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Determination of the piezoelectric coefficients d_{ij} of PZT ceramics and composites by laser interferometry

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Abstract

We have measured the piezoelectric coefficients of PZT ceramics by resonance and laser interferometry methods. The surface displacement was measured by a single-beam Michelson interferometer. A stable double-beam interferometer was also used to suppress the effect of bending. The piezoelectric coefficients d_{ij} of the PZT ceramic and of the 0–3 ceramic–polymer composites were determined from the displacements. The results for PZT d_{ij} coefficients obtained by the both methods are in good agreement.

Keywords: Composites; Laser interferometry; PZT

1. Introduction

The electromechanical properties of the piezoelectric ceramics and composites are investigated by various measurement techniques. For the design of piezoelectric applications such as actuators, sensors, positioners and others, knowledge of the piezoelectric coefficients d_{ij} is significant. Those can be determined through the direct piezoelectric effect, i.e. measuring the charge induced by an applied stress, or through the converse piezoelectric effect, i.e. measuring the strain induced by an applied electric field or standard resonance methods. In general, a specific resonance mode may be excited by application of variable frequency ac field to a piezoelectric sample of a specific shape and a specific polarization orientation.

Subresonance methods use a wide frequency range, but amplitude of the vibration is small and it is not simple to measure it accurately. The precise method for the determination of induced strain by electric field is the laser interferometry. The measurements of bulk materials by single-beam and double-beam interferometer systems were reported.[1–3] The piezoelectric coefficients d_{33}, d_{11} of some materials were measured in different frequency ranges. The values showed significant peak for some frequency.[1,2] In fact, the presence of the peaks motivated us to study the frequency dependence of PZT d_{ij} coefficients in more details.

2. Piezoelectric coefficients d_{ij}

2.1. Laser interferometry

For a monochromatic light of wavelength λ interfering with a reference beam, the light intensity I at a detection point is

$$I = I_p + I_r + 2\sqrt{I_p I_r}\cos(4\pi\Delta d/\lambda). \tag{1}$$

I_p is the light intensity of the probing beam, I_r is the light intensity of the reference beam and Δd is the optical path-length difference between the two beams. Eq. (1) can be rewritten as

$$I = \frac{1}{2}(I_{max} + I_{min}) + \frac{1}{2}(I_{max} - I_{min})\cos(4\pi\Delta d/\lambda). \tag{2}$$

I_{max} and I_{min} are the maximum and minimum interfering light intensities. For small displacement measurement, it is desirable to set the path difference at a point ($\pi/2$ point) about $(2n+1)\lambda/8$, n-ordinal number. The light intensity change will be maximized for the

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same change in Δd. Near this point we can write the optical path-length difference Δd as:

$$\Delta d = d_{ac} + (2n+1)\lambda/8, \quad (3)$$

d_{ac} periodical change of sample length induced by electric field.

Eq. (1) can be reduced to

$$I = I_p + I_r \pm 2\sqrt{I_p I_r}\sin(4\pi d_{ac}/\lambda), \quad (4-1)$$

$$I = I_p + I_r \pm 2\sqrt{I_p I_r}\,(4\pi d_{ac}/\lambda). \quad (4-2)$$

The approximation of sin x is valid for small x (for $|d_{ac}| < 130$ Å).[1] In Eq. (4) the sign '+' or '−' depends on whether n is an even or odd number. For the sinusoidal displacement $d_{ac} = d_0 \cos(\omega t)$, the displacement amplitude d_0 can be calculated as

$$d_0 = \left(\lambda/\sqrt{2}\pi\right)\left(V_{out}/V_{p-p}\right) \quad (5)$$

V_{out} is a rms value of the detected signal and V_{p-p} is the peak to peak value of the interference signal, which corresponds to the maximum change in the interference signal (I_{max}–I_{min}).

The single-beam laser interferometer systems have been used to measure the surface sample displacements. The samples were griped in nodal points by the edges of holder. The scheme of the single-beam Michelson interferometer is shown in Fig. 1. A He–Ne laser (Coherent, Model 200), was used for the measurement. The surface displacement was measured by application of an ac field to the sample. The piezoelectric actuator changes the length of the reference arm in accordance with the driving voltage. The feedback is introduced for stabilization of the working point of the interferometer. The voltage response from the preamplifier is measured with a lock-in (Stanford Research Systems, SR830 DSP). The reliable measurement with a single-beam instrument was more difficult in the case when the sample is glued on the holder.

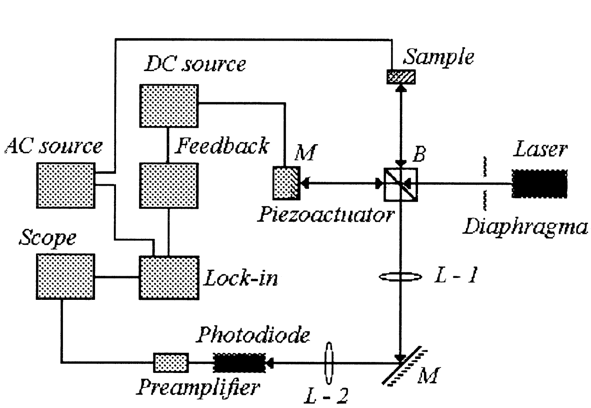

Fig. 1. Scheme of the single-beam laser interferometer.

A stable double-beam interferometer was used to suppress the effect of bending. The experimental set up of the double-beam interferometer for measurements of d_0 is shown in Fig. 2.

The piezoelectric coefficients d_{ij} were calculated using the following equation

$$d_{ij} = \frac{\partial S_j}{\partial E_i} = \frac{d_0}{U}\cdot\frac{t}{x}. \quad (6)$$

S_j are strain tensor components, E_i are components of electric-field intensity, U is the driving voltage amplitude, x is the corresponding length in the direction of sample deformation, t is thickness of the sample in the direction of the applied electric field.

2.2. Resonance method

Piezoelectric material PZT belonging to point group 4 mm has two independent components of permitivity (ε_{11}, ε_{33}), six independent components of elastic coefficient (s_{11}, s_{12}, s_{13}, s_{33}, s_{55}, s_{66}) and three independent components of piezoelectric coefficient (d_{31}, d_{33}, d_{15}). According to IEEE standard,[4] we measured resonance frequencies and we calculated these independent components. The frequency and dielectric measurements we performed using an impedance analyzer (Hewlett Packard, HP 4192A).

2.3. Quasi-static method

A ZJ-3C d_{33} meter (Institut of Acoustic, Academia Sinica) was also used to measure the effective d_{33} and d_{31} value with a force frequency of 110 Hz.

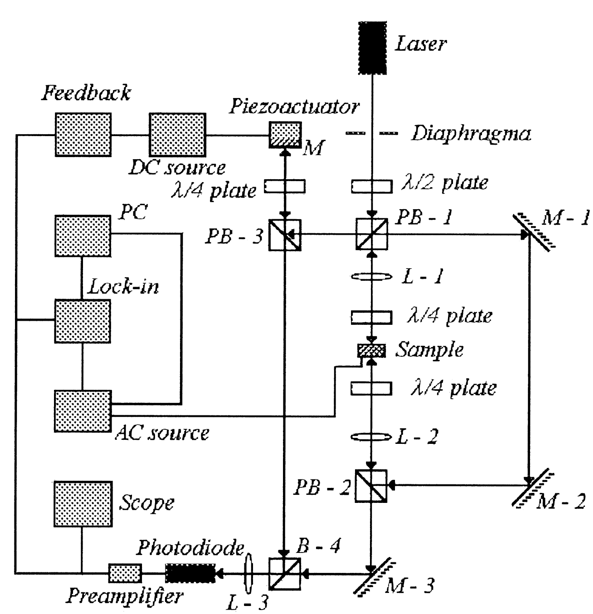

Fig. 2. Scheme of the double-beam laser interferometer.

3. Samples

We studied the PZT samples of APC856 type from APC International, Mackeyville, PA, USA. The bars were 4×15×1 mm in size, the disks of the thickness 1 mm were 12 mm in diameter. Plates were 4×4×2(3) mm and 6×6×3 mm in size. Ag electrodes were evaporated on main surfaces and the samples were polarized in thickness. The PZT plates of APC841 type, from the same maker, were 3×4×3 mm in size. The composites of type 0–3 PZT-polymer were made by embedding piezoceramics APC856 particles in Epoxy1200. The composite plates and disks had thickness 1–3 mm. The secular composites samples were 12 mm in diameter.

4. Experimental results

The measured surface displacement d_0 of the bar as a function of frequency from 200 Hz to 100 kHz is shown in Fig. 3 for a driving voltage amplitude of 1 V. The resonance peak is observed in this frequency range at 95 kHz. The value of the resonance frequency agrees well with the value measured by resonance method. The bar was grinding from 15 to 13 mm in length. There is no peak observed because its resonance frequency was moved to higher frequency. Fig. 3 shows also the displacement as a function frequency for PZT disk. There is no observed peak. Its resonance frequency is over 100 kHz.

The calculated piezoelectric coefficient d_{31} of PZT bar as a function of frequency from 200 Hz to 30 kHz is shown in Fig. 4 for a driving voltage amplitude of 1 V.

The obtained value of d_{31} was 256×10^{-12} C N^{-1}. This agrees well with the value measured by the resonance method 250×10^{-12} C N^{-1} in Table 1 and reported value by manufacturer (260×10^{-12} C N^{-1}). By the d_{33} meter it was measured 251×10^{-12} C N^{-1}. It is obvious, the value of d_{31} is not possible calculate by the same procedure in frequency range near mechanical resonance.

A stable double-beam interferometer was used to suppress the effect of bending. The displacement as a function of frequency for the bar sample is shown in Fig. 5. The calculated PZT d_{31} coefficient is presented in Table 1. Fig. 6 shows the linearity of the displacement with driving voltage.

We determined the PZT d_{33} coefficients for two materials. Figs. 7 and 8 show frequency dependence of displacement and d_{33} coefficient for PZT of APC856 type, respectively APC841. The samples were attached by Ag paint on the holder. The value of d_{33} coefficient is

Table 1
Piezoelectric coefficients d_{ij}

	PZT (APC856)		PZT (APC841)	Composite
	$-d_{31}$ (10^{-12} C N^{-1})	d_{33} (10^{-12} C N^{-1})	d_{33} (10^{-12} C N^{-1})	d_{33} (10^{-12} C N^{-1})
Frequency method	250	591	–	–
Interference method	256	549	320	7, 8
d_{33} meter	251	547	313	8

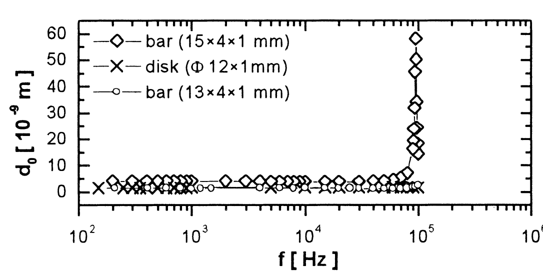

Fig. 3. The frequency dependence of displacement d_0.

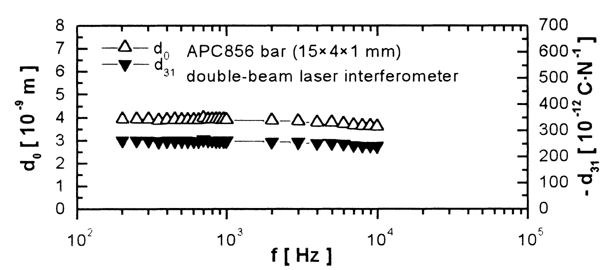

Fig. 5. Frequency dependence of displacement d_0 and d_{31} coefficient.

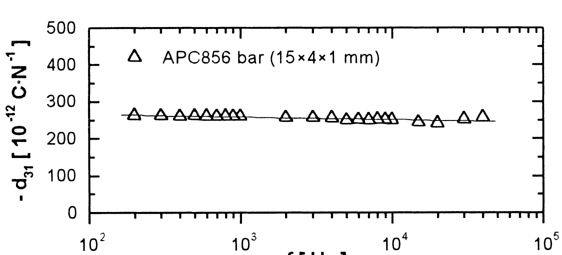

Fig. 4. The frequency dependence of piezoelectric coefficient d_{31}.

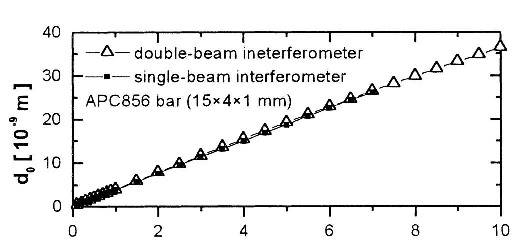

Fig. 6. Linearity of the displacement d_0 with driving voltage.

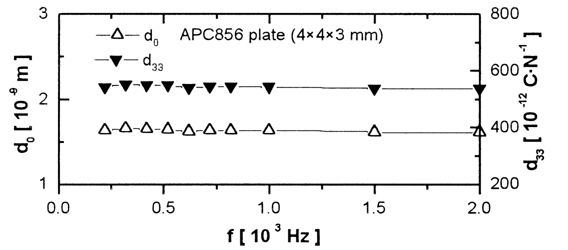

Fig. 7. Frequency dependence of displacement d_0 and d_{33} coefficient.

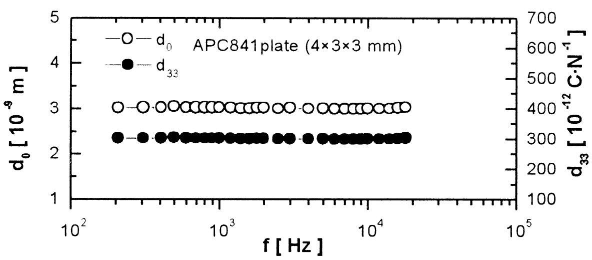

Fig. 8. Frequency dependence of displacement d_0 and d_{33} coefficient.

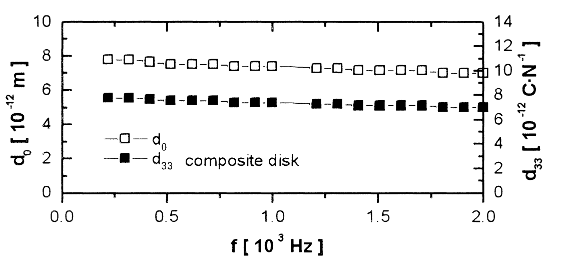

Fig. 9. Frequency dependence of displacement d_0 and d_{33} coefficient.

in good agreement the value determined by frequency method (Table 1).

The same experiment we performed with composites (PZT-polymer) of type 0–3. The disk was attached on to steel holder using silver paint. The measured d_0 and d_{33} coefficients as a function of frequency are shown in Fig. 9. The value of d_{33} is 7.8×10^{-12} C N^{-1}.

5. Conclusion

The resonance method is widely used, but the measurements are limited to the specific frequencies. The results of the PZT d_{ij} coefficients obtained by the single-beam and double-beam laser interferometer methods are in good agreement with resonance method. The significant peak was observed in frequency dependence displacement as result of mechanical resonance.

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