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Influence of friction on piezoelectric sensors

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Abstract

Piezoelectric sensors are usually made of a sensing element compressed between two plates. Therefore, the applied point/distributed load is transferred through these plates to the piezoelectric sensing element. In this sandwich configuration, surface friction has an inevitable and significant impact on the resultant output of the sensor. This paper reports on the influence of the friction on the output of piezoelectric sensing element in a sandwich structure. Although the numerical analysis as well as experiments are performed on the piezoelectric Polyvinylidene Fluoride (PVDF) films, the results are applicable to similar structures with other piezoelectric materials. The results show the remarkable contribution of the friction induced component in the total output for both uniaxial and biaxial PVDF films. The outcome can be used for the optimization of sensor manufacturing processes. In addition, results suggest an alternative new method for the measurement of d_{33}, the PVDF piezoelectric coefficient in the thickness direction. Alternately, it is possible to use the proposed method in order to accurately measure friction coefficients, particularly for low friction range, namely $\mu < 0.1$.

Keywords: Piezoelectricity; Friction; Polyvinylidene Fluoride (PVDF); Piezoelectric coefficients

1. Introduction

The various applications of the piezoelectric Polyvinylidene Fluoride (PVDF) film, particularly in sensory mode, are increasingly reported by numerous researchers [1–5]. In addition, many companies have started supplying piezoelectric PVDF based sensors. Although much research has been conducted since the discovery of the piezoelectric property of PVDF by Kawai [6], the accurate characterization of the PVDF still needs further investigation. For instance, the influence of the surface roughness or friction on the output of the piezoelectric PVDF film has not yet been comprehensively studied. The PVDF film is mainly supplied in the form of thin sheets ranging in size from a few micrometers to more than 100 micrometers thickness. Due to thinness of the PVDF films, the only practical area to deposit electrodes is the film surface, hence the electrical charge can only be collected from the thickness direction. Although the application of the PVDF films in extensional modes are dominant, there are many situations in which the PVDF film must be placed between two surfaces. For instance, in the traditional piezoelectric force sensors, it is customary to place the piezoelectric sensing element between two plates which also act as electrodes. These plates transmit the normal force to the surface of the piezoelectric films, so that they transform the applied point load to a distributed load over the piezoelectric surface. Traditionally, to avoid the complexity of considering friction forces, the sensor package is treated as a black box and just the relationship between input and output is considered. Therefore, for a given set of piezoelectric element and surfaces, the output of the sensor is empirically calibrated in terms of the input load. Fortunately, the force sensors which are calibrated in this way perform well. However, in this case, the output charge of the sensor is a combination of the thickness mode charge and another component which is caused by the friction force. Nonetheless, the response of the piezoelectric sensor is highly sensitive to the surface conditions and varies with any change in the manufacturing process or material that affects the surface conditions.

As we see in this article, the results of this study are helpful for the modification and optimization of the manufacturing of piezoelectric force sensors. This research was performed on the piezoelectric PVDF film, nevertheless, the results could be applied to any other piezoelectric force sensor in which the friction force is involved.

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This study also has another fundamental application in the measurement of d_{33}, the piezoelectric coefficient in the thickness mode. The piezoelectric coefficient d_{33} is the most difficult coefficient to measure, as it is extremely difficult to apply a normal force to the film, without constraining the lateral movement of the film and thus inducing other stresses within the film. The output can thus have contributions from both the applied normal stress and the induced friction stresses. In order to avoid difficulties associated with the direct measurement of d_{33}, most researchers have used two indirect ways to calculate this value [7–10]. In one method, d_{33} is determined using the converse piezoelectric effect. In this method one measures the change in thickness of a small sample that results from the application of a known field. The problem with this approach is the mounting of the sample in a way that does not restrict its lateral motion. This restriction could affect the accuracy of measurement. In the second method, d_{33} is measured indirectly by measuring the hydrostatic piezoelectric coefficient, $d_{3\mathrm{h}}$. Using this value and knowing the values of d_{31} and d_{32} the value of d_{33}, can be calculated. For a hydrostatic pressure P, the amount of charge is related to all three coefficients by [10]: $\Delta Q/A = -(d_{31} + d_{32} + d_{33})P$, in which $-(d_{31} + d_{32} + d_{33}) = d_{3\mathrm{h}}$. The present study introduces a new approach for this problem. If we can characterize the effect of friction on the PVDF output by finding the trend of variations for some known friction coefficients, then it is possible to calculate the d_{33} for the case that friction approaches zero. Therefore, a finite element contact analysis is performed in which piezoelectric PVDF is considered as an orthotropic material and the coefficient of friction is varied between zero to one and the output is recorded. The results are validated by performing an experiment on a similar geometry using some pre-characterized surfaces. It is found that the inverse procedure can also be used in determining the friction coefficients of surfaces. The later method offers many advantages over traditional friction measurement methods, such as being an *in situ* friction measurement, being non-invasive and having low weight and cost.

2. Background

The PVDF is semi-crystalline polymer that, depending on the production process, can be found in four different stable crystal structures at room temperature. The form I or β-phase exhibits highly piezoelectric sensitivity [11] and can be defined by a 3×6 strain piezoelectric coefficients matrix d with non-zero elements $d_{31}, d_{32}, d_{33}, d_{24}, d_{15}$. The difference between two distinct types of the piezoelectric PVDF film, referred to as uniaxial (or uniaxially oriented) and biaxial PVDF film, is mainly in the mechanical stretching of the film. In the uniaxial films, a mechanical stretch of more than four times of initial length, tends to align the 1-axis of the crystals parallel to the stretching direction, giving the crystals the desired orientation.

The stretch in one direction creates a preferred direction for uniaxial PVDF film and could explain the anisotropic property of the uniaxial films verses transversely isotropic biaxial films in which the film is stretched equally in two perpendicular directions.

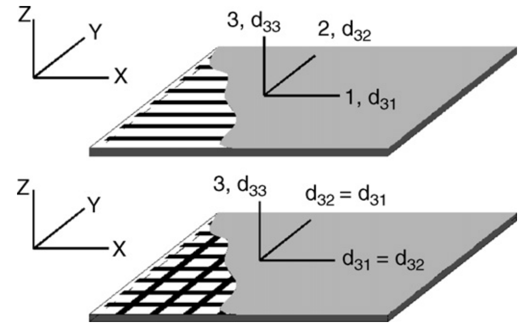

Fig. 1. The conventional notations of the principal directions of the *uniaxial* (top) and *biaxial* (bottom) piezoelectric PVDF film. The uniaxial PVDF film can be classified as an orthotropic material, while the biaxial film shows behavior similar to transversely isotropic materials.

Fig. 1 illustrates a metalized PVDF film with its principal directions and their associated piezoelectric coefficients. In the uniaxial PVDF film, the drawn direction which also exhibits the highest sensitivity, is labeled as the 1-axis, whereas the perpendicular direction with a sensitivity of about 1/10 of that of drawn direction, is referred to as the 2-axis. The thickness direction, the 3-axis, is normal to the plane of the 1 and 2-axes. The biaxial films show isotropic behavior in the plane of the film. Therefore, the piezoelectric coefficients for the directions 1 and 2 (d_{31} and d_{32}, respectively) are equal. In dealing with piezoelectric coefficients, d_{ij}, the first and second subscripts represent the electrical and mechanical direction, respectively. For instance, d_{31} is the piezoelectric coefficient that relates the charge collected from the area of film, i.e., the 3-axis, to the force applied in the 1-axis direction. The linearized equations governing the electrical and mechanical properties of the piezoelectric PVDF, at constant temperature and negligible electric field can be deduced from the general constitutive equations of crystals [12] as follows:

$$Q_i = d_{ij}\sigma_j \quad (i = 1, 2, 3 \text{ and } k, j = 1, 2, \ldots, 6) \tag{1}$$

$$\varepsilon_k = S_{kj}\sigma_j \tag{2}$$

in which, S is the orthotropic stiffness matrix. The second equation is the generalized Hook's formula, in which ε and σ are strain and stress developed in the material. From Eq. (1), the output charge along the thickness direction per unit area, Q_3, due to the stress in the film can be expressed as:

$$Q_3 = d_{31}\sigma_1 + d_{32}\sigma_2 + d_{33}\sigma_3. \tag{3}$$

When a PVDF film is compressed between two rigid flat surfaces, assuming that there is no friction between the surfaces and the PVDF films, the film is free to expand laterally, i.e., in the directions of the 1 and 2-axes. The output charge can thus be deduced from Eq. (3) as:

$$Q_3 = d_{33}F_\mathrm{n} \tag{4}$$

where F_n is the applied normal load. This assumption, however, is difficult to use in practice. Friction force always exists and develops unwanted charge components. In general, therefore, the total output charge is different from above Q_3 by the magnitude of the friction induced components. Some authors have