USE OF POROUS LEAD ZIRCONATE TITANATE CERAMICS IN PIEZOELECTRIC HYDROPHONES

S Marselli (1), F Silvano (1), C Galassi (2), E Roncari (2), F Craciun (3), G Guidarelli (3)

(1) Whitehead Alenia Sistemi Subacquei S.p.A., Livorno, Italy
(2) CNR, Istituto di Ricerche Tecnologiche per la Ceramica, Faenza, Italy
(3) CNR, Istituto di Acustica "O.M. Corbino", Area di Ricerca Roma-Tor Vergata, Roma, Italy

1. INTRODUCTION

In the last decades piezoelectric composites (mixtures of an elastically and dielectrically hard piezoelectric phase, like lead zirconate titanate PZT ceramics, with a soft non-piezoelectric phase, like a polymer or air) which present improved hydrostatic piezoelectric properties, high figure of merit (FOM) $d_h g_h$ and better matching with the transmitting medium have been investigated [1-14]. It has been shown that a high hydrostatic FOM is necessary in order to obtain a high signal-to-noise ratio of a piezoelectric hydrophone [15].

In this paper we show that porous PZT ceramics can be successfully used in piezoelectric hydrophones, operating in a hydrostatic mode, with a linear response up to high pressures. In Sec. 2 the construction, measurements and properties of porous piezoelectric ceramic hydrophone are presented. The preparation of porous PZT samples with high FOM employed in this hydrophone is also described. In Sec. 3 hydrophones with similar design but different piezoelectric materials are presented and compared with those based on porous piezoelectric ceramics.

2. CONSTRUCTION AND CHARACTERIZATION OF POROUS PIEZOELECTRIC CERAMIC HYDROPHONE

In order to test the porous piezoelectric ceramic material as active element in a hydrophone, we have selected a simple design, made of 9 elements assembled in a planar array. The porous piezoelectric ceramics were prepared by mixing $Pb(Zr_xTi_{1-x})O_3$ (x = 0.52) powder, added with 1% Nb, with starch powder in 50% vol. ratio. The preparation procedure was described elsewhere [14] therefore here it is only briefly mentioned. From the mixed powder square plate samples have been pressed, heated to burn out the organic additive and then sintered at 1150° C for 30 min. The mean value density of the samples was 4.78 g/cm^3. which corresponds to a total porosity of about 39%.

USE OF POROUS PZT CERAMICS IN PIEZOELECTRIC HYDROPHONES

The sintered samples were ground, electroded with silver paste and poled into silicone oil at 120°C under a d.c. field of 3 kV/mm for 40 min.

The crystallographic structure was identified by X-ray diffraction (XRD) analysis. XRD patterns showed the coexistence of ferroelectric rhombohedral and tetragonal perovskitic phases. Scanning electron microscopy (SEM) performed on sample fracture showed the presence of interconnected pores of different dimensions, ranging between fractions of micron and few microns diameter [14].

Piezoelectric, elastic and dielectric properties were measured on standard shape samples as recommended by the IEEE standards. The dielectric constant ε_{33} was obtained from the measured capacity, by taking into account the effective geometry of the plates and electrodes. The piezoelectric d_{33} charge constant was measured by a direct method based on a d_{33}-meter, while the hydrostatic voltage constant was obtained from measurements of samples sensitivity in air at 250 Hz under hydrostatic load. The main physical properties of the porous samples are reported in Table 1 (next section), together with the corresponding properties of other piezoelectric materials, used for comparison.

From the porous square samples with dimensions 27x27x5 mm^3 nine elements with similar characteristics were selected and assembled in a planar hydrophone [13]. The array was embedded in polyurethane resin and a cable of length 3 m and capacity 150 pF/m was used for the electrical connection. The final dimensions of the hydrophone were 110x110x20 mm^3 and its total capacity was 5517 pF. The admittance vs. frequency curve was measured by using an impedance bridge HP 4194A, with the hydrophone immersed in a large water tank, in order to assure free-field conditions [16]. The main length and thickness resonances of the hydrophone have been found to be approx. 35 kHz and 167 kHz, respectively.

The hydrophone free-field voltage sensitivity was measured by comparing the electrical output voltages of the unknown and standard hydrophones subjected to the same pulsed sound field produced by a projector in a the water tank [16]. A standard B&K 8100 hydrophone has been used for calibration. A rotating device allowed the hydrophone to change the orientation with respect to the projector acoustic axis with fine angular steps. The measured free-field voltage sensitivity of the constructed planar hydrophone in the frequency range between 1 kHz and 40 kHz shows that the hydrophone is characterized by a high sensitivity of approximately -193 dB//V/μPa, which remains constant within ±1 dB, up to 22 kHz. The first resonance mode of the piezoelectric elements, at 35 kHz, limits the linear response regime of the hydrophone.

The same experimental set-up used for the sensitivity characterisation was also employed for obtaining the directivity patterns. The sensitivity was measured as a function of the angle between the hydrophone and projector acoustic axis. The directivity patterns measured at different frequencies (up to 40 kHz) are bi-directional, since the hydrophone was symmetrically loaded on each face. At frequencies below 5 kHz the wavelength is much higher than hydrophone dimensions therefore it becomes omnidirectional (within ±1.5 dB).

USE OF POROUS PZT CERAMICS IN PIEZOELECTRIC HYDROPHONES

The measured directivity patterns nevertheless correspond to those calculated for a 86-mm line [16].

The sensitivity variation as a function of hydrostatic pressure was also measured, on a smaller hydrophone formed by only three elements. This hydrophone was introduced in a pressure vessel, where the pressure was varied between the ambient value and 60 bars. It was observed that the sensitivity had only a very small increasing, within 0.7 dB, when the static pressure was increased up to 60 bar, for all the frequency range between 2 kHz and 20 kHz.

The equivalent noise pressure P_H of the hydrophone was estimated at different frequencies, with and without including the preamplifier noise, by using the noise model presented in Fig. 1 (the description of the different elements is given in the caption).

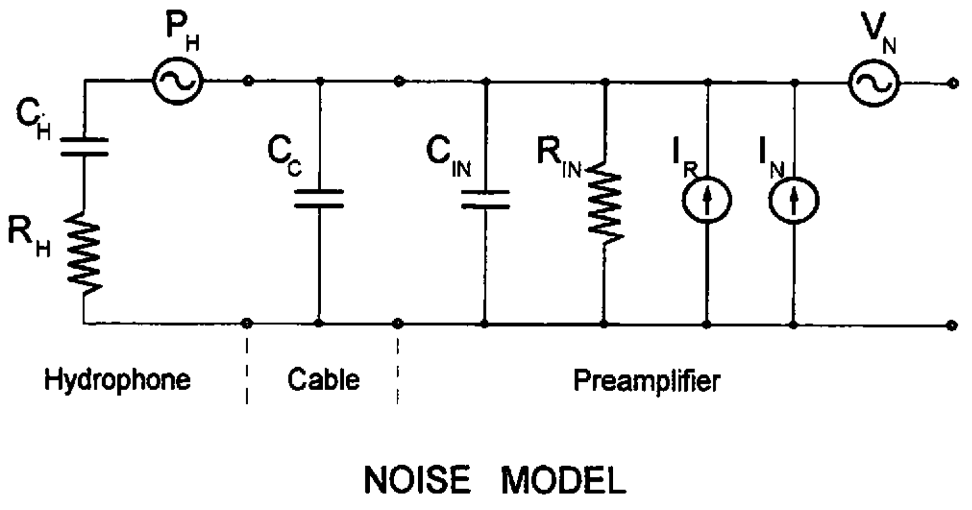

Fig. 1. Noise model circuit used to evaluate the equivalent noise pressure of the hydrophones together with the preamplifier and the connecting cable. C_H – hydrophone capacitance; R_H – hydrophone thermal noise resistance; P_H – hydrophone equivalent noise pressure; C_C – cable capacitance; C_{IN}, R_{IN} – preamplifier input capacitance and resistance; V_N, I_N, I_R – preamplifier noise voltage, noise current and noise resistance sources

The hydrophone thermal noise resistance R_H is given by the relationship $R_H = \tan\delta/\omega C_H$, with $\tan\delta$ the loss factor of the piezoelectric material and ω the angular frequency, while the equivalent noise pressure P_H, without the preamplifier, was obtained from the relationship [13, 15]: $P_H = \sqrt{\dfrac{4kT\tan\delta}{\omega V d_h g_h}}$, by considering the measured values of piezoelectric constants,

USE OF POROUS PZT CERAMICS IN PIEZOELECTRIC HYDROPHONES

dielectric loss factor, ambient temperature T = 286 K and the volume V of the active elements (Table 1). The results are plotted as a thin continuous line in Fig. 2 (next section), for the frequency range 0.1-10 kHz. The inherent noise pressure of a preamplifier stage has been also included, by hypothesising a noise voltage source V_N = 4 nV, a noise current source I_N = 7 fA and an input resistance R_{IN} = 10 MΩ. The total equivalent noise pressure of hydrophone including preamplifier should be lower than the noise pressure corresponding to Knudsen sea state zero [16], which is the lowest noise field that the hydrophone would be expected to measure. This is evident in Fig. 3 (next section), when comparing the total hydrophone noise pressure, represented by a thin continuous line, with the noise level at sea state zero, displayed as a simple thick curve on the same graph.

3. COMPARISON WITH HYDROPHONES BASED ON DIFFERENT PIEZOELECTRIC MATERIALS

In order to compare the properties of the hydrophone based on porous piezoceramics with those of similar devices but with different materials employed as active elements, the following piezoelectric materials have been considered for the evaluation:

a) lead titanate piezoceramics (PT2 type);
b) polyvinylidene fluoride film (PVDF);
c) lead zirconate titanate ceramics (PZT5A type) (hydrostatic mode);
d) lead zirconate titanate ceramics (PZT5A type) (uniaxial 33-mode, with the lateral surfaces acoustically shielded).

Their properties are presented in Table 1.

It can be observed that the hydrostatic FOM of the porous material is a few orders of magnitude higher than that corresponding to PZT5A and a few times higher than for the other materials. Lead titanate has a relatively high FOM value, due to its highly anisotropic piezoelectric properties (the piezoelectric effect along the polar axis is much more intense than along the perpendicular directions).

For different planar hydrophones with the same construction design as the device based on porous ceramics previously described, we considered the same volume of piezoelectric material, and, excluding the PVDF hydrophone, the same thickness and area. For the hydrophone based on PZT5A either the hydrostatic mode as well as the uniaxial 33-mode (lateral surfaces acoustically isolated) were considered. Their characteristics have been evaluated (without considering the connecting cable) and presented in Table 2.

The equivalent noise pressure values for the different hydrophones, which have been evaluated by using the same noise model as in the previous section are presented in Fig. 2. It can be observed that, in the range 100 Hz-10 kHz all the hydrophones, excepting the device based on PZT5 working in hydrostatic regime, have an equivalent noise pressure below the sea state zero (SS0) level. The best devices from this point of view are those

USE OF POROUS PZT CERAMICS IN PIEZOELECTRIC HYDROPHONES

based on porous ceramics and on dense ceramics which are acoustically shielded on the lateral faces.

Table 1. Main physical properties of the piezoelectric materials used in hydrophone construction.

	Porous ceramics	Lead titanate (PT2)	PVDF	PZT5A
Relative dielectric constant ε_r	499	210	12	1700
Dielectric loss factor $tg\delta$ [%]	3	2	1.8	2
Curie temperature [°C]	>300	255	90	365
Charge constant d_{33} [10^{-12} m/V]	295	68	-30	374
Charge constant d_{31} [10^{-12} m/V]	-41	-3	18	-171
Charge constant d_{32} [10^{-12} m/V]	-41	-3	2	-171
Hydrost. charge constant d_h [10^{-12} m/V]	213	62	-10	32
Voltage constant g_{33} [10^{-3} Vm/N]	67	37	-290	24.8
Voltage constant g_{31} [10^{-3} Vm/N]	-9.2	-2	180	-11.4
Voltage constant g_{32} [10^{-3} Vm/N]	-9.2	-2	20	-11.4
Hydrost. voltage constant g_h [10^{-3} Vm/N]	49	33	-90	2
Figure of merit $g_h d_h$ [10^{-12} m^2/N]	10.4	2	0.9	0.064

Table 2. Characteristics of planar hydrophones constructed with different piezoelectric materials (without including the connecting cable).

	Porous ceramics hydroph.	Lead titanate hydroph.	PVDF hydroph.	PZT5A hydroph. (hydrost.)	PZT5A hydroph. (uniaxial)
Active elem. vol. [10^{-6} m^3]	30.8	30.8	30.8	30.8	30.8
Active elem. area [10^{-4} m^2]	61.7	61.7	308.5	61.7	61.7
Act. elem. thickness [mm]	5	5	1	5	5
Sensitivity [dB//V/µPa]	-193	-195.6	-201	-220	-198
Capacity [pF]	5067	2132	3046	17262	17262

USE OF POROUS PZT CERAMICS IN PIEZOELECTRIC HYDROPHONES

In Fig. 3 the diagrams of the equivalent noise pressure of the same hydrophones including the connection cable and the preamplifier are presented. These diagrams evidence that:

- the hydrophone based on dense PZT5A ceramics working in hydrostatic regime is the noisiest;
- the hydrophone based on PVDF has noise pressure lower than SS0 only up to 3.5 kHz;
- the hydrophones using highly anisotropic lead titanate ceramics and PZT ceramics shielded on the lateral faces have noise pressure below SS0 only up to 7 kHz;
- the only hydrophone which keeps the noise pressure below SS0 level in all the considered frequency range is that based on porous ceramics;

These evaluated characteristics have been thoroughly verified on porous ceramics hydrophone and on similar planar devices based on PT2 ceramics and PVDF film. It has been also experimentally observed that the sensitivity response of the PVDF hydrophone was much less flat than for the other hydrophones. Moreover the ceramic hydrophones allow to operate in more difficult thermal ambients, due to their higher Curie temperature.

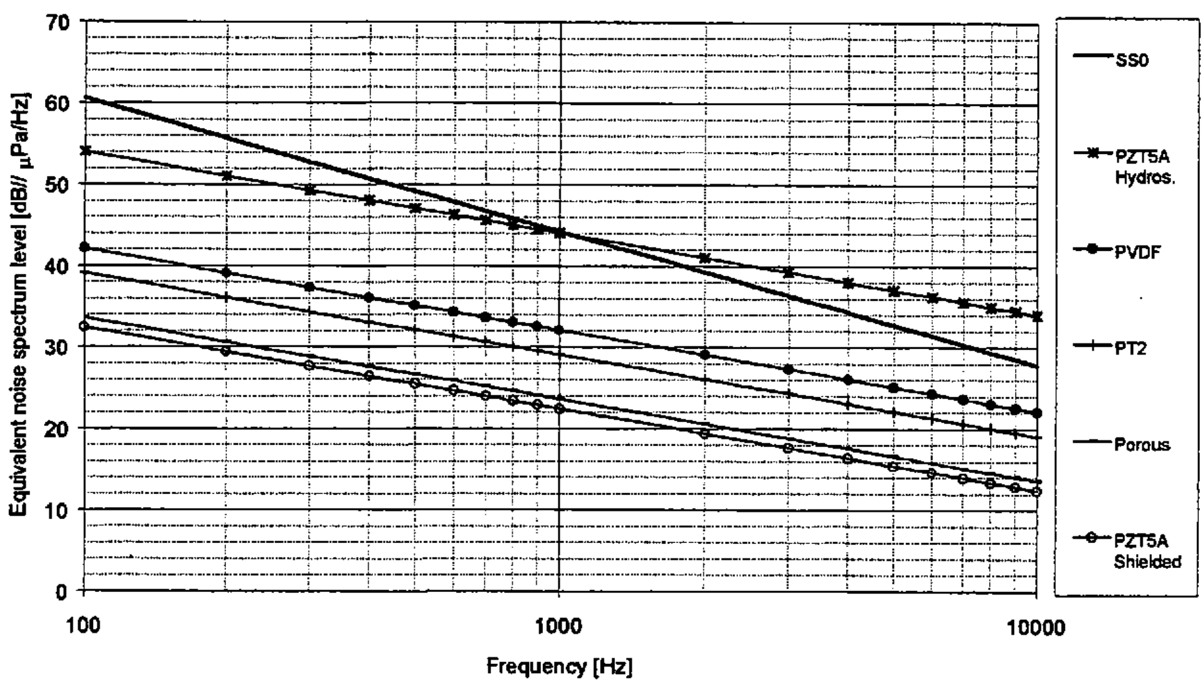

Fig. 2. The equivalent noise pressure of different hydrophones with the same volume of active material.

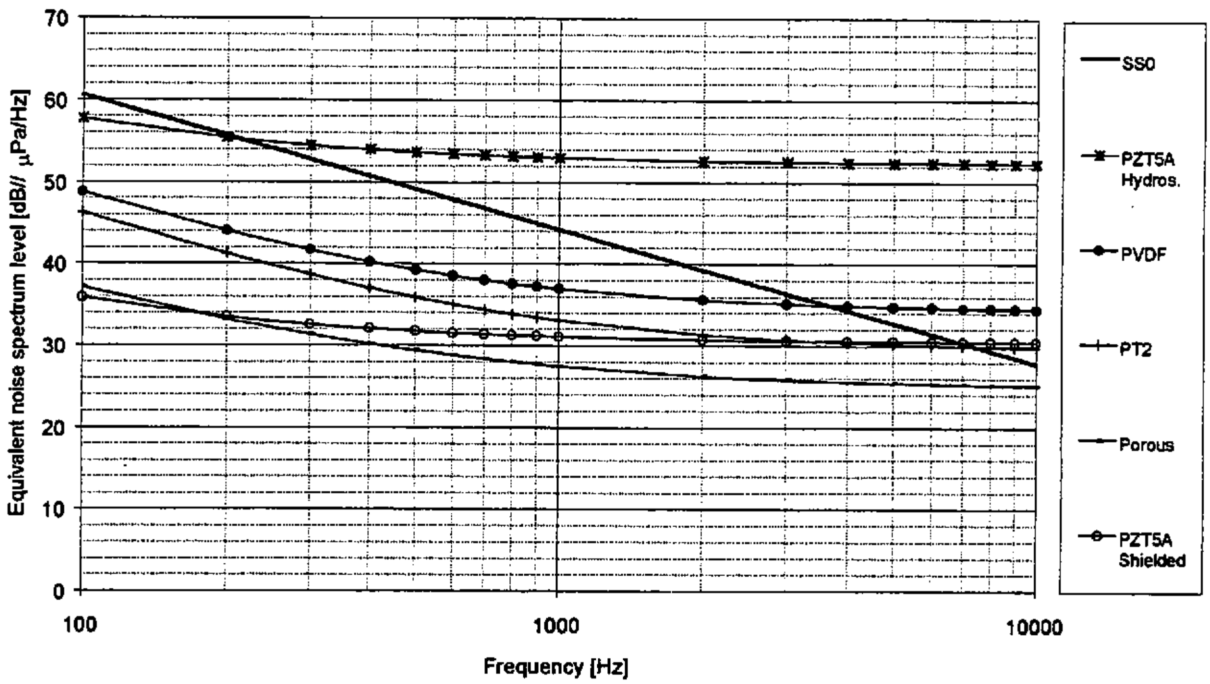

Fig. 3. The equivalent noise pressure of the hydrophones (including connecting cable and preamplifier).

4. CONCLUSIONS

In conclusion it has been evidenced that

- the use of porous piezoelectric ceramics as active elements in hydrophones allows to obtain devices with simple design and improved hydrostatic response;
- porous PZT materials have a very high figure of merit ($d_h g_h$ >10^{-12} m^2/N) and a relatively high dielectric constant (approx. 500); this allows the design of hydrophones with low noise level and the use of simple preamplifiers connected to the hydrophone with a relatively long cable, which simplifies the use of the device;
- porous ceramics have the advantage of low acoustic impedance which allows a better matching with water medium;
- they have an almost linear behaviour when subjected to a pressure as high as 60 bar, which allows the construction of hydrophones with linear response up to high depth.

USE OF POROUS PZT CERAMICS IN PIEZOELECTRIC HYDROPHONES

5. REFERENCES

[1] T.R. Gururaja, W.A. Sculze, L.E. Cross, R.E. Newnham, B.A. Auld, Y.J. Wang, "Piezoelectric Composite Materials for Ultrasonic Transducer Applications" Part I, IEEE Trans. Sonics and Ultrasonics **SU 32**, 481 (1985).

[2] W.A. Smith, Ultrasonics Symposium (IEEE, New York, 1989), p. 755 (and ref. therein).

[3] K. Hikita, K. Yamada, M. Nishioka, M. Ono, "Piezoelectric properties of the porous PZT and porous PZT composite with silicone rubber", Ferroelectrics **49**, 265 (1983).

[4] R.Y. Ting, "Piezoelectric properties of a porous PZT ceramic", Ferroelectrics **65**, 11 (1985).

[5] U. Bast, W. Wersing, "The influence of internal voids with 3-1 connectivity on the properties of piezoelectric ceramics prepared by a new planar process", Ferroelectrics **94**, 229 (1989).

[6] T. Hayashi, S. Sugihara, K. Okazaki, "Processing of porous 3-3 PZT ceramics using capsule-free O_2- HIP", Jpn. J. Appl. Phys **30**, 9B, 2243 (1991)

[7] K. Mizumura, Y. Kurihara, H. Ohashi, S. Kumamoto, K. Okuno, "Porous piezoelectric ceramic transducer", Jpn. J. Appl. Phys. **30**, 9B, 2271 (1991).

[8] M.L. Dunn, M. Taya, "Electromechanical properties of porous piezoelectric ceramics", J. Am. Ceram. Soc. **76**, 1697 (1993).

[9] P. Loebmann, W. Glaubitt, "Densification and crystallization of lead titanate aerogels", J. Am. Ceram. Soc. **80**, 2658 (1997) and references therein.

[10] F. Craciun, G. Guidarelli, C. Galassi, E. Roncari, "Elastic wave propagation in porous piezoelectric ceramics", Ultrasonics **36**, 427 (1998).

[11] F. Craciun, C. Galassi, E. Roncari, A. Filippi, G. Guidarelli, "Electro-elastic properties of porous piezoelectric ceramics obtained by tape casting", Ferroelectrics **205**, 49 (1998).

[12] F. Craciun, C. Galassi, E. Roncari, "Experimental evidence for similar critical behavior of elastic modulus and electric conductivity in porous ceramic materials", Europhys. Lett. **41**, 55 (1998).

[13] S. Marselli, V. Pavia, C. Galassi, E. Roncari, F. Craciun, G. Guidarelli, "Characteristics of hydrophones based on porous piezoelectric materials, Proc. 4th European Conference on Underwater Acoustics (Eds. A. Alippi and G.B. Cannelli, CNR-IDAC, Rome, Italy, 1998), p. 921.

[14] E. Roncari, C. Galassi, F. Craciun, G. Guidarelli, S. Marselli, V. Pavia, "Ferroelectric ceramics with included porosity for hydrophone applications", Proc. ISAF XI (ISAF XI, Montreux, 1998), in print.

[15] J.W. Young, "Optimization of acoustic receiver noise performance", J. Acoust. Soc. Am. **61**, 1471 (1977).

[16] R. J. Bobber, "*Underwater Electroacustic Measurements*" (Naval Research Laboratory, U.S. Government Printing Office, Washington, DC, 1970).