Measurement of Temperature Dependence in the Piezoelectric Active Element of a Knock Sensor

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ABSTRACT

The article describes experimental research on PZT ceramics used in knock sensors. The aim of the paper is to investigate the temperature effects related to the parameters of piezoelectric materials and to characterize the influence and changes exerted by these parameters on the properties of knock sensors. The material properties of such elements based on PZT ceramics are significantly affected by temperature changes; we therefore examined the temperature effect during the heating phase and analysed the subsequent permanent changes to the piezoelectric coefficients. In the experiment, emphasis was placed on investigating the piezoelectric coefficient changes up to the limit value (i.e., the Curie temperature): we determined the Curie temperature of the piezoelectric material used in the knock sensor, measured the impedance and phase characteristics at the given thermal value, and cooled the material down to the ambient temperature. Subsequently, the piezoelectric constants were calculated from these characteristics, and the related influence was evaluated. The experiments demonstrated that temperature can affect the piezoelectric coefficients and thereby also to accuracy of a knock sensor or piezoelectric sensors generally.

Keywords: knock sensor; ring; Sonox P502; temperature measurement; impedance analyzer

1. Knock sensor measurement

1.1 Introduction

The cross-section shown in Fig. 1 relates to a knock sensor utilizing, as its active measuring element, the Sonox P502 ring-shaped PZT ceramics produced by the CeramTec company. The dimensions of the applied ceramics are presented in Fig. 1b. The sensor consists of several parts; the main structural component is a steel casing made to be fastened with a bolt to the measured surface. This support casing carries an active ring-shaped piezoelectric element placed between two insulation pads. The element is polarized in the direction of the sensor axis; in Fig. 1b, the polarization direction is denoted as E. The electrical signal from the piezoelectric element is conducted by copper electrodes to pins in the sensor casing; alternatively, these pins are directly interconnected with the lead-in conductor inside the casing. Another part of the knock sensor consists in a defined seismic matter fitted onto the active piezoelectric element and tightened with a locknut through a spring; the entire structure is then coated with plastic. Such solution provides the knock sensor with sufficient ruggedness to withstand harsh operating conditions, including those characteristic of the automotive industry.

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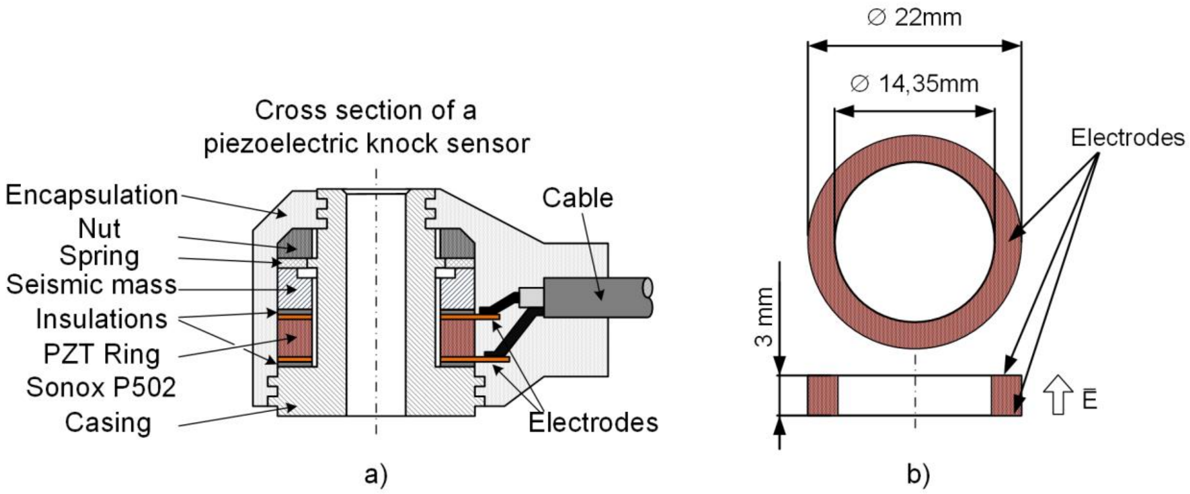

Fig. 1 a) The cross section of the knock sensor [3], and b) dimensions of the Sonox P502 ring.

1.2 Determining the resonant frequency of the Sonox P502 ring-shaped ceramics

Considering the dimensions of the ring shown in Fig. 1b), the value of the capacitance C^T at 1kHz quoted by the manufacturer of the Sonox P502 piezoelectric ceramics equals 1100 ± 150pF, and the related electromagnetic coupling coefficient is k_{eff} = 0,3275±0,0425. To verify these values, we used an Agilent 4294A impedance analyzer and an Agilent 16334A tweezer test fixture. The impedance and phase characteristics are introduced in Fig. 2; the measured value of the capacitance C^T at 1kHz equals 1062pF±5%. The electromechanical coupling coefficient according to the European standard EN50324-2 [1] is, for radial oscillations of the ring, determined to be to be fs = 49,7 kHz and fp = 53,5 kHz; the resulting k_{eff}, according to (1), equals 0,370±5%. Possible differences between electromechanical coefficient values are often caused by minor discrepancies between the dimensions of individual rings. If, however, the differences between these dimensions are within tolerance, their effect on the behaviour of the sensor remains insignificant.

$$k_{eff}^2 = \frac{f_p^2 - f_s^2}{f_p^2} \tag{1}$$

The orientation value of the resonant frequency for radial oscillations of the ring can be verified by means of formula (2) [4, p. 202]. We have

$$fs = \frac{1}{2\pi r_s} \cdot \sqrt{\frac{E}{\rho}} \text{ , where } r_s = \frac{1}{2}(r_e + r_i). \tag{2}$$

Here, r_s denotes the arithmetic mean of the external and internal radii of the ring, r_e and r_i; E is Young's modulus, namely the reciprocal value of the elastic coefficient s_{ij}; and ρ is the density of the applied PZT ceramics. The calculation can be performed using the datasheet values ρ and s_{ij}^E for the used disc: r_e = 0,02186/2 m a r_i = 0,01435/2. The final resonant frequency value after substituting was approximately 46.5 kHz as compared to the measured value of 49.7 kHz. The smaller errror can be attributed to the reading of the impedance analyzer, the rounding in the calculation, and the Young's modulus value calculated from the datasheet values.

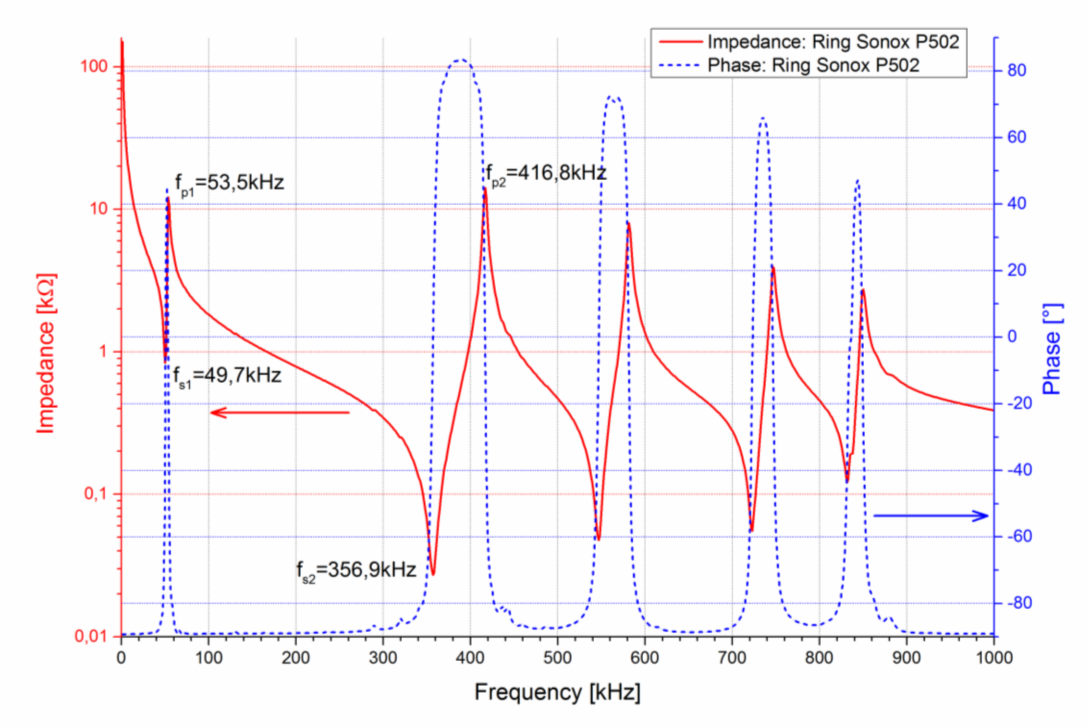

Fig. 2 The impedance and phase characteristic of the Sonox P502 PZT ceramics ring

2. Temperature measurement of the PZT ceramics ring

2.1 Description of the measuring station

The operational set for the measurement of temperature dependences of material coefficients of PZT ceramics comprises an Agilent 4294A impedance analyzer interconnected with a personal computer via a GPID bus. The temperature measurement is carried out using two calibrators supplied by the AOIP company, and these devices are also connected to the personal computer (via an RS422/RS232 bus). The first calibrator, a Hyperion Basic, operates within the range of between -20°C and 140°C; the second one, a Gemini 700LRI, is suitable for use between 30°C and 700°C. The measurement process, setting of the devices, and data reading are all performed through an appropriate application in LabVIEW. The above-described connection is introduced in Fig. 3 [5].

2.2 Description of the Experiment and Discussion

Before starting the actual measurement of the dependence of material coefficients on the temperature, we had to determine the Curie point of the applied type of piezoelectric ceramics. The Curie temperature, as set forth within both the European standard EN50324 [1] and the world standard CEI/IEC 60483: 1976 [2], can be obtained by measuring the hysteresis curves of the capacity temperature dependence measured deep below the resonant frequency. For this reason, the measurement of temperature dependences in PZT ceramics was divided into two stages. In the first phase, we measured the dependence of the capacitance C^T at 1 kHz for the heating from 300°C to 420°C and the subsequent cooling down to 300°C. The temperature range was selected based on the Curie point of 335°C, which is specified by the manufacturer of the Sonox P502 ceramics. The ceramics fall within the class of piezoelectric materials chemically denoted as Pb (Zr_x, Ti_{1-x}) O_3; the actual proportion of zirconate (Zr) and titanate (Ti) is then utilized by the manufacturer to modify the values of not only the material coefficients but also the Curie point. However, the Curie temperature value is often indicated lower than the real rate; in many cases, the real value is then higher by several units or even tens of degrees. If the Curie point specified within the datasheet is exceeded accidentally, the PZT ceramics will not be immediately depolarized. Rather than this, the sufficient temperature reserve will enable the ceramics to regain, during the cooling phase, the initial material coefficient values. It therefore follows from such reaction that a significant change of the parameters generally occurs only when the Curie point has been approached critically.

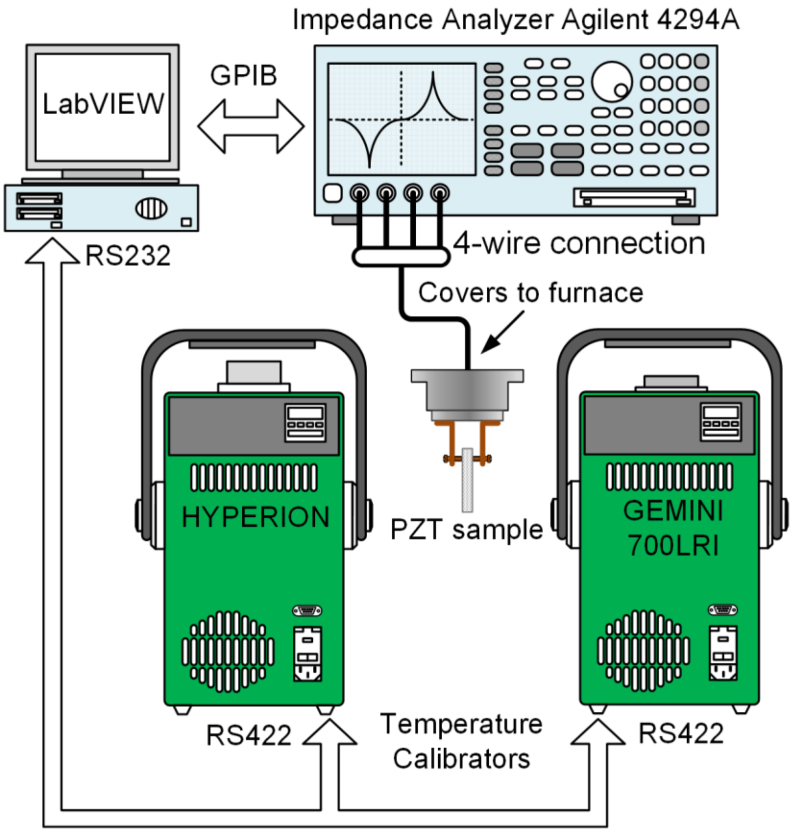

Fig. 3 Connection scheme for the measurement of temperature dependences in PZT ceramics [5].

After the initial termal test, which exposes the Curie point value, we will be able to carry out the actual temperature test of the piezoelectric ceramics. This test follows the pattern outlined in Fig. 4, according to which the measured sample is gradually cooled down to -20°C. When the temperature stabilizes, the input parameters for the calculation of the material coefficients are measured; these parameters include the resonant frequency and capacity at 1kHz. Subsequently, the sample is stabilized at the reference temperature of 25°C, and the input parameters are measured again. The described procedure is then repeated cyclically up to the temperature of 370°C, which was – from the Curie temperature measurement – established as very close to the Curie point value. The measurement did not aim to depolarize the ceramics but to capture and specify any possible effect of the temperature on the parameters of the sensor's active element in various thermal conditions; thus, the Curie point was not exceeded during the experiment.

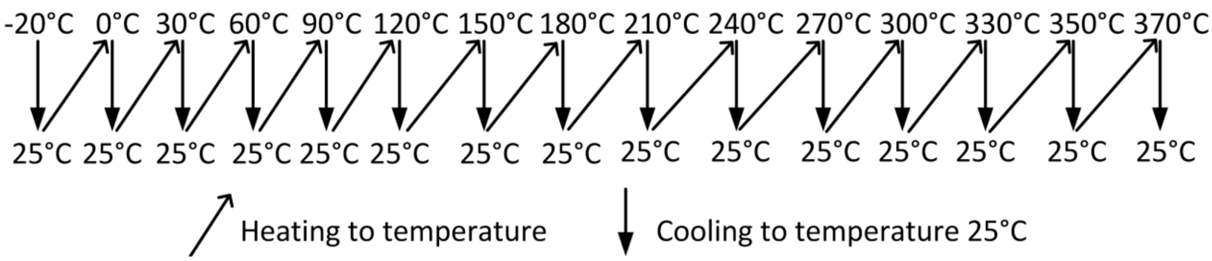

Fig. 4 The Sonox P502 piezoelement measuring process: A description of the steps involved in the procedures of heating and cooling down to the temperature of 25 °C.

Fig. 4 shows the dependence of the capacitance C^T on the temperature within the range of between 300°C and 420°C. The PZT ceramics were measured during CT-heating and then also in the course of CT-cooling to the initial temperature of 300°C; the related diagram is wholly presented in Fig. 4.

Whenever the required temperature was reached, we stabilized the ceramics to measure them using the impedance analyzer. The Curie point is defined at the maximum value of the capacitance C^T, and (pursuant to the European standard EN50324-2) it should be read during the cooling phase. The difference between the Curie points acquired in the heating and during the cooling should be minimal, assuming that sufficient stabilization of the PZT ceramics at every pre-set temperature has been ensured. In this case, the temperature at the maximum capacitance C^T equals 374°C, a value substantially higher than that specified by the manufacturer of the ceramics.

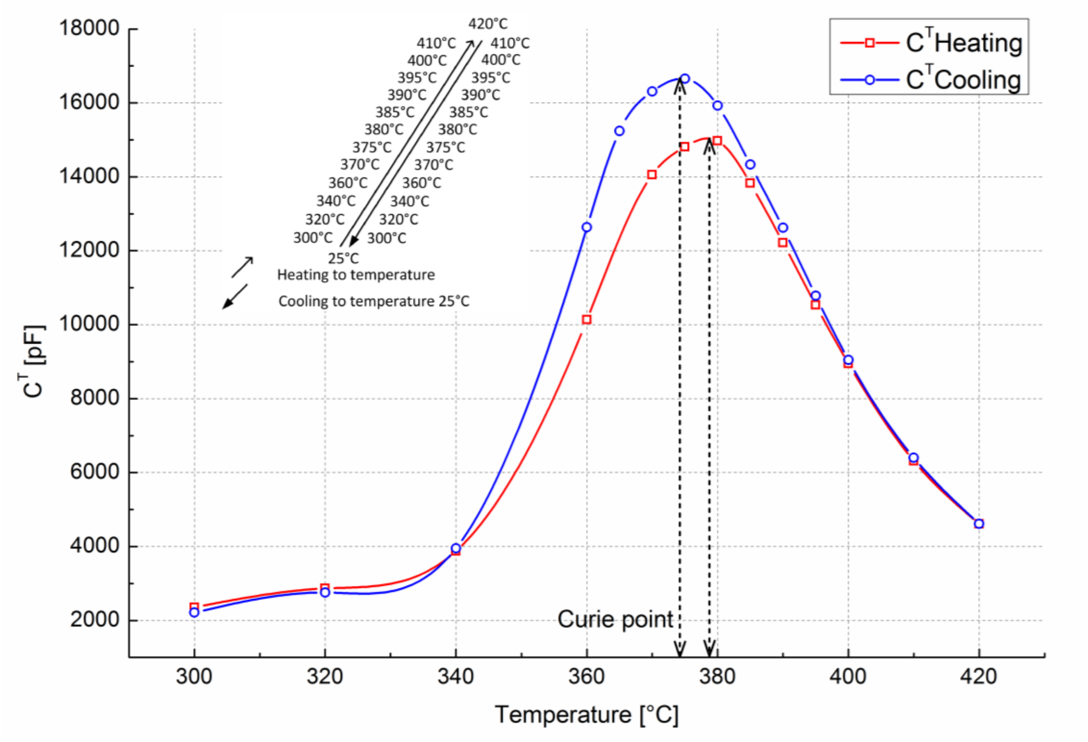

Fig. 5 The temperature dependence of the capacitance CT measured at 1 kHz within the temperature range near the Curie point (300 °C to 420 °C).

After comparing the effects of the temperature on the PZT ceramics sample, we selected the effective electromechanical coefficient k_{eff}, which is specified by the manufacturer for the given ceramics shape. This coefficient is directly calculated from the resonant and anti-resonant frequencies, and we can use it to evaluate the influence of the temperature on the resonant frequency. To verify the obtained results, we also measured (again) the capacitance C^T at 1 kHz. The temperature range indicated in Fig. 5 was selected according to the use of PZT ceramics in practical applications, and it ends at 370°C, a temperature approaching the Curie point. The characteristics presented in Fig. 5 show that both the curves, which represent the value of the electromechanical coefficient measured at the current temperature and the value measured at the reference temperature, decrease with growing temperature. A significant drop occurs only when the Curie point of the given PZT ceramics is approached; this drop is caused by the nearing phase transition of the crystallographic structure. If the Curie point is exceeded, the PZT ceramics become depolarized; such depolarization denotes the random backward shift of the domains inside the changer. To enable rearrangement of the domains and resetting of the coefficient to the initial value, we need to repolarize the changer by means of a high electric field.

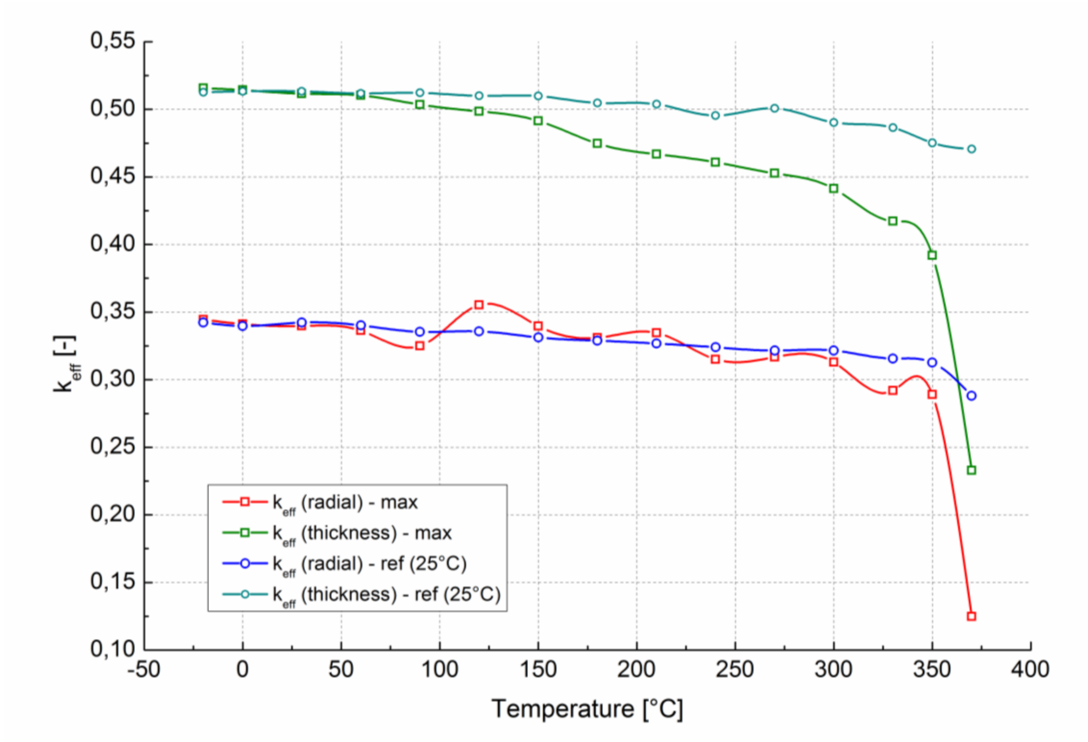

Fig. 6 The temperature dependence of the effective electromechanical coefficient k_{eff} for radial and thickness oscillations of the PZT ceramic ring within the temperature range of -20 °C to 370 °C.

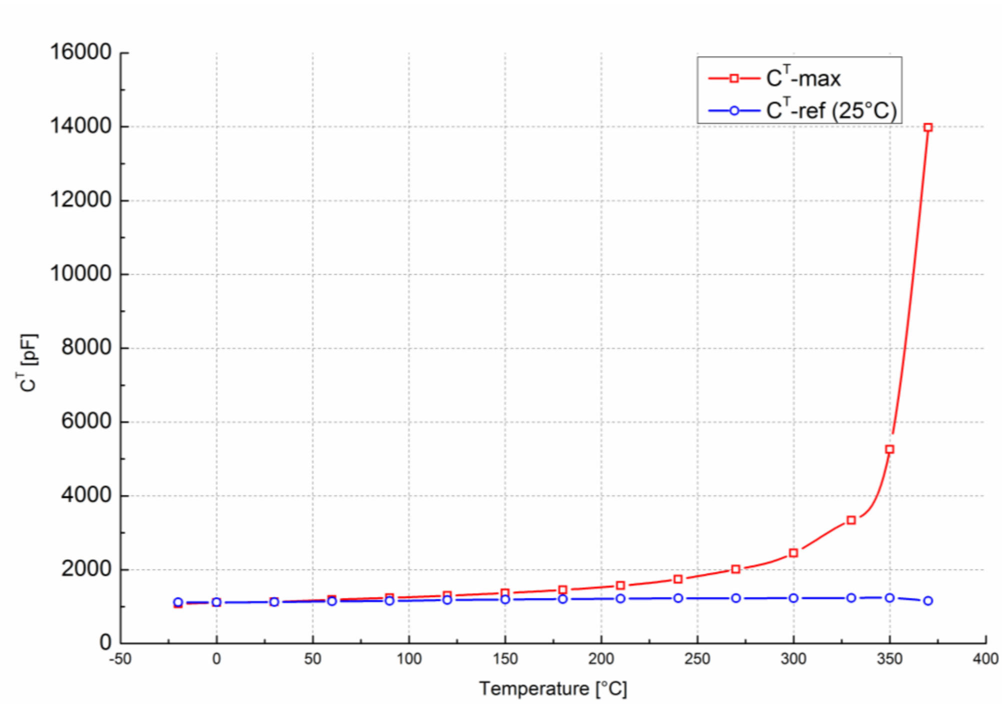

Figure 7 The temperature dependence of the capacitance on 1kHz of the PZT ceramic ring within the temperature range of -20 °C to 370 °C.

The check measurement of the capacitance C^T presented in Fig. 7 exhibits capacitance increase when the Curie point is approached. In capacitance, no major changes usually occur in the reference value measured at 25 °C. At high temperatures, capacitance at the currently set temperature grows markedly; conversely, after stabilization of the sample, the reference temperature decreases compared to the initial values. Repoarization of the sample then results in a return to the original values..

3. Conclusion

The measurement of temperature dependences on a ring sample of the Sonox P502 piezoelectric ceramics has pointed to a significant influence of temperature within the range of 350 °C to 370 °C, a band where gradual depolarization of the PZT ceramics already occurs. The indicated region, however, stands substantially higher than the Curie point value of 335 °C, which is specified by the manufacturer of the PZT ceramics. In practical applications of the material, this value can be partially exceeded without the ceramics being depolarized and the knock sensor damaged.

NOMENCLATURE

C^T	[F]	Free capacitance
E	[V/m]	Polarization vector
f_s	[Hz]	Series resonance frequency
f_p	[Hz]	Parallel resonance frequency
k_{eff}	[-]	Effective electromechanical coupling factor
r_s	[m]	Arithmetic average of the outer and the inner radius of the ring resonator
r_e	[m]	Outer radius of a ring resonator
r_i	[m]	Inner radius of a ring resonator
s_{ij}	[m^2/N]	Elastic compliance constant
Y	[Pa]	Young's modulus
ρ	[kg/m^3]	Density

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