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Soft type PZT material used to fabricate a high intensity air siren

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A high quality soft type PZT material was designed and produced in order to be used as sensor for a high intensity air siren. Two thin disks from this material were assembled into a parallel bimorph type sensor with an intermediate metallic plate for the siren. This assembly behaves like an acoustic resonator in the high frequency audio range. This structure transforms the radial mode of vibration into a flexural one, with a much lower frequency. A mechanical impedance adapter was used in order to assure a good match between the oscillating ceramic and the surrounding air. A theoretical approach was outlined, which allows the evaluation of the resonance frequency for the working transducer. The theoretical and experimental data agree to a satisfactory degree up to the input errors assumed by the model. Acoustical and impedance measurements were made in order to appreciate the influence of the metallic plate on the frequency. The bimorph necessary for making the siren was designed as a parallel structure and the corresponding transducer was measured and evaluated. In order to increase the acoustic emission a frontal cardboard horn was added to the resonator.

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1. Introduction

The increasing demand for high performance and sophisticated piezoelectric devices and transducers requires high quality piezoceramic materials and innovation in transducer design continues to be the driving force for the development of new piezoelectric materials. Piezoelectric ceramics based on PZT type material are currently the choice, since they offer high piezoelectric activity and electromechanic coupling as well as a large range of high strains, dielectric constants and low dielectric loss. Traditional applications of piezoelectric ceramics include buzzers, speakers, sonars, ultrasonic transducers for nondestructive testing, sophisticated transducers for medical diagnostics and therapy, actuators for precise positioning systems, ultrasonic motors, vibration control and so forth [1-9]. The large area of application of piezoelectric materials is based on the fundamental property of such materials to develop an electric charge when subjected to a mechanical stress and vice versa, that is to say the direct and converse piezoelectric effects, respectively [10]. A simple and direct measure of the strength of these effects is the electromechanical coupling factor k which measures the fraction of electrical energy converted into mechanical energy or vice versa, when the material is stressed. This factor is obviously less than 1 and typically for PZT ceramics it ranges between 0.5-0.7. The choice of a particular piezoelectric material depends on the specific application to which the transducer is destined, but a material with a high k factor is always desirable [11-13]. Therefore, for the present application we developed a new soft type piezoceramic material with a high electromechanical coupling factor k_p and a high displacement constant d_{33} as well. This material is doped with Sr, Nb, Ni and Fe.

2. Experimental

Donor dopants were used for the new PZT material since they proved to increase the piezoelectric constants such as k_p, d_{33}, and ε_r. This is due to the excess positive charge which is compensated by lead vacancies and take place by electron exchange between oxygen and lead vacancies owing the presence of the defects in every doped PZT material [14].

The composition we have chosen has the following chemical formula $Pb_{0.85}Sr_{0.15}Nb_{0.05}Ni_{0.04}Fe_{0.04}Zr_{0.47}Ti_{0.40}O_3$. Such a composition is situated within the morphotropic phase boundary as indicated earlier in literature (see for example [15, 16]). Strontium was added in order to increase the polarisability and the dielectric constant, while Ni and Fe to increase the displacement charge constant d_{33} [17]. The raw materials used for the preparation were oxides of p. a. purity (over 99.5 %) and processing technique was the conventional mixing oxide route, followed by solid state reaction at high temperature. The stoichiometric amounts of oxides were wet mixed (in methanol) for 4 hours by means of a planetary ball mill, Retsch 400PM, using agate jars and balls at a weight ratio ball/oxides of 2/1. The mixed slurry was dried, with continuous agitation, on electrically heated plates, manually crushed in a mortar, sieved and then double calcined in alumina crucibles at 850 and 900 ^oC for 3 hours. The calcined powder was now finally milled in the same mill for 6 hours, dried and prepared for pressing, by slightly wetting it with distilled water sprayed on to the powder and gently manually mixed. Cylindrical shaped samples of different diameters and about 1.5 mm height were then uniaxially pressed using steel dies and pressures of about 50-60 MPa. The pressed samples were sintered in sealed alumina crucibles at 1250 ^oC for 6 hours and then slices of different thicknesses were cut and mechanically processed by abrasion to the desired dimensions. Electroless nickel contacts were deposed on the sample surfaces and then they were poled in a silicon oil bath at 220 ^oC under an electric field of 30 kV/cm.

3. Results and discussion

3.1. The material

The material was characterized by the impedance spectroscopy method using an Agilent 4294A Impedance Analyzer. The main parameters of the materials were determined and the results are shown in the Table 1.

Table 1. The main parameters of the soft material.

Parameter	Unit	Value
Density ρ	g/cm^3	7.86
Dielectric constant ε_r		4330
Dielectric losses $tg\delta$		0.015
Planar coupling factor k_p		0.68
Charge constant d_{33}	pm/V	640
Charge constant d_{31}	pm/V	-130
Voltage constant g_{33}	10^{-3}Vm/N	25.8
Voltage constant g_{31}	10^{-3}Vm/N	-11.4
Mechan. quality factor Q_m		75
Curie temperature T_C	^oC	289

As can be seen, the material shows very good characteristics for a soft type high quality material, recommended to be used as sensors for high performance transducers.

The application we have made in the present investigation was a high intensity air siren working within the audio frequency range.

3.2. The siren

The practical advantages of using PZT ceramics as bimorph sensors for high intensity sirens are numerous:

a. smallness: the driving part of such a siren is as large as a thumbnail and its mass does not exceed several grams.

b. toughness: the ceramic resists to mechanical shocks, chemical corrosion, and temperatures up to 200 ^oC.

c. efficiency: due to its high converting rate a high acoustical output is obtained with a low *emf* and a low current.

d. easiness in manipulation: the transducer can be comfortably fixed using a rubber o-ring fixed on the edge of its horn.

The small width of the frequency band make this kind of transducers suitable for working as sirens with a limited frequency sweep. A good characterization of such a transducer is achieved by using both electrical impedance measurements as well as acoustic ones.

3.2.1. The bimorph sensor

Two PZT disks, having 20 mm diameter and 0.15 mm thickness, have been glued on the two sides of a brass disk of 21 mm diameter and 0.1 mm thickness, using a conductive epoxy resin and having the poling directions parallel. The free sides of the PZT disks were electrically connected as shown in figure 1. This induces an opposite radial movement when an *emf* is applied between the free sides and the metallic disk.

Fig. 1 The parallel bimorph. The arrows indicate the polarization directions of the discs.

When an alternative *emf* at a resonance frequency is applied, a stationary movement is generated. In order to increase the acoustic emission of the resonator in free space (air) an impedance matching between the high impedance ceramic and the low impedance air is necessary [18-20]. This was achieved by using a rigid thin conical cardboard horn fixed in a ventral point of the bimorph i.e. in its center as illustrated in figure 2.

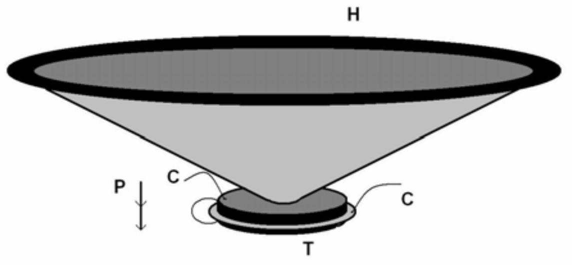

Fig. 2 The siren assembles: C-the electrical connectors, T- the bimorph and metallic plate, P- the parallel polarization vectors and H the acoustic horn.

This horn assures an easy fixing of the device with small losses, using a rubber o-ring washer and improves the forward directionality of the sonic energy, thus contributing to the forward direction of the acoustical waves. Its small weight perturbs, but a little the functioning of the resonator and at the working frequency it is suited as a propagating medium. It also attenuates a little the acoustic wave driven by the oscillating ceramic and minimizes the attenuation of the bimorph due to the inertia. In order to evaluate the frequency of the oscillating transducer at resonance parallel with the flexural movement of the vibrating plates is necessary. In a satisfactory approximation the bimorph can be assimilated to a thin circular plate, whose dimensions satisfy the condition:

$$h << a \tag{1}$$

If the metal plate surpasses but a little the edge of the ceramic, it can be neglected in a first approximation. The cardboard horn can also be considered to affect but a little the movement of the bimorph.

Following these steps, the transducer can be regarded as displaying essentially the behaviour of a thin circular plate in its flexural oscillation state with the edge free border condition. This border condition is attained because of the central fixing of the bimorph on the horn.

The shape of a free edge circular thin plate in its flexural oscillation is described by a superposition of Bessel functions. When only the fundamental is present the number of the necessary functions reduces to 2.

In order to calculate the frequency of this mode in its fundamental state one can appeal to the simple movement of a thin clamped plate oscillating in its fundamental flexural mode. The reason is simple: when a system undergoes a given stationary oscillating movements it can be regarded as being composed from parts separated by nodes (or nodal lines, surfaces etc). If we imagine detaching any of these parts and keeping its edges clamped so that the former nodal conditions on its edges is preserved, this part, when put in oscillation, will display the same behaviour as in its initial state, when being part of the system. It may be compared for example with a guitar string when playing flageolets. Creating a node on some point of the string by touching it with the tip of the finger produces the same pitch of the sound as playing the string at a length equal to the smallest of the two segments in which the finger parts it. The fundamental of the flexural mode for a free edge thin plate has one nodal circle dividing it into a disc and a circular crown as shown in Fig. 3.

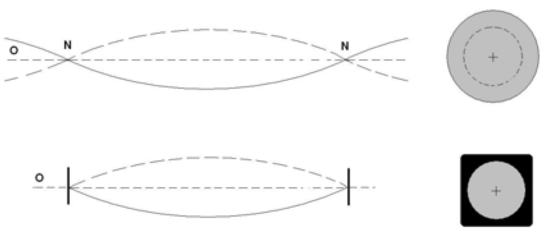

Fig. 3 The common border conditions for the fundamental flexural mode: free edge (above) and clamped (bellow) - N are two symmetrical points on the nodal circle drawn on the right of figure. The blacken square represents the fixing frame for the clamped disk.

The diameter of the nodal circle is known and, applying the former reasoning, the frequency of the free edge disk must be the same with the frequency of the clamped disc which has the same diameter as the nodal circle of the free edge plate. The advantage of this is that it reduces more complicated situations to simpler ones. In the present case, the formula for the flexural fundamental of the clamped thin plate is:

$$f = \frac{3.2^2 \sqrt{qh}}{2\pi \cdot a^2 \sqrt{3\rho(1-\mu^2)}} \tag{2}$$

where q is the elastic modulus and equals 8.2 10^{10} N/m^2, h is the thickness of the plate, a is its diameter, ρ is the mass density and equals 7.5 g/m^3 and μ the Poisson coefficient taken as being 1/3.

3.2. Measurements and calculations

In order to evaluate the behaviour of the siren its electrical impedance and phase spectra has been measured by means of an *Agilent 4294A Impedance Analyzer*. The obtained spectra for the fundamental flexural mode are given in figure 4. Both the impedance and the phase spectra a given, (continuous curves) together with the ideal curves given by the typical equivalent circuit corresponding to a piezoelectric resonator (the dashed curves). The chosen frequency range corresponds to the fundamental of the flexural mode, i.e. when the disk oscillates freely around a nodal circle, situated at a distance of $0.678 \cdot a$ from the centre, a being the radius of the disk [21]. The irregularities present on the curves are probably due to the proximity of other secondary modes and to the alteration of the pure plate oscillation by the metallic plate [18, 22]. The working point of the transducer is readily found as corresponding to the resonance point on the module of impedance at its minimum.

From the impedance spectra it is apparent that the best resonance is obtained at 7.74 kHz.

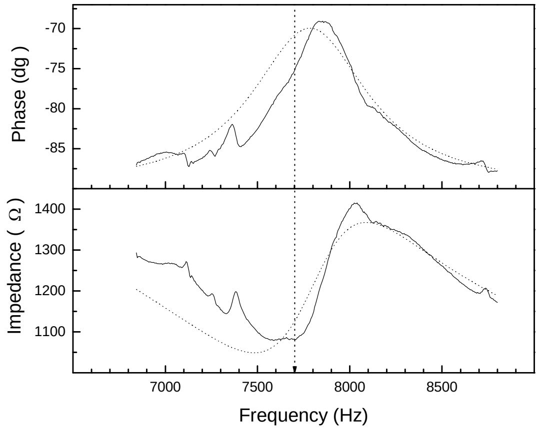

Fig. 4 The impedance and phase spectra for the syren (continuous line), and the ideal spectra coresponding to the well known equivalent circuit of a piezoelectric rezonator (dashed line). These spectra refer to the discussed parallel bimorph transducer. The arrow indicates the working point at full resonance.

This result can be compared with the acoustic spectrum of the siren shown in Fig. 5 where the maximum value occurs at 7.74 kHz. The spectrum appearance is not symmetric indicating a higher output at high frequencies induced by the proximity of other higher modes. The acoustic spectrum was determined using a *Bruel-Kjaer 2024 Sound Level Meter*.

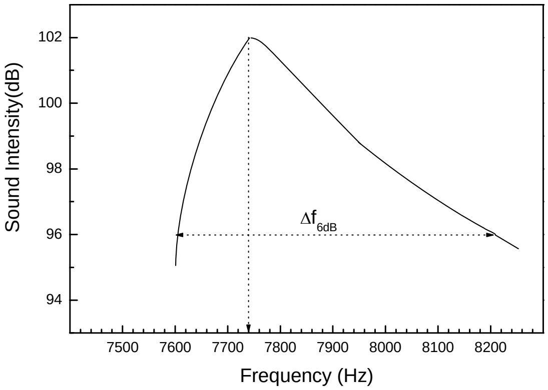

Fig. 5 The acoustic spectrum of the siren at 10 cm in front of it on the axial line. The downwards arrow marks the resonance, while the horizontal one measures the bandwidth at 6 dB (~600 Hz)

From the acoustical spectra shown in Fig. 5 the bandwidth and the relative bandwidth at 6 dB have been calculated. This is related to the mechanical Q factor by the following relation [23]:

$$\text{relative bandwidth} = \frac{(\Delta f)_{6dB}}{f_{rez}} = \frac{1}{Q_m} \qquad (3)$$

From (2), the relative bandwidth at 6 dB is 0.078, which gives a mechanical quality factor Q_m of 13. This means that the excited system set free will still execute essentially 13 oscillations until it will regain its state of rest. The acoustical output of the siren has been measured, giving a level of 130 dB at 10 cm on the axial line in front of the siren, with a driving emf of 10 V_{ef} at full resonance.

The experimental values obtained for the working point of the transducer are compared with the theoretical curve depicting the frequency of oscillation of a clamped thin plate in its fundamental flexural mode (fig. 6) the radius of the plate being reduced to the nodal circle diameter of a free edge plate as discussed above.

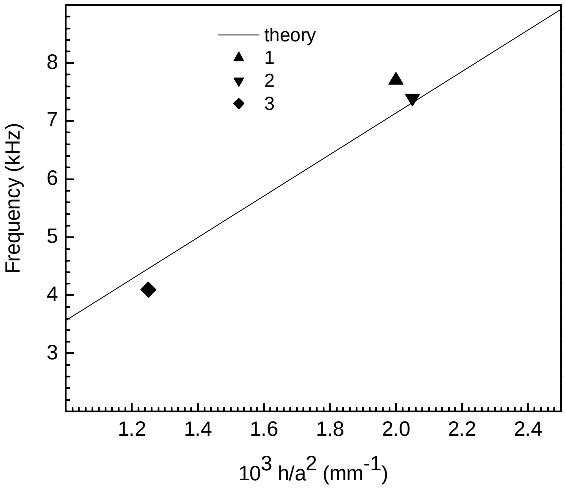

Fig. 6. A comparison between the theoretical curve (continuous) and the experimental values for the working frequencies of the transducers (see figs 4 & 5 and formula 2).

From this graphic it is apparent the good fitting for the parallel bimorphs. The metal plate is supposed to "soft" the elasticity modulus and to increase the radius of the plate, thus decreasing the value of the frequency. The high acoustical value corresponding to full resonance indicates a good quality transducer.

4. Conclusion

A high quality acoustic siren has been fabricated from parallel PZT bimorphs. A good acoustic impedance matching was realized through adapting the oscillating ceramic with the surrounding air by mean of a cardboard horn. A theoretical observation regarding the equivalence of frequency for an edge free plate and a clamped plate with a reduced diameter has allowed a simple computing of the resonance for the fundamental flexural mode. This useful artifice can be further employed in any situation in which frequencies and shapes for clamped oscillators is simpler to be evaluated than those for free edge with the same type of oscillators.

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