Modeling and simulation of the structural and electrical characteristics for a polarized piezoelectric sensor actuator

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Abstract: The present work aims to design a new polarized piezoelectric sensor actuator. This sensor actuator not only can achieve sensing and execution at the same time, but also has the advantages of small size and high integration. A mathematical model of stack displacement with input voltage and number of layers was established. The relationship between the charge generated by quartz crystal and external force was numerically analysed. The static and modal analysis of the structure were carried out to obtain the measured force range and the maximum working frequency. The transient simulation is used to verify the follow-up law of the actuator to the alternating signal. The Electric field interference analysis of the piezoelectric sensor actuator was performed to eliminate the interference from the electric field generated by the actuator. The results show that the measured force range of the actuator is up to 1 kN, with the maximum working frequency is 1000 Hz, and the actuator can follow the drive voltage signal well, with an almost negligible electric field interference in the sensor part. This paper provides a new method and theory for the study of self-sensing actuators.

Keywords: self-sensing actuator, piezoelectricity theory, electric field interference, sensing system, polarization sensing

1. Introduction

A piezoelectric sensor actuator, which is an integration of a piezoelectric sensor and a piezo actuator, can enable sensing and execution functions simultaneously [1–4]. Compared with traditional structures, it does not require complicated control circuits, and is small in size, light in weight, and easy to get modularized. It can compensate the deformation of the component by accurately outputting the displacement while detecting the force of the component area in a small space. All these advantages promise it a good application prospect in the fields of the gravity unloading [5–7], the active vibration suppression [8, 9], the system identification [10] and MEMS products [11–13].

The piezoelectric sensor and the piezoelectric actuator are made using the positive and negative piezoelectric effects of the piezoelectric material, respectively. Among various piezoelectric materials, piezoelectric ceramics are generally used to manufacture actuators, for its characteristics of obvious piezoelectric effect, large output force, accurate output displacement, easy processing, and low price. The output displacement and force of the monolithic piezoelectric ceramic are relatively small, and generally cannot meet the system requirements. Therefore, the piezoelectric stack is generally used to double the output force and output displacement [14]. Since it will generate a certain electric field interference when the piezoelectric actuator works, and the interference electric field will change as the driving signal changes, which is difficult to eliminate, if we use piezoelectric ceramics as sensors, the sensing accuracy is greatly affected. However, sensors made of quartz crystal not only has good performance, but also has strong anti-interference ability to the environment. Therefore, if we integrate the piezoelectric ceramic stack and the piezoelectric quartz crystal into a piezoelectric sensor actuator,
we can not only perform the force detection while outputting force, but also improve the accuracy of the sensor.

The piezoelectric force sensor can be divided into a resonant piezoelectric sensor and a polarized piezoelectric sensor according to the working principle of the sensor. The resonant piezoelectric sensor measures the external load by detecting the change in the natural frequency of the quartz crystal when it’s subjected to an external load. It has high frequency stability and high sensitivity, and can realize high-precision static measurement [15, 16]. However, it needs to use a specific excitation to make the sensor work at the resonant frequency, and requires an additional structure to ensure the radial force of the quartz crystal. The polarized piezoelectric sensor realizes the measurement of the external load by measuring the relationship between the polarization charge and the measured force [17, 18]. This method is simple in structure, because it does not require an additional force transmission device, and can measure the force and displacement simultaneously. However, the collected charge needs to be amplified and the sensing accuracy can be affected by the charge leakage.

Therefore, this paper aims to design a new type of polarization sensing actuator by integrating a piezoelectric stack and a quartz crystal together. Based on the piezoelectric equation, the mathematical model and structural model of the actuator and sensor are established. The finite element method is used to simulate the static and modal of the whole structure, and the transient analysis and electric field interference analysis are performed to verify the validity of the design.

2. Structural design of the sensor actuator

Figure 1 illustrates the structure of a polarized piezoelectric sensor actuator. This actuator consists of a package cavity, a piezoelectric ceramic stack, two mounts, a sensor integration, an end cap, and a push rod. The piezoelectric stack acts as an actuator, and is guided by a set of mounts in the cavity to ensure the axial force during operation. The end cap is bolted to the cavity to realize the overall packaging of the device, making the piezoelectric stack properly pre-tightened at the same time. The mechanical cooperation of the end cover and the push rod ensure the axial force of the sensor. The push rod transmits the external load $F$ to the sensor part to generate a charge output. The sensor integration is a package design for quartz wafer sensors that guarantees the sensor accuracy and reduces the external interference to sensing signals.

![Cavity Piezoelectric stack Sensor integration End cap Rod](a) Overall schematic

![Lower mount Upper mount](b) Explosion map

**Figure 1.** Structural diagram of a piezoelectric sensor actuator

Figure 2 shows the arrangement of the piezoelectric stack, which is structurally connected in series and electrically connected in parallel to maximize the output displacement.
According to the first type of piezoelectric equation, when the applied electric field \( E_j = 0 \), and piezoelectric stress \( T_n \neq 0 \), the electric displacement \( D_i = d_{mn} T_n \), where \( d \) (C/N) is the piezoelectric strain constant; when the applied electric field \( E_j \neq 0 \), and the piezoelectric stress \( T_n = 0 \), the electric displacement \( D_i = e^T_{ij} E_j \), where \( e^T \) (F/m) is a free dielectric constant at a constant stress. So when the applied electric field \( E_j \neq 0 \), the piezoelectric stress \( T_n \neq 0 \), then the electric displacement can be written as

\[
D_i = d_{mn} T_n + e^T_{ij} E_j
\]  

(1)

By converting it to a matrix form, it is as follows:

\[
\begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4 \\
T_5 \\
T_6 \\
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 0 & d_{15} & 0 \\
0 & 0 & 0 & d_{15} & 0 & 0 \\
d_{31} & d_{31} & d_{33} & 0 & 0 & \end{bmatrix}
\begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4 \\
T_5 \\
T_6 \\
\end{bmatrix} +
\begin{bmatrix}
\varepsilon_{11}^T & 0 & 0 \\
0 & \varepsilon_{11}^T & 0 \\
0 & 0 & \varepsilon_{33}^T \\
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
\end{bmatrix}
\]  

(2)

The piezoelectric strain \( S_n = S_{mn} T_n (m \neq n) \), where \( S^E \) (m²/N) is the short-circuit elastic compliance coefficient when the electric field is constant; when the applied electric field \( E_j \neq 0 \), and piezoelectric stress \( T_n = 0 \), the piezoelectric strain \( S_n = d_{mn} E_j \). So when the applied electric field \( E_j \neq 0 \), and piezoelectric stress \( T_n \neq 0 \), the piezoelectric strain could be

\[
S_n = S^E_{mn} T_n + d_{mn} E_j
\]  

(3)

By converting it to the following matrix form

\[
\begin{bmatrix}
S_1 \\
S_2 \\
S_3 \\
S_4 \\
S_5 \\
S_6 \\
\end{bmatrix} =
\begin{bmatrix}
S_{11}^E & S_{12}^E & S_{13}^E & 0 & 0 & 0 \\
S_{12}^E & S_{11}^E & S_{13}^E & 0 & 0 & 0 \\
S_{13}^E & S_{13}^E & S_{13}^E & 0 & 0 & 0 \\
0 & 0 & 0 & S_{43}^E & 0 & 0 \\
0 & 0 & 0 & 0 & S_{44}^E & 0 \\
0 & 0 & 0 & 0 & 0 & 2(S_{11}^E - S_{13}^E) \\
\end{bmatrix}
\begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4 \\
T_5 \\
T_6 \\
\end{bmatrix} +
\begin{bmatrix}
0 & 0 & d_{31} \\
0 & 0 & d_{31} \\
0 & 0 & d_{31} \\
0 & 0 & d_{45} \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
\end{bmatrix}
\]  

(4)

The polarization direction of the piezoelectric ceramic is along the \( z \)-axis, and the two electrodes of the applied external electric field are located on the upper and lower surfaces of the \( z \)-axis of the piezoelectric piece. The direction of the load is also along the \( z \)-axis, in order to facilitate the expression of the formula, the \( x \), \( y \), and \( z \)-axes are represented by numbers 1, 2, and 3, respectively. When the piezo stack works, \( T_3 \neq 0, T_n = 0 (n \neq 3) \); \( E_3 \neq 0, E_j = 0 (j \neq 3) \), the piezoelectric equation of the actuator can be simplified into:
According to these expressions, when there is no external load on the piezoelectric stack, the strain of each piezoelectric ceramic piece is

\[ S_3 = d_{33} E_3 = d_{33} \frac{U_p}{h} \]  

The total output displacement of the piezoelectric stack is

\[ Z_3 = L \cdot S_3 = L \cdot d_{33} \frac{U_p}{h} = n \cdot h \cdot d_{33} \frac{U_p}{h} = n \cdot d_{33} \cdot U_p \]  

From Eq. (8), it can be seen that, in the case of no external load and the total length \( L \) of the stack is constant, the thinner the monolithic ceramic, and the more the number of layers, the greater the output displacement obtained at the same input. Assume that the maximum displacement of the stack is 32 \( \mu \)m when the input voltage does not exceed 150 V, we chose PZT-554 with a coefficient \( d_{33} \) of 810 pC/N as the material of the piezoelectric stack, and set its size to \( 11 \times 11 \times 37 \) mm (0.13 mm \times 284 pieces).

For piezoelectric quartz crystals, differently cut quartz crystals have piezoelectric effects in different directions. According to the internal structure of the quartz crystal [19], Figure 3(a) illustrates the basic unit of the quartz crystal, which can be equivalent to the positive and negative charges of the regular hexagonal arrangement, where ‘+’ stands for \( \text{Si}^{4+} \) and ‘−’ for \( \text{Si}^{2−} \).

\[ \sum p_i = 0 \]  

\[ (p_1 + p_2 + p_3)_x > 0 \]  

Figure 3(b) describes the change when the crystal is subjected to the pulling force in the \( x \) direction \( (T_1 > 0) \). The component of the electric dipole moment in \( x \) direction at this time will be

\[ (p_1 + p_2 + p_3)_x < 0 \]  

It is similar to \( T_1 \) when the crystal is subjected to stress \( T_2 \) in the \( y \) direction. In the \( z \) direction, when the crystal is under the action of \( T_3 \), since the strains of the crystal in the \( x \) and \( y \) directions are exactly the same, the positive and negative charge centers still coincide, and the electric dipole moment vector sum is 0. Due to the above reasons, when the quartz crystal plate is subjected to an external force in the \( x \) direction, the crystal plate is deformed in thickness and is polarized on the surface of the crystal perpendicular to the \( x \)-axis. This phenomenon is called transverse piezoelectric effect. When the quartz crystal oscillator is subjected to a force along the \( y \)-axis, the crystal oscillator will still exhibit an electrification phenomenon on a plane perpendicular to the \( x \)-axis. This phenomenon is called transverse...
piezoelectric effect. When the quartz crystal oscillator is subjected to a force along the \( z \)-axis, the quartz crystal does not exhibit a piezoelectric effect.

According to the Neumann principle of the macroscopic physical properties of the crystal, the piezoelectric effect expression of quartz can be calculated by

\[
\begin{bmatrix}
 p_1 \\
 p_2 \\
 p_3
\end{bmatrix} =
\begin{bmatrix}
 d_{11} & -d_{11} & 0 & d_{14} & 0 & 0 \\
 0 & 0 & 0 & -d_{14} & 2d_{11} & 0 \\
 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
 T_1 \\
 T_2 \\
 T_3 \\
 T_4 \\
 T_5 \\
 T_6
\end{bmatrix}
\]

When the crystal is subjected to force \( F \) along the \( x \)-axis, it is known by elastic mechanics

\[
\sigma_i = \frac{F}{S}
\]

\[
\sigma_x = \sigma_y = \tau_y = \tau_x = \tau_z = 0
\]

Substituting Eqs. (12) and (13) into Eq. (11) to obtain the polarization of the \( x \)-axis

\[
p_i = d_{11}\sigma_x
\]

The charge generated on a plane perpendicular to the \( x \)-axis will be

\[
q_x = p_x \cdot \mathbf{n}\cdot S = d_{11} \cdot F
\]

It can be seen from the above mathematical model that when the crystal is subjected to mechanical stress parallel to the \( x \)-axis, a bound charge is generated on the surface, and the amount of charge has a strict linear relationship with the applied mechanical stress. According to this law, the \( x0^\circ \)-cut wafer (Namely: the thickness direction is parallel to the \( x \)-axis, the wafer surface is perpendicular to the \( x \)-axis, and there is no rotation along any coordinate axis.) was chosen as the sensor, working in a state where only its \( x \)-axis is stressed. When determining the parameters of the quartz wafer, to meet the sensor frequency response characteristics and reduce the size of the sensor, the thickness of the quartz wafer is generally \((0.75~1)\) mm.

Figure 4 illustrates the design of the sensor structure. In order to add the pre-tension before the quartz sensor package, this design uses a circular quartz wafer, which is pre-tightened with a screw before packaging. The inner diameter of the annular quartz wafer is preferably greater than 4 mm due to the limitations of the process. Considering the above factors, the final annular quartz wafer used in this design has an inner diameter of 5 mm, an outer diameter of 12 mm, and a thickness of 1 mm.

A single piece of quartz wafer is often not used for direct force measurement. To ensure the accuracy of the sensor and reduce the interference of the external sensing signal, the sensor needs to be packaged. The exterior is packaged in stainless steel to shield the outside from the sensor. The aviation joint is designed on the stainless steel casing to extract the charge of the quartz wafer for access to the external processing circuit.

**Figure 4.** Quartz force sensor structure diagram
3. Structural analysis

In the analysis process, in order to ensure the accuracy of the simulation and to increase the calculation speed as much as possible, different parts of the mesh are divided into different sizes. The unimportant parts such as the cavity are roughly processed, and finite element model parameters are assigned according to the material of the object. Table 1 shows the materials used in the simulation analysis and related parameters.

| Part name     | Materials                 | Elastic Modulus (GPa) | Poisson's ratio | Density (kg/m³) |
|---------------|---------------------------|-----------------------|-----------------|-----------------|
| Piezo stack   | PZT-554                   | —                     | 0.34            | 7600            |
| Quartz wafer | x0°-cut quartz            | —                     | 0.17            | 2650            |
| Sensor housing | Stainless steel          | 206                   | 0.25            | 7900            |
| Package cavity | Aluminum alloy           | 72                    | 0.33            | 2810            |
| Mount         | Aluminum alloy            | 72                    | 0.33            | 2810            |
| Rod           | Aluminum alloy            | 72                    | 0.33            | 2810            |

3.1. Static analysis

Assume that the piezoelectric sensor actuator designed in this paper is not subjected to a working pressure of more than 1000 N. The force on the push rod is assigned to 1000 N during the simulation. Considering that the end cap and the cavity are bolted, the pre-pressure is also applied to the end cap during the analysis. Here, the pre-pressure is given as 50 N, and the bottom surface of the cavity is fixed for simulation analysis.

Figures 5 and 6 illustrate the results of the static analysis. The simulation model is shown in Figure 5(a). The analysis shows that the maximum deformation of the model is 3.188 μm, and the maximum stress is 20.594 MPa, which appears at the edge of the sensor housing, as shown in Figure 6(c). It is found that the maximum stress of the quartz wafer in the sensor is 14.848 MPa, which is much smaller than the allowable stress of 130 MPa, and the maximum deformation is only 0.656 μm.

![Figure 5. Results of static analysis](image1)

![Figure 6. Static analysis of the partial map](image2)
3.2. Modal Analysis
By performing modal analysis on the established model, one can initially determine the natural frequencies and mode shapes of the various stages of the model, and avoid the resonance point during the work process. Figure 7 shows the first four natural frequencies of the model and the corresponding mode shape. From the modal analysis results, it can be found that the first 3 natural frequencies of the model are very close, and the rear natural frequencies afterwards are quite different from the front 3 orders. The first order resonance frequency of the sensor actuator is over 3000 Hz, while it generally works at 0 to 100 Hz. It ensures that the designed structure will not reach its resonance frequency during working.

![Figure 7. First four natural frequencies and mode shapes of the model](image)

4. Performance simulation and evaluation of the sensor actuator
In order to evaluate the performance of the sensor actuator, the actuator and sensor were simulated and analysed separately. The transient simulation of the piezoelectric stack actuator under different wave drive voltages is carried out from the real-time perspective of the response. The electric field interference analysis of the quartz sensor is carried out from the perspective of the electric field interference affecting the sensing accuracy.

4.1. Transient response analysis of the piezoelectric stack
To explore the displacement response of the actuator to different voltage signals, this paper applies three different waveforms to the actuator. The voltage amplitude is 90 V, the frequency is 1 Hz. The bottom surface of the actuator is fixed to ensure it has an ideal output displacement.

Figure 8 shows the results of the transient analysis. From Figure 8, it can be found that the output displacement response of the actuator can follow the driving voltage well. When the amplitude and frequency of the driving voltage are the same, the maximum output displacement of the actuator is approximately the same. The actuator follow-up to sine and triangle waves is better than that of the square wave. It can be seen from the partial enlargement in Figure 8 (d) that in the square wave response, the output displacement of the actuator is unstable at the peak. It is mainly because the square wave signal contains a wealth of high-order harmonic signals, while the actuator does not respond quickly to
high-order signals. In general, the actuators designed in this paper have a good response performance under different voltages.

![Actuator response under different excitations](image)

**Figure 8.** Actuator response under different excitations

4.2. Actuator-to-sensor charge interference analysis

When a voltage is applied to the ceramic stack of the actuator, an electric field is generated, and the electric field may interfere with the sensor. Therefore, it is necessary to analyse the electric field generated by the piezoelectric ceramic. Figure 9 shows the electric field generated by a monolithic piezoelectric ceramic when subjected to a voltage of 100V. It can be seen that the piezoelectric ceramic can be approximated as a uniform electric field, and the electric field intensity is the largest. And a large electric field is generated in the nearer region, but as the distance increases, the electric field strength drops sharply. Therefore, when designing the sensor actuator, the two parts are separated by a certain distance. Hence, the sensor part is integrated with a stainless steel housing to minimize the electric field interference of the actuator to the sensor part.

![Electric field space diagram generated by monolithic piezoelectric ceramics](image)

**Figure 9.** Electric field space diagram generated by monolithic piezoelectric ceramics
Figure 10 illustrates the obtained simulation results of the packaged sensor actuator. The model is simplified, the number of piezoelectric ceramics is reduced from 284 to 50, the thickness is increased to 0.7 mm, and the metal shell package of the sensor part is also simplified. The simplified model is shown in the bottom right corner of Figure 10. The voltage applied to each piezoelectric piece was 100 V, and the air boundary was set to a square with a length of 0.2 m. From Figure 10, it can be obtained that the maximum electric field strength is $1.96 \times 10^5$ V/m, while the minimum is 0.72 V/m, and that the electric field strength around the quartz wafer is in the weakest blue region, which is much smaller than the coupling electric field at other positions. Accordingly, one can conclude that the shielding effect with the metal cavity package is very good and the electric field interference experienced by the sensor section is extremely small and can be ignored.

**Figure. 10 Overall electric field distribution of the sensing actuator**

5. Conclusions
This work designs a new polarized piezoelectric sensor actuator which can perform well in the range of load amplitude within 1000 N and frequency within 1 kHz. Transient analysis and electric field interference analysis were performed on the piezoelectric stack and quartz crystal respectively to verify the follow-up performance of the actuator for different input signals and the anti-jamming performance of the sensor. The results show that the actuator can follow the low frequency drive voltage signal well and follow the performance sine wave > triangle wave > square wave when applied to dynamic signal, and the actuator's charge interference to the sensor is minimal enough to be ignored in the application. The present work provides a theoretical support for the further study of self-sensing actuators.

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