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Large signal characterization of hard PZT materials

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Abstract

In the last years new high-power resonant applications of piezoceramic devices such as motors and transformers became more and more important. Therefore, there is a need for a better understanding of the nonlinear behavior of piezoceramic material under driving conditions which cause large dynamical stress.

The main problem for such measurements is the self-heating of the samples caused by increasing electric driving fields and the increasing vibration velocity.

This paper presents a new measurement method where the specimen are excited under constant voltage conditions in such a way that the frequency is changed step by step in the range of the serial resonance frequency. The excitation can be intermitted between two frequency steps to reduce the temperature rise of the specimen. The vibration velocity, the resonator current, the phase shift between the voltage and the current and the temperature can be recorded simultaneously.

Results of transverse length vibrators made of different hard PZT materials will be presented.

Keywords: Piezoelectric properties; Thermal properties; Actuators; PZT ceramics

1. Introduction

Ferroelectrically hard piezoceramics are needed for the development of electromechanical elements, e.g. piezoelectric motors and transformers.

Up to now there are no standard mechanical, electrical and electromechanical parameters for hard piezoceramic material characterization.

In all cases there is the pragmatic approach to obtain large vibration ampltudes with as small as possible electric fields and resonator currents. Also, the dielectric and mechanical dissipation factors have to be small. This is valid for the temperature coefficients of the electrical, mechanical and piezoelectric parameters as well.

For the evaluation of piezoelectric ceramics under these aspects PI Ceramic has developed a measurement setup which measures the following parameters simultaneously: vibration displacement amplitude, resonator current, phase shift between control voltage and resonator current and temperature at the sample. All these parameters can be recorded as a function of the control frequency and the control voltage amplitude.

In this paper the measurement setup as well as some results of the measurements are presented and a comparison with similar published results is made.

2. Experimental

Fig. 1 shows the circuit diagram of the measuring setup.

The measurement setup is designed in such a way, that the parameters can be measured simultaneously.

The displacement is measured by a so called photonic sensor. The resonator current is determined by a voltage measurement at a series resistor $R_{\text{mes}} = 0.1\ \Omega$. The resonator temperature is measured by an IR thermometer.

The control of the whole setup, e.g. the output of the control signal, the determination of the photonic sensor signal and the voltage drop at the measuring resistor, is done by a frequency response analyzer (FGA).

The geometry of the samples (37 mm × 7 mm × 1 mm) has been chosen according to the limited bandwith of the

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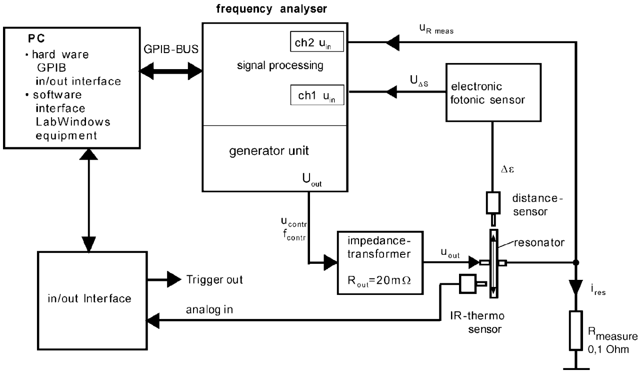

Fig. 1. Measuring set-up.

photonic sensor (80 kHz). The output resistance of the control amplifier is 20 mΩ, which results in a constant control voltage amplitude in the vicinity of the series resonance frequency.

3. Results

The measurements were performed with three different samples of piezoceramic materials. Figs. 2 and 3 show the vibration velocity as a function of the control frequency and the control voltage amplitude. The frequency parameter was changed from higher to lower values. The results of the diagram in Fig. 2 were measured by a bursted signal where the control voltage was switched off for 10 s after each measurment frequency change. The procedure was different for the results shown in Fig. 3 where the control voltage was continuously applied to the sample during the whole measurement period.

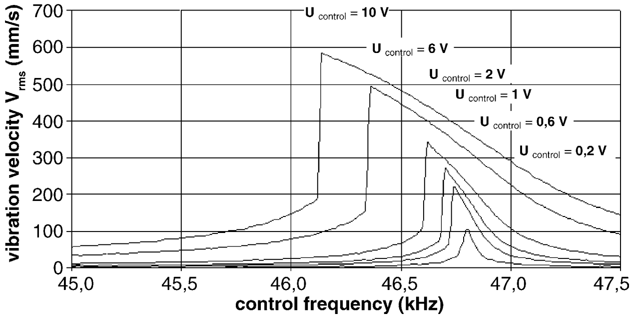

Fig. 2. Vibration velocity vs. control frequency and voltage (continuous signal).

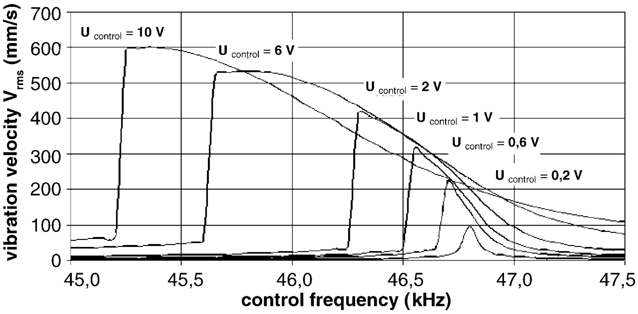

Fig. 3. Vibration velocity vs. control frequency and control voltage (bursted signal).

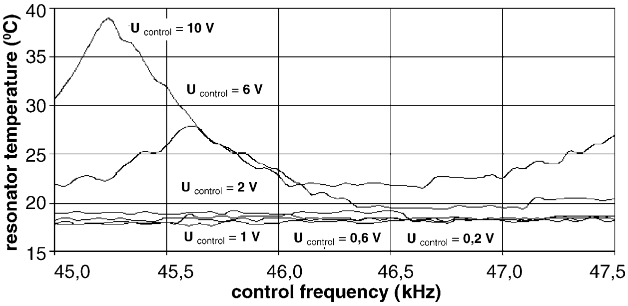

Fig. 4. Resonator temperature vs. control frequency and control voltage (continuous signal).

The vibration velocities in all the Figures shown are average values.

The Figures principally show rising vibration speeds with rising control voltage amplitudes. The well-known jump features in direct vicinity of the resonance frequency can be observed at control voltage amplitudes >0.6 V. The frequency shift for continuous control is larger than in the bursted case because of the rising sample temperature.

Fig. 4 show the associated temperature results. Only a small rise of the resonator temperature of approximately 3 K can be recognized for the bursted control voltage. In contrast, the continuous voltage signal with an amplitude of 10 V causes a resonator temperature rises of >40 K.

For the characterization of the mechanical losses we introduced the relative quality factor Q_{rel}.

For the quality factor we have

$$\Delta s \approx Q d_{31} \frac{lU}{d}$$

Δs is the expansion; l; d is the resonator length and thickness; U is the control voltage; Q is the mechanical quality factor and d_{31} is the deformation coefficient

$$Q_{\text{rel}} = \frac{Q_i}{Q_0} = \frac{v_i}{v_0}\frac{U_0}{U_i}$$

$U_{0;\,i}$ is the control voltage and $v_{0;\,i}$ is the maximum vibration velocity.

Fig. 5 shows the resonator temperatures and the relative quality factor Q_{rel} as a function of the maximum vibration velocity.

The diagrams in Figs. 6 and 7 allow a comparison between three different investigated materials.

Another compressed representation of the measured values is shown in Figs. 6 and 7. The representations show frequency shift, resonator current, temperature and quality factor in dependence on the maximal value of the vibration velocity for three different materials.

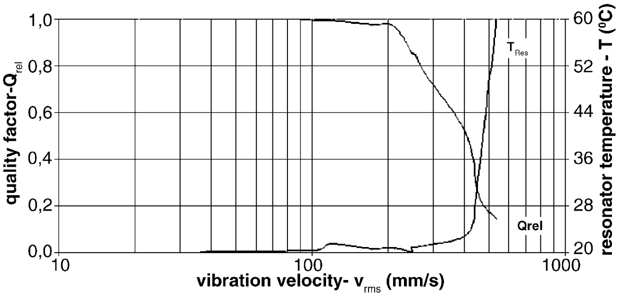

Fig. 5. Relative quality factor and resonator temperature vs. vibration velocity (continuous signal).

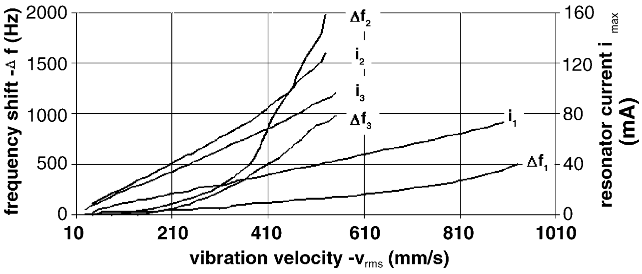

Fig. 6. Frequency shift and resonator current vs. vibration velocity.

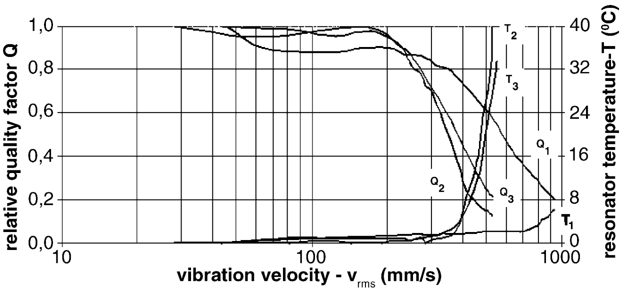

Fig. 7. Relative quality factor and resonator temperature vs. vibration velocity.

For large vibration the piezoceramic material 1 shows low current, low frequency shift, slight increase of the resonator temperature and a flat slope of the relative quality factor compared with the materials 2 and 3.

4. Discussion

We compared the results of our investigations with published results. Table 1 gives a survey of the principal measurement results of different research groups in Japan, in the USA and in Europe in comparison to our results.

Fig. 8 shows the determined vibration velocity results of a Japanese group as well as the result of this work as an example.

Piezoelectric materials can be also compared by the help of the EC standard draft P2EN50324 CENELEC (2001). According to the regulations of this draft PI Ceramic materials were measured and the coefficients α and β were determined.

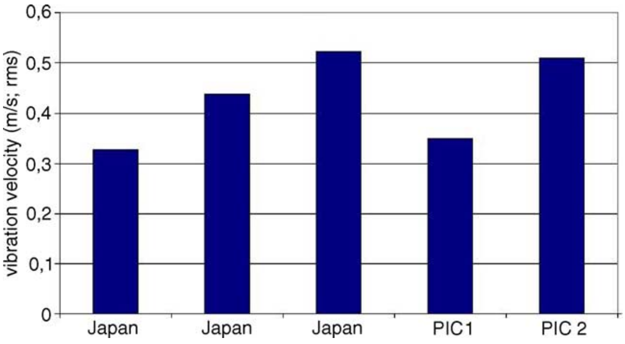

Fig. 8. Vibration velocities of Japanese- and PI-Ceramic materials.

Table 2 shows that the coefficients of the compositions examined in this paper strongly deviate from typical values of the standard. Therefore, we checked the formulas in the draft by recalculating a velocity from the $\langle S\rangle = 3.74 \times 10^{-4}$ and $\omega = 85$ kHz values of the specified example material; see Table 3.

We found that the calculated velocity (1.97 m/s) is about two times higher than the specified velocities in the references[2–4] as well as in our paper.

This is very surprising because the highest velocity ever measured is about 0.92 m/s in an Eu- and Yb-doped material.[2]

Table 1
Principal equipment parameters

Requirement	Japan	USA	Europe	PIC
Constant current		×	×	
Constant voltage	×			×
Frequency scanning	×	×		×
Frequency sweep		×	×	
Measuring parameter				
Expansion/velocity	×			×
Current	×	×	×	×
Voltage		×	×	
Temperature	×	×		×
Specimen size (mm)	43 × 7 × 1	43 × 7 × 2	20 × 6 × 2	35 × 7 × 1

Table 2
Calculation results according to the EC standard

	$\alpha \times 10^5$	$\beta \times 10^5$
Publication[1]	0.4	4.3
PIC sample 1	10	65.8
PIC sample 2	3.3	19

Table 3
Results of the recalculation check (EC standard)

u (μm)	v_{rms}[1] (m/s)	$v_{\max}$[1] (m/s)	v_{rms}[2] (m/s)
3.74	1.4	1.97	0.92

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