A Multi-Purpose Dynamic and Tactile Sensor for Robot Manipulators

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In this article, a multi-purpose tactile/acceleration sensor system made of newly developed thick polymeric piezoelectric material and capable of sensing acceleration, contact force and pressure is developed and evaluated using analytical and experimental techniques. The sensor system is discretized and modeled by a single degree of freedom second order system from which equations of electromechanical dynamics are formulated to evaluate its performance. Analytical solutions are compared favorably with experimental results.

INTRODUCTION

Accurate acceleration, force, and pressure measurements provide information to robotic system for high precision manipulation and control in performing various tasks. In various sensor designs for dynamic measurements and control, piezoelectricity is probably the most widely used electromechanical characteristics. In general, piezoelectric material responds to mechanical forces and/or pressures and generates an electric charge which is referred to as the direct piezoelectric effect. Conversely, application of electric field to the material can produce mechanical stress or strain which is named as the reciprocal, or converse piezoelectric effect. Temperature change also affects electric polarization on some
piezoelectrics, which is referred to as the pyroelectric effect. The Curie brothers, Pierre and Jacques, first observed piezoelectricity in natural crystals in 1880. Brain investigated piezoelectric polymers in 1924. Kawai discovered piezoelectric polymeric polyvinylidene-fluoride (PVDF) in 1969. Bergman and McFee also found pyroelectric properties in PVDF polymer.

PVDF is planar, tough, lightweight, and flexible and can be made in large flat sheets. On the contrary, piezoelectric ceramics and natural crystals are usually dense, brittle, stiff, and difficult to produce large size and impractical to fabricate into complex shapes. In applications of the synthetic piezoelectric materials to dynamic measurements and control, the flexibility, continuous surface area, dimensional stability, arbitrary geometric configurations, and low production cost of the PVDF polymer do provide great advantages over other crystalline materials, which directly result in increasing its popularity since the mid-1970's. Thin PVDF polymer film has been used in audio-frequency transducers, ultrasonic and underwater transducers, pyroelectric and optical transducers, electromechanical transducers, etc. DeReggi investigated impact pressure transducer and catheter pressure transducers. Tamura et al. and Yamamoto proposed PVDF applications in audio equipment. Naono, Gotoh, and Rikow also discussed microphone design using the film. Ricketts studied a pressure transducer used in underwater hydrophone. However, in these applications, the thickness of the polymer is usually very thin, in terms of microns so that the sensitivity is relatively low. Tzou recently studied the electromechanical dynamics of thick polymeric piezoelectric PVDF systems.

Tactile sensors are made to respond to contact forces/pressures, which can be further divided into (i) binary type-on/off and (ii) continuous type-output proportional to degree of contacts. Hill and Seward designed a gripper equipped with push-button tactile sensors made of light emitting diode (LED) and photo detectors. Conductive elastomers are also used in force/pressure measurements by Bejczy and St. Clair/Snyder. Coifet discussed a number of tactile sensors in either single analog or matrix configuration using strain-gage, LED, conducting polymer, magnetic coil, etc. Shahinopoulos presented piezoelectric tactile sensors made of lead-zirconate-titanate (PZT) and lithium-niobate (LiNbO3). Thin PVDF polymer film is also used in ultrasonic tactile force measurement by Schoenberg. The dynamic characteristics of the newly developed thick polymeric piezoelectric PVDF (1 mm) need to be evaluated and its robotic applications also need to be further explored.

This article is intended to develop a general design principle for multi-purpose dynamic and tactile sensors made of thick polymeric piezoelectric PVDF. The proposed sensor having simple configuration can measure acceleration of a moving robot arm and serve as a tactile sensor for contact force/pressure measurement and shape recognition. Furthermore, the damping effect conventionally excluded in design equation of piezoelectric transducer is included in the mathematical derivations. Dynamic characterization and evaluation of the multi-purpose polymeric PVDF sensor system are studied using theoretical and system identification techniques.
FORMULATION

Piezoelectricity in Thick Polymeric PVDF Flat

The relationship between electric polarization and mechanical strain/stress in piezoelectric material can be generally expressed in a complex matrix form:

<table>
<thead>
<tr>
<th>Compression</th>
<th>Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>$e$</td>
</tr>
<tr>
<td>$E_1$</td>
<td>$P_1$</td>
</tr>
<tr>
<td>$E_2$</td>
<td>$P_2$</td>
</tr>
<tr>
<td>$E_3$</td>
<td>$P_3$</td>
</tr>
</tbody>
</table>

(1)

where $T_j$ is the stress tensor, $S_j$ is the mechanical strain, $E_i$ is the strength of electric field, $P_i$ is the electric polarization, and $d_{ij}$ is the piezoelectric (stress) coefficient. Note that, as indicated in subscripts, polarization and field strength are in three different directions and mechanical stress and strain have six components, three are normal and three are shear respectively. Following the arrow directions and carrying out the products yields:

1. **Direct piezoelectric effect**

   $$\{ P_i \} = - \{ d_{ij} \} \cdot \{ T_j \}$$  \(2\)

   or

   $$\{ P_i \} = \{ e_{ij} \}^T \cdot \{ S_j \}$$  \(3\)

2. **Converse piezoelectric effect**

   $$\{ S_j \} = \{ d_{ij} \}^T \cdot \{ E_i \}$$  \(4\)

   or

   $$\{ T_j \} = - \{ e_{ij} \} \cdot \{ E_i \}$$  \(5\)
where \([e_{kl}]_{6 \times 3}\) is the dielectric permittivity or piezoelectric strain coefficient matrix. The relationship between \([d_{ij}]\) and \([e_{kl}]\) can be expressed as

\[
[e_{kl}] = [c_{kl}] \cdot [d_{ij}]
\]

(6)

where \([c_{kl}]_{6 \times 6}\) is the elastic compliance or compressibility coefficient. Alternative formulations relating dielectric displacement \(\{D_k\}\) to mechanical stresses \(\{T_j\}\) can also be derived in a similar manner.

The piezoelectricity of polymeric PVDF material is due to the non-centrosymmetric arrangement of its long chain of \(\text{CF}_2\text{CH}_2\) molecules in a so called \(\beta\)-crystalline form in which all fluoride atoms face in one direction, thus creating the maximum dipole moment per unit cell. The polymeric piezoelectric PVDF is basically two dimensional as shown in Figure 1.

Thus, the piezoelectric matrix can be simplified as

\[
\begin{array}{c|cccc|ccc}
\text{Compression} & S_1 & S_2 & S_3 & S_4 & S_5 & S_6 \\
\text{Shear} & T_1 & T_2 & T_3 & T_4 & T_5 & T_6 \\
\hline
E_1 & P_1 & 0 & 0 & 0 & 0 & d_{15} & 0 \\
E_2 & P_2 & 0 & 0 & 0 & d_{24} & 0 & 0 \\
E_3 & P_3 & d_{31} & d_{32} & d_{33} & 0 & 0 & 0
\end{array}
\]

(7)

The piezoelectric stress coefficients \(d_{24}\) is equal to \(d_{15}\) if the PVDF polymer is poled without being stretched. Thus, the stress-strain-electric polarization equations for the polymer can be simplified from Eqs. (2) and (7) as:

\[
\begin{align*}
P_1 &= -d_{15} \cdot T_3 \\ P_2 &= -d_{24} \cdot T_4 \\ P_3 &= -[d_{31} \cdot T_1 + d_{32} \cdot T_2 + d_{33} \cdot T_3].
\end{align*}
\]

(8a) (8b) (8c)

Figure 1. Polymeric piezoelectric PVDF flat.
Tactile Response of Polymeric PVDF

For a homogeneous isotropic polymeric PVDF flat with an effective area \( A \) excited by an axial force \( F = F_0 \cdot \sin \omega t \) in the transverse direction, the normal stress \( T_3 \) is

\[
T_3 = \frac{F}{A} = \frac{F_0 \cdot \sin \omega t}{A}
\]

(9)

where \( \omega \) is the excitation frequency. The transverse compression/tension results in tension/compression in the plane of polymer. Thus, the induced normal stresses, \( T_1 \) and \( T_2 \), and strains, \( S_1 \) and \( S_2 \), are

\[
T_1 = T_2 = -\nu \cdot \frac{F_0 \sin \omega t}{A} = -\nu \cdot T_3
\]

(10a)

\[
S_1 = S_2 = \frac{1}{E} \left( -\nu T_3 \right) = -\nu \cdot \frac{F_0 \sin \omega t}{EA}
\]

(10b)

where \( E \) is the Young's modulus and \( \nu \) is the Poisson's ratio. Since there is no torsion in the third axis, the shear stresses \( T_4 \) and \( T_5 \) are negligible. Substituting Eqs. (10a and b) into Eq. (8c) yields an expression of the induced electric charge due to transverse excitation.

\[
P_3 = - \left[ \left( d_{31} \right) \left( -\nu \cdot \frac{F_0 \sin \omega t}{A} \right) + (d_{32}) \left( -\nu \cdot \frac{F_0 \sin \omega t}{A} \right) + (d_{33}) \left( \frac{F_0 \sin \omega t}{A} \right) \right]
\]

\[
= \left[ d_{33} - \nu (d_{31} + d_{32}) \right] \cdot \left( \frac{F_0 \sin \omega t}{A} \right)
\]

\[
= \frac{-F_0}{A} \left[ d_{33} - \nu (d_{31} + d_{32}) \right] \cdot \sin \omega t
\]

(11a)

or simply

\[
P_3 = -T_0 \cdot \left[ d_{33} - \nu (d_{31} + d_{32}) \right] \cdot \sin \omega t
\]

(11b)

Notice that \( T_0 \) or \( (F_0/A) \) is the induced normal stress in the PVDF polymer. Equations (12a and b) can be used to estimate output from the PVDF polymer when the normal stress is known. The source of excitation can be pressure, acceleration, impact force, acoustic wave, etc.
DESIGN OF POLYMERIC PVDF TACTILE SENSORS

In practical application, a polymeric piezoelectric PVDF tactile/acceleration sensor can be directly mounted on a robot gripper as illustrated in Figure 2.

In laboratory evaluation, two piezoelectric PVDF tactile sensors, S-1 and S-2, made of newly developed experimental material—thick piezoelectric PVDF polymer (1 mm)—were made to evaluate the dynamic characteristics. The basic configurations of the two test PVDF sensors are about the same except using different size of the PVDF polymer. The first sample is tested as a dynamic force/pressure sensor and the second is tested as an acceleration sensor. The polymeric PVDF system is modeled by a single degree of freedom second order system to verify the experimental results.

The polymeric PVDF sensor is composed of three basic components: (1) protective surface-seismic mass, (2) piezoelectric polymer-sensing element, and (3) connectors, equivalent to housing. The PVDF polymer (1 mm thickness) is sandwiched between two pieces of plexiglas to ensure the same boundary condition on both sides. On the top of the plexiglas is an exchangeable protective surface (seismic mass) and beneath the bottom plexiglas is a connector with 10-32 stud which can be directly mounted on the top of a standard calibration accelerometer. The seismic mass is used as the primary element to respond to the motion; and the PVDF element converts the mechanical energy to an electrical charge. Signal coming from the PVDF polymer film surfaces is transmitted by two leads to an oscilloscope and a micro-computer based data acquisition system in which data can be recorded and analyzed. Figure 3 shows the basic configuration of the polymeric piezoelectric PVDF tactile/acceleration sensor.

Modeling of the Polymeric Piezoelectric PVDF Sensor

The polymeric piezoelectric PVDF sensor is modeled as a one degree of freedom second order system as illustrated in Figure 4a in which seismic mass \( m_s \), connector mass \( m_c \) which includes all screws, equivalent masses \( m_{PVDF} \) and \( m_{plx} \), equivalent dampings \( c_{PVDF} \) and \( c_{plx} \), and equivalent springs \( k_{PVDF} \) and \( k_{plx} \) can be observed.

The equivalent stiffness for a vertically excited plate can be approximated by

\[
k_{PVDF} = \frac{E_{PVDF} \cdot A_{PVDF}}{t_{PVDF}}
\]

(12a)

\[
k_{plx} = \frac{E_{plx} \cdot A_{plx}}{t_{plx}}
\]

(12b)

Since those three equivalent springs are in series. Figure 4a, the equivalent spring \( K_{eq} \) of the system, Figure 4b, can be determined by
Figure 2. Robot gripper with polymeric piezoelectric PVDF tactile/acceleration sensor.

Figure 3. Polymeric piezoelectric PVDF tactile/acceleration sensor.

Figure 4. Modeling of polymeric PVDF sensor.
\[
\frac{1}{K_{eq}} = \frac{1}{k_{\text{plx}}} + \frac{1}{k_{\text{PVDF}}} + \frac{1}{k_{\text{plx}}} \\
K_{eq} = \frac{k_{\text{PVDF}} \cdot k_{\text{plx}}}{k_{\text{plx}} + 2k_{\text{PVDF}}}. \tag{13b}
\]

The equivalent mass $M_{eq}$ can be expressed as

\[
M_{eq} = m_s + m_c + 2 \cdot m_{\text{eff(plx)}} + m_{\text{eff(PVDF)}}. \tag{14}
\]

For a continuous spring, the effective mass of the spring is one-third of the overall spring mass. Thus, the effective mass of the PVDF polymer, for instance, can be approximated as $1/3 \cdot m_{\text{PVDF}}$. Therefore, the equivalent mass of the polymeric PVDF sensor system is

\[
M_{eq} = m_s + m_c + \frac{1}{3} \left( 2 \cdot m_{\text{plx}} + m_{\text{PVDF}} \right). \tag{15}
\]

The PVDF system equation with base excitation, Figure 4b, can thus be formulated as

\[
M_{eq} \ddot{z} = -C_{eq} (\dot{x} - \dot{y}) - K_{eq} (x - y) \tag{16}
\]

where the equivalent damping $C_{eq}$ can not be determined analytically. Defining a relative motion $\zeta$ where $\zeta = (x - y)$ and substituting it into the above equation gives:

\[
M_{eq} \ddot{\zeta} + C_{eq} \dot{\zeta} + K_{eq} \zeta = -M_{eq} \dot{\eta}. \tag{17}
\]

Substituting equations of $M_{eq}$ and $K_{eq}$ into the equation of motion yields

\[
\begin{align*}
\left[ m_s + m_c + \frac{1}{3} \left( 2 \cdot m_{\text{plx}} + m_{\text{PVDF}} \right) \right] \cdot \ddot{\zeta} + C_{eq} \dot{\zeta} + \frac{k_{\text{PVDF}} \cdot k_{\text{plx}}}{k_{\text{plx}} + 2k_{\text{PVDF}}} \cdot \zeta \\
= - \left[ m_s + m_c + \frac{1}{3} \left( 2 \cdot m_{\text{plx}} + m_{\text{PVDF}} \right) \right] \cdot \ddot{\eta}
\end{align*} \tag{18a}
\]

or simply represented as
\[ \ddot{z} + 2\zeta \omega_n \dot{z} + \omega_n^2 z = -\ddot{y} \]  

(18b)

where \( \zeta \) is the damping ratio in which \( \zeta = C_{eq}/2\sqrt{K_{eq}M_{eq}} \); and \( \omega_n \) is the natural frequency in which \( \omega_n = \sqrt{K_{eq}/M_{eq}} \).

Assuming a sinusoidal motion \( y = Y \cdot \sin \omega t \) to the base excitation, the steady-state solution of the PVDF system is

\[ z = \left( \frac{Y \cdot \left( \frac{\omega}{\omega_n} \right)^2}{\sqrt{1 - \left( \frac{\omega}{\omega_n} \right)^2 + \left[ 2\zeta \frac{\omega}{\omega_n} \right]^2}} \right) \cdot \sin \left( \omega t - \tan^{-1} \left( \frac{2\zeta \frac{\omega}{\omega_n}}{1 - \left( \frac{\omega}{\omega_n} \right)^2} \right) \right) \]  

(19a)

or simply

\[ z = Z \cdot \sin(\omega t - \varphi) \]  

(19b)

where \( Z \) is the magnitude and \( \varphi \) is the phase and they can be written as

\[ Z = \frac{Y \cdot \left( \frac{\omega}{\omega_n} \right)^2}{\sqrt{1 - \left( \frac{\omega}{\omega_n} \right)^2 + \left[ 2\zeta \frac{\omega}{\omega_n} \right]^2}} \]  

(20)

\[ \tan \varphi = \frac{2\zeta \frac{\omega}{\omega_n}}{1 - \left( \frac{\omega}{\omega_n} \right)^2} \]  

(21)

Differentiating \( y = Y \cdot \sin \omega t \) twice yields acceleration equation as \( \ddot{y} = -(Y\omega^2) \cdot \sin \omega t \). Comparing this expression with the amplitude equation results in that \( Y \cdot \omega^2 \) term represents the acceleration of the base. Thus, the magnitude of relative motion, \( Z \), can be written in terms of base acceleration, \( \ddot{y} \), as

\[ Z = \frac{-\ddot{y}}{\omega_n^2 \cdot \sqrt{1 - \left( \frac{\omega}{\omega_n} \right)^2 + \left[ 2\zeta \frac{\omega}{\omega_n} \right]^2}} \]  

(22)
The induced strain, $S_3^*$, in the PVDF polymer can be approximated by $Z/t_{PVDF}$ and the induced normal stress $T_3^*$ is

$$T_3^* = \frac{E_{PVDF} \cdot (Z)}{t_{PVDF}}$$

$$= E_{PVDF} \cdot \left( \frac{Z}{t_{PVDF}} \right)$$ (23a)

or

$$T_3^* = -E_{PVDF} \cdot \left( \frac{\ddot{y}/t_{PVDF}}{\omega_n^2 \cdot \sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\xi \frac{\omega}{\omega_n}\right]^2}} \right) .$$ (23b)

Thus, the electric charge generated in the PVDF polymer due to base excitation can be determined by substituting Eq. (23b) into (11):

$$P_3^* = E_{PVDF} \cdot \left[ d_{33} - \nu (d_{31} + d_{32}) \right]$$

$$\left[ \frac{\ddot{y}/t_{PVDF}}{\omega_n^2 \cdot \sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\xi \frac{\omega}{\omega_n}\right]^2}} \right]$$ (24)

And the electrodynamic response of the PVDF polymer can be expressed as

$$P_3^* = E_{PVDF} \cdot \left[ d_{33} - \nu (d_{31} + d_{32}) \right]$$

$$\left[ \left( \frac{1}{t_{PVDF}} \right) \cdot \left( \frac{-\gamma \cdot \left(\frac{\omega}{\omega_n}\right)^2}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\xi \frac{\omega}{\omega_n}\right]^2}} \right) \right] .$$
\[
\sin \left( \omega t - \tan^{-1} \left[ \frac{2\xi \frac{\omega}{\omega_n}}{1 - \left( \frac{\omega}{\omega_n} \right)^2} \right] \right)
\]

(25)

The parameters involved in the final electromechanical dynamic equation are the frequency ratio \((\omega/\omega_n)\), the damping ratio \(\xi\), and other given parameters. The natural frequency can be determined using the equivalent mass and stiffness of the polymeric PVDF sensor system. The damping ratio cannot be determined analytically. Thus, system identification techniques, the half-power method\(^2\(^5\)\) and the slope of phase diagram method\(^2\(^6\)\), are incorporated to estimate the damping ratio from the measurement data.

**Damping Estimation**

System identifications are widely applied to identify system dynamic characteristics using experimental techniques such as modal analysis in aerospace and automobile industries. The polymeric PVDF sensor system is modeled as a single degree of freedom second order system as discussed earlier. The natural frequency can be analytically calculated from the equivalent mass, \(M_{eq}\), and the equivalent stiffness, \(K_{eq}\), derived earlier; and it can also be determined and verified from the experimental data. However, the equivalent damping, \(C_{eq}\), of the PVDF system cannot be determined from any available analytical technique; thus, it has to be estimated from measurement data. Two methods were used in this study: (1) the half-power method\(^2\(^5\)\) and (2) the slope of phase diagram method\(^2\(^6\)\).

In the half-power method, the damping can be estimated by determining a frequency bandwidth, \(\Delta \omega\), of the PVDF system defined as the frequency interval between 1/2 power points. For small damping, say \(\xi < 0.1\), the damping ratio, \(\xi\), can be estimated from the bandwidth using

\[
2\xi \omega_n \equiv (\omega_2 - \omega_1)
\]

\[
\xi \equiv \frac{(\omega_2 - \omega_1)}{2\omega_n} = \frac{\Delta \omega}{2\omega_n}.
\]

(26)

The slope of the phase diagram can also be used to estimate the damping ratio of the PVDF polymer system, i.e.,
Thus, the damping factor $C_{eq}$ of the polymeric PVDF sensor system can be determined by

$$C_{eq} = 2 \cdot \zeta \cdot \left\{ \left[ m_s + m_c + \frac{1}{3} \left( 2 \cdot m_{plax} + m_{PVDF} \right) \right] \cdot \left[ \frac{k_{PVDF} \cdot k_{plax}}{k_{plax} + 2k_{PVDF}} \right] \right\}^{1/2}$$

(28)

substituting $\zeta$ into the above equation yields

(1) Half-power method:

$$C_{eq} = 2 \cdot \left( \frac{\Delta \omega}{2 \omega_n} \right) \cdot \left\{ \left[ m_s + m_c + \frac{1}{3} \left( 2 \cdot m_{plax} + m_{PVDF} \right) \right] \cdot \left[ \frac{k_{PVDF} \cdot k_{plax}}{k_{plax} + 2k_{PVDF}} \right] \right\}^{1/2}$$

(29)

(2) Slope of phase diagram:

$$C_{eq} = 2 \cdot \left[ \frac{1}{\omega_n \cdot \left( \frac{d \Psi}{d \omega} \right)_{\omega = \omega_n}} \right] \cdot \left\{ \left[ m_s + m_c + \frac{1}{3} \left( 2 \cdot m_{plax} + m_{PVDF} \right) \right] \cdot \left[ \frac{k_{PVDF} \cdot k_{plax}}{k_{plax} + 2k_{PVDF}} \right] \right\}^{1/2}$$

(30)

These two methods are incorporatedly used to check out each other's estimation.
EXPERIMENTATION

Tactile Response of the PVDF Sensor

To evaluate the tactile dynamic response of the polymeric PVDF sensor S-1, three steel balls are used to be dropped at different heights and the outputs from the PVDF polymer are recorded for analysis and comparison. The schematic diagram of the experiments is shown in Figure 5. The impact force/pressure is proportional to the product of the mass and the contact velocity and the latter is linearly proportional to the square root of drop-height, i.e., \( v = \sqrt{2gh} \). Thus, the output from the PVDF system S-1 should be linearly proportional to the ball mass or the square root of drop-height. Two other transducers, one a Kistler mini accelerometer and the other a PCB impact force transducer, are subjected to the same excitation to compare and evaluate the results.

Due to the disturbance of low frequency noise, a Krohn-Hite filter set at high-pass is always used in conjunction with all the experimental set-ups discussed here.

Frequency Response

The polymeric piezoelectric PVDF sensor system S-2 is mounted at top of a Kistler 808K standard calibration accelerometer through a 10-32 stud, and the latter is directly mounted on a B & K mini shaker.

Sinusoidal signal over wide frequency range is generated by a Precision signal generator and it is input to the shaker to excite the PVDF sensor system. Output

![Diagram of experimental setup for evaluating tactile response.](image)

Figure 5. Schematic diagram of experimental setup for evaluating tactile response.
signals from the calibration accelerometer is used as a measure of input excitation to the test PVDF system, (see Figure 6). The output from the PVDF system as well as that from the calibration accelerometer are recorded to determine the amplitude ratio and the sensitivity of the test PVDF system. The sensitivity ($S$) of the test system can be determined by $S = S_{std} \cdot \left( \frac{V_{PVDF}}{V_{std}} \right)$ in which $S_{std}$ is the sensitivity of the calibration transducer and $V_{std}$ and $V_{PVDF}$ are the output voltages.

**System Identification**

As discussed earlier that the damping of the sensor can not be determined by any analytical method, therefore, experimental measurements are used to estimate the damping. An HP spectrum analyzer interfaced with an IBM microcomputer is used to determine the transfer function and phase of the polymeric piezoelectric PVDF sensor, Figure 7, in which the damping ratio can be estimated from the transfer function by the half-power method and from the phase response by the slope of phase diagram method. Thus, all parameters in the mathematical model of the PVDF polymer system are determined and analytical evaluation of the system model can be further performed.

The experimental setup is similar to that of determining system sensitivity. However, instead of using sinusoidal excitation, an alternative signal source, pseudo random noise provided by the HP spectrum analyzer is input to the shaker for validating the same system at different excitation.

**RESULTS AND DISCUSSION**

Electromechanical dynamics of the polymeric PVDF sensor system is evaluated using analytical and experimental techniques. The tactile response, frequency
response, sensitivity, transfer function, and analytical solutions are to be presented.

Tactile Force / Pressure Response

To evaluate the tactile response of the polymeric PVDF sensor S-1, test data obtained for three ball masses and for four different heights of drop were recorded and analyzed. An average of seven values was taken for each ball drop from a given height. Two sets of plots are provided. One is output voltage versus masses, Figures 8 and 9; and the other is output voltage versus square root of drop-heights, Figures 10 and 11. Each set has two figures: one is the comparison of output voltage with an impact transducer, Figures 8 and 10; and the other is the comparison of that versus a standard mini-accelerometer, Figures 9 and 11.

It is observed that the output voltage varies linearly with respect to the dropped masses (Figs. 8 & 9) and the square root of drop-heights (Figs. 10 & 11). However, the biases in all four figures can also be observed, which can be compensated by adjusting a constant DC offset in the measurement instruments. The maximum deviation is 1.9% in Figure 8, 3.3% in Figure 9, and 5.3% in Figures 10 and 11. The experimental results show that the polymeric PVDF sensor system responds impact loading rather linearly; however, measurement biases should be corrected.
Figure 8. Comparison of the polymeric PVDF sensor S-1 with an impact force transducer as a function of drop-mass.

Figure 9. Comparison of the polymeric PVDF sensor S-1 with a mini-accelerometer as a function of drop-mass.
Figure 10. Comparison of the polymeric PVDF sensor S-1 with an impact force transducer as a function of drop-height.

Figure 11. Comparison of the polymeric PVDF sensor S-1 with a mini-accelerometer as a function of drop-height.
Frequency Response and Sensitivity

The frequency response and sensitivity of the PVDF sensor S-2 were calibrated using a standard calibration accelerometer. Sinusoidal excitation over wide frequency range was input to the shaker and the outputs from the standard accelerometer and the tested PVDF system were recorded for further analyses. Because of very high noise occurring at the low frequency range, a high-pass filter set at 90 Hz is used to eliminate line noise.

The frequency operating range of the PVDF system is defined as the maximum flat frequency range within \( \pm 5\% \) deviation. The frequency response of the PVDF sensor S-2 with protective surface (seismic mass) of 1.28 grams is shown in Figure 12. It is observed that the natural frequency is 6100 Hz and the operating range is up to 2600 Hz with a sensitivity of 160 mV/g.

The transfer function curve obtained from the HP spectrum analyzer is shown in Figure 13 from which the natural frequency is observed to be 6300 Hz and operating range is up to 2200 Hz. The phase response is also presented in Figure 14 in which the deviation in the low frequency is relatively significant. This might be caused by the high-pass filter, the pseudo random excitation, and/or the viscoelastic effect of the bonding material. It is also observed that frequency response at the low frequency deviates from that in the sinusoidal excitation (Figure 13) which is introduced by the deficiency of HP pseudo random noise generator within low frequency range.

![Graph](image.png)

**Figure 12.** Frequency response of the polymeric PVDF sensor S-2.
**System Identification and Mathematical Modeling**

The mathematical model of the polymeric PVDF sensor system is constructed using the equivalent mass and stiffness calculated from the equivalent system and the damping ratio obtained from the system identification techniques. The damping ratio for the PVDF system S-2 is found to be 0.044 from the half-power method and 0.052 from the slope of phase diagram method. The frequency response curves of the amplitude and phase of the mathematical model can be determined by Eqs. (22) and (21) and they are plotted in Figures 15 and 16. It should be noticed that the amplitude is normalized.

The natural frequency of the model is calculated to be 6154 Hz which compares very well with the experimental data; and the operating range is estimated up to 1990 Hz which is lower than the experimental results. It can also be observed that the amplitude of frequency response curve (Figure 15) compares very well with the experimental results (Figures 12 & 13). In the phase response curves (Figures 14 & 16), however, the low frequency region has relatively high deviation which might be introduced by the high-pass filter, the pseudo random excitation, and/or the viscoelastic effect of the bonding materials.

In practical application, a test transducer is installed on an IBM 7535 robot gripper as shown in Figure 2. Then, a "close" command is given to the gripper. Figure 17 shows the output due to gripping action.
Figure 14. Phase response for the polymeric PVDF sensor S-2.

Figure 15. Theoretical frequency response (amplitude) of the polymeric PVDF sensor S-2.
SUMMARY AND CONCLUSIONS

In this article electromechanical characterization of polymeric piezoelectric PVDF polymer sensors made of a newly developed experimental material, thick PVDF polymer (1 mm) is carried out using the mathematical modeling and system identification techniques, in which system damping is considered. The two PVDF sensor systems developed in the Dynamics and System Laboratory are evaluated for their tactile response, sensitivity, frequency response, phase response, and analytical modelings.

The PVDF sensor S-1 (2 × 2 PVDF polymer) responds to tactile force (force/pressure) rather linearly. The output voltage varies linearly with respect to either the drop-mass or the square root of drop-height. However, biases are observed in the experimental results, which can be compensated for by an offset in measurement instruments.

The PVDF sensor S-2 (1 × 1 PVDF polymer) has sensitivity of 160 mV/g and that of operating frequency range is found up to 2600 Hz from the frequency response method, 2200 Hz from the transfer function method, and 1990 from the theoretical analysis. The estimation of the natural frequency from the equivalent system is rather accurate. The deviation is 0.9% between the theoretical value and the frequency response method and 2.4% between that and the transfer function method. The prediction of the operating frequency range is relatively low and it is on the conservative side.
The damping ratios of the polymeric PVDF sensor determined by the half-power method and the slope of phase diagram method are compared closely. The estimation from the analytical model provides a smoother amplitude and phase response curves. The amplitude response curve is compared favorably with the experimental results and the phase response curve has some deviation in the low frequency range introduced by the high-pass filter, the pseudo random excitation, and/or the viscoelastic effect of the bonding material.

The tested polymeric piezoelectric PVDF sensor system has a very simple configuration and can be easily made in the laboratory; and it can act as accelerometer and tactile sensor (dynamic force/pressure sensor) simultaneously. The mathematical model developed in this article can be used to estimate the electromechanical dynamic response of the polymeric piezoelectric PVDF polymer sensor system.

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References

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