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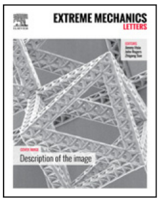

The universal and easy-to-use standard of voltage measurement for quantifying the performance of piezoelectric devices

Yewang Su [a,b,c,d,*], Shuang Li [a,b], Yong Huan [a], Rui Li [c], Zhaohui Zhang [e], Pauline Joe [f], Canan Dagdeviren [g,h,**]

[a] *State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China*
[b] *School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China*
[c] *State Key Laboratory of Structural Analysis for Industrial Equipment, Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China*
[d] *State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China*
[e] *Naval Academy of Armament, Beijing 100161, China*
[f] *The David H. Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[g] *Harvard Society of Fellows, Harvard University, Cambridge, MA 02138, USA*
[h] *Media Lab, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

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ABSTRACT

The output voltage is a key parameter to quantify the performance of piezoelectric devices, particularly for energy harvesters and sensors. Our recent work (Su et al., 2015) reported that the measured output voltage depends on the inner resistance of voltmeter used. It is contrary to the established concept that the measured results should be independent of the instruments used. Similar measurements, however, widely exist in recent published literature, which is actually not suitable to quantify the performance of piezoelectric devices. This paper proposes a universal and easy-to-use standard for the voltage measurement of piezoelectric devices. The output voltage measurements of a micro-fabricated, flexible lead zirconate titanate (PZT) mechanical energy harvester by two voltmeters with a resistance of 10 MΩ and 55 GΩ, present significantly different output voltage values (∼0.2 V vs. ∼2.0 V), which provide strong evidence for the unusual conclusion. A universal and easy-to-use standard of voltage measurement for piezoelectric devices requires that the inner resistance of voltmeter must be larger than a critical value in terms of effective capacitor, loading frequency and accuracy requirement of measured voltage. This standard is developed to obtain the open-circuit resistance-independent voltage. A self-developed electronic system meeting the standard requirement was built and the universality of all the findings was further validated by a commercial piezoelectric device.

1. Introduction

Over the last decades, there have been immense studies on piezoelectric based devices [1]. The unique property of piezoelectric materials to harness and convert the mechanical energy from the environment has particularly attracted many attentions to use these materials as power generators for wearable and implantable electronic devices. In addition to energy harvesters, sensors and actuators are other areas of interests due to the capability of piezoelectric materials to create high sensitivity and precision devices. Zinc oxide (ZnO) [2–6], polyvinylidene fluoride (PVDF) [7–11] and lead zirconate titanate (PZT) [12–25] are the examples of piezoelectric materials/systems that have been constantly studied.

The output voltage is a key factor to determine the performance of piezoelectric devices, especially for mechanical energy harvesters and sensors. The literature investigation shows that the output voltage is characterized by alternating positive and negative variations, even though the strain or stress in piezoelectric materials stays as positive during cycling load [6,10,26–32], as demonstrated in Fig. 1(a) & (b). However, piezoelectric theory of open circuit that is adopted in the literature [6,26–32] to predict the peak voltage, yield positive outputs throughout the voltage vs. time curve (Fig. 1(c)). This is much different from the experimental findings in the literatures. In conventional concept, the measured results should be independent of the instruments used. Recently, Su et al. pointed out that the measured output

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[*] Corresponding author at: State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

[**] Corresponding author at: Media Lab, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

E-mail addresses: yewangsu@imech.ac.cn (Y. Su), canand@media.mit.edu (C. Dagdeviren).

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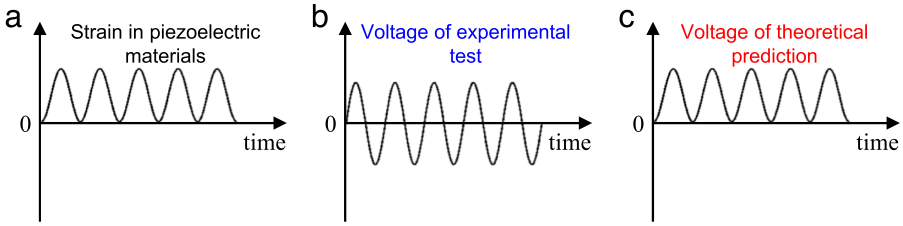

Fig. 1. The contradiction between the theory and experimental voltage measurement. Schematic illustrations of the curves of (a) strain in piezoelectric materials vs. time, (b) voltage of experimental test vs. time and (c) voltage of theoretical prediction vs. time.

voltage of piezoelectric devices depends on the inner resistance of the voltmeter used [33] by both experiment and theory derivation. Three voltmeters with different inner resistances were used to evaluate a piezoelectric device, obtaining the associated voltage–time curves. It was noted that the amplitude of peak output voltage increases with the increase of the inner resistance of the voltmeter. This finding denoted a 'trouble' in quantifying the performance of piezoelectric devices that different performance evaluations may be reported even for the same device due to the usage of different measurement instruments.

This study demonstrates a universal and easy-to-use standard of voltage measurement for piezoelectric devices, by which the performance of a piezoelectric device can be quantified by a unique output voltage value. Firstly, a flexible PZT mechanical energy harvester (MEH) was fabricated and tested by two commercial voltmeters with different inner resistances. Experimental findings clearly show the dependence of output voltage value on voltmeter resistance. Based on an analytical model, which can predict the experimental findings very well, the standard of voltage measurement is proposed for evaluating the performance of piezoelectric devices. Additionally, a self-developed electronic system was built to follow the same experimental procedure to further validate our proposed standard. Finally, a commercial piezoelectric device was tested by those of voltage measurement systems, and verified the universality of all the findings.

2. Results

A flexible PZT mechanical energy harvester (MEH) [16] was designed and fabricated for the evaluation of output voltage measurement (Fig. 2(a)). See SI for the details of fabrication steps (Appendix A). A PZT MEH module consists of 120 capacitor-type structures were transfer-printed on a flexible substrate (Fig. S1a). Each capacitor-type structure is comprised of a layer of PZT (500 nm) between the top (PI/Au/Cr, 1.2 μm/200 nm/10 nm) and bottom (Pt/Ti/PI, 300 nm/20 nm/1.2 μm) electrodes (Fig. S1b). These capacitor-type structures are formed into twelve groups, in each of which, ten capacitors are electrically connected in parallel. The twelve groups are connected in series to enhance the output voltage.

To quantify the performance of the PZT MEH, a mechanical stage was used to compress the flexible MEH cyclically, yielding the deformation mode of Euler buckling (Fig. 2(b) and Fig. S2). The output voltage was captured during the mechanical cycling (See SI for details, Appendix A). The length of unconstrained part of the device is $L = 4$ cm. The amplitude of compression $\varDelta L$ between the two ends of the device is a periodic function of time t, $\varDelta L = \varDelta L_{\max}\left[1-\cos\left(2\pi ft\right)\right]/2$, where $\varDelta L_{\max}$ and f are maximum amplitude and frequency, respectively. The two voltmeters with inner resistance of 10 MΩ and 55 GΩ were used for the voltage measurement, respectively, at various amplitudes of compression ($\varDelta L_{\max} = 5, 10$ and 15 mm) and frequency ($f = 0.25, 0.5$ and 1 Hz). Fig. 2(c)–(f) show that the measured voltage values via different voltmeters are significantly different. The output voltage obtained by the 10-MΩ-resistance voltmeter yields alternating positive and negative variations with peak value of ∼0.2 V, while, for the test by the 55-GΩ-resistance voltmeter, most portion of the output voltages are positive throughout the curve with peak value of 2.0 V (slightly decay to the negative value). The difference of the peak values between the two voltmeters can be as large as 10 fold. These results, indeed, suggest that the measured output voltage does depend on the inner resistance of the voltmeter. Both of the experimental results show that the measured output voltage increases with the increase of the amplitude of compression ($\varDelta L_{\max} = 5$, 10 and 15 mm) for a given frequency ($f = 0.5$ Hz). However, the voltage obtained by the 55-GΩ-resistance voltmeter almost does not depend on the frequency, while it depends significantly on the frequency for the 10-MΩ-resistance case (Fig. e&f). See Fig. S3 for detailed systematic results. The mechanism will be further explained with the analytic model.

According to the alteration of output voltage curves as well as the voltage dependence on the inner resistance of voltmeter and the frequency, we deduce that the electrical charge on electrodes of the piezoelectric layer can go through the voltmeter during measurement, instead of ideal open circuit. A simple test was conducted to confirm this inference: (1) Compressed the PZT MEH to yield the buckled case and held without connecting it to the voltmeter; (2) Connected the PZT MEH to the voltmeter promptly. Fig. 2(g) & (h) show the output voltage vs. time curves for $\varDelta L_{\max} =$ 5, 10 and 15 mm, respectively. The output voltage pattern obtained by the 10-MΩ-resistance voltmeter increases rapidly to its peak value from zero, and then decays to almost zero in 0.2 s. Note that the periods of the voltage measurement are 1–4 s, which is much larger compared to 0.2 s of the decay time. In this case, the charge can go through the voltmeter 'freely' during the cyclical movement. The status of the measurement is much far from the ideal open circuit. On the other hand, the output voltage pattern tested by the 55-GΩ-resistance voltmeter decays for only 10 % of its peak value in 30 s, which is much larger than the periods of voltage measurement, 1–4 s. In this case, the status of the circuit approaches that of ideal open circuit during the voltage measurement.

The process of voltage measurement can be captured by an analytic model that includes the finite inner resistance of the voltmeter, instead of ideal open circuit, as shown in Fig. 3(a). The charge is allowed to pass through the voltmeter and to change direction as the strain in PZT layer increases and decreases. The coupling of the deformation and the piezoelectric effect of the PZT MEH, as well as the closed circuit, can be described as the following governing equation (See SI for details, Appendix A)

$$\frac{dV}{dt} + \frac{d}{AR\bar{k}}V = -\frac{\bar{e}d}{\bar{k}}\frac{d\varepsilon}{dt}, \tag{1}$$

where V is the measured voltage between two electrodes of PZT MEH, R is the inner resistance of voltmeter, ε is the tensile strain of PZT yielded by bending of the device, d and A are the total thickness of twelve series-wound group of PZT ribbons and total area of each group, respectively, $\bar{e}$ and $\bar{k}$ are the effective piezoelectric