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ULTRASOUND UNDERWATER TRANSDUCER FOR EXTRACORPOREAL SHOCK WAVE LITHOTRIPSY (ESWL)

IRINELA CHILIBON[1], MARTINE WEVERS[2], JEAN-PIERRE LAFAUT[3]

[1] *National Institute of Research and Development for Optoelectronics, INOE-2000, 077125, P.O. Box MG 5, Bucharest, Romania, qilib@yahoo.com*
[2] *K. U. Leuven, Department of Metallurgy and Materials Engineering (MTM), Kasteelpark Arenberg 44, B-3001 Leuven (Heverlee), Belgium, Martine.Wevers@mtm.kuleuven.ac.be*
[3] *K. U. Leuven Campus Kortrijk, Interdisciplinary Research Center, E. Sabbelaan 53, B-8500 Kortrijk, Belgium, Jean-Pierre.Lafaut@kulak.ac.be*

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Abstract. This paper presents an ultrasound piezoceramic transducer, centred into an extracorporeal shock wave lithotriptor system. The electromagnetic acoustic source lithotriptor initiates the incident shock waves into the water, and the ultrasound transducer improves the caviational effects of the bubbles. The piezoelectric transducer is powered by a Function/Pulse Generator type IWATSU SG-4511, and converts the electrical signal mechanical vibrations, which are propagated into the water. The underwater waves, received by the PZT disc sensor, are converted electrical signals and displayed by an oscilloscope type LeCroy 9310 AM. The transducer exhibits low resonance frequency, tuneable energy, broad bandwidth, between 16 kHz to 36 kHz, and low quality factor, that means it is optimum for this application. The extracorporeal shock wave lithotriptor system generates cavitation bubbles that have an essential role in the disintegration of renal calculi.

Key words: transducer, ultrasound, lithotripsy, shock waves, UPST, cavitation bubble.

1. INTRODUCTION

When a shock wave generated by extracorporeal shock wave lithotripsy (ESWL) interacts with a solid, it can create cavitation bubbles at the interface between the solid and the surrounding liquid. The implosion of the cavitation bubbles plays an important role in the disintegration of renal calculi [1]. The generation of large cavitation bubbles is one of the most important areas of investigation in the search to improve the efficiency of extracorporeal shock wave lithotripsy, therefore the possibility of an enlargement of the induced cavitation size should not be ignored. The stresses generated at large bubble implosion are larger than those generated during incidence of the primary shock wave [2].

To study the cavitation bubble formation process by ESWL shock wave under different ultrasonic field characteristics, an ultrasonic piezoceramic sandwich traducer (UPST) has been designed and manufactured.

The UPST converts the electrical oscillations from a signal power generator mechanical vibrations, and the ultrasonic waves propagate into the water up to the target. The metallic horn radiator concentrates and amplifies the ultrasonic energy.

The acoustical demands, for a good efficiency, are conditioned by the necessity to realize a working regime at the resonance frequency of the cavitation bubble, and limited by some factors, such as: the transducer type, PZT material properties, the transducer manufacture mode, etc.

The ultrasonic piezoceramic sandwich transducer has three parts: one central and active vibration source (piezoceramic tores), and two end-metal masses (reflector and radiator). The active source of vibration is placed inside the transducer body making one sandwich (metal-piezoceramic) structure bonded by two end-metal masses.

2. PIEZOCERAMIC MATERIAL PROPERTIES

Piezoelectricity is a property of certain classes of crystalline materials. When mechanical pressure is applied to one of these materials the crystalline structure produces a voltage proportional to the pressure. Conversely, when an electrical field is applied, the structure changes shape producing dimensional changes in the material. The PZT materials are used to manufacture electromechanical transducers.

Lead zirconate titanate ceramics (PZT) present extremely strong piezoelectric effects for compositions near the morphotropic phase boundary (MPB) [3]. Rhombohedral and tetragonal phases co-exist and are related to the presence of a maximum of the dielectric constant, a large number of orientable polarization directions and a maximum mechanical compliance preventing cracking during domain orientation [4].

The choice of a piezoelectric material depends on the specific application to which the transducer will be designated. Efficiency for emitters and sensitivity for receivers are fundamental characteristics, which need to be maximized in ultrasonic transducers [5]. Both are dependent directly on the electromechanical coupling factor k, in such a way that high k factor is always desirable.

The electrical properties and dimensions of a piezoelectric transducer are dependent on the dielectric, piezoelectric and elastic constants of the material. Thus, for low and medium ultrasonic frequencies (between 20 and a few hundred kHz) high values of permittivity and elastic compliance can be favorable in obtaining adequate practical values for electrical impedance and the linear dimension governing the resonance of the piezoelectric element.

The use of short ultrasonic pulses requires a low mechanical Q factor for a wide bandwidth, and a compact impulse response. A low Q is not related to the losses, but especially to a good transfer of acoustic impedance. Thus the acoustic impedance of the piezoelectric material is an other essential factor. Table 1 from the [5] lists the most useful properties of lead zirconate titanate ceramics. PZT-5A has the following characteristics suitable for the emitter sandwich transducer: high electromechanical coupling factor, high Curie point, low dielectric loss at high drive, very high permitivity, low Q, high compliance, and stable properties over time and temperature.

For sensing the underwater acoustic fields, piezoelectric sensors offer unique capabilities, which are typically not found in other sensing technologies. Piezoelectric sensors have the advantages (such as wide frequency and amplitude range) and disadvantages (like no static measuring capability), which need to be taken into account depending on the particular application. Therefore, a PZT disc sensor was chosen, because it is important to pay close attention to the performance specifications.

A stack of several piezoelectric elements was connected mechanically in series and electrically in parallel. The displacement of each transducer element adds to the total displacement. The displacement of the whole stack assembly is equal to the sum of the individual displacements. Stacks are generally required for applications requiring large displacements.

It is difficult to make a block of ceramic resonating below about 100 kHz. Instead a composite half wave resonator is used consisting of two or more piezoceramic tores sandwiched between metal layers.

3. PIEZOCERAMIC SANDWICH TRANSDUCER DESIGN

The active element of the device is a sandwich transducer, made of two piezoceramic tores stack with metal cylinders (Fig. 1). This electromechanical transducer works on the basis of the inverse piezoelectric effect, converting electrical power into a mechanical displacement in the range of tens of microns. All device elements are fixed and pre-stressed by a stainless steel screw, which induces an initial polarization of the piezoceramic stack. The vibration amplitude of the sandwich radiator depends on PZT tores number, PZT material elasticity coefficients and the metal elasticity coefficients. Maximum peak to peak displacements of the transducer radiating face would be in order of tens microns, when operating at resonance frequency.

The design of a simple metal-piezoceramic-metal sandwich transducer [6] to resonate at a given fundamental frequency, $2\pi\omega$, in the plate thickness direction is based on the following equation:

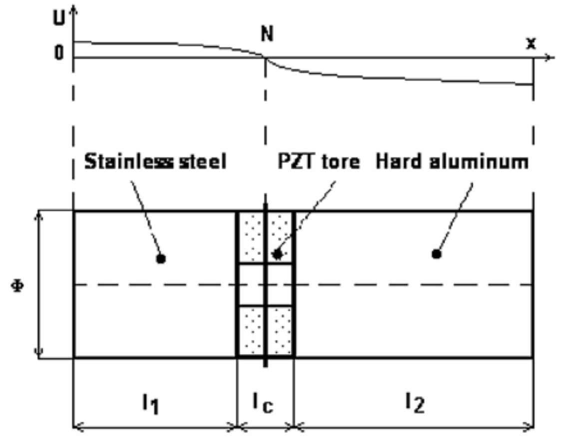


Fig. 1 – Simple sandwich piezoceramic transducer.

$$\frac{\varpi l_c}{v_c}+\mathrm{arctg}\left[\frac{A_1\rho_1 v_1}{A_c\rho_c v_c}\mathrm{tg}\left(\frac{\varpi l_1}{v_1}\right)\right]+\mathrm{arctg}\left[\frac{A_2\rho_2 v_2}{A_c\rho_c v_c}\mathrm{tg}\left(\frac{\varpi l_2}{v_2}\right)\right]=\pi \text{ (or } 180^0) \quad (1)$$

where:

l_1, l_2, l_c: lengths of the 1st metal, the 2nd metal, ceramic sections,

v_1, v_2, v_c: sound velocities in the 1st metal, the 2nd metal, ceramic sections,

A_1, A_2, A_c: cross sections of the 1st metal, the 2nd metal, ceramic sections,

ρ_1, ρ_2, ρ_c: densities of the 1st metal, the 2nd metal, ceramic sections.

If the metal plates are assumed to be identical and the ceramic placed symmetrically between them, the calculation of the transducer dimensions can be greatly simplified by approximation. A graphical representation of the general solution is shown as being a rapid and easy solution of the transducer equation (1), and one can determine the optimum component lengths of the sandwich transducer. Fig. 2 is the graphic representation of the equation (1′):

$$\tan(\pi/2*y)*\tan(\pi/2*x)=qi \quad (1')$$

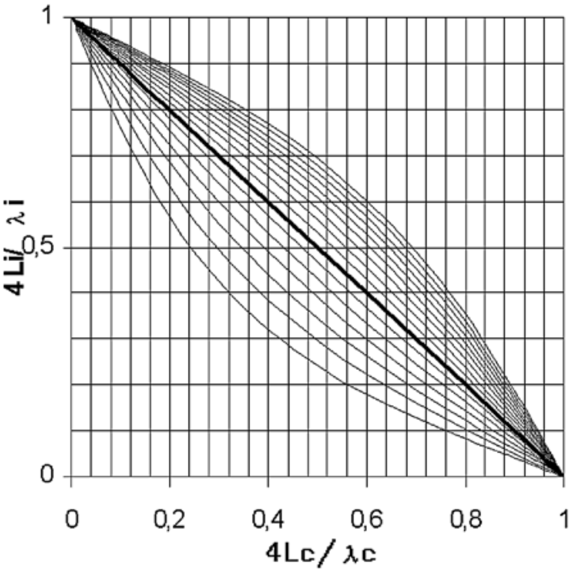
where: $qi=\rho_i*v_i/\rho_c*v_c$ and $i=1$ or 2.

In this case, the effect of the ceramic on the resonance frequency is almost entirely due to its compliance, and the effect of its mass is negligible. This is fairly obvious when one considers that the section at the center is subjected to high stress and strain levels and therefore contributes to the total potential energy, but experiences little vibratory motion and therefore contributes little to the total kinetic energy.

This conclusion may be proven by applying the equation to the case, in which the ceramic is replaced by a metal of the same type and cross-section as that used for the outer plates, and of length given by:

$$l^1\approx l_c\frac{A_1Y_1}{A_cY_c} \quad (2)$$

Fig. 2 – Graphical representation of equation (1′), where $0.3 < qi < 2$.



then Y_1, Y_c and Y_c^E has to be defined the solid metal bar of length $\mathbf{2l_1 + l^1}$ has the same resonance frequency as the original sandwich. This result is derived by assuming that the θ phase angle across both ceramic and equivalent metal section (*i.e.* $\omega l_0/v_0$ and $\omega l^1/v_1$) are small enough for the approximation $\tan\theta = \theta$ to be used. This formula gives a section of the same total compliance as the ceramic. The sound velocity value of v_c is obtained from the relation:

$$v_c = \sqrt{\frac{Y_c^E}{\rho}} \tag{3}$$

If the sound velocity in the ceramic is the modulus relating to open circuit or constant displacement conditions, then the antiresonance frequency of the transducer is found. The coupling coefficient of the whole transducer may be calculated from the resonance and antiresonance frequencies, f_r and f_a as follows:

$$k^2 = \frac{f_r^2 - f_a^2}{f_a} \approx \frac{2\Delta f}{f_r} \qquad (\Delta f = f_a - f_r) \tag{4}$$

For the most effective use of a transducer, it is usually desirable to achieve as high a value of the coupling coefficient, k, as possible. The approximate formula for k^2 shows that this means making the proportional difference between $\mathrm{f_r}$ and f_a as great as possible.

To do this, the piezoelectric material must be incorporated into the sandwich in such a way that the effect of the boundary conditions (short or open circuit at the electrodes) on its elastic modulus will have the maximum influence on the resonance of the sandwich.

The simplified model of the piezoceramic transducer can only approximate the resonance frequency for the entire device. Therefore, it is necessary to manufacture several sandwich piezoceramic transducers with different dimensions. The electromechanical sandwich transducer works on the reverse piezoelectric effect, converting an electrical power into a mechanical microdisplacement. Each PZT tore of the stack contributes to the entire device displacement.

The ΔL total displacement for a stack made by n piezoceramic tores with L length is a function of d_{33}, the piezoelectric coefficient of the piezoceramic material and U the sandwich stack applied voltage, and the relation between them is:

$$\Delta L = d_{33} n U \tag{5}$$

4. ACOUSTICAL TRANSFORMER

The simple sandwich piezoelectric transducers produce motion of a too small amplitude for high power applications. It is common practice to amplify the mechanical motions by means of a tapered resonant horn and the shape of the taper most commonly chosen is exponential. Also, other configurations can be utilized, for example to obtain two resonance frequencies.

The stepped horn consists of two cylinders of different diameter placed end to end concentrically, and its most useful characteristic is that large motion amplification is obtainable. In high power applications of ultrasound, an exponentially tapered solid horn in half-wave resonance is used. The solutions apply to loosely systems and assume Poisson's ratio may be neglected *i.e.*, lateral dimensions are small compared with the length (Fig. 3).

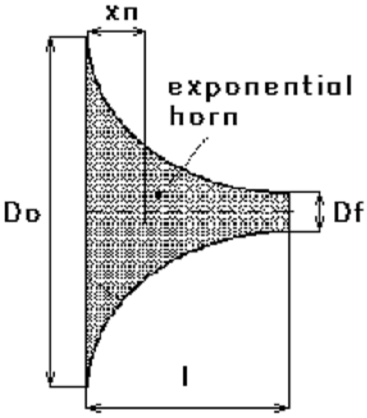


Fig. 3 – Ultrasonic exponential solid horn.

The relation, which represents the cross-section of the ultrasonic exponential solid horn is:

$$S_x = S_0 \mathrm{e}^{-\frac{\alpha x}{2}} \tag{6}$$

where:

$$\alpha = \frac{\omega}{c} \frac{\ln N}{\sqrt{\pi + (\ln N)^2}} \tag{7}$$

$N = D_0 / D_f$ magnifying factor of the vibration amplitude

$l = \frac{c}{2f}\sqrt{1+\left(\frac{\ln N}{\pi}\right)^2}$ length of the ultrasonic exponential solid horn

$x_n = \frac{l}{\pi}\arctan\left(\frac{\ln N}{\pi}\right)$

Condition: $l = n\lambda'/2 = (\mathrm{n}c')/2f$

The relation for a practical calculation is:

$$N = \frac{v_L}{v_0} = (-1)^n \mathrm{e}^{\frac{\lambda l}{2}} \tag{8}$$

The results are: $\ln N = \frac{\lambda l}{2}$ and $\lambda = \frac{2\ln N}{l}$

For a better precision in the calculation of a one can use the following relation:

$$\lambda = \frac{2\omega}{c} \frac{\ln N}{\sqrt{\pi^2 + (\ln N)^2}} \tag{9}$$

As an improvement, the ultrasonic acoustical power of the sandwich transducer can be increased in the following ways:

- take an optimum PZT material and metallic elements (for radiator and reflector);
- increase the size (diameter, thickness) of the piezoceramic tores;
- take a greater number of piezoceramic tores;
- use a proper acoustical transformer (different forms and sizes) to amplify the vibrations;
- realize a narrow acoustical angle of the directivity pattern.

5. EXPERIMENTAL UPST TRANSDUCER

Due to many variable factors which can have an influence (PZT material parameters, variation of temperature, preset-up pressure of the stack elements, size of the component elements, etc.) the simplified model of the piezoceramic transducer cannot indicate the real resonance frequency. Practically one should realize a series of piezoceramic transducers with sandwich stack of PZT tores (variable size, number of PZT tores, type of PZT material and metal elements, shape of acoustical transformer). Steel and aluminum respectively have elastic modulus of 210 GPa and 69 GPa. Steel has been used for reflector and aluminum for radiator.

The main and active element of the high power ultrasonic piezoceramic transducer is the stack, made like a sandwich of PZT tores. Knowing the complete material properties of the piezoceramic is the first step for a precise transducer research and development [7].

To obtain a high ultrasonic power, a large frequency bandwidth and a low Q, the PZT material type PZT5A has been chosen, which has the following typical values for the piezoelectric, dielectric and elastic properties [8]:

- coupling coefficients: $K_p = 0.6$; $k_{33} = 0.71$
- $k_{33}^T = 1700$
- piezoelectric charge constants:
  $d_{33} = 374 \cdot 10^{-12}$ m/V
  $d_{31} = -171 \cdot 10^{-12}$ m/V
- piezoelectric voltage constants:
  $g_{33} = 24.8 \cdot 10^{-3}$ Vm/N
  $g_{31} = -11.4 \cdot 10^{-3}$ Vm/N
- mechanical quality factor $Q = 75$
- density 7700 Kg/m^3
- Curie temperature 365°C.

The familiar dielectric, elastic, and piezoelectric constants for piezoelectric ceramics may readily be measured employing generally available laboratory equipment, plus simple specimen holders and a switch box which was constructed from standard elements [9].

The material properties for all transducer components (metals and piezoceramic tores) were measured by utilizing the KrautKrämer – BRANSON USIP 12. Out of the measured v_c propagated sound velocities and the weights measured with an analytical balance, the impedance Z is calculated. The results are presented in the Table 1.

Table 1

Material properties of transducer components

Material type	Density [g/cm^3]	v_c [m/s]	$Z \times 10^{-6}$ [kg/m^{2}s]
PZT 5A (PI)	7.66	4400	33.704
Steel	7.84	5750	45.080
Hard aluminum	2.77	6400	17.728

To obtain a high electroacoustical efficiency, the materials of the sandwich transducer must be chosen with proper acoustical impedance.

6. USPT TRANSDUCER MANUFACTURE

The USPT technological manufacture requires special mechanical processes to realize the piezoceramic stack, metallic elements and then to encapsulate all together. In this construction (Fig. 4), four piezoceramic tores are bolted between a pair of end-metal elements (steel cylinder reflector and exponential hard aluminum radiator).

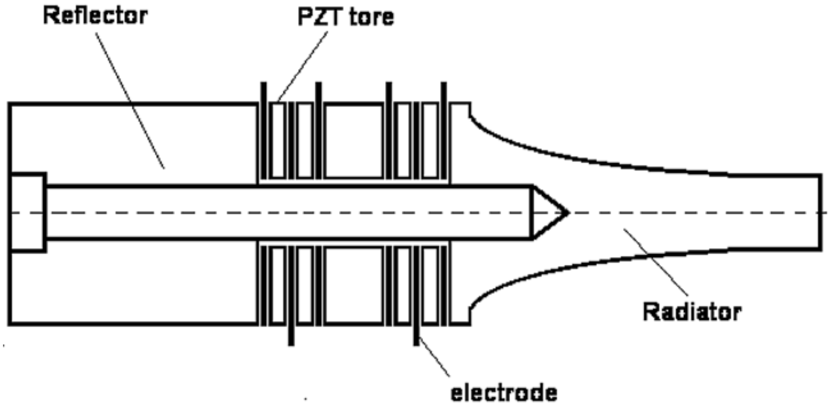


Fig. 4 – UPST experimental transducer cross section.

The piezoceramic elements are of pre-polarized lead titanate zirconate composition, which exhibit high activity coupled with both low loss and aging characteristics. They are ideally suited to form the basis of an efficient and rugged transducer. The assembly is clamped together by means of a high tensile bolt, which ensures the ceramics are in compression mode at maximum transducer displacement. Between the PZT tores there are copper electrodes, to make the electrical connection. The PZT-5A tores dimensions are: ϕ30 external diameter, ϕ12 mm inner diameter and 4 mm thickness, the steel cylinder reflector is 60 mm in length and the hard aluminum reflector is 90 mm in length.

7. EXPERIMENTAL MEASUREMENTS AND RESULTS

The frequencies at minimum and maximum impedance (resonance and antiresonance) and the impedances are determined by using the set-up from Fig. 5.

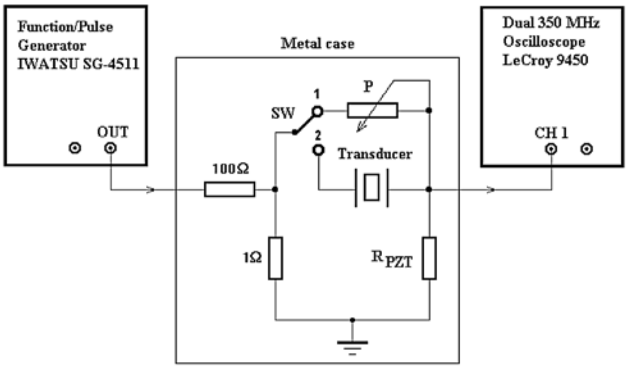


Fig. 5 – Set-up for parameter measurement of the experimental transducer.

Also, the impedance-frequency characteristics of the UPST transducer can be determined with this circuit. A metallic box, like an electroacoustic screen, which reduces the noise effects, protects the electronic set-up, realized according the IRE Standard [9], [10] and [11].

A Hewlett Packard HP 4284A Analyzer, USA, interfaced to a PC (Fig. 6) was used to obtain the UPST impedance-frequency characteristics. The analyzer has a frequency bandwidth between 20 Hz to 1 MHz, and a LAB VIEW program is implemented to acquire characteristic data in the PC.

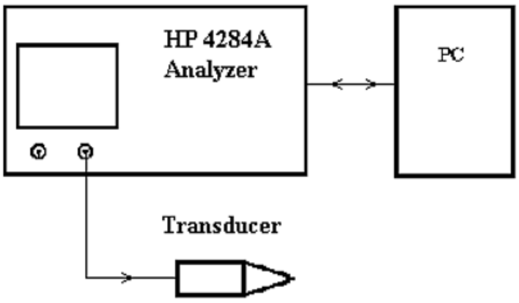


Fig. 6 – Impedance-frequency characteristic measurement equipment.

The UPST transducer is centered into a shock wave device of lithotriptor, and the hard aluminium radiator is immersed into the water tank, see Fig. 7. The Function/Pulse Generator type IWATSU SG-4511 supplies the UPST with burst signals (Fig. 8). The burst signal properties are adjusted from the Function/Pulse Generator front panel, like this: number of pulses $n = 2$, maximum amplitude $A = 8$ V, train pulses period $T = 10$ ms and frequency $f = 17{,}3$ kHz.

According to the reverse piezoelectric effect, the transducer converts the electrical signal in mechanical vibrations, which are propagated in water, reach a target and the PZT disc sensor. The acoustical waves, received by a PZT disc sensor (ϕ20 diameter and 1 mm thickness), are converted in electrical signals and displayed by an oscilloscope type LeCroy 9310 AM. (Fig. 9). The oscilloscope has a PC interface and the signal can be digitized and processed.

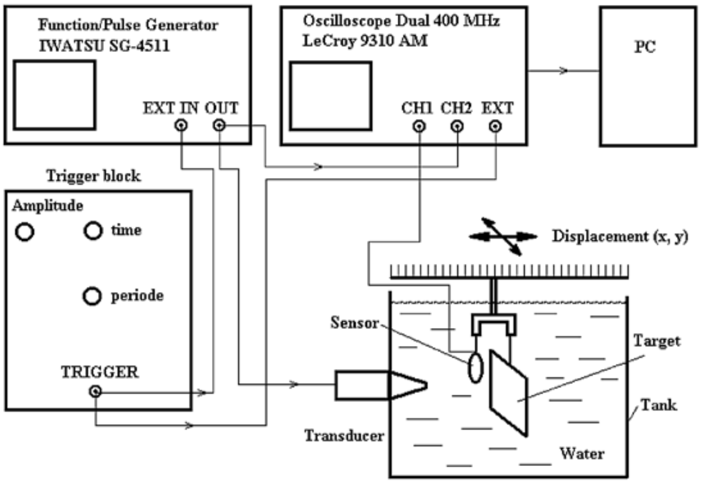
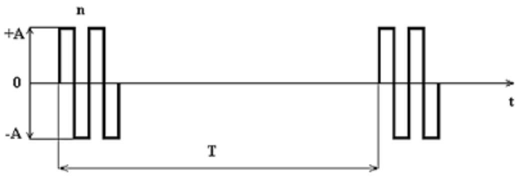


Fig. 7 – Set-up for parameter measurement of the experimental transducer put into a water tank.

Fig. 8 – Burst signals.



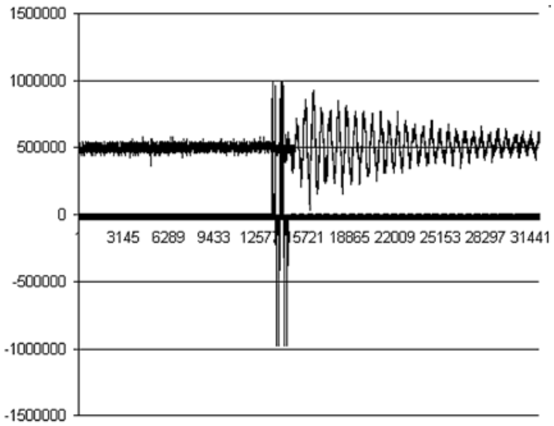


Fig. 9 – Acoustical signal.

As a result, the UPST impedance-frequency characteristics in air and water are shown in the Figs. 10 and 11. When the UPST is supplied with the water impedance, one can observe some changes in the impedance-frequency characteristic, such as: greater resonance frequency and impedance (Fig. 12). One can expect greater changes for a greater water volume.

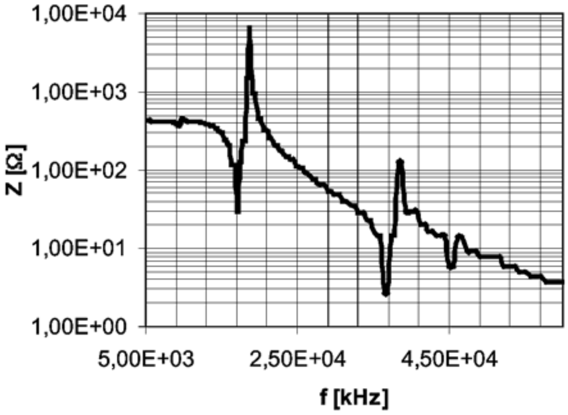


Fig. 10 – UPST impedance-frequency characteristic in air, $n = 200$ points.

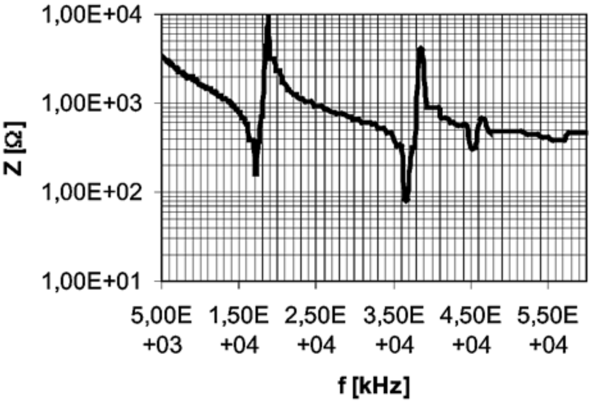


Fig. 11 – UPST impedance-frequency characteristic in water, $n = 200$ points.

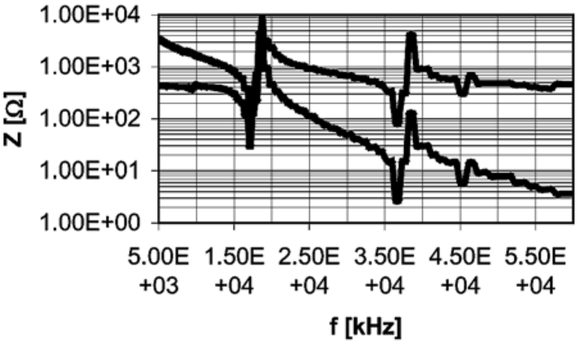


Fig. 12 – UPST impedance-frequency characteristics in air and in water, $n = 200$ points.

The UPST was not measured at high power conditions, but one can approximate some properties. For instance, by utilizing relation (5) and knowing $d_{33} = 374 \cdot 10^{-12}$ m/V for PZT-5A, $n = 4$ tores, supposing a 1000 V pulse voltage amplitude and a radiator amplifier coefficient of 5, one can approximate that 7.5 μm is the maximum vibration displacement at the UPST transducer end radiator.

8. CONCLUSIONS

It is necessary to know and take into account, that the ultrasonic transducer is realized in air, but it works in water medium [12]. The interface air-water has particular characteristics, which determine different resonance frequencies in air and water for the ultrasonic transducer. The experimental UPST, centered in the shock wave device of the lithotriptor presents a low resonance frequency characteristic and wide bandwidth.

For our research purposes the transducer seems to offer the following advantages:

- it is possible to achieve much grater vibration amplitudes by utilizing a horn with an exponential shape as radiator;
- as a result of this, much grater energy densities can be achieved;
- the acoustical power can be increased by utilizing a greater number of tores and a large tore surface.

The vibration amplitude of the UPST sandwich radiator depends on the PZT tores number, voltage amplitude, PZT material elasticity coefficients and the metal elasticity coefficients. The PZT-5A piezoceramic material, utilized for the active elements of transducer is suited for high power acoustic radiation to improve the cavitational effects.

The ultrasonic field generation of the UPST together with the incident shock wave of the ESWL will be used to realize an enlargement of the cavitation bubble size in the water at the surface of the renal calculi.

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