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Study of vibratory behavior of interconnected porous PZT by impulse method

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Abstract

Performances in ultrasonic active transducers of interconnected porous lead zirconate titanate (PZT) piezoelectric disks with a porosity ranging from 30 to 70%, and polarized along their axial axis, are investigated. The characterization method used is based on the measurement of the voltage, which appears between the two faces of the piezoelectric element when it is excited by a current impulse. The device used, allows the acquisition of axial and radial vibrations of the transducer, and from these data, electromechanical and acoustic parameters are deduced. One observes that interconnected porosity causes the disappearance of the radial vibrations, and for large porosities the disk vibrates exclusively according to the axial mode. k_t is increased, the acoustic impedance is reduced, and the axial propagation velocity reaches $\sim$2500 m s^{-1} for 30% of porosity. These results show that interconnected porous PZT are suitable for making ultrasonic active transducer, such as biomedical imaging devices.

Keywords: PZT; Porosity; Piezoelectric properties; Ultrasonic sensors

1. Introduction

In this paper, interconnected porous lead zirconate titanate (PZT) piezoelectric ceramics are characterized by an original method developed by Jayet et al.[1] to determine the dielectric, piezoelectric and mechanic properties on a wide range of porosity (30–70%). This method is based on the measurement of the voltage that appears between the two faces of the thin piezoelectric element when excited by a current impulse. It allows the study of the vibratory behavior of these ultrasonic transducers. Usually, one uses the resonance method which gives access to the various electromechanical parameters by measurement of the impedance of a transducer for various frequencies.[2] The resonance method, however, is valid only in the case of dense piezoelectric ceramics, since in the case of porous ceramics it is very difficult to distinguish parallel resonance frequencies from series ones. In our investigation, we used the impulse method where immediate response of the sensor is recorded. In this method, the parasitic phenomena of damping of the waves and radial vibrations are strongly reduced. This study makes a new contribution to the knowledge of the vibratory behavior of interconnected porous ceramics discs that are polarized according to their axial axis and excited by a current impulse according to the same axis. These materials, which have tri-dimensionally porous structure, present many advantages over dense ceramics in ultrasonic applications such hydrophone,[3] biomedical imaging; extensive studies are done for better controlling their manufacture and electromechanical behavior according to porous volume and to the pore shapes.[4–9]

Ultrasonic systems for medical imaging employ piezoelectric transducers (1–30 MHz), which operate in the pulse-echo mode to transmit ultrasonic pulses into the body and also to receive the echoes produced by reflections from internal structures. Optimal design of such transducers requires a piezoelectric ceramic with high thickness electromechanical coupling coefficient k_t and minimal planar electromechanical coupling coefficient k_p so to make the ratio k_t/k_p as large as possible.[10] Large values of piezoelectric charge coefficient d_{33} and piezoelectric voltage coefficient g_{33} are highly desirable in order to get a large value of a figure of merit ($d_{33} \times g_{33}$) for pulse echo transducers.[11] The transducer's acoustic impedance must be near that of body tissue ($\sim 1.5 \times 10^{-6}$ kg m^{-2} s^{-1}) for strong acoustic coupling, mini-

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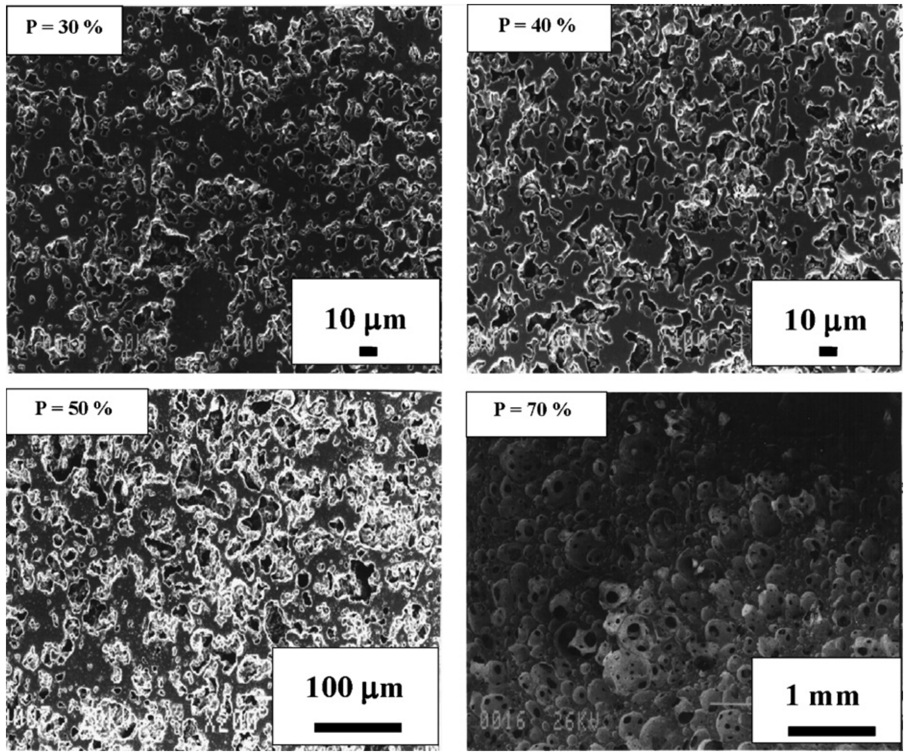

Fig. 1. Microstructure of interconnected porous PZT ceramics.

mizing the reflection of acoustic signal at the transducer/skin interface.

In earlier studies progress was made in investigating the electromechanical applications of porous PZT. Using the Berlincourt-d_{33}-Meter (CPDT 3300), we showed that d_{33} keeps the same value as that of a dense PZT on a wide range of porosity, and using resonance method we found that k_t increases strongly with increasing porosity while k_p decreases.[12,13] The data presented in this paper are collected using the impulse method, which allows us to get better informed about the optimal design and the ideal functioning of axial ultrasonic transducers such as biomedical imaging devices.

2. Experiments and measurements

Interconnected porous PZT disks characterized in this paper were obtained by mixing glucose with a commercial PZT powder followed by die pressing with 25 mm in diameter and 1–3 mm in thickness, and sintering at 1310 °C. The porosity of samples varies from 30 to 70% and the pore size varies from 50 to 500 µm (Fig. 1). The technique developed to fabricate porous ceramic has been reported earlier.[12]

We have used an original method developed by Jayet et al.[1] to characterize interconnected porous PZT, which allows to study the vibratory behavior and to determine dielectric, piezoelectric, and acoustic parameters. It is based on the measurement of the voltage which appears between the two faces of a thin piezoelectric element (thickness $a \ll$ diameter d) when it is excited by a current impulse. The theoretical curve representing the voltage $U(t)$ versus time is given in Fig. 2, and from this curve different electromechanical and acoustic parameters in axial and radial modes of a transducer vibrations are deduced, such as; the propagation velocity V_a, the axial resonance frequency F_a, the elastic constant at a constant electric displacement C_{33}, the acoustic impedance Z_a, the relative permittivity ε_r, the thickness electromechanical coupling coefficient k_t, and the piezoelectric deformation coefficient h_{33}. The porosity is calculated from this relation: $p = 1 - q$, p represents the fraction of vacuum and q represents the fraction of PZT. q is calculated from the ratio of porous PZT density d with respect to theoretical density d_{th}; $q = d/d_{\text{th}}$. To determine the figure of merit $d_{33} \times g_{33}$ for pulse echo transducers; the piezoelectric coefficients d_{33} and g_{33} are calculated from these formulas:

$$g_{33} = \frac{h_{33}}{C_{33}} \quad (1)$$

$$d_{33} = g_{33}\varepsilon_0\varepsilon_r \quad (2)$$

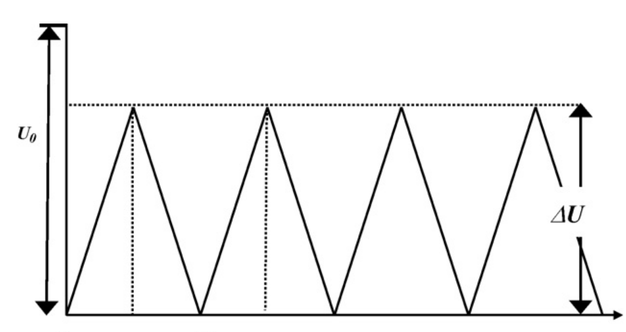

Fig. 2. Theoretical voltage ΔU in a piezoelectric element excited by a current (*Ta*: axial resonance period).

3. Results and discussion

The voltage produced by interconnected porous PZT and dense PZT along the axial and radial axis is reported in Fig. 3. We made the following observations.

In axial vibration, porous ceramics develop more voltage than dense ones. Furthermore, the larger the porosity the higher is the generated voltage. For $p = q = 50\%$, the generated voltage is 2.5 larger than that of dense PZT ceramics, whereas in radial vibration, the voltage is decreased by 10 times. Beyond 50% of porosity; the voltage generated in radial vibration becomes negligible and the transducer vibrates exclusively according to its central axis. We observe also an increase in the resonance period T_a with increasing porosity volume, which causes a reduction in the axial frequency of resonance ($F_a = 1/T_a$). According to Table 1, the ratio of the amplitude of the first radial vibration to the amplitude of the first axial vibration R, decreases strongly with increasing porosity; $R \sim 0.66$ for dense PZT is reduced to 0.11 for $p = 30\%$, and $R < 0.05$ for $p > 50\%$. The ratio of the axial resonance frequency F_a to the radial resonance frequency F_r also increases strongly with increasing porosity volume; $F_a/F_r = 10$ for dense PZT, is increased to values greater than 20 for $p > 30\%$. These results show that radial vibrations of interconnected PZT decrease with increasing porosity volume, and for strongly porous PZT the radial vibrations are non-existent ($R \ll 0.05$), and the vibrations are exclusively in the axial direction. In contrast, dense PZT discs vibrate in the axial and radial directions in the same way in spite of a low discs thicknesses ($a \ll d$).

Electromechanical and acoustic parameters are deduced from these data (Fig. 3) at different transducers thicknesses ($a = 1$, 1.5, and 3 mm), and plotted versus the fraction of PZT q to investigate the interconnected porous PZT. According to Fig. 4, we observe for a = constant, the axial resonance frequency F_a increases proportionally with the increase of the PZT fraction q, and for PZT of low porosity ($q > 0.7$), the thickness increase reduces strongly the axial frequency: F_a decreases by four times when a is increased by three times. For PZT of high porosity, the thickness of the transducer seems not to have an influence on F_a. In the other hand, the values of the axial propagation velocity V_a (Fig. 5), the acoustic impedance Z_a (Fig. 6), the elastic constant C_{33} (Fig. 7), and the piezoelectric stiffness h_{33} (Fig. 8), decrease with the introduction of porosity in PZT transducers. In this case, the thickness has no influence on these parameters for a wide interval of porosity (from 30 to 70%). One observes also, that interconnected porosity improves the electromechanical coupling factor k_t, and the maximum value is obtained in an interval of porosity from

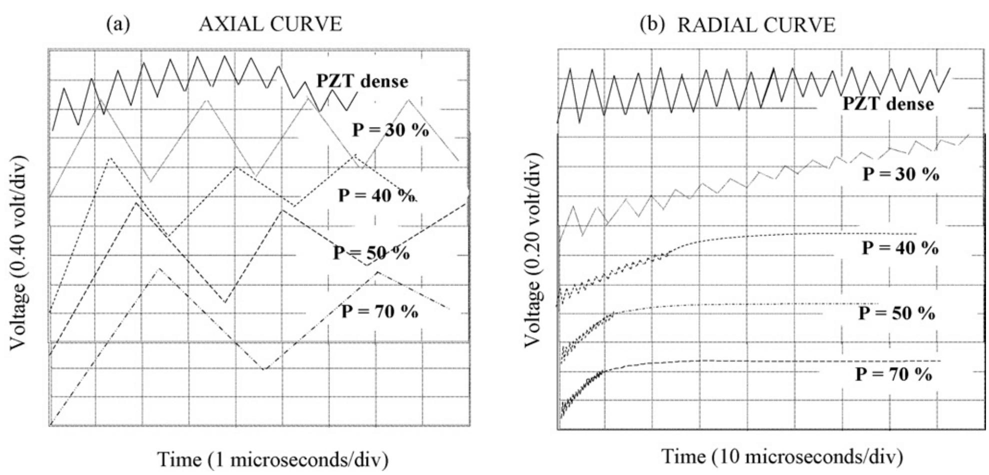

Fig. 3. Voltage produced in porous piezoelectric PZT excited by a current impulse: (a) in axial axis and (b) in radial axis.

Table 1
Electromechanical parameters of porous PZT and dense PZT (thickness $a = 1$ mm).

Parameters		Dense PZT	Porous PZT			
Density	d (g cm^{-3})	7.25	5.30	4.40	3.70	2.40
Fraction of PZT	$q = (d/7.4^{a})$	0.98	0.71	0.60	0.50	0.30
Porosity	$p = (1 - q)$ 100 (%)	~2	~30	40	50	70
Ratio of the amplitude of the first radial vibration to the amplitude of the first axial vibration	R	0.66	0.11	0.05	<0.05	≪0.05
Relative permittivity	ε_r	1300	627	490	390	205
Ratio of the axial resonance frequency to the radial resonance frequency	F_a/F_r	~10	16	20	22	35
Piezoelectric voltage coefficient	g_{33} (10^{-3} V m N^{-1})	23	49	61	91	200
Piezoelectric charge coefficient	d_{33} (10^{-12} pC N^{-1})	270	267	264	262	274
Figure of merite	$d_{33} \times g_{33}$ (10^{-12} m^2 N^{-1})	62	131	161	238	548

[a] 7.4 g cm^{-3} is the theoretical density of PZT.

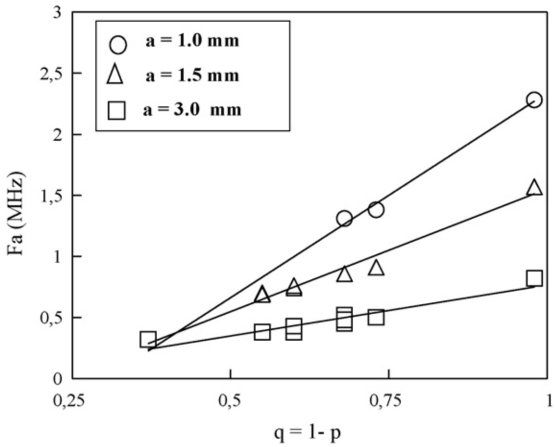

Fig. 4. Axial frequency (Fa) as a function of fraction of PZT (q) at various thicknesses.

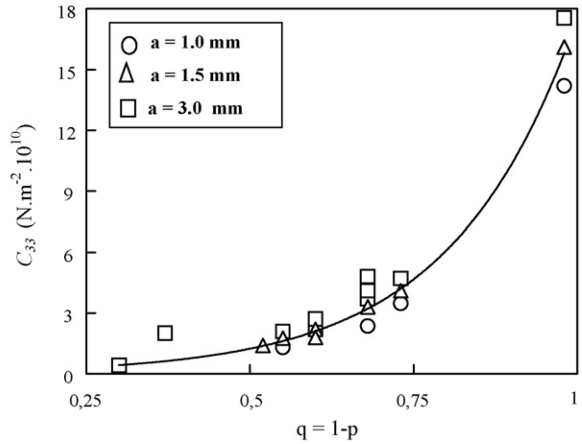

Fig. 7. Elastic constant (C_{33}) as a function of fraction of PZT (q) at various thicknesses.

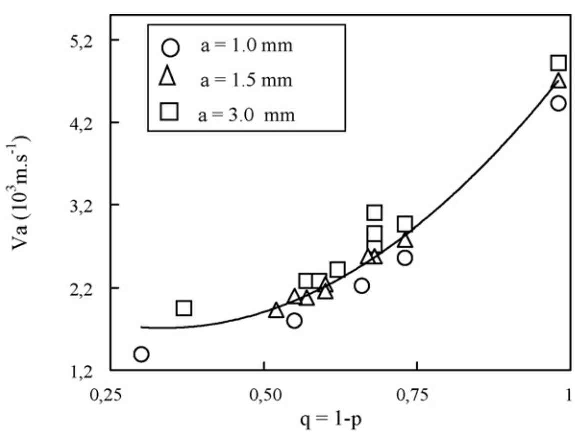

Fig. 5. Axial propagation velocity (Va) as a function of fraction of PZT (q) at various thicknesses.

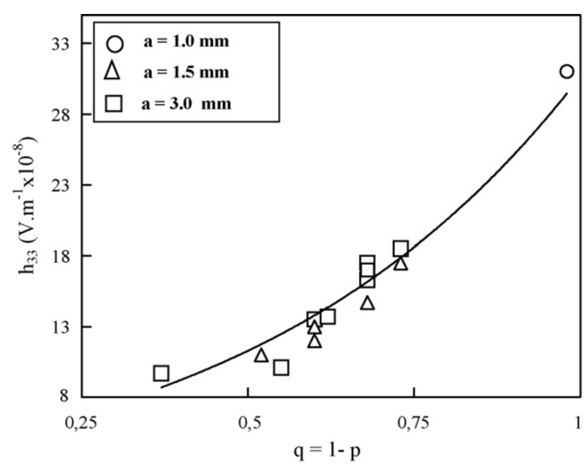

Fig. 8. Piezoelectric stifness constant (h_{33}) as a function of fraction of PZT (q) at various thicknesses.

30 to 40% (Fig. 9). However, porosity strongly reduces the frequency constant Faxa, and a compromise must be found between porous volume and frequency of ultrasonic transducers according to conditions of applications (Fig. 10). In ultrasonic biomedical imaging applications, the transducers vibrate at frequencies ranged from 1 to 30 MHz. So to make sure a frequency is higher than 1 MHz, the porosity should not be higher than 50%.

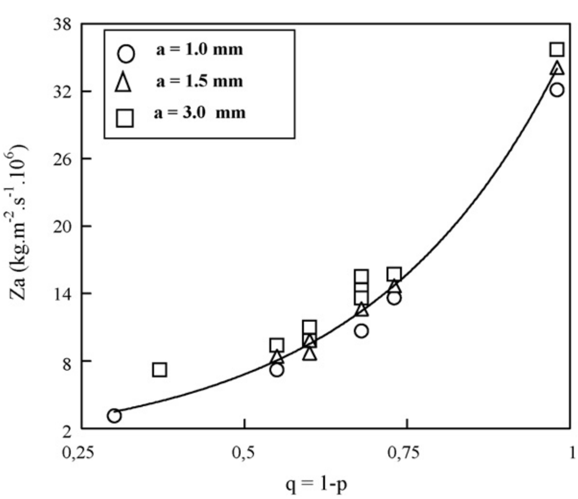

Fig. 6. Axial acoustic impedance (Za) as a function of fraction of PZT (q) at various thicknesses.

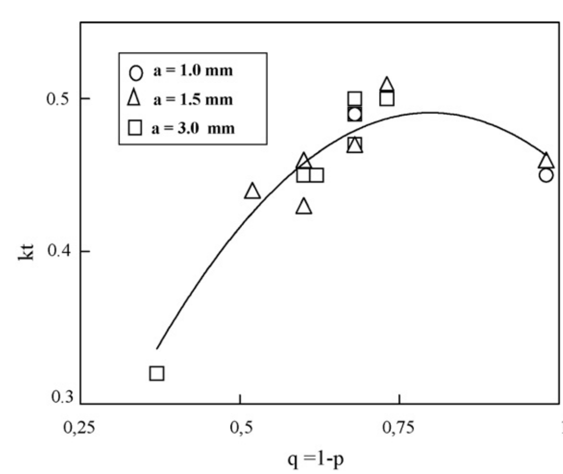

Fig. 9. Axial electromechanical coupling factor (k_t) as a function of fraction of PZT q at various thicknesses.

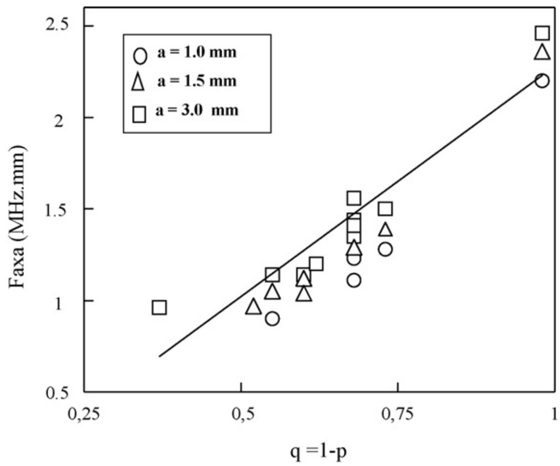

Fig. 10. Axial frequency constant (Faxa) as a function of fraction of PZT (q) at various thicknesses.

One observes that the impulse method is useful to optimize the axial performances of transducers according to porous volume and the thickness of the PZT disc. The radial vibrations generated in a dense PZT thin disc when axially excited, harm the performances of the transducer functioning in a thickness mode (axial vibration), however, the creation of a relative high small volume fraction of porosity (∼30%), considerably reduces radial vibrations, enhanced the figure of merit for pulse echo transducers $d_{33} \times g_{33}$ and reduces the acoustic impedance Z_a, which improves the acoustic coupling with media (water, or biological tissue). The optimal design of transducers such medical imaging can be realized with porous PZT discs having 30–50% of porosity which vibrate at 1 MHz and more with a propagation velocity $V_a > 2000\,\mathrm{m\,s^{-1}}$.

4. Conclusion

Interconnected porous piezoelectric PZT discs excited along their axis have been characterized and investigated by the impulse method over the porosity range of 30–70%. The results show that introduction of porosity in PZT reduces radial vibrations in favour of axial vibrations, and for large porosities (>70%) the discs vibrates exclusively along the axial axis. Porosity improves k_t, g_{33} and $d_{33} \times g_{33}$, reduces Z_a to values of better acoustic coupling with biological tissue or with water. The porosity, however, reduces the velocity and the frequency. A compromise must be found between porous volume, thickness, and frequency of PZT discs, depending upon the applications sought. For biomedical ultrasonic active transducers, we found that optimal axial performances are found in an interval of porosity from 30 to 50%.

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