Electromechanical characterization of piezoceramic elements around resonance frequencies at high excitation levels and different thermodynamic conditions

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***Abstract*— Electromechanical characterization of piezoceramic bulk elements around resonance is usually done with low-level continuous excitation signals at room temperature, but in real applications such elements are driven with different types of electrical signals, usually at higher levels and at different ambient temperatures. Both homemade and commercial soft and hard PZT piezoceramic elements were characterized using the established characterization methods that include the measurements of electrical admittance and surface displacement of the piezoceramic elements around the series resonance frequencies of two modes of vibration (radial and thickness extensional). The measurements included fast frequency sweeps at constant voltage excitation levels, burst measurements, at different temperatures and at different levels of excitation. A novel method for electromechanical characterization of piezoceramic elements that utilizes the resonance frequency tracking at different excitation levels (electric fields up to 5 kV/m, currents up to 1.3 A at resonance) and temperature conditions (up to 150 °C) has been proposed. The main idea is to keep the investigated element in resonance as the excitation level changes by constant tracking of its resonance frequency. The electromechanical parameters of the considered elements change mostly due to the nonlinear effects and the changes due to different thermodynamic conditions can be neglected when fast algorithm is applied. The decrease of the input electrical admittance magnitude is more expressed than the change of the resonance frequency when algorithm is applied.**

Keywords*— electromechanical characterization, linear and nonlinear driving conditions at different temperatures, tracking the resonant frequency.

I. INTRODUCTION

The piezoceramic elements are widely used in high-power ultrasonic transducers [1]. Their properties around resonance frequency of interest (radial, thickness) are often determined at low-level excitation signals (constant voltage, current or surface velocity) [2,3]. The low-level parameters are often used in virtual prototyping to obtain transducer properties before the construction of the overall transducer [4]. The input electrical impedance measured with different excitation signals (continuous, impulses) can give different results in estimated dielectric, piezoceramic and elastic constants around the considered mode of operation [5]. It is also important to excite the element with constant voltage, current or surface velocity level around the resonance mode of interest [6], due to impedance mismatch between the output impedance of the power amplifier and the impedance of the piezoceramic element around series resonance.

The thermal effects are always coupled with nonlinear effects due to self-heating, when a piezoceramic sample is excited with high electrical power at resonance, especially in unloaded conditions when it vibrates in air [7].

To study how thermal effects are coupled with nonlinear effects, input electrical admittance and surface displacement have been measured around two modes of interest (radial-R and thickness extensional-TE) for four PZT piezoceramic elements (commercial and homemade). The temperature was changed from room temperature up to 150 °C in steps of 25 °C. Low (0.5 V_{RMS}) and higher (5.0 V_{RMS}) level constant voltage excitation signals were used in down-frequency sweeping around resonance as required in standards [8]. In addition, measurements with burst excitation have been done to examine the influence of ambient temperature and level of excitation on the resonance frequency changes in the beats appearing in current waveforms [9].

Finally, the algorithm for tracking the resonance frequency has been implemented to examine the changes in

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the resonance frequency and the magnitude of the input electrical admittance depending on the excitation levels and at different temperatures. The algorithm starts at low-level excitation and finds the low-level resonance and admittance magnitude, then increases the excitation level and finds the new resonance frequency by doing fast step search around the previous level resonance. The sample surface temperature monitoring has been done to observe temperature changes in the samples.

II. EXPERIMENTAL SETUP

The basic geometric data of measured piezoceramic elements are shown in Table I. Two of the elements (PIC181 - hard and PIC155- soft PZT) were made by PI Ceramic, and the other two, also a hard and a soft PZT, were made at Jozef Stefan Institute in Ljubljana, Slovenia.

TABLE I. GEOMETRICAL DIMENSIONS OF CONSIDERED PIEZOCERAMIC SAMPLES

Sample name	D=2a (mm)	t (mm)
PIC 181 and PIC 155	50	5
Homemade hard PZT	25.7	5.4
Homemade soft PZT	24.5	4.8

The experimental setup consisted of an oven, photonic sensor for displacement measurements, a function generator, a digital oscilloscope, a differential voltage probe, a current probe, a temperature sensor, a programmable vector network analyzer, and an RF power amplifier (Fig. 1).

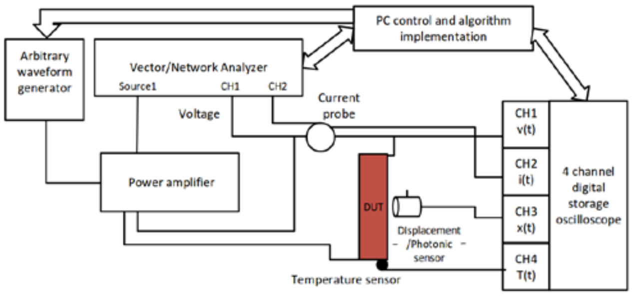

Fig. 1. Measurement setup for electromechanical characterization of samples at different driving and thermodynamical conditions

First, the input electrical admittance and displacement were measured around the resonance mode of interest (R and TE) and in wide band using the BODE 100 vector network analyzer, to determine all resonance frequencies in the frequency range from 1 kHz up to 500 kHz. Electrical admittance/surface displacement are measured using the classical constant-voltage method at six different ambient temperatures (up to 150 °C) and two different excitation levels (0.5 V_{RMS} and 5 V_{RMS}).

The second type of measurements was done with burst signals.

In the third type of experiments resonance tracking was done using the tracking algorithm at several different excitation levels (up to 25 V_{RMS}), by measuring the change of maximum admittance and the series resonance frequency, and by monitoring the surface temperature of the sample due to self-heating.

III. MEASUREMENT RESULTS

The measured parameters (the series resonance frequency (f_s), the maximum real part of the input electrical admittance ($Re(Y_s)$), maximum root mean squared displacements (X_{RMS}) and the quality factors (Q_m) at series resonance) are shown in Table II for radial and TE mode at each temperature, for all four samples and low voltage excitation level. The corresponding data obtained at the higher excitation level is shown in Table III.

TABLE II. ELECTRICAL AND MECHANICAL PARAMETERS OBTAINED FROM FREQUENCY SWEEPING AROUND RESONANCE AT LOW LEVEL EXCITATION (0.5 V_{RMS})

Sample	Parameters/T	25 °C	50 °C	75 °C	100 °C	125 °C	150 °C
PIC181-Rad	f_s(Hz)	45234	45281	45281	45328	45421	45560
	$Re(Y_s)$(Si)	0.157	0.173	0.122	0.124	0.122	0.112
	Q_m	539	627	388	374	346	287
	X_{RMS}(nm)	93.0	81.0	113.1	57.4	157.0	94.8
PIC181-TE	f_s(Hz)	413625	413781	413828	413969	414266	414719
	$Re(Y_s)$(Si)	0.233	0.222	0.229	0.209	0.195	0.192
	Q_m	619	525	507	403	327	280
	X_{RMS}(nm)	21.7	20.0	17.6	13.6	2.4	1.6
PIC155-Rad	fs(Hz)	38612	38491	38370	38370	38571	38894
	$Re(Y_s)$(Si)	0.023	0.024	0.026	0.028	0.032	0.036
	Q_m	54	51	51	51	52	58
	X_{RMS}(nm)	77.4	62.3	63.7	70.4	66.1	56.8
PIC155-TE	f_s(Hz)	403847	403594	403566	403819	404550	405591
	$Re(Y_s)$(Si)	0.096	0.103	0.113	0.121	0.127	0.128
	Q_m	127	124	121	116	110	106
	X_{RMS}(nm)	2.3	2.2	2.1	2.7	2.1	2.3
Homemade hard - Rad	f_s(Hz)	86218	85920	85397	85397	85397	85023
	$Re(Y_s)$(Si)	0.033	0.030	0.021	0.009	0.020	0.036
	Q_m	505	349	239	83	166	258
	X_{RMS}(nm)	59.9	48.9	49.3	29.7	44.7	46.6
Homemade hard - TE	f_s(Hz)	375781	375156	373781	373375	373313	373438
	$Re(Y_s)$(Si)	0.027	0.024	0.021	0.024	0.022	0.038
	Q_m	354	316	283	288	169	297
	X_{RMS}(nm)	84.9	67.6	72.3	70.0	73.6	86.6
Homemade soft-- Rad	fs(Hz)	81365	80148	78288	76069	73922	72992
	$Re(Y_s)$(Si)	0.006	0.006	0.007	0.009	0.012	0.016
	Q_m	44	43	43	41	39	42

	X_{RMS}(nm)	21.9	24.7	32.1	40.4	58.0	63.7
Homemade soft – TE	f_s(Hz)	426500	423263	419194	414513	409963	421425
	$Re(Y_s)$(Si)	0.009	0.010	0.011	0.012	0.011	0.014
	Q_m	95	87	82	77	64	87
	X_{RMS}(nm)	5.5	6.1	3.9	3.9	5.3	5.3

TABLE III. ELECTRICAL AND MECHANICAL PARAMETERS OBTAINED FROM FREQUENCY SWEEPING AROUND RESONANCE AT HIGH LEVEL EXCITATION (5 V_{RMS})

Sample	Parameters/T	25 °C	50 °C	75 °C	100 °C	125 °C	150 °C
PIC181-Rad	f_s(Hz)	44484	44469	44484	44500	44563	44750
	$Re(Y_s)$(Si)	0.083	0.079	0.074	0.072	0.072	0.070
	Q_m	545	433	333	283	258	221
	X_{RMS}(nm)	606.6	574.2	521.3	358.3	853.0	1582.6
PIC181-TE	f_s(Hz)	412641	412641	412531	412922	413391	414016
	$Re(Y_s)$(Si)	0.154	0.135	0.150	0.146	0.167	0.169
	Q_m	381	291	290	247	246	220
	X_{RMS}(nm)	140.5	132.3	108.1	94.1	13.0	7.7
PIC155-Rad	f_s(Hz)	37575	37363	37188	37188	37363	37700
	$Re(Y_s)$(Si)	0.012	0.012	0.013	0.015	0.017	0.019
	Q_m	24	23	23	23	24	25
	X_{RMS}(nm)	362.7	288.5	308.0	324.0	318.0	308.7
PIC155-TE	f_s(Hz)	401288	401091	401091	401288	401850	402806
	$Re(Y_s)$(Si)	0.070	0.075	0.082	0.088	0.094	0.098
	Q_m	67	67	64	62	58	54
	X_{RMS}(nm)	9.9	15.2	13.4	10.7	10.6	10.5
Homemade hard - Rad	f_s(Hz)	85719	85406	84844	84438	84156	83625
	$Re(Y_s)$(Si)	0.014	0.017	0.017	0.022	0.025	0.027
	Q_m	144	162	192	163	159	136
	X_{RMS}(nm)	258.9	254.4	308.2	335.6	316.2	302.3
Homemade hard - TE	f_s(Hz)	374344	373281	372000	371938	371719	371094
	$Re(Y_s)$(Si)	0.015	0.018	0.019	0.024	0.027	0.027
	Q_m	169	194	175	179	172	150
	$X_{,RMS}$(nm)	579.7	432.5	530.0	582.5	568.5	418.3
Homemade soft – Rad	fs(Hz)	79250	77469	75125	72906	70625	70156
	$Re(Y_s)$(Si)	0.003	0.003	0.004	0.005	0.007	0.009
	Q_m	21	19	18	17	17	19
	X_{RMS}(nm)	85.1	94.8	116.8	166.0	235.3	280.1
Homemade soft – TE	f_s(Hz)	421338	417750	413025	408081	416306	416131
	$Re(Y_s)$(Si)	0.006	0.006	0.006	0.006	0.010	0.013
	Q_m	44	40	35	18	21	38
	X_{RMS}(nm)	11.8	4.1	3.5	13.4	16.3	20.1

The example of the burst signals (voltage and current for the homemade hard sample) is shown in Fig. 2.

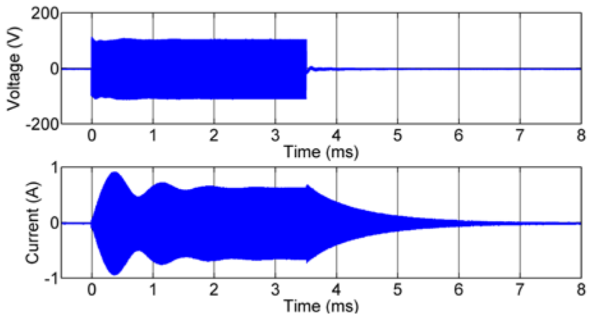

Fig. 2. Burst excitation and current response (homemade hard sample, number of cycles 300, burst period 50 ms, Voltage level 75 V_{RMS}, radial mode)

In the case of the excitation with the burst signal, the recorded parameters are the beat frequency (f_b), the initial increase rate of the response current (dI/dt), and the quality factor (Q_d) obtained from the current decay curve, at level of excitation (75 V_{RMS}). The results are shown in Table IV.

TABLE IV. TABLE MEASURED ELECTRICAL PARAMETERS WITH BURST SIGNALS AROUND RADIAL MODE OF VIBRATION

Sample	Parameters/T	25 °C	50 °C	75 °C	100 °C	125 °C	150 °C
PIC181	f_b (Hz)	732	1516	1681	1692	1643	1727
	dI/dt (A/s)	4062	15631	12588	12506	14900	16183
	Q_d	235	*N/A	*N/A	*N/A	*N/A	*N/A
PIC155	f_b (Hz)	2089	2051	2196	2124	1902	1704
	dI/dt (A/s)	4565	4846	5050	5480	6213	6691
	Q_d	35.5	32.5	32.6	32.1	30.1	27.9
Homemade-hard	f_b (Hz)	1091	1105	1167	1137	1173	1282
	dI/dt (A/s)	2033	2186	2311	2578	2944	3302
	Q_d	245	248	250	258	266	270
Homemade-soft	f_b (Hz)	4242	5106	7295	7210	9040	8553
	dI/dt (A/s)	2546	2559	2640	3279	4153	6428
	Q_d	26.4	32.0	37.2	44.0	42.6	45.3

*N/A due to failure caused by driving the sample at highest temperature and high excitation level

The results obtained with the algorithm for tracking the resonance frequency at different levels of excitations are shown in Figs. 3 and 4. Figure 3 shows the changes of the resonance frequency and the input electrical admittance at room temperature, depending on the excitation level expressed as applied electrical field (E) at f_s. Figure 4. shows the same dependencies for the temperature of 150 °C. Both parameters are normalized to the lowest-level values, and thus the relative change is shown.

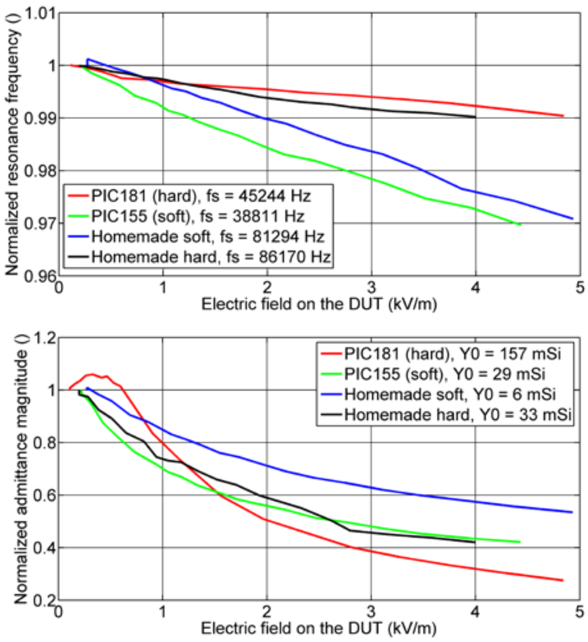

Fig. 3. Changes in resonance frequency (up) and admittance magnitude (down) tracked with the tracking algorithm on all considered samples at different levels of excitation (radial mode, T=25 °C).

The changes in temperature of the samples due to fast implementation of the algorithm can be neglected. The maximum change of the temperature was up to 10 °C which doesn't have significant influence on the resonance behavior.

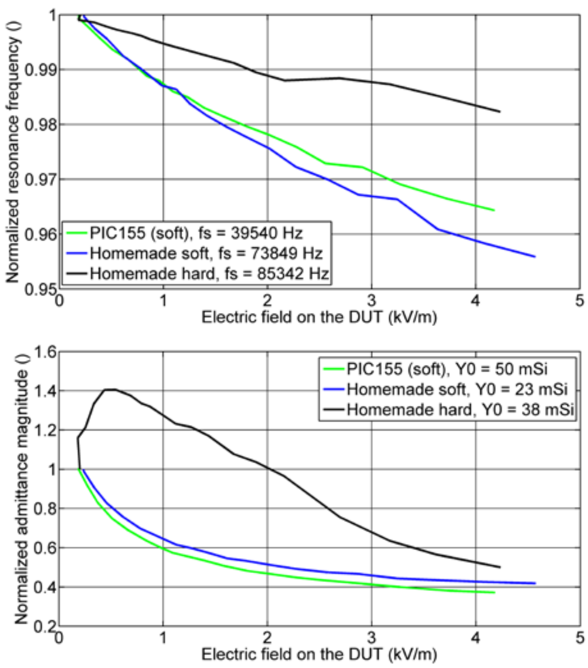

Fig. 4. Changes in resonance frequency (up) and admittance magnitude (down) tracked with the tracking algorithm on all considered samples at different levels of excitation (radial mode, T=150 °C).

IV. DISSCUSION AND CONCLUSION

The series resonance frequency of commercial samples is increased at low and higher excitation level, and for homemade samples it decreases with (see Table II and III). The real part of the input electrical admittance magnitude,e determined by using low voltage level frequency sweeping signals is decreased for commercial hard PZT samples and increased for other samples (Table II). The maximum displacement measured at resonance is almost constant for all samples at each considered temperature for lower excitation levels (Table II). At higher excitation levels the displacement magnitude is mostly decreased at higher temperatures (Table III). When burst signals are considered, the initial current rate is increased at higher temperatures as well as the beat frequency in current signal (Table IV).

When the algorithm for tracking the resonance frequency is implemented, the resonance frequency and admittance magnitude at resonance is decreased for all samples (Figures 3. and 4.). The decrease of the resonance frequency (up to 4.5 %) and admittance magnitude (up to 60 % at 150 °C) is more expressed for soft PZT samples due to higher level domain wall mobility.

Tracking the resonance behavior of the piezoceramic elements at harsh environments and at different excitation conditions can improve the construction process of more efficient sensors and transducers.

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REFERENCES

[1] G.S. Kino, Acoustic waves, devices imaging and analog signal processing, Book, Prentice –Hall Inc., 1987.

[2] IEEE Standard on piezoelectricity, IEEE Std 176-1978, New York , The Institute of Electrical and Electronics Engineers, 1978.

[3] K. W. Kwok, H. L. W. Chan, C. L. Choy, ''Evaluation of Piezoelectric Parameters by Various Methods'', IEEE Transaction of UFFC, Vol 44, ,1997, pp. 733-743.

[4] N. N. Abboud, G. L. Wojcik, D. K. Vaughan , J. Mould, D. J. Powell, L. Nikodym, Finite Element Modeling for Ultrasonic Transducers, Proc. SPIE Int. Symp. Medical Imaging 1998, San Diego, Feb 21-27, 1998.

[5] A. Petošić, N. Pavlović, M. Budimir: Comparison between piezoelectric material properties obtained by using low-voltage magnitude frequency sweeping and high-level short impulse signals, Ultrasonics (53),6, 2013, pp.1192-9 .

[6] Blackburn J F and Cain M G 2007: Non-linear piezoelectric resonance: a theoretically rigorous approach to constant i/v measurements J. Appl. Phys, 100, 2006, 11401.

[7] S. Sherrit, G. Yang, H.D. Wiederick and B.K. Mukherjee: Temperature Dependence of the Dielectric, Elastic and Piezoelectric Material Constants of Lead Zirconate Titanate Ceramics, Journal of Applied physicis, 2007, pp. 102, 114103.

[8] EN 50324-3:2002 Piezoelectric properties of ceramic materials and components - Part 3: Methods of measurement - high power.

[9] Blackburn J. F., Cain M. G. Non-linear piezoelectric analysis using burst mode: a rigorous solution. Journal of Physics D, 40 , 2007, pp. 227-233.