{2A}{\rho c} = J_p\,,\quad A = \pi a^2$$

for the plane piston transducer (6a)

$$J = \frac{M}{S_I} = \frac{2A}{\rho c} = J_{sf}\,,\quad A = 2\pi R^2(1-\cos\beta)$$

for the spherically focusing transducer (6b)

where:

a is the effective radius of the radiating surface for the plane piston transducer; or the effective half-aperture for the spherically focusing transducer

R is the curvature radius of the spherical segment radiating surface of the focusing transducer

β is the focus (half-) angle, the half-aperture angle. $\beta = \arcsin(a/R)$

J depends only on the area of the transducer and is identified as the plane wave reciprocity parameter J_p for the plane piston transducer. And J is identified as the spherical convergent wave reciprocity parameter J_{sf} for the spherically focusing transducer depended on the curvature radius R and the focus (half-) angle β. With J_p or J_{sf} known, the measurements of U and I lead directly to the determination of p, and thus S_I and M.

Hence from Equations (2) and (6):

$$S_I = \left(\frac{U}{IJ}\right)^{1/2} \tag{7}$$

$$M == \left(\frac{UJ}{I}\right)^{1/2} \tag{8}$$

In practical measurements, the diffraction effect, the attenuation of medium and the reflection loss on the reflector should not be neglected, so that the diffraction correction coefficient G (G_1 for plane piston transducer or G_{sf} for spherically focusing transducer), and the attenuation correction factor $e^{-2\alpha d}$, where d is the distance of the reflector from the transducer and α is the attenuation coefficient in medium (usually water), and the reflection coefficient r (<1) needs to be applied:

$G = p_{rec} / p_{tr}$ for neglecting attenuation and reflection loss, i.e. α=0, r=1.

where $G=G_1(2d)$ for the plane piston transducer, which was calculated by B. Fay[12] in 1976 as shown in Table 1; $G=G_{sf}$ $(R/\lambda, \beta)$ for the spherically focusing transducer where $R=d$, which was calculated by W. D. Shou *et al* [5,6,10] as shown in Fig.2.

Table 1 The diffraction correction coefficients of the plan piston transducer in self-reciprocity calibration

$s=2d\lambda/a^2$	2.66	2.57	2.49	2.40	2.32	2.24	2.17	2.09	2.02
G_1	0.753	0.758	0.760	0.763	0.763	0.760	0.758	0.758	0.753
$s=2d\lambda/a^2$	1.96	1.89	1.83	1.77	1.72	1.66	1.61	1.55	1.51
G_1	0.750	0.745	0.743	0.740	0.753	0.753	0.753	0.753	0.740

Note: d is the distance between the reflector and the transducer; a is the helf-aperture or the radius; λ is the wavelength; G_1 is the diffraction correction coefficient (according to Fay B., 1976[12])

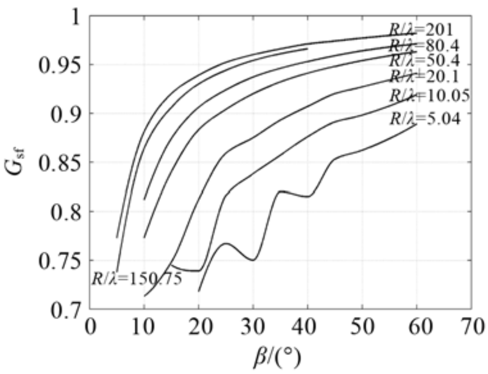

Fig.2 The diffraction correction coefficient $G_{sf}(R/\lambda, \beta)$of spherically focusing transducer in self-reciprocity calibration *vs.* focus helf-angle β and the ratio R/λ of the curvature radius R to wavelength λ where $R=F_{pres}$, the pressure focal length

The effective radius a of the plane piston transducer is determined by the optimum fitting of the pressure data acquired from the hydrophone which scans along the beam axis in the normalized distance ranged from 1.5 to 3 and that from theoretical calculation for some ideal transducers[4].

The pressure focal length F_{pres} of focusing transducer is substituted for the curvature radius R in experiment. The half-aperture a is determined by calculation from the beam widths detected on the focal plane of the focusing transducer[6,10,11].

Considering the diffraction, the attenuation in medium and the reflection coefficient of the reflector in measurements, the real free-field pressure on the receiving surface, if it were removed, becomes $p_{rec} = \rho cvrG e^{-2\alpha d}$ and the corresponding $F = 2A\rho cvrG e^{-2\alpha d}$, and the open-circuit voltage also reduces by a factor of $rG e^{-2\alpha d}$ in proportion really. Therefore

$$S_I = (\frac{U_{rec}}{IJrG})^{1/2} e^{\alpha d} \quad (9)$$

$$M = (\frac{U_{rec} J}{IrG})^{1/2} e^{\alpha d} \quad (10)$$

where U_{rec} is the detected open-circuit output voltage of the transducer.

The amplitude reflection coefficient r in the plane wave is a constant, for example it is 0.937 on the interface of water-stainless steel. But for the spherically focused beam the average amplitude reflection coefficient $r_{av}(\beta)$ should be substituted for r because the incident angles of the most rays in the beam are not zero and the transverse waves exist in the reflector. The calculation of $r_{av}(\beta)$ was expressed by W D Shou *et al*[10], where $r_{av}(\beta)$ =0.937 if $\beta \le 13°$.

2 BASIC RELATIONSHIPS

2.1 The relations of free field transmitting voltage (current) response and voltage sensitivity with acoustic radiation conductance

From the definition of the free field transmitting voltage response of transducer

$$S_V = p_0 / U_T = p_{0rms} / U_{Trms} = S_I \frac{I_T}{U_T} = \frac{S_I}{|Z_T|} \quad (11)$$

Where:

p_0, p_{0rms} are the pressure and the effective pressure on the radiation surface of the transducer, *i.e.* $p_0 = p_{tr}$ and $p_{0rms} = p_{tr,rms}$;

U_T, U_{Trms} are the exciting voltage and the exciting effective voltage of the transducer.

Z_T is the electric impedance of the transducer in water.

The definition of the radiation conductance of transducer is:

$$G_r = P / U^2_{Trms} \quad (12)$$

The definition of acoustic output power

$$P = p^2_{0rms} A / (\rho c) \quad (13)$$

Thus

$$G_r = S^2_V A / (\rho c) \quad (14)$$

$$S_V = \sqrt{\frac{2G_r}{J}} \quad (15)$$

$$S_I = S_V |Z_T| = \sqrt{\frac{2G_r}{J}} |Z_T| \quad (16)$$

$$M = S_I J = \sqrt{2G_r J}\,|Z_T| \tag{17}$$

2.2 The relation of radiation conductance G_r with electroacoustical efficiency $\eta_{a/e}$

$$\eta_{a/e} = \frac{P}{P_e} = \frac{P}{U_{Trms}^2 G_T} = G_r / G_T \tag{18}$$

where:

P_e is the electric input power of the transducer;

$G_T = \cos\theta / |Z_T|$ is the electric input conductance of the transducer.

2.3 The relation of transmitting voltage response with acoustic output power

$$P = I_0 A = \frac{p_{0rms}^2}{\rho c} A = \frac{(S_V U_{Trms})^2 A}{\rho c} \tag{19}$$

From previous analysis it is judged that all the electroacoustical parameters can be measured by the self-reciprocity method (SRM) including the acoustic output power which is measured by the radiation force balance (RFB) usually. And, vise versa[10,11], if the acoustic output power and the radiation conductance have been measured by RFB, all the electroacoustical parameters can also be derived almost by using Equations (14) to (19).

3 THE DERIVED ELECTROACOUSTICAL PARAMETERS DERIVED FOR APPLICATIONS

The measurement system is arranged as shown in Fig.3.

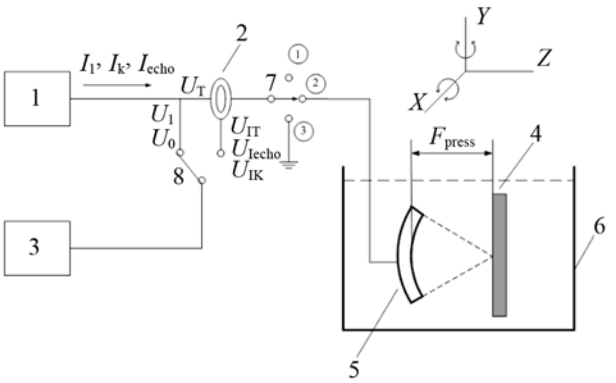

Fig.3 Scheme of free field self-reciprocity calibration apparatus
1-tone burst generator; 2- current monitor; 3- oscilloscope; 4- reflector; 5-focusing transducer; 6- water tank; 7- three-way switch for open circuit/work load/short circuit of the generator; 8- two-way switch for voltage/current signal detection

Because the cable end of transducer is connected with the tone burst gengrator as the load of the transducer when detecting the open-circuit voltage U_{rec}, the real detected output echo voltage of trnsducer is its cable end-loaded echo voltage U_1 rather than U_{rec}, and then $U_1 = U_{rec}|Z_i/(Z_i + Z_T)|$ where Z_i is the inner impedance of the generator, and U_0 is the open-curcuit output voltage of the generator. On the side, the exciting current of the generator $I_T = U_0/|Z_i+Z_T|$, and the short-curcuit current $I_k = U_0/|Z_i|$. As the detected first echo current I_{echo} is equal to $U_{rec}/|Z_i+Z_T|$, $U_{rec}I_T = U_1 I_k = U_0 I_{echo}$ is valid. In experiments the real detectable electric parameters are U_1, I_T, I_{echo}, I_k and U_0 when the three-way switch 7 is placed on the positions of ②, ③ and ① respectively. The $U_1 I_k$ or $U_0 I_{echo}$ shoud be substituted for $U_{rec}I_T$ in the previous formulas.

$$S_I = \left(\frac{U_{rec}}{IJrG}\right)^{1/2} e^{\alpha d} = \left(\frac{U_1 I_k}{JrG I_T^2}\right)^{1/2} e^{\alpha d} \tag{20}$$

$$M = \left(\frac{U_{rec}J}{IrG}\right)^{1/2} e^{\alpha d} = \left(\frac{U_1 I_k J}{rG I_T^2}\right)^{1/2} e^{\alpha d} \tag{21}$$

3.1 Free field maximum transmitting voltage (current) response--S_{Vm} (S_{Im})

Definition: The ratio of the maximum pressure in free field transmitted by transducer to the input exciting voltage (current) at a specified frequency.

Note 1: The maximum pressure exits at the position on the beam axis where is $N_1 = a^2/\lambda$ apart from the acoustic center of plane piston transducer or at the pressure focus for focusing transducer.

Note 2: The signal frequency should be noted.

Note 3: The unit is Pascal per volt (Pa/V) or Pascal per ampere (Pa/A).

For plane piston transducer, $S_{Im} = 2e^{-\alpha N_1} S_I$, $S_{Vm} = 2e^{-\alpha N_1} S_V$, where $N_1 = a^2/\lambda$ is the near length.

Because the pressure focused gain of the spherically focusing transducer equals kh, thus

$$S_{Im} = kh S_I e^{\alpha d} = kh\sqrt{\frac{U_1 I_k \rho c}{2A|r_{av}(\beta)| G_{sf} I_T^2}} \tag{22}$$

$$S_{Vm} = kh S_V e^{\alpha d} = kh\sqrt{\frac{U_1 I_k \rho c}{2A|r_{av}(\beta)| G_{sf} U_T^2}} \tag{23}$$

where

$k = 2\pi/\lambda$ is the circular wave numble;

$h = R(1-\cos\beta)$ is the effective height (depth) at the center of spherical segment.

For plane piston transducer, $S_{Im} = 2e^{-\alpha d} S_I$, $S_{Vm} = 2e^{-\alpha d} S_V$.

The pressure at pressure focus of the transducer excited by a given voltage (current) at a specified frequency can be calculated from S_{Vm} (S_{Im}) multiplied by the exciting voltage U_T (current I_T). The measured pressure at the focus was used to calibrating the miniature hydrophone by placing the hydrophone at the focus[4].

3.2 Pulse – echo sensitivity--$M_{pe}L$

Definition: The ratio of the received transducer's open-circuit voltage of the first echo signal to the exciting voltage of the spherically focusing transducer transmitting the tone burst beam normal to an ideal plane reflector at the focal plane, which is expressed in dB.

From the definition

$$M_{pe}=\frac{U_{rec}}{|r_{av}(\beta)|U_T}=\frac{U_1 I_K}{|r_{av}(\beta)|U_T I_T} \tag{24}$$

where:

U_{rec} is the transducer's open-circuit voltage of the first echo signal from the ideal reflector;

U_1 is the real detected transducer's output voltage of the first echo signal from the ideal reflector.

$$M_{pe}L=20\log_{10} M_{pe}=20\log_{10}\frac{U_1 I_K}{|r_{av}(\beta)|U_T I_T} \tag{25}$$

The equations, $U_{rec}=U_1 I_K/I_T=U_0 I_{echo}/I_T$, have been demonstrated. And, the following formula can be derived

$$M_{pe}=2G_r|Z_T|G_{sf}e^{-2\alpha d} \tag{26}$$

The ability of the pulse echo detection of focusing transducer can be identified by using $M_{pe}L$.

3.3 Free field voltage sensitivity for the pressure nearby the focus--M_f

Definition: The ratio of the open-circuit voltage of the spherically focusing transducer to the free field pressure on the divergent spherical wave front with the radius equal to half-wavelength transmitted by a point source at the focus, if the transducer were removed.

$$M_f=\frac{U_{rec}}{p_s}=\frac{U_1 I_k}{p_s I_T}=\frac{M\lambda}{2d}e^{-\alpha(d-\frac{\lambda}{2})} \tag{27}$$

where:

p_s is the free field pressure on the divergent spherical wave front with the radius $\lambda/2$ transmitted by a point source at the focus, if the transducer is removed.

Note 1: The signal frequency should be noted.

Note 2: The unit is volt per pascal (V/Pa).

When the spherically focusing transducer is used as a hydrophone, applying the time (distance) gate technique, the echo voltage of the specified wave front with the distance of $\lambda/2$ from the pressure focus can be acquired. The acquired echo voltage divided by M_f may be used to evaluate the pressure at nearby points at the distance $\lambda/2$ from the focus.

4 MEASUREMENTS OF TRANSMITTING CURRENT (VOLTAGE) RESPONSE AND RECEIVING VOLTAGE SENSITIVITY

4.1 Operation program of self-reciprocity method

4.1.1 Measurements of the first echo voltage and echo current

The three-way switch 7 is placed on position ② in the measurement system of Fig.2. Adjust the working frequency of the tone burst generator to be the measured frequency f and keep the output voltage constant, the pulse duration equal to or less than 30 cycles and the duty cycle factor about 1/30. Primary adjustment of the transducer is to make the beam focus at the vicinity of the reflector center. Then adjust the angles in azimuth and elevation directions of the beam untill the received first echo maximized. Furthmore adjust the distance between the transducer and the reflector as well as these two direction angles precisely and repeatedly untill the received echo amplitud attains the maximum in the field. Finally the exciting voltage U_T and current I_T, the first echo voltage U_1 and the first echo current I_{echo} are detected and recorded. Generally when the exciting voltage is much great, I_{echo} should be deteced rather than I_k to avoit damage of the generator in detecting short current. The echo current signal with great distortion and low signal noise ratio needs processing to reduce noise.

The RMS echo current after reducing noise equals the squal root of the difference between the mean squal value of the detected echo current with noise and that of the detected background noise in circuit without the echo when the beam is insulated.

4.1.2 Measurements of open circuit voltage and short circuit current

Keep the working frequency and the exciting voltage constant, place the three-way switch 7 on positing ① and detect the open-circuit voltage U_0 of the generator. Under the safety condition of the generator, place the three-way switch 7 on position ③ to detect the short-circiut current I_k. But I_k should not be detected under the condition of much great exciting voltage for safety of the generator, while I_{echo} has sufficintly great signal noise ratio so $U_1 I_k$ should be replaced by $U_0 I_{echo}$ in experiment.

5 EXPERIMENTS

As previous description, the measurements of the electroacoustic characteristics can be conducted by either SRM or RFB[6-8] which are independent primary methods. The aim of experiments is to exam the reproducibility of the radiation conductance measurement of the same transducer by using SRM and RFB to evaluate their effectiveness and accuracy of both methods.

In the National Institute of Metrology of China, Guangzhen Xing and Ping Yang measured the output power and the radiation conductance for two plane piston transducers of 1 MHz and 25 MHz in 2012[9], and for two spherically focusing transducers of 5 MHz[9] and 15MHz in August 2013 as following:

1. 5 MHz transducer (with backing) Olympus V308 (SN 763325), normal aperture: 0.75 inch, normal focal length: 50 mm; determined pressure focal length F_{pres}=51.7 mm, β=10.62°

The measured data listed in Tab.2 are shown in Fig.4 and the slop of the curves of the output power *vs.* the squared exciting RMS voltage is G_r by the least-square fit. Then

G_{rRFB} =1.43 mS, G_{rSRM} =1.36 mS,

$$\Delta=\frac{G_{rSRM}-G_{rRFB}}{G_{rRFB}}=-4.5\%$$

2. 15 MHz transducer (with backing) Olympus V319 (SN 76332)

The data of measurement are listed in Table.3 and the results are shown in Fig.5. G_{rSRM}, the slop of the curves of P vs. U^2_{rms} is 2.06 mS by the least-square fit. G_{rRFB}=2.16 mS, Δ=−4.6%.

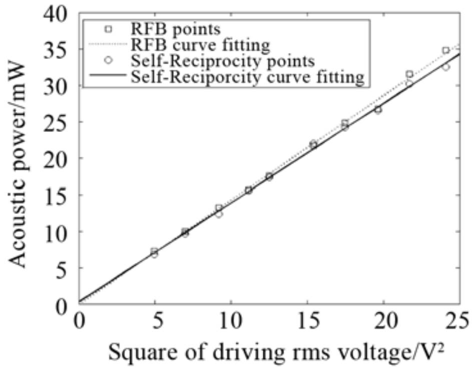

Fig.4 Measurement result of output power *vs.* exciting RMS voltage squared for 5 MHz focusing transducer(Olympus V308, SN 763325)

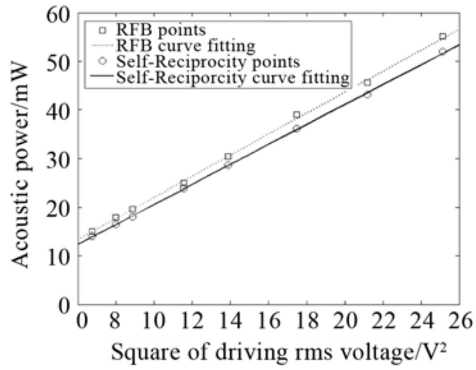

Fig.5 Measurement result of output power vs. exciting RMS voltage squared for 15MHz focusing transducer (OlympusV319, SN 76 3322) with backing ,normal aperture: 0.5 inch, normal focal length: 60 mm

3. 1 MHz plane piston transducer (Olympus A302S, Panametrics Inc., Waltham, MA; center

Table 2 Measurement data of output power and radiation conductance for 5 MHz focusing transducer (Olympus V308) by SRM and RFB

	i	1	2	3	4	5	6	7	8	9	10
$U_{T,i}$	$U_{Tpp,i}$/V	6.286	7.477	8.572	9.444	10.00	11.11	11.83	12.54	13.174	13.89
RFB	$P_{RFB,i}$/mW	7.24	9.99	13.25	15.62	17.59	21.67	24.85	26.74	31.53	34.83
	$G_{rSRM,i}$/mS	1.46	1.43	1.44	1.40	1.42	1.408	1.424	1.36	1.456	1.448
SRM	$P_{RFB,i}$/mW	6.85	9.67	12.38	15.59	17.37	21.99	24.19	26.53	30.16	32.53
	$G_{rSRM,i}$/mS	1.384	1.384	1.344	1.40	1.392	1.424	1.384	1.352	1.392	1.352
	Δ_i	−5.3%	−3.2%	−6.6%	−0.2%	−1.8%	1.5%	−2.7%	−0.8%	−4.3%	−6.6%

注：$\Delta_i=(G_{rSRMi}-G_{rRFBi})/G_{rRFBi}, i=1,2,3,\cdots,10; \Delta_{av}=\frac{1}{10}\sum_{i=1}^{10}\Delta_i=-3.0\%$

Table 3 Measurement data of output power and radiation conductance for 15 MHz focusing transducer (Olympus V319) by SRM and RFB

U_{pp}/V	7.343	8.432	8.000	9.617	10.543	11.828	13.023	14.183	$G_{rav}; u_A(G_{rav})/G_{rav}$
P_{RFB}/mW	15.074	19.69	17.945	24.913	30.39	38.963	45.562	55.131	
G_{rRFB}/mS	2.24	2.224	2.232	2.152	2.184	2.232	2.152	2.192	2.20; 0.62%
P_{SRM}/mW	14.04	18.11	16.53	23.89	28.63	36.14	43.1	52	
G_{rSRM}/mS	2.08	2.04	2.064	2.064	2.064	2.064	2.032	2.072	2.06; 0.27%
Δ_i	−7.1%	−8.3%	−7.5%	−4.1%	−5.5%	−7.5%	−5.6%	−5.5%	Δ_{av} = −6.4%

注：$\Delta_i=(G_{rSRMi}-G_{rRFBi})/G_{rRFB_i}, i=1,2,3,\cdots,8; \Delta_{av}=\frac{1}{8}\sum_{i=1}^{8}\Delta_i=-6.4\%$

frequency 1MHz with a radius of 0.5 inch).

The lower limit of ultrasonic power determined by using self-reciprocity is 0.1 mW, which is much lower than 4.62mW for the RFB; the maximum derivation for self-reciprocity is 3.7%, while 7.2% for RFB at 1MHz. The radiation conductance in the two techniques is around 1.571 mS,

4. 25 MHz plane piston transducer (Olympus V324, Panametrics Inc., Waltham, MA; with a radius of 0.25 inch).

The lower limit of power measurement by using SRM is 1mW while 4.18 mW for RFB. The radiation conductance is around 1.02 mS, the maximum derivation for SRM is 1.9% while 8.4% for RFB.

5. 10 MHz transducer (air backing) made in Wuxi Lanhui Ultrsonic Electonic Equipment Factory, normal aperture: 8mm, normal focal length: 25 mm; determined pressure focal length F_{pres}=27.45 mm, half-aperture a =2.95mm, focus half-angle β =6.17°

Measurements of the transducer were conducted in Shanghai Institute of Ultrasound in Medicine.

The data of measurement listed in Tab.4 and Tab.5 are shown in Fig.6. G_{rSRM} is 10.1 mS by the least-square fit, G_{rFRB}=10.5 mS, Δ=−4.5%.

Combining other published experiment results[6-8], the measured radiation conductance of 8 transducers by RFB and SRM are listed in Tab.6 for comparison.

The data in Tab.6 show the differences of measured radiation conductance by SRM and RFB, which are less than 5% in the frequency range 1 MHz to 15 MHz. The radiation conductance of the air-backed transducer is at least two times greater than that of the transducer with backing.

Table 4 Measured data of 10MHz focusing transducer by RFB(UPM-DT-1 AV Ultrasound Power Meter, Omic Instruments Co., with an absorbing target)

U_{Trms}/V	3.05	2.98	2.86	2.77	2.67	2.29
U^2_{Trms}/V^2	9.32	8.85	8.16	7.76	7.15	5.23
P_{RFB}/mW	97.4	91.5	86.2	79.5	73.6	54.3

Table 5 Measured data of 10MHz focusing transducer by SRM ($e^{2\alpha F_{pres}}$=1.143)

U_{Trms}/V	2.66	2.41	2.09	1.73	1.35	1.10
U^2_{Trms}/V^2	7. 08	5.81	4.35	2.99	1.82	1.20
P_{SRM}/mW	72.8	61.6	46.6	32.1	21.1	14.0

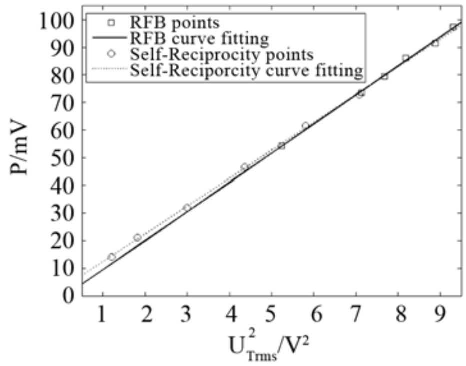

Fig.6 Measurement result of output power vs. exciting RMS voltage squared for 10MHz focusing transducer (air backing)

6 CONCLUSION

The principles of reciprocity are clarified for the plane piston transducer and the spherically focusing transducer in the uniform model where both differences of the two are in the radiation area, the diffraction correction coefficient, and the beam pressure reflection coefficient.

The relations of the electroacoustical parameters based on SRM with that based on RFB are given with much significance and show these absolute methods are almost of the same accuracy and applicability in transducer calibration. A series of reproducibility measurements show both methods have close results in the radiation conductance and power measurements. This closeness can be inferred to the measured results of other electroacoustical parameters. The analysis of the measurement result for 1.92 MHz transducer shows that the measurement uncertainties are better than 15% (k=2) for the output power and the radiation conductance, better than 9% (k=2) for the transmitting voltage response and the receiving voltage sensitivity, and better than 18% (k=2) for the electroacoustical efficiency. Some new derived electroacoustical parameters are significant in applications. The main advantages of SRM method in the output power and radiation conductance measurement are of higher signal noise ratio, much lower interference and noise, which

Table 6 Comparison of measured radiation conductance G_r (mS) of transducers by RFB and SRM

Transducer	Plane piston		Spherically focusing transducer					
Frequency	1MHz*	25MHz*	1.52MHz	5MHz*	1.92MHz*	5.27MHz	10MHz	15MHz*
RFB	1.63	1.04	80.8	1.43	3.82	8.70	10.54	2.16
SRM	1.68	1.11	82.0	1.36	3.84	8.55	10.07	2.06
Δ/%	−3.5	−6.5	1.5	−4.5	0.5	−1.8	−4.5	−4.6

Note: Δ=(G_{rSRM}-G_{rRFB})/G_{rRFB}; Symbol “*” notes the transducer with backing ,and others are air backed.

is better than that in using RFB where the thermal drift, the streaming and the base vibration exist, so as to have better accuracy and lower power limit especially for the measurement in lower level and at higher frequency. The upper limit frequency is expected up to 20MHz or higher. The determinations of the diffraction correction coefficient and the average pressure reflection coefficient in SRM are with some inconvenience. These problems have been resolved by interpolation method in the reference data table or by calculation in a new draft of National Standard of China, "Acoustics-electroacoustic characteristics and measurements of piezoelectrical spherically focusing ultrasonic transducer" which will be issued in 2014.

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超声换能器的自易校准法及其在功率测量中的应用和它与辐射力法的关系

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摘要：论述了电声互易原理和用于平面活塞型与球面聚焦换能器校准的自易法(Self Reciprocity Method, SRM)。介绍了一系列的定义和发送电压(电流)响应与电压灵敏度。阐述了 SRM 与辐射力天平(Radiation Force Balance, RFB)法之间的关系。在 1~25 MHz 频率范围内，对超声换能器校准和输出功率测量的实验显示，两种方法具有相近的准确度。SRM 法比 RFB 法测量具有更高的信噪比和更好的稳定性。

关键词：自易法；辐射力天平；声功率；辐射电导；发送电压(电流)响应；电压灵敏度

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