Large signal characterization of hard PZT materials

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Abstract
In the last years new high-power resonant applications of piezoceramic devices like 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 stresses.
The main problem for such measurements is the self-heating of the samples caused by increasing electric driving fields and the increasing vibration velocity, respectively.
This paper will present a new measuring method were the specimen are excited under constant voltage conditions in such a way that the frequency is changed step by step in the vicinity 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, actuator, PZT.

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1 Introduction

For the development of electromechanical elements, e.g. piezoelectric motors and transformers, ferroelectrically hard piezoceramics are needed.
The preferred electrical, mechanical and electromechanical parameters of these materials cannot be given in detail yet.
From the point of view of the plausibility at present large vibration amplitudes have to be generated by small electric fields and small resonator currents. The dielectric and mechanical dissipation factors have to be small. This can be applied 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 measuring set up 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 measuring set up as well as some characteristic representations of the results of the measurements are presented and additionally a comparison with similar published results is drawn.

2 Experimental

Figure 1 shows the circuit diagram of the measuring set up.

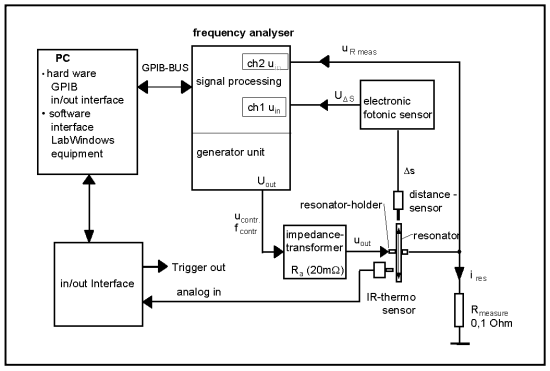

Fig. 1: Measuring set-up

The measuring set up 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 measuring resistor R_{mes}= 0,1Ω. The resonator temperature is quantified 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 of (37x7x1) mm³ was chosen in a way that the limited bandwith of the photonic sensor of 80 kHz can be tolerated. The output resistance of the control amplifier is just 20mΩ, which results in a constant control voltage amplitude in the vicinity of the series resonance frequency.

3 Results

The measurements were accomplished at samples of three different piezoceramic materials. Figure 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 high to low frequencies. The results of the diagram in figure 2 were measured by a bursted signal were the control voltage was switched off for 10 seconds after each measuring frequency change. The procedure was different for the results in figure 3 were the control voltage was continuously applied to the sample during the whole measuring time. The vibration velocities of all pictures are average values.

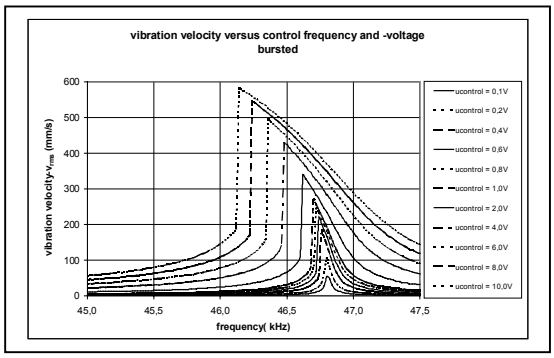

Fig. 2: Vibration velocity versus control frequency and voltage (bursted signal)

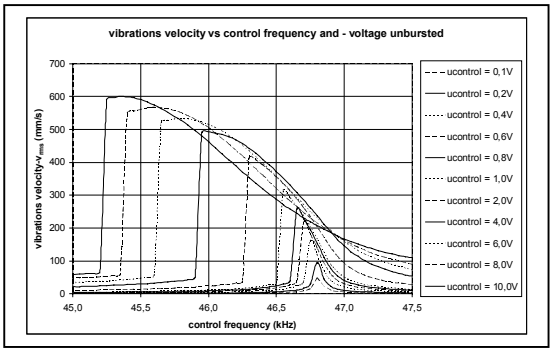

Fig. 3: Vibration velocity versus control frequency and voltage (continous signal)

The illustrations 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.
Figures 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 causes a resonator temperature rises of > 40 K with a control voltage amplitude of 10 V.

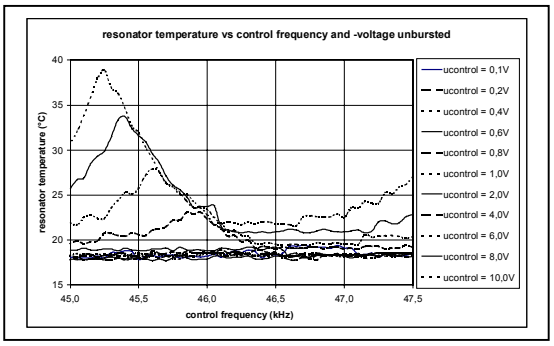

Fig. 4: Resonator temperature versus Control frequency and control voltage (continuous signal)

In the figure 6 the relative quality factor and the resonator temperature as a function of the vibration velocity
For the evaluation of the mechanical losses we introduced the relative quality factor Q_{rel}.
The quality factor one computes

$$\Delta s = Q \cdot d_{31} \cdot \frac{l \cdot U}{d}$$

Δs - expansion
l ;d - resonator length; thickness
U - control voltage
Q - mechanische Güte
d_{31} - deformation constante

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

$U_{0;\,i}$ - Steuerspannung
$v_{0;\,\iota}$ - max. vibration velocity
y $U_{0;}$ U_i

Figure 5 shows the resonator temperatures and the relative quality factor Q_{rel} versus the maximum vibration velocity.
The diagrams in the figures 6 and 7 allow a comparison of three different investigated materials.
Figure 6 shows the frequency shift at the maximum vibration velocity and the belonging maximum resonator current.

Figure 8 shows the behavior of the relative quality factor and the resonator temperature versus the maximum vibration velocity.

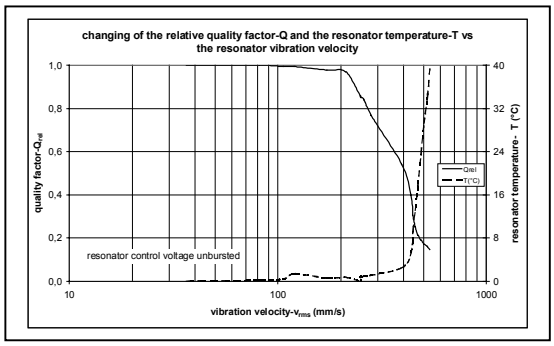

Fig. 5: Relative quality factor and resonator temperature versus vibration velocity (continuous signal)

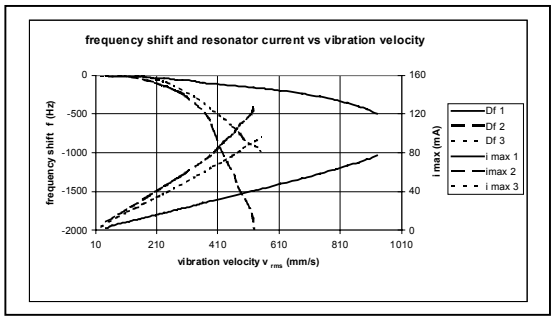

Fig. 6: Frequency shift and resonator current versus vibration velocity

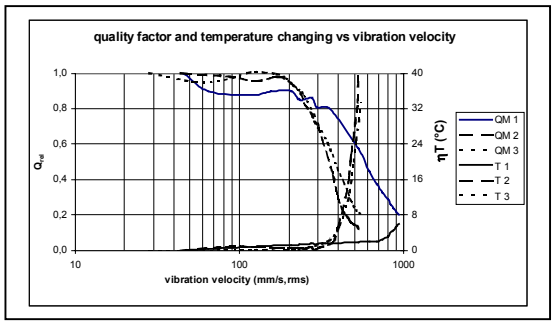

Fig. 7: Relative quality factor and resonator temperature versus vibration velocity

Figure 7 shows the relative quality factor at the maximum vibration velocity and the belonging maximum resonator temperature.

4 Discussion

We compared the results of our investigations with published results.
The table 1 gives an survey of the principal measuring results of different research groups in Japan, in the USA and in Europe in comparison to our results.

Table 1: Principal equipment parameters

requirement	Japan	USA	Europe	PIC
constant current		X	X	
constant voltage	X			X
frequency scanning	X	X		X
frequency sweep		X	X	
measuring parameter				
expansion / velocity	X			X
current	X	X	X	X
voltage		X	X	
temperature	X	X		X
specimen size (mm)	43x7x1	43x7x2	20x6x2	35x7x1

Illustration 9 shows the determined vibration velocity results of a Japanese group as well as the result of this work as an example.

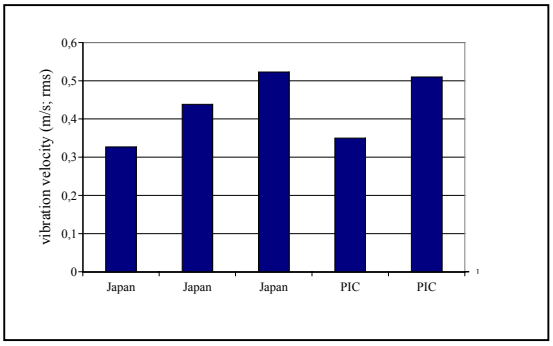

Fig. 8. Vibration velocities of japanese and PI Ceramic materials

Furthermore materials can be compared by the help of the EC standard draft P2ËN50324 CENELEC (2001). According to the regulations of the draft PI Ceramic materials were measured and the coefficients α and β were determined.

Table 2: Calculations results according to the EC standard

	α *(10^5)	β* (10^5)
Literatur	0,4	4,3
PIC Probe A	10	65,8
PIC Probe B	3,3	19

Table 2 shows that the coefficients of the compositions examined in this work deviate strongly from typical designated values of the standard. Therefore we checked the formulas in the draft by recalculating a velocity from the <S> $=3{,}74\text{x}10^{-4}$ and ω=85 kHz values of the specified example material.

Table 3. Results recalculation check (EC standard)

u (μm)	ν_{rms} (m/s)	ν_{max} (m/s)	$\nu_{max\ rms}^2$ (m/s)
3,74	1,4	1,97	0,92

We found that the calculated velocity (1,97m/s) is about two times higher that the specified velocities in the references 2, 3 and 4 as well as in our work.
This is very surprising because the highest velocity ever measured is 0,92 m/s at an Eu- and Yb-doped material [2].

References

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