ELSEVIER

Ultrasonics 37 (2000) 549–554

Ultrasonics

www.elsevier.nl/locate/ultras

Measurement of ultrasonic power and electro-acoustic efficiency of high power transducers

Shuyu Lin *, Fucheng Zhang

Applied Acoustics Institute, Shaanxi Teachers University, Xian, Shaanxi 710062, People's Republic of China

Received 3 July 1999; received in revised form 9 September 1999

Abstract

In this paper, an improved method for the measurement of acoustic power and electro-acoustic efficiency of high power ultrasonic transducers is presented. The measuring principle is described, the experimental results are given. In comparison with traditional methods, the method presented in this paper has the advantages of simplicity, economy and practicality. The most important is that it can measure the output acoustic power and the electro-acoustic efficiency of the transducer under the condition of high power and practical applications, such as ultrasonic cleaning and soldering.

Keywords: Electro-acoustic efficiency; Measurement; Transducers; Ultrasonic power

1. Introduction

High power ultrasonics is a traditional applied subject. During the past decades, high power ultrasonics has found many applications in industry, electronics and many other fields [1–4]. Apart from some traditional applications, such as ultrasonic cleaning, ultrasonic plastics soldering and metal welding, and ultrasonic machining, some new applications of high power ultrasonics, such as sonochemistry and ultrasonic therapy, have also received more and more attention [5–8].

In the case of high power ultrasonic energy applications, the vibrational characteristics of a transducer used are essential for the rational design and safe work of the vibrational system. The measurement of the vibrational characteristics of the transducer is important for the evaluation of the transducer performance and the practical process the transducer is involved in. The high power characteristics of the transducer include the output acoustic power, the electro-acoustic efficiency, the temperature rise, the vibrational displacement distribution and others. As these characteristics of the transducer under the condition of high power affect the performance of the transducer and the process effect, a lot of work has been done to analyze and improve the design of the vibrational system [9–12]. In the case of a low input electrical signal, the characteristics of the transducer can be obtained using a number of methods. The admittance circle method is one of the most popular methods. It can measure the equivalent electromechanical parameters, the resonance frequency, the electro-acoustic efficiency and other parameters. However, in the case of high power excitation, the characteristics of the transducer are different from those measured under the condition of a low excitation signal. As for the measurement of performance parameters of the ultrasonic transducers under high input power, no traditional methods similar to the admittance method are available.

In the evaluation of the high power ultrasonic transducer, the output acoustic power and the electro-acoustic efficiency are two important performance parameters. A method called the high frequency wattmeter method proposed by Japanese researchers has been used in the measurement of the transducer under high input power [13]. In this method, three measurement steps are needed. They are the clamp test, the no-load test and load test. In the measurement of the transducer using this method, we found that, although the method can be used to measure the high power characteristics, there are three disadvantages that need to be overcame. First, in this method, two identical transducers must be used to obtain the dielectric loss power. Second, in order to obtain the mechanical loss power, the relation between the mechanical loss power and the vibration velocity must be obtained in advance. Third, the relation between

* Corresponding author.

0041-624X/00/$ - see front matter
PII: S0041-624X(99)00076-1

the dielectric loss power and the terminal voltage must be measured to obtain the dielectric loss power. Considering these factors, the method is time consuming and cumbersome, and it has not been widely used in practical applications.

In this paper, an improved method based on the high frequency wattmeter method is presented. In this method, the measurement of the dielectric and mechanical losses is unnecessary. Therefore, it is simple, time saving and suitable for practical applications.

2. The measuring principle of the high frequency wattmeter method

The high frequency wattmeter method proposed by Japanese researchers measures the input electrical power of a transducer at no-load, load and clamp conditions. Under high power conditions, the input electrical power W_e of the transducer to be measured can be expressed as:

$$W_e = W_d + W_m + W_a. \tag{1}$$

In Eq. (1), W_d is the dielectric loss power, W_m is the mechanical loss power, and W_a is the radiated acoustic power into the medium. When these quantities are measured, the electro-acoustic efficiency η_{ea} and the radiated resistance R_a can be obtained according to the following equations:

$$\eta_{ea} = W_a/W_e, \tag{2}$$

$$R_a = W_a/v^2. \tag{3}$$

Here v is the effective vibration velocity at the output end of the transducer. It is obvious that, in order to obtain the radiated acoustic power, the dielectric and mechanical loss powers must be measured in advance. In the wattmeter method, three experimental steps are employed to accomplish this task.

2.1. Clamp test

The objective of this experiment is to measure the dielectric loss power and the relation between the dielectric loss power and the terminal voltages of the transducer to be measured. In the experiment, a pair of transducers, which have almost the same vibrational characteristics, are mechanically connected together at their output ends by a central bolt. When they are driven with the same signal at their original resonance frequency, the vibrations of the transducers are cancelled by each other, and there is no vibration in the transducers. In this case, the electrical input power gives the dielectric loss power of the vibrational system. As these two transducers have the same characteristics, the dielectric loss power of one transducer equals to the half of the electrical input power as expressed in the following equation:

$$W_d = W_e/2. \tag{4}$$

When the input voltage is changed, the relation between the dielectric loss power and the terminal voltage of the transducer to be measured can be obtained. By means of the measured relation, the dielectric loss power of the transducer corresponding to different terminal voltages can be obtained. Since the relation between the dielectric loss power and the terminal voltage is different for different transducers, it must be measured in advance for every transducer to be measured.

2.2. No load test

When the transducer to be measured is without load, the transducer radiates no acoustic power, we have $W_a = 0$. For example, when the transducer radiates into air, it can be regarded as the case of no load. In this case, since there is no radiated acoustic power, the electrical input power can be expressed as:

$$W_e = W_m + W_d. \tag{5}$$

Using Eq. (5), since the dielectric loss power has been measured in the above step, the mechanical loss power can be obtained. In order to get the relation between the mechanical loss power and the vibrational velocity, the vibrational velocity of the transducer must be measured at the same time. Based on the measured relation, the mechanical loss power of the transducer to be measured at different vibrational velocities can be obtained. When the mechanical loss power is measured, the equivalent mechanical loss resistance can be calculated from the following equation:

$$R_m = W_m/v^2. \tag{6}$$

It can be seen from Eq. (6) that, in order to get the equivalent mechanical loss resistance, the measured vibrational velocity must be calibrated. This process is complex and requires complicated experimental equipment.

2.3. Load test

When the transducer is radiating into a certain medium, such as water in ultrasonic cleaning, acoustic power is produced in the medium. In this case, when the electrical input power, the terminal voltage and the vibrational velocity are measured, using Eq. (1) and the measured relations between the dielectric (mechanical) loss power and the terminal voltage (vibrational velocity), the radiated acoustic power and the equivalent radiated resistance can be obtained according to the above equations.

From the above analysis, it can be seen that in the high frequency wattmeter method a pair of transducers with almost the same vibrational characteristics are needed. Furthermore, the relations between the dielectric (mechanical) loss power and the terminal voltage (vibrational velocity) must be obtained in advance. Therefore, the measuring procedures are complex and time consuming. On the other hand, the measurement of the dielectric loss power is not accurate, because it is impossible for the transducers clamped together to have the same vibrational characteristics. In this case, some vibration in the vibrational system can be produced, and a mechanical power loss can be caused.

3. The on–off resonance method

In this paper, an improved method for the measurement of the radiated acoustic power and other parameters based on the wattmeter method is developed. Since the measurement is done when the transducer to be measured is on the resonance and off resonance, the method presented here is called the on–off resonance method. The experimental set-up is shown in Fig. 1. In the figure, the frequency and the output electrical power of the ultrasonic generator are tunable. The high frequency wattmeter measures the input electrical power of the transducer to be measured, the voltage meter measures the terminal voltage, and the velocity pick-up measures the vibrational velocity of the transducer. The measuring procedures are divided into two steps. First, in the on-resonance condition, the electrical input powers are measured when the transducers are under conditions of load and no load. Second, in the off-resonance condition, the electrical input powers are also measured when the transducers are under conditions of load and no load. In the following analysis, there are a number of quantities to be used. To avoid confusion, primes and subscripts are used. The prime represents the off-resonance condition, and the subscripts l and n represent the load and no-load conditions, respectively. The detailed measuring procedures are described in the following sections.

3.1. *On resonance test*

3.1.1. *Load test*

When the transducer to be measured is radiating into a certain medium, using Fig. 1, the electrical input power W_{il}, the terminal voltage V_l and the vibrational velocity v_l of the transducer can be measured. The electrical input power can be expressed as:

$$W_{il} = W_{ml} + W_{dl} + W_a. \tag{7}$$

Here W_{ml} and W_{dl} are the mechanical and dielectric loss powers of the transducer under the load condition.

3.1.2. *No-load test*

When the transducer is without load, there is no radiated acoustic power, and we have $W_a = 0$. The terminal voltage of the transducer is adjusted until the vibrational velocity of the transducer is equal to that of the transducer under the condition of load in the above step, i.e. v_l. In this case, the terminal voltage of the transducer can be measured as V_n. The input electrical power can be expressed as:

$$W_{in} = W_{mn} + W_{dn}. \tag{8}$$

In Eq. (8), W_{in}, W_{mn} and W_{dn} are the electrical input power, the mechanical and dielectric loss powers, respectively, of the transducer at the condition of no load. Since the vibrational velocity of the transducer is the same as that in the above case, the mechanical loss powers are the same for these two cases. Therefore, we have $W_{mn} = W_{ml}$. From Eqs. (7) and (8), we have:

$$W_a = W_{il} - W_{in} - (W_{dl} - W_{dh}). \tag{9}$$

3.2. *Off resonance test*

3.2.1. *Load test*

When the transducer is radiating into a certain medium, we adjust the exciting frequency of the ultrasonic generator and make it off the resonance frequency of the transducer slightly. At the same time, we adjust

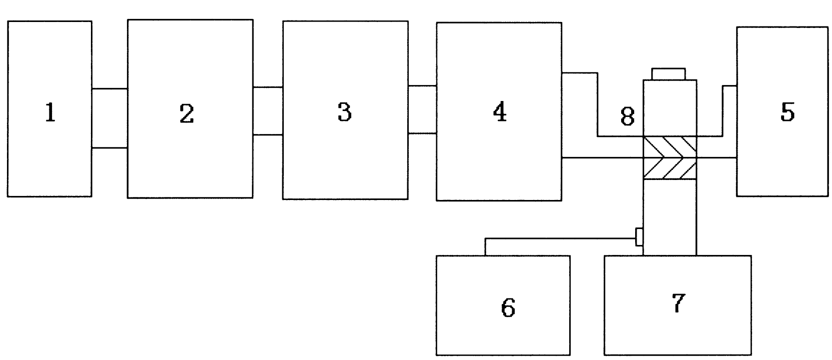

Fig. 1. The experimental set-up for the measurement of the high power ultrasonic transducer. 1: Frequency meter, 2: ultrasonic generator, 3: electric wattmeter, 4: electric matching circuit, 5: voltage meter, 6 velocity pick up, 7: ultrasonic load, 8: ultrasonic transducer.

the output signal of the generator until the terminal voltage of the transducer is equal to V_l, which is the terminal voltage of the transducer with load on resonance. In this case, we have:

$$W'_{il} = W'_{ml} + W'_{dl} + W'_{a}. \tag{10}$$

In Eq. (10), W'_{il}, W'_{ml}, W'_{dl} and W'_{a} are the electrical input power, the mechanical loss power, the dielectric loss power and the radiated acoustic power of the transducer when its working frequency is of its resonance frequency. Since the terminal voltage is equal to that of the transducer in the load-on resonance condition, the dielectric loss powers in these two cases are the same, and we have $W'_{dl} = W_{dl}$. In this step, the vibration velocity of the transducer is measured as v'_l.

3.2.2. No load test

When the transducer to be measured is without load, we adjust the frequency and the output electrical signal of the ultrasonic generator until the terminal voltage and the vibrational velocity of the transducer are equal to V_n and v'_l. In this case, the electrical input power can be expressed as:

$$W'_{in} = W'_{dn} + W'_{mn}. \tag{11}$$

Here W'_{in}, W'_{mn} and W'_{dn} are the electrical input power, the mechanical loss power and the dielectric loss power, respectively, of the transducer without load and off resonance. Since the vibrational velocity of the transducer is equal to that of the transducer with load and off resonance, the mechanical loss powers are the same, and we have $W'_{mn} = W'_{ml}$.

It should be noted that in this step the adjustment for the terminal voltage and the vibrational velocity are complex compared with the above steps, especially for high Q transducers. The reason is that for high Q transducers the bandwidth of the transducer is narrow, and the power varies rapidly with frequency. To overcome this problem, two procedures may be used. First, when the transducer is off resonance, the frequency variation may be positive or negative relative to the resonance frequency of the transducer without load. That is to say, the frequency of the transducer off resonance may be lower or higher than the resonance frequency of the transducer without load. Therefore, we have two choices in adjusting the frequency of the transducer off resonance. Second, in the experiment, the adjustment of the frequency and the input electrical voltage of the transducer must be made at the same time in order to make the terminal voltage and the vibrational velocity of the transducer without load and off resonance equal to each other. For a low Q transducer, the adjustment is comparatively simple. The reason is that in this case the input electrical power varies slowly with the frequency.

From Eqs. (10) and (11), we can obtain the following equation:

$$W'_{a} = W'_{il} - W'_{in} - (W'_{dl} - W'_{dn}). \tag{12}$$

Since the terminal voltage of the transducer with load and on resonance is the same as that of the transducer with load and off resonance, and the terminal voltage of the transducer without load and on resonance is also the same as that of the transducer without load and off resonance, we have $W'_{dn} = W'_{dn}$ and $W'_{dl} = W'_{dl}$. Using these relations, we obtain:

$$W'_{a} = W'_{il} - W'_{in} - (W_{dl} - W_{dn}). \tag{13}$$

Combining Eqs. (9) and (13), we can obtain the following equation:

$$W_{a} - W'_{a} = W_{il} - W_{in} - (W'_{il} - W'_{in}). \tag{14}$$

For a certain medium, the radiated acoustic power of the transducer on and off resonance can be expressed as:

$$W_{a} = R_{a} v_{l}^{2}, \tag{15}$$

$$W'_{a} = R'_{a} (v'_{l})^{2}. \tag{16}$$

Substituting Eqs. (15) and (16) into Eq. (14) yields:

$$W_{a} = \frac{W_{il} - W_{in} - (W'_{il} - W'_{in})}{1 - R'_{a}(v'_{l})^{2}/R_{a} v_{l}^{2}}. \tag{17}$$

In these equations, R_a and R'_a are the radiated resistances of the transducer at the conditions of on resonance and off resonance. As for the radiated resistance, it is a very complex subject. It is well known that the radiated resistance of a high power transducer depends on a number of factors. First, it depends not only on the vibrational velocity but also on the working frequency of the transducer. Second, it depends on the medium and the surrounding environment, such as the temperature, atmospheric pressure, etc. However, if the medium and the surrounding environment are invariant, the radiated resistance depends only on the transducer itself and its working condition. Although the radiated resistance of an ultrasonic transducer is complex, its ratio is used in the calculation of the radiated ultrasonic power in the above equation. This is beneficial to the method.

For a liquid medium, when the transducer is excited by a low electrical signal, the radiated resistance can be regarded as a constant. However, when the transducer is excited by a high electrical signal, so-called cavitation will be created. In this case, the radiated resistance becomes complicated. In high power ultrasonics, this is the common case. That is why the measurement for high power ultrasonic transducers is difficult. However, in the above analysis, it can be seen that the ratio of the radiated resistance rather than the radiated resistance itself is used. In contrast, when the exciting frequency of the transducer is changed slightly from its resonance frequency, the variation of the frequency is very small.

Table 1
The measured results for the transducer on resonance under conditions of load and no load

f_l (kHz)	W_{il} (W)	V_{il} (V)	v_{ml} (V)	f_n (kHz)	W_{in} (W)	V_{in} (V)	v_{mn} (V)	W_a (W)
20.159	80	455	20.8	20.245	7	225	20.8	66.1
20.187	50	378	17.6	20.278	5	172	17.6	43.5
20.214	40	335	14.9	20.313	4	159	14.9	35.2

Table 2
The measured results for the transducer off resonance under conditions of load and no load

f'_l (kHz)	W'_{il} (W)	V'_{il} (V)	v'_{ml} (V)	f'_n (kHz)	W'_{in} (W)	V'_{in} (V)	v'_{mn} (V)	η_{ea} (%)
20.205	72	455	19.5	20.211	7	225	19.5	82.6
20.223	41	378	15.9	20.238	4	172	15.9	87.0
20.247	32	335	13.1	20.279	4	159	13.1	88.0

In this case, the radiated resistances of the transducer at the conditions of on resonance and off resonance can be regarded as invariant. Eq. (17) can be written as:

$$W_a = \frac{W_{il} - W_{in} - (W'_{il} - W'_{in})}{1 - (v'_l)^2/v_l^2}. \tag{18}$$

In Eq. (18), W_{il} and W_{in} are the measured electrical input powers of the transducer on resonance under the conditions of load and no load. W'_{il} and W'_{in} are the measured electrical input powers of the transducer off resonance under the conditions of load and no load. v_l and v'_l are the measured vibrational velocities of the transducer with load under the conditions of on resonance and off resonance. It is obvious that these parameters can be measured easily using the experimental set-up in Fig. 1. On the other hand, it can be seen that in Eq. (18) the velocity ratio and the difference in the measured electrical input powers of the transducer are used. This is beneficial to the precision increase of the experimental results. The reason is that it is unnecessary to measure the absolute value of the vibrational velocity, so the absolute calibration of the velocity pick-up is not needed. In contrast, since the difference in the measured electrical input power of the transducer to be measured is used, the measurement error of the input electrical power can be eliminated.

When the radiated acoustic power is measured using the above method, the electro-acoustic efficiency and the radiated resistance of the transducer can be calculated indirectly from Eqs. (2) and (3). In order to obtain the radiated resistance, the vibrational velocity must be calibrated.

4. Experiment

Using the method presented in this paper, the radiated ultrasonic power and electro-acoustic efficiency of some sandwiched ultrasonic transducers under the condition of high power are measured. The transducers to be measured are traditional sandwiched ultrasonic transducers used for ultrasonic cleaning. Their mechanical quality factors without load can be calculated according to the following equation, approximately:

$$Q_{m0} = \frac{f_m}{2(f_n - f_m)}\sqrt{\frac{Z_n}{Z_m}}. \tag{19}$$

In Eq. (19), Q_{m0} is the mechanical quality factor of the transducer without load. For high power ultrasonic transducers, it is important that the mechanical quality factor of the transducer without load should be high. f_m and f_n are the minimum and maximum impedance frequencies of the transducer without load. Z_m and Z_n are the minimum and maximum impedances of the transducer to be measured. For a high Q transducer, Eq. (19) is accurate. It can be used in the calculation of the mechanical quality factor for a transducer without load. For the transducer used in the experiment, the parameters measured by means of the transmission line method under the condition of low exciting electrical signal are as follows: $f_m = 20\,275$ Hz, $f_n = 21\,064$ Hz, $Z_m = 132.4\ \Omega$, $Z_n = 122\ \mathrm{k}\Omega$. Using Eq. (19), the mechanical quality factor of the transducer is calculated as $Q_{m0} = 390$. The experimental set-up is shown in Fig. 1. In the figure, the velocity pick-up is a piezoelectric ceramic vibrator that converts mechanical vibration into electrical quantity. The measured results are listed in Tables 1 and 2. In the table f_l, W_{il}, V_{il}, v_{ml} and f_n, W_{in}, V_{in}, v_{mn} are the resonance frequency, the input electrical power, the terminal voltage and the vibrational velocity of the transducer on resonance under the conditions of load and no load, respectively. f'_l, W'_{il}, V'_{il}, v'_{ml} and f'_n, W'_{in}, V'_{in}, v'_{mn} are the working frequency (which is slightly away from the resonance frequency of the transducer under the conditions of load and no load), the input electrical power, the terminal voltage and the vibrational velocity of the transducer off resonance under the conditions of load and no load, respectively. W_a and η_{ea} are the measured radiated ultrasonic power and the electro-acoustic efficiency of the transducer. Since the velocity pick-up is not calibrated, the absolute measurement of the vibrational velocity cannot be measured, and therefore the radiated resistance cannot be obtained. It can be seen from Tables 1 and 2 that, when the input electrical power is changed, the electro-acoustic efficiency of the transducer is different. When the electrical input power is increased, the electro-acoustic efficiency of the transducer is decreased. The reason may be that, when the input electrical power is increased, the dielectric and mechanical loss powers are increased. As for the error in the measurement, the following factors should be taken into account. First, when the exciting frequency of the transducer is changed, the vibrational velocity is different, and the radiated resistance is also different. Second, when the input electrical power is low, the reading error of the high frequency wattmeter is increased.

5. Discussions and conclusions

In the above analysis, an improved method for the measurement of ultrasonic transducers under the condition of high power is studied. By means of this method, the radiated ultrasonic power and the electro-acoustic efficiency of the transducer can be measured. In the method, the assumption that the radiated resistance of the transducer to be measured is constant is used. This assumption may lead to some measurement error. Therefore, in order to decrease the measurement error, the frequency variation should be kept as small as possible when the transducer works under the condition of off resonance. To sum up the above analysis, the following conclusions can be drawn.

1. The measurement of the dielectric and mechanical loss powers of the transducer is unnecessary in this method, so two transducers with the same characteristics are not needed, and the measurement precision can be increased.
2. As the velocity ratio is used in the calculation of the radiated ultrasonic power, the absolute measurement of the vibrational velocity of the transducer is unnecessary. Therefore, the absolute calibration of the velocity pick-up is not needed.
3. The difference in the measured electrical input powers of the transducers is employed, so the error resulting from the electrical power consumption in the electrical matching elements can be eliminated.
4. This method can be used in the measurement of the transducer under the condition of high power and in practical cases, such as ultrasonic cleaning, ultrasonic liquid processes and other applications.

References

[1] E.A. Neppiras, Macrosonics in industry: 1. Introduction, Ultrasonics 10 (1972) 9–13.
[2] K.F. Graff, Macrosonics in industry: 5. Ultrasonic machining, Ultrasonics 13 (1975) 103–109.
[3] T.J. Bulat, Macrosonics in industry: 3. Ultrasonic cleaning, Ultrasonics 12 (1974) 59–68.
[4] A.P. Hulst, Macrosonics in industry: 2. Ultrasonic welding of metals, Ultrasonics 10 (1972) 252–261.
[5] P.K. Chendke, H.S. Fogler, Macrosonics in industry: 4. Chemical processing, Ultrasonics 13 (1975) 31–37.
[6] T.J. Mason, T.P. Lorimer, D.M. Baters, Quantifying sonochemistry: casting some light on a black art, Ultrasonics 30 (1) (1992) 40–42.
[7] P.N.T. Wells, Ultrasonics: a window into biomedical science, Ultrasonics 30 (1) (1992) 3–7.
[8] C. Campos-Pozuelo, J.A. Gallego-Juarez, Limiting strain of metals subjected to high-intensity ultrasound, Acustica 82 (6) (1996) 823–828.
[9] R.A. Lemaster, Influence of ceramic location on high power transducer performance, Ultrasonics Symposium Proceedings (1978) 296–299.
[10] M.P. Johnson, Velocity control and the mechanical impedance of single degree of freedom electromechanical vibrators, J. Acoust. Soc. Am. 84 (6) (1988) 1994–2001.
[11] R. Coates, R.F. Mathams, Design of matching networks for acoustic transducers, Ultrasonics 26 (1988) 59–64.
[12] S. Ueha, M. Kuribayashi, Y. Tsuda, E. Mori, An ultrasonic power meter, J. Acoust. Soc. Am. 79 (4) (1986) 985–989.
[13] E. Mori, K. Ito, Measurement of the acoustical output power of ultrasonic high power transducer using electrical high frequency wattmeter, Proceedings Ultrasonics International '81, Brighton, 1981 pp. 307–31.