Comparison of several methods to characterise the high frequency behaviour of piezoelectric ceramics for transducer applications

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Abstract

Thickness mode resonances in commercial piezoelectric ceramics have been characterised as a function of frequency by two methods. The first is based on a fit on the electrical impedance for the fundamental and the overtones. This method has been applied to a large number of PZT ceramic samples and frequency dependence for all the parameters is investigated, in particular for the piezoelectric coefficient $e_{33}$. The second is based on the measurement of the mechanical displacement at the centre of the surface of a PZT ceramic disk. With a modified KLM scheme, this displacement is modelled. The dielectric, elastic and piezoelectric parameters are extracted and compared for the fundamental and the third overtone. The results are found to be in good agreement. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

To this day, a majority of the applications of piezoelectricity (i.e. sensors, transducers and actuators) make use of poled ferroelectric ceramics, the most common composition being a mix of oxides of lead, zirconium and titanium (PZT) with very small quantities of additives. PZTs have relatively high electromechanical coupling coefficient and their cost and ease of manufacture in bulk pieces are more favourable than for many other piezoelectric materials. High frequency transducers, over 20 MHz, now have many applications, in particular in the medical imaging field (ophthalmology, dermatology, or intra-vascular examinations) and the use of piezoelectric ceramics often implies machining of disks or plates to obtain thicknesses between 10 and 100 μm. This operation is delicate and only fine-grained and low porosity materials can be used. The characterisation of the low frequency fundamental resonance of a bulk ceramic (typically 1 MHz for a thickness around 2 mm) does not allow the behaviour of the same ceramic above 10 MHz to be deduced. Indeed, the characterisation of the electromechanical properties at high frequency is necessary since the performances change as a function of the frequency (in particular the coupling coefficient in thickness mode decreases) [1]. The goal of this paper is to compare two characterisation methods to predict and verify the high frequency behaviour of two commercial bulk PZT materials. This study has been performed on a large number of samples with different resonant frequencies and dimensions.

In the next section, the modelling by two methods, one based on the modified IEEE Standard [2] and the other on the KLM scheme, are briefly described. The first characterisation method is based on the measurement of the electrical impedance, as a function of frequency, of a free resonator in thickness extensional mode on the fundamental and the overtones. The second method uses the measurements of the ceramic surface displacement by laser interferometry for different frequencies corresponding to the fundamental and the third overtone.

2. Characterisation methods

2.1. Method based on the electrical impedance measurement

The electrical admittance of a thickness mode of a piezoelectric resonator is given by [2]:

$$Y(\omega) = \left(\frac{\text{tan}(\omega t/2\omega_0^2)}{\omega t/2\omega_0^2}\right)^{-1}, \quad (1)$$

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where \( \omega \) is the angular frequency (rad s\(^{-1}\)), \( \varepsilon_{33r} \) the relative dielectric constant at constant strain, \( \varepsilon_0 \) the dielectric constant of vacuum (F m\(^{-1}\)), \( a \) the electrode area, \( t \) the thickness, \( k_i = \varepsilon_{33r}/\varepsilon_{33} \) the electro-mechanical coupling factor in thickness mode, \( c_l = \sqrt{\varepsilon_0/\rho} \) the longitudinal wave velocity (m s\(^{-1}\)), \( \rho \) the density (kg m\(^{-3}\)), \( C_{33} \) the elastic stiffness coefficient at constant electrical displacement (N m\(^{-2}\)) and \( \varepsilon_{33} \) piezoelectric coefficient (pC m\(^{-1}\)).

Moreover, in piezoelectric materials, two kinds of losses can be distinguished: mechanical and dielectric. The introduction of the mechanical losses (\( \delta_{m} \)) gives a complex elastic constant (\( C_{33}^2 \)) while a complex dielectric constant (\( \varepsilon_{33}^2 \)) is used because of the dielectric losses (\( \delta_{d} \)).

\[
C_{33}^2 = C_{33}^2(1 + i\delta_{m}),
\]

\[
\varepsilon_{33}^2 = \varepsilon_{33}^2(1 - i\delta_{d}).
\]

Thus, with the introduction of \( C_{33}^2 \) and \( \varepsilon_{33}^2 \), a complex coupling coefficient (\( k_i^2 \)) and a complex velocity (\( v_{i}^m \)) can be defined:

\[
k_i^2 = \frac{k_i^2}{(1 + 6\delta_m/\varepsilon_{33}^2)},
\]

\[
v_i^m = v_i\sqrt{1 + \frac{6\varepsilon_{33}^2}{\varepsilon_{33}^2}}.
\]

where \( \delta = (1 - k_i^2)\delta_m + k_i^2\delta_{d} \) represents the total loss factor [3].

Considering all the dimensions and the density of the sample, the different parameters are determined by a fit of the electrical impedance around the resonance. All these parameters are assumed to be constant in the range of the fit. This approximation is valid for piezoelectric materials such as PZT ceramics, with small variations of properties versus frequency. This assumption could not be applied to all other piezoelectric materials, in particular to copolymers or 0-3 composites, for which dielectric relaxation must be taken into account [4,5]. For our study, this method is applied to the fundamental resonance as well as to the overtones. Fig. 1 shows a fit of the electrical impedance around the third overtone with fits and experimental curves up to the 13th overtone. Between the fit on the third overtone and the experiments, a disagreement is found for higher overtones: fits are necessary at each overtone to obtain precise values of the parameters at the frequency considered. Using these fits, the behavior of all the parameters can be extracted as a function of frequency.

### 2.2. Method based on the surface displacement measurement

In order to calculate the displacement on the surface of a free resonator vibrating in thickness extensional mode, a modified KLM [6] equivalent circuit has been used. The dielectric and mechanical losses have been introduced (as explained in Section 2.1) and thus complex coefficients are used. With the transfer matrix formalism [7], we are able to calculate the displacement velocity at the surface of the piezoelectric element when a unit electrical voltage is applied between the electrodes. Then, the displacement per volt is easily deduced by integrating the displacement velocity.

### 3. Results and discussion

Two types of PZT ceramic have been used for this study. A first batch of commercial Ferroperm Pz27 [8] contains 14 different disks. Fundamental resonance frequencies are between 1.1 and 8.1 MHz. The number of resonance measurements on fundamental frequencies and on their overtones represents a total of 44 points. The second batch consists of commercial Ferroperm Pz29 ceramics (6 different disks with 1.1 ≤ \( f_i \) ≤ 8.1 MHz. 26 measurements are extracted on the fundamental resonances and the overtones). For all these samples, the ratio between the lateral dimensions and thickness is between 20 and 40. In this case, the thickness mode clearly dominates the lateral mode.

An HP4195A impedance analyser was used for the measurements. The experimental set-up is composed of this analyser with its impedance test kit and a spring-clip fixture which applies very little mechanical loading in such a way that the sample is under free piezoelectric resonator conditions.

From the experimental points obtained, the frequency dependence of the thickness mode coupling factor is calculated and is shown in Fig. 2. The variation observed
for Pz29 ($-2.1 \times 10^{-3} \text{ MHz}^{-1}$ with a linear regression) is lower than that of Pz27 ($-4.8 \times 10^{-3} \text{ MHz}^{-1}$). These results are of the same order of magnitude as those obtained by Forster et al. [1] and Zipparo et al. [9] (around $-1 \times 10^{-3} \text{ MHz}^{-1}$).

The measured elastic stiffnesses ($C_{33}$) and dielectric constants ($\varepsilon_{33}$) are respectively represented in Figs. 3 and 4. Their frequency dependence is very low. The small variations observed are probably due to slight inhomogeneities of geometric characteristics, whose effects increase with frequency. The variation of the piezoelectric coefficients ($e_{33}$) with frequency is relatively large (Fig. 5). Comparison between the dielectric, elastic and piezoelectric constants shows that it is the piezoelectric coefficient which is mainly responsible of the decrease in the electromechanical coefficient ($k_t$).

Finally, mechanical and dielectric losses are represented as a function of frequency in Figs. 6 and 7. The dielectric losses are relatively similar for both compositions and increase slightly with frequency (the slope is around $10^{-3} \text{ MHz}^{-1}$). The frequency dependence of the mechanical losses for the two PZTs can also be considered as nearly linear. This variation is around $7 \times 10^{-4} \text{ MHz}^{-1}$ for Pz27 and $7 \times 10^{-6} \text{ MHz}^{-1}$ for Pz29.

The results obtained ($\kappa_t$ and $\Delta_m$) for the two ceramics seem to be consistent. The variations of $\kappa_t$ and $\Delta_m$ for
Pz29 are lower than those of Pz27. According to previous studies [1,9,10], two main factors could explain these differences. The first is the porosity which could be higher in the Pz27 samples and the second is the average grain size which could be slightly different for the two materials. A complete study of the microstructure is necessary to confirm these assumptions.

Surface displacement at the centre of a Pz27 ceramic disk has been measured using a commercially available interferometer (SH 140 from B.M. Industries, France). This optical probe described in Ref. [11], is a compact Mach Zehnder heterodyne interferometer, equipped with a 100 mV diode-pumped and doubled frequency YAG laser. The resolution varies from $10^{-5}$ Å Hz$^{-1/2}$ on a mirror-like surface to $3 \times 10^{-4}$ Å Hz$^{-1/2}$ on a black diffusing surface. Absolute measurements of the mechanical displacement can be obtained with an uncertainty of 5–10% in a frequency range from 40 kHz to 40 MHz.

With the HP4195A analyser in transmission mode and a high impedance probe, the surface displacement per volt is measured. The fundamental and the third overtone anti-resonance frequencies are respectively 4.78 and 14.34 MHz. In Fig. 8, surface displacement per volt is shown in a frequency range from 0.2 to 20 MHz. On this curve are observed:

1. radial modes at low frequencies;
2. fundamental resonance of the thickness extensional mode;
3. first overtone anti-resonance.

Fig. 12. Experimental (thin full curve) and theoretical (thick full curve) displacements of a Pz27 disk as a function of frequency for the third overtone.
Table 1
Electromechanical properties of a Pz27 ceramic (A, electrode area; ρ, density; v_l, longitudinal velocity; f_a, antiresonance frequency; k_t, thickness mode coupling factor; ε^33/ε_0, relative dielectric constant at constant strain; δ_e, dielectric losses; δ_m, mechanical losses)

<table>
<thead>
<tr>
<th></th>
<th>A (mm^2)</th>
<th>ρ (kg m^-3)</th>
<th>v_l (m s^-1)</th>
<th>f_a (MHz)</th>
<th>k_t (%)</th>
<th>ε^33/ε_0</th>
<th>δ_e (%)</th>
<th>δ_m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental resonance</td>
<td>460</td>
<td>7720</td>
<td>4445</td>
<td>4.78</td>
<td>46</td>
<td>790</td>
<td>0.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Third overtone</td>
<td>460</td>
<td>7720</td>
<td>4465</td>
<td>3.43</td>
<td>810</td>
<td>1.3</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

3. peaks due to interactions between high frequency radial overtones and thickness mode [12];
4. resonance due to the electrical connection (typically an inductor component);
5. third overtone resonance of the thickness extensional mode.

In Fig. 9, the experimental and fitted electrical impedance locus are represented. Table 1 gives the values extracted for the fundamental and third overtone resonances. These values are used to simulate the surface displacement per volt. Figs. 10 and 11 show the good agreement between theoretical and experimental curves. These results demonstrate that the parameters deduced from the electrical impedance fit allow the electromechanical performance of piezoelectric materials to be correctly predicted.

4. Conclusion
A large number of samples of two commercial PZT ceramics (Pz27 and Pz29) have been characterised. The electrical behaviour of these ceramics as a function of frequency has been studied using a fit of the complex electrical impedance for the fundamental resonance and the overtones. The piezoelectric coefficient (ε^33) appears to be mainly responsible for the decrease of the electro-mechanical coupling factor in thickness mode. A laser interferometer has also been used to measure the mechanical displacement at the surface of the ceramic as a function of frequency. This experimental curve has been modelled with a modified KLM scheme, using all the parameters extracted from the electrical impedance of the same sample. The experimental and theoretical results obtained for the fundamental and third overtone are close.

The comparisons of these different results show that the high frequency thickness extensional mode behaviour of a piezoelectric ceramic can be deduced from measurements on the overtones of a relatively thick (i.e. low resonance frequency) sample.

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References