A measurement method for piezoelectric material properties under longitudinal compressive stress–-a compression test method for thin piezoelectric materials

2011 Meas. Sci. Technol. 22 065701

(http://iopscience.iop.org/0957-0233/22/6/065701)

IOP Publishing — Measurement Science and Technology
Meas. Sci. Technol. **22** (2011) 065701 (9pp) doi:10.1088/0957-0233/22/6/065701

A measurement method for piezoelectric material properties under longitudinal compressive stress—a compression test method for thin piezoelectric materials

Lae-Hyong Kang, Dae-Oen Lee and Jae-HungHan[1]

Department of Aerospace Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Korea

E-mail: jaehunghan@kaist.ac.kr

Received 2 December 2010, in final form 23 February 2011
Published 26 April 2011
Online at stacks.iop.org/MST/22/065701

Abstract
We introduce a new compression test method for piezoelectric materials to investigate changes in piezoelectric properties under the compressive stress condition. Until now, compression tests of piezoelectric materials have been generally conducted using bulky piezoelectric ceramics and pressure block. The conventional method using the pressure block for thin piezoelectric patches, which are used in unimorph or bimorph actuators, is prone to unwanted bending and buckling. In addition, due to the constrained boundaries at both ends, the observed piezoelectric behavior contains boundary effects. In order to avoid these problems, the proposed method employs two guide plates with initial longitudinal tensile stress. By removing the tensile stress after bonding a piezoelectric material between the guide layers, longitudinal compressive stress is induced in the piezoelectric layer. Using the compression test specimens, two important properties, which govern the actuation performance of the piezoelectric material, the piezoelectric strain coefficients and the elastic modulus, are measured to evaluate the effects of applied electric fields and re-poling. The results show that the piezoelectric strain coefficient d_{31} increases and the elastic modulus decreases when high voltage is applied to PZT5A, and the compression in the longitudinal direction decreases the piezoelectric strain coefficient d_{31} but does not affect the elastic modulus. We also found that the re-poling of the piezoelectric material increases the elastic modulus, but the piezoelectric strain coefficient d_{31} is not changed much (slightly increased) by re-poling.

Keywords: piezoelectric materials, compressive stress, compression test, nonlinear property, piezoelectric strain coefficient, elastic modulus, poling

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In piezoelectric unimorph actuator design, the elastic modulus ratio of adjoining layers (a piezoelectric layer and a substrate) determines the piezoelectric actuation performance if the thickness ratio is fixed [1]. In addition, the actuation performance is primarily governed by the piezoelectric strain coefficient which indicates how much piezoelectric strain is induced when a unit electric field is applied to the piezoelectric material. For this reason, the evaluation of the actual material properties of piezoelectric materials is an important issue to estimate the actuation performance of piezoelectric unimorph actuators. Although their material properties have been well characterized using a standard test method like the resonance–antiresonance method [2], the properties are not applicable to overall operational ranges. For example, piezoelectric actuators are often driven under strong electric fields in order

[1] Author to whom any correspondence should be addressed.

to obtain higher mechanical outputs, but in cases of higher electric field applications the piezoelectric strain coefficient can be as much as twice the nominal value measured using the resonance–antiresonance method. Recently, furthermore, several pre-stressed piezoelectric unimorph actuators such as RAINBOW [3], THUNDER [3], LIPCA [4] and PUMPS [5] have been developed and widely studied due to their good actuation performance, reliability and durability. There are many research works on the performance evaluation of pre-stressed piezoelectric unimorph actuators but the highly nonlinear characteristics of the piezoelectric material cause differences between analytic and experimental results. For example, even the actuation displacements are not well matched between the analysis and the experiment in many cases [3, 4]. For these reasons, we started the evaluation of the piezoelectric nonlinear properties, and this paper focuses on the piezoelectric property changes according to the compressive stress and the applied voltages.

In the cases of pre-stressed piezoelectric unimorph actuators, the piezoelectric layer is under a permanent stress condition, generally the longitudinal compressive stress condition. Therefore, the compressive stress effects on the material properties need to be investigated. The piezoelectric layer in the pre-stressed piezoelectric unimorph is very thin and can be easily broken or buckled during the conventional compression test because the conventional compression test method uses a pressure block for the application of compression. This is the reason why test specimens are always bulk piezoelectric materials. Therefore, a new compression test method was introduced in this study for the evaluation of the compressive stress effects on thin piezoelectric materials.

Furthermore, some of the pre-stressed piezoelectric unimorph actuators such as RAINBOW and THUNDER need re-poling due to the loss of piezoelectric characteristics during the high temperature adhesion process. Thus, this study also took into account the re-poling effect on the piezoelectric properties under compressive stress conditions.

The research scope of each section in this paper is given as follows. Section 1 summarizes the literature on the existing compression test method for the piezoelectric materials and describes the research background, objectives and scope. Section 2 introduces the present compression test method for piezoelectric materials that allows the testing of a thin piezoelectric layer. Section 3 presents the compressive stress effects on the piezoelectric material properties such as the piezoelectric strain coefficient d_{31} and the elastic modulus using compression test specimens with different compressive stresses. Section 4 investigates the effects of re-poling of the piezoelectric material on the piezoelectric material properties under compressive stress and section 5 summarizes the conclusions of this work.

2. New compression test method for thin piezoelectric materials

The piezoelectric properties of the thin piezoelectric plate which is used in unimorph actuators may be different from the thick piezoelectric ceramics. However, the compression tests

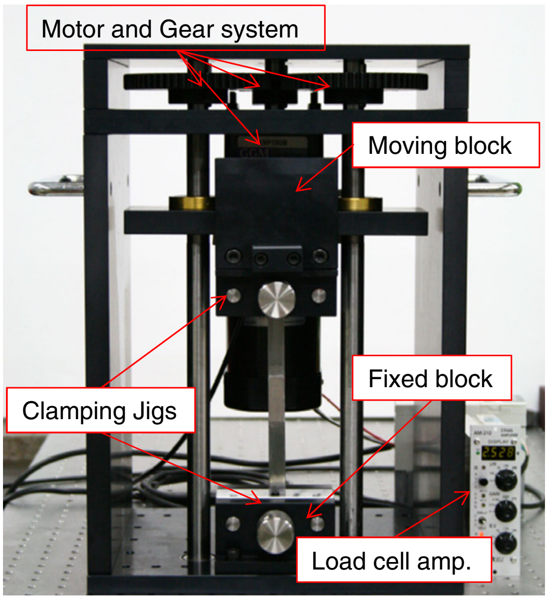

Figure 1. PUMPS fabrication device: this is used for the fabrication of the compression test specimens in this paper.

performed so far have treated bulky and thick piezoelectric blocks with thicknesses that are much larger than those of the piezoelectric materials applied in unimorph-type actuators [6–8]. In addition, compressive stresses have been applied through mechanical contact [6–9], which may affect the measured piezoelectric properties because the boundary constrains the movements of the piezoelectric materials under the electric fields.

Therefore, we propose a new compression test method, which allows the free–free boundary condition during experiments, for slender piezoelectric materials. In order to achieve the free–free boundary condition, we used upper and lower guide plates which compressed the piezoelectric layer without any external connections such as pressure blocks. The two guide plates with sandpaper at both ends were initially stretched together using the PUMPS fabrication device with a motor and a gear system similar to a tensile test machine as shown in figure 1. When we applied the tensile stress to the guide plates, we monitored the strains and the loads using strain gauges and a load cell inside the PUMPS fabrication device for the first test. The strains of the guide plates have to be measured for consistent fabrication, but it would be wasteful to use strain gauges every time the compression test specimens are manufactured. Therefore, the tensile load was monitored during the fabrication of the compression test specimens instead of using strain gauges because the tensile load is directly proportional to the tensile strain. While the tensile stress was applied to the guide plates, the piezoelectric layer was attached between the stretched guide plates and the guide plates and the piezoelectric layer were clamped together until the bonding layer dried. By removing the initial tensile stress in the guide plates after curing the bonding material, compressive stress is induced in the piezoelectric material. The overall manufacturing process of compression test specimens was performed at room temperature. Figure 2 summarizes the

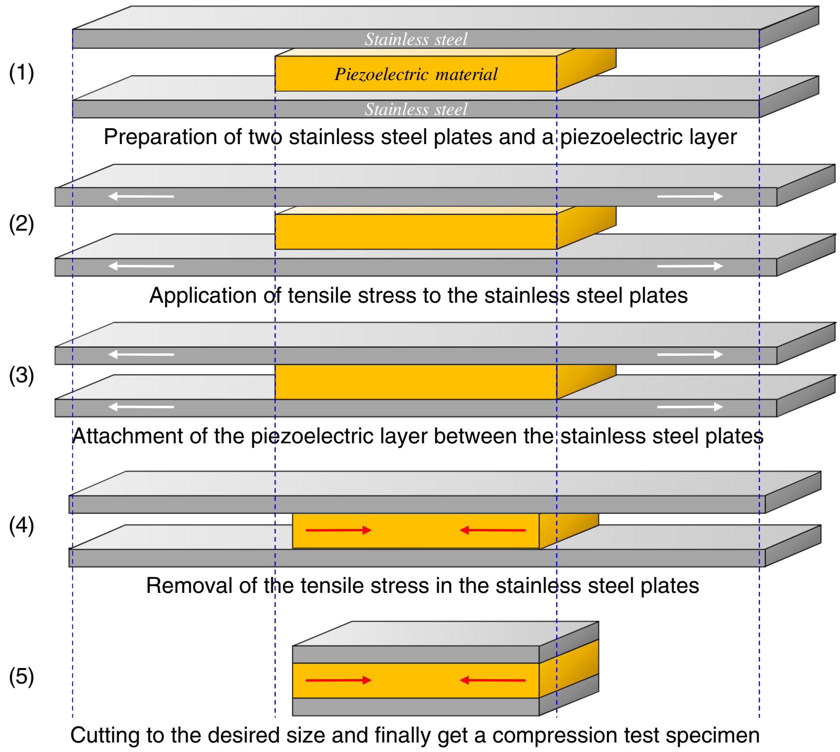

Figure 2. Preparation process of a compression test specimen.

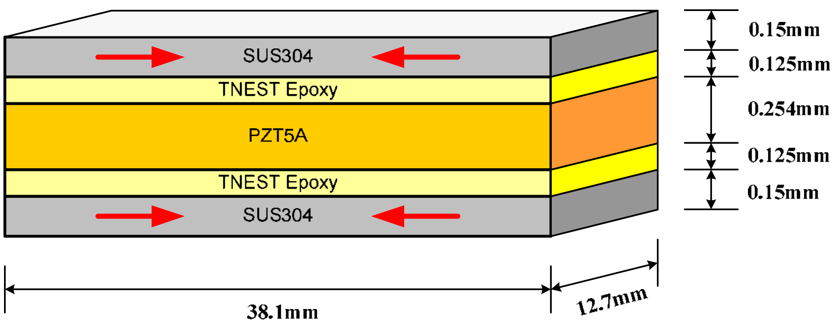

Figure 3. Layout of the specimen for the compression test.

preparation process of a compression test specimen proposed in this paper. Note that the compression test specimen in this study is under uniaxial compressive stress (in the longitudinal direction) with direction perpendicular to the poling axis of the piezoelectric layer.

Although we can apply compressive stress to the piezoelectric layer, we cannot directly measure the stress level inside the layer but can only monitor the surface strain of the compression test specimen. Therefore, ABAQUS simulation was performed to calculate the internal stress level of the piezoelectric layer and the relationship between the surface strain of the specimen and the internal stress of the piezoelectric layer. In this study, stainless steel 304 (SUS304) plates were used as guide plates and a pre-poled PZT5A [10] layer with electrodes was bonded between the SUS304 plates using TNEST epoxy [11] having the curing time of 30 min at room temperature. The dimensions of PZT5A are 38.1 × 12.7 × 0.254 mm^3, those of the TNEST epoxy are 38.1 × 12.7 × 0.125 mm^3 and those of SUS304 are 38.1 × 12.7 × 0.15 mm^3. Figure 3 shows the overall dimensions of the compression test specimen and table 1 lists the material properties of the guide plate, PZT, and the adhesive layer. In the calculation, 10 × 4 quadratic hexahedral solid elements were used for modeling each layer. The boundary condition of ABAQUS simulation in this study is the simply supported boundary at both ends of the compression test specimen. The simulation results showed that the residual compressive strain and stress inside PZT5A are 775 $\mu\varepsilon$ and 51.80 MPa, respectively, when the initial strain of the SUS304 plate is 1000 $\mu\varepsilon$. Several specimens with various internal stress levels were prepared in order to investigate the effects of compressive stresses on the piezoelectric properties of the PZT5A layer.

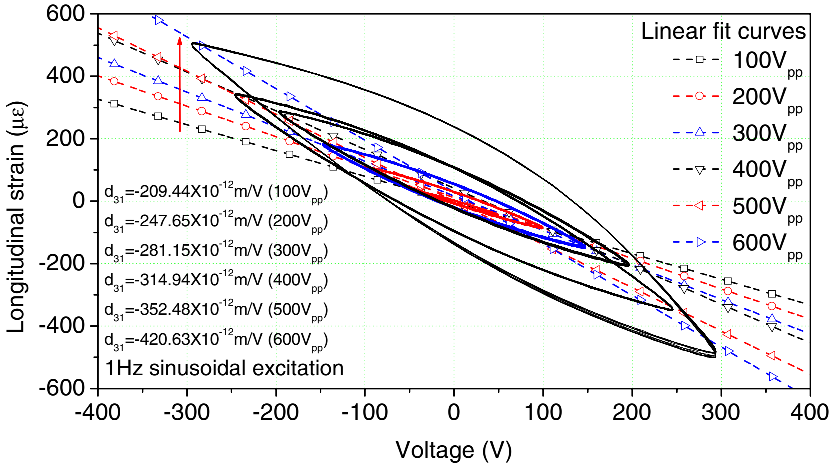

Figure 4. Strain hysteresis loops and apparent d_{31} according to the applied voltages.

Table 1. Nominal material properties of the constituent parts of the compression test specimen.

	SUS304	TNEST epoxy	PZT5A [10]
Density (kg m^{-3})	8000	970	7700
Elastic modulus (GPa)	190	3.93	61
Poisson's ratio	0.3	0.45	0.3
d_{31} (10^{-12} mV^{-1})	–	–	−171
Dielectric constant (F m^{-1})	–	–	1.5×10^{-8}
Tensile strength (MPa)	505	130 ± 40	100
Compressive strength (MPa)	–	–	>600
Shear strength (MPa)	–	75 ± 15	–

3. Piezoelectric material properties of PZT5A under various compressive stresses

The material properties of PZT including the elastic modulus and the piezoelectric strain coefficients are generally obtained from the standard resonance–antiresonance method. The resonance–antiresonance method uses the vibration mode of a piezoelectric material of a certain shape to calculate corresponding piezoelectric material properties. The vibration mode depends on the shape of the piezoelectric material, the orientation of polarization and the direction of the electric field. Each of these vibration modes has unique resonant frequency and piezoelectric characteristics. More detailed information about the resonance–antiresonance method is given in [2]. Even though the standard method provides us the mechanical and piezoelectric material properties of the piezoelectric materials, the nominal properties from the standard test method are no longer valid when a high electric field or mechanical stress (electrical or mechanical loading) is applied to the piezoelectric materials. Therefore, the properties need to be measured directly under various loading conditions. In this research, we investigated compressive stress effects on the piezoelectric strain coefficient d_{31} and the elastic modulus of PZT5A using the proposed compression test specimens. Note that these two properties mainly govern the actuation performance of the piezoelectric unimorph actuators.

3.1. Piezoelectric strain coefficient d_{31} of PZT5A under various compressive stresses

The piezoelectric strain coefficient d_{ij} indicates how much piezoelectric strain occurs under a unit electric field, and the relation between the piezoelectric strain and the external electric field can be expressed as

$$\varepsilon_j = d_{ij} E_i, \qquad i = 1, 2, 3, \qquad j = 1, 2, 3, 4, 5, 6, \quad (1)$$

where ε_j is the piezoelectric strain, d_{ij} is the piezoelectric strain coefficient and E_i is the electric field. The first subscript i of the d coefficient gives the electrical direction (field or dielectric displacement), and the second subscript j gives the component of a mechanical deformation or stress. In unimorph actuators, the d_{31} has a dominant effect on the actuation performance because the d_{31} contributes the longitudinal motion of the piezoelectric layer which leads to the bending moment of the unimorph. As described in (1), we can obtain d_{31} by monitoring the external electric field and corresponding longitudinal piezoelectric strain. We applied 1 Hz quasi-steady sinusoidal voltages to the specimens and obtained the strain–voltage diagram as shown in figure 4. Then, we calculated the apparent piezoelectric coefficient, $\bar{d}_{31}$, directly from the linear curve fit of the strain–voltage hysteresis loop. As is very well known, the $\bar{d}_{31}$ became as much as twice its nominal value when high electric field is applied.

The apparent piezoelectric coefficients of each specimen which has different compressive stress levels—0, 51.80, 103.60, 155.40 and 181.30 MPa—were also measured and they were divided by the apparent piezoelectric coefficients at the stress-free condition, $\bar{d}_{31@\text{free}}$, yielding normalized variations of $\bar{d}_{31}$ (or the $\bar{d}_{31}$ ratio) according to the applied stresses as shown in figure 5. The results showed that the longitudinal compressive stress decreases d_{31} and the degree of decrement increases with the applied voltage.

3.2. Elastic modulus of PZT5A under various compressive stresses

Changes in the elastic modulus of PZT5A due to the applied electric field have been calculated using variations of the first

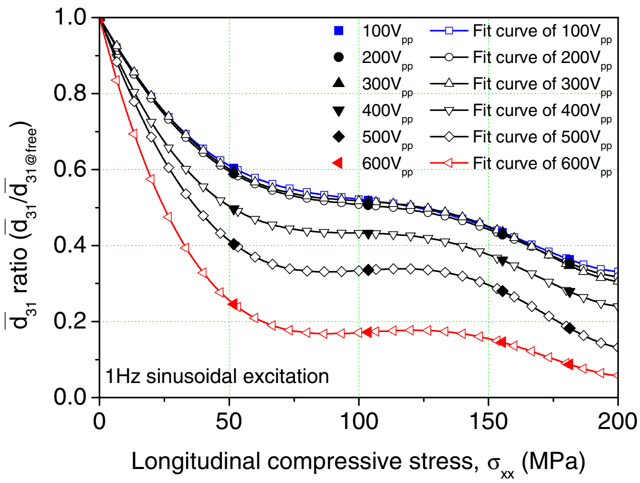

Figure 5. Piezoelectric coefficient ratio under the longitudinal compressive stress.

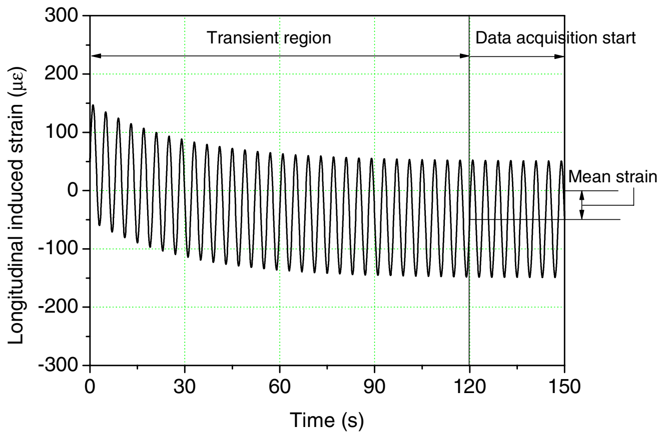

Figure 6. Typical piezoelectric strain signal of the compression test specimens during the sinusoidal excitation test.

natural frequency measured at free–free boundary conditions in the authors' previous work [12]. The same experiments were conducted using the present compression test specimens, but the specimens were burned during the test because the guide plates blocked very rapid movements of the piezoelectric material (the first natural frequency of the compression test specimen was around 3 kHz) producing excessive heat. Therefore, another measurement method was required.

The proposed method in this paper uses the mean strain variation of the compression test specimens under applied ac voltages to obtain the elastic modulus of the piezoelectric material. During the 1 Hz sinusoidal excitation experiment on the compression test specimen, the drift of the longitudinal strain was observed and the signal finally saturated as shown in figure 6. The saturated strain hysteresis loops of compression test specimens are indicated in figure 7 and each hysteresis loop was measured by applying 1 Hz

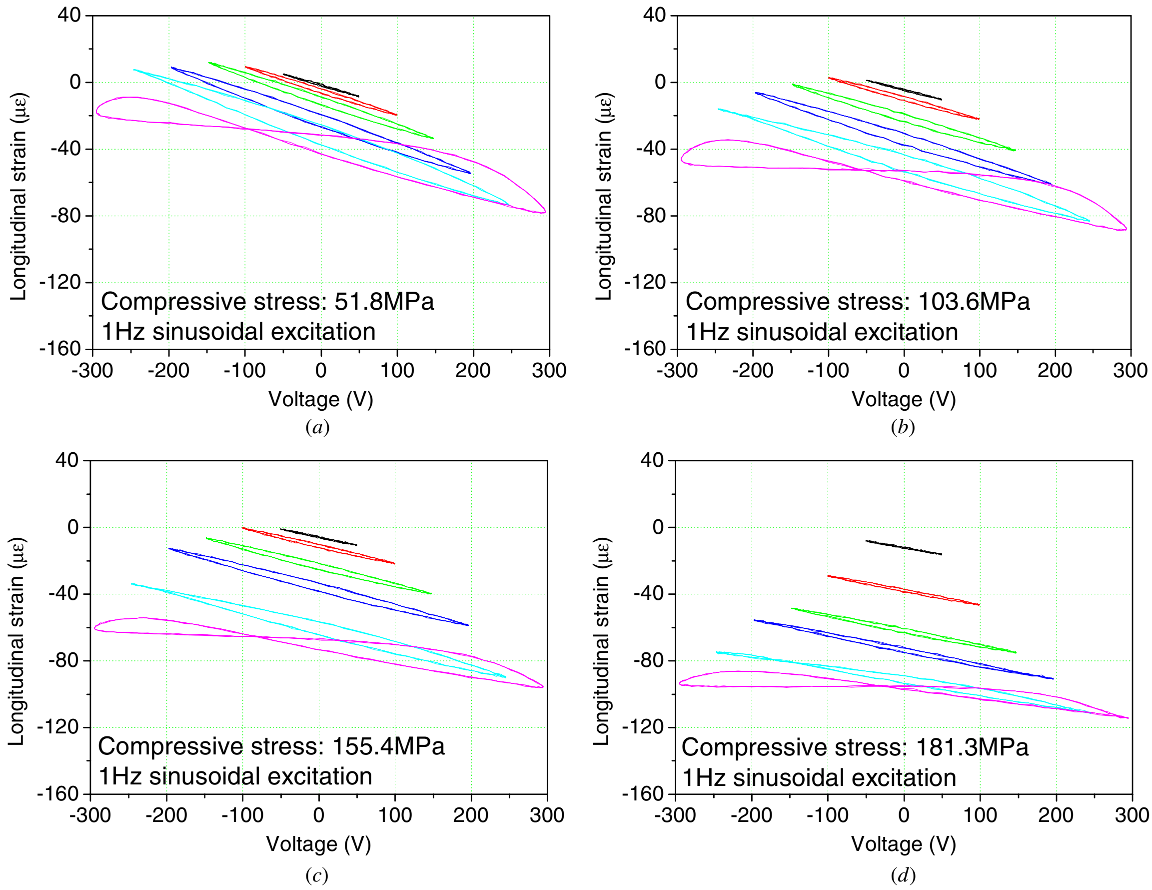

Figure 7. Strain hysteresis loops of the compression test specimens: (*a*) 51.80 MPa; (*b*) 103.60 MPa; (*c*) 155.40 MPa; (*d*) 181.30 MPa.

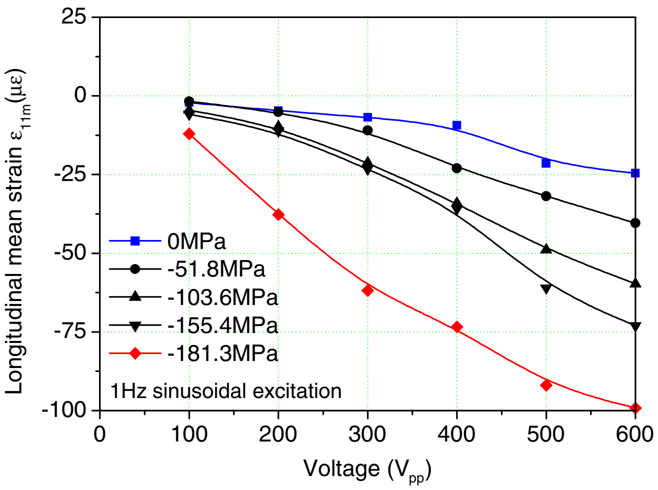

Figure 8. Mean strains of the compression test specimens.

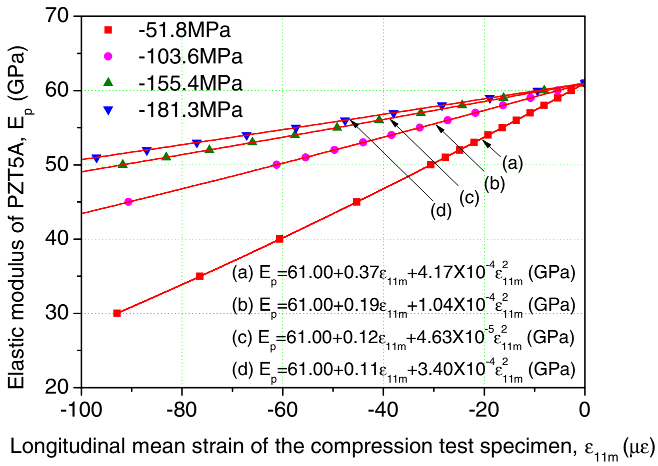

Figure 9. Elastic modulus of the compression test specimen according to the mean strain variation.

Table 2. Estimated elastic moduli of PZT5A before re-poling of the compression test specimen.

Voltage (V_{pp})	Reference [10]	Compressive stress (MPa) 51.8	103.6	155.4	181.3
		Elastic modulus (GPa)			
100	61.00	60.35	60.16	60.28	59.72
200	56.44	59.10	59.20	59.63	57.03
300	54.55	56.96	57.10	58.14	54.55
400	52.24	52.66	54.79	56.61	53.38
500	52.06	49.57	52.14	53.60	51.51
600	51.72	46.62	50.26	52.18	50.78

sinusoidal voltages from 100 to 600 V_{pp} at intervals of 100 V_{pp}. The corresponding mean strains of the hysteresis loops in figure 7 are shown in figure 8. The drift signal disappeared after removing the applied electric fields. Note that the mean strain variation measured on the surface of the compression test specimen occurs due to changes in the elastic modulus of the piezoelectric layer because two guide plates apply uniform compressive stress to the piezoelectric layer and the material properties of the guide plates and the adhesives are not changed during tests.

In addition, figure 8 also shows an obvious trend that the mean strain decreases when the magnitude of the compressive stress increases. Using the mean strain variations, the elastic modulus of the piezoelectric layer can be calculated. Figure 9 shows the ABAQUS simulation results of various compression test specimens with different elastic modulus of the piezoelectric layer. Mean strains in figure 8 were substituted with the simulation results in figure 9 and the calculated elastic moduli of PZT5A are summarized in table 2. The results were compared with variations of the elastic modulus at the stress-free condition which represent the electric field effect. As described in table 2, the elastic moduli of PZT5A under compressive stresses are almost the same as those at the stress-free condition.

In this section, the piezoelectric strain coefficient d_{31} and the elastic modulus of the pre-poled PZT5A were obtained under compressive stress conditions. The results show that the compressive stress decreases the d_{31} significantly and has no influence on the elastic modulus, which is affected only by the applied voltages.

4. Re-poling effects on the piezoelectric material properties of PZT5A with compressive stress

In section 3, we dealt with the compressive stress effects on the material properties of the initially poled piezoelectric material before the fabrication of the compression test specimen. However, the piezoelectric material properties might change if the compression test specimen is re-poled. Some researchers have reported the property changes according to the poling state (poled/unpoled) [8, 13] and the poling direction [6–8] but literature concerning the re-poling effect on the properties of piezoelectric material with compressive stress is rare.

Referring to the re-poling process of PZT5A in THUNDER [14], re-poling was performed with a dc voltage of 600 V, applied for 5 min to PZT5A in a silicon oil bath. Because the temperature of the oil bath was maintained at room temperature, the temperature effect can be neglected. Using the re-poled compression test specimens, the piezoelectric strain coefficient d_{31} and the elastic modulus of PZT5A were calculated with the same method as explained in section 3. The experimental results—strain–voltage diagrams—are shown in figures 10, and figures 11 and 12 are obtained from figure 10. The comparison of figures 11 and 5 shows a slight change in the piezoelectric strain coefficient d_{31} after re-poling. Table 3 compares the $\bar{d}_{31}$ ratios under longitudinal compressive stress before and after re-poling. The values in table 3 represent the percentage of the $\bar{d}_{31}$ ratio calculated using the value before re-poling as denominator. After re-poling, the averaged values in terms of the applied electric fields are sometimes less than 0, but averages in terms of stress levels increased 3–7% compared with the values of the specimens before re-poling. Although the d_{31} values after re-poling are not very different from those

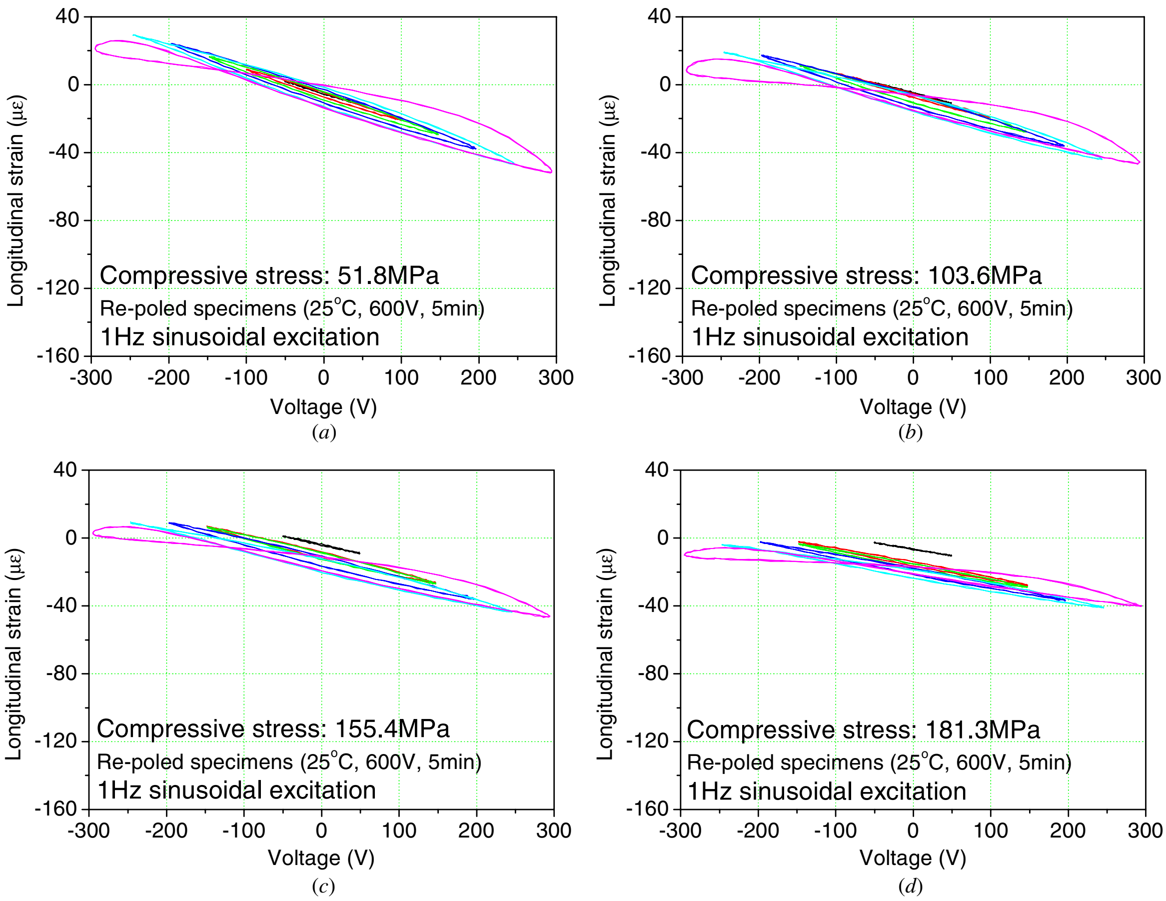

Figure 10. Strain hysteresis loops of the compression test specimens after re-poling: (*a*) 51.80 MPa; (*b*) 103.60 MPa; (*c*) 155.40 MPa; (*d*) 181.30 MPa.

Table 3. Variation of the $\bar{d}_{31}$ ratios due to re-poling.

	Applied voltage (V_{pp})						
	100	200	300	400	500	600	
Compressive stress (MPa)	Variation of the $\bar{d}_{31}$ ratios due to re-poling (%)						Average (%)
51.80	5.01	2.33	0.15	−2.66	−6.27	20.67	3.21
103.60	3.85	2.41	−1.06	−3.50	−6.50	30.53	4.29
155.40	6.01	6.04	−0.27	−2.72	−6.16	40.45	7.22
181.30	−4.67	−1.00	−4.53	−3.78	1.95	44.70	5.45
Average (%)	2.55	2.44	−1.43	−3.17	−4.24	34.09	

before re-poling, interesting changes occur in the measurement of the elastic modulus of PZT5A with the compressive stress after re-poling. As shown in figure 12, the variation of mean strains of the compression test specimens under 1 Hz sinusoidal input voltages is much less compared to the data in figure 8. It means that the elastic modulus of PZT5A with compression after re-poling increases. Table 4 indicates the estimated elastic moduli of PZT5A with compression after re-poling and the values are increased compared with those in table 2.

In this section, the piezoelectric strain coefficient d_{31} and the elastic modulus of the re-poled PZT5A with compression are obtained. The results show that the re-poling causes a significant increase in the elastic modulus, but has minor effects on d_{31} (very similar to the results in section 3).

Table 4. Estimated elastic moduli of PZT5A after re-poling of the compression test specimen.

	Compressive stress (MPa)			
	51.8	103.6	155.4	181.3
Voltage (V_{pp})	Elastic modulus (GPa)			
100	59.14	60.06	60.52	60.31
200	58.81	59.83	59.76	59.41
300	58.59	59.47	59.73	59.28
400	58.49	59.22	59.34	58.94
500	58.16	58.88	58.97	58.70
600	57.43	58.57	58.85	58.75

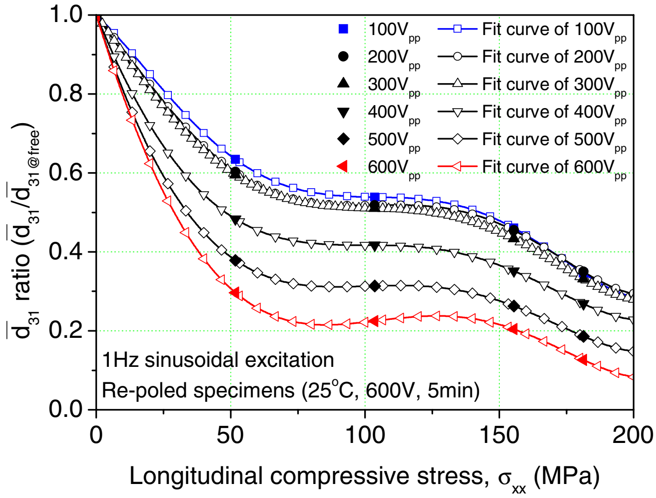

Figure 11. Piezoelectric coefficient ratio under longitudinal compressive stresses after re-poling.

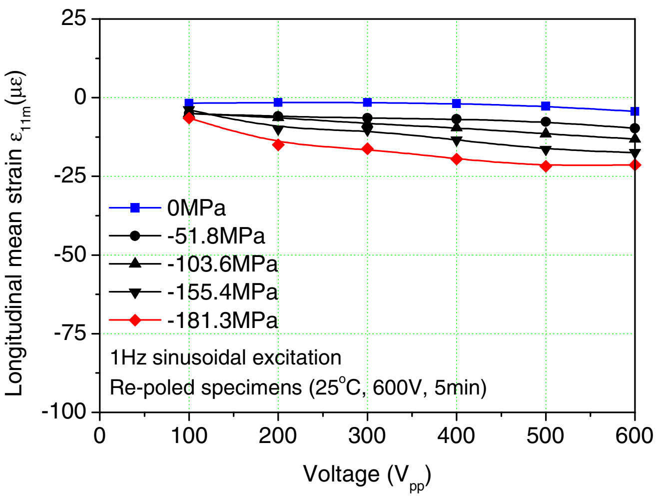

Figure 12. Mean strains of the compression test specimens after re-poling.

5. Conclusion

In this study, we propose a new compression test method for thin piezoelectric ceramics whose material property variations under compressive stresses are difficult to investigate using conventional compression test methods. For the preparation of the present compression test specimens, two guide plates were used and they applied compressive stress continuously to the piezoelectric material. Using the present compression test specimens, we measured the d_{31} and the elastic modulus of PZT5A under various applied electric fields. The results showed that the piezoelectric strain coefficient d_{31} increases while the elastic modulus of PZT5A decreases when high voltage is applied to it. In terms of the compressive stress level, the compression in the longitudinal direction decreases the piezoelectric strain coefficient d_{31} and the d_{31} decrement rate is larger when the compression test specimen is under higher electric fields. On the other hand, the elastic modulus changes are affected by the applied electric fields regardless of the compressive stress condition—the elastic moduli of the compression test specimens at each electric field were the same as the elastic moduli measured by the original piezoelectric material under the same electric field at a stress-free condition. In addition, it is found that the re-poling of the compression test specimen increases the elastic modulus significantly but the piezoelectric strain coefficient d_{31} only slightly.

The advantage of the present method is that it can be used in thin piezoelectric ceramics but, on the other hand, this method is not acceptable if the size, especially the thickness of the test material, is large because strain transmission may not be uniform through the thickness and the achievable compression level using the guide plate can be limited. Furthermore, the transverse effects can be included in the present compression test due to Poisson's ratio of the guide plates. We expect that the present test method can be improved if we use guide plates with very low Poisson's ratio, which can be achieved using two or more anisotropic composite materials, or apply biaxial tensile stress to the guide plates to compensate the transverse stress effects.

The purpose of this study is not only to get the material properties of the piezoelectric material but also to use the material properties for the estimation of the piezoelectric actuators in various operating conditions especially under compressive stress. It is expected that the present compression test method can be used for the evaluation of other thin piezoelectric materials, and the elastic moduli and the piezoelectric strain coefficients of PZT5A obtained from this study can be used in the analysis of the actuation performance of pre-compressed piezoelectric actuators such as RAINBOW, THUNDER, LIPCA and PUMPS.

Acknowledgment

This research was supported by NSL (National Space Lab) program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (grant number 2009-0091934).

References

[1] Smith J G, Dalke S I and Cooney T K 1991 The constituent equations of piezoelectric bimorphs *Sensors Actuators* A **28** 41–61
[2] Murata Manufacturing Co., Ltd, Catalog No P19E-6 http://www.symmetron.ru/suppliers/murata/sensors/p19e6.pdf
[3] Wise S W 1998 Displacement properties of RAINBOW and THUNDER piezoelectric actuators *Sensors Actuators* A **69** 33–8
[4] Yoon K J, Park K H, Goo N S and Park H C 2004 Analytical design model for a piezo-composite unimorph actuator and its verification using lightweight piezo-composite curved actuators *Smart Mater. Struct.* **13** 459–67
[5] Kang L-H, Lee J-W, Han J-H, Chung S-J and Ko H-Y 2009 Development of a piezoelectric unimorph using a mechanically pre-stressed substrate *Smart Mater. Struct.* **18** 104007
[6] Krueger H H A 1968 Stress sensitivity of piezoelectric ceramics: part 3. Sensitivity to compressive stress perpendicular to the polar axis *J. Acoust. Soc. Am.* **43** 583–91

[7] Zhou D, Kamlah M and Munz D 2005 Effects of uniaxial prestress on the ferroelectric hysteretic response of soft PZT *J. Eur. Ceram. Soc.* **25** 425–32
[8] Fett T, Munz D and Thun G 2002 Young's modulus of soft PZT from partial unloading tests *Ferroelectrics* **274** 67–81
[9] Jang S-H, Kim Y, Lee S, Park H and Yoon K 2003 Dependency of electric field and mechanical stress on piezoelectric strain of PZT 3203HD *Proc. SPIE* **5053** 498–504
[10] Morgan Electro Ceramics http://www.morganelectroceramics.com
[11] TNEST http://www.tnest.co.kr
[12] Kang L-H and Han J-H 2010 Prediction of actuation displacement and the force of a pre-stressed piezoelectric unimorph (PUMPS) considering nonlinear piezoelectric coefficient and elastic modulus *Smart Mater. Struct.* **19** 094006
[13] Tanimoto T, Yamamoto T and Okazaki K 1990 Mechanical and electrical properties of piezoelectric ceramics under repeated compression fatigue tests *IEEE 7th Int. Symp. on Applications of Ferroelectrics (Urbana-Champaign, IL, USA)* pp 202–5
[14] Mossi K M, Selby G V and Bryant R G 1998 Thin-layer composite unimorph ferroelectric driver and sensor properties *Mater. Lett.* **35** 39–49