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What is really measured on a d_{33}-meter?

Jiří Erhart *, Lidmila Burianová

Department of Physics and International Center for Piezoelectric Research, Technical University of Liberec, Hálkova 6, CZ-461 17 Liberec 1, Czech Republic

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Abstract

Mechanical boundary conditions of PZT sample are not well defined in the measurement process on a d_{33}-meter due to the misfit in size or shape of the jaws and of the sample. Result of such d_{33} measurement is usually an effective value d_{33}^{eff}. Mechanical stress/strain conditions are simulated for PZT discs/cylinders in a d_{33}-meter by the finite element method (ANSYS® software) and an effective d_{33}^{eff} is calculated and compared to the original input d_{33} value as well as to the values measured on a d_{33}-meter (type ZJ-3C). Relative $d_{33}^{\mathrm{eff}}/d_{33}$ value seems to be more sensitive to the disc aspect ratio than to the PZT material type tested. Although such strong dependence on the aspect ratio has been found in simulations, it is not correlated with experiments. Coefficient d_{33}^{eff} is not significantly sensitive to the position of a d_{33}-meter metallic jaws with respect to the disc center.

Keywords: Piezoelectric properties; PZT

1. Introduction

The Berlincourt d_{33}-meter is one of the most commonly used piece of testing equipment for piezoelectric materials. A simple dynamic (or quasistatic) testing method is applied as recommended in the IEEE Standard.[1] A piezoelectric sample between metallic jaws is subjected to the mechanical load and the electric charge on the electrodes is analyzed.[1,2] However, although this testing equipment is very effective (PZT products are 100% tested in manufacturing process), the mechanical boundary conditions are not usually well defined. One of the reasons is the misfit between the size of the jaws and the sample. Another source of the possible errors could be the position of the jaws' contact points with the sample relative to the sample geometry and to the electrode pattern. Although it is recommended to test d_{33} by pressing the disc with fully electroded faces in the center, it is not always done so.

In this work, we tried to address the problem of the size incompatibility between the metallic jaws and the sample, i.e. the non-uniformity of the mechanical stress applied. The distribution of the mechanical stress in the piezoelectric disc/cylinder has been calculated by the finite element method (software ANSYS®) and the effective d_{33}^{eff} has been calculated as a function of the jaws' position with respect to the disc center. An attempt has been made to compare simulations with the measurement of the effective d_{33}^{eff} on a d_{33}-meter (ZJ-3C type).

2. FEA simulation and measurement

PZT disc/cylinder samples have been simulated by the finite element analysis (FEA) in a d_{33}-meter assuming an open circuit electrical condition for the sample in static approximation. In reality, a measured sample is shunted by some capacitance, which is recommended to be much higher than the capacitance of the sample.[1] Shunting capacitance could hardly be specified without knowing details of the d_{33}-meter design. Static approximation is also an assumption which is a good estimate. The dynamic force frequency generated in a d_{33}-meter should be much lower than any of the resonant frequencies of the measured sample. A d_{33}-meter used as a model in simulations as well as in measurements has an operating frequency of 110 Hz which is fairly well below the resonant frequencies of the samples. The amplitude of the force applied was 0.250 N.

* Corresponding author. Tel.: +42-48-535-3400; fax: +42-48-510-5882.

E-mail address: jiri.erhart@vslib.cz (J. Erhart).

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The jaws and PZT sample (taking into account symmetry conditions) were created as a 3D-model for FEA. We used the real dimensions of a d_{33}-meter jaws (i.e. metallic rods of 6 mm in diameter, capped by half spheres with the contact face of 2 mm in diameter; see Fig. 1) and the force amplitude. The effective d_{33}^{eff} value was calculated from the FEA nodal solution as

$$d_{33}^{\mathrm{eff}} = \frac{\sum_{(j)} A^{(j)} \left(d_{31} T_{11}^{(j)} + d_{31} T_{22}^{(j)} + d_{33} T_{33}^{(j)} \right)}{\sum_{(j)} A^{(j)} T_{33}^{(j)}} \tag{1}$$

where $A^{(j)}$ is an area corresponding to the jth node on the disc/cylinder main faces, $T_{kl}^{(j)}$ is a mechanical stress for the jth node and d_{31}, d_{33} are input values of the piezoelectric coefficients for FEA simulations. Eq. (1) includes the possible effect of the non-uniform mechanical stress distribution. FEA simulations were done under the assumption of ideal contact of the d_{33}-meter jaws and a sample (i.e. we keep the same degrees of freedom for each node at the contact between ceramics and the metallic jaws, but possibly different among nodes at the contact). No displacement in the direction parallel to the disc/cylinder axis is allowed for the upper section of the upper metallic jaw. Electric potential is equal for all nodes in the upper jaw and on the upper electrode. A similar electrical constraint is applied for the lower jaw and on the lower electrode. Measurements have been made on PZT discs/cylinder electroded on main surfaces (PZT of APC850 type from APC International, Mackeyville, PA, USA) in a ZJ-3C d_{33}-meter. The manufacturer suggests the relative error[3] of such a measurement as 2% in the measurement range 20–2000 pC/N. It corresponds to the error estimate done in Ref. 2. Results are summarized in Tables 1–3.

3. Results and discussion

Results obtained by FEA simulations and measured on a d_{33}-meter are very similar for thin discs, but differ significantly for thin cylinders. FEA results are also different from the input d_{33} value by 10–15% for thin discs and by 60% for thin cylinders. Such a big discrepancy for thin cylinders between simulations and measurement is understandable on the basis of the contact between

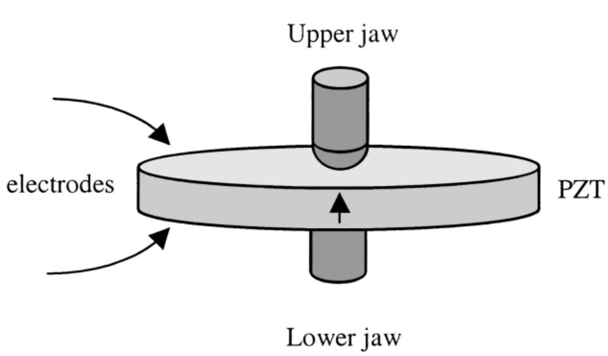

Fig. 1. Geometry of the PZT disc between d_{33}-meter jaws.

Table 1
FEA simulated and measured d_{33}^{eff} for discs/cylinders in center position in a d_{33}-meter

t/d	d_{33}^{eff} [pC/N] simulated	d_{33}^{eff} [pC/N] measured
0.076	523	460
0.083	494	455
0.110	519	465
0.125	490	461
0.137	494	474
0.276	528	471
0.337	520	473
1.000	193	474
1.039	178	462

Table 2
FEA simulations for disc/cylinder in center position for different PZT types

		t/d = 1.000	t/d = 0.137
PZT type	d_{33} [pC/N]	$d_{33}^{\mathrm{eff}}/d_{33}$	$d_{33}^{\mathrm{eff}}/d_{33}$
Model PZT	593	0.326	0.834
VIBRIT1100 [4]	640	0.241	0.788
N-6 [4]	302	0.342	0.806
N-8 [4]	226	0.359	0.792
N-10 [4]	635	0.325	0.810
N-21 [4]	417	0.291	0.799
N-61 [4]	296	0.346	0.799
PZT 5A [4]	374	0.326	0.784
48/52 PZT [5]	110	0.438	0.809

Table 3
FEA simulations (using Model PZT) and measurement of $d_{33}^{\mathrm{eff}}/d_{33}^{C}$ for disc/cylinders in a non-centered position[a]

	Distance from the disc edge x/d [1/16]							
	t/d	1	2	3	4	5	6	7
Measured								
	0.076	1.05	1.05	1.04	1.03	1.01	1.01	1.00
	0.083		1.02		1.00		0.99	
	0.110		0.96		0.98		0.99	
	0.125				1.00			
	0.137		0.98		0.98		0.99	
	0.276		1.00		1.00		1.01	
	0.337		1.00		1.01		1.01	
	1.000				1.01			
	1.039				1.00			
Simulated								
	0.200	0.86	0.96	0.95	1.00	0.96	1.00	0.96

[a] Values are expressed relatively to the value in the center d_{33}^{C}. Aspect ratio t/d is given by the thickness t and diameter d of the disc/cylinder.

the jaws and a sample surface. In simulations, equal strain for every node at the contact between the jaws and a sample is held, contrary to the possible 'sliding' of the jaws and the sample in measurements. Sliding is more important for the cylinders than for the discs because of the relatively larger contact area, i.e. the mechanical stress distribution is more non-homogeneous in cylinders than in discs. Moreover, the IEEE Standard[1] recommends the lateral dimension of the measured sample to be at least twice as large as the sample thickness. This condition is true for all discs used, but it is not satisfied for cylinders. As is evident from Table 2, there are not significant differences between $d_{33}^{\mathrm{eff}}/d_{33}$ in the center of the disc/cylinder simulated for different PZT types. Material data were taken from the company's published Materials Data Sheets.[4,5] If the jaws' position is not in the disc/cylinder center, the FEA results give us the d_{33}^{eff} values as a function of the jaws position (Table 3). There is not a big difference, except for the jaws' position very close to the disc edge. Otherwise, the simulated values are close to the range given by the d_{33}-meter suggested measurement error.

4. Conclusions

Comparison of the simulated and measured d_{33}^{eff} values suggest the following conclusions.

- The $d_{33}^{\mathrm{eff}}/d_{33}$ value is not sensitive to the PZT type tested, but sensitive to the disc aspect ratio t/d. d_{33}^{eff} in the disc center is smaller then input d_{33} value in simulations by 10–15%. Measured d_{33}^{eff} values for thin discs correspond to the FEA results.
- Experimental and FEA results for thin cylinders differ significantly because of the mechanical clamping between the metallic jaws and a sample.
- For thin discs, the non-central jaws position with respect to the sample does not influence significantly the d_{33}^{eff} values, unless the contact points are too close to the disc edge. Differences are within the measurement error for the d_{33}-meter.

We tried to quantify some common expectations from the d_{33}-meter measurements. Although the d_{33}-meter measurements are very comfortable, they have also some limits. The measured d_{33}^{eff} value is not always the exact material d_{33} value. Despite this, the d_{33}-meter remains a commonly used piece of testing equipment for piezoelectric materials.

FEA allowed us to analyze the d_{33}-meter measurement performance. Calculations of the respective non-uniform distribution of the mechanical stress/strain has been effectively done. The values simulated in static approximation were correlated with measured values on the commercially available d_{33}-meter.

Acknowledgements

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