Classification and simulation method for piezoelectric PVDF sensors

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Abstract

The piezoelectric polymer Polyvinylidene fluoride (PVDF) holds the potential to be the core material of novel structure-borne sound sensors not only in research but also in industrial applications. This paper will give an overview of possibilities when PVDF is useful and when PVDF reaches its limits of applicability. To do so, a state of the art about current applications of PVDF will be given. Furthermore, the consecutive equations and an experimental setup for the classification of the piezoelectric constants and Young’s moduli over frequency and temperature will be presented. A simplified FE simulation method will also be shown to model PVDF film sensors by computer aided design.

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1. Introduction

Structural-Health-Monitoring (SHM) techniques are commonly used to optimize technical processes and to reach performance levels of mechanical systems without touching their maximum limits. Especially in technical advanced situations SHM demands technically advanced sensor solutions. Polyvinylidene fluoride (PVDF) as core material for piezoelectric polymer based vibration sensors is showing a great potential to fulfill various SHM functions. PVDF is generating electrical charge when it is stretched. It can be glued onto surfaces and will generate an

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electrical signal which is proportional to the surface elongation of structure-borne sound waves. In contrast to that, ceramic piezoelectric sensors are commonly built up as spring mass systems, reacting on the surface acceleration. The output signals from stretch sensitive and acceleration sensitive structure-borne sound sensors carry the same informational content but the technologies show differences in many other attributes. For instance, PVDF sensors don’t have an additional seismic mass as acceleration sensors and therefore they are not bandlimited in frequency by a mechanical resonance. Due to this, PVDF sensors can be used in a wide range of frequency from almost stationary pressure and force sensing [1,2], over low frequency applications such as heartbeat and respiration sensing [3,4] to high frequency use in crack detection [5,6] or ultrasonic sensing [7]. Furthermore, PVDF sensors are flexible polymer thin film elements. They can be easily glued onto curved surfaces like vehicle bodies to detect damage [8]. Their flexibility and light weight cause very low mechanical impedance, meaning that PVDF film sensors need a very low mechanical force only to be deformed. In other words, PVDF is very sensitive to small mechanical deformations what makes it also a suitable material for sentient robot skin [9]. In those robot skin application the PVDF polymer layer is not only equipped with one upper and one lower electrode to measure the electrical charge but with a two dimensional array of electrodes allowing also spatial resolution of touch. As these electrodes can be easily printed by silver ink screen printing, the PVDF film sensor’s geometrical layout can be made in almost every shape. In [10] a triangular multi-channel PVDF film sensor is described making it possible to calculate the direction of incoming structure-borne sound by a time-difference-of-arrival (TDOA) algorithm. Beyond those vibrational applications, PVDF even shows pyro electricity what can be used for energy harvesting [11] or motion sensing by infrared radiation [12].

The examples above show the wide range of applications for PVDF by its superior properties to piezo ceramic sensors. So far not discussed are the disadvantages of PVDF film sensors hampering their commercial breakthrough. One reason is certainly the variance from sensor to sensor in the charge generation per mechanical force caused by film-to-film production variations and also by temperature dependency. In the assumption of the authors another reason might be the higher complexity of predictive computer aided sensor design methods as the charge output has to be calculated by a strain profile over an area instead of simulating the acceleration at a specific point. As an assistance to overcome these issues, this paper describes methods and results to characterize the electromechanical properties of PVDF film sensors and to simulate the sensor output by means of a simplified finite element analysis.

2. Electromechanical characterization of PVDF film elements

The piezoelectric behavior of PVDF can be described by the linear electro-elastic relation [14] of the electric displacement vector $D$ (3x1), the electric field vector $E$ (3x1) the mechanical strain vector $\varepsilon$ (6x1) and the mechanical stress vector $\sigma$ (6x1)

$$
[D] = \begin{bmatrix} e & d^e \\ d^e & s \end{bmatrix} [E]$$

Equation (1) describes both the complete direct and inverse piezoelectric effect (sensor and actuator principle). For pure sensing applications, where there is no external electrical field to actuate the piezo, $E$ is zero. In this case, the electro-elastic relation can be split into a pure piezoelectric part of the electric displacement $D$ and a pure mechanical part of the strain $\varepsilon$.

Even though PVDF sensors are not bandlimited by a seismic mass, they are band limited by their geometry. But their linear frequency behavior is very high in comparison to ordinary acceleration sensors [12].
With $E_i$ as Young’s moduli, $\mu_{ij}$ as Poisson’s ratio and $G_{ij}$ as shear moduli.

The piezoelectric film elements under test are the DT1-52K/L elements of Measurement Specialties [15]. Their electrodes conduct the piezo film’s xy plane denoted by index 3 in the equations (2), (3). Thus, the measured electrical signal $Q_3$ at a film elongation due to structure-borne sound can be expressed as electrical surface charge meaning $D_3$ over electrode area $A_3$.

$$Q_3 = \oint_A D_3 \, dA_3$$

A combination of the equations (2,3,4) leads to the expression of the electrical surface charge as function of piezoelectric constants, Young’s moduli and strain.

$$Q_3 = \oint_A (d_{31} E_1 \varepsilon_{11} + d_{32} E_2 \varepsilon_{22} + d_{33} E_3 \varepsilon_{33}) \, dA_3$$

So, the piezoelectric constants and the Young’s moduli have to be characterized to describe the piezoelectric output at a given strain profile or elongation. To do so, an experimental setup to stretch the directions selectively has been created measuring the surface charge $Q(t)$, the elongation $\Delta l(t)$ as double integrated acceleration signal $a(t)$ and the mechanical force $F(t)$ simultaneously. By the definition of Hooke’s law, the strain $\varepsilon$ and Young’s modulus $E$ can be derived as

$$\varepsilon(t) = \frac{\Delta l(t)}{l_0} = \frac{\int a(t) \, dt^2}{l_0},$$

$$E = \frac{\varepsilon(t) A}{F(t)},$$

which finally recombines with equation (5) to the piezoelectric constant

$$d = q(t) E \frac{\varepsilon(t) A}{F(t)} = \frac{q(t) F(t)}{A} \left( \frac{l_0}{\int [a(t) \, dt]^2} \right)^2.$$
(Kistler 9301B) on one holder and an accelerometer (Kistler 8714B100M5) on the other holder. Furthermore, the piezo film (Measurement Specialties DT1-52kK/L w/rivets) is connected to a charge amplifier (Kistler 5165A4K) and measured as well. The signal AD conversion and signal driving of the smart shaker is done by National Instrument hardware (cDAQ9178, 9234, 9239, 9263) controlled by a PC via MATLAB.

To define the Young’s modulus \( E_1 \) and the piezoelectric modulus \( d_{31} \) at room temperature 10 films have been evaluated at 27 frequency points from 50Hz to 2000Hz. Every measurement has been repeated 20 times to ensure statistical validity. Within these measurement series the 50Hz measurements had to be deleted as they were interfered with present 50Hz electric hum.

The results show an overall Young’s modulus between 3GPa and 4GPa and a \( d_{31} \) in the range of 20pC/N to 30pC/N, what fits to the values of Measurement Specialties [13,15] and the comparable results of Seminara et al [9], Dahiya et al [14] and Thompson [16].

As Fig. 2 indicates, the standard deviation within a measurement sequence of one element is rather low (±0.3% mean) in contrast to the element to element standard deviation (±12%). Furthermore, the element has been repeated
over a temperature range of -5°C to 35°C in steps of 5K by putting the entire setup into a climate chamber. To ensure thermal stationarity each temperature has been held for 2h before the measurements over frequency were taken. Fig. 3 shows the measurements results over frequency and temperature (measurement point as line crossings) with an interpolated field between the measurement points.

![Fig. 3. Piezoelectric constant (left) and Young’s modulus (right) over frequency (x axis) and temperature (y axis)](image)

Both parameters, the piezoelectric constant and the Young’s modulus are influenced by temperature. The piezoelectric constant gets higher with temperature up to 35pC/N while the Young’s modulus gets higher with low temperatures to over 5GPa. This trend over temperature correlates to an ordinary polymer behavior as it becomes more ridged and stiffer when it cools down. The raise of the piezoelectric constant at higher temperature is also caused by the higher flexibility of the film element, meaning the polymer chains need less energy to be moved and thus they create more charge per force. Looking back to equation (5) the product of the piezoelectric constant and the Young’s modulus is of real relevance to the charge output of the sensor at a given strain. Fig. 4 illustrates that the almost inversely proportional trend with frequency and temperature cause a compensation in the product of $d_{31}$ and $E_1$.

![Fig. 4. Temperature drift compensation in the product of piezoelectric constant Young’s modulus](image)

Even though both parameters do not fully compensate the temperature drift, this effect is of very well use since the effect of temperature is weakened. The product filed in Fig. 4 can now serve as input variable for the FE simulation.
3. FE Simulation of PVDF film elements

Target of the finite element simulation is to provide an easy to use design method of PVDF film sensors. This chapter will address a simplification method of the geometric model of the sensor film by modeling the entire film as one component instead of modeling the real stack of material layers inside the film sensor (Mylar coating, screen printed silver electrode, PVDF, screen printed silver electrode, Mylar coating). To do so, the PVDF film sensor DT1-52K/L has been redrawn in COMSOL Multiphysics (see Fig. 5).

![Fig. 5. 3D finite element model of Measurement Specialties DT1-52K/L Piezo film](image)

The film element consists of one rectangular Mylar block (41x16x0.9mm³) with two lead attachments of 4mm in diameter. The area of electrode (30x16mm²) is marked by another rectangular but of the same material than the outer shape. Exactly this is the key point in the simplification method. Since the Young’s modulus has been classified in the experiment over the entire film (see Fig. 3), the simulation model is also seeing the film as isotropic virtual material with the measured mechanical behavior (except the lead attachments).

![Fig. 6. Visualization of FE model during a sine force period at 1π/2 (left), 2π/2 (middle) and 3π/2 (right) – graphic not to scale](image)

Fig. 6 visualizes that the film has been fixed on the side of the lead attachments and pulled on the counter side in x direction exactly like in the experiment. To calculate the charge output, the electrode surface has been integrated over the product of piezoelectric constants and Young’s modulus as given in equation (5). The comparison with measurement results shall verify how well the simulation fits to reality at an example of a 1kHz sine wave with a measured force peak amplitude of 0.735N (see Table 1). Furthermore, Fig. 7 shows the graphical signal comparison.
Table 1. Comparison of FE simulation to measurement data at 1000Hz

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
<th>Simulation</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>0.735N</td>
<td>0.735N</td>
<td>0 (input parameter)</td>
</tr>
<tr>
<td>Strain peak</td>
<td>4.774µm</td>
<td>4.874µm</td>
<td>2.05%  (0.10µm)</td>
</tr>
<tr>
<td>Strain phase</td>
<td>-12.96°</td>
<td>0°</td>
<td>-3.60% (-12.96°)</td>
</tr>
<tr>
<td>Charge peak</td>
<td>3699.6pC</td>
<td>3719.9pC</td>
<td>0.55%  (20.32pC)</td>
</tr>
<tr>
<td>Charge phase</td>
<td>-4.32°</td>
<td>0°</td>
<td>-1.20% (4.32°)</td>
</tr>
</tbody>
</table>

The deviation from the simulation to the measurement results is 2.05% of the total strain and 0.55% of the generated electrical charge amplitude. Besides that relative small deviation in amplitude there is a phase shift in the measurement signals to the simulated signals, since the simulated signals are fully aligned with the force signal but the measurements of strain and charge are not.

This phase delay between force, strain and charge respectively is described in the theory of viscoelastic polymers [17] where the elastic material properties are discussed as velocity dependent parameters. In the here presented FE simulation those assumptions where neglected for the sake of model simplicity. To summarize the results of the simulation it can be stated that the results of this simplified FE model fit very well to the real behavior of the PVDF film element since the deviation between simulation and measurement is less than the standard deviation of the piezoelectric constants from sensor to sensor. From this it also follows that every film element has to be known in its piezoelectric constant and Young’s modulus at the corresponding frequency of excitation to simulate sufficient results.

4. Conclusion and final remarks

PVDF shows great potential in a wide range of applications within structure-borne sound sensing. This paper has presented a method to identify the piezoelectric constants and Young’s moduli by axis selective stretching of a film sensor. The parallel measurements of force, acceleration and charge over frequency and temperature made it possible to derive all necessary input parameters for a simplified FE simulation of the PVDF film sensor. An exemplary run of the classification and simulation has been shown for the major stretch direction of a commercially available PVDF film sensor from Measurement Specialties as these sensors are used very common. By creating a simplified 3D model consisting of one polymer block with the measured Young’s modulus and two lead attachments it has
been possible to derive the electrical charge as surface integration over $d_{31}E_1$ in the area of the electrode. The simulation outcome fitted very well to the peak amplitudes of strain and charge but showed a slight variance in the phase angle because of no viscoelastic polymer model.

Future work is necessary to classify the $d_{32}E_2$ and $d_{33}E_3$ products over frequency and temperature to complete the simplified PVDF model. Furthermore, the temperature range has been limited from -5°C to +35°C in this publication as the entire experimental setup has been put into a climate chamber and the smart shaker is neither specified for lower nor higher temperatures. One solution to overcome this limitation would be the usage of a dedicated measurement device for temperature and frequency dependent dynamic-mechanic-analysis.

The described classification and simulation method for PVDF sensors can be used as enabler for various functions. For instance, as predictive design method of the geometrical electrode layout to yield the maximum signal from a specific structure-borne sound wave. Another idea is to validate the best sensor mounting position on a specific part under oscillation without the need of experimental testing. This helps a lot if empirical tests are relatively expensive like in crash testing. Last but not least, this simulation method also makes it possible to predictively vary the underground where the PVDF sensor is mounted to see the effect of gained mechanical strain or to perform material sweeps of sensor housing materials. All in all, the presented classification and simulation method for PVDF sensors can help to raise the general applicability of PVDF sensors.

**References**