Design and fabrication of piezoelectric sensor based on PVDF film for human pulse measurement

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KEYWORDS : PVDF sensor, curved structure, double-layer film, human pulse measurement

This paper reports a fabrication method for producing a sensor module made by double-layer piezoelectric Polyvinylidene Fluoride (PVDF) film, which is supposed to be used for monitoring human pulse. The sensor was composed of double-layer PVDF film and silicon rubber base. The double-layer film was consisted of a single film which folded into two layers and jointed together by pumping away the air between the layers. A very thin silicon rubber was coated in the double-layer PVDF film surface to protect the film and prevent interference from human body, and the film was bonded to the curved silicon rubber structure having a front contact face. On the basis of previous scholars presented that curved PVDF film had greater sensitivity than flat PVDF film, this paper further investigated the sensitivity of PVDF film structure with different curvature, and simulated different curved PVDF structures by ANSYS software. Finally, an appropriate curvature was provided for fabricating the curved PVDF sensor. Detecting on human wrist, the pulse signal contained much pathological information is picked up, and then the information could be used as diagnostic reference of illness.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

1. Introduction

It is well known that piezoelectric polyvinylidene fluoride (PVDF) is a widely applied sensor material. There are two basic operating modes of PVDF: the thickness mode (g_{33} mode) and the length mode (g_{31} mode), it depends on which type of structure the PVDF contacting with. To induce an electric field in the g_{33} mode, PVDF is always bonded to a rigid structure; on the contrary, a flexible structure is useful for generating an electric field when PVDF is under the g_{31} mode. According to the specific application, people choose the appropriate work mode. Many researchers use PVDF sensors to monitor bridge structure health, design biomedical instruments, portable fold-down keyboard and underwater sensor, etc [1]. In these applications, most PVDF sensors work in the g_{31} mode.

Due to the high mechanical strength, soft and stable chemical characteristics, PVDF film can be used as various sensors in harsh environments. It has been applied to audio and ultrasonic air acoustic receivers; a new type of contact vibration sensor is made by bonding PVDF film to a curved frame structure, which can work for generating length mode stress, so this sensor has much higher acoustic sensitivity than the thickness mode [2]. Although PVDF as piezoelectric loudspeakers are characterized by their simple structure, but their sound radiation performance is poor in the low frequency region because their diaphragms are too stiff for large amplitude vibration, using a flat-boxy loudspeakers unit with a pleated tuck-shape flexible diaphragm formed of a laminated sheet of PVDF film, which helped to improve the low frequency radiation performance of piezoelectric direct-radiator loudspeakers [3]. In addition, Li etc. fabricate a dome and bump shape piezoelectric tactile sensors using PVDF-TrFE copolymer as a sensing component by a new mold-transfer technique, this module can simulate smart microcatheter well, the sensors show a high sensitivity and can measure as small as several dozens mN force [4]. The most common design concept among the piezoelectric sensors involves increasing piezoelectric effects. A new approach that embedding two layers of PVDF film into a rubber mold to produce a double-layer piezoelectric membrane keyboard, which has demonstrated that this keyboard could produce more charge than monolayer PVDF keyboard [5], this method can surely give references to other sensors design. To sum up, these applications of PVDF film have all carried through innovation in curved sensor structure or enlarging the sensing area to improve the piezoelectric effect.

For PVDF is soft, light, and its frequency response range covers human pulse signal (0.1Hz to 30Hz); these advantages make it very suitable for medical electronic research. In this paper, the authors propose a new approach to design and fabricate a PVDF film sensor; the sensor is suitable for human pulse measurement. As Minoru Toda found that the curved PVDF film structure produced much higher sensitivity than the planar PVDF film structure [2], this paper further investigates the sensitivity of different curvature radius of PVDF film structure which has a definite arc length. The sensor shows high sensitivity and good comfortableness, and the use of lower cost PVDF film as measuring element signally reduces the cost of sensor.

2. The Basic principle

2.1 Theoretical analysis

Considering PVDF sensor's electric boundary conditions and mechanics boundary conditions, we use the first kind of piezoelectric equations to calculate electric displacement. By the reason of the thickness of PVDF film is usually only a few dozen microns, the electrodes are only applied to the top and bottom film surfaces, thus the charge or voltage is always transferred through the thickness of the film. Under the circumstances, the piezoelectric equation can be simplified as follows：

$$D_3=Q/A=\sum d_{3n}T_n \quad (n=1,\ 2,\ \text{or}\ 3) \tag{1}$$

The mechanical axis of the applied stress is:

1 = length (or stretch) direction

2 = width (or transverse) direction

3 = thickness direction

Where

D_3 = charge density developed in thickness direction

Q = charge developed

A = conductive electrode area

n = axis of applied stress or strain

d_{3n}= appropriate piezoelectric coefficient for the axis of applied stress or strain

T_i = stress applied in the relevant direction

Normally, d_{31} is 10 times larger than d_{32}, and d_{32} can be neglected in calculation. In order to increase positive piezoelectric effect, Silicon rubber is chosen as sensor base, which can promote PVDF working in the g_{31} mode; therefore T_3 in equation (1) is zero.

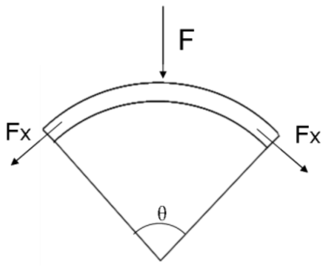

Fig. 1 stress on curved PVDF sensor

Consider a curved PVDF film forming an arc with the internal angle θ. When a force is applied on it, PVDF will produce distortion. In Fig.1, the applied force is represented by F, and the tangential force created by F is

$$F_x=\frac{F}{2\sin\frac{\theta}{2}} \tag{2}$$

Two of these components F_x are perpendicular to the PVDF thickness direction. The generated charge Q, from (1), is

$$Q=A\cdot d_{31}\cdot T_1 \tag{3}$$

We can get sensor sensitivity

$$S=\frac{Q}{F}=\frac{A\cdot d_{31}\cdot T_1}{F}=\frac{A\cdot d_{31}}{2A_1\sin\frac{\theta}{2}} \tag{4}$$

Note here that A_1 is lateral area which perpendicular to length axis and the range of θ is $0<\theta<\pi$. Equation (4) indicates that the smaller the angle θ, the higher sensitivity the senor has. However, we should choose an appropriate curvature according to the actual need, because when the angle θ is too small, the sensor will be inappropriate for our applications. For example, in the design of human pulse sensor, when θ is less than 30 degrees will arouse users' discomfort by reason of the tip of the sensor is sharp.

2.2 The design and simulation of PVDF sensor

The above analysis shows that the sensitivity of PVDF sensors under different curvatures is different. Here we will design an applicable structure for human pulse measuring sensor. When this sensor is used for detecting human pulse, it is rightly required that the sensor joints human wrists well. Therefore, the structure should be designed according to human body engineering, and many factors such as the feeling of users, the design of cost and operational environment should be considered.

In numerous materials, organic silicon rubber is chosen to be the sensor base and coating layer of the human pulse sensor, precisely because it has moderate softness and good elasticity. Using silicon rubber as sensor base can make PVDF working in the stretching mode and helps to increase the deformation of PVDF film, further, lead to the augment of output charge.

In order to further validate the analysis, the simulation of different curved PVDF structures was carried out using the ANSYS® finite-element package, ANSYS static structural analysis. Three types of PVDF structure are simulated; the size parameters are listed in Table.1. The chord length and dome height of three different models are different, but their arc length is fixed, so these structures have different curvatures.

Name	Arc length(mm)	Chord length(mm)	Dome height (mm)
PVDF1	4	4	0
PVDF2	4	3.6	1
PVDF3	4	3	1.5

Table.1 Parameters of sensor structures

First, we should establish the entity model of the structure. In three different structures, we ensure the length of PVDF is a definite value and change the dome height of the curved structure. One of the three entity models is shown in Fig.2. This model includes two parts: PVDF film and silicon rubber base, the corresponding parameters are listed in Table.2. PVDF film is glued to the base. A piece of PVDF

Items	PVDF	Silicon rubber
Length(m)	4×10^{-3}	4×10^{-3}
Thickness(m)	2×10^{-5}	1×10^{-3}
Modulus of elasticity(N/m^2)	2×10^{9}	2.14×10^{6}
Poisson's ratio	0.29	0.48
Shear modulus(N/m^2)	0.775×10^{9}	
permittivity	11.75	
d_{31} (pC/N)	22	
d_{32} (pC/N)	3	
d_{33} (pC/N)	-30	

Table.2 Material constants and dimensions

film is curved along the X-axis and two edges of it are clamped, the deformation of the edges is almost considered as zero. Next, analyzes their output voltage when they suffer deformation under the same force. Through this analysis, we are trying to find the relationship between the curvature and the output voltage. When the force (in Newton) is applied normal to the PVDF surface, it is converted to the longitudinal stress in the PVDF film, and induces the generation of charge on the PVDF surfaces.

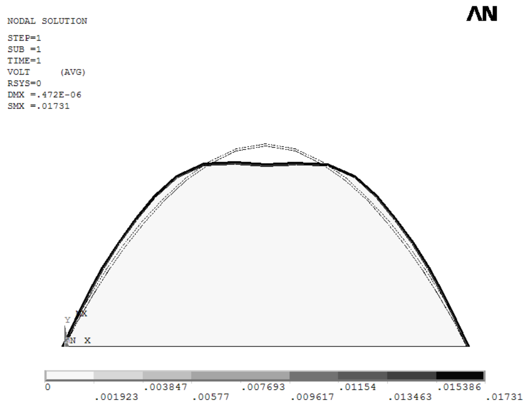

Fig. 2 Sensor model of before and after stressing

Because of PVDF is an electric insulator, these charge produce an open-circuit voltage (in volts). The gray dashed in Fig.2 represents the undeformed sensor, and black line represents the deformed sensor shape. It can be observed clearly from the figure that the sensor has obvious deformation and an electric field is created between the upper surface and the lower surface. The open-circuit voltage value in this figure is about 17mV at 1N force.

The three structures under some same loads have produced different open-circuit voltages as shown in Fig.3. With the same load force, PVDF3 with the largest curvature produces the highest open-circuit voltage, and the plain model PVDF1 produces the minimum voltage. It is proved that this simulation results is consistent with theoretical analysis before, and using curved PVDF sensor to increase the sensor's sensitivity is feasible. Admittedly, different dome heights represent different curvatures. As we can see in Fig.3, the linear slope is the sensitivity of the corresponding sensor. PVDF3 has the biggest sensitivity, PVDF1 has the smallest sensitivity. Through the simulation, we know that PVDF film with a larger curvature has greater deformation under the same force; it also can be contributed to the function of silicon rubber.

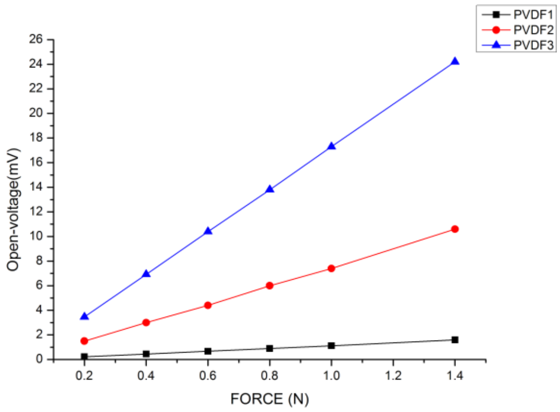

Fig. 3 The simulation results of three models

In addition, it is important to emphasize that the parameters of silicon rubber like Poisson's ratio and Shear modulus will have influence on the output voltage of PVDF sensor; therefore, we have to choose the appropriate materials according to our actual needs in experiments.

3. Fabrication of sensor structure, Test and discussion

In this paper, under room temperature, we use two-component organic silicon encapsulating glue as coating layer. This kind of silicon has good liquidity and adhesive ability, can be deeply solidified, also has electrical insulation, both excellent high-temperature property and low-temperature property. Technical parameters of organic silicon are shown in Table.3. Piezoelectric constants of PVDF are d_{31}= 21pC/N, d_{33}=-30pC/N.

The sensor is comprised of PVDF film and silicon rubber. Putting the matched silicon gel filling into mold, which has PVDF cling to the inside upper surface. The advantage of this method is that when silicon gel formed, PVDF can also properly stick on it. Moreover, due to the good liquidity of silicon gel, PVDF glued to the inside of mould will also have a very thin silicon gel coating on its surface. When the front face of sensor is put in contact with human wrist, body surface will introduce much noise in the output voltage of PVDF. The very thin silicon rubber coated in the multi-layer PVDF film surface can help to protect the film and prevent interference from human body.

Proportion	1.3
Preliminary curing time	3~5 hours
completely curing time	12 hours/25°
Volume resistivity	1×10^{15}
Insulation intensity	15
Applicable temperature range	-55~200°

Table.3 Parameters of organic silicon

Besides of using the monolayer PVDF film, we have tested the double-layer PVDF film as well. The double-layer film is consisted of a single film which folded into two layers and jointed together by pumping away the air between the layers. Here, we only experiment the double-layer PVDF as an example, the method is similar in multi-layer cases. The positive electrode is in the inside surface and the negative electrode is in the outside surface which connected to outside metal shell of the sensor as signal ground. We use power signal generator and vibrator to test their sensitivity, the input current of vibrator is 3A, the output voltage of monolayer and double-layer are 810mV and 920mV, respectively. It has been found that the double-layer film structure generates more charge than monolayer under the same pressure conditions. Furthermore, the advantages of this folded structure are that the negative electrode connecting to metal shell wrapped the positive electrode for shielding interference, and layers of the film integrated closely without bonding by conducting resin; the structure also could avoid improper bonding and layers asymmetry.

Parameters about this sensor are given in Table.4. The fabricated two curved PVDF sensors are shown in Fig.4. The lead wires of the upper sensor are welded to pieces of copper foil, and the copper foil is posted conductively on the surface of PVDF film; the PVDF film of the lower sensor is made by MEAS INC. In experiment, we find that the output voltage of upper sensor is not very steady, it is occasionally influenced by electrodes position, but the lower one doesn't have such problems. The results of experiment indicate that strong electrodes can ensure the accurate output of sensor.

Curvature radius(mm)	13
Arc length(mm)	13.6
Length(mm)	30
PVDF thickness(mm)	2×10^{-2}

Table.4 Parameters of the fabricated sensor

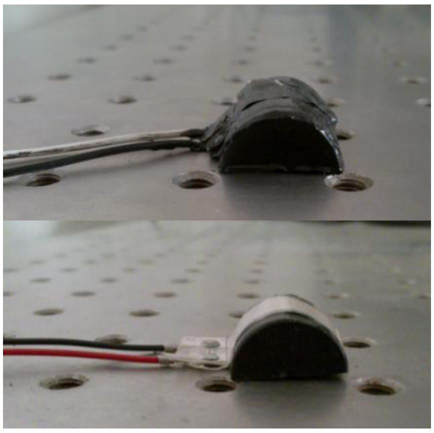

Fig. 4 The fabricated sensor

In general, the piezoelectric signals are easily interfered by environmental noise and static electricity. Furthermore, the output voltage of PVDF film is a very small value (almost several millivolts). In order to facilitate the extraction of human pulse signal, we collect charge by the charge amplifier, because the charge amplifier has high impedance and low noise. The circuit contains charge amplifier, low-pass filtering and voltage amplifier as shown in Fig.5. Then the signal can be controlled by a micro-controller and communicate with a computer. There is one point to stress that the charge amplifier gain is depended on the capacitance value, so the smaller capacitance has a larger amplifier gain.

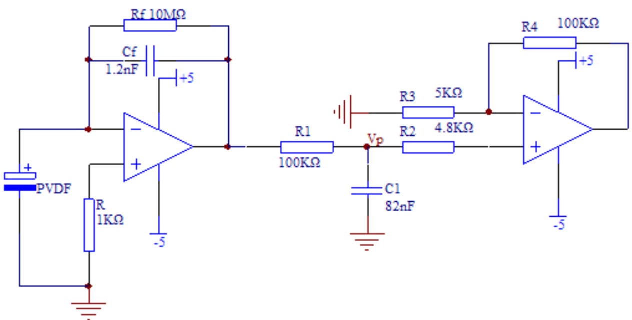

Fig. 5 Signal processing circuit

The measured pulse signal recorded by oscilloscope is shown in Fig.6. The peak voltage is 640mV, accordingly, we can get that the output of charge amplifier is 30.48mV, by considering the puniness of human pulse vibration, such measurement is desirable. The pulse signal consists of two pulse waves; each period has a high wave (the main wave) and a low wave (the predicrotic wave). As we have known, human pulse contains much pathological information. The predicrotic to main wave ratio and the time interval between these two waves represent different physiological information in Chinese medicine discipline, from which doctors could observe patients' health and diagnose the illnesses.

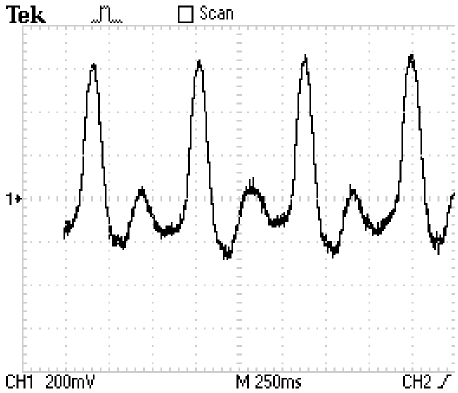

Fig. 6 The measured pulse signal on an oscilloscope

4. Conclusions

This paper successfully designs a curved PVDF sensor for human pulse measurement and further investigates the sensitivity of different curvature of PVDF film structures with a definite arc length. The ANSYS simulation results have verified the fact that the larger the curvature, the higher sensitivity of the PVDF sensor will be.

Based on the results of simulation, we fabricated a curved PVDF sensor for pulse application, which had 13mm curvature radius and 13.6mm arc length. Afterwards, we got the desirable human pulse signal by using the sensor on wrist. The signal contains much pathological information which is considered very valuable. In addition, it has been found that the double-layer film structure generates more charge than monolayer under the same force.

Finally, experimental results show that the curved sensor is suitable for improving sensitivity. The pulse signal can be picked up by microcontroller, and then the information about the user's physical state could be extracted. This system can be used in ward monitoring and family health care, and may be extended to many application fields in the future.

ACKNOWLEDGEMENT

The authors express appreciation to MEMSIC Transducer Systems Corporation for providing scholarship encouragement in this paper.

REFERENCES

1. Sayyed Alireza Arabshahi and Zhongwei Jiang, "Development of a Tactile Sensor for Braille Pattern Recognition: Sensor Design and Simulation". Smart Materials And Structures, Vol.14, pp.1569-1578, 2005.
2. Minoru Toda and Mitchell L.Thompson, "Contact-type vibration sensors using curved clamped PVDF film". IEEE Sensors Journal, Vol.6, no.5, pp.1170-1177, October 2006.
3. Juro Ohga, Toshitaka Takei and Nobuhiro Moriyama, "Wideband Piezoelectric Rectangular Loudspeakers Using A Tuck Shaped PVDF bimorph". IEEE Transactions on Dielectrics and Electrical Insulation, Vol.17, No.4, pp.1074-1078, August

2010.

4. Chunyan Li, Pei-Ming Wu and Soohyun Lee, et al, “Flexible Dome and Bump Shape Piezoelectric Tactile Sensors Using PVDF-TrFE Copolymer”. Journal of Microelectromechanical Systems, Vol.17, No.2, pp.334-341, April 2008.
5. Peter F. RADICE. Piezoelectric polymer keyboard apparatus. America, United States Patent, NO.463 3123. 1986.