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POWER MEASUREMENT OF AIR-BORNE ULTRASONIC TRANSDUCERS

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ABSTRACT

The use of radiation force balances is the standardized method for the measurement of ultrasonic power in water, IEC-EN 61161 Ed1. This paper presents and discusses the application of radiation force balances to the measurement of ultrasonic power generated by air-borne transducers. Experimental results from several transducers are presented and discussed.

INTRODUCTION

In the last three decades, developments in the ultrasonic transducer technology with the introduction of new materials and new designs [1-8] have made it possible to produce new air-coupled ultrasonic transducers more efficient and with wider useful frequency bands. These new devices can be well suited for non-contact medical, both for therapy and diagnosis, and industrial applications. One of the first medical uses of non-contact ultrasound was the evaluation of burnt skin and bed sores in burnt victims [9]. Many new applications have been reported since then, mainly in dermatology [10].

The appearance of these non-contact air-coupled applications presents new challenges to medical ultrasonic metrology. Most of the present standards on both transducer design and performance evaluation have been devised for water-borne devices in a water environment and have to face serious drawbacks, especially those derived from the high attenuation of sound in air and the non-existence of standard microphones operating at frequencies above 100 kHz. However, the extensive application of the new devices will demand the development of specific measuring techniques and new standards. In the last years, several authors have proposed different approaches, among them, three-transducer reciprocity and optical tomography, to characterize and calibrate air-borne transducers above 150 kHz [11-17]. However, there is an important magnitude, the radiated ultrasonic power that, in our opinion, can still be measured with the classical procedure, that is, the use of radiation force balances.

The final purpose of this research, in which the content of this paper is only a preliminary step, is to study the validity of the use of radiation force balances for the measurement of the ultrasonic power produced by these new high-frequency air-coupled ultrasonic transducers.

RADIATION FORCE BALANCE METHOD

The radiation force arises from the transfer of momentum from an ultrasonic beam to a target that intercepts it. In the simplest case, under the Langevin condition (open vessel conditions), for small amplitude plane ultrasonic waves and for a perfectly absorbing target that intercepts the whole ultrasonic beam, the relation between the radiation force component F (time-averaged value) on the target in the direction of propagation of the ultrasonic wave, and the output power of the ultrasonic transducer P (time-averaged value) is given by [18]

$$P = c \cdot F \qquad \text{(Eq. 1)}$$

where c is the speed of sound.

In practice, the measurement of the radiation force is based on the determination of the change in the apparent weight of the target caused by the radiation force of the ultrasound. If a static gravimetric balance is used, then

$$P = c \cdot M \cdot g \qquad \text{(Eq. 2)}$$

where M is the change in the balance reading with and without ultrasound and g is the acceleration due to gravity.

Equations (1) and (2) are well known simple approaches whose validity and degree of attainable accuracy in the ultrasonic power estimation have been widely treated in the literature [18-23]. We will apply them to estimate the output ultrasonic power of air-coupled ultrasonic transducers.

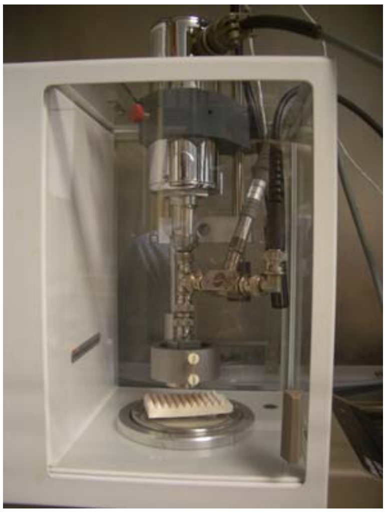
POWER MEASUREMENTS IN AIR

Measurement facilities

The radiation force balance set-up used in these measurements fulfils the requirements from IEC61161 ed 2.0 [18], corresponding to the arrange C, with an absorbing target . It is composed of the following elements:

- Precision balance Metter-Toledo, model AE-163 with electromagnetic compensation and a sensitivity of 10µg, corresponding to a power of 0,15 mW. The balance is placed on heavy marble plate to reduce vibrations
- HP 3336C Synthesizer/Level generator
- AR 75A250 power amplifier
- Precisión positioning system, with an accuracy of 0,25 mm
- Ballantine 1394A Thermal converter
- Keithley 197 digital voltmeter target
- Rohde &Schwarz URV5 millivolmeter
- Tempcontrol 1411 PT100 thermometer
- Compaq Prolinea 5100 PC, with data acquisition card and Test Point based calculation programs developed by R. Hekkenberg.
- Two absorber slabs, 59 × 30 × 10 mm, with piramidal wedges on top of about 3 mm high, made from resin epoxy with 70 % porosity, with and acoustic characteristic impedance of 215 Mrayl. The absorber slabs were placed directly on the balance plate

An scheme and a picture of the of the measuring set-up can be seen in figure 1



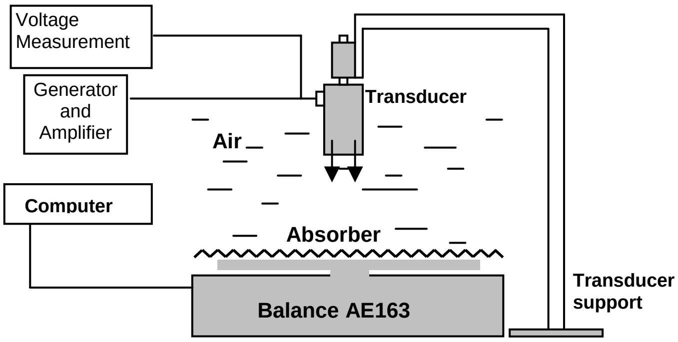


Figure 1.- Measuring set-up

Measurement method

As mentioned above, the power measurements are based on the change in the apparent weight of the target, caused by the radiation force of the ultrasound, as the ultrasound is alternatively switched on and off. As the weight of the target is temperature dependent, the period during which ultrasound is radiated onto the target should be as short as possible to minimise any temperature variation. Using a step response by switching the transducer excitation voltage on for a short period (10 to 15 s) and then off for a longer period (at least 20 s) reduces the effect of temperature variations

In general, to improve the measurement accuracy the on- and off-values of the balance readings are acquired and processed by the computer for several subsequent off-on steps (maximum 5). However. In the case of our air-coupled transducers, the step repetition caused an excessive heating of the transducer causing instabilities and performance degradation. In consequence only two periods, one on and one off, have been used in our measurements. During the off- and subsequent on-periods the mass corresponding to the apparent weight of the target is measured by the balance and about 15 to 25 successive readings, depending of the transducer used, were taken and stored into the computer. The readings are separated in time by about 0,8 s for the AE163. For the calculation of the difference in mass between the off- and on-situation the balance readings occurring during the step response are being ignored. An algorithm calculates the linear regression line (least-square fit) for each off- and on-period. The actual change in the mass corresponding to the apparent weight is then calculated as the difference between the extrapolated linear regression lines at the moment halfway the step response. In this way, short-term drift-effects, among which is heating of the transducer and of the target, are corrected for.

From the determined mass difference, the acoustic power can be calculated using Equation (2). However, real fields of ultrasonic transducers are not plane and their structure usually are between that of a plane wave and that of a theoretical, circular plane piston source. Assuming that the real field is more or less the average of the two extremes, for a circular single-element transducer, Equation (2) becomes [19,20]:

$$P_m = (1 + \frac{0.6531}{2ka}\left(1 + \frac{1.407}{(ka)^{2/3}}\right)) \cdot Mgc \,. \qquad \text{(Eq.3)}$$

where k is the wave number and a is the transducer radius. After this, the total power P_r at the transducer surface is calculated from P_m through correcting for the attenuation of the ultrasonic beam in the air, using the relation

$$P_r = P_m \cdot e^{2\alpha} \quad \text{(Eq. 4)}$$

in which $e^{2\alpha}$ is the correction factor for attenuation. The parameter $\alpha>0$ denotes the attenuation of air, expressed as the relative decrease of pressure amplitude over the air path. The sound attenuation along a distance d can be expressed as:

$$\alpha = \alpha_0 f^2 d \qquad \text{(Eq. 5)}$$

where α_0 is the attenuation coefficient of sound in air (in $m^{-1}MHz^{-2}$), f is the ultrasonic working frequency (in MHz). The attenuation coefficient α_0 in humid air is a complex magnitude that depends on temperature, static pressure and humidity. In our work, as a first approach we have used a value of 4,66 x 10^{-13} corresponding to the dry air at 23 ºC [24].

Something similar happens with the speed of sound c that for humid air is a function of temperature and humidity. In our calculations, we have used the expression corresponding to dry air [25], $c = 331{,}3 \times 0{,}6\ T$, where T is the temperature, in ºC.

In order to compensate for errors in the measurement of the separation distance between the transducer and the absorbent and for a rather doubtful value of the attenuation coefficient, the power determination was made at different distances, namely 1 mm, 3 mm, 5 mm 8 mm and 15 mm. Then the value of the radiated power at the transducer surface was determined by extrapolation to $d = 0$ using a regression line fit.

Radiation conductance

Since the radiated power is a function of the input voltage, a better way of characterising the transducer behaviour is by means of the electro-acoustic radiation conductance, G ,defined as $G = P_r/U^2$, where U is the rms value of the input voltage [18] measured through a Ballantine voltage thermal converter. Provided the transducer behaves linearly, G is a characteristic quantity of the transducer and will be the quantity used to analyze our measurement results. This magnitude is used to compare the measurement results in metrological comparisons [22,23,27,28]

RESULTS

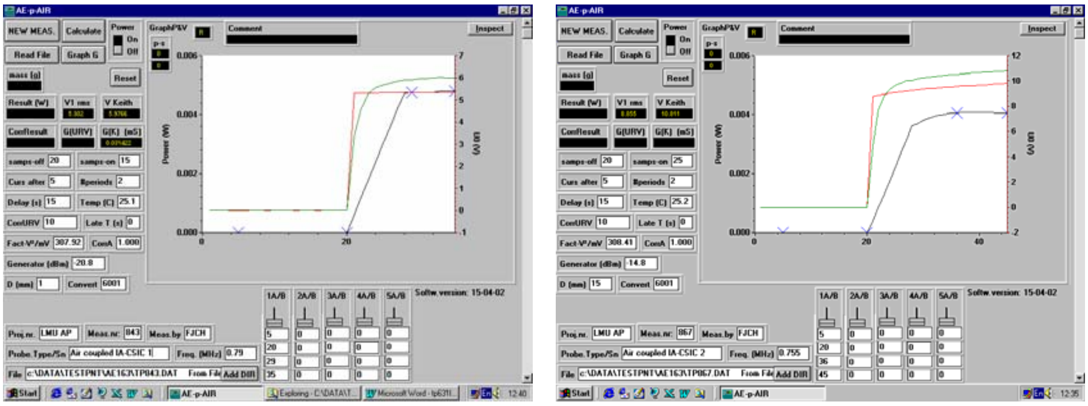
Three non-comercial air-coupled ultrasonic transducers made at Instituto de Acústica have been measured. The transducers are unbacked, 1-3 piezocomposites with two matching layers, one made with

Araldit – D (Cyba & Geigy), and the other with a micropored cellulose filter [29,30]. Two of them, referred to as IC-CSIC 1 and IA-CSIC 2, are cylindrical with an effective radiating surface of 20 mm of diameter and with main resonance frequencies at 790 kHz and 755 kHz, respectively. The third one, IA-CSIC 3, is rectangular with an effective radiating surface with dimensions 14,5 mm × 15,5 mm, and a main resonance frequency at 760 kHz.

At a first stage, the transducers were fed with input voltages from 6, 0 V (rms) to 14,4 V (rms) to check linearity and the heating effect. Then, most measurements were made with input voltages around 7,0 V (rms). Due to its low sensitivity, 10 V (rms) had to be used with IA-CSIC 3.

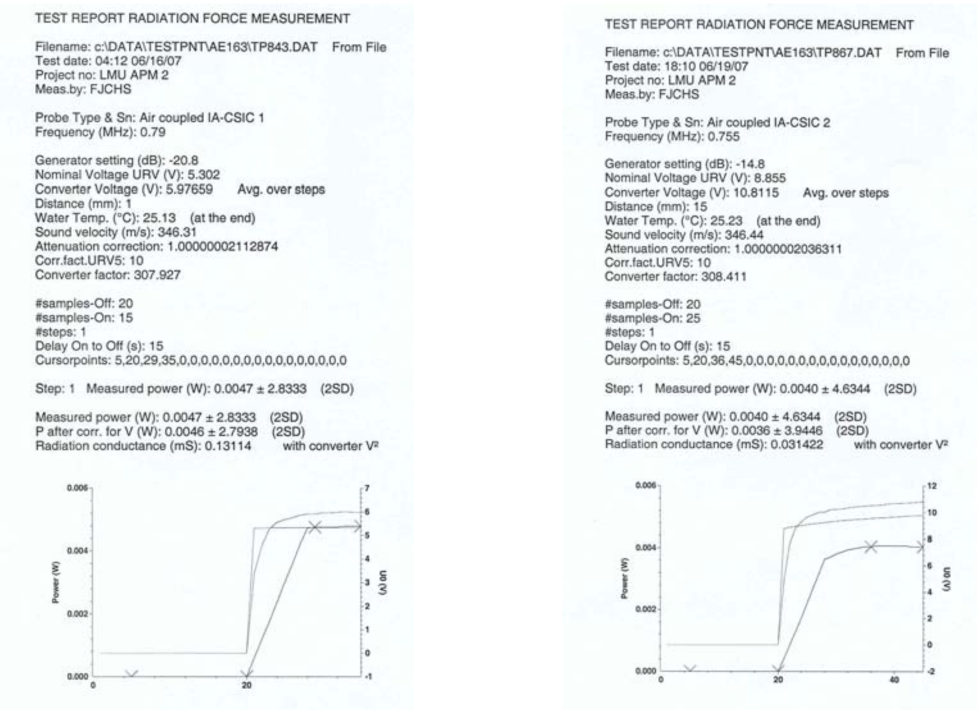
Measurements were made at separation distances of 1 mm, 3 mm, 5 mm, 8 mm and 15 mm. All measurements were made at stable conditions with temperatures in the range 22-27 ºC and relative humidity in the range 40-45 %

In figure 2, some samples of the measuring results are given, while, in figure 3, the calculations corresponding to these results are presented.



a) IA-CSIC 1 b) IA-CSIC 2

Figure 2 – Measurement results samples



TEST REPORT RADIATION FORCE MEASUREMENT

Filename: c:\DATA\TESTPNT\AE163\TP843.DAT From File
Test date: 04:12 06/16/07
Project no: LMU APM 2
Meas.by: FJCHS

Probe Type & Sn: Air coupled IA-CSIC 1
Frequency (MHz): 0.79

Generator setting (dB): -20.8
Nominal Voltage URV (V): 5.302
Converter Voltage (V): 5.97659 Avg. over steps
Distance (mm): 1
Water Temp. (°C): 25.13 (at the end)
Sound velocity (m/s): 346.31
Attenuation correction: 1.00000002112874
Corr.fact.URV5: 10
Converter factor: 307.927

#samples-Off: 20
#samples-On: 15
#steps: 1
Delay On to Off (s): 15
Cursorpoints: 5,20,29,35,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0

Step: 1 Measured power (W): 0.0047 ± 2.8333 (2SD)

Measured power (W): 0.0047 ± 2.8333 (2SD)
P after corr. for V (W): 0.0046 ± 2.7938 (2SD)
Radiation conductance (mS): 0.13114 with converter V²

TEST REPORT RADIATION FORCE MEASUREMENT

Filename: c:\DATA\TESTPNT\AE163\TP867.DAT From File
Test date: 18:10 06/19/07
Project no: LMU APM 2
Meas.by: FJCHS

Probe Type & Sn: Air coupled IA-CSIC 2
Frequency (MHz): 0.755

Generator setting (dB): -14.8
Nominal Voltage URV (V): 8.855
Converter Voltage (V): 10.8115 Avg. over steps
Distance (mm): 15
Water Temp. (°C): 25.23 (at the end)
Sound velocity (m/s): 346.44
Attenuation correction: 1.00000002036311
Corr.fact.URV5: 10
Converter factor: 308.411

#samples-Off: 20
#samples-On: 25
#steps: 1
Delay On to Off (s): 15
Cursorpoints: 5,20,36,45,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0

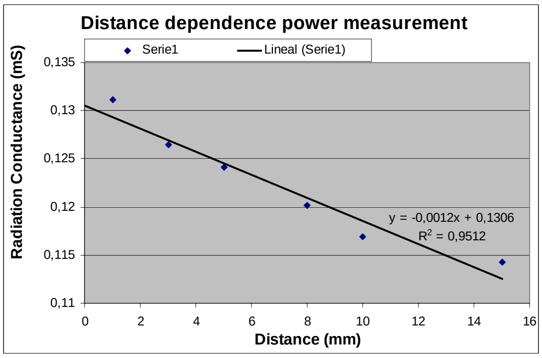
Step: 1 Measured power (W): 0.0040 ± 4.6344 (2SD)

Measured power (W): 0.0040 ± 4.6344 (2SD)
P after corr. for V (W): 0.0036 ± 3.9446 (2SD)
Radiation conductance (mS): 0.031422 with converter V²

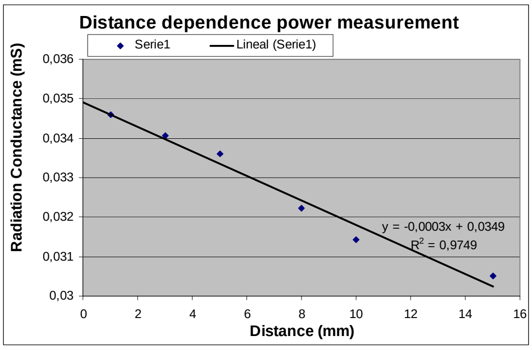
a) IA-CSIC 1 b) IA-CSIC 2

Figure 3 – Calculation samples

In figure 4, some results corresponding to the radiation conductance extrapolation for each transducer are presented



a) IA-CSIC 1



b

b) IA-CSIC 2

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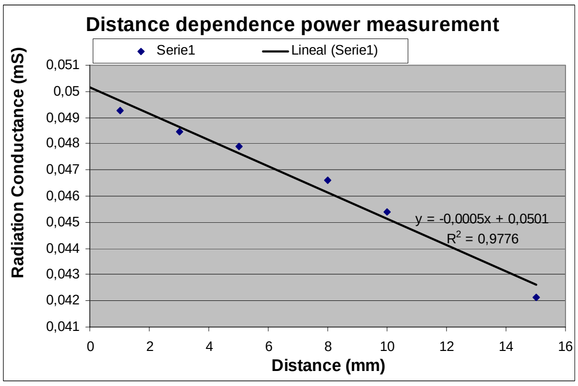

c) IA-CSIC 3

Figure 4 – Radiation conductance extrapolation results

In table 1 a summary of the extrapolated radiation conductance results for the three transducers is given

Table I.- Radiation conductance at transducer surface: extrapolated results

IA-CSIC 1		IA-CSIC 2		IA-CSIC 3	
G (mS)	Reg. Coeff	G (mS)	Reg. Coeff	G (mS)	Reg.Coeff
0,101	0,9589	0,034	0.9092	0,050	0,9776
0,126	0,9323	0,035	0,9749	0,056	0,9096
0,127	0,7584			0,052	0,958
0,132	0,9512			0,051	0,7694

Measurement uncertainty

Since this work is in its very preliminary stages, no serious attempt has been made to determine the measurement uncertainties. However, taking into account the assumptions made, the experimental deviation of the results and the uncertainty associated to the measuring system when used in water, we are confident that our uncertainty must be lower than 20 %

Measurement validation

As, at the present time, we do not have any other method to determine the radiated power from our air-coupled transducers, we have made a theoretical estimation of the radiated power. To do it so, we have assumed that our transducers behaved as a baffled circular piston. Then, for high frequencies (ka >> 1), the power radiated from such a source can be expressed as [26] :

$$P = \frac{1}{2}\rho_0 \cdot c \cdot S \cdot U_0^2 \qquad \text{(Eq.5)}$$

where ρ_0 is the density of the radiated medium, c its sound propagation speed, S is the surface of the radiating source and U_0 is the velocity distribution of the radiating surface.

In our case, the velocity distribution of the radiating surface of our transducers can be measured by laser interferometry using a Polytec laser vibrometer, composed of an OFV-500O vibrometer controller and an OFV-505 sensor head.

In table II, the theoretically determined radiation conductance values for the three transducers are given. In these calculations, in agreement with previous assumptions, the values of the density and sound velocity and been chosen as those for dry air at 25 ºC, the mean temperature at which the measurements have been made.

Table II.- Radiation conductance at transducer surface: theroretical results

IA-CSIC 1		IA-CSIC 2		IA-CSIC 3	
Desp.dist. (nm/V)	G (mS)	Desp.dist. (nm/V)	G (mS)	Desp.dist. (nm/V)	G (mS)
8,5	0,113	4,3	0,026	3,4	0,012

From the comparison of tables I and II, a reasonably good agreement for the cylindrical transducers, IA-CSIC 1 and IA-CSIC 2, can be observed. However, for the rectangular one, IA-CSIC 3, the agreement is not so good.

CONCLUSIONS

With all the reserves imposed for the many simplifying assumptions introduced in the practical and theoretical approach used to study the measurement the output power of air-coupled ultrasonic transducers, the very reduced experimental deviation of our measurement results and the good agreement found between the theoretical and the measured radiation conductance values for the two cylindrical air-coupled transducers suggest us that we are in the right way and encourages us to go further with the use of radiation force balances for the measurement of the output power of air-coupled piezoelectric transducers.

ACKNOWLEDGMENTS

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