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PvdF Piezoelectric Film Based Force Measuring System

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Abstract: In this study, a force measuring system based on PVDF piezoelectric sensor was designed. Firstly, piezoelectric equation of PVDF was simplified for the following analysis. Secondly, circuits of charge amplifier and signal filter were designed. Noise induced by electronic components and 50 Hz power frequency were restrained heavily by 5^{th}-order Butterworth low-pass filter and 50 Hz double T trap filter. Finally, a measuring circuit board was made based on the above research, so as to construct measuring system and measure experiment. Measuring experiment proved the effective of this system.

Keywords: Mechanical sensor, piezoelectric, PVDF

INTRODUCTION

The phenomenon of piezoelectricity in quartz was discovered by Curie and Curie (1880). Since then, such phenomenon was found in many solid crystals and ceramics. Using the direct piezoelectric effect that can transform imposed force/pressure to charge-voltage signal, piezoelectric ceramics and quartz are frequently used in mechanical sensing. They, however, are hard and have poor impact resistance, which are not suitable for using in components with varieties of shape. Kawai (1969) found the Piezoelectricity of Polyvinylidene Fluoride (PVDF) polymer, which can be got by polarizing organic fluorine polymer materials. Kawai (1969). After that, researches in piezoelectric polymer gradually flourished. Bauer did a lot of work in this field (Bauer, 2000; Klein *et al.*, 2005; Chu *et al.*, 2006) and made high performance PVDF sensors.

As a new type of piezoelectric material, PVDF piezoelectric film is soft and thin, which are different with quartz and piezoelectric ceramics. It can fit sufficiently with the shape of measured surface. It can be used not only in sensing shockwaves in laser machining, high frequency vibration and earthquake waves, but also in vehicle inline weighting, robotics tactile sensing and medical measurement.

In this study, we made a force sensing system based on PVDF piezoelectric sensor. It realized dynamic measurement of time-varying forces and shown good linear response to forces.

PIEZOELECTRIC EQUATION OF PVDF

When a force was exerted on PVDF film, charges appeared due to direct piexoelectric effect. Figure 1 shows the schematic of PVDF piezoelectric film. Metal film such as aluminum was coated on both sides the PVDF polymer, which can be used as electrodes for transferring force induced charges to amplifying circuit.

In Fig. 1, X axis is the direction stretching the polymer and Z axis is perpendicular to PVDF piezoelectric film and is parallel to polarization direction.

Piezoelectric equation is the formula that describes relations between electricity amounts and mechanical ones in piezoelectric crystals. Mechanical sensor utilizes direct piezoelectric effect and can be described by type 1 piezoelectric equation. Shown in (1), the equation used stress tensor and electric-field intensity vector as argument and used strain tensor and electric displacement vector as dependent variable:

$$D = dT+\varepsilon^T E \tag{1}$$

In (1),D,d,T,ε^T and E were deposited charge density matrix, piezoelectric constant matrix, stress tensor, dielectric constant matrix and electric-field intensity, respectively:

Since the piezoelectric material in this study was not in electric field, (1) can be simplified as:

$$D = dT \tag{2}$$

where, $D = [D_1\ D_2\ D_3]^T$. Subscripts 1, 2 and 3 represented three different directions along X, Y and Z axis that illustrated in Fig. 1. And $T = [T_1\ T_2\ T_3\ T_4\ T_5\ T_6]^T$. Here, subscripts 1~6 stood for different stress directions. T_1,T_2 and T_3 was normal stresses in X, Y and Z directions and T_4,T_5 and T_6 was corresponding shear stresses.

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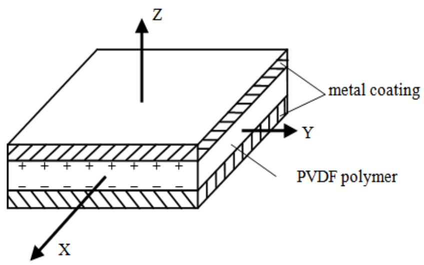

Fig. 1: Structural schematic of PVDF piezoelectric film

In this study, direction 3 that corresponded to Z axis in Fig. 1 was polarized direction. Since polarized PVDF material belongs to C_{6V} (6 mm point group) symmetry, the piezoelectric constant matrix can be written as:

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & -d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \tag{3}$$

Here, d_{15}, d_{13} and d_{33} were three independent variables. The first number in the subscripts signified the direction of electric effect, while the second one stood for the direction of mechanical effect.

The charge density deposited on both sides of PVDF film wasD_3. According to (2):

$$D_3 = d_{31}T_1+d_{31}T_2+d_{33}T_3 \tag{4}$$

Equation (4) means the normal stress in the three directions can all deposit charges in both sides of the film.

As was given in Eq. (5), the amount of output charge of PVDF piezoelectric film was the accumulation of D_3 in the area of the film surface:

$$Q = (d_{31}T_1+d_{31}T_2+d_{33}T_3)A \tag{5}$$

where A was the area that two electrodes covered PVDF. When force only along Z axis was exerted on the film, T_1 and T_2 were zero. Then, (5) can be simplified as:

$$Q = d_{33}T_3A \tag{6}$$

PVDF force measuring system in this study was developed according to the above algorithm.

MEASURING CIRCUIT DESIGN

Commercial PVDF piezoelectric film in 30 μm width was used. The film was packaged by polyethylene. Aluminum alloy was coated on both sides as electrodes and copper lines were used as wires. The sensor was slim, soft and was good in conductivity and fatigue resistance.

As is shown in Fig. 2, the PVDF force measure system contains PVDF sensor, charge amplifier, signal filter, A/D, MCU and computer. The signal from PVDF sensor is very weak, which cannot be measured directly. Then it was amplified and converted to voltage signal by charge amplifier. After that, Voltage signal was processed by signal filter circuit, so as to eliminate interference from 50 Hz power frequency. Then, the analog voltage signal was transformed into digital signal through A/D and was sent to MCU and Computer for processing, display and analysis.

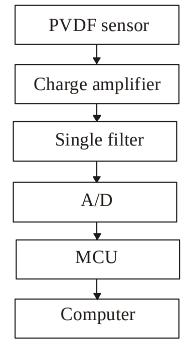

Fig. 2: Flow chart of PVDF force measure system

A/D transform circuit used ADC0832 (National Semiconductor, US), which was a chip with 8-digital resolution and double channels. MCU used in this study was STC89C52. LCD1602 was chosen as and display screen. RS-232 serial interface was used for communication between computer and MCU.

In Fig. 2, Charge Amplifier and Signal Filter are two key parts in signal processing. Charge Amplifier can both transform high-impedance input into low impedance output and amplify the weak signal from the sensor. While, Signal Filter can attenuate and restrain noises. As two key parts of the measure system, circuits of charge amplifier and signal filter were detailed as following.

- **Charge amplification circuit:** Charge amplifier is a high-gain operational amplifier with feedback capacitor. Its output voltage V_o is proportional to input charge amount Q, which is determined by feedback capacitance C_f and has no relations with frequency characteristics of the signal. In measuring system using charge amplifier, furthermore, one of advantages is that output voltage signal is not affected by cable capacitance.

  Due to charge leakage on PVDF film through discharge circuit, errors emerged. So, discharge time constant in the circuit should be increased in the amplifier, so as to minimize the error. In this study, preamplifier with high input impedance was utilized, which can improve time constant.

  Figure 3 schematically shows the charge amplifier circuit in this study. High input impedance operational amplifier CA3140 (Intersil Inc.) was used in charge transform part of the circuit to transform charge into voltage. CA3140 has input impedance

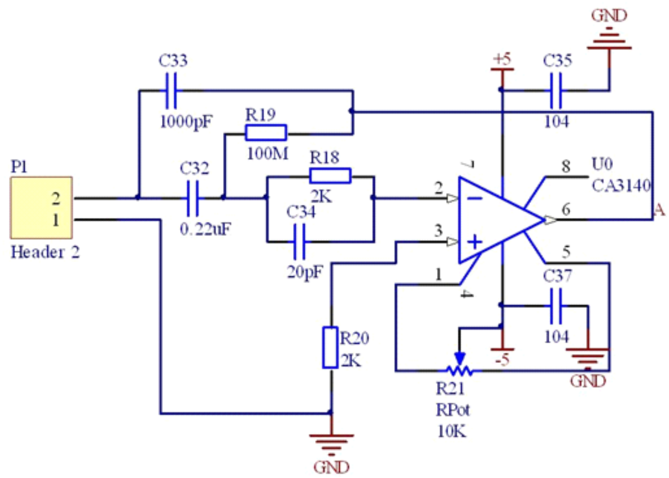

Fig. 3: Schematic of charge amplifier circuit

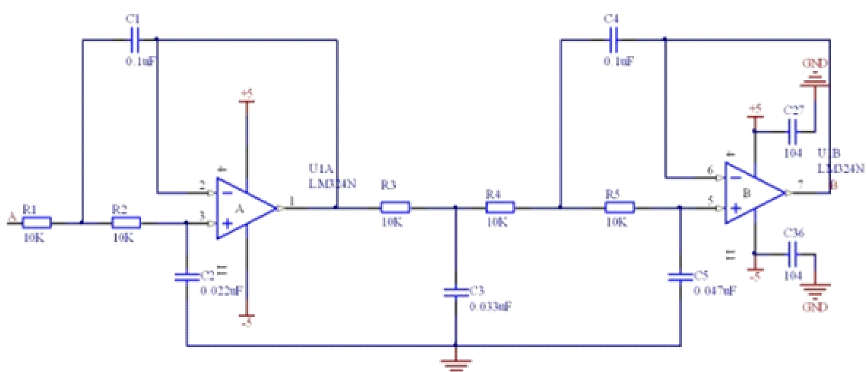

Fig. 4: Schematic of 500 Hz cutoff frequency low-pass filter circuit

of 1.5 TΩ, bandwidth of 4.5 MHz, typical bias current intensity of 10 pA and input offset voltage of <5 mv.

- **Signal filter circuit:** Noises in the system came from components, 50 Hz frequency interference, electromagnetic interference and thermoelectric effects. Low-pass filter and double T 50 Hz trap filter were used to attenuate and restrain noises from components and 50 Hz frequency interference respectively. In this study, signal filter circuit contains the above two parts.
- **Low-pass filter:** PVDF piezoelectric sensor is a weak damping oscillation system. In high frequency band, a high resonance peak exists, which initiates high-frequency noises. Additionally, in some dynamic force measurement, the pass band sometimes far exceeded actual needs and the unwanted high band can interfere the accuracy of low band testing. Thus, a low-pass filter was needed in the force measuring system in this study. It let the low-frequency AC component pass and attenuated the unwanted high-frequency component greatly.

LC and RC are frequently used two types of filter. Each type can be divided into active and passive filter. Passive RC type low-pass filter is simple and has strong anti-interference characteristics. Yet, their impedance frequency characteristic has weak resonance performance, which led to weak selective feature. To overcome such shortcoming, active component such as Operational Amplifier was added in RC type filter in this study, which formed active RC filter. In such active RC filter, signals in pass band was not attenuated, but gained.

Figure 4 showed the schematic of filtering unit, which was consisted of 5th-order Butterworth low-pass filter with 500 Hz cutoff frequency. Low noise preamplifier and high-precision metal film resistors and ceramics capacitors were used to restrain noises from components.

- **50 Hz double T trap filter:** Using 50 Hz trap filter and MCU processing, 50 Hz frequency interference were well restrained. Figure 5 showed the circuit of 50 Hz double T trap filter.

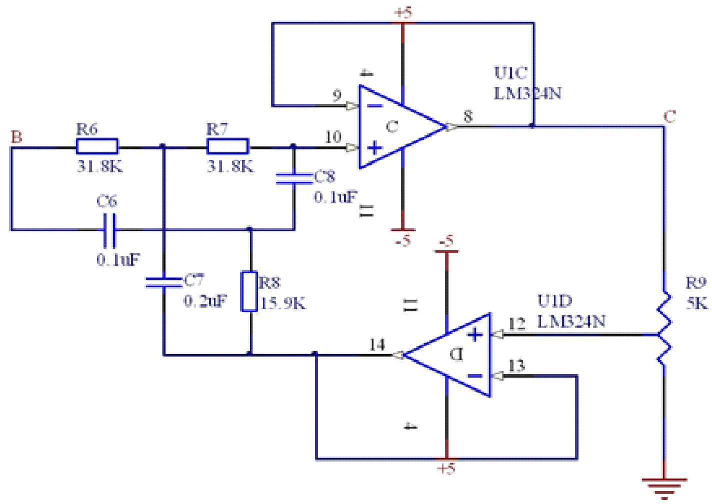

Fig. 5: Schematic of 50 Hz double T trap filter circuit

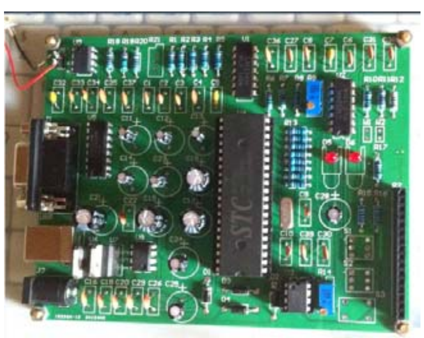

Fig. 6: Circuit board of force signal measurement

In Fig. 5, traditional double T trap structure was utilized in the circuit, which contained two parts. The first part was a double T trap and it can be looked on as a 2nd-order band-stop filter. For 50 Hz trap filter, the central frequency and central angular frequency were 50 Hz and 100TΩ rad/s respectively. Such circuit can only work for the 50 Hz signal. The second part was an Integrated Operational Amplifier. LM324 was selected in this study. It can provide active feedback for signals and improve signal quality.

Constructing measuring system and measure experiment: The force measuring circuit was designed based on the above work. Passing simulations in Proteus, a circuit board was made. The physical circuit board was shown in Fig. 6.

The two pin in red and black color of PVDF piezoelectric sensor was connected on the board. When force is exerted on the sensor, 0~3.645 V voltage will be got. The value varies quickly with force changes.

Table 1: Maximum instantaneous voltage to coins

Force (number of coin)	Output voltage (V)
1	0.606
2	0.637
3	0.649
4	0.673
5	0.681
6	0.702

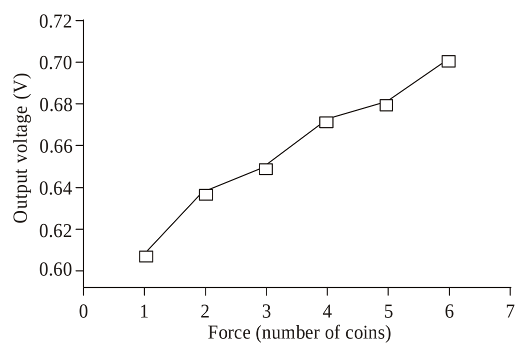

Fig. 7: Force dependent output voltage

To verifying the linear relations between forces and the output voltage values, an experiment was carried out. The sensor was fixed on a flat and one yuan coins was superpositioned successively. Maximum instantaneous voltage values were recorded, as is shown if Table 1.

From Table 1, the value of output voltage increases as the exerted force increasing. According to Table 1, force dependent output voltage figure was drawn, as is shown in Fig. 7.

From Fig. 7, nearly linear relations between forces and output values can be found. Since charge amount appeared in PVDF sensor is proportional to exerted force/pressure, the experiment proved that the measuring circuit kept such linear relation. Thus, forces can be measured by the measuring system designed in this study.

CONCLUSION

In this study, a force measuring system based on PVDF piezoelectric sensor was designed. The measuring system consisted of PVDF sensor, charge amplifier, signal filter, A/D, MCU and LCD. Firstly, piezoelectric equation of PVDF was studied and simplified for the analysis in this study. Secondly, circuits of charge amplifier and signal filter were designed. A 5^{th}-order Butterworth low-pass filter with 500 Hz cutoff frequency was used for attenuating high frequency noise from electronic components. And noise induced by 50 Hz power frequency was restrained heavily by 50 Hz double T trap filter. Finally, a measuring circuit board was made based on the design in this study, so as to construct measuring system. Measuring experiment proved the effective of this system. Further research will be carried out in sensing ultra-high frequency and ultra-fast mechanical signals.

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