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A MULTILAYER METHOD FOR LINEARITY DETERMINATION OF THE PVDF HYDROPHONE FOR PRESSURES UP TO 2.3 MPa

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A new method of linearity measurements of a PVDF membrane hydrophone was elaborated. High pressure pulses up to 6 MPa were obtained in the focus of a concave PZT transducer with the frequency of 3 MHz. The method is based on the pressure decrease of these pulses transmitted through metal layers with known acoustic impedances, immersed in water. In this way one obtained pressure changes at constant shapes (spectrum) of the pulses which were measured by means of the hydropbone under investigation. The measurement results confirmed the linearity of the hydrophone up to pressures equal to 2.3 MPa. Correlation coefficients of 5 measured relations were in average equal to $r = 0.994$.

1. Introduction

The PVDF (polyvinylidene fluoride) hydrophones became nowadays very useful for acoustic measurements of ultrasonic diagnostic devices. Ultrasonic pressures, obtained in such cases, are sometimes higher than 1 MPa (about 10 atm), being 7 orders of magnitude higher than acoustic pressures corresponding to the laudness level of 80 dB. Parameters of these hydrophons are given by producers except their linearity properties. In the literature there was published a paper [3] showing a good linearity of such a hydrophone up to 30 MPa, and a little worse for pressures up to 70 MPa. This problem is for us especially important since we are carring out measurements of nonlinear effects caused by nonlinear wave propagation. In our PVDF hydrophone, which was fabricated in laboratory [1], after some years of use we have noticed a partial damage of gold electrodes caused probably by cavitation. The thin plastic foil could be also partially damaged although there are no visible signs of destruction. So the authors decided to check the hydrophone's linearity to ensure the correctness of future measurements of nonlinear wave propagation. The question of the possible decrease of its sensitivity will be discussed in an another paper. To solve the linearity problem a multilayer method was elaborated, where metal layers with various acoustical properties [2], immersed in water, are used to decrease the measured pressure pulse without changing its shape (spectrum).

2. Decrease of the pressure pulse penetrating metal layers

When mesuring by means of our PVDF hydrophone pressure pulses with the same spectrum, however with different pressures, different sections of the linear or nonlinear hydrophone's characteristics are used.

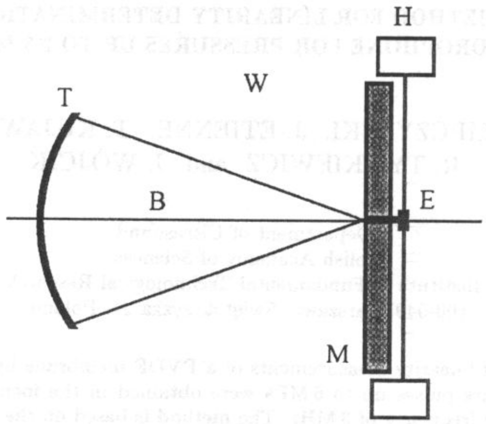

Fig. 1. The system used in measurements. T – transmitting PZT transducer, W – water, P – metal layer, B – ultrasonic focused beam, H – membrane PVDF hydrophone, E – its sensitive electrode.

The measurements were carried out in the system shown in Fig. 1. The PZT concave, circular transducer 2 cm in diameter, with 3 MHz frequency and the focal length of 65 mm was used as the source of ultrasonic pulses. The electrical voltage applied to the transducer was changed from $47V_{pp}$ to $320V_{pp}$ (Fig. 2). Pressure pulses were measured by means of the PVDF hydrophone under investigation. The maximum pressure obtained in the focus was equal to several MPa. Its axial distribution showed the constant pressure in the distance from 65 to 70 mm from the PZT transducer, while its perpendicular focal width was 2 mm (−6 dB). The measurements were carried out with layers of metal 5 mm in thickness, made of steeel, aluminium alloy and electron (alloy of magnesium with addition of aluminium, zink and manganese). Acoustic impedances of the materials listed above are gradually decreasing as shown in Table 1.

Table 1. Measured parameters of metal plates.

	Density ϱ [g/cm^3]	Velocity c [m/s]	Acoust. impedance ϱc [MRayl]	Attenuation α [dB/cm]
Stainless steel	8.59	4890	42	
Carbon steel	7.87	5926	46.6	$\alpha_{3\,\mathrm{MHz}} = 0.24$ $a_{10\,\mathrm{MHz}} = 0.66$
Dural 1	2.83	5897	16.7	
Dural 2	2.81	6350	17.8	
Elektron	1.86	6366	11.9	

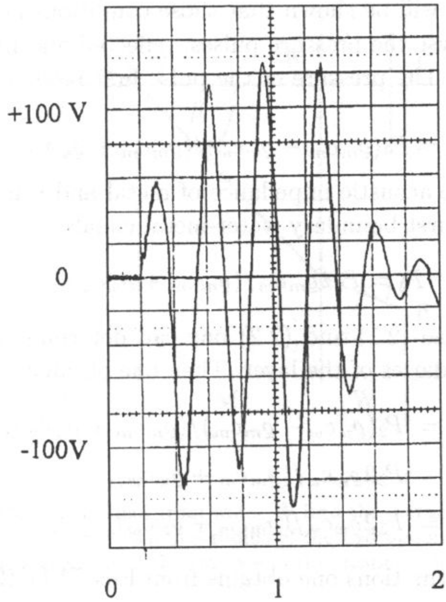

Fig. 2. Example of an electrical pulse with the voltage of $265V_{pp}$ generated by the transmitter. Vertical scale – 20 V. Horizontal scale – 0.2 μs.

Figure 3 shows in coordinates z, t the reflections of the pressure pulse P_0 incident on the metal layer. The pulse width is short enough to avoid standing waves in the layer. So formulae for propagating plane waves penetrating the metal layer will be assumed.

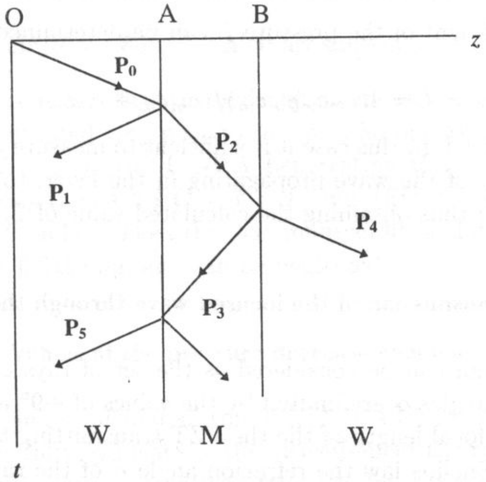

Fig. 3. Reflections of the plane wave pressure pulse in a metal layer M immersed in water W. z, t – distance and time coordinates, AB – metal layer thickness, for $A < z > 0$ and $z > B$ there is water, P_0 – incident pulse, P_1, P_5 – pulses reflected from the front surface of the layer, P_2, P_3 – pulses penetrating into the layer, P_4 – pulse transmitted through the layer.

In the following section it will be shown that those conditions are justified.

It is necessary to analyse the pressure pulses, reflected and propagated in the metal layer, immersed in water. The pressure of the pulse first reflected from the metal layer equals

$$P_1 = P_0(\varrho_m c_m - \varrho_w c_w)/(\varrho_m c_m + \varrho_w c_w), \tag{2.1}$$

where $\varrho_m c_m$, $\varrho_w c_w$ denote acoustic impedance of metal and water. The pressure of the pulse P_2 penetrating the first boundary water-metal equals

$$P_2 = P_0 2\varrho_m c_m/(\varrho_m c_m + \varrho_w c_w). \tag{2.2}$$

Using respectively formulae (2.1) and (2.2) one can determine all the waves reflected and penetrating the boundaries of the layer. Then one obtains

$$P_3 = P_2(\varrho_w c_w - \varrho_m c_m)/(\varrho_m c_m + \varrho_w c_w), \tag{2.3}$$

$$P_4 = P_2 2\varrho_w c_w/(\varrho_m c_m + \varrho_w c_w), \tag{2.4}$$

$$P_5 = P_3 2\varrho_w c_w/(\varrho_m c_m + \varrho_w c_w). \tag{2.5}$$

After some simple transformations one obtains from Eqs. (2.1)–(2.5) the relation

$$P_4/P_0 = -P_5/P_1\,. \tag{2.6}$$

It means that the decrease coefficient of the pressure pulse $L = P_4/P_0$, transmitted through the metal layer, equals $-P_5/P_1$; the negative ratio of the second pulse reflected from the front surface of the layer to the first pulse reflected from the back surface of the layer. The relation (2.6) makes it possible to determine the value of L by means of one simple direct mesurement using for this purpose only one plane transmit-receive transducer.

The decrease coefficient of the pressure L can be determined also directly from the equation

$$L = 4(\varrho_w c_w \varrho_m c_m)/(\varrho_m c_m + \varrho_w c_w) \tag{2.7}$$

that can be easily derived. In this case it is sufficient to measure the metal density ϱ, the longitudinal velocity c of the wave propagating in the layer, to introduce these values into the equation (2.7) thus obtaining the calculated value of L.

3. Transmission of the focused wave through the layer

The ultrasonic beam can be considered as the set of rays crossing themself in the focus. Their incident angles α are limited by the values of $+9°$ and $-9°$, resulting from the diameter and the focal length of the the PZT transmitting transdcuer.

According to the Snelius law the refracion angle β of the ray penetrating the layer (Fig. 4) equals

$$\beta = \arcsin(4\sin\alpha), \tag{3.1}$$

since the ratio of wave velocities in metals and in water equals $\cong 4$ (see Tabl. 1).

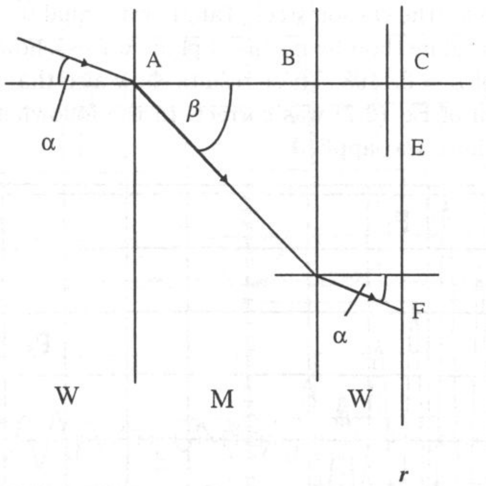

Fig. 4. The path of the ray incident from water W into the metal layer M. $AB = d = 5$ mm, $BC = d' = 1.5$ mm. $CE = 0.25$ mm – radius of the hydrophone's sensitive electrode, $CF = \Delta r$ – displacement of the ray, α and β – incident and refraction angles.

So one can determine the refraction angles β for all the incident angles α to find the ray displacement Δr due to the pulse transmission through the layer $AB = d$ (Fig. 4)

$$\Delta r = d \operatorname{tg} \beta. \tag{3.2}$$

The radius of the sensitive electrode of the PVDF hydrophone equals 0.25 mm, so the equations (3.1) and (3.2) make it possible to determine the following limiting angles for rays, which arrive the electrode and in this way will be measured by the hydrophone

$$\beta' = \operatorname{arc\,tg} \Delta r/d = 2.86^\circ, \qquad \alpha' = \arcsin[(\sin \beta)/4] = 0.72^\circ \tag{3.3}$$

Therefore, one can conclude that the hydrophone measures only the rays for $\alpha < \alpha'$; and $\beta < \beta'$ which are situated very near to the axis. So our assumption of plane waves in derivation of Eq. (2.7) is justified. After penetrating the layer, the pressure pulse propagates in water along the path $BC = d' = 1.5$ mm (Fig. 4) causing only a very small changes of the angles β' and α'. Then the maximum additional displacement for limitng rays equals only $\Delta r' = 0.019$ mm, and can be neglected.

4. Values of the pressure decrease coefficient L

The decrease of L can be calculated from Eq. (2.7), after having measured the values of ϱ and c, or experimentally by means of the measurement the ratio P_5/P_1 according to the relation (2.6). In this case a plane transmitt-receive transducer 10 mm in diameter with the resonanse frequency of 3.7 MHz was used. The elecrical voltage applied to the transducer equaled $140V_{pp}$. The measurements were performed in the near field of the beam.

The calculated value for the carbon steel (Tab. 1) was equal to $L = 0.119$. The results of the second, experimental method by means of plane waves, shown in Fig. 5, have given almost the same value of $L = 0.1198$. These results show also that our assumption of the plane wave in derivation of Eq. (2.7) was correct. In the following work the first, much simpler calculation method, was applied.

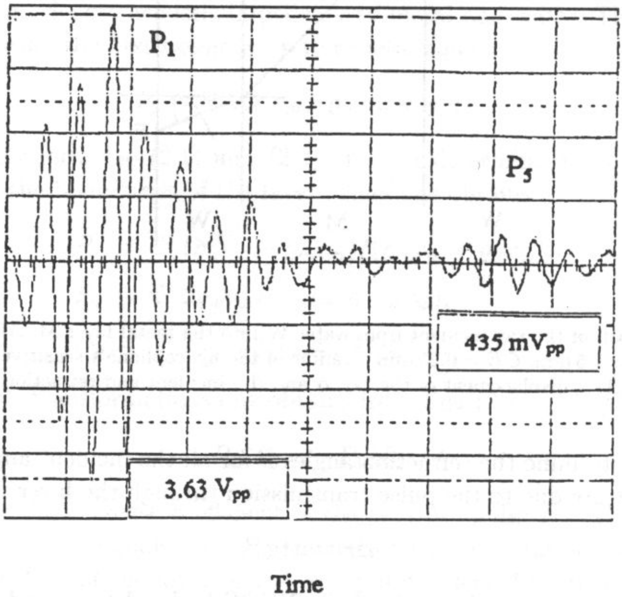

Fig. 5. The first P_1 and the second P_5 pressure pulses reflected from the layer of carbon steel immersed in water (see Fig. 3). Vertical scale – 50 mV, horizontal – 0.5 μs.

Our expectation regarding the shape and the pressure value of pulses, penetrating the various metal layers, were fulfiled as can be shown in Fig. 6. The shapes of pulses presented in Fig. 6 are identically distorted due to nonlinear propagation in water, especially in the focus, where the pressures are maximum.

Using the described technique the diagram in Fig. 7 was drawn. The horizontal axis represents the value L (the pressure pulse decrease coefficient – see Table 2). The vertical axis shows the maximum values of the pressure signals [in $\mathrm{m}V_{pp}$] obtained from our investigated PVDF hydrophone The measurements were carried out for 320, 275, 230, 140 and $47V_{pp}$ applied to the transmitting transducer PZT. Figure 7 shows the straight lines that best fit the measurement points. At every line the corresponding correlation coefficient is given. They are equal from $r = 0.999$ to 0.987, in average 0.994, demonstrating the linearity of the hydrophone. In such a case one can try to extrapolate this linearity for higher pressures. The highest pulse pressure measured in the focus of the system of Fig. 1 (without the metal layers) was 6 MPa. So taking into account the maximum value of the pressure decrease coefficient $L = 0.39$ (see Fig. 7) one obtains the maximum pulse pressure equal to 2.3 MPa, for which the linearity of the hydrophone was really demonstrated.

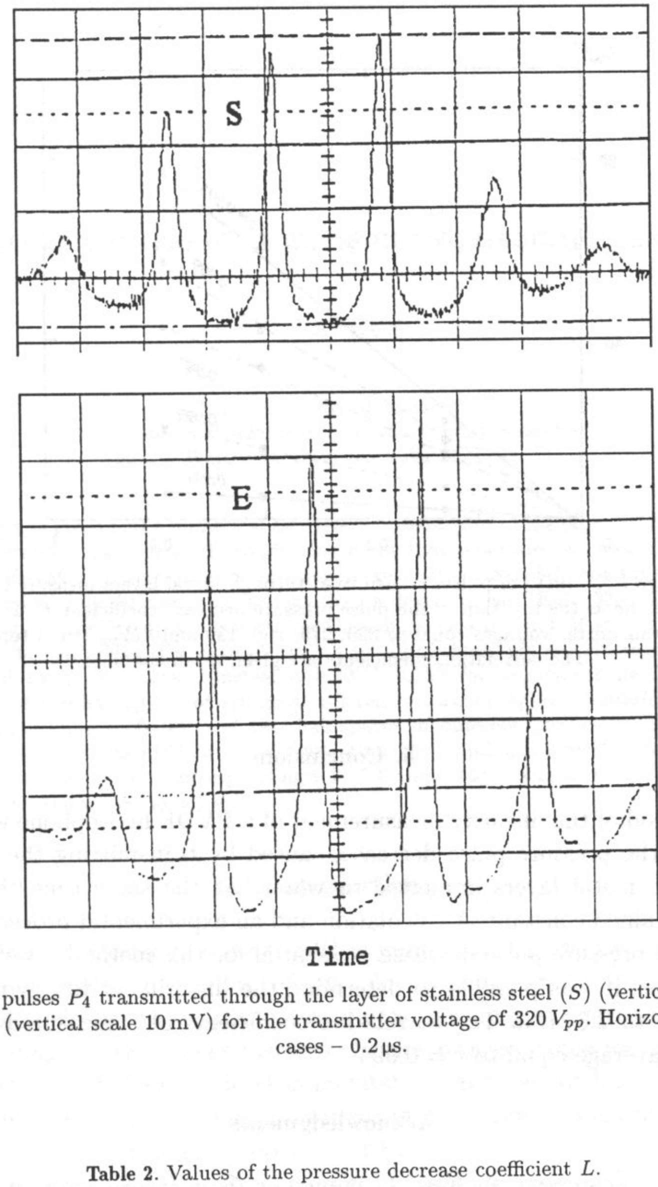

Fig. 6. Pressure pulses P_4 transmitted through the layer of stainless steel (S) (vertical scale 5 mV) and of electron (E) (vertical scale 10 mV) for the transmitter voltage of 320 V_{pp}. Horizontal scale in both cases – 0.2 μs.

Table 2. Values of the pressure decrease coefficient L.

	ϱc [MRayl]	L
Stainless steel	42	0.13
Carbon steel	46.6	0.12
Dural 1	16.7	0.3
Elektron	11.9	0.39

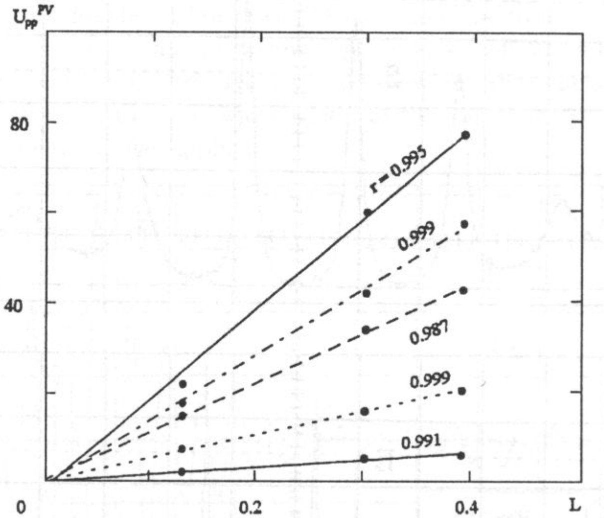

Fig. 7. The voltage U_{pp}^{PV} [mV] of pulses transmitted through metal layers measured by means of the PVDF hydrophone as the function of the pulse pressure decrease coefficient L. The results were obtained at transmitter voltages equal to 320, 275, 230, 130 and 47V_{pp} (from top to bottom). The correlation coefficients are given at all the lines.

5. Conclusions

A new method of the linearity measurement of a PVDF hydrophone was elaborated. It is based on the pressure pulse decrease, caused by transmitting the pressure pulse through various metal layers immersed in water. At the same time the pulse shape (spectrum) remained constant. A calculation and an experimental procedures for determination of the pressure pulse decrease – essential for this method – were given. Using these procedures, it was possible to determine the linearity of the hydrophone up to pressures equal to 2.3 MPa. The correlation coefficients of 5 measured relations were found to be in average equal to $r = 0.994$.

Acknowledgments

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