Evaluation of porous PZT with 3-3 connectivity for biomedical ultrasonic imaging applications

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Abstract : PZT porous ceramics with 3-3 connectivity is characterized on the large range of porosity from 25 % to more than 80 %, for possible use in ultrasonic systems for medical imaging. Two methods are used to evaluate the electromechanical properties of these transducers, the resonance method and an original method based on the analysis of the time response of transducer excited by a current impulse. Porous PZT developed a same d_{33} than Structural PZT ceramic which gives a large voltage coefficient g_{33}, thickness coupling coefficients kt are very large, and then planar coupling coefficients are reduced strongly, for 60 % of porosity $k_t / k_p = 3{,}1$ the for PZT ceramic $k_t / k_p = 0{,}67$ These results showed that the presence of the three-dimensional porosity in ceramic causes a decoupling of the piezoelectric effects axial radial directions, to privilege the axial mode, and for large porosities the transducer vibrates exclusively according to the axial mode. The acoustic impedance (Z_a) is decreased by the reduction of the density of PZT. Porous PZT constitute an excellent material for use in ultrasonic systems for medical imaging.

Key-Word : Porous PZT, Transducer, connectivity 3, Electromechanical properties, Impulse method

1 Introduction

Ultrasonic systems for medical imaging employ broad band (1 to 30 MHz) piezoelectric transducers. This process utilizes an electromechanical transducer operating in the pulse-echo mode to transmit ultrasonic pulses into the body and also to receive the faint echoes produced by reflections from internal structures. Optimal design of such transducers requires a piezoelectric material with high thickness mode electromechanical coupling coefficient k_t, and minimal planar thickness mode coupling coefficient (k_p) for to give the ration k_t/k_p as larger as possible [1].
Large values for d_{33} and g_{33} are highly desirable for gives a large figure of merit for pulse echo transducers. The dielectric constant ε_r must be low to increase the voltage coefficient g_{33}, ($g_{33} = d_{33} / \varepsilon_r \, \varepsilon_0$), and $\varepsilon_r \sim 100$ permit a large voltage coefficient and eases the electrical impedance matching between the transducer and the system instrumentation [2].
The transducer's acoustic impedance must be near that of body tissue (~ 1,5) for strong acoustic coupling, minimizing the reflection of acoustic signal at the transducer/skin interface.
In earlier studies we have been obtained porous PZT on a large interval of porosity and which developed the same piezoelectric longitudinal charge coefficient d_{33} than the PZT ceramic [3], and the large longitudinal piezoelectric voltage coefficient g_{33}, because ε_{33} is strongly reduced by the porosity. The acoustic impedance is reduced also by the decreases of the density of PZT for created a strong acoustic coupling with body tissue.
In this paper we evaluated the performances of porous PZT material on the large range of porosity, from dense ceramic to more than 80 %, to investigated in the ultrasonic imaging.

2 Measurements

The electromechanical coupling coefficients in thickness mode k_t and in planar mode k_p were measured using resonance method in accordance with IEEE-standard [4], we have also used an impulse method to characterized our transducers [5]. This method is based on the measurement of the voltage which appears between the two faces of the thin piezoelectric element(thickness e, area A, density ρ) when it is excited by current impulse whose duration is much smaller than the axial resonance period. The theoretical curve representing the voltage *U(t)* as a function of time is given in figure 1, and from this curve we deduce :

1) The axial resonance period (T_a),

2) The thickness propagation velocity

$$V_a = 2e/T_a \quad (1)$$

3) The elastic constant

$$C_{33} = \rho.V_a^2 \quad (2)$$

3) The elastic constant

$$C_{33} = \rho.V_a^2 \quad (3)$$

4) The thickness acoustic impedance

$$Z_a = \rho.V_a \quad (4)$$

5) The thickness electromechanical coupling coefficient

$$k_t = (\Delta U/2U_0)^{1/2} \quad (5)$$

6) The relative permittivity at constant strain

$$\varepsilon_r = Q.e/A.U_0 .\varepsilon_0 (\varepsilon_r). \quad (6)$$

And the ratio of the amplitude of the first radial vibration to the amplitude of the first axial vibration *(R)*.

We have also used a LCR meter to measured the dielectric losses $tg\delta$ and the capacitance at 1kHz.

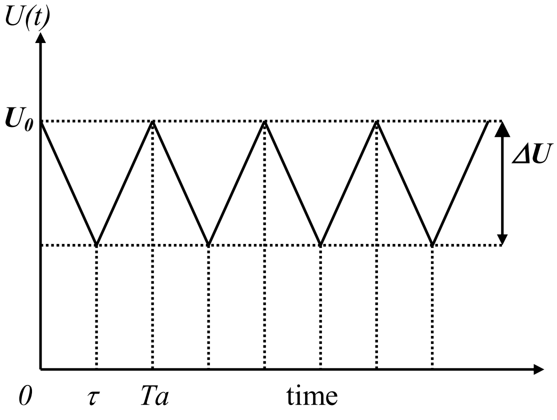

Fig. 1 : Theoretical voltage *U(t)* in a piezoelectric element excited by a current

3. Results and discussion

Porous PZT transducers were fabricated by sintering starting from a PZT-PKG 21 powder obtained from Quartz and silica (French) which is mixed an organic substance, the method of elaboration is reported in earlier [3].

3.1. Characterization of structural PZT

At first we have characterized the structural PZT ceramic, and their electromechanical properties are reported in table 1. The voltage measured on the structural PZT indicate that the transducer vibrates in both direction, axial and radial (figure 2), and the ratio R = 0,77 confirm this result.

Table 1:
Electromechanical properties of a PZT PKG 21 Quartz and silica France

ε_r	1825
$tg\delta$	0,02
d_{33} (pC/N)	500
g_{33} (mV/N)	30,96
k_t	0,47
k_p	0,70
Z_a (kg/m².s)	40,9 x10^6
C_{33} (N/m²)	14,30 x10^{10}
V_a (m/s)	5510
F_a (Hz)	2,3 x10^6
R	0,77

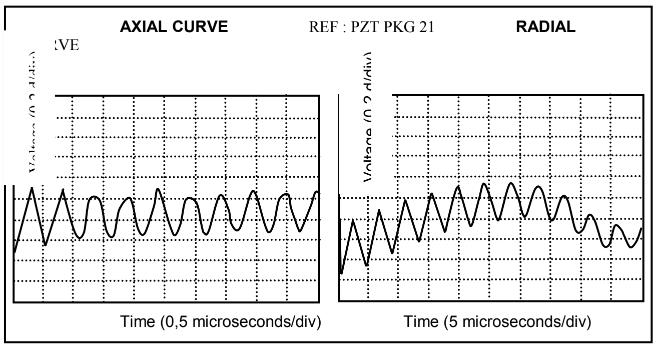

Fig. 2 : Voltage measured in piezoelectric PZT ceramic

3.2. Characterization of porous PZT ceramics

The results of characterization of porous PZT ceramics are reported in table 2. we consider the average value of longitudinal piezoelectric coefficient d_{33} = 500 pC/N the same value than PZT ceramic. This result was obtained and confirmed early. Fig.3 shows that the acoustic impedance and the elastic constant C_{33} decreases strongly when the fraction of ceramics decreases : for 40 % of porosity Z_a is divided by 4 and C_{33} is so divided by 6.

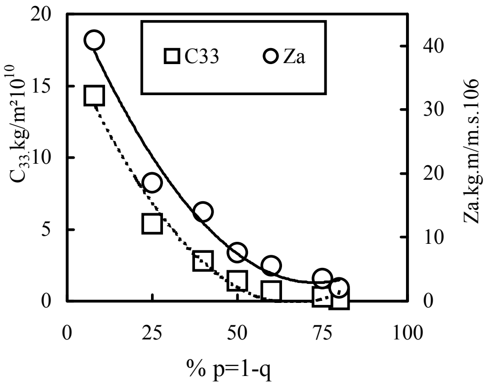

Fig.3 : Elasticity constant C_{33} and acoustic impedance Z_a as a function of porosity

According to table 2 and Fig.4, the ration of k_t/k_p increases as the porosity increases, and for 60 % of porosity $k_t/k_p = 3{,}1$. We observed also that porosity improves strongly k_t and reduced k_p.

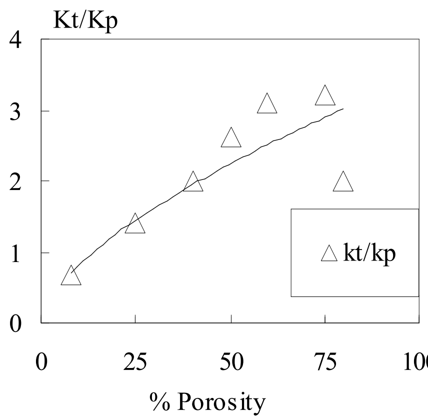

Fig.4 : k_t and k_p as a function of porosity

The variation of the axial frequency resonance and the axial velocity is given by the fig.5, it's showed that the presence of air in the transducer affect highly theirs properties.

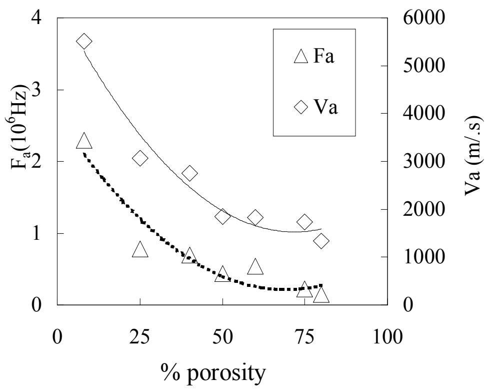

Fig. 5 : Axial resonance frequency and axial velocity as a function of porosity

According the Fig. 6 porous PZT with 50 % of porosity, the radial curve is very much attenuated, and for PZT with 70 % of porosity, the radial curve is missing (figure 7). Then porous PZT vibrates only on the axial (thickness) mode and the vibration on the radial mode is reduced strongly for porous ceramic with high porosity.

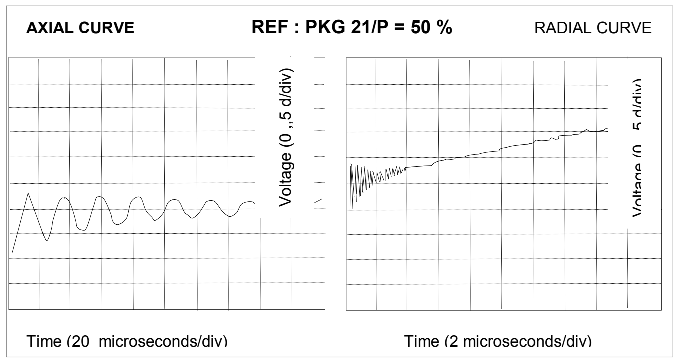

Fig.6 : Voltage measured in porous PZT excited by a current impulse (Porosity = 50 %)

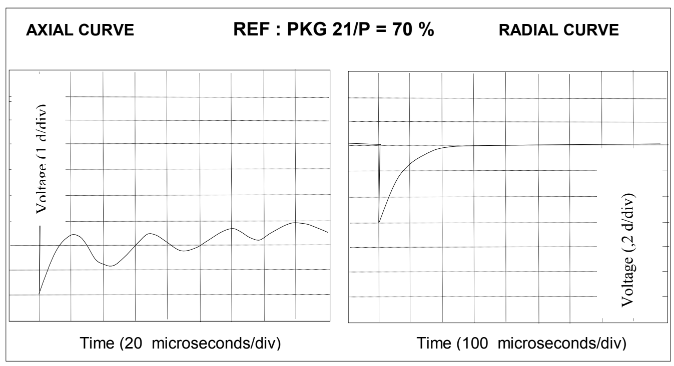

Fig.7 : Voltage measured in porous PZT excited by a current impulse (Porosity = 70 %)

Table 2 : Electromechanical properties of porous ceramics

Porosity (± 2 %)	ε_r	$tg\delta$	k_t	k_p	Z_a (x10^6 kg/m².s)	C_{33} (x10^6 N/m²)	V_a (m/s)	F_a (x10^6 Hz)	R
80	185	5	0,35	0,18	2 ,1	0,1	1340	0,15	0,05
75	222	6	0,64	0,20	3,5	0,3	1740	0,22	0,05
60	290	3	0,62	0,20	5,5	0,7	1833	0,54	0,14
50	450	3	0,55	0,21	7,6	1,4	1850	0,44	0,21
40	690	3	0,54	0,27	14,0	2,8	2750	0,70	0,24
25	910	3	0,46	0,33	18,6	5,4	3070	0,78	0,60

Table 3: k_t measured by the impulse method and by the resonance method

Porosity (± 2 %)	60	50	40	25
k_t *(resonance method)*	0,60	0,55	0,54	0,46
K_t *(impulse method)*	0,53	0,50	0,49	0,47

4. Conclusion

Porous PZT materials with 3-3 connectivity is very suitable to realized ultrasonic biomedical imaging device. Porosity has not influence on the piezoelectric coefficient d_{33}, and porous PZT has the same d_{33} than the structural ceramic which gives large voltage coefficient g33. Porosity improves The thickness electromechanical coupling coefficient k_t, for 60 % of porosity kt = 0,65 which is higher than kt = 0,47 of PZT, and the planar electromechanical coupling coefficient kp decreases with the increase of porosity and tends towards zero for high porosities. The ratio of the amplitude of the first radial vibration to the amplitude of the first axial vibration (R) is strongly reduced from 0,77 of PZT to 0,05 of porous PZT (P= 70 %). These properties show that the porous PZT ceramic vibrates exclusively according to the axial mode. Optimal design for ultrasonic system for medical imaging can be realized with porous PZT ceramic having 60 % of cavities filled of air, K_t = 0,62, K_p = 0,20, the figure of merit in transmission mode $d_{33}xg_{33} = 97{,}4x10^{-12}$ m² / N is very large than PZT ceramic $d_{33}xg_{33} = 1{,}54x10^{-12}$ m² / N. The acoustic impedance Za = 5,5 x10^6 kg/m².s which gives a good acoustic coupling with body tissue.

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