White Paper – Practical guide to characterization of piezoceramic components and materials using Bode100 impedance analyzer

Study025 Report01

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Revision History

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Contents

1 Purpose of the study

To describe a practical approach towards characterization of piezoceramic components and materials using Bode 100 impedance analyzer by Omicron Lab.

2 Introduction

2.1 Why?

Device and systems comprising piezoelectric components are ubiquitous. One can find them in aerospace and automotive systems (e.g. vibration monitoring, diesel engine injection valves), medical diagnostics and therapeutic systems (e.g. ultrasonic scanners) and in everyday life situations such as mobile devices and simple igniters. No matter what the application a good understanding of piezoelectric components and materials is fundamental for everyone developing new systems or repairing existing ones. And an impedance analyses such as Bode100 is an essential tool for variety of tasks, e.g.:

- Incoming or outgoing inspection
- Functionality testing
- Component/material selection
- Material identification
- Design optimization
- Prototyping

2.2 Piezoceramic materials

Piezoelectric materials are a subgroup of functional materials exhibiting direct (generation of electric charge when subject to strain) and indirect piezoelectric effect (responding with mechanical strain to external electric charge). One can say that in case of piezoelectric materials electrical and mechanical fields are intimately coupled. There are several distinct groups of piezoelectric materials, e.g. single crystals, quartz, or even polymer based. This paper is mostly dealing with piezo materials based on polycrystalline ceramics based on PZT (Lead Zirconate Titanate), which is by far the most used material in the modern world. Some aspects discussed in here are specifically related to PZT, however many of the techniques can be easily applied to piezoelectric materials belonging to other groups, as well.

There are many kinds of materials even within the PZT group itself. The basic chemical formula is the same, however the producers change and optimize the parameters using small amounts of dopants affecting electric properties (e.g. dielectric permittivity), sensitivity (e.g. coupling coefficients), etc. Donor doping creates so called soft PZT, and acceptor doping creates so-called hard PZT. Due to high sensitivity and high dielectric permittivity soft PZT is used mostly for sensing and transducer applications, while hard PZT, thanks to its high electric strength, low dielectric loss and high mechanical quality factor make perfect actuators. This distinction can be easily mare with the use of Bode100 even without prior knowledge of the material that a component is made of (material identification).

The presence of strong electro-mechanical coupling in piezoelectric materials means that not only electric and mechanical properties need to be identified separately, but also the couplings. In general, all the field interactions within the materials can be described by a system of tensors, but luckily for uses a knowledge of the essential subset of the parameters is in practice sufficient. Fig. 1 depicts a typical way the producers of piezoelectric materials presents the portfolio of products together with selected parameters.

Luckily for Bode100 users, many of the listed parameters (highlighted in Fig. 1), mechanical, electrical as well as electromechanical can be measured using an impedance analyzer.

Latest revision date: April 2011

			Traditional Soft PZT				*Traditional Hard PZT*				
	Symbol	**Unit**	**Pz23**	**Pz27**	**P188****	**Pz29**	**Pz24**	**Pz26**	**Pz28**	**P762****	**P189****
Navy Type / Industry "equivalent"			**N/A**	**Navy 2 "PZT5A"**	**Navy 2 "PZT5A"**	**Navy 6 "PZT5H"**	**"PZT7A"**	**Navy 1 "PZT4D"**	**Navy 3 "PZT8"**	**Navy 1 "PZT4D"**	**Navy 3 "PZT8"**
Electrical Properties											
Relative Free Dielectric Constant (1 kHz)	K_{33}^T		1500	1800	1850	2900	400	1300	1030	1300	1150
Dielectric dissipation factor (1 kHz)	$\tan\delta$ ($_3^\sigma$)	10^{-3}	15	17	20	19	3	3	4	5	3
Curie Temperature	$T_C >$	°C	350	350	340	235	330	330	330	300	320
Recommeded maximum working range	$T <$	°C	250	250	240	150	230	230	250	200	220
Electromechanical Properties											
Coupling factors	k_p		0,52	0,59	0,65	0,64	0,50	0,56	0,58	0,58	0,51
	k_t		0,45	0,47	0,49	0,52	0,52	0,47	0,47	0,47	0,46
	k_{31}		-0,29	-0,33	-0,37	-0,37	-0,29	-0,33	-0,34	-0,35	-0,32
	k_{33}		0,65	0,70	0,74	0,75	0,57	0,68	0,69	0,68	0,65
Piezoelectric charge coefficients	$-d_{31}$	10^{-12} C/N	130	170	185	240	55	130	120	130	108
	d_{33}	10^{-12} C/N	330	425	425	575	90	300	275	300	240
	d_{15}	10^{-12} C/N	420	500	400	700	150	330	400		280
Piezoelectric voltage coefficients	g_{31}	-10^{-3} V m/N	10	11	11	10	16	11	13	-11	-11
	g_{33}	10^{-3} V m/N	25	27	26	23	54	28	31	26	23
Frequency constants	N_p	m/s	2160	2010	1970	1970	2400	2230	2180	2250	2350
	N_t	m/s	2030	1950	2020	1960	2100	2040	2010	2050	2150
	N_{31}	m/s	1480	1400	1450	1410	1670	1500	1600	1650	1750
	N_{33}	m/s	1600	1500	1890	1500	1600	1800	1500	1920	2060
Mechanical Properties											
Density	ρ	kg/m³	7700	7700	7700	7460	7700	7700	7700	7600	7650
Mechanical quality factor	$Q_{m,t}^E$		100	80	80	90	>1000	>1000	>1000	>600	>1000

Fig. 1 An example of typical table of piezoceramic materials listing essential parameters (from Meggitt A/S, Denmark). Parameters that can be measured using Bode100 are singled out.

2.3 Piezoceramic components

Of course, PZT materials always come in a predefined shape and size constituting a component. The components come in a great verity of shapes, e.g. disks, rings, tubes, plates, etc. Typically, a PZT component is having a pair of metal electrodes, that also define the polarization direction (so called 33 direction). However, multielectrode components are also available, and components that have been polarized in a different direction than the one defined by the electrodes (e.g. shear components). This paper deals however, with very typical situation (covering some 70% of all cases) when a PZT disk or ring needs to be characterized or identified.

2.4 Resonance frequency

It is a good practice to try to understand the component even before commencing any measurements. One of the essential things then is to understand the geometry as well as the main vibration modes of a given component. This is because due to the strong electro-mechanical coupling the purely mechanical features, such as natural resonance frequencies will also be manifested in the electrical behavior, i.e. impedance or admittance spectrum that can be easily measured by an impedance analyzer. Resonances, in general, are determined by the components shape as well as the dimensions, combined with the material properties. However, it needs to be emphasized that in many cases modes/resonances might interfere with each other producing so called spurious modes. Moreover, in many cases fundamental modes are also accompanied by overtones, i.e. higher harmonics. All those factors are making the proper identification of vibration modes difficult, requiring careful analysis and experience.

Fig. 2 presents a typical impedance response around selected mechanical resonance. It is manifested by a local minimum of magnitude of impedance (remember, impedance is a complex number) followed by a maximum. Frequencies at minimum and maximum of magnitude of impedance are called resonance frequency f_r and anti-resonance frequency f_a, respectively.

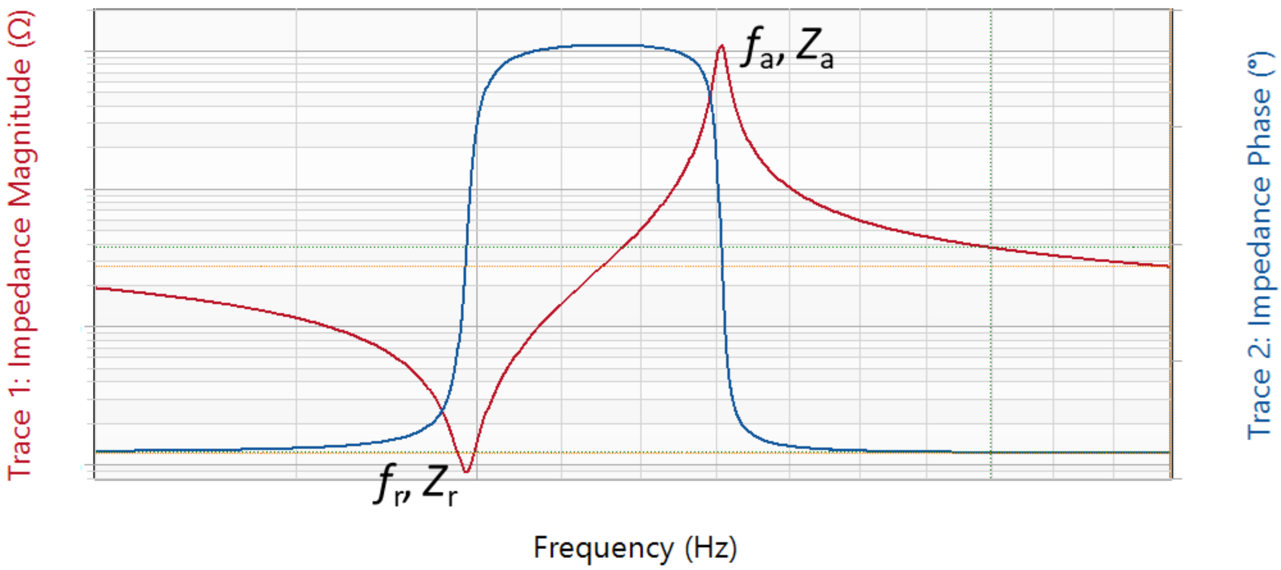

Fig. 2 Typical impedance spectrum pf a piezoelectric component around resonance

The location of resonances in the impedance spectrum depends on the speed of sound in the material for the particular mode of vibrations as well as the characteristic dimension *dim* associated with the mode (e.g. thickness, diameter, width, length, etc.):

$$f_r = \frac{c}{2 \times dim} = \frac{N}{dim}, \qquad (1)$$

where *c* is speed of sound, *N* is frequency constant for the specific mode of vibrations.

2.5 Typical shapes

2.5.1 Disc

A disc is one of the most popular shapes that PZT parts are produced in. It is characterized by a diameter *d* and thickness *t* as depicted in Fig. 3. If the thickness is significantly smaller than the diameter, i.e. *d* > 10 x *t*, one can expect two fundamental models of vibration: planar direction as well as the thickness direction (see Fig. 3).

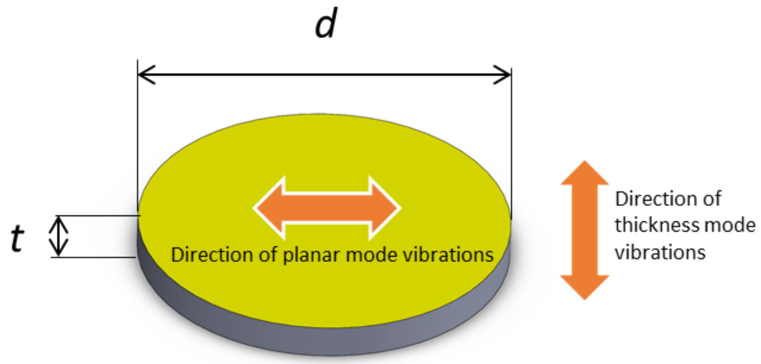

Fig. 3 Disc component and its fundamental modes of vibration (yellow color depicting electrodes)

Capacitance and dielectric loss can be easily measured directly using LCR meter (e.g. Bode100 in fixed frequency mode). Given that the dimensions of a disc component are known a number of other parameters can be measured/estimated using impedance analyzer as listed in Table 1. It must be emphasized that disc shaped components are the easiest to use for material characterization.

Table 1 Equations related to piezoelectric disc

Parameter	Unit	Equation	Number
Capacitance	F	$C = \frac{\varepsilon_{33}^{\mathrm{T}} \times \varepsilon_o \times \pi \times d^2}{4 \times t}$	(2)
Planar resonance frequency	Hz	$f_{\mathrm{r}}^{\mathrm{p}} = \frac{N_{\mathrm{p}}}{d}$	(3)
Thickness resonance frequency	Hz	$f_{\mathrm{r}}^{\mathrm{t}} = \frac{N_{\mathrm{t}}}{d}$	(4)
Planar coupling factor		$k_{\mathrm{p}} = \sqrt{2.51 \times \frac{(f_{\mathrm{a}}^{\mathrm{p}} - f_{\mathrm{r}}^{\mathrm{p}})}{f_{\mathrm{r}}^{\mathrm{p}}} - \frac{(f_{\mathrm{a}}^{\mathrm{p}} - f_{\mathrm{r}}^{\mathrm{p}})^2}{f_{\mathrm{r}}^{\mathrm{p}}}}$	(5)
Thickness coupling factor		$k_{\mathrm{t}} = \sqrt{\frac{\pi}{2} \times \frac{f_{\mathrm{r}}^{\mathrm{t}}}{f_{\mathrm{a}}^{\mathrm{t}}} \times \cot\left(\frac{\pi}{2} \times \frac{f_{\mathrm{r}}^{\mathrm{t}}}{f_{\mathrm{a}}^{\mathrm{t}}}\right)}$	(6)
Mechanical quality factor in thickness mode		${Q_{\mathrm{m}}^{\mathrm{t}}}^{\mathrm{E}} = \frac{{f_{\mathrm{a}}^{\mathrm{t}}}^2}{2\pi \times f_{\mathrm{r}}^{\mathrm{t}} \times Z_{\mathrm{r}}^{\mathrm{t}} \times C \times \left({f_{\mathrm{a}}^{\mathrm{t}}}^2 - {f_{\mathrm{r}}^{\mathrm{t}}}^2\right)}$	(7)

Explanation of symbols in Table 1 are given in Table 2.

Table 2 List of used symbols

Quantity	Symbol	Unit
Relative dielectric permittivity of piezoelectric material at constant stress	$\varepsilon_{33}^{\mathrm{T}}$	
Dielectric permittivity of vacuum	ε_o	F/m
Planar frequency constant	N_{p}	m/s
Thickness frequency constant	N_{t}	m/s
Magnitude of impedance at resonance frequency as depicted in **Fig. 2**	$Z_{\mathrm{r}}^{\mathrm{t}}$	

2.5.2 Ring

Ring shaped components are also very common since they can be easily assembled into a stack using single pin. They are characterized by outer and inner diameter d_o, d_i, respectively, as well as thickness t as depicted in Fig. 4. Ring components exhibit more complex vibration modes comparing to disc shaped parts, and one can expect three fundamental models of vibration: planar direction (here called medium diameter mode), the thickness direction as well as so called wall thickness vibrations as illustrated in Fig. 4. Depending on the relations between the individual dimensions of the component particular modes can interact producing spurious modes.

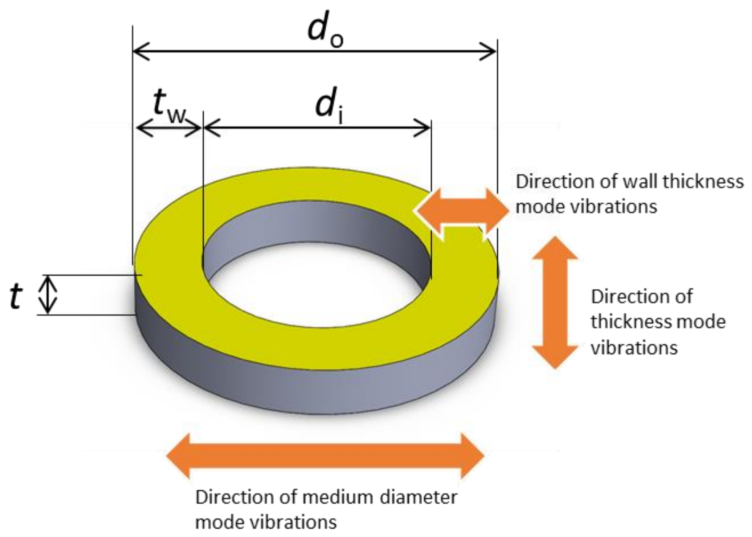

Fig. 4 Ring component and its fundamental modes of vibration (yellow color depicting electrodes)

Again, similar to disc component the capacitance and dielectric loss or a ring component can be easily measured directly using LCR meter (e.g. Bode100 in fixed frequency mode). Given that the dimensions are known i.e. d_o, d_i, t a number of other parameters can be measured/estimated using impedance analyzer as listed in Table 3.

Table 3 Equations related of piezoelectric rings

Parameter	Unit	Equation	Number
Capacitance	F	$C = \frac{\varepsilon_{33}^{\mathrm{T}} \times \varepsilon_o \times \pi \times \left(d_o{}^2 - d_i{}^2\right)}{4 \times t}$	(8)
Planar resonance frequency (medium diameter)	Hz	$f_{\mathrm{r}}^{\mathrm{p}} = \frac{2 \times N_{\mathrm{MD}}}{(d_o + d_i)}$	(9)
Planar resonance frequency (wall-thickness)	Hz	$f_{\mathrm{r}}^{\mathrm{p}} = \frac{2 \times N_{31}}{(d_o - d_i)}$	(10)
Thickness resonance frequency	Hz	$f_{\mathrm{r}}^{\mathrm{t}} = \frac{N_{\mathrm{t}}}{t}$	(11)
Planar coupling factor		$k_{\mathrm{p}} = \sqrt{2.51 \times \frac{\left(f_{\mathrm{a}}^{\mathrm{p}} - f_{\mathrm{r}}^{\mathrm{p}}\right)}{f_{\mathrm{r}}^{\mathrm{p}}} - \frac{\left(f_{\mathrm{a}}^{\mathrm{p}} - f_{\mathrm{r}}^{\mathrm{p}}\right)^2}{f_{\mathrm{r}}^{\mathrm{p}}}}$	(12)
Thickness coupling factor		$k_{\mathrm{t}} = \sqrt{\frac{\pi}{2} \times \frac{f_{\mathrm{r}}^{\mathrm{t}}}{f_{\mathrm{a}}^{\mathrm{t}}} \times \cot\left(\frac{\pi}{2} \times \frac{f_{\mathrm{r}}^{\mathrm{t}}}{f_{\mathrm{a}}^{\mathrm{t}}}\right)}$	(13)
Mechanical quality factor in thickness mode		$Q_{\mathrm{m}}^{\mathrm{t}}{}^{\mathrm{E}} = \frac{f_{\mathrm{a}}^{\mathrm{t}}{}^2}{2\pi \times f_{\mathrm{r}}^{\mathrm{t}} \times Z_{\mathrm{r}}^{\mathrm{t}} \times C \times \left(f_{\mathrm{a}}^{\mathrm{t}}{}^2 - f_{\mathrm{r}}^{\mathrm{t}}{}^2\right)}$	(14)

Most of the symbols are explained in Table 2, N_{MD} is a medium diameter frequency constant that is roughly equal to 50% of N_p. N_{31} is another frequency constant that, roughly speaking, is suitable for samples of wall thickness that is comparable with the other dimensions.

3 Measurement setup

3.1 Test fixture and boundary conditions

A good measurement setup needs to assure good electrical contact with the component's electrodes as well as proper mechanical boundary conditions. In our case, we are interested in free boundary conditions, which ideally mean that the sample can freely vibrate when excited by the input signal. Of course, in practice it is very difficult to achieve, therefore it is normally recommended to gently clamp the part preferably in a symmetry point (e.g. center of a disc, etc.) using contact electrodes in order not to excite spurious modes. This related both to purely dielectric measurements (capacitance and dielectric loss) as well as impedance spectrum measurements.

Usually, impedance test tweezers are used for the measurements as well as custom built fixtures. Bode100 comes with BNC connector that makes it perfect for custom built fixture. TOOsonix test fixture comprises a base unit with bottom contact (pogo pin) connected to ground and a spring-loaded slider with the top contact (pogo pin) activated by a lever, as depicted in Fig. 5. Top contact is connected to the input (center pin of BNC) using a short coaxial cable in order to minimize the noise level. The electrical schematic of the TOOsonix test fixture is analogue to the one depicted in Fig. 7.

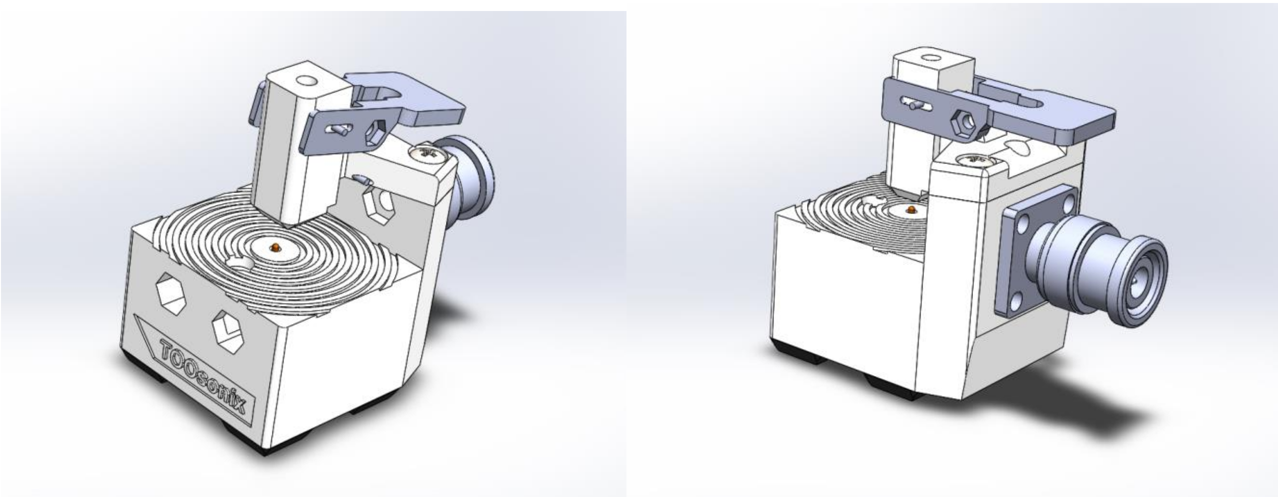

Fig. 5 Drawings of the TOOsonix impedance test fixture for Bode100

TOOsonix test fixture connects directly to the BNC Output port of Bode100 as shown in Fig. 6.

Fig. 6 Bode100 with the test fixture

3.2 Hardware setup

The presented examples require measurement of impedance in a very broad range, however the lower range is of more interest due to sharp resonance peaks of the piezoelectric components. Therefore, a single port setup has been selected as depicted in Fig. 7. Attenuation on input 1 and 2 has been set top 0 dB in order to use most of the signal level. Of course, a as narrow as possible receiver bandwidth is recommended, however it significantly affects the sweep time, therefore a good compromise has been achieved using 100 Hz bandwidth (fixed frequency measurements have been performed at 1 Hz bandwidth).

One important aspect of the presented results is that the setup presented in Fig. 7 is suitable for measurement of impedance in the range of 0.5 Ω to some 10 kΩ. Which means that some part of the measured impedance spectra, especially around anti-resonance frequencies might fall out of the recommended range. This is the compromise that one can in practice apply, due to the fact that in most of the measurements/formulas the value of frequency is being used (which is believed to be still correct given the reasonably good conditions) and good measurement of low level impedance is more important as it is used for estimation of the mechanical quality factor.

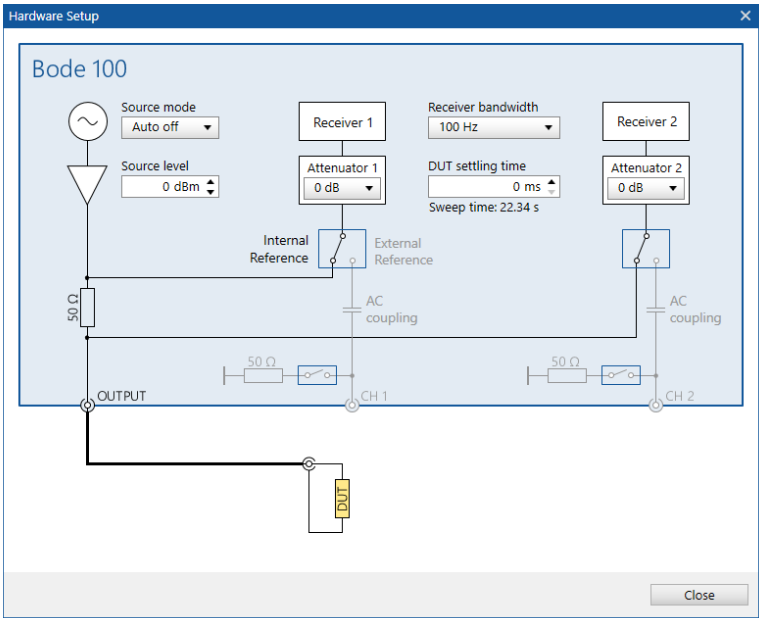

Fig. 7 Hardware setup of Bode100

3.3 Calibration

The test fixture is essentially translating the calibration plane from the BNC output of Bode100 to the plane defined by the contacts of the fixture. The proper calibration of the system is extremely important for the good quality measurements.

A specially designed calibrator has been used in the presented examples. It is comprising a plastic holder and 51 Ω +/-1% thick film resistor as well as top and bottom copper contacts. The calibrator is depicted in Fig. 8. It has been used for both open circuit as well as load calibration.

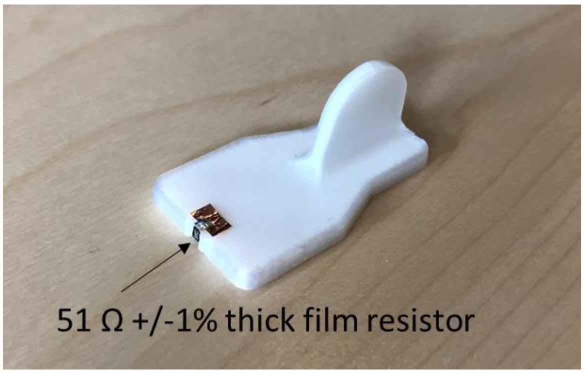

Fig. 8 Impedance calibrator used in conjunction with TOOsonix test fixture

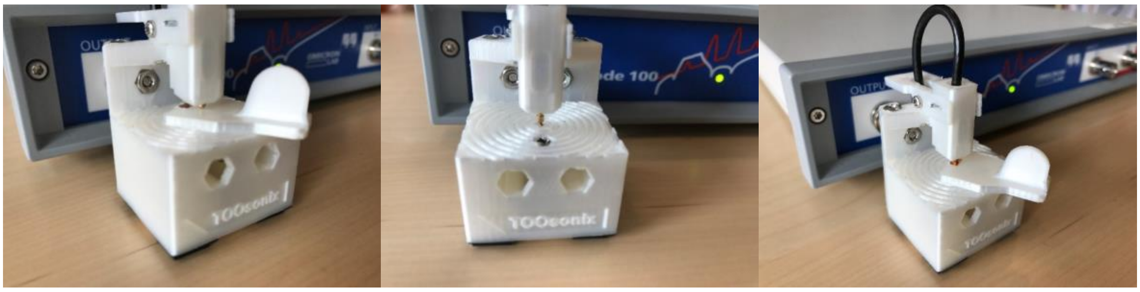

Fig. 9 Calibration process using thick film resistor based calibrator, open-circuit (left), short-circuit (middle), load (right)

It is worth mentioning, that 50.0 Ω loads are typically used to calibrate similar systems, however 51 Ω resistors are more commonly available (resistor series E24). In the presented example, a 51.0 Ω thick film resistor has been selected based on the DC measurements with an assistance of a very good quality multimeter. It must be also emphasized, that thick film resistors are known to exhibit very flat impedance response in a wide frequency range, that is why they are good candidates for calibration devices in practice.

It must be emphasized, that a custom value of the calibration load needs to be entered before user/full range calibration in the Advanced Settings as depicted in Fig. 10.

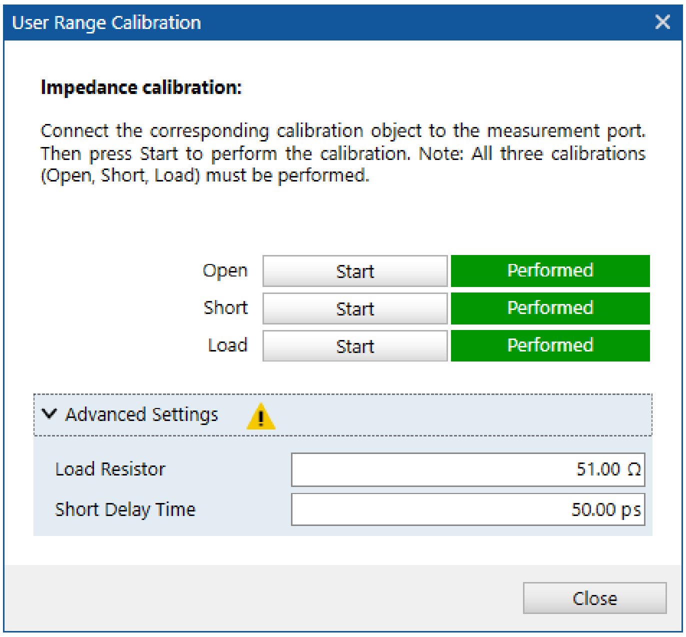

Fig. 10 Custom value of the calibration load used in advanced settings

It is a good practice to verify every single calibration process, by performing an impedance measurement of a known resistance.

The following examples cover two kinds of measurements of piezoelectric materials/components: dielectric as well as piezoelectric. The dielectric measurements typically require a single frequency measurement (industry standard - 1 kHz) of capacitance and dielectric loss, while piezoelectric measurements need broad frequency response measurements.

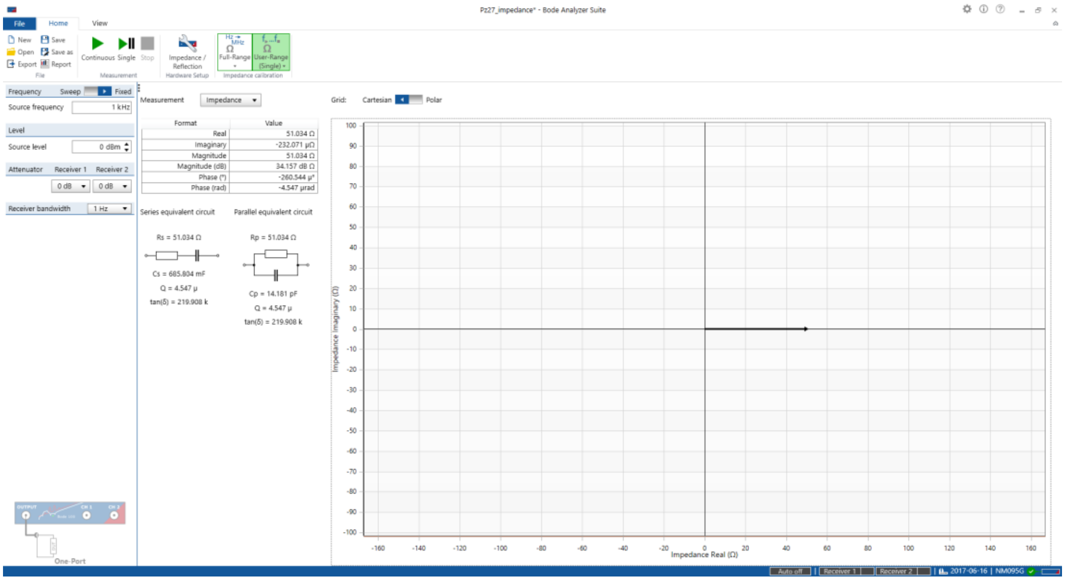

Fig. 11 Verification of the impedance value after calibration at fixed frequency

Due to the broadband response of the tested devices a full-range calibration (100 kHz to 15 MHz) has been used in the presented examples. However, in practice it is more advantageous to use user-range calibration once a proper frequency range has been established.

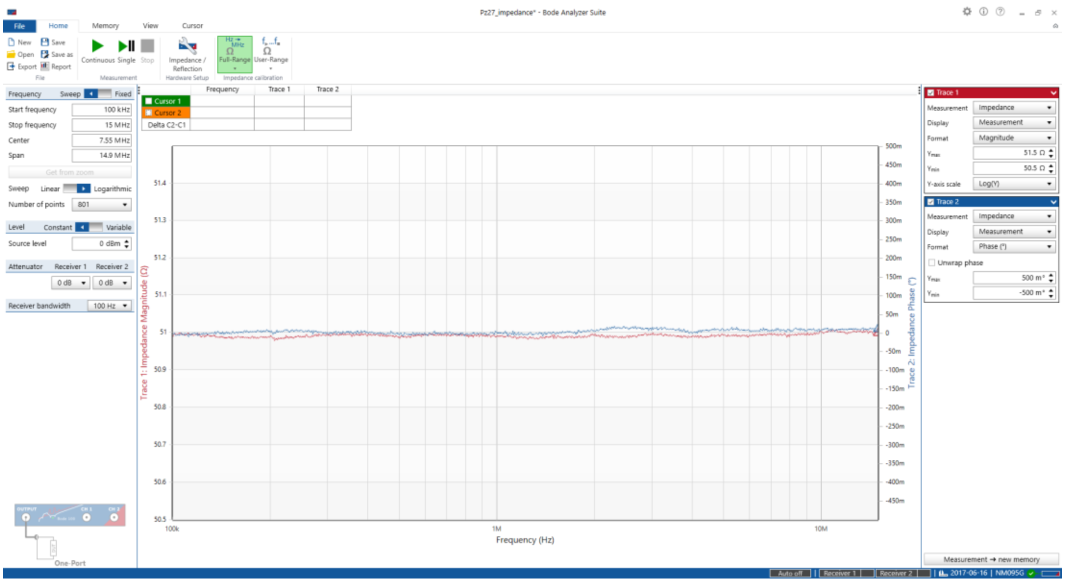

Fig. 12 Verification of the impedance value after calibration with frequency sweep from 100 kHz to 15 MHz

4 Characterization of piezoelectric disks – sample A

A disc sample of a piezoelectric material has been characterized using Bode100 as depicted in Fig. 13.

Fig. 13 Disc sample - material A (left), sample in the TOOsonix fixture (right)

The sample has the following dimensions, diameter = 20.20 mm, total thickness = 0.66 mm. Typically, piezoelectric components are electroded using so-called thick film silver (other materials and processes are also available). The thickness of the electrodes need to be taken into account the calculations. Normally it is quite difficult to measure the thickness of the electrodes, but in average one thick film electrode has a thickness of 8 μm, therefore 16 μm need to be deducted from the total thickness of the sample giving some 0.64 mm thickness (including number rounding) of the material that will be used in the calculations.

4.1 Dielectric properties

In order to measure the dielectric properties of the sample a capacitance measurement at a fixed frequency of 1 kHz has been performed. The result is given in Fig. 14. Parallel equivalent circuit is more appropriate to model the piezoelectric sample.

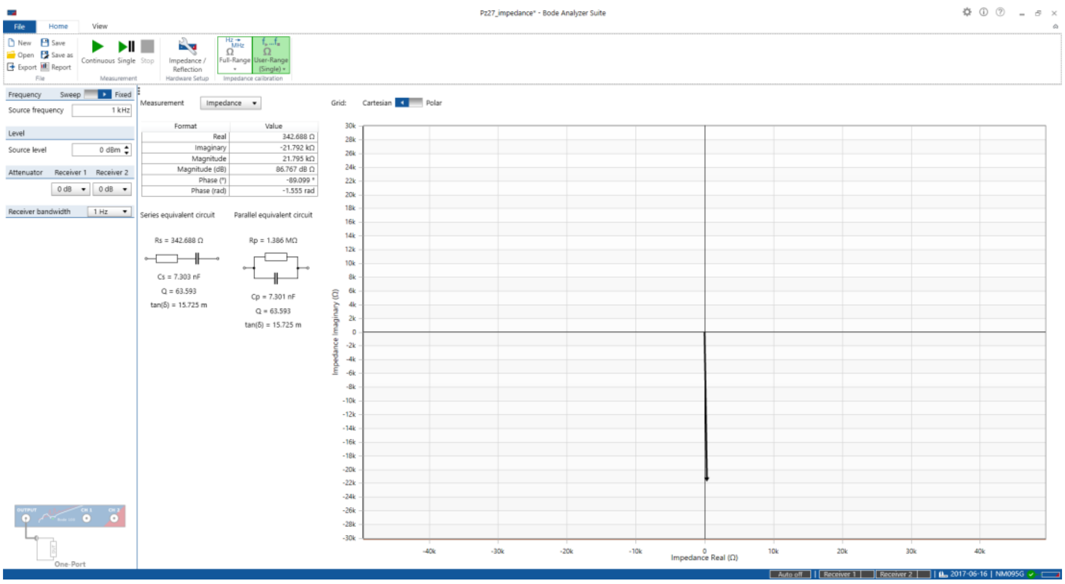

Fig. 14 Result of capacitance measurement of sample A at fixed frequency

The dielectric permittivity can be calculated using formula (2).

$$\varepsilon_{33}^{\mathrm{T}} = \frac{4 \times t}{\varepsilon_o \times \pi \times d^2} = \frac{4 \times 0.64\ mm}{8.85418781 \times 10^{-12} \frac{F}{m} \times \pi \times (20.20\ mm)^2} = 1647$$

The dielectric loss is directly measured and is equal to 1.57 %.

4.2 General impedance spectrum

General impedance spectrum of sample A is given in Fig. 15. As expected, several resonances are visible in the frequency spectrum from 50 kHz to 15 Mhz. Two of them need close attention, as mentioned in section 2.4, the planar resonance expected at approximately 2000/20.2 = 99.0 kHz and thickness resonance expected at 2000/0.64 = 3125 kHz. In fact, the measurement is confirming this theoretical analysis, and it is further discussed in the following sections. It is also worth mentioning that the resonances following the planar one are odd harmonics of the planar resonance. Similarly, the resonance appearing at around 10 MHz is the 3rd harmonic of the thickness resonance.

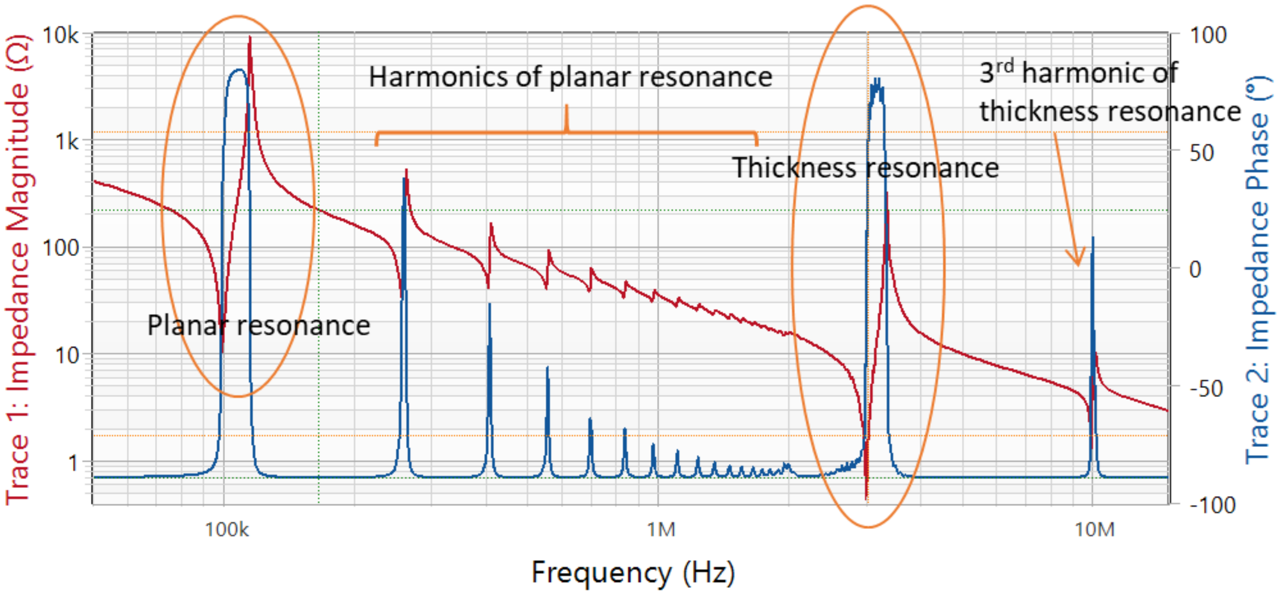

Fig. 15 General impedance spectrum of sample A

4.3 Planar resonance

Close-up of the impedance spectrum around the planar response is given in Fig. 16. Bode100 gives a very convenient way to identify the characteristic points on the spectrum using cursors, namely the minimum and maximum of the magnitude of impedance. The respective readings are given in the table in Fig. 16. Planar frequency constant as well as planar coupling coefficient can be calculated using formula (3) and (5), respectively.

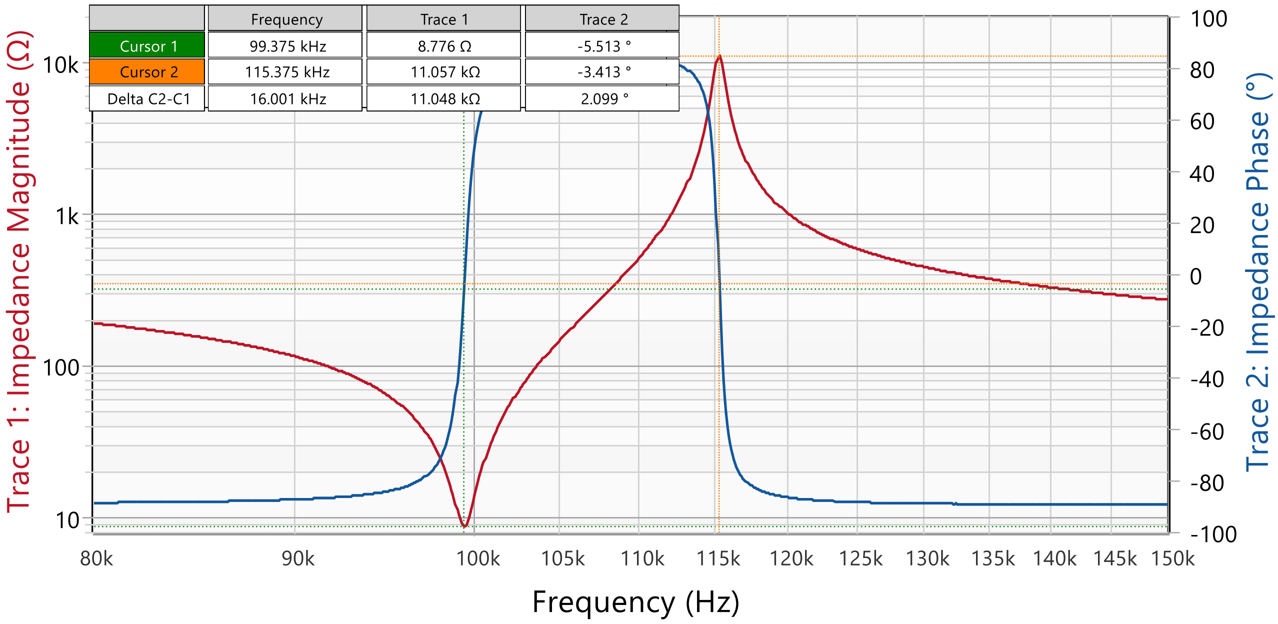

Fig. 16 Close-up of the impedance spectrum around planar resonance

Planar frequency constant is given by:

$$N_{\mathrm{p}} = f_{\mathrm{r}}^{\mathrm{p}} \times d = 99.375\ kHz \times 20.20\ mm = 2007\ \frac{m}{s}.$$

Planar coupling coefficient is equal to

$$k_{\mathrm{p}} = \sqrt{2.51 \times \frac{\left(f_{\mathrm{a}}^{\mathrm{p}} - f_{\mathrm{r}}^{\mathrm{p}}\right)}{f_{\mathrm{r}}^{\mathrm{p}}} - \frac{\left(f_{\mathrm{a}}^{\mathrm{p}} - f_{\mathrm{r}}^{\mathrm{p}}\right)^2}{f_{\mathrm{r}}^{\mathrm{p}}}}$$

$$= \sqrt{2.51 \times \frac{(115.375\ kHz - 99.375\ kHz)}{99.375\ kHz} - \frac{(115.375\ kHz - 99.375\ kHz)^2}{99.375\ kHz}} = 0.574$$

In many cases the coupling coefficients are given in %. Hence, the estimated coupling coefficient of sample A is equal to 57.4%.

4.4 Thickness resonance

Close-up of the impedance spectrum around the thickness resonance is given in Fig. 17. The characteristic points on the spectrum have been identified using cursors, namely the minimum and maximum of the magnitude of impedance. The respective readings are given in the table in Fig. 17. Thickness frequency constant, thickness coupling coefficient as well as mechanical quality factor can be calculated using formula (4), (6) and (7), respectively.

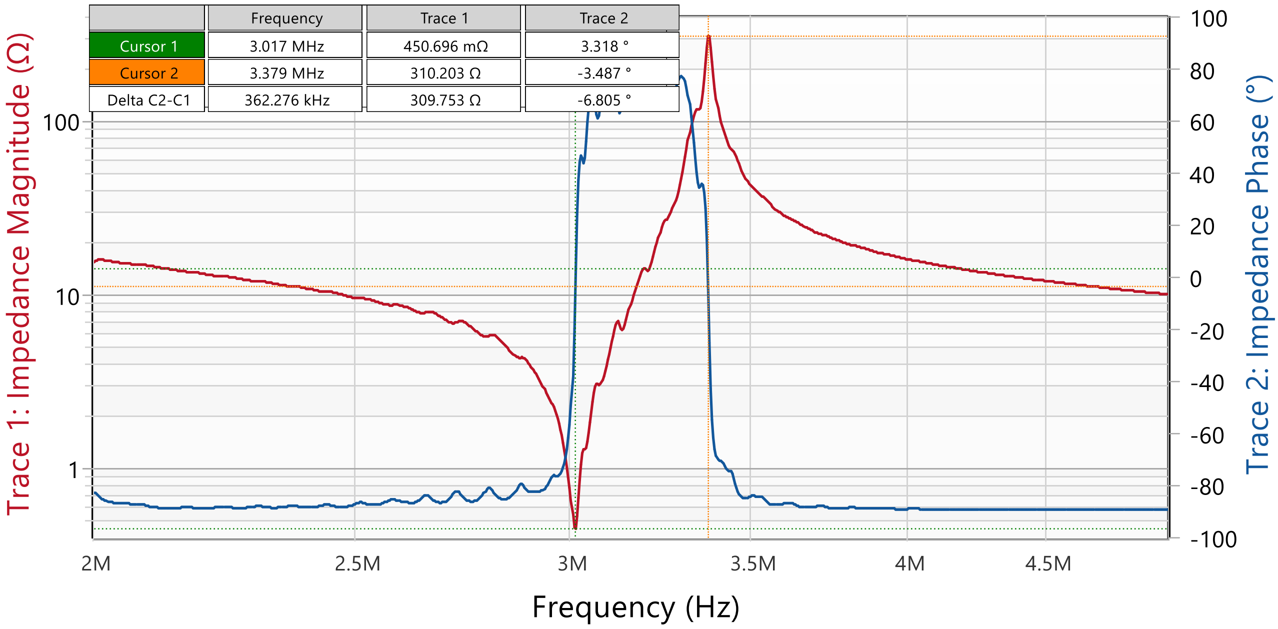

Fig. 17 Close-up of the impedance spectrum around thickness resonance

Thickness frequency constant is given by:

$$N_{\mathrm{t}} = f_{\mathrm{r}}^{\mathrm{t}} \times t = 3.017\ MHz \times 0.64\ mm = 1931\ \frac{m}{s}.$$

Thickness coupling coefficient is equal to

$$k_{\mathrm{t}} = \sqrt{\frac{\pi}{2} \times \frac{f_{\mathrm{r}}^{\mathrm{t}}}{f_{\mathrm{a}}^{\mathrm{t}}} \times \cot\left(\frac{\pi}{2} \times \frac{f_{\mathrm{r}}^{\mathrm{t}}}{f_{\mathrm{a}}^{\mathrm{t}}}\right)} = \sqrt{\frac{\pi}{2} \times \frac{3.017\ MHz}{3.379\ MHz} \times \cot\left(\frac{\pi}{2} \times \frac{3.017\ MHz}{3.379\ MHz}\right)} = 0.488$$

As in the case of planar coupling the thickness coupling coefficient can be expressed in %. Hence, the estimated thickness coupling coefficient of sample A is equal to 48.8%.

Mechanical quality factor is given by the following formula

$$Q_{\mathrm{m}}^{\mathrm{t}\ \mathrm{E}} = \frac{{f_{\mathrm{a}}^{\mathrm{t}}}^2}{2\pi \times f_{\mathrm{r}}^{\mathrm{t}} \times Z_{\mathrm{r}}^{\mathrm{t}} \times C \times \left({f_{\mathrm{a}}^{\mathrm{t}}}^2 - {f_{\mathrm{r}}^{\mathrm{t}}}^2\right)} = \frac{(3.379\ MHz)^2}{2\pi \times 3.017\ MHz \times 0.45\ \Omega \times 7.301\ nF \times (3.379^2 - 3.017^2)} = 79$$

4.5 Short analysis of sample A

Given the dielectric properties of the analyzed sample one can conclude that it is made from soft PZT, due to medium range dielectric permittivity and relatively high dielectric losses. This is further reconfirmed by the analysis of the impedance spectrum, where the harmonics of the planar mode are well suppresses comparing with the main peak. The close-up of the thickness resonance is also very “clean” supporting the hypothesis. In fact, sample A was made from Pz27 (Meggitt Denmark) and the estimated parameters fit very closely the values published in the catalogue (see Fig. 1).

5 Characterization of piezoelectric disks – sample B

A disc sample of a piezoelectric material has been characterized using Bode100 as depicted inFig. 18 Disc sample - material B (left), sample in the TOOsonix fixture (right).

Fig. 18 Disc sample - material B (left), sample in the TOOsonix fixture (right)

The sample has the following dimensions, diameter = 20.02 mm, total thickness = 0.68 mm. For the reasons described in section 4 16 µm need to be deducted from the total thickness of the sample giving some 0.66 mm thickness (including number rounding) of the material that will be used in the calculations.

5.1 Dielectric properties

In order to measure the dielectric properties of the sample a capacitance measurement at a fixed frequency of 1 kHz has been performed. The result is given in Fig. 19. Parallel equivalent circuit is more appropriate to model the piezoelectric sample.

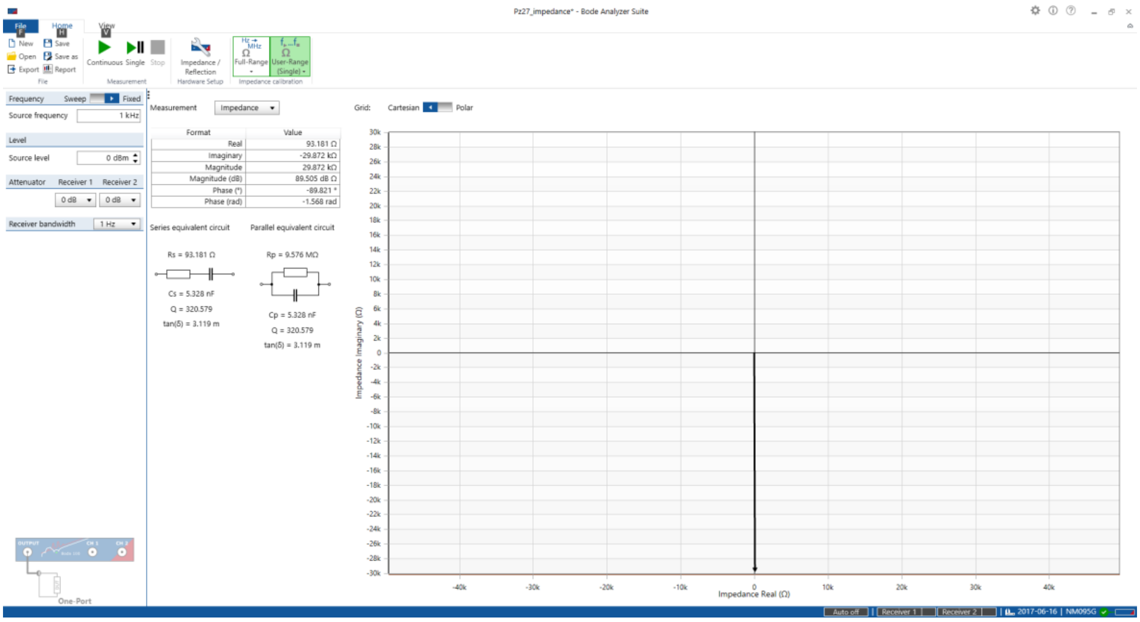

Fig. 19 Result of capacitance measurement of sample B at fixed frequency

The dielectric permittivity can be calculated using formula (2).

$$\varepsilon_{33}^{T} = \frac{4 \times t}{C \times \varepsilon_o \times \pi \times d^2} = \frac{4 \times 0.66\,mm}{5.328\,nF \times 8.85418781 \times 10^{-12}\frac{F}{m} \times \pi \times (20.02\,mm)^2} = 1262$$

The dielectric loss is directly measured and is equal to 0.31%.

5.2 General impedance spectrum

General impedance spectrum of sample B is given in Fig. 20. Again, several resonances are visible in the frequency spectrum from 50 kHz to 15 MHz. Two of them need close attention, as mentioned in section 2.4, the planar resonance expected at approximately 2000 m/s / 20.0 mm = 100.0 kHz and thickness resonance expected at 2000 m/s / 0.66 mm = 3030 kHz. In fact, the measurement is confirming this analysis, and it is further discussed in the following sections. It is also worth mentioning that the resonances following the planar one are odd harmonics of the planar resonance, and are more pronounced comparing with the results given in Fig. 15, suggesting piezoelectric material of substantially different properties. Similarly, the resonance appearing at around 10 MHz is the 3rd harmonic of the thickness resonance.

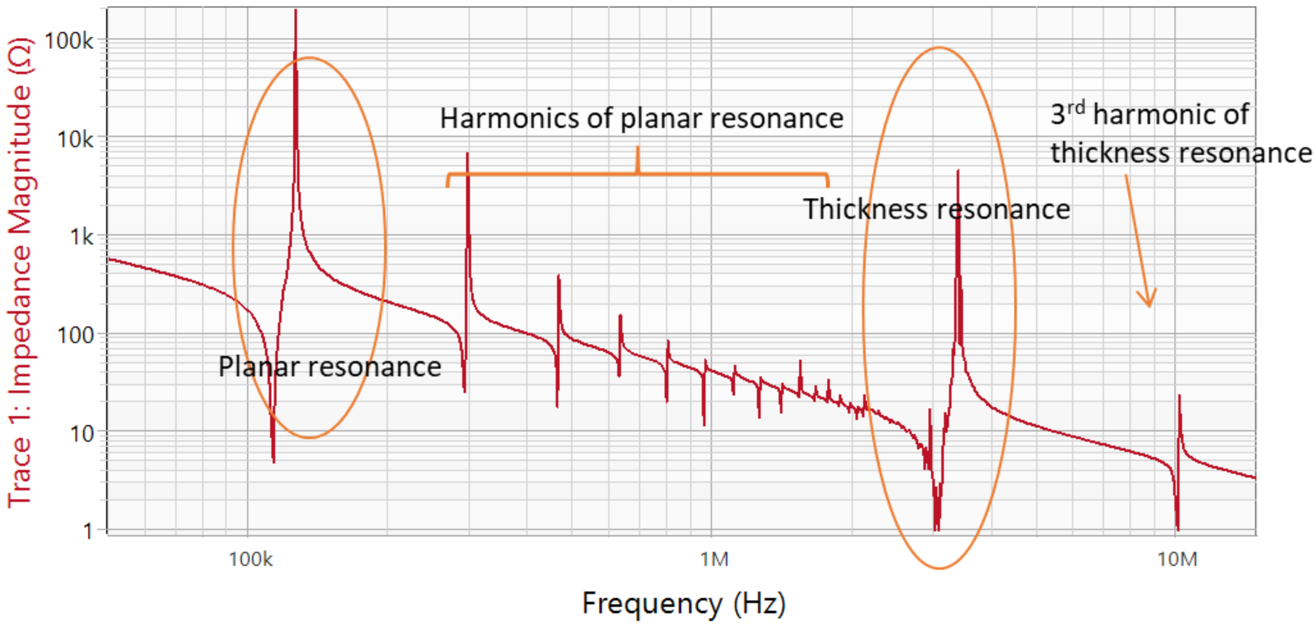

Fig. 20 General impedance spectrum of sample B

5.3 Planar resonance

Close-up of the impedance spectrum around the planar response is given in Fig. 21. Bode100 gives a very convenient way to identify the characteristic points on the spectrum using cursors, namely the minimum and maximum of the magnitude of impedance. The respective readings are given in the table in Fig. 21. Planar frequency constant as well as planar coupling coefficient can be calculated using formula (3) and (5), respectively.

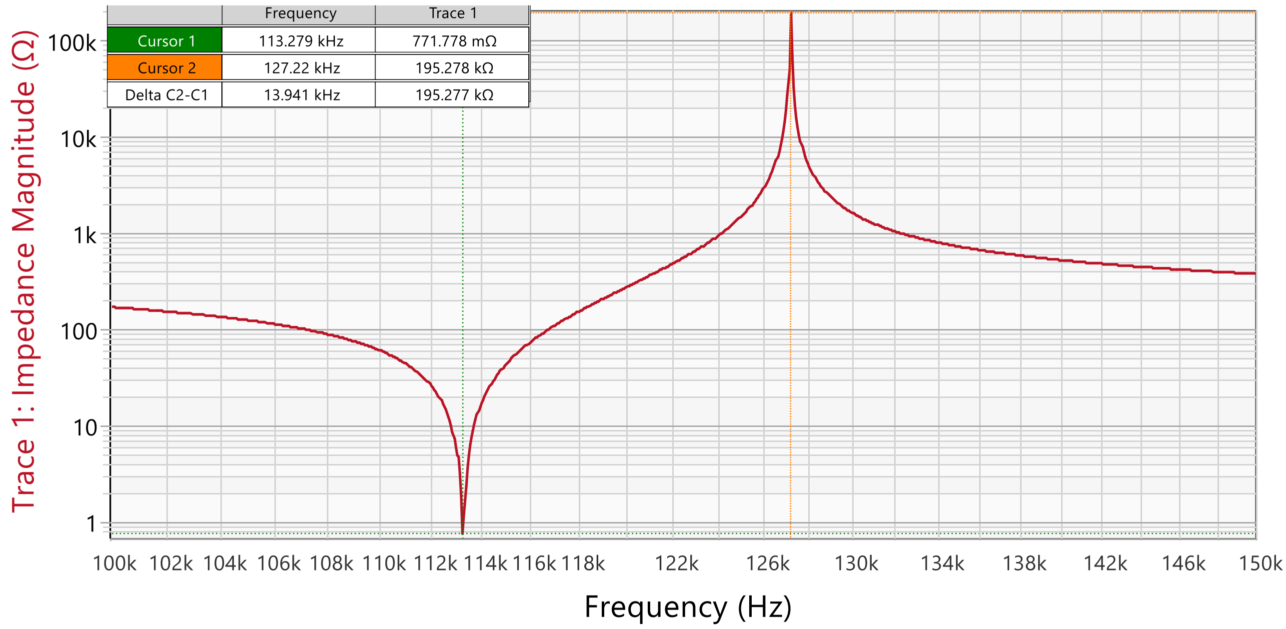

Fig. 21 Close-up of the impedance spectrum around planar resonance - sample B

Planar frequency constant is given by:

$$N_{\mathrm{p}} = f_{\mathrm{r}}^{\mathrm{p}} \times d = 127.22\ kHz \times 20.02\ mm = 2268\ \frac{m}{s}.$$

Planar coupling coefficient is equal to

$$k_{\mathrm{p}} = \sqrt{2.51 \times \frac{(f_{\mathrm{a}}^{\mathrm{p}} - f_{\mathrm{r}}^{\mathrm{p}})}{f_{\mathrm{r}}^{\mathrm{p}}} - \frac{(f_{\mathrm{a}}^{\mathrm{p}} - f_{\mathrm{r}}^{\mathrm{p}})^2}{f_{\mathrm{r}}^{\mathrm{p}}}}$$

$$= \sqrt{2.51 \times \frac{(127.22\ kHz - 113.28\ kHz)}{113.28\ kHz} - \left(\frac{(127.22\ kHz - 113.28\ kHz)}{113.28\ kHz}\right)^2} = 0.513$$

In many cases the coupling coefficients are given in %. Hence, the estimated coupling coefficient of sample B is equal to 51.3%.

5.4 Thickness resonance

Close-up of the impedance spectrum around the thickness resonance of sample B is given in Fig. 22. The characteristic points on the spectrum have been identified using cursors, namely the minimum and maximum of the magnitude of impedance. The respective readings are given in the table in Fig. 22. Thickness frequency constant, thickness coupling coefficient as well as mechanical quality factor can be calculated using formula (4), (6) and (7), respectively.

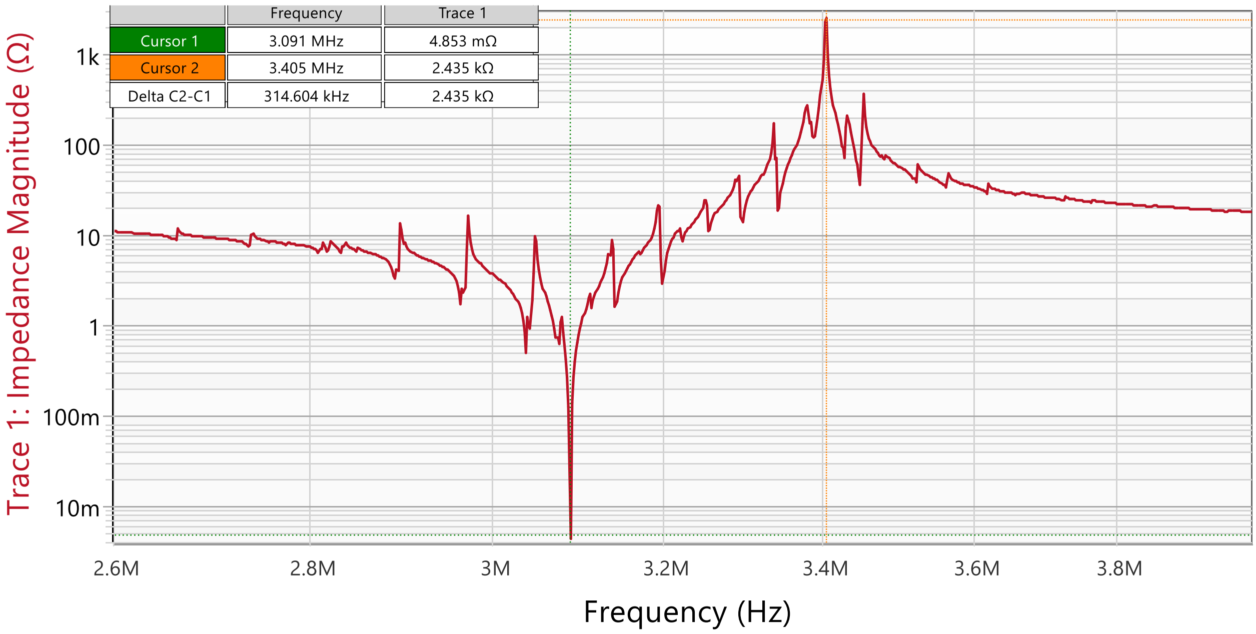

Fig. 22 Close-up of the impedance spectrum around thickness resonance - sample B

Thickness frequency constant is given by:

$$N_{\mathrm{t}} = f_{\mathrm{r}}^{\mathrm{t}} \times t = 3.091\ MHz \times 0.66\ mm = 2040\ \frac{m}{s}.$$

Thickness coupling coefficient is equal to

$$k_{\mathrm{t}} = \sqrt{\frac{\pi}{2} \times \frac{f_{\mathrm{r}}^{\mathrm{t}}}{f_{\mathrm{a}}^{\mathrm{t}}} \times \cot\left(\frac{\pi}{2} \times \frac{f_{\mathrm{r}}^{\mathrm{t}}}{f_{\mathrm{a}}^{\mathrm{t}}}\right)} = \sqrt{\frac{\pi}{2} \times \frac{3.091\ MHz}{3.405\ MHz} \times \cot\left(\frac{\pi}{2} \times \frac{3.091\ MHz}{3.405\ MHz}\right)} = 0.456$$

As in the case of planar coupling the thickness coupling coefficient can be expressed in %. Hence, the estimated thickness coupling coefficient of sample A is equal to 45.6%.

Mechanical quality factor is given by the following formula

$$Q_{\mathrm{m}}^{\mathrm{t}\ \mathrm{E}} = \frac{{f_{\mathrm{a}}^{\mathrm{t}}}^2}{2\pi \times f_{\mathrm{r}}^{\mathrm{t}} \times Z_{\mathrm{r}}^{\mathrm{t}} \times C \times \left({f_{\mathrm{a}}^{\mathrm{t}}}^2 - {f_{\mathrm{r}}^{\mathrm{t}}}^2\right)} = \frac{(3.405\ MHz)^2}{2\pi \times 3.091\ MHz \times 0.004\ \Omega \times 5.328\ nF \times (3.405^2 - 3.091^2)} = 11444$$

It is important to emphasize, that the measured impedance magnitude at resonance frequency goes well below the recommended level in the given one-port measurement setup. Therefore, this measurement may bear a large measurement error. Obviously, in many cases this would require an additional measurement of impedance using the appropriate measurement setup, however in our case it is fair to conclude that material B has significantly larger mechanical quality factor comparing to sample A.

5.5 Short analysis of sample B

Given the relatively low dielectric permittivity as well as very low dielectric loss of the analyzed sample one can conclude that it is made from hard PZT. This is further reconfirmed by the analysis of the impedance spectrum, where the harmonics of the planar mode are well pronounced together with the very sharp main peak. The close-up of the thickness resonance is showing a lot of interferences (spurious modes) supporting the hypothesis. Moreover, the sample exhibits a large mechanical quality factor, also pointing at hard PZT. In fact, sample B was made from Pz26 (Meggitt Denmark) and the estimated parameters fit very closely the values published in the catalogue (see Fig. 1).

6 Characterization of piezoelectric ring made from hard PZT

A ring sample of a piezoelectric material has been characterized using Bode100 as depicted in Fig. 23.

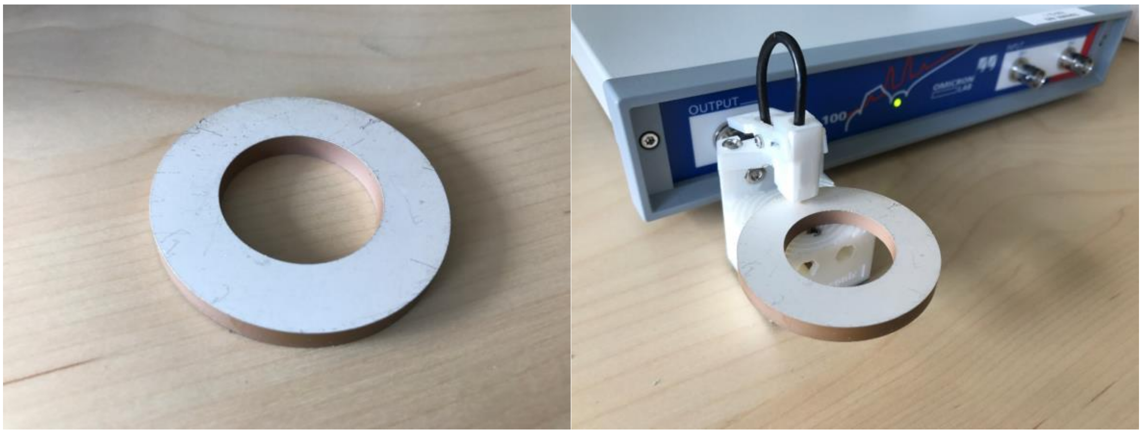

Fig. 23 Ring sample (left), sample in the TOOsonix fixture (right)

The sample has the following dimensions, outer diameter = 50.80 mm, inner diameter = 28.20 mm total thickness = 5.00 mm. For the reasons described in section 4, 16 µm need to be deducted from the total thickness of the sample giving some 4.98 mm thickness (including number rounding) of the material that will be used in the calculations.

6.1 Dielectric properties

Dielectric porperties of a ring sample can be estimated using cpacitance measurement and the methodology shown in section 4.1 and equaltion (8).

6.2 General impedance spectrum

Due to the existence of an extra inner diameter in case of a ring component one should expect a richer and more difficult to analyze impedance spectrum. Fig. 24 shows an impedance spectrum of the ring sample measured in the range from 10 kHz to 15 MHz. A quick analysis of the sample dimensions indicates that one should expect a medium-diameter resonance at around 2x1000 m/s /(50.80 mm + 28.20 mm) = 25.3 kHz. Moreover, the wall-thickness resonance should appear at around 2000 m/s / (50.80 mm – 28.20 mm) = 176.9 kHz. Thickness resonance should be expected at 2000 m/s / 4.98 mm = 401.6 kHz.

Fig. 24 shows the general impedance spectrum of the ring sample together with the interpretation of the responses as well as the indication of the characteristic frequencies. The actual frequencies differ slightly from those estimated above, mostly because a rough estimate of the frequency constant has been used. Moreover, complex shapes exhibit complex impedance spectra where vibration modes interfere with one another.

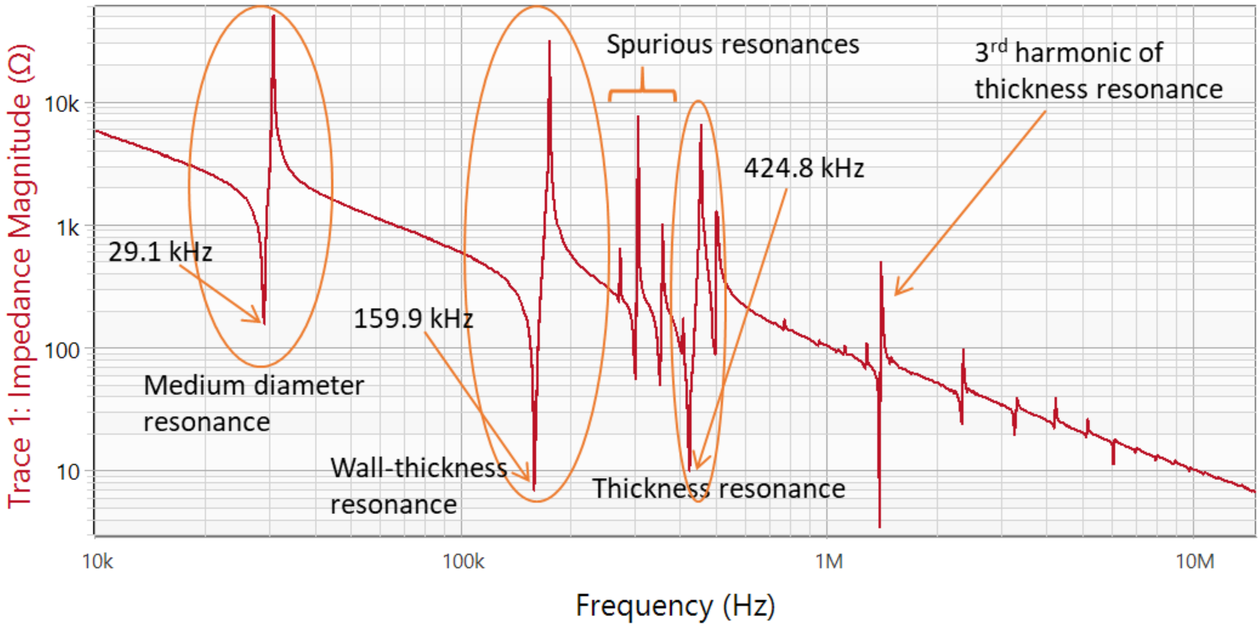

Fig. 24 General impedance spectrum of ring sample

7 Conclusions

- Dielectric as well as piezoelectric properties of piezoelectric material and devices can be measured using impedance analyzer.
- Even relatively simple piezoelectric components and devices may exhibit complex impedance spectra.
- Good understanding of the vibration modes is necessary to correctly identify and interpret impedance spectra.
- Impedance analyzer data can be applied for verity of research as well as production tasks including, material quality control, product development, inspection.
- Bode100 is an excellent, cost effective solution that can be used for measurement of dielectric as well as piezoelectric properties of piezoelectric materials, components and devices.

8 Acknowledgements

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