Electromechanical characterization of didactical piezoelectric sensors based on crystalline grade PET

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Abstract A mechanical shock or impact sensor system for teaching purposes was developed and characterized. The device consists of Mylar layers (3×3 to 21×21 cm²) confined by aluminum sheets. The metallic surfaces are wired in order to send their signals to a digital oscilloscope. The instrument receives voltage variations after the surface of the transducer is stroked by a plastic projectile (capsule mass: 50 g) released in free fall (heights: 0.15 - 3 m). The respective piezoelectric constant was determined to be \( d = 42.02\pm10^{-12} \text{ m/V} \). This proposed experiment can be attractive for a basic instrumentation course which combines both theoretical and experimental concepts of mechanics and materials sciences.

1. Introduction
The trend of technological improvement of sensors leads to deeper and more detailed scientific investigations [1]. That is a reason for institutions to promote both research and development of sensor engineering. Besides, this topic is a key element of the curricula for numerous scientific profiles in Physics and Engineering. For instance, since collisions are an important concept in the field of mechanics; it can be used to link other technological concepts such as electromechanical transducers; this scope could be very attractive for academic courses oriented to applications in several fields such as sports, liberal arts or forensic science. In fact, many applications arise from the force evaluation of a left-jab boxing movement or the estimation of the initial speed of vehicles after collisions. Accordingly, if the academic interest is focused on Physics, teachers center the lesson on the mechanical phenomena, paying no attention to the data acquisition details. Such didactic proposals use the sensors as black-boxes to only correlate the observable inputs vs. the output parameters [2]. On the other hand, if the interest is centered in the instrument, the engineering aspects take priority over the physical analysis. Concerning the subject of collisions, we found only few didactic proposals based on inexpensive components to manufacture suitable transducers. In this work we suggest the construction of a cost-effective system based on an array of aluminum-Mylar-aluminum layers used as transducer and a didactic oscilloscope to monitor the electrical signals produced by an impact. Such development and the corresponding characterization are also attractive and useful for several biomechanical applications.
1.1. Piezoelectricity in polymers

Under mechanical stress, some ceramic and polymeric materials exhibit a change in their electric charge density; the inverse effect leads to mechanical deformations induced by external electric fields; this material property is known as piezoelectricity [3]. A theoretical toy-model could be the following: the mechanical stress modifies the electronic orbitals around the molecules; in this action, some regions acquire positive or negative charge, this reconfiguration promotes the formation of local dipole moments [3]. The aggregate effect of the dipole moments produces the macroscopic and observable electric field. Piezoelectric materials have a molecular configuration suitable for electrical polarization: a non-centrosymmetric structure; this morphological asymmetry permits the migration of electric charges in defined molecular regions [1]. Particularly, in a polymer composed by bulky monomers and stable macromolecules, the electric polarization is easily promoted within the system by different kind of stimuli; where the type of atomic bonds and their location is crucial for increasing the local dipole moment. Thus, structures with adequate molecular architectures and regular arrangements are suitable to exhibit a polar order [3, 4]. For instance, organic materials such as vinylidene polyfluoride / PVDF and polyethylene terephthalate / PET, display such structural characteristics. In fact, PVDF is an efficient piezoelectric-polymer utilized in several instruments [4-6], but it can be expensive for some schools. In contrast, PET is less efficient but almost costless. A highly crystalline PET (within in the polymers context) is Mylar, a common use product in many home appliances and also in some piezoelectric applications [3, 4]. Fig. 1 shows the molecular structure of a Mylar monomer. In its manufacture, Mylar is slowly cooled, favoring the formation of spherulites and lamellae arrangements which exhibit crystalline structures at a local level, being these structures responsible for the whitish color of the material due to scattering effects.

2. Context of the characterization equation

In general, the constituent equations of a piezoelectric material can be described by four fundamental parameters [1, 4]: 1) the electric field $E$ [N/C], 2) the mechanical tension $T$ [N/m²], 3) the electric displacement $D$ [C/m²] (linked with the material polarization under stress), and 4) the mechanical deformation $S$ (a dimensionless quantity). These four variables are complemented by three intrinsic material properties: A) the mechanical flexibility $f$ [m²/N], B) the piezoelectric constant $d$ [C/N] (associated with the ratio of mechanical deformation produced by an external electric field), and C) the electric permittivity $\varepsilon$ [C²/m²N], related to the vacuum permittivity $\varepsilon_0$ (8.9 x 10⁻¹² F/m) where: $\varepsilon = K\varepsilon_0$ and $K = 3.1$ for the Mylar polymer [7].

Figure 1. Schematic representation of the non-centrosymmetric molecular structure of a Mylar monomer; its abundant delocalized electrons favors the formation of electric dipoles.

The fundamental equations that describe the piezoelectric effect are complex: they interconnect electrical and mechanical variables in all directions; so their description requires tensor theory, a subject that students should learn in advanced physics-math courses. The scope of this document is a didactic approach for first-year university students; thus, for simplicity, we use a uniaxial model where the effects of mixed components of voltage, load, and electric field, are considered irrelevant [8]. In this way, the one-dimensional equations for our piezoelectric material are:

$$S = fT + d * E$$
$$D = dT + \varepsilon E,$$

(1)
where \( d^* \) represents the mechanical deformation produced by an electromagnetic stimulus. However, our interest is centered on the electrical response to a mechanical stress, and then this parameter is neglected. In addition, if the material is dielectric, the global electric displacement is zero, i.e. there are no free electric charges. Hence, Eq. 1 is simplified as follows:

\[
E = -\frac{d}{\varepsilon} T.
\]  

(2)

According to the characteristics of the system, we can approximate this electric field to that of a parallel plate capacitor (gap: \( h \)), so the voltage is \( V = Eh \). In addition, if an average tension \( T \) is applied on the area \( A \) of the capacitor during a short period, it can be associated to a constant force of value \( F = TA \). Thus, we can rewrite Eq. 2 as follows:

\[
V = \frac{dh}{\varepsilon A} F.
\]

As the voltage generated by the piezoelectric system is proportional to the applied force, we can consider \( F \) as the average force of the corresponding momentum (the impact on the piezoelectric), thus we can approximate it by the average linear momentum change \( \Delta p \) in the time interval \( \Delta t \):

\[
F = \frac{\Delta p}{\Delta t}.
\]

In our experimental case, the impetus corresponds to the impact of a body of mass \( m \) in free fall from a height \( x \). In fact, the momentum change is: \( \Delta p = m\Delta v = m\sqrt{2gx} \), \((g = 9.78 \text{ m/s}^2)\). Finally, Eq. 2 becomes:

\[
V(h, A, m, x) = -\frac{dmgx}{\varepsilon A \Delta t}.
\]  

(3)

Eq. 3 represents the theoretical reference used to evaluate our experimental characterization. Indeed, in order to obtain the experimental value of \( d \), a voltage study was performed as a function of: 1) the distance between the Al-sheets, 2) the condenser area \( A \), and 3) the initial height of the projectile in free fall. Although \( \Delta t \) is neither a constant nor a controllable parameter for each impact, we calculate the average value for each case.

3. Materials and methods.

The experimental device was made-up from several simple and cheap elements, as it is shown in Fig. 2. Plastic capsules (parts of candies and toys by Ferrero and Kinder-Surprise) used as projectiles were filled with lead filings and drooped on the center of the sensor. The piezoelectric transducer was composed by a square core of Mylar (dimensions: 3x3 to 21x21 cm\(^2\)) covered on both sides with aluminum foil sheets (commonly used in food packaging) and adhered with double-face tape to ensure a steady and homogeneous blending; the tape also prevents electrical contact between Al-sheets. The metallic surfaces were connected to thin Cu wires of negligible impedance and to a BNC cable connected the transducer to send the signals to a digital oscilloscope (Tektronix TDS-210). Furthermore, the number of Mylar layers was varied in order to register any variation on the voltage responses. The aluminum foils provided an easy handling of the condenser, as well as the possibility of building sensors of different areas and geometries. However, this material also leads to some disadvantages since it is prone to tearing after some impacts; thus each event was carefully carried out.
The experimental implementation of our device intends to determine the scope and validity of Eq. 3, as well as the accurate evaluation of the piezoelectric deformation coefficient $d$. In this way, by modifying a single variable and controlling the others, it is possible to obtain voltage trends in terms of: 1) the height of the free fall, 2) the number of Mylar plates, and 3) the area of the capacitor. In order to reduce the stochastic error; for each case, we obtained the mean of ten measurements. Finally, in order to ensure that the impact of the projectile happened at nearly the same point, a thread was vertically suspended as a track.

4. Results and Discussion.

The acquired data was adjusted via linear functions and the $d$ coefficient was obtained from the slope value analyses. It is also important to mention that the time interval $\Delta t$ of the impact was variable, within an average time range of 0.5-15 ms.

4.1. Signals recorded on the oscilloscope

Fig. 3 exhibits a typical electric signal recorded from the impact of a projectile on the transducer. The oscilloscope shows a variable voltage or pulse profile which develops over a period of 15 ms. By means of the automatic average command of the digital oscilloscope we obtained a voltage value which is representative and suitable to use in the Eq. 3; as explained before. Nevertheless, future work should take advantage of the dynamic character of these signals to deepen into the mechanics and physical meaning of the impact.

4.2. Voltage depending on the height of the free fall

Fig. 4 shows the obtained experimental data (voltage as a function of the square root of the height $x$) for three different sensor areas: 5x5, 7x7 and 10x10 cm². It was observed that stronger signals (with respect to the background noise) were produced by implementing two plates. The worst theoretical fitting gave rise to a correlation coefficients of $V_{5\times5}=0.460\sqrt{x}+0.058$, $R^2=0.933$.

4.3. Signals according to the number of Mylar plates

Fig. 5 shows the dependence of voltage with the number of Mylar plates for sensors of 5x5, 7x7 and 10x10 cm². In these experiments, the projectile was dropped from a constant height of 1 m in free fall (the average thickness of the transducers was 43 μm). In this case, the voltage signal increases almost linearly with the number of plates. At first, we expected to observe a saturation effect as a result of attenuation occurring in the inner layers of the device due to Mylar deformations. A possible
explanation for the observed trend is that in a parallel plate capacitor, the accumulated voltage is directly proportional to the separation between plates, as described Eq. 3. This suggests that the thicker the Mylar stacks, the stronger the output signal. In this case, the worst theoretical fitting gave rise to a correlation coefficients of \( V_{10\times10}=0.382N+0.175, \) \( R^2=0.973. \)

**Figure 4.** Mean voltage as a function of the square root of the height for three different sensor areas (projectile mass: 50 ± 0.05 g).

**Figure 5.** Mean voltage as a function of the number of Mylar plates (Height: 1 m; projectile mass: 50 ± 0.05 g; sensor areas: 5x5, 7x7 and 10x10 cm\(^2\)).

**Figure 6.** Voltage signal as a function of the Mylar plate’s sensor area (Projectile mass: 50 ± 0.05 g; height: 1 m; sensor areas: 3x3, 5x5, 7x7, 10x10, 13x13, 17x17 and 21x21 cm\(^2\)).

4.4. Voltage depending on the sensor area
Fig. 6 shows the sensor area dependent voltage signals obtained for free fall experiments performed at a fixed height. It is observed that the experimental data nearly satisfies the theoretical description given by Eq. 3. Here, the linear fitting gave rise to the following results: \( V = 0.002/A -0.013, \) \( R^2 = 0.997. \) In general, we can observe that Eq. 3 is adequate to reasonably describe the proposed physical sensor-system.

4.5. Average piezoelectric constant
Finally, from the obtained experimental results, an average value for the piezoelectric constant was obtained, namely \( d = 42.02 \pm 5 \times 10^{-12} \) m/V (estimated error: 12%). In the case of PVDF, some reports claim experimental values ranging from 23 to 30×10\(^{-12}\) m/V [4]. Therefore, our result is congruent in the order of magnitude and very acceptable, at least for didactic scientific applications.
5. Conclusions
We determined that the observed variations in the voltage signals of the developed sensor are caused by the piezoelectric characteristic and geometry of the sensor. In fact, we calculate a satisfactory value of the d coefficient. The precise measurement of this kind of constants requires of finer instruments and a more complex theoretical model. However, the proposed method is suitable for an initial approach in the study of piezoelectric materials. We were able to describe the trends between voltage and some physical parameters such as separation between metallic surfaces and the geometry of the system; our experimental findings show that the piezoelectric with the smallest area turned out to be the most sensitive device. This proposal can also be useful for future studies in the fields of sports, forensic science or biomechanical studies. For instance, after a proper calibration, it can be possible to obtain the force of a punch from a voltage measurement, and obtain comparative information concerning the impact time on different surfaces. Finally, in order to improve this proposal, future works may pursue to economize the experimental device, probably replacing the digital oscilloscope by suitable instrumentation based on Arduino-smartphone interfaces; the increase of the device sensitivity is also important, this could be performed via bending geometries of the Mylar (e.g. a cantilever) among other upcoming studies.

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