Extreme Mechanics Letters 15 (2017) 10–16

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

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

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ARTICLE INFO

Article history:
Received 2 December 2016
Received in revised form 11 February 2017
Accepted 24 March 2017
Available online 29 March 2017

Keywords:
Piezoelectric devices
Voltage measurement
PZT
Energy harvester
Flexible electronics

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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http://dx.doi.org/10.1016/j.eml.2017.03.002

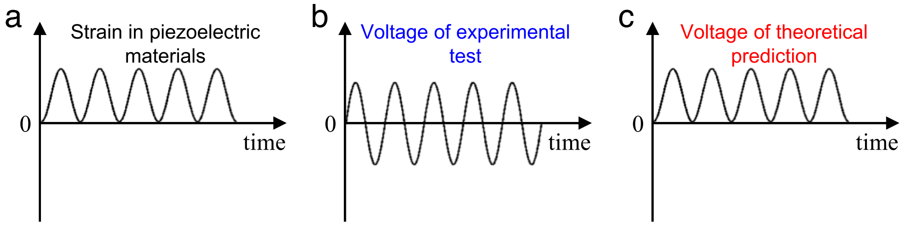

Fig. 1. The contradiction between the theory and experimental voltage measurement. Schematic illustrations of the curves of (a) strain in piezoelectric materials vs. time, (b) voltage of experimental test vs. time and (c) voltage of theoretical prediction vs. time.

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 ΔL between the two ends of the device is a periodic function of time t, $\Delta L = \Delta L_{\max}\left[1 - \cos\left(2\pi f t\right)\right]/2$, where $\Delta L_{\max}$ 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 ($\Delta L_{\max} = 5$, 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 ($\Delta L_{\max} = 5$, 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 $\Delta L_{\max} = 5$, 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)

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

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

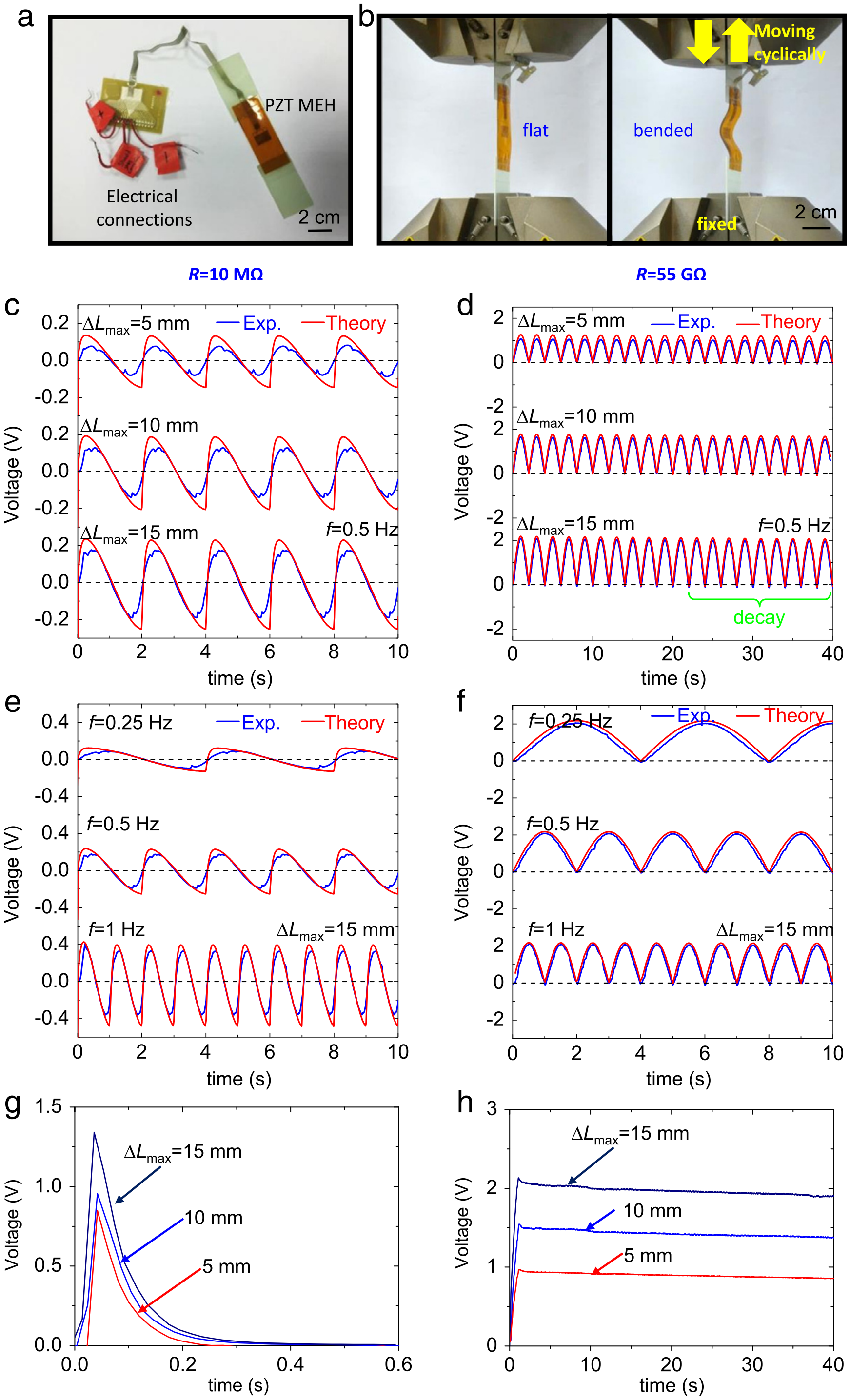

Fig. 2. Experimental and theoretical studies on the output voltage of PZT MEH. (a) Photograph of a PZT MEH. (b) A PZT MEH is subjected to a cyclic compression, which yields the deformation mode of Euler buckling and the tensile strain in PZT ribbons. Effects of compression amplitude ΔL on the output voltage for the voltmeters with a resistance of (b) 10 MΩ and (c) 55 GΩ. Effects of compression frequency f on the output voltage for the voltmeters of with a resistance of (e) 10 MΩ and (f) 55 GΩ. The test of decay time for the voltmeters with a resistance of (g) 10 MΩ and (h) 55 GΩ.

constants. Using the initial condition $V(t=0) = 0$, the voltage is obtained as

$$V = \frac{(-\bar{e})\,d}{\bar{k}}\varepsilon - \frac{(-\bar{e})\,d^2}{AR\bar{k}^2} e^{-\frac{d}{AR\bar{k}}t} \int_0^t \varepsilon e^{\frac{d}{AR\bar{k}}t} dt. \qquad (2)$$

Eq. (2) can also work for a piezoelectric block with thickness d and area A, being subjected to a periodic tensile load, and is not only limited to the specific PZT MEH with Euler buckling. For the applied loading $\Delta L = \Delta L_{max}\left[1-\cos(2\pi f t)\right]/2$ in the experiment, the tensile strain in PZT can be obtained as $\varepsilon = 4\pi\alpha\,(h/L)\sqrt{\Delta L_{max}/L}\,|\sin(\pi f t)|$ according to the theory of finite deformation [34], where α is ratio between the bending stiffness of the PI substrate without and with capacitor-type structure, h is the distance from the center of PZT layers to the neutral mechanical plane (Fig. S1b) and L is the total length of the device (See SI for details, Appendix A). For $\alpha = 0.45$, $d = 6\ \mu m$, $h = 24.7\ \mu$m, and $A = 2.24\ \text{mm}^2$ in the experiment, $\bar{e} = -3.4\ \text{C/m}^2$ and $\bar{k} = 2\times10^{-8}\ \text{C/(Vm)}$, being consistent with the order of magnitude

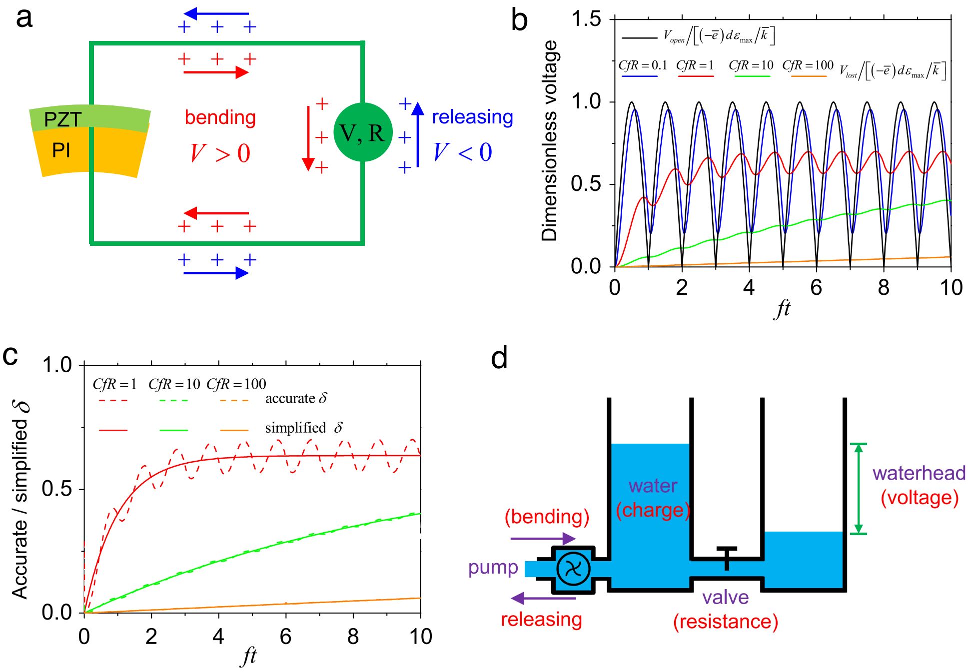

Fig. 3. The mechanism analysis. (a) The schematic illustration of mechanical–electrical coupling system for voltage measurement. (b) Comparison of dimensionless open voltage and dimensionless lost voltages. (c) Comparison of the accurate value of δ and the simplified expression. (d) An illustration of the water-flow system for the analogy of mechanical–electrical coupling system.

to those in the literature [35], Fig. 2(c)–(f), Fig. S3 and Fig. S4 show the voltage output V vs. time t obtained from Eq. (2) agrees well with the experimental findings. It is straightforward to understand the effects of the compression amplitude on the voltage. Larger compression yields larger bending strain ε, and therefore, larger voltage value according to Eq. (2). Eq. (2) can also be rewritten as $V=\left(-\bar{e}d/\bar{k}\right)e^{-[d/(AR\bar{k})]t}\int_0^t(d\varepsilon/dt)\,e^{[d/(AR\bar{k})]t}dt$, which shows that the voltage actually depends on the strain rate, i.e. the frequency of the applied load (Fig. 2(e)). However, the dependence on frequency can be very small for large-resistance voltmeter (Fig. 2(f)). According to Eq. (2), the first term dominates the output voltage, while the second term may be negligible if the inner resistance of voltmeter is large enough.

Noting the second term of Eq. (2) vanishes as the inner resistance R approaches infinity, the first term is the real voltage for ideal open circuit, and is linearly proportional to the tensile strain of PZT ε and total thickness d; however, it is irrelevant to the inner resistance of voltmeter R and total area A. Here, we define the first and second term of the voltage as open-circuit voltage and lost voltage,

$$V_{open}=\frac{(-\bar{e})\,d}{\bar{k}}\varepsilon,\quad V_{lost}=\frac{(-\bar{e})\,d^2}{AR\bar{k}^2}e^{-\frac{d}{AR\bar{k}}t}\int_0^t\varepsilon e^{\frac{d}{AR\bar{k}}t}dt,\tag{3}$$

respectively. Fig. 3(b) shows the comparison of the open-circuit voltage and the lost voltage for the strain in piezoelectric material $\varepsilon=\varepsilon_{\max}\left|\sin(\pi ft)\right|$, in the same form of the above experiment. The curve for dimensionless open-circuit voltage $V_{lost}/\left[(-\bar{e})\,d\varepsilon_{\max}/\bar{k}\right]$ vs. dimensionless time ft does not change with any parameter, while the dimensionless lost voltage $V_{open}/\left[(-\bar{e})\,d\varepsilon_{\max}/\bar{k}\right]$ increases with the decrease of the dimensionless resistance CfR. Here, $C=A\bar{k}/d$ is the effective capacitance of the devices. The lost voltage can be comparable with the open circuit if $CfR<0.1$, for which, the measured voltage $V=V_{open}-V_{lost}$ is characterized by alternating positive and negative variations. On the other hand, the lost voltage approaches zero if $CfR>100$, for which, the measured voltage is almost equal to the open-circuit voltage, being throughout positive and does not depend on the resistance of the voltmeter.

Let δ be the ratio between the lost voltage at $t=t_\delta$ and the maximum open-circuit voltage, $\delta=V_{lost}|_{t=t_\delta}/\max\left(V_{open}\right)$, which stands for the error of voltage measurement for open-circuit. By approximation, it can be obtained from Eq. (3) as (See SI for details, Appendix A),

$$\delta=\frac{1}{CfR}e^{-\frac{1}{CfR}(ft_\delta)}\int_0^{ft_\delta}\frac{\varepsilon}{\varepsilon_{\max}}e^{\frac{1}{CfR}(ft)}d(ft)\approx\bar{\varepsilon}_{aver}\left[1-e^{-\frac{1}{CfR}(ft_\delta)}\right],\tag{4}$$

where $\bar{\varepsilon}_{aver}=\int_0^1\varepsilon/\varepsilon_{\max}d(ft)$ is the average of dimensionless strains in piezoelectric material. For the strain $\varepsilon=\varepsilon_{\max}\left|\sin(\pi ft)\right|$ in the above experiment, the average of dimensionless strains is $\bar{\varepsilon}_{aver}=0.6366$. Fig. 3(c) shows that the accurate value of δ vibrates around the simplified expression. They agree very well when the dimensionless resistance CfR is larger than 10, but always at the same order even for $CfR<1$. In the practical application point of view, the inner resistance of voltmeter must be larger than a critical value, so that the measured voltage approaches the open-circuit voltage, which is independent of the inner resistance of the voltmeter, i.e., the instrument used. For the required accuracy denoted by δ at (ft_δ)th period, the critical resistance can be obtained by the simplified expression of δ as

$$R_{critical}=\frac{ft_\delta}{Cf\ln\left[1/(1-\delta/\bar{\varepsilon}_{aver})\right]}.\tag{5}$$

This analysis also works for the ZnO energy harvesters and PVDF pressure sensors in our previous work [3,10]. As the universal and easy-to-use standard for the voltage measurement of piezoelectric devices, the inner resistance of the voltmeter used must be larger than the critical resistance $R_{critical}$. Note that Eq. (5) can work for a piezoelectric block with effective capacitor of C, being subjected to a periodic tensile load of frequency f, but is not only limited to the specific PZT MEH with Euler buckling. For the above experiment, the inner resistance of the voltmeter must be larger than $R_{critical}=85$ GΩ to ensure the error of voltage measurement for open-circuit $\delta<1\%$, for $ft_\delta=10$ and $f=1$ Hz.

The mechanical–electrical coupling system (Fig. 3(a)) can be further understood by an analogy with a water-flow system as

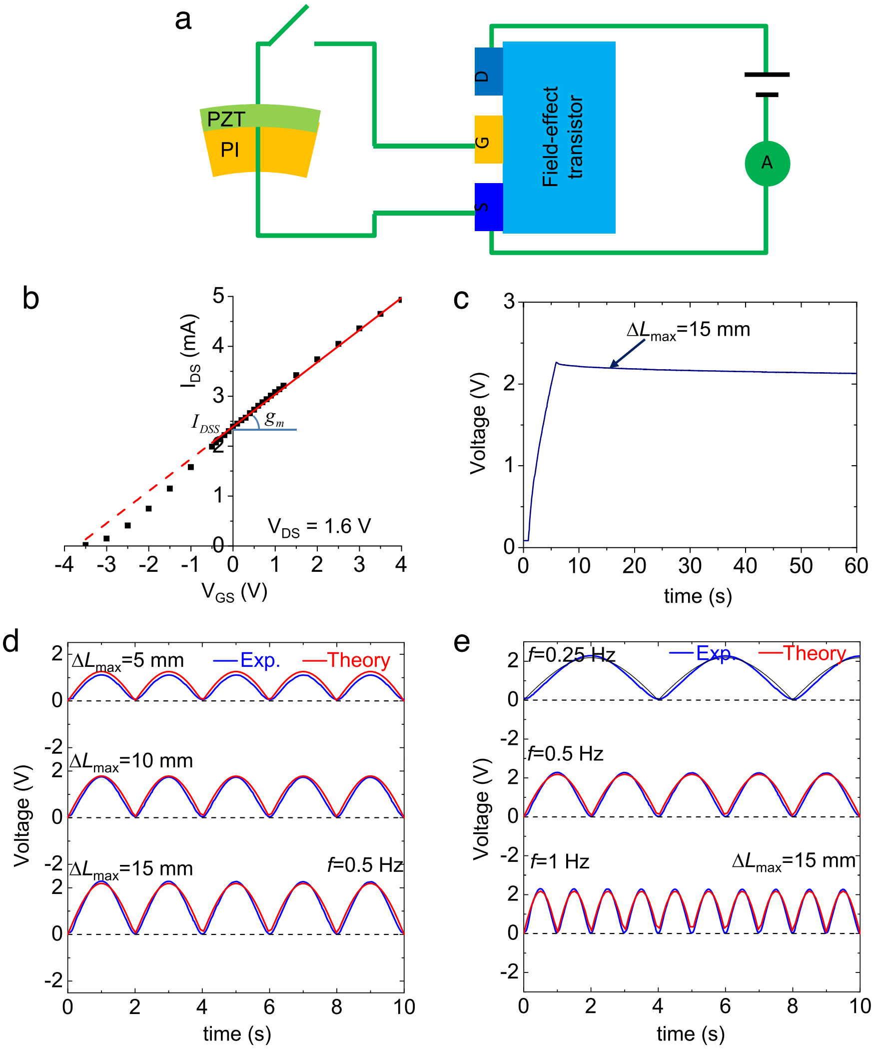

Fig. 4. Application of a self-developed electronic system for voltage measurement. (a) Schematic illustration of the self-developed electronic system for voltage measurement. (b) Calibration of the self-developed electronic system. (c) The test of decay time for the self-developed electronic system. Effects of (d) compression amplitude ΔL_{max} and (e) freguency f on the output voltage for the self-developed electronic system.

shown in Fig. 3(d). Two containers are connected via a tube, in which the flow is controlled by a valve. These two containers are equivalent to the two electrodes connected by a wire, in which the resistance of the voltmeter controls the current. The bending and releasing of the PZT MEH are compared to the inflow and outflow of the water driven by the 'double-direction' pump, which increases/decreases the voltage and the waterhead, respectively, in the two systems. The case of finite resistance of the voltmeter for the mechanical–electrical coupling system is represented like the water-flow system with the unclosed valve. In this case, the water/charge goes through valve/resistance during the measurement. On the other hand, the case of infinite resistance for the mechanical–electrical coupling system is illustrated like the water-flow system with closed valve. With the help of water-flow analogy, it is easier to understand that the measured water-head/voltage depends on the valve/resistance.

The inner resistance of the voltmeter should be as large as possible to obtain the open-circuit voltage according to the above analysis. Eq. (5) and the calculation suggest that the inner resistance should be at least larger than 85 GΩ for the PZT MEH. Here, a new electronic system for voltage measurement is developed by simply utilizing a field-effect transistor (ALD114935) due to its large resistance ($>10^{12}$ Ω) between the gate and source electrodes (Fig. 4(a) and S6). The electrodes of PZT MEH are connected to the gate and source electrodes of the field-effect transistor, respectively, between which the resistance is larger than 10^{12} Ω. The voltage signal from the PZT MEH is converted to the current I_{DS} between the source and drain electrodes, in which the circuit involves an amperemeter and a battery (EXCELL alkaline battery, LR6) with a voltage of 1.6 V that are connected in series. The measurement system is calibrated by the circuit with a known and controllable applied voltage V_{GS} between the gate and source electrodes of transistor (Fig. S8). Fig. 4(b) shows the calibration results, i.e. the relation between I_{DS} and V_{GS}. The inverse relation can be fitted by the following equation according to the theory of field-effect transistor,

$$V_{GS} = \frac{I_{DS} - I_{DSS}}{g_m} \tag{6}$$

for the range $I_{DS} > 2$ mA, where $I_{DSS} = 2.39$ mA and $g_m = 0.645$ mA/V are saturated drain current and transconductance, respectively. Eq. (6) can be used to calculate the measured voltage V_{GS} by the experimentally obtained current of I_{DS}. Similar to the test shown in Fig. 2(g) & (h), Fig. 4(c) shows the voltage decay for this designed system. After the connection of the circuit, the voltage produced by PZT MEH decays ∼3% in 10 s, which is in an acceptable range for the voltage measurement. The measured voltage of PZT MEH by our designed measurement system is given in Fig. 4(d) &

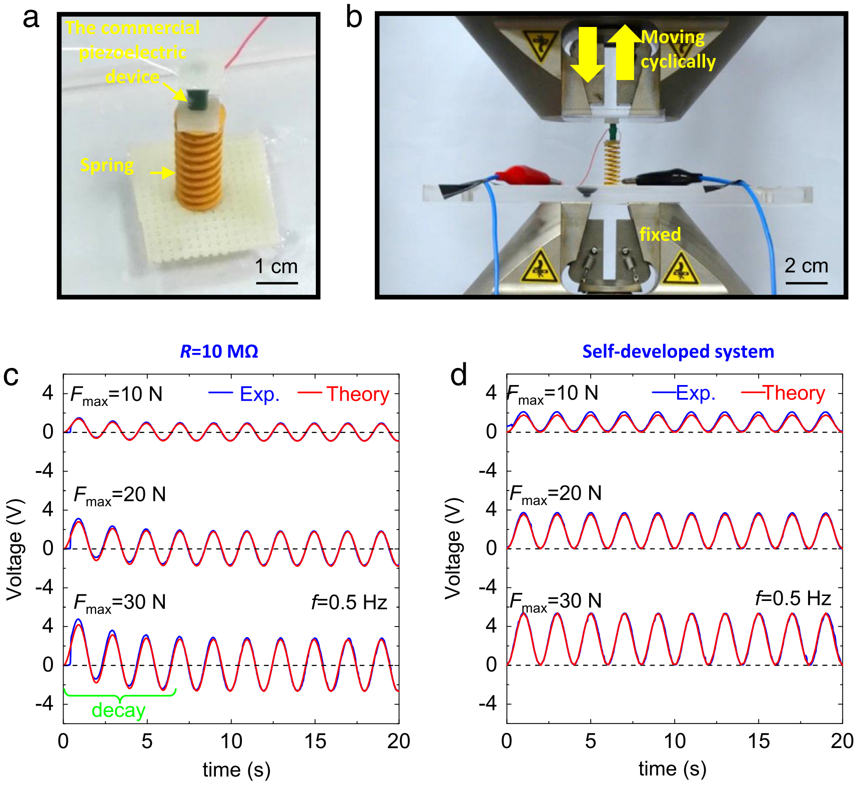

Fig. 5. The voltage measurement of a commercial piezoelectric device. (a) The commercial piezoelectric device with the support of a spring for loading. (b) The commercial piezoelectric device is subjected to cyclic compression. Effects of compression amplitude $F_{\max}$ on the output voltage for (c) 10 MΩ-resistance voltmeter and (d) self-developed electronic system.

(e) for different amplitude and frequency values. The peak voltage increases with the increase of the amplitude of applied load, but does not change with the frequency, which is different from the trend of the result obtained by previous test. Most importantly, all these curves of voltage vs. time are throughout nonnegative, and agree with the theoretical solution for open-circuit $V_{open} = \left[(-\bar{e})\, d/\bar{k}\right] \varepsilon$ very well. These results verify the ability of the self-developed system to measure the open-circuit voltage values of any piezoelectric devices.

In order to validate the universality of all the findings, similar procedure was performed on a commercial piezoelectric device. This device is a block consisting of multilayer PZT films, as depicted in Fig. 5 & S10. These PZT films are electronically connected in parallel, and are equivalent to an intact thick PZT film (See SI for details, Appendix A). The applied compressive force is a function of time, i.e. $F = F_{\max}\left[1 - \cos(2\pi f t)\right]/2$, where $F_{\max}$ and f are maximum amplitude and frequency, respectively. A spring is mechanically attached in series to the commercial piezoelectric device, since enlarging the displacement is helpful to control the applied force during experimental tests (Fig. 5(a) & (b)).

Fig. 5(c) shows the output voltage measured via the 10-MΩ-resistance voltmeter, for the amplitude of applied force $F_{\max} = 10$, 20 and 30 N and the frequency $f = 0.5$ Hz. Each curve shows the highest peak at the first period, then decays rapidly and becomes an alternating positive and negative periodic variation after the third cycle. As expected, the amplitude of the measured output voltage increases with the increase of applied force $F_{\max}$, as well as the frequency, but it is not significant (Fig. S7). Our self-developed electronic system was also used to test the same PZT block. The calibration of the field-effect transistor is shown in Fig. S8. Here, $I_{DSS} = 2.46$ mA and $g_m = 0.640$ mA /V are slightly different from those in Fig. 4(b), since the environmental temperature changed slightly during the test. All the measured output voltage is nonnegative, which approaches the real open-circuit voltage, as shown in Fig. 5(d) and Fig. S9. The voltage increases with the increase of the maximum applied force $F_{\max}$, but is independent of the frequency.

Figure S10 gives the schematic illustration of a commercial PZT device (NEC Tokin, AE0203D08F) subjected to an applied force F. The theoretical analysis is similar to that for PZT MEH (See SI for details, Appendix A). By the analogy to the case of PZT MEH, the measured voltage of the PZT block can be obtained by replacing ε with $F/(\bar{E}w_1w_2)$ (without negative sign to ensure the positive sign of the open voltage), where $\bar{E}$ is the effective elastic modulus,

$$V = \frac{(-\bar{e})d}{\bar{k}}\frac{F}{\bar{E}w_1w_2} - \frac{(-\bar{e})d^2}{AR\bar{k}^2}e^{\frac{d}{AR\bar{k}}t}\int_0^t \frac{F}{\bar{E}w_1w_2}e^{\frac{d}{AR\bar{k}}t}dt. \tag{7}$$

Here, $\bar{e}$ and $\bar{k}$ are effective piezoelectric parameters, but they are different from that for the case of flexible PZT MEH. For $d = 0.11$ mm, $w_1 = 2$ mm, $w_2 = 3$ mm, $A = 2 \times 3 \times 68$ mm^2, $R = 10$ MΩ in the experiment, $\bar{e}/\bar{E} = -4.66 \times 10^{-10}$ C/N and $\bar{k} = 4.76 \times 10^{-8}$ C/(Vm), being consistent with the order of magnitude to those in the literature [35], the theoretical predictions agree well with the experimental results for various applied load $F_{\max} = 10$, 20 and 30 N and frequency $f = 0.5$, 1/3 and 0.25 Hz (Fig. 5(c) & S7).

Additionally, Eq. (5) can also be used to calculate the critical resistance of voltmeter for the measurement of open-circuit voltage for the commercial piezoelectric device. For $C = 176.6$ nF, $f = 0.5$ Hz and $\bar{\varepsilon}_{over} = \int_0^1 F/F_{\max} d(ft) = 0.5$ in the experiment, the inner resistance of the voltmeter must be larger than $R_{critical} = 5.6$ GΩ to ensure the error of voltage measurement for open-circuit $\delta < 1\%$ at $ft_\delta = 10$. In this study, the inner resistance of the self-developed electronic system is significantly larger than the required value 5.6 GΩ. The theoretical open-circuit voltage $V = (-\bar{e})dF/(\bar{k}\bar{E}w_1w_2)$ matches very well with the experimental results obtained by the self-developed electronic system for piezoelectric devices (Fig. 5(d) & S9).

3. Conclusion

The output voltage is an important parameter for quantifying the performance of piezoelectric devices. The theoretical prediction suggests positive output voltages throughout the application of positive strains, while the literatures and our previous experimental findings show oscillating positive and negative variation in the measured output voltage. We found that the measured output voltage depends on the inner resistance of voltmeter, although this concept is contrary to the established knowledge that the measured results should be independent of the instruments used. This paper presented intensive experimental evidences with extremely different output voltages (0.2 V vs. 2 V) obtained from two commercial voltmeters with an inner resistance of 10 MΩ and 55 GΩ, respectively. Our universal analytic model can explicitly capture both sets of the experimental findings by the substitution of inner resistance values of the voltmeters. The universal and easy-to-use standard of voltage measurement for piezoelectric devices reported that the inner resistance of the voltmeter must be larger than the critical resistance in order to achieve the open-circuit resistance-independent voltage. A new electronic system meeting the standard requirement was developed by utilizing the field-effect transistor due to its large resistance value between the gate and source electrodes. The same experimental test and theoretical analysis were conducted on a commercial piezoelectric system to validate the universality in all the findings, i.e., the unusual conclusion of resistance dependence and the standard of voltage measurement. The proposed standard of voltage measurement offers a universal platform to quantify the performance of piezoelectric devices.

Acknowledgments

Y. S. acknowledges support from National Natural Science Foundation of China (No. 11572323), the support from Chinese Academy of Sciences via the "Hundred Talent program", the support from the State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology (No. DMETKF2017008) and the support from State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology (No. GZ1603). Y. H. acknowledges support from National Natural Science Foundation of China (No. 11372323). R. L. acknowledges the support from the National Natural Science Foundation of China (grant 11302038). Y. S. and C. D. thank Prof. John A. Rogers of Northwestern University for his continued support.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.eml.2017.03.002.

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