Noise in Piezoelectric Ceramics at the Low Temperatures

Petr SEDLAK, Jiri MAJZNER, Josef SIKULA

Czech Noise Research Laboratory, Department of Physics, Brno University of Technology,
Technicka 8, Brno 616 00,Czech Republic

sedlakp@feec.vutbr.cz, majzner@feec.vutbr.cz, sikula@feec.vutbr.cz

Abstract. *The piezoelectric ceramic belongs to materials with widespread spectrum of applications. It can be found in sensors as well as in ceramic capacitors. The main sources of voltage or current fluctuation in piezoelectric ceramics are thermal noise, polarization noise and low frequency 1/f noise. The observed spectra of fluctuating voltage or current can be very well described by the generalized Nyquist relation for linear dissipative system. In this work, we focused on validity of the Nyquist relation for piezoelectric ceramics in temperatures 150 K-270 K. The electrical impedance and noise spectral density are measured and compared in frequency range 100 kHz - 1 MHz. The measurements were made in thermal stable condition and under equilibrium conditions in the case of noise measurement.*

Keywords

Piezoelectric ceramics, thermal noise, 1/f noise.

1. Introduction

Piezoelectric ceramics belong to materials which found widespread spectrum of applications, for example, electronic, electro-optical, and electromechanical applications. This material is widely used in non-destructive acoustic/ultrasonic methods, especially in acoustic emission (AE). This technique offers great potential due to its ability of quantitative evaluation such as crack location and crack characterization. The AE sensors are almost of piezoelectric ceramics type due to its ability of high sensitivity with wide bandwidth. The signal-to-noise ratio of these sensors depends on many factors including minimization of the own noise in piezoelectric part.

The noise in piezoelectric materials can be described on the basis of fluctuation-dissipation theorem which relies on the assumptions that the response of a system in thermodynamic equilibrium to a small applied force is the same as its response to a spontaneous fluctuation and the thermal motion of charge carriers in any conductor is a source of random fluctuations of current. This theorem was formulated by Nyquist [1] in 1928. Since temperature plays a key role for piezoelectric ceramics, Brophy [2] examined the fluctuations of ferroelectrics ($BaTiO_3$) near Currie temperature and proposed a model for the fluctuation of polarization vector on the basis of fluctuation dissipation theorem. He also found that noise minimum occurs at Currie temperature due to fast impedance decrease of material. Courtard et al. [3] and, later, Sedlak et al. [4] concerned the temperature influence on noise of piezoelectric ceramics at temperature range 300 K - 350 K and 300 K - 390 K, respectively. Both papers showed that voltage fluctuations can be very well described by generalized Nyquist relation. It implies the question concerning the noise at low temperatures.

This work focuses on comparison of the noise measurements and calculations in frequency range from 100 kHz to 1 MHz for temperatures 150 K - 270 K in order to prove the validity of Nyquist relation.

2. Theory

The main sources of voltage or current fluctuation in piezoelectric ceramics are thermal noise, polarization noise and low frequency 1/f noise. Thermal noise is given by interaction of phonons with free electrons or holes and noise spectral density of voltage fluctuations is proportional to sensor resistance and temperature. Fluctuation of electrical polarization in piezoelectric ceramics is an additional source of the voltage noise. Electrical dipoles are vibrating due to thermal energy and their motions create induced electric charges on electrodes, with time dependent value of the total charge. Induced electric charge fluctuates and this is the origin of voltage fluctuation. This is generation recombination noise with exponential distribution of relaxation constant [1]. Noise 1/f originates from superposition of particular generation recombination spectra [5], [6]. The observed spectra of fluctuating voltage or current can be very well described by a relation which was derived in a very fundamental way by Nyquist [1]. He analyzed the experiments made by Johnson [7] who observed the equilibrium noise in conductors and proved experimentally that noise spectral density of voltage fluctuations is proportional to the resistance of the conductor and to its absolute temperature. The generalized Nyquist theorem for voltage fluctuations is described by

$$S_U(\omega) = 4kT\ \mathrm{Re}\big(Z(\omega)\big) \qquad (1)$$

where k is Boltzmann constant, T is absolute temperature and Re($Z(\omega)$) denotes a real part of electrical impedance. Fig. 1 shows the noise spectral density of piezoceramic disc used in AE sensors. This dependence is a simulation of PZ27 disc, and was calculated by our mathematical model [8], which is based on theory of finite element method and on Nyquist relation. Also several another approaches create models based on this relation for electronic noise in ultrasonic transducers [9-11].

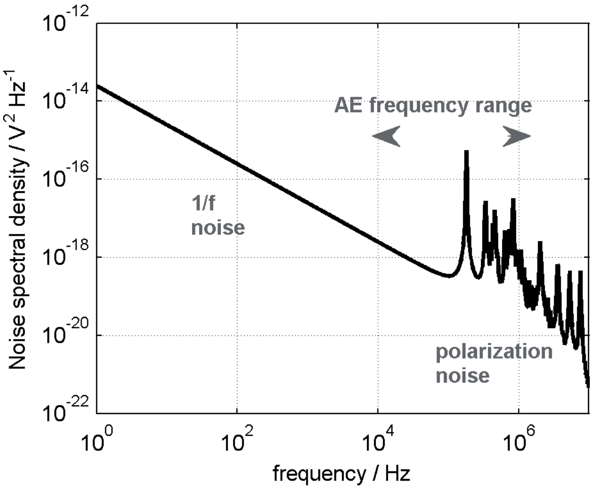

Fig. 1. Simulation results of the mathematical model based on Nyquist relation [8] at room temperature.

3. Experiment

The experiment was carried out on PZ27 disc specimen of diameter 12.74 mm and thickness 2.54 mm. The material is produced by Ferroperm Piezoceramics A/S, and belongs to piezoelectric soft materials, which are suitable for sensing applications.

The measurements of electrical impedance were provided by RLC meter E4980A (Agilent Technologies, Inc.). The band of analysis covers the frequency range from 100 kHz to 1 MHz. Measurement of noise spectral density frequency dependence requires amplifier and filter competent quality. Our apparatus consists of input low noise preamplifier (PA 15, 3S Sedlak), amplifier (AMP 22, 3S Sedlak) with high selective filters and 8bit A/D converter (National Instrument NI 5114). The sampling rate was 4 MHz and the sample was measured under equilibrium conditions. For each temperature, the 200 realization of noise measurement were made to get fine resolution of noise spectral density. The noise background level of measurement set-up was $5\mathrm{x}10^{-18}\ \mathrm{V}^2\,\mathrm{Hz}^{-1}$. Fig. 2 shows it as well as the noise spectral density for various values of resistance on PA15's input at room temperature

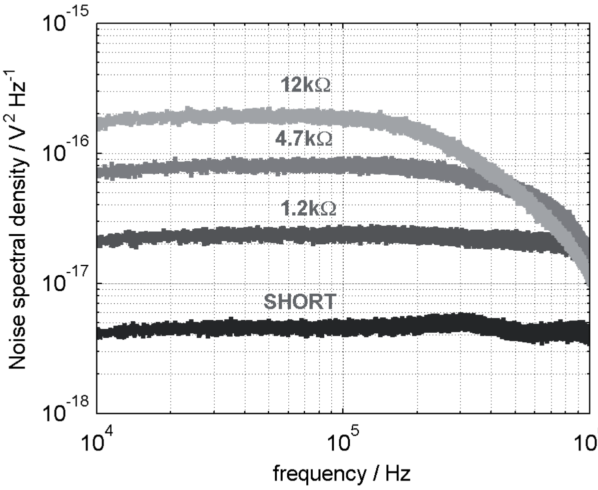

Fig. 2. Noise spectral density of measurement set-up for short input and three resistors (1k2, 4k7 and 12k).

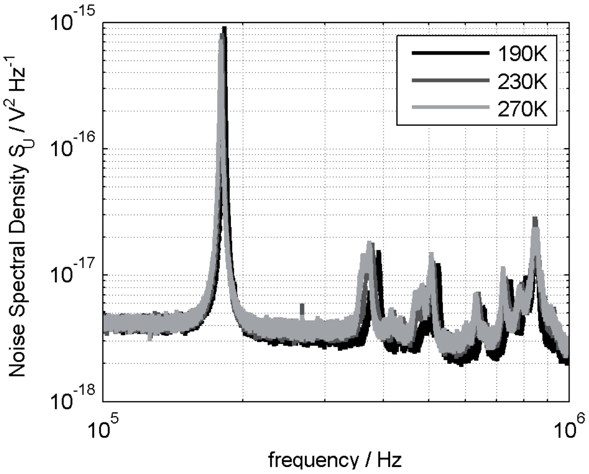

Fig. 3. Noise spectral density for temperatures 190 K, 230 K and 270 K.

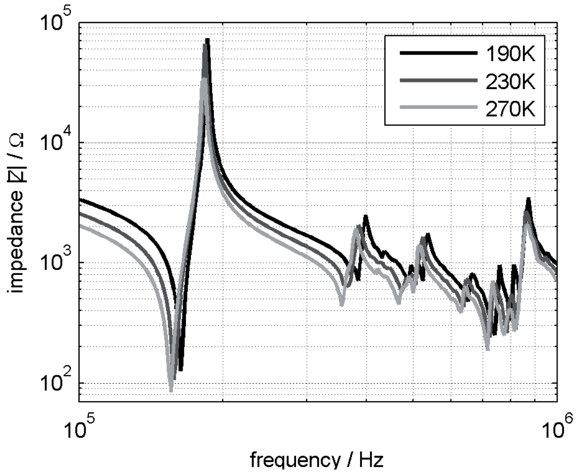

Fig. 4. Electrical impedance for temperatures 190 K, 230 K and 270 K.

The temperature was monitored and controlled by developed software from the PC via GPIB interface.

Sample was cooled using liquid nitrogen and was tempered by ordinary heating on desired temperature. To eliminate interference arising from the ambience, the sample and preamplifier PA15 were shielded electrically and magnetically. Both amplifiers were powered from batteries.

4. Results and Discussion

The noise and impedance measurement were done for temperatures from 150 K to 270 K. The acquired curves show a frequency shift to lower values with temperature increase. The electrical impedance decreases with increasing temperature while noise spectral density is not changed significantly. Fig. 3 and 4 illustrate this behavior on measured dependences for temperature 190 K, 230 K and 270 K.

In order to Nyquist theorem, our focus concentrates to influences of temperature on noise spectral density and real part of impedance. Only maximal value in both dependences is considered in selected frequency range. These values correspond to the fundamental planar resonance of the specimen. With increasing temperature, the noise spectral density remains almost the same as shown in Fig. 5. To the contrary, real part of impedance shows linear dependence on temperature with negative slope - 379.73 Ω/K (Fig. 6) for planar resonance.

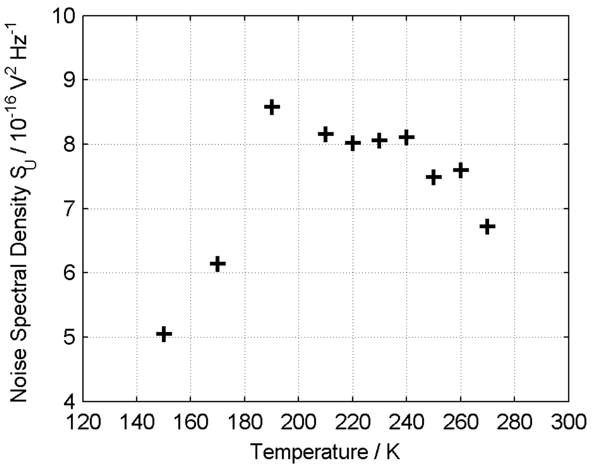

Fig. 5. Noise spectral density vs. temperature.

The specimen temperature seems to have slight influence on the level of noise spectral density in temperature range 150 – 270 K. On the other hand, the thermal influence on impedance is not insignificant. The decrease of the real part of impedance is explained by thermal sensibility of certain characteristics of the piezoelectric material such as the dielectric constant [12]. In view of Nyquist relation, the decrease of real part of impedance compensates the increase of the thermal noise, when the temperature increases.

In our previous study [4] at temperatures 300 K-390 K, a commercially available material PCM51 shows similar behavior. We also compared the measured and calculated noise spectral density for correspond temperature in percentage. Fig. 7 represents this comparison. With increasing temperature, the results of measurement and calculations are less different, nevertheless this difference is insignificant.

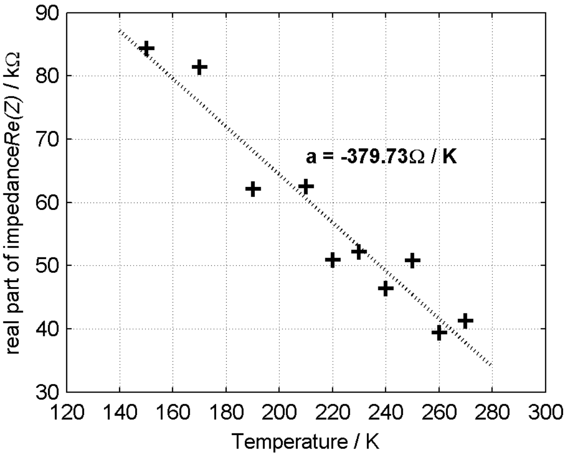

Fig. 6. Real part of impedance Re(Z) vs. temperature.

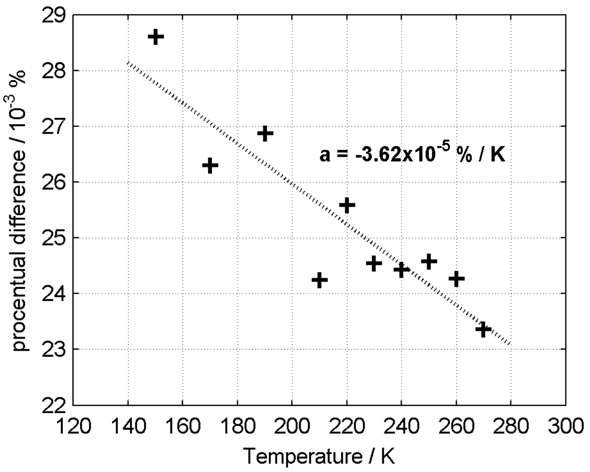

Fig. 7. Mean of percentage differences vs. temperature.

5. Conclusion

This work concerns the validity of Nyquist relation on piezoelectric ceramics considering the lower temperature. The experiment was carried out on PZ27 specimen. The noise and impedance measurements were made for temperatures 150 K - 270 K in frequency range from 100 kHz to 1 MHz. Comparing these measured and calculated noise spectral densities, we found that calculated results based on Nyquist relation gave us a good agreement with the noise measurement.

The temperature has slight influence on the noise spectral density of sample for range from 150 K to 270 K. The decrease of real part of impedance compensates the increase of the thermal noise, when the temperature increases.

Acknowledgements

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About Authors ...

Petr SEDLAK was born in 1980. He received his M.Sc in 2003 and his Ph.D. in 2007 from the Brno University of Technology. From 2007 to 2009, he was a postdoctoral researcher at the Department of Materials Engineering at the University of Tokyo, Japan. Currently, he is an assistant professor at the Department of Physics, Brno University of Technology. His research interests include fluctuation phenomena in solids, sensorics and non-destructive testing.

Jiri MAJZNER was born in 1976. He received his M.Sc in 2001 and his Ph.D. in 2008 from the Brno University of Technology. His main interests are noise measurements, and non-destructive testing.

Josef SIKULA was born in 1933. He received his M.Sc. degree in Electronics from the Technical University of Prague in 1957, and his M.Sc. degree in Physics from Komensky University, Bratislava in 1960. He received his Ph.D. degree in Semiconductor Physics in 1965. From 1980 he is Professor of Applied Physics at the Brno University of Technology. In 1970 he founded a group dealing with studies of noise and fluctuation phenomena in solids. His main interests are the noise spectroscopy, non-destructive testing, and defect engineering. In 2006 he received Dr.Felix Zandman Passive Electronic Industry Technology Award in recognition of Acknowledged Industry Leadership and Perseverance of Vision.