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MEASUREMENT TECHNIQUE OF SHOCK WAVE PULSES AT EXTREMELY HIGH PRESSURES

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Two methods were developed for measuring the pressure of shock wave pulses generated by lithotriptors: with a piezoelectric foil transducer and a capacitance one. In the study, the properties of a PVDF type foil transducer working in water were analysed. Its sensitivity was determined as a function of frequency. Compliance was gained between measurements and theory. The impacts of fixed metal electrodes, an additional back plastic load and an electric load on the frequency responses were shown. The principle and various design alternatives of a capacitance transducer designed for measuring the extremely high pressure of shock wave pulses in water were presented. A transducer of this type makes it possible to perform absolute measurements. After implementation, the two transducer types were applied for measuring purposes. Their advantages and disadvantages were shown. The pressure of shock wave pulses measured on this basis in a domestic and a foreign lithotriptors were found to be very close to each other. The pulse rise times were approximately the same for the two devices compared.

1. Introduction

The lithotriptor model designed for noninvasive disintegration of renal calculi required above all the development of methods for measuring shock wave pulses the peak pressure of which in amplitude may reach values of about 100 MPa (≅ 100 atm.) and the rise times are a fraction of a microsecond. Because, for obvious reasons, measurements of these pulses are impossible "in situ", they are made in water the acoustic impedance of which is practically the same as that of soft human tissues, although attenuation is different [6].

As studies began on the subject there was no system anywhere permitting measurements of this type to be carried out. Conventional hydrophones applied in underwater acoustics are not suitable for measuring such high pressures, for they disintegrate immediately, just as do renal calculi. At present, expensive piezoelectric foil hydrophones sporadically used for this purpose are quickly destroyed even after a few minutes of work.

In this situation, a decision was taken by the authors to develop their own methods for measuring the extremely high pressures of shock wave pulses based on two transducer types: piezoelectric foil and capacitance transducers.

2. Piezoelectric foil transducers

In lithotripsy problems, it is necessary to carry out measurements over a high ultrasound frequency range caused by very short rise times of shock wave pulses. Piezoelectric plastic foil transducers, e.g., of PVDF (polyvinyldifluoride), provide such a possibility [11], although they show small nonlinearity of about 5% for high pressures of 80 MPa [12]. The basic parameters of such a transducer are shown in Table 1 as compared with those of a quartz one.

Table 1. A comparison of the properties of PVDF and quartz transducers

Material		Multiplier	Quartz, *x*-cut, [3], [8]	PVDF transducer [12]
1. Density	ρ	10^3 kg/m^3	2.65	1.8
2. Dielectric constant	ε	1	$\varepsilon_1^T=4.5$	$\varepsilon_1^T=5.2$
3. Longitudinal wave velocity	c	10^3 m/s	$c^E=5.74$	$c=2.15$
4. Acoustic impedance	ρc	10^6 kg/m^{2}s	$\rho c^E=15.4$	$\rho c=3.86$
5. Piezoelectric coefficient	h	10^9 N/C	$h_{11}=4.2$	$h_{11}=2.08$
6. Electromechanical coupling coefficient for thickness vibration	k	1	0.1	0.15*

* Determined by authors after [12]

The frequency response of a PVDF transducer developed in cooperation with the Limburg University in Maastricht may now be considered. It has an active diameter of 0.5 mm and the piezoelectric foils is 25 μm thick. Electrodes were fixed using a very thin gold layer. The electroacoustic properties of the transducer can be determined from Mason's equivalent circuit [10], [7], derived for one-dimensional, longitudinal vibrations and an electric field with the same direction (Fig. 1). This scheme will be expanded in an appropriate way so as to account for the impact of metal electrodes [9] and that of internal foil damping [1]. It is assumed that this transducer is a linear element. The wave source is adopted in the form of the generator of the force $2F$ with internal impedance such as for water, i.e. $R_A=\rho_A c_A A=0.294$ kgs^{-1}. Here, F is the force and $A=19.6\times10^{-8}$ m^2 is the active surface area of the transducer. The value of the generator force results from Thevenin's theorem [13], [14], according to which in a linear system the electromotor force of the source is equal to the voltage at open output clamps, whereas the internal resistance of the source is equal to the resistance measured at clamps at a shorted source.

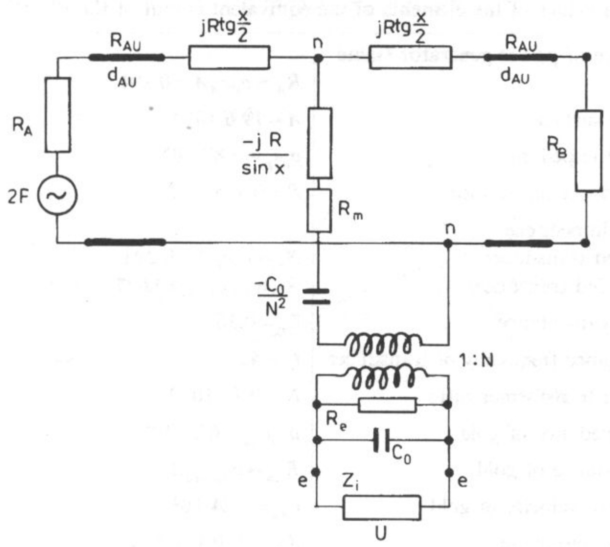

Fig. 1. The equivalent circuit of a transducer, according to Mason, expanded with metal electrode layers in the form of long lines and the internal foil damping in the form of the resistances R_m and R_e. The source of the incident wave has the form of a generator of the electromotor force 2 F with the internal resistance R_A.

The mechanical impedance R and the electrical impedance Z can can be transformed by an electromechanical transformer (Fig. 1), according to the relation

$$R\,[\mathrm{kg\,s^{-1}}]=N^2 Z[\mathrm{m^2kg\,s^{-3}\,A}], \tag{2.1}$$

where A is amper.

On the other hand, the force F, the electrical voltage U, the velocity V and the current I are transformed according to the relation

$$\begin{aligned} F\,[\mathrm{kg\,m\,s^{-2}}]&=N\,U\,[\mathrm{m^2kg\,s^{-3}}\,I\,\mathrm{A^{-1}}],\\ V\,[\mathrm{m\,s^{-1}}]&=N^{-1}\,[\mathrm{A}], \end{aligned} \tag{2.2}$$

where electromechanical transformer ratio has the form

$$N=h\,C_0\,[\mathrm{s\,A\,m^{-1}}]. \tag{2.3}$$

By solving the circuit in Fig. 1 and applying dependencies (2.1), (2.2) and (2.3), the following relation can be obtained between the output voltage signal U at the electrical clamps of the transducer and the force F

$$U/F=\frac{2bNZ}{a\left[R_B+jR\left(\mathrm{tg}\,\frac{x}{2}-\frac{1}{\sin x}\right)+\frac{jN^2}{2xf_mC_0}+ZN^2\right]+b\left[\frac{jN^2}{2xf_mC_0}-\frac{R}{\sin x}+ZN^2\right]}, \tag{2.4}$$

Table 2. The values of the elements of the equivalent circuit of the PVDF transducer

1. Internal impedance of power generator (same as for water)	$R_A=\rho_A c_A A=0.294$	kg/s
2. Active transducer surface	$A=19.6\ 10^{-8}$	m^2
3. Characteristic foil impedance	$\rho_p c_p=3.87\ 10^6$	kg/m^2s
4. Mechanical transducer impedance	$R=0.758$	kg/s
5. Mechanical back impedance		
— of water loaded transducer	$R_B=\rho_B c_B A=0.294$	kg/s
— of plastics loaded transducer	$R_{B'}=\rho_{B'} c_{B'} A=0.627$	kg/s
6. Static transducer capacitance	$C_0=0.36$	pF
7. Mechanical resonance frequency of transducer	$f_m=43$	MHz
8. Electromechanical transformer ratio	$N=0.75\ 10^{-3}$	sA/m
9. Characteristic impedance of gold	$\rho_{Au} c_{Au}=62.5\ 10^6$	kg/m^2s
10 Mechanical impedance of gold	$R_{Au}=\rho_{Au} c_{Au} A$	kg/s
11. Longitudinal wave velocity in gold	$c_{Au}=3.24\ 10^3$	m/s
12. Thickness of gold electrodes	$d_{Au}=0,\ 0.1,\ 0.5,\ 1$	μm
13. Resistance of mechanical losses inside foil $R_m=W_m R\tan\delta_m$ (see [1] and [9] formula (11))	$\mathrm{tg}\delta_m=0.1$	
14. Resistance of dielectric losses inside foil $R_e=(\omega C_0)^{-1}\tan\delta_e$	$\mathrm{tg}\delta_e=0.1$	

where $a=R_A+jR\tan x/2$, $b=R_B+jR\tan x/2$ (see Table 2), $Z=Z_i/(1+jZ_i 2xf_m C_0)$, Z_i is the electrical impedance loading the transducer, C_0 is the static capacitance of the transducer, $x=nf/f_m$, f is the current frequency, f_m is the mechanical resonance frequency of the transducer. When on both sides of the transducer there is the same medium ($R_A=R_B$), formula (2.4) becomes greatly simplified.

In the further calculations for the PVDF transducer, Mason's equivalent circuit will be expanded to include thin gold layers in the form of two long lines with the impedance R_{Au} and the thickness d_{Au}, and the mechanical and dielectric losses inside the foil, represented by the resistances R_m and R_e. The values of the parameters of the expanded circuit in Fig. 1 are listed in Table 2.

In numerical calculations, purpose-built programmes were applied in calculations for piezoelectric transducers used to generate and receive ultrasound pulses [9].

Figure 2 shows the calculated sensitivity of the PVDF transducer for different electric loads, based on the equivalent circuit in Fig. 1, accounting for the thin bilateral gold electrode layers with different thickness. For all the cases demonstrated, the load at electrical clamps was adopted in the form of capacitance of 130 pF.

A lossless transducer, bilaterally loaded by water, with a thin gold layer of zero thickness (H_2O, 0 μm) and with no internal losses (dashed curve), shows electrical resonance at a frequency of ≅ 40 MHz. In keeping with theory, this frequency is lower than the mechanical frequency of 43 MHz [7].

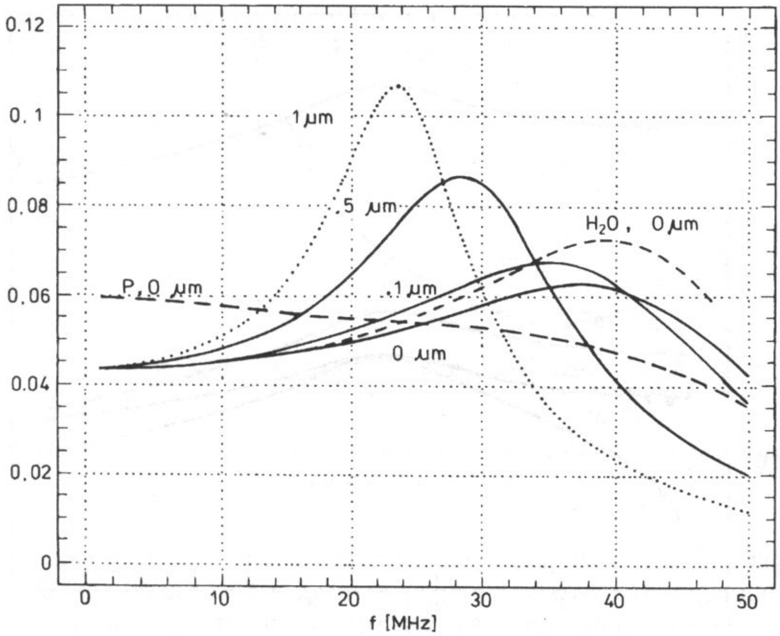

Fig. 2. The sensitivity characteristics of a PVDF transducer loaded by 130 pF capacitance, calculated without internal losses (dashed curves) in the case of bilateral water (H_2O) loading and additional plastic back load (*P*). The solid curve denotes the characteristics, taking into account internal damping. The thicknesses of gold electrodes are given along all the curves.

When the back surface of the transducer is loaded by plastics (P, 0 µm), its resonance peak becomes blurred and the 3 dB transmission band expands by a factor of about 1.5. When internal losses in foil are introduced (solid curves), the curve (H_2O, 0 µm) turns into the curve (0 µm) which is lower only by about 0.7 dB at the resonance frequency, it does not change at the lowest frequency.

It is interesting to observe the response as the thickness of the gold electrodes grows. In this case, the frequency of the electrical resonance distinctly decreases, by as much as a factor of 0.65 for 1 µm layer thickness. It is a very important conclusion from the point of view of the design of the PVDF transducer, to which no attention has been paid to date in the literature.

Figure 3 shows the frequency responses of the PVDF transducer calculated for different electrical load types in the case of 1 µm thick gold electrodes. The real load with 50 Ω resistance fully distorts the response, making the transducer useless for measuring purposes. The capacitance load, on the other hand, makes is possible to obtain a plane response, ensuring high-fidelity representation of the measured shape of the shock wave pulse. In the present experimental study, electrical clamps were connected with an amplifier with 30 dB amplification. The capacitance of the cable was 130 pF. When it is cut down to, e.g., 50 pF, the sensitivity of the transducer grows

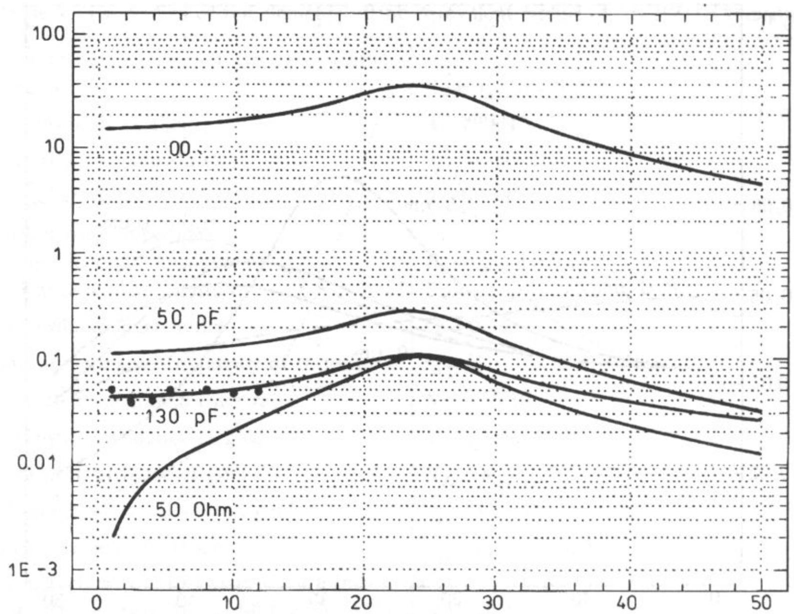

Fig. 3. The sensitivity characteristics of a PVDF transducer calculated for bilateral loading with water, with gold electrode thickness of 1 μm. The electrical loads were 50 Ω, 130 pF and 50 pF, and was equal to ∞.

2.5 times. In the extreme case of opening electrical clamps ($z_i = \infty$), the sensitivity grows by another 125 times. Such a case is, however, practicaly impossible to implement.

The experimental results (the points in Fig. 3), obtained by calibration using a hydrophone manufactures by Marconi Company [11], showed good compliance with the theoretical curve. The capacitance $C_k = 130$ pF was used in the measurements, providing the mean sensitivity of the transducer in question of 0.018 μV/Pa. In this case, the upper cut-off frequency (within the 3 dB limits) was 15 MHz. The lower one was, on the other hand, limited by the plane nature of the wave.

The experimentally confirmed flat sensitivity curve over the range up to 12 MHz is completely sufficient for high-fidelity representation of the shape of the shock wave pressure pulse (see the pulse spectrum in Fig. 6).

Figure 4 shows the shape of a shock wave pulse with a pressure peak of 20 MPa, measured in water, using a PVDF transducer. This pulse was obtained using an electromagnetic generator involving the use of a plastic shock wave focussing lens [4]. The pulse rise time was about 100 ns.

A further increase in the upper cut-off frequency of the PVDF transducer can be obtained by applying an additional acoustic load of its back surface with plastics (Fig. 2, curve P). Because of the thickness of the material loading the back surface of the transducer, however, the duration of the measured pluse is limited up to 7 μs in the case of a 1 cm thick plastic layer.

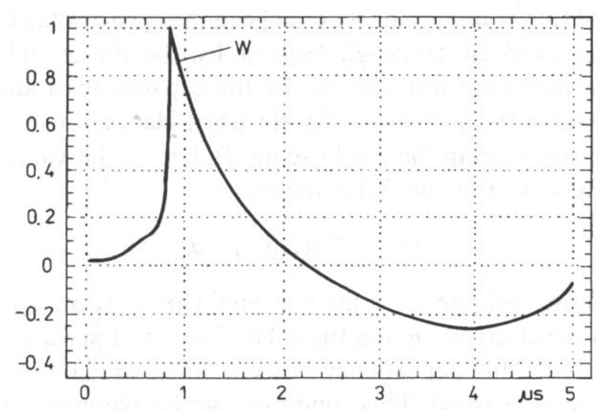

Fig. 4. The shock wave pulse shape obtained by the authors using a PVDF transducer with the positive peak pressure of 20 MPa.

In the course of measurements taken for large-amplitude shock wave pulses, it was found that the PVDF transducer was quickly destroyed. These damages were of the cavitation-incited type. Point pinholes were observed, and so were breakdowns in the gold electrodes and in the PVDF foil itself.

Given this, a decision was made to use a transducer of this type only in single, most important measurements. A capacitance transducer was developed for "mass" measurements. For, an advantage of an PVDF transducer is the accurate representation of the shape of the acoustic pressure; both in its rise phase and its drop as a function of time. In this range, a capacitance transducer shows some limitations.

3. The capacitance method for measuring shock wave pressures

Figure 5 shows the idea of a transducer which measures the absolute value of plane wave displacement in water [2]. The plane wave pulse P penetrates the water-solid, $W-F$, boundary. Then, it is totally reflected from the solid-air boundary

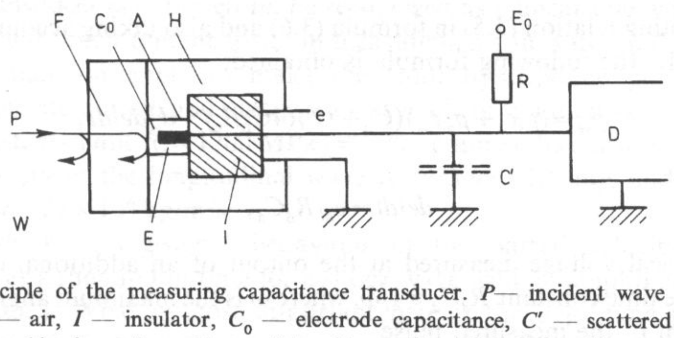

Fig. 5. The principle of the measuring capacitance transducer. P— incident wave pulse, F— solid, W — water, A — air, I — insulator, C_0 — electrode capacitance, C' — scattered capacitances, E_0 — biassing voltage, R — resistor, D — calibrated digital oscilloscope.

A. The vibrations of this boundary cause change in the capacitance C_0, created by this boundary, and the fixed electrode E, biassed by the direct voltage E_0. For an appropriately large time constant, created by the capacitancies and resistance R in this circuit, one obtains the voltage at the electrical clamps of the transducer. This voltage is then measured using the oscilloscope D, hence, the value of the measured displacement is determined in the following way:

$$\zeta=(C_0+C')(E_0C_0)^{-1}d_0e, \tag{3.1}$$

where E_0 is the biassing voltage, C' is the scattered capacitance, d_0 is the thickness of the air slit between the electrode E and the solid F, e is the measured voltage signal at the transducer clamps. This dependency is valid when the condition that ζ is very much smaller than d_0 is satisfied. This condition can be expressed in a different way:

$$e(C_0+C')(E_0C_0)^{-1}\ll 1. \tag{3.2}$$

After differentiation relative to time, the partial velocity can be obtained from formula (3.1):

$$u_g=d\zeta/dt. \tag{3.3}$$

on the solid-air boundary. There is the following relation between the pressure p_w of the measured plane wave, incident perpendicularly onto the water-solid boundary and the wave pressure p_s penetrating this boundary and going on:

$$p_s/p_w=2\rho_sc_s/(\rho_wc_w+\rho_sc_s), \tag{3.4}$$

where ρ_sc_s and ρ_wc_w are, respectively, the acoustic impedances of the solid and water.

Therefore, using dependence (3.4), the partial wave velocity in a solid medium is

$$u_s=p_s/\rho_sc_s=2(\rho_wc_w+\rho_sc_s)^{-1}p_w. \tag{3.5}$$

In turn, on the solid-air boundary there is perfect backscattering of a wave pulse and the partial velocity u_s at this boundary doubles. Thus,

$$u_g=2u_s. \tag{3.6}$$

By substituting relation (3.5) in formula (3.6) and also taking account of (3.3) and (3.1), ultimately, the following formula is obtained:

$$p_w=(\rho_sc_s+\rho_wc_w)(C_0+C')(4C_0E_0)^{-1}d_0\,de/dt, \tag{3.7}$$

where

$$de/dt=e_d/R_dC_d, \tag{3.8}$$

e_d is the electrical voltage measured at the output of an additional differentiating system with the time constant $R_dC_d\ll 1/\omega$, where ω is the maximum angular frequency in the spectrum of the measured pulse.

The shape of the shock wave pulse measured in water using a PVDF transducer is shown in Fig. 4, whereas the spectrum of this pulse is demonstrated in Fig. 6.

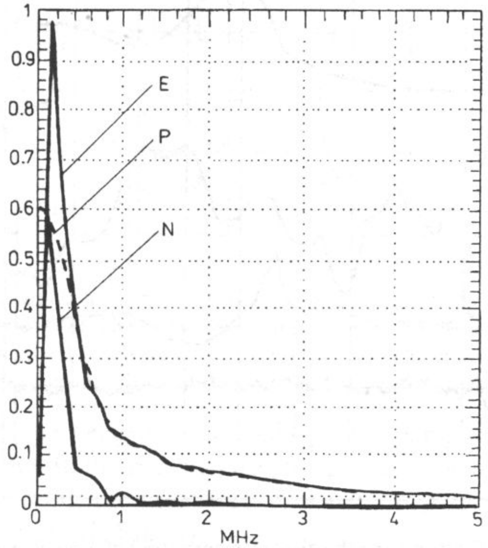

Fig. 6. The amplitude spectrum of a shock wave pulse measured using a PVDF transducer (see Fig. 4). E — spectrum of the whole pulse, P — of its positive part, N — of its negative part.

In deriving formula (3.7) a linear dependency was assumed between the acoustic pressure and the partial velocity, which is satisfied with appropriate approximation. Moreover, it is necessary to account for the fact that water is a medium which is more nonlinear than a solid out of which the front plate is made.

The ratio between the acoustic pressure and the partial plane wave velocity as well as its deviation from the acoustic impedance for a given value of the acoustic pressure may be regarded as a measure of medium linearity. These deviations for water and soft tissues are, for $p=100$ MPa, respectively, smaller than 7% and 12%, on the other hand, for steel and aluminium they are smaller by three orders of magnitude [5]. A capitance transducer can, therefore, be recognized as a linear one, which does not introduce any additional nonlinearities in measurements in water and soft tissues.

Following many attempts to make the front hydrophone plate from such materials as steel, aluminium and plastics, it was made of titanium and showed a high value of the elasticity limit $R_r=1200$ MPa ($\cong$ 120 kg/mm^2). Its density is $\rho=4.5\times10^3$ kg/m^3, the velocity of the longitudinal wave is $c=5.99\times10^3$ m/s and the acoustic impedance is $\rho c=27\times10^6$ kg/m^{2}s.

Figure 7 shows a registered behaviour of the partial velocity u and the displacement γ as a function of time for a shock wave with an amplitude of about 20 MPa ($\cong$ 200 atm.). What is most important here is the 3 μs time interval after a cross-shaped marker. After this time there emerge multiple wave reflections within

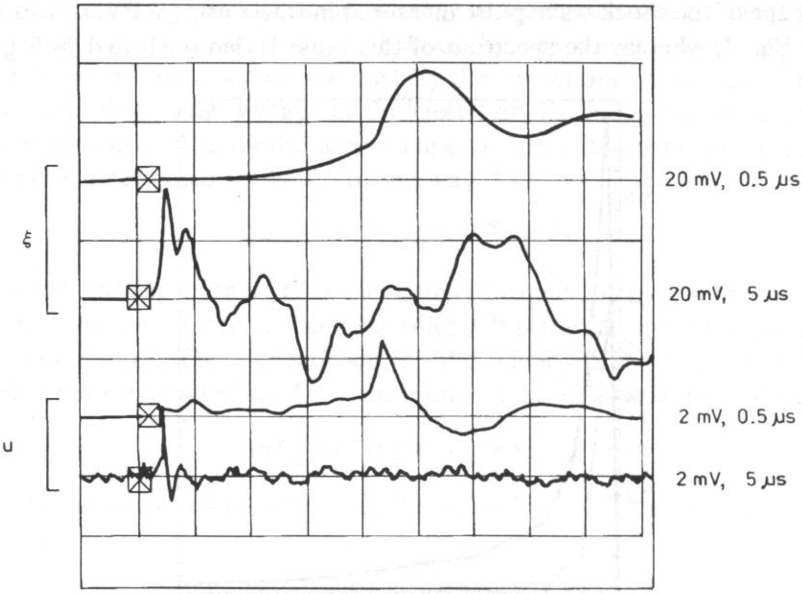

Fig. 7. The partial velocity u (bottom) and the displacement γ (top) of a shock wave pulse with an amplitude of 20 MPa, registered using a capacitance transducer in two time scales. The horizontal scale corresponds to time intervals of 5 μs and 0.5 μs; and the vertical scale corresponds to voltages of 2 mV and 20 mV.

the transducer which interfere with one another. The upper course which represents the partial velocity has been obtained by electronic differentiation of the lower curve denoting the displacement.

The same figure shows the partial velocity pluse u extended in time by a factor of ten and detected in conditions close to those in Fig. 4. Here, the rise gain time is 50 ns. Probably, this time is shorter, however, the sampling interval of the applied digital oscilloscope Tektronix 2230, 50 ns, limits the possibilities of measuring shorter rise times.

In the case of a focussed wave, the use of the transducer in the form represented in Fig. 5 may lead to distortions as a result of the refraction of the wave on the water-solid body boundary because of the different wave velocities in these media. In the case of a focussed beam, this may cause a change in the position of the focus and its defocussing (Fig. 8a). Therefore, it would be desirable to use a solid with a possibly lowest velocity of the longitudinal wave so as to minimize the refraction.

A semicircular front surface (Fig. 8b) may also be used. Then, however, the transducer cannot be used for absolute measurements. For in its front plate there emergies a focus with a greater longitudinal dimension than in water because of the longer wavelength in solid media. Therefore, there occur a different beam concentration and a lower maximum pressure than in water. Hence, a practical conclusion follows. The wave refraction may be avoided by taking measurements in the focus of

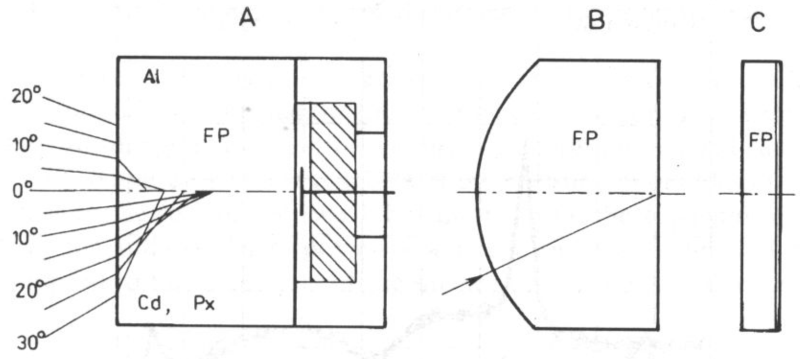

Fig. 8. Different versions of capacitance transducers. A — with a thick front plate (*FP*), from aluminium (Al), cadmium (Cd) or plastics (Px). The refraction of acoustic rays on the water-front plate boundary is shown. The critical angle for Al is 15° and for Cd or Px it is 33°. B — semicircular front plate, C — thin, flat front plate from Al, Cd or Px, coated with the conducting layer (*L*).

the shock wave, where the beam is practically plane, using at the same time a 1 cm thick front plate (Fig. 8c). In the present case, the plane range of this wave in the focus is much longer, considering the measured pressure drop relative to the maximum pressure in the focus itself (cf. Fig. 9).

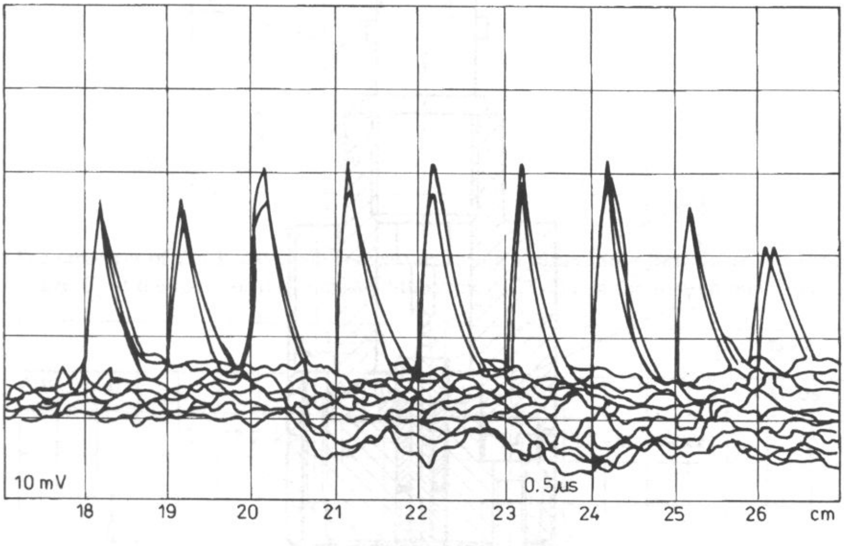

Fig. 9. The acoustic pressure distribution along the beam axis of the authors' lithotriptor, measured within the focal area.

Figure 10 indicates the repeatibility of the measured results gained using the present capacitance transducer. It shows the results of ten measurements of the same shock wave pulse registered on the oscilloscope screen.

Then, Fig. 11 shows the design drawing of the capacitance transducer in question, used for measuring the pressure of shock wave pulses.

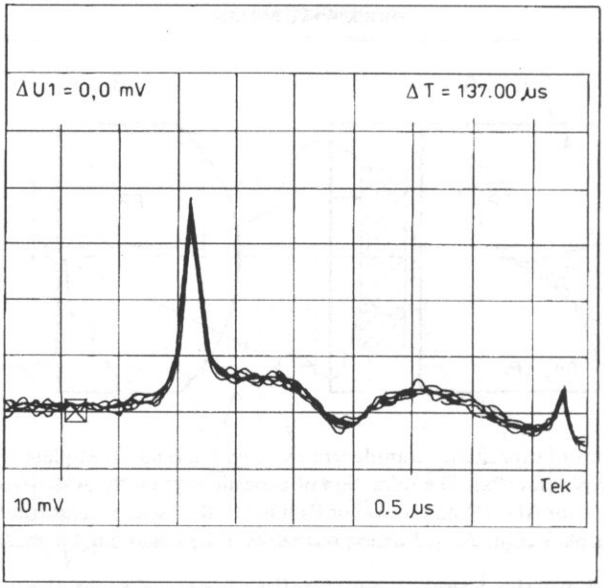

Fig. 10. The recordings of ten shock wave pulses using the capacitance transducer, on the same oscilloscope image.

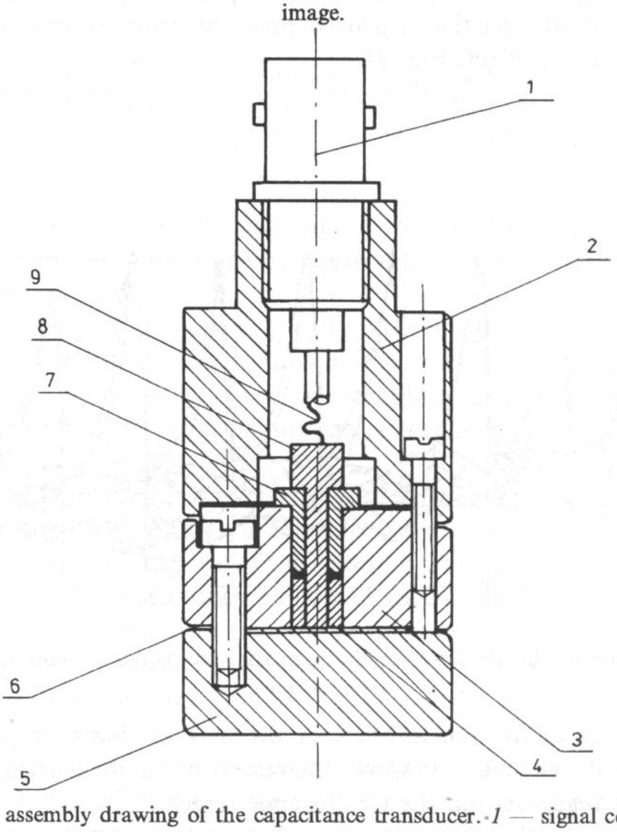

Fig. 11. The design assembly drawing of the capacitance transducer. *1* — signal connector, *2* — metal housing, *3* — electrode holder, *4* — electrode reductor, *5* — metal front plate, *6*— metal foil 50 μm thick, *7* — isolating tube, *8* — brass electrode, *9* — connecting wire.

4. The results of application of the designed measuring transducers

The transducers were used for measuring acoustic pressures in the lithotriptor designed by the authors team and the Lithostar type lithotriptor from Siemens used at the Medical Academy in Warsaw for routine disintegration of renal calculi.

Figure 12 compares the measurements of the pressure amplitudes of shock wave pulses taken at the foci of the two lithotriptors using the capacitance transducer designed by the authors. These pressures were measured as a function of the high voltage supplied to the generators of the shock heads of the two devices.

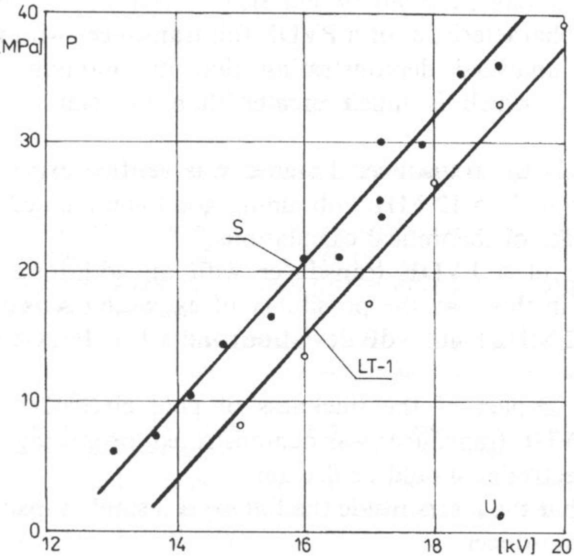

Fig. 12. The pressures of shock wave pulses measured using a capacitance transducer as a function of the supply voltage U_0 at the focus of the domestic lithotriptor (LT-1) and the foreign one from Siemens (S).

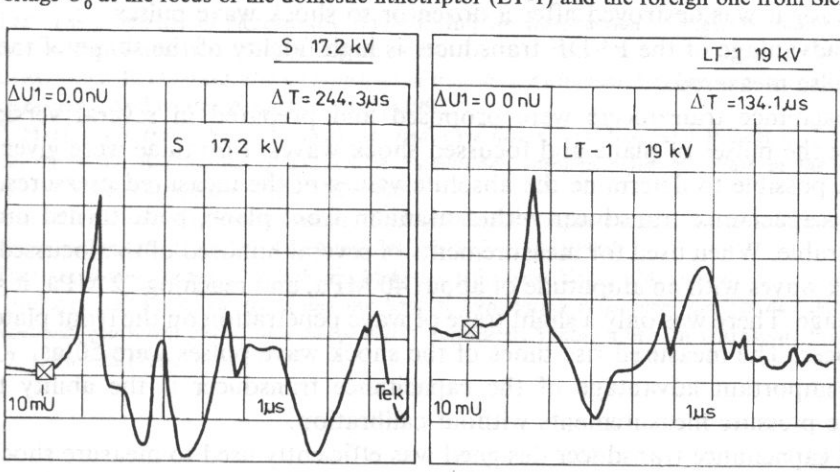

Fig. 13. The pressures pulses of the two lithotriptors in Fig. 12, determined using a capacitance transducer.

Then, Fig. 13 shows the shapes of pressure pulses detected for the two devices. In keeping with the properties of the capacitance transducer, for the two curves only the pressure curve was well reproduced over the range of about 2 μs, including the rise, the peak and the beginning of the falling slope of the shock wave pulse. The farther part of the course was distorted as a result of wave interference inside the front plate of the transducer.

5. Conclusions

The sensitivity characteristics of a PVDF foil transducer with an active diameter of 0.5 mm were analyzed demonstrating that its optimum electrical load is the capacitance C_k, which is much greater than the static capacitance of the transducer, C_0.

The sensitivity of the transducer designed was verified experimentally over the frequency range from 1 to 12 MHz, obtaining good compliance between measurements and the results of theoretical calculations.

A new version of a PVDF transducer with an additional plastic load was proposed, to gain in this way the possibility of extending sensitivity characteristic from 28 MHz to 42 MHz (with 3 dB deviation) and a 1.5 dB increase in sensitivity at low frequencies.

A quantitative impact of the thickness of gold electrodes on the frequency responses of the PVDF transducer was demonstrated, proposing that the maximum thickness of the electrodes should be 0.1 μm.

It was shown that the losses inside the foil exert a small impact on the frequency responses of the transducer.

The PVDF transducer prepared was used to measure the pressure and the shape of the shock wave pulse generated in water. It was found that this transducer is not durable for it was destroyed after a dozen or so shock wave pulses.

An advantage of the FVDF transducer is high fidelity of the shape of the shock wave pulse measured.

Capacitance transducers were proposed and prepared in several versions, to measure the pulses of plane and focussed shock waves. Formulae were given which make it possible to determine the absolute values of the measured pressures.

The capacitance transducer with a titanium front plane, plate turned out to be very durable. When used for measurements of several hundred of the focussed pulses of shock waves with an amplitude of about 40 MPa, and reaching 72 MPa, it showed no damage. There was only a slight trace of wave penetration on the front plate of the transducer. The measured rise times of the shock wave pulses were 50 ns.

An important advantage of the capacitance transducer is the ability to take absolute pressure measurements without calibration.

The capacitance transducer designed was efficiently used to measure shock wave pulses. It is simple, cheap and reliable and the results obtained show good repeatibility. Its disadvantage is the limitation of its faithful reproduction of the pulse shape only to the rise, the peak and the first drop phase of pressure as a function of time.

The use of these transducers made it possible to compare the shock wave pulses generated by the one domestically designed and those for a foreign lithotriptor from Siemens. This comparison showed that there was an almost linear increase in the shock wave pressure with an increase in the supply voltage over the pressure range from 6 MPa to 40 MPa. But these pressures were the same in the two devices for a 10% higher supply voltage in the pressure range of 6–40 MPa. The rise times of the pulse measured for the two devices were almost the same and shorter than 0.5 μs.

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