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ACOUSTIC FIELD MEASUREMENTS USING A PVDF FOIL HYDROPHONE

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This study was concerned with a membrane, pdvf foil and double-screened hydrophone, manufactured by Sonic Technologies, USA. Using the producer's data in the form of discrete data, power functions, describing the input impedance and the sensitivity of the hydrophone, depending on the frequency, were found. This made it possible to represent the measuring system in the form of a equivalent circuit containing a pressure source, a transformer which converted the acoustic pressure into the electric intensity (the hydrophone sensitivity), the hydrophone impendance, an additional coaxial cable and the input receiver impedance. The impacts of the receiver impedance and that of the additional cable on the accuracy of measurements of the acoustic pressure using a hydrophone were subsequently investigated.

As an example, an ultrasonographic measurement using the hydrophone in question was cited.

1. Introduction

The broad application of ultrasound methods in medical diagnostics requires accurate knowledge of the intensities of acoustic waves being applied. Ultrasonography is considered a safe method for the patient, but to an even greater extent this obliges producers and doctors to define accurately the doses used in the course of an examination. Ultrasound fields are defined by a number of parameters – the wave frequency, the repetition frequency, the pulse duration, the beam cross-section and the wave intensity – the maximum and mean ones in time and space. The mechanism of the impact of ultrasound on the organism is complex [3], depending to a varying degree on each of these quantities. Therefore, measurements of the diagnostic apparatus are performed in keeping with the recommendations of international standards developed by the IEC (the International Electrotechnical Commission) [1], [4], which recommend that a foil hydrophone should by applied for this purpose.

The object of this study is a membrane hydrophone of PVDF foil, screened on both sides, with a 60 cm long coaxial cable, and produced by Sonic Technologies, USA. The producers give its sensitivity and input impedance for frequencies from

1 to 20 MHz. Oscilloscopes with different input impedances and capacitances are applied in measurements. When the hydrophone cable is too short it is elongated by an additional cable. The producers give a formula for calculating the hydrophone sensitivity, depending on the input impedance of the receiver and the additional cable, which is treated as lumped capacitance. To check the admissibility of this approximation and to investigate more accurately the impact of the additional cable on the pressure measurement, it was represented in the form of a long line. Then, functions were found which described the input impedance and sensitivity, depending on the frequency and a equivalent circuit of the measuring system was applied in the further analysis. In the work performed at the Department on the design and work analysis of ultrasound transmitting-receiving systems their equivalent circuits were used, in the form of a chain of four-terminal networks, and so was the FFT technique [6], [7]. The representation of the measuring hydrophone in an analogous way will make it possible for it to be read in a simple way into computer programmes developed by the authors and to analyze systems with a receiving transducer in the form of a hydrophone.

2. The parameters of the hydrophone

Piezoelectric foil hydrophones are usually built in two versions a needle or foil extended over a ring with a diameter of several cm, with sputtered electrodes of diameters below 1 mm [2]. Because of good acoustic matching to water, the latter do not disturb significantly the acoustic field being measured.

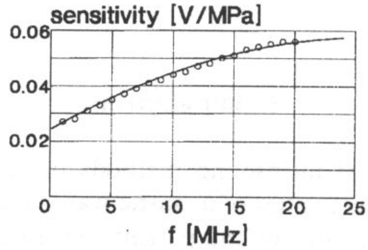

Fig. 1. Sensitivity modelling using the power functions (the circles denote the producer's data).

An analysis of measurements using a hydrophone produced by Sonic Technologies, USA, will be presented below. The producer gives the characteristics of sensitivity and input impedance of the hydrophone as a function of the frequency f in the range of 1 to 20 MHz [5]. To examine the impact of the parameters of the receiving system on the accuracy of measurements, the parameters of the hydrophone were described with power functions. The sensitivity function of the hydrophone was adopted in the following form:

$$\mathrm{a}\left(\frac{f-b}{b}\right)^2+c,$$

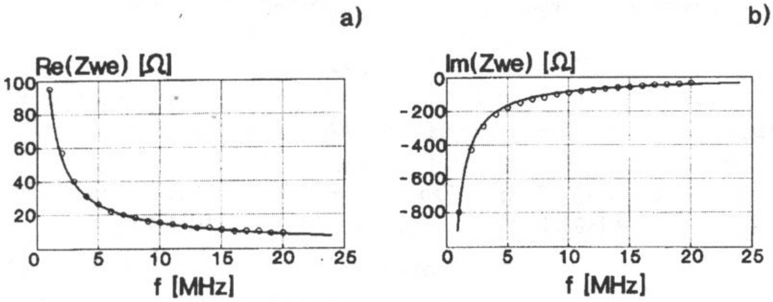

Fig. 2. Modelling of the real part (a) and the imaginary part (b) of the input impedance of the hydrophone (the circles denote the producer's data).

while the constants *a, b* and *c* were varied so that the calculated curve would coincide with the producer's data. It was achieved for $a = -0.335$, $b = 26.5$ and $c = 0.0578$.

The impedance of the hydrophone was described by the functions

$$\mathrm{Re}(Z_{\mathrm{in}}(f)) = \frac{d}{f^g} \qquad \mathrm{Im}(Z_{\mathrm{in}}(f)) = \frac{h}{f^k}.$$

The calculated functions coincided with the producer's data for $d = 95$, $g = 0.8$, $h = -815$ and $k = 0.955$. Figure 1 shows the calculated sensitivity curves, whereas Fig. 2 represents the real part (a) and the imaginary part (b) of the impedance of the hydrophone, along with the producer's data marked with points. It can be seen that the curves coincide with the points, therefore, the work of the hydrophone may be described using the system shown in Fig. 3. It includes a pressure source, a four-terminal network, describing a transformer which converts the acoustic pressure into the electric voltage (the hydrophone sensitivity), the hydrophone impedance, a coaxial cable in the form of a long line and the input impedance of the receiver in a parallel system of resistances and capacitances.

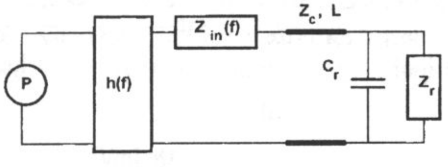

Fig. 3. A equivalent circuit for the hydrophone: *P* the measured pressure, *h*(*f*) a fourterminal network representing a transformer which converts the acoustic pressure *P* into intensity (with the hydrophone sensitivity as a function of frequency), $Z_{\mathrm{in}}(f)$ – the input impedance of the hydrophone, Z_cL the additional coaxial cable (with the characteristic impedance Z_c and the lenght *L*), Z_r the input receiver impedance and C_r the input receiver capacitance.

To examine the impact of the impedance of the receiver and the parameters of the additional coaxial cable on the accuracy and sensitivity of field measurements using the hydrophone, the received transmission functions and electric pulses were calculated with the assumption of the acoustic pressure in the form of one sinusoid course with a frequency of 3.5 MHz and an amplitude of 1 MPa [6], [7].

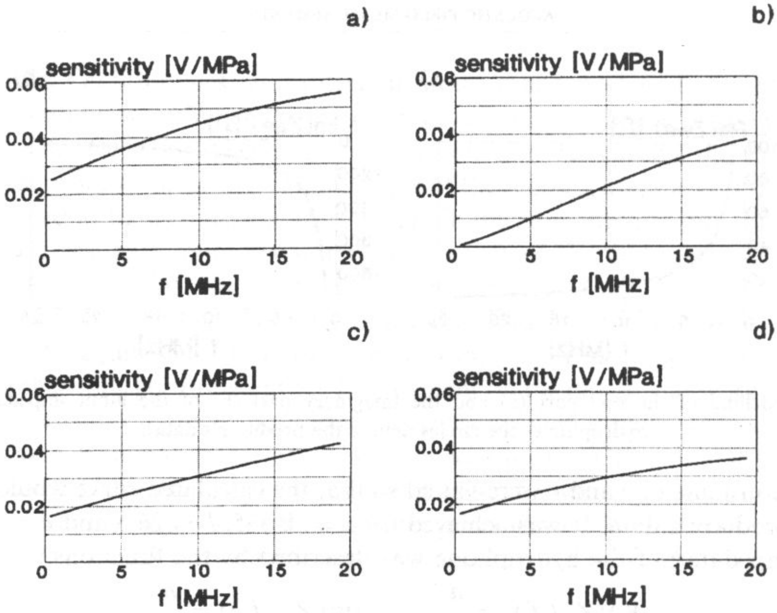

Fig. 4. Hydrophone sensitivities for dirrerent input receiver impedances:
a – 1 M Ω, 0 pF, no additional cable,
b – 50Ω, 0 pF, no additional cable,
c – 1MΩ, 0 pF, an additional 1 m cable,
d – 1 MΩ, 100 pF, no additional cable.

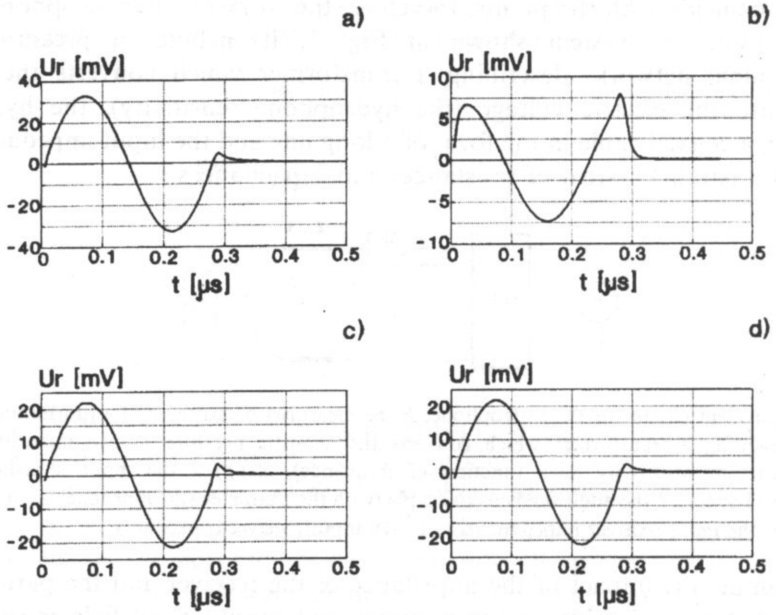

Fig. 5. The pulses detected by the hydrophone as in Fig. 4. The transmitted pressure pulse in the form of a single sinusoid with a frequency of 3.5 MHz and an amplitude of 1 MPa.

The results of these calculations are shown in Figs. 4 and 5. Figures 4a and 5a show the results calculated for the optimum case, for a system without an additional cable and a receiver with the real impedance of 1MΩ, i.e., for the producer's data.

Figures 4b and 5b show the results calculated for the receiver impedance of 50Ω. It can be seen that the low-ohm input of the receiver causes a sensitivity drop; moreover, it is distinctly greater for low frequencies, which, in turn, causes a disastrous distortion of the pulse. Therefore, it should be borne in mind that a high-ohm input of the receiver should be applied.

Figures 4c and 5c show the results calculated for a system with an additional, 1 m long cable. It can be seen that the addition of the cable causes lower sensitivity, but the shape of the pulse does not deteriorate visibly.

Therefore, the hydrophone producers [2], [3] recommend that the sensitivity drop should be considered, in keeping with the formula

$$M_{\text{eff}} = M_c \left\{ \frac{\operatorname{Re}(Z_L)^2 + \operatorname{Im}(Z_L)^2}{[\operatorname{Re}(Z_L) + \operatorname{Re}(Z)]^2 + [\operatorname{Im}(Z_L) + \operatorname{Im}(Z)]^2} \right\}^{1/2},$$

where Z_L – the impedance of the measuring device (the receiver and cable), Z – the hydrophone impedance, M_c – the sensitivity given by the producer.

According to the producer, an additional cable should be regarded as lumped capacitance. In order to check the validity of this assumption and to examine more accurately the impact of the impedance of the measuring equipment on the sensitivity and shape of the pluses received, the sensitivity and pulses received by the hydrophone were calculated for the case when lumped capacitance, equal to the capacitance of a 1 m long open cable, i.e., one of 100 pF, was added. Comparing the results of hydrophone sensitivity calculations when the lumped capacitance is added (Fig. 4d) with those obtained with an added cable (Fig. 4c), it can be seen that the sensitivity curves are close to each other at low frequencies. It is permissible to treat the cable as lumped capacitance (of 100 pF in this case) up to about 10 MHz. On the other hand, at higher frequencies, the error committed for this assumption grows, reaching 10% at 20 MHz (the hydrophone is scaled up to this frequency).

3. Conclusion

The equivalent circuit of the system for measuring acoustic pressures will make it possible to read it into the computer programmes developed by the authors for the purposes of not only designing ultrasound transmitting-receiving systems, but also conducting analyses of systems with a receiving transducer in the form of a hydrophone.

Foil hydrophones are primarily applied for measuring ultrasound wave doses in diagnostic apparatus. The mechanism of the impact of ultrasound on the organism is complex, depending on particular parameters, such as the wave frequency, the repetition frequency, the pulse duration, the beam cross-section, the wave intensity the maximum and those averaged in time and space. Knowledge of these quantities is necessary from the point of view of the patient safety and the research on the ultrasound impact on living organisms.

Only the impact of the electric circuit on the measured results was discussed in this study. When measuring the acoustic field distribution it should be borne in mind that these measurements involve an error which results from the finite hydrophone diameter comparable to the wavelength being measured. The measurement error diminishes as the distance from the transducer grows, and, according to the standards, it may be neglected when the following condition is satisfied for the hydrophone radius [2]:

$$b_{\mathrm{Max}} = \frac{\lambda}{4}\,[(1/2a)^2 + 0.25]^{1/2},$$

where 1 – the distance from the transducer and a – the transducer radius.

It should also be borne in mind that the hydrophone sensitivity as a function of frequency is provided by the producer for measurements along the axis of the transducer being measured; the higher the frequency, i.e., the shorter the wave, to the greater extent the directivity grows. Usually, the producer provides directivity curves for a few chosen frequencies.

4. Appendix: Measurements of the ultrasonographic parameters in keeping with international standards

The development of foil hydrophones facilitated measurements of the parameters of ultrasound diagnostic apparatus in keeping with the requirements of international standards of the IEC (the International Electrotechnical Commission). As an example, the relevant definitions as introduced by the ICC [1] are shown and so are the methods for measuring excited to vibration, resembling the one applied in ultrasonographs manufactured by Echoson S.A.

The pulses applied in ultrasonography should be as short as possible, with a wide frequency band. The **pulse frequency** is defined as the arithmetic mean from the lobe frequencies of the main pulse spectrum as read out for a 6 dB drop in the spectrum amplitude. Fig. 6a shows a pulse measured by the hydrophone and in Fig. 6b its Fourier transform may be seen.

In keeping with the definition, the pulse frequency is $f_0 = \dfrac{f_1 + f_2}{2} = 2.4$ MHz.

The amplitude of an electric pulse as measured using a hydrophone placed in the focus of the probe was $U_m = 0.04$ V. **The pressure amplitude in the focus** may be calculated taking into account the hydrophone sensitivity M for the measured frequency (in the case under consideration, it was 2.4 MHz).

$$p_{\mathrm{m}} = U_m \;/\; M = 0.04\mathrm{V} \;/\; 0.028\,\frac{\mathrm{V}}{\mathrm{MPa}} = 1.43\ \mathrm{MPa}.$$

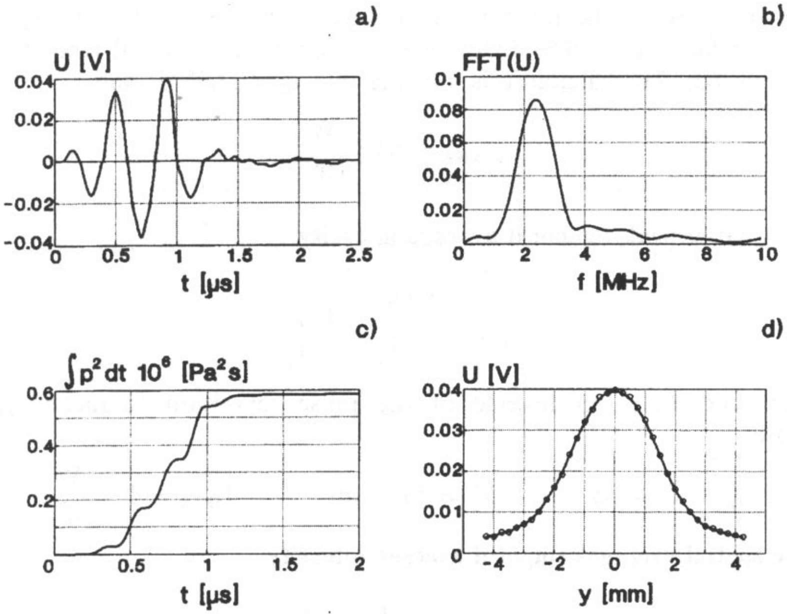

Fig. 6. The ultrasonographic parameters having been measured using the hydrophone. The acoustic pulse in the focus (a), its Fourier transform (b), an integral over time with a squared pressure (c) and the focal pressure distribution (d).

The mechanism of the ultrasound wave impact on the human organism is complicated. Therefore, it was necessary to perform accurate measurements of such parameters of the wave as could be responsible for mechanical, thermal or cavitation impacts. International standards recommend that measurements should be taken not only of the maximum wave intensity in the focus, but also **the one averaged it time and space.** The subscripts introduced in the intensity terms reflect the first letters of English words:
maximum – *m*, spatial – *s*, temporal – *t*, peak – *p* , averaged following a pulse – *p* and average – *a*.

The intensities are measured with the assumption that the wave is a plane one; this is met in practice as the measurements are carried out in the focal plane.

I_{SPTP} — the spatial peak-temporal peak intensity:

$$\mathbf{I}_{\mathbf{SPTP}} = \frac{p^2}{Z} \qquad \mathbf{I}_{\mathbf{SPTP}} = 136\ \frac{\mathrm{W}}{\mathrm{cm}^2}$$

($Z = 1.5 \cdot 10^6\ \dfrac{\mathrm{kg}}{\mathrm{m}^2\mathrm{s}}$ – the acoustic water impedance);

I_{SPPA} – the spatial peak – pulse avarege intensity:

$$\mathbf{I}_{\mathbf{SPPA}} = \frac{\int_{t_d} p^2 dt}{Z t_d},$$

where the duration of the pulse is defined as: $t_d = 1.25(t_2 - t_1)$, and t_2 and t_1 are calculated for 90% and 10% drops in the value of the integral from the squared pressure (Fig. 6c). The calculations indicate that $t_d = 0.625$ μs and

$$\mathrm{I_{SPPA}} = 54.5\,\frac{\mathrm{W}}{\mathrm{cm}^2},$$

$\mathrm{I_{SPTA}}$ – the spatial peak-temporal avarage intensity:

$$\mathrm{I_{SPPA}} = \frac{\int_T p^2 dt}{Z T_p} = \frac{\mathrm{I_{SPPA}}\, t_d}{T_p},$$

where the time T_p is an inverse of the pulse repetition frequency f_p. In the present case,

$$f_p = 1224\ \mathrm{Hz}, \qquad T_p = 0.817\ \mathrm{ms}, \qquad \mathrm{I_{SPTA}} = 42\,\frac{\mathrm{mW}}{\mathrm{cm}^2},$$

$\mathrm{I_{SATA}}$ – the spatial average-temporal average intensity:

$$\mathrm{I_{SATA}} = \frac{\int_A \mathrm{I_{SPTA}}\, dA}{A},$$

where A is the integration space.

Figure 6d shows the pressure distribution in the focus as measured using the hydrophone. By calculating the integral over the surface and by averaging it, the following result is obtained:

$$\mathrm{I_{SATA}} = 2\,\frac{\mathrm{mW}}{\mathrm{cm}^2},$$

The ultrasonic power:

$$P = \int_A \mathrm{I_{SATA}}\, dA$$

For the measurements described above: $P = 0.96$ mW.

The results, presented in the Appendix, of the determination of the parameters of the acoustic field radiated by an ultrasound probe are examples of measurements and should be carried out by all producers or users of ultrasound devices, in keeping with the recommendations of international standards as developed by the IREC (the International Electrotechnical Commission).

5. References

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