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Tonpilz Underwater Acoustic Transducer Integrating Lead-Free Piezoelectric Material

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Abstract

A Tonpilz transducer based on lead-free piezoelectric material was fabricated, modeled and characterized. The stack is composed of two rings of doped $BaTiO_3$. This composition was initially chosen due to good electromechanical performance (k_t at 40%) and high mechanical quality factor (Q_m over 500). Comparison of the displacement at the center of the head mass was performed with a PZT-based Tonpilz with the same design for a center frequency at 22 kHz.

Keywords: Tonpilz transducer; Piezoelectricity; Lead-free material; FEM modelling

1. Introduction

The Tonpilz transducer is one of the most popular types of sonar transducer, and its low cost, simplicity and good performance are well known. This considered longitudinal vibrator is typically composed of piezoelectric rings

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stack surrounded by head and tail masses [1]. For decades, piezoelectric PZT ceramics, and its derived compositions have dominated the market due to their high piezoelectric properties and efficient production processes. Currently, these materials are integrated in a wide range of devices and, in particular, in underwater sonar systems. This increasing success of these materials is associated with health and environmental problems due to presence of lead. Today, many countries and worldwide organizations are restricting or including in their legislation hazardous substances to be substituted by safer alternatives [2]. Among the most researched lead-free compositions perovskite barium titanate is a good candidate. In this study, a lead-free Tonpilz transducer was fabricated integrating $BaTiO_3$:Co rings to evaluate and to compare corresponding performances with those of lead-based Tonpilz with the same configuration. $BaTiO_3$:Co composition was originally chosen due to their good electromechanical performance with a thickness coupling factor k_t around 40% and high Q factor over 500. First of all, in the next section, a specific characterisation method was used and directly applied to a ring to deduce in *operating condition*s the electromechanical performance. This method involves a genetic algorithm (for optimization process) and finite element method (FEM), with the help of ATILA [3], to calculate the electrical impedance. In section 3, Tonpilz fabrication and modelling are briefly described. Finally, comparison between simulated and experimental displacements at the center of the head mass, in air, is performed for Tonpilz integrating lead-based and lead-free compositions.

2. Piezoelectric rings characterization

2.1. Geometrical characteristics

The choice of the number of rings used in the stack is made in agreement with the final desired characteristics of the Tonpilz. In our case, the main goal is to compare properties between two Tonpilz integrating lead-free and lead-based piezoelectric materials and the number of two rings is retained for this study. The dimensions of the ring are given in Fig. 1.a and the measured density is 5656 kg/m^3. In a first step, reproducibility of the properties of the two rings was verified comparing their electrical impedance as a function of frequency (Fig.1.b). The three main observed modes are numbered on the Fig.2.b. Resonance and antiresonance frequencies are almost the same for the two rings.
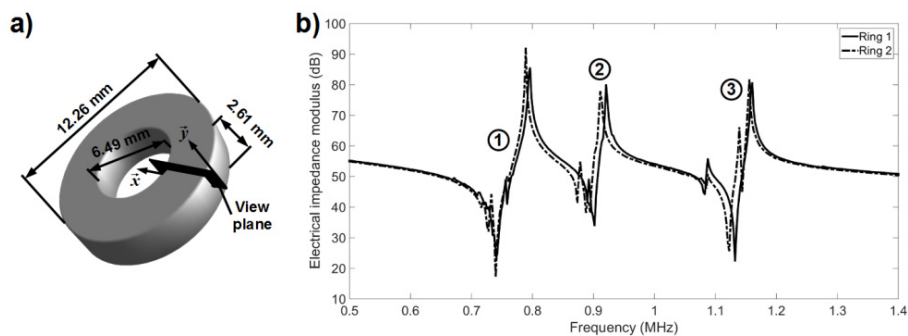

Fig. 1. (a) Geometrical dimensions of rings (b) electrical impedances of the two $BaTiO_3$:Co rings used for the Tonpilz fabrication.

In the measured frequency range and according to commercial data given in Table 1, the resonance frequency of the pure thickness mode (if the ring is considered as a disk with the same thickness) should be at around 1 MHz. Around this frequency, the three modes observed are slightly coupled. Thus, equivalent electrical circuit scheme such as KLM [4] cannot be used for electromechanical characterization and FEM is preferred.

The deformed structures for the three modes in a given radial observation plane (specified in Fig. 1.a) are represented in Fig. 2. Calculations were performed in 2D with axisymmetric and symmetric conditions on the half thickness of the ring. These results confirmed that these modes are not pure thickness and radial modes even if mode 1 delivers a behavior close to a standard radial mode.
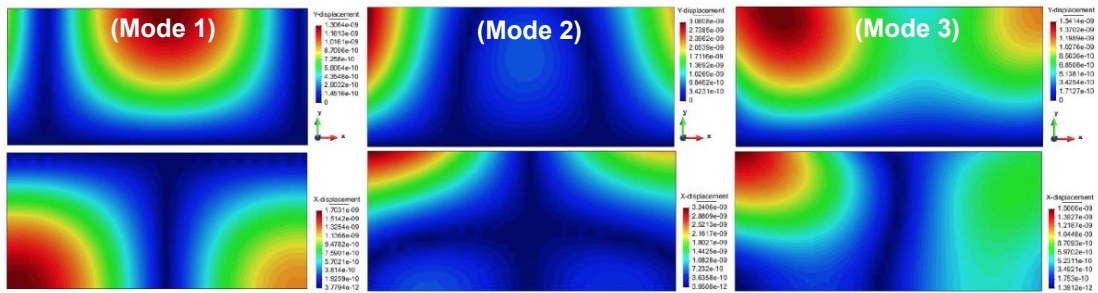
Fig. 2. Displacement fields (highest displacement in red and lowest displacement in blue) in a radial plane (y-direction for the thickness of the ring and x for the radial direction of the representative ring) for the three modes.

2.2. Functional characterization

Specific optimization algorithm was developed to deduce dielectric, elastic and piezoelectric parameters of the considered piezoelectric material. This algorithm used two main tools. A numerical calculation is performed using finite element ATILA software. In this case, the behavior of the electrical impedance as a function of frequency for complex shape structures such as our rings is obtained. This theoretical result is compared to the experimental data thanks to an objective function that has to be minimized. This function is composed of an addition of several values with specific weights such as the differences of frequency for maximum and minimum impedance values for each mode and the difference of capacitance (deduced from the imaginary part of the impedance) for several frequencies. To converge toward the solution (i.e. corresponding to the minimum value of this objective function), a genetic algorithm is used. This algorithm allows using a wide number of parameters to be determined and, above all, keeping a complete independence from an initial situation that is, normally, impossible using gradient methods. This fitting process is a recursive method where, at each set of determined parameters, several essential conditions are verified to ensure that the corresponding intermediate solution is coherent (for example, the coupling coefficients must be between 0 and 1 and verifications related to the thermodynamic stability conditions are verified). If one of these conditions is not verified, the corresponding solution is not acceptable and not kept in the optimization process. All this procedure is detailed in [5].

For one mode, a set of three parameters (one elastic, one dielectric and one piezoelectric) is mainly involved. For example, the thickness mode can be characterized with c_{33}^D, e_{33} and ε_{33}^S. If additional modes (slightly coupled) are defined in the structure, the corresponding number of parameters to be determined increases. Thus, in our present procedure, a large number of parameters can be deduced using only one sample, on contrary to the standard IEEE method [6] where several samples are required to favor only one vibration mode and corresponding parameters. Moreover, our procedure allows a full characterization in *operating conditions*. In our case, the ring used for the functional characterization is also the one which will be directly integrated in the Tonpilz. For the characterization of the BaTiO$_3$:Co rings, a preliminary study delivered the most sensitive parameters: c_{11}^E, c_{12}^E, c_{13}^E, c_{33}^E, c_{44}^E, e_{31}, e_{33} and ε_{33}^S. A commercial BT database [7] was initially used (given in Table 1) for the first calculation of electrical impedance and delivers a correct approximation.

This characterization was performed with ring 1. After the fitting process, adjusted electrical impedance curve is very close to the experimental data (Fig. 3). Only small differences are observed on the first mode probably due to small errors in the evaluation of geometrical dimensions (typically the flatness). This difference could be decrease by increasing the calculation time of the process. All the adjusted values with the corresponding differences (with initial data) are summarized in Table 1. According to this database, thickness and planar coupling coefficients are 40% and 31%, respectively.

Table 1: BT databases initially used (commercial [7]) and deduced (adjusted).

Properties	Commercial data	Adjusted data	Differences (%)
C_{11}^E (GPa)	164.9	173.5	5.1
C_{12}^E (GPa)	57.7	83.6	36.7
C_{13}^E (GPa)	61.5	76.1	21.3
C_{33}^E (GPa)	151.5	160.4	5.7
C_{44}^E (GPa)	37.7	42.3	11.5
C_{66}^E (GPa)	53.5	-	-
e_{31} (C/m^2)	-1.9	-2.3	20.2
e_{33} (C/m^2)	11.6	17.9	37.6
e_{15} (C/m^2)	7.7	-	-
$\varepsilon_{11}^S/\varepsilon_0$	1696	-	-
$\varepsilon_{33}^S/\varepsilon_0$	454	1090	56.2

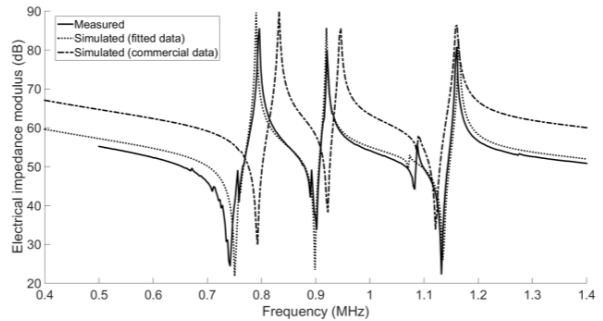

Fig. 3. Comparison of electrical impedances of ring 1 (solid line: experimental, dashed line: commercial data, dot line: adjusted data).

3. Tonpilz fabrication and modeling

The fabricated Tonpilz with the two BaTiO3:Co rings is shown on Fig. 4. For comparison, the second Tonpilz used the lead-based composition Pz26 [7]. The corresponding rings have exactly the same dimensions as those of BT:Co. Head mass and tail mass are in aluminum and brass, respectively. The pre-stress is applied with a metallic rod. For the numerical simulation, all the mechanical properties of elements are taken from [8]. This modeling allowed measuring the displacement values at the center of the head mass in air for a further comparison with experimental value.

4. Results and discussion

On Fig. 5, are represented the normalized displacements (with the applied voltage) at the center of the head mass. A frequency delay is observed between the measured resonance frequency (21.7 kHz) and the two simulations with the commercial data and adjusted data (22.2 kHz). This variation is equivalent to a difference of around 2% and can be explained by possible small differences of the metallic material (head mass and tail mass) database used and also, by mechanical contacts and axial alignment of the rings which are considered as perfect for the simulation. Results show that the maximum experimental displacement is 2.23 10^{-8} m.V^{-1}. With the commercial data, the corresponding value is 1.26 10^{-8} m.V^{-1}. With the adjusted data of the two rings, this difference decreases at 18% (Table 2) and show the benefit of the fit process. However, this remaining variation is mainly due to effect of the pre-stress which can significantly modified the electromechanical performance of the ring and which is not taken into account in our simulation. The results were compared to those obtained with the lead-based Tonpilz (with Pz26). The maximum displacement reaches 7.28 10^{-8} m.V^{-1} for an antiresonance frequency at 20.6 kHz. For the two Tonpilz, antiresonance frequencies are very close and performance comparison is possible. Thus, the measured displacement is 3.3 higher for the PZT-based than the lead-free based Tonpilz. This large difference decreases for theoretical results but a variation remains between experimental and theoretical values which confirms the importance of the pre-stress in the behavior of the device. A pre-stress of 40 MPa was applied for the PZT-based Tonpilz. This value was chosen according to previous published results [9] which optimise piezoelectric properties (such as d_{33}). The pre-stress chosen for the BT:Co tonpilz was lower (at 10 MPa) according to previous work [10] and to avoid breaking the rings. However, in this case, optimum values are not reached and a systematic study should be done to deduce optimal pre-stress value.

Table 2. Normalized displacements at the center of the head mass and corresponding antiresonance frequencies for theoretical and experimental Tonpilz configurations.

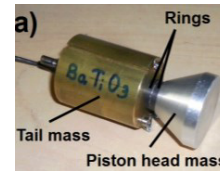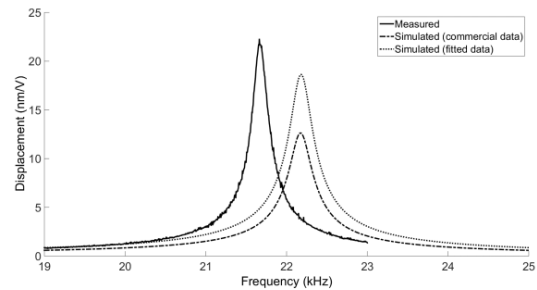| Ring		Displacement (m/V)	f_a (kHz)
BaTiO$_3$:Co	Experimental value	$2.23 \cdot 10^{-8}$	21.7
	Simulation (commercial data)	$1.26 \cdot 10^{-8}$	22.2
	Simulation (adjusted)	$1.87 \cdot 10^{-8}$	22.2
PZT (Pz26)	Experimental value	$7.28 \cdot 10^{-8}$	20.6
	Simulation (commercial data)	$3.72 \cdot 10^{-8}$	20.1

Fig. 4. Picture of the BT:Co Tonpilz.

Fig. 5. Displacements at the center of the head mass of the BT:Co tonpilz (solid line: experimental, dashed line: commercial data, dot line: adjusted data).

5. Conclusion

A lead-free Tonpilz transducer was modelled, fabricated and evaluated integrating two piezoelectric rings of BaTiO$_3$:Co. Previously, a specific characterization method coupling a genetic algorithm for the optimization process and finite element method was used and directly applied to a ring to calculate its electrical impedance. Comparison of performances (maximum displacement at the center of the head mass) between this Tonpilz and another using PZT rings was performed. The center frequency of the transducers is around 22 kHz. According to the following figure of merit (FOM) of the piezoelectric materials for underwater active acoustic applications: $k^2 \times Q_m$ (k: electromechanical coupling factor, Q_m: mechanical quality factor), chosen PZT material (Pz26) delivers the best properties and it is confirmed by simulated and measurements. However, further study must be performed to optimize the applied pre-stress but also the behavior with high drive fields and high duty cycles. Recently, new lead-free compositions such as KNNTL:Mn single crystal delivers ultrahigh electromechanical coupling factor [11] could definitely compete lead-based compositions such as PIN-PMN-PT single crystals.

Acknowledgements

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