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A Flexible Thin Film Single-Point Force Sensor from PVDF Film

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Abstract: On the basis of piezoelectric effect of PVDF film, the flexible thin film single-point force sensor with total dimension $75mm \times 20mm \times 1mm$ is devised to dynamically measure single-point force in biomedical or mechanical field. New flat interlayer structure with cavum is firstly introduced to enlarge the deformation of PVDF thin film, and a conductive supporting rack is firstly utilized to construct a detecting cavum and to realize the connection between PVDF film and down conductive electrode. Such structure is flat as the traditional sandwich structure; but its cavum may make sensor have a sensitive reaction and larger measurement range. Its measurement range is from 0 to 6217N and it works between -40°C and 80°C. The total thickness 1mm is so thin that the given sensor can be easily placed into aperture. Results of experiment and analysis illustrate that the developed sensor is available and that it may be used to dynamically sense a single-point force. The flat interlayer structure given is thin and flexible and flat and implantable. Such sensor makes that it becomes possible to dynamically measure single-point force in mechanical field or biomedical field.

Keywords: PVDF film, flexible thin film single-point force sensor, piezoelectric effect, Interlayer structure.

1. INTRODUCTION

Plenty of research has been done for the measurement of planar pressure distribution [1-4]. The mechanical stress between foot and shoes has been linked with pressure distribution [5-6]. But if a single-point force needs to be known, pressure distribution sensor will be difficultly utilized. For an example, the single-point force between neb and paper needs to be known to optimize neb's structure and layout; and single-point friction force between cam and drum roller needs to be understood to change the profile of cam. Zhou GF, Zhao YL, Jiang ZD utilized a piezoresistive ink to fabricate a flexible single-point force sensor through silk screen printing techniques [7], low sensitivity makes their sensor be difficultly applied to mechanical field and biomedical field. A bite force sensor was developed to detect some bad teeth in mouth on basis of silicon material [8]. For an accidental rigid object, such sensor is easily destroyed and single-point force is difficultly measured. So the sensor for single-point force measurement needs to be considered and further researched. PVDF (polyvinylidene fluoride, PVDF) thin film has been extensively used in a large variety of sensor applications [9-11]. The majority of published work involves ultrasonic transducers used in applications such as nondestructive testing and acoustic emission monitoring, since PVDF film is flexible and easily shaped and highly sensitive [12-15]. It's known that PVDF film may be used to fabricate thin film sensor. However for dynamic measurement of single-point force, relevant researches are seldom done. Hence, sensor from PVDF film can be considered to solve the dynamic measurement problem of single-point force because PVDF thin film is suitable for dynamic measurement.

The aim of study is to develop a flexible thin film single-point force sensor from PVDF film for dynamically measuring single-point force in biomedical or mechanical field. The sensor consists of four sensor elements. The relevant principle is narrated simply. Then relevant testifying experiments are done, analyzed and discussed. This study is concentrated on sensor's design, fabrication and experiment because basic researches on PVDF thin film have been done. The displayed sensor is our first prototype. The developed sensor adopts new flat interlayer structure with cavum to make it be easily placed in a gap. Here, the flat interlayer structure with cavum is a new interlayer structure given out by authors and a supporting rack is firstly utilized to improve the deformation of PVDF film. Furthermore supporting rack is also used to conduct output voltage from PVDF film and to protect PVDF film from the damage caused by larger force. Such sensor could further expand the range of dynamically measuring single-point force. And it's thin and flexible and flat and implantable.

2. DETECTING PRINCIPLE OF PVDF FILM

2.1. PVDF Film Background

PVDF thin film is a kind of polymer that when stretched or poled in a strong electrical field it produces a certain charge on the up and down surfaces. Such piezoelectric polymer is flexible, lightweight, and tough

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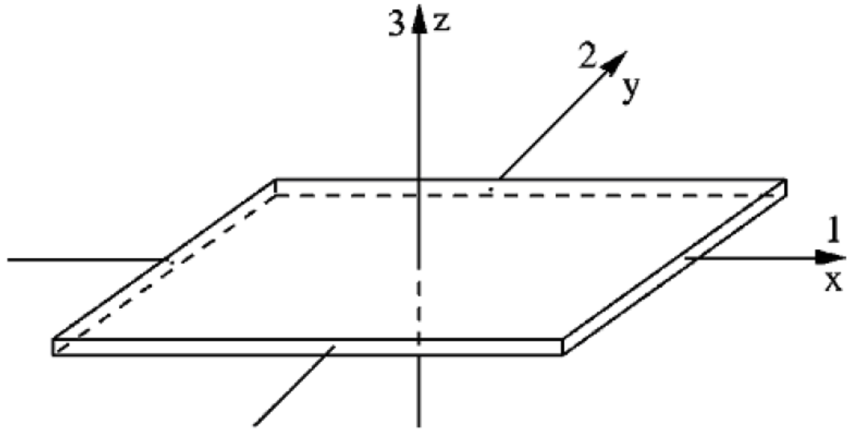

Figure 1: Numerical illustration of PVDF axes.

plastic film which could generate a certain charge. Piezoelectric PVDF film is an anisotropic material since its electrical and mechanical responses are different depending on the axis of applied electrical field or the axis of mechanical stress. Its axes are classified by numerically 1, 2, and 3 representing length (or stretch) direction, width (or transverse) direction, and thickness direction, respectively, as shown in Figure **1**.

Electrodes are only applied to the top and bottom surfaces of sensing film; thus the electrical axis is always in direction 3. The mechanical axis can be either in length, width, or thickness indicated by 1, 2, or 3 directions depending on the stress applied. The notation used to describe how PVDF film is used in application is an ordered pair of numbers, with the first number representing the electrical axis and the second representing the mechanical axis. The PVDF sensor described here uses mode (3, 1). This mode could produce the largest output voltage since output charge is proportional to stress. This is the reason that mode (3, 1) will be adopted. There is less variation of temperature if the explored sensor is used in workshop or ward. However output wave will be difficultly avoided due to a larger pyroelectric constant $40C / cm^2 .K$. Here, pyroelectric constant means that the sensing area of every square centimeter will supply the definite charge with 40C. Generally speaking, output voltage of PVDF sensor is also proportional to pyroelectric constant. And the affection of temperature needs to be further researched and explored in future.

2.2. Sensing Principle

PVDF thin film has an excellent electromechanical conversion properties based on mode (3, 1). Electrical parameters are linked with mechanical parameters. The output charge Q from PVDF piezoelectric film is the transient response on all strain at all polarized directions. The output charge Q from piezoelectric PVDF film could be expressed in equation (1):

$$Q = \sum d_{ij} E_{PVDF} S_j A \ \ (i = 1,2,3 ; j = 1,2,\cdots\cdots 6) \tag{1}$$

Here, E_{PVDF} is the elastic modulus from PVDF film, A is the effective sensing area covered by PVDF film, S_j is the polarized displacement at the relevant polarized direction.

The aim sensor is used to dynamically detect single-point force vertical to the touching area from PVDF film; that's to say, the sensing component is used to only sense the one dimension force along z axis. If the piezoelectric constant from PVDF film is not zero, equation (2) can be gotten and simplified from equation (1):

$$Q = d_{31} E_{PVDF} S_1 A = d_{31} F \ \ \text{(Here, } F = E_{PVDF} S_1 A = \sigma_x A \text{)} \tag{2}$$

PVDF thin film is used as a sensing component in fact. The surface which is vertical to the polar direction will produce a certain charge when it endures a single-point force. Then positive charge accumulates on one surface, and the equivalent negative charge will appear on another surface simultaneously. Therefore, PVDF film may be regarded as a charge generator. Actually the sensing component from PVDF film is equivalent to a parallel capacitor [16]. Hence, above sensing principle is available for dynamically measuring force.

2.3. Converting and Amplifying Principle of Signal in Circuit

The surface charge caused by single-point force has to be amplified from PVDF film because it is so small that it can not be sensed by common detecting

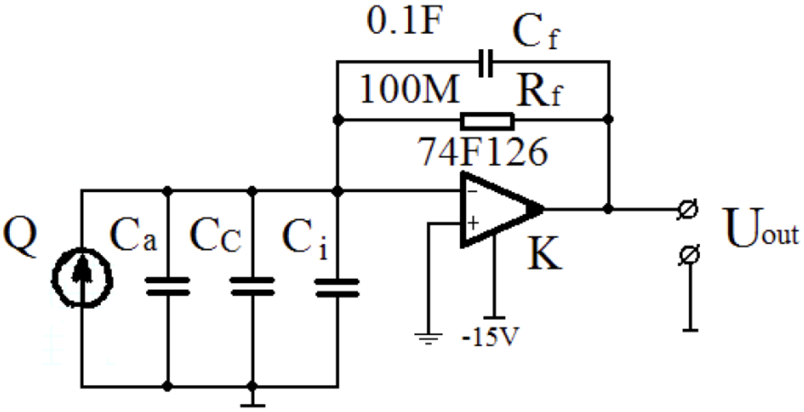

Figure 2: Equivalent circuit on charge amplifier from PVDF film.

equipment such as voltage meter. Equivalent circuit is seen in Figure **2** for the flexible thin film single-point force sensor from PVDF film.

In Figure **2**, C_f is the feedback capacitor from charge amplifier, C_c and C_a are the capacitor from wires and the capacitor from PVDF film respectively. If the magnification of amplifier is K, the output voltage can be expressed in equation (3):

$$U_{out} = \frac{-KQ}{C_a + C_c + C_i + (1+K)C_f} \tag{3}$$

If the magnification of amplifier is enough large, authors think that capacitors (C_c, C_i and C_a) can be neglected. Then the output voltage is as follows:

$$U_{out} = \frac{-Q}{C_f} = \frac{-d_{31}E_{PVDF}S_1A}{C_f} = -\frac{d_{31}}{C_f}F \tag{4}$$

3. DESIGNING THE NARRATED SENSOR

3.1. Structure Design

The flat interlayer structure is put forward and constructed in Figure **3** to dynamically detect the single-point force between point touching objects. An airtight cave is built to increase the deformation of PVDF film. Insulating layer is utilized to avoid the direct connection between top and down conductive electrodes.

The reference space in the given sensor is set to increase the deformation of PVDF film. Top conductive electrode is connected with the top surface of PVDF film, and down conductive electrode is connected with the down surface of conductive supporting rack. Both conductive supporting rack and down conductive electrode are also used to limit the deformation of PVDF film. Top and down plastic films are adhered to the top and down conductive electrodes and to protect whole sensing component from damage. The insulating glue is used to package top and down plastic films. When a point force is exerted to the given sensor, the PVDF film will be pressed and bent because there is a cavity under PVDF film. Then charge caused by single-point force will be immediately converted into output voltage. Then single point force can be known immediately.

Here, piezoelectric thin film is simulated to know whether the given sensor is fit for the generally dynamic single-point force measurement in mechanical or biomedical field. A point force with 6000N is exerted to the center of PVDF film because the center point of PVDF film is the point of maximum displacement in reality. The boundary condition is that the flank of PVDF film is fastened in the course of enduring point force 6000N.Through the static structure analysis on PVDF film by ANSYS software, the sum displacement is given out in Figure **4**. In Figure **4**, the red part represents the maximum displacement caused by the load 6000N; and the blue part represents the minimum displacement at the same load. There the maximum displacement $233\mu m$ is less than the height of conductive supporting rack $600\mu m$. In the course of PVDF film's deformation; the down surface of PVDF film doesn't touch the top surface of down conductive electrode. Hence; the aim sensor could be perhaps fit for the general case in the mechanical or biomedical fields after common single-point force is exerted to the developing sensor; namely the aim sensor could endure the external force 6000N.

3.2. Fabrication Procedures

Above narrated sensor can be made by some methods such as adhering or bonding technologies.

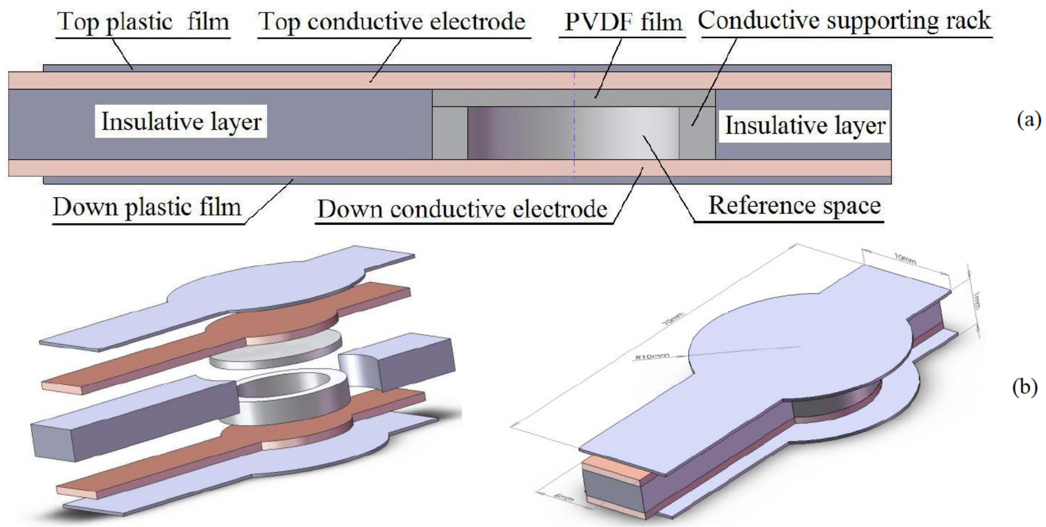

Figure 3: Structure design of single-point force sensor. (**a**) Full section drawing on the given sensor (scale: 2:1); (**b**) 3D explosion drawing and assembly drawing on the given sensor (scale: 1:1); note: the dimensions of displaying sensor is 70 mm ×20 mm×1mm.

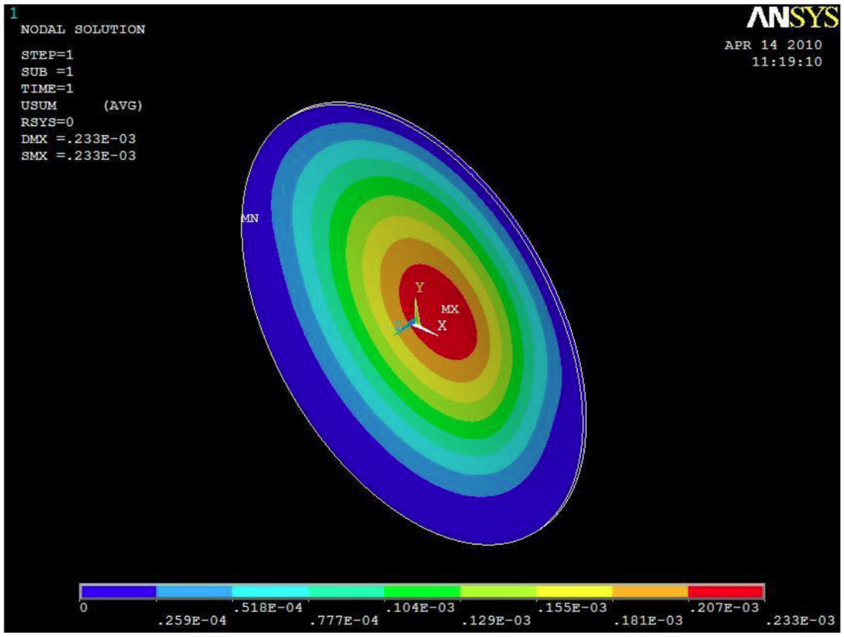

Figure 4: PVDF film's sum displacement at 6000N.

Fabrication condition parameters are such: work temperature: 25˚C, fabrication pressure: 734mmHg (0.975MPa). Conductive supporting rack and PVDF film should be processed to build a cavum of increasing deformation. And then top and down conductive aluminum film electrodes are processed into the given design shape. Conductive film electrodes are respectively adhered on the surface of top and down plastic films by insulative glue. Then conductive supporting rack is placed and fastened on the circle area of down conductive aluminum film electrode; here, conductive glue should be coated between conductive supporting rack and down conductive aluminum film electrode to fasten the supporting rack. As insulative layer, insulative glue is daubed on the above surface of down conductive aluminum film electrode. Same, conductive glue is coated on the top surface of conductive supporting rack to adhere PVDF film. Same procedures is realized and finished between top conductive aluminum film electrode and PVDF film. Then insulative glue is used to felt top plastic film and top conductive electrode. The same insulative glue is coated along the profile of conductive aluminum film electrode to felt top and down plastic films. Finally, the appearance of single-point force sensor from PVDF film is sheared into the design in Figure **3b**.

Figure 5: Flexible thin film single-point force sensor from PVDF film.

3.3. Package

The flexible thin film single-point force sensor from PVDF film can be packaged by two-way mode. That's to say, the sensing component and detecting circuit are fabricated and packaged respectively, and then they are linked together; possibly sensing component and detecting circuit are integrated together and packaged into same device. Authors selected the former mode on basis of their experiment condition. In light of such packaging idea, relevant packaging principle should be only given out apart. However, for the detecting circuit adopted is general circuit, there is no difference from the packaging principle of general circuit. Therefore, here the package on the given sensor is only brought forward and narrated.

The sensing component is placed between two conductive aluminum film electrodes to dynamically sense single point force. Related connection is realized through conductive glue. External protecting layer---plastic film is used to adhere and protect top and down conductive aluminum film electrodes. Here, the blank area should be adhered to fasten and seal the components of sensor. Non-conductive glue has to be also utilized to package the edge of sensor and to avoid the damage of internal components such as film electrodes. The end of top and down conductive aluminum film electrodes should be exposed to be connected to the detecting circuit. The flexible thin film single-point force sensor from PVDF film is fabricated according to above procedures, seen in Figure **5**. If the general wire connection is required for the given sensor; the interface of above narrated sensor should be adjusted and designed solely.

4. TESTING PARAMETERS

The given sensors should be fastened on a work platform (experiment temperature: 25˚C, Work atmospheric pressure: 0.975MPa, relevant humidity: 58%), here transparent tape is advised to be available. The given sensor should tightly touch the surface of platform. Then the connecting wires are connected to a detecting circuit. The used multimeter is used to display and observe whether signal could be displayed after a random force is imposed. Original voltage from sensor is recorded by pen. Then a set of point force is exerted on sensing area; corresponding voltage will be written down respectively to form relative curves by Microsoft Excel 2003. In order to realize the dynamic test continuously for a random force, the given sensor are connected to oscilloscope and random forces are exerted to observe the relevant change under the same experiment conditions. A larger force such as 6000N was not applied to the given sensor because our first aim was applied to biomedical fields such as the dynamic force from toe and finger. However, the developed sensor may endure a larger force such as 6000N according to the results of static structure simulation. Aim work circumstance of sensor is ward of hospital or process workshop, and then authors may think that there is a constant work temperature 25˚C before they develop such sensor. Hence, the experiments of different work temperature were not done in this article.

4.1. Basic Geometry Parameters

The relevant geometry parameters of the given sensor from PVDF film are listed in Table **1**.

Parameters on PVDF film itself are supplied by the Jinzhou Kexin electronical material limited corporation (China), and other parameters are tested in laboratory. Authors tested the basic parameters in Table **1**: PVDF thin film thickness, sensor total dimensions (width, length and thickness), PVDF density, effective detecting area, experiment response time, tolerance. Based on experiment data, tolerance of sensor is calculated according to standard tolerance formula in tolerance theory.

Table 1: Geometry Parameters of Flexible Thin Film Single-point Force Sensor from PVDF Film

Parameters	Value	parameters	Value
PVDF thin film thickness	$200\mu m$	PVDF strain constant	$d_{31} = 23\times10^{-12} C/N$
PVDF Young's modulus	$2.5\times10^{9} N/m^{2}$	PVDF volume resistivity	$\rho = 1\times10^{13}\Omega\bullet cm$
Range of work temperature	-40˚C to 80˚C	PVDF density	$1.78\times10^{3} kg/m^{3}$
PVDF pyroelectric constant	$40C/cm^{2}.K$	Stretched strength	$35\sim55MPa$
Width of the given sensor	$20mm$	Length of the given sensor	$75mm$
Effective detection area	$113.04mm^{2}$	Total thickness	$1mm$
Experiment response time	5sec	Tolerance	±0.004V

4.2. Character Test

When a scheduled force is exerted on the flexible thin film single-point force from PVDF film, the relevant output voltage will be obtained. Because PVDF film is only used to detect the dynamic force or an instantaneous point force, a set of point force is only exerted onto the sensing point and duration time of every point force is about 5sec to gain an objective and right number. Sensor output after instantaneous input of point force produces a corresponding value, and furthermore output of sensor does not always keep a stable value because PVDF film has pyroelectric effect. Then authors got the relationship curve between the detected point force and output voltage in Figure **6**.

At the same time, a set of random single-point force including 5 data is detected to known whether the flexible thin film single-point force sensor could be used to dynamically measure single-point force. The relevant graphs are displayed in Figure **7**.

5. ANALYSIS AND DISCUSSION

5.1. Test Parameter Analysis

According to the parameters supplied by manufacturer and author's test parameters, it's known that the range of flexible thin film single-point force sensor is from 0 to 6217N($F = \sigma_s A$) and that the maximum strain of PVDF film is $4.4\mu m$. The given sensor only works under the given range of temperature from -40˚C to 80˚C, hence the given sensor may satisfy the generally dynamic measurement of single-point force in the biomedical field or mechanical field because the given sensor may also endure the single-point force 6000N according to the results of static structure analysis. That's to say, the developed sensor could be applied to ward in hospital.

However, the given sensor is affected by ambient temperature for its pyroelectric constant is $40C/cm^{2}.K$. Here, pyroelectric constant $40C/cm^{2}.K$ means that the sensing area of every square centimeter will supply the

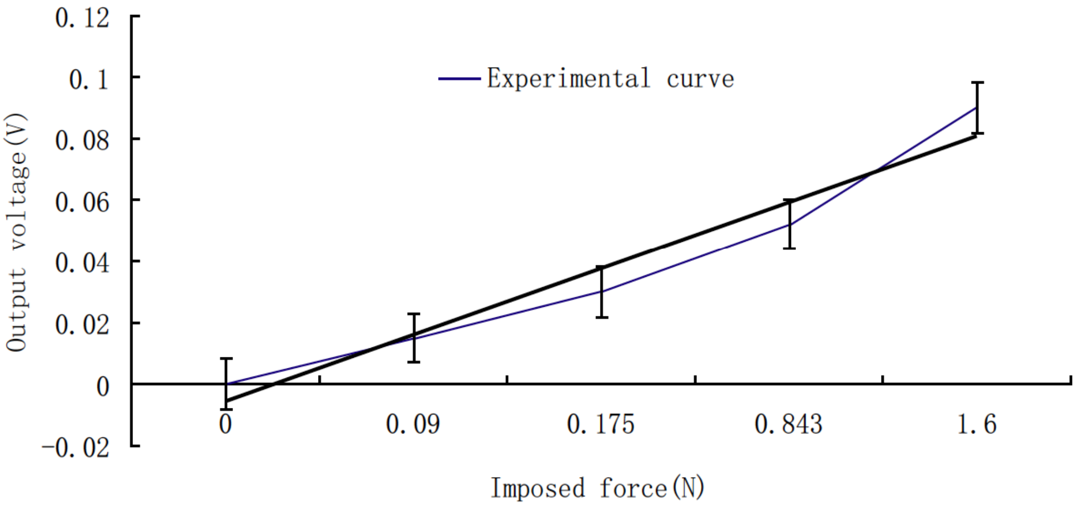

Figure 6: Experimental curve between imposed force and output voltage.

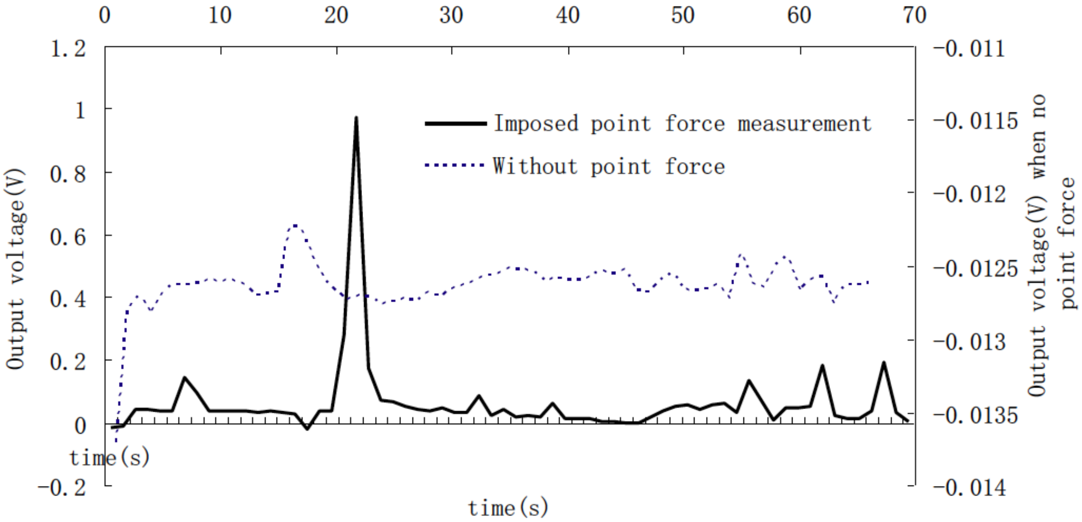

Figure 7: Dynamic test curve from the given sensor.

definite charge40C. For an example, the dot curve in Figure **7** shows that there is a certain output without any input force. Through observing the dot curve without point force in Figure **7**, output voltage of the given sensor is not zero because the ambient temperature 25˚C doesn't absolutely keep constant. That's to say, output voltage always include the ingredient of temperature for there is always pyroelectric effect in PVDF film. For another example, in Figure **6** the tested curve is not completely linear due to pyroelectric effect. And the black curves in Figure **7** include some small waves where there is no any point force; and these small waves are caused by small change of ambient temperature because PVDF film itself has also pyroelectric effect at any time. The work temperature is 25˚C, however it does not keep an absolute constant in experiment. And it always gives a very small wave at 25˚C; Hence it's found that there are a lot of small waves in Figure **7**.

Ambient work temperature 25˚C of given sensor always affects the measurement result, but it can not change the trend of direct proportion between point force and output voltage. In Figure **6**, with the increase of point force, the output voltage will increase. On the whole, displaying the tendency of curve in figure6 is the same as the significance in equation (4). That's to say, ambient work temperature does not seriously affect the correct judgment of worker or doctor.

Of course, the given sensor is also affected possibly by the serious change of work atmospheric pressure. When work atmospheric pressure sharply changes, sensing area will have to endure the pressure change; then PVDF film produces output voltage due to deformation and the cavum in the flat interlayer structure will be perhaps destroyed for the cavum is in a sealed state. In experiment, the intense change of work atmospheric pressure does not happen; hence the fracture of cavity does not appear. However such phenomenon possibly takes place in reality.

5.2. Character Analysis

The given sensor does not keep absolute constant without single-point force due to small change of work temperature. When a random force is imposed, output voltage will immediately increase. But if the imposed force keeps constant, any voltage change will not be found. That's to say, the flexible thin film single-point force sensor from PVDF film is only used to find a dynamic single-point force. In Figure **7**, a larger output voltage will be found at about 20s; such illustrates that an instantaneous single-point force is changed on the flexible thin film single-point force sensor at that time. In the same way, authors randomly changed the point force for five times to know whether the corresponding variation would be caused. That's to say, the change of output voltage is the same as that of imposed single point force. In Figure **7**, the small variation of output voltage illustrates that the small change of point force could lead to the corresponding change of output voltage. Other smaller waves in Figure **7** are produced completely by the small wave of ambient temperature because pyroelectric constant of the used PVDF film is $40C/cm^2.K$. Temperature affect should be weakened in the dynamic measurement of actual singe-point force. Here temperature compensation circuit can be added to weaken the affect of temperature's small wave in future. Hence, the narrated sensor could be used to dynamically measure single-point force in biomedical or mechanical field.

However, there are also some flaws according to above measurement and analysis. Although the flexible thin film single-point force sensor may dynamically sense the single-point force, it is not directly placed into the mouth of patient because its dimension is too large to be foisted into the pointed position in mouth. Certainly, the designed sensor can not detect the single-point force with irregular touching point because there is a supporting rack made from steel in it. Authors think that the supporting rack should be replaced by a soft rack if possible in future. The given sensor is not also used to measure the single-point force of transient friction in the mechanical field because the adhering and packaging material is non-conductive glum and because it's easily destroyed. Vacuum of sensor in Figure **3** makes sensor easily crack if pressure difference between inner and outside of sensor is very larger. Response time (5 sec) is too long for sensor application. In order to apply the given sensor to the field of Microsystems measurement, the thinner and smaller PVDF film has to be adopted in future development. Besides above flaws, the method for measuring temperature should be also considered to develop an integrated thin film sensor in future research because PVDF film also has pyroelectric effect.

The given sensor in Figure **3** is used to dynamically detect single-point force such as point force from hand and foot, not pressure distribution and heartbeat in biomedical field for the PVDF thickness $200\mu m$ used is very thick. Furthermore, the flexible thin film single-point force sensor from PVDF film has a lower cost of research with 1000RMB.The developed sensor is thin and flexible and flat and implantable. Although the developed sensor is flexible, it can not be randomly folded and deformed for there is a steel supporting rack in sensing area. Due to thicker PVDF film, response time of given sensor in Figure **3** is very long. Different thickness of PVDF film has a different response time because electron moving time is different in PVDF film. When thickness of PVDF film is greater than 0.5mm, there will be almost no any output voltage. Of course, PVDF thinner film such as 3μm can be used to sensitively detect the radio respiratory cycle from heartbeat [17]; however it can not be used to dynamically measure point force from hand, foot or tooth because PVDF film is too thin to endure common point force. Hence, aim at different cases, different thickness of PVDF film should be selected carefully.

6. CONCLUSIONS

In order to solve the dynamic measurement problem of single-point force in biomedical or mechanical filed, the new flat interlayer structure with cavum is brought forward and the flexible thin film single-point force sensor from PVDF film is firstly devised and fabricated, which is based on piezoelectric effect. Its total dimensions are 70 mm ×20 mm×1mm.Sensor output voltage increases with the increase of input force. New flat interlayer structure with cavum is firstly introduced to increase the PVDF deformation. And furthermore a conductive supporting rack is firstly introduced to build a cavum to expand the range of PVDF film's deformation. Such conductive supporting rack can dynamically conduct the signal caused from single-point force. Experiments illustrate that the flat interlayer structure with cavum is available in dynamically measuring single-point force. According to the previous experiment and analysis; it's known that the given sensor may realize the dynamic measurement of single-point force. But it is easily affected by small wave of ambient temperature because PVDF film also has pyroelectric effect. Generally speaking, the developed sensor could be fit for dynamic measurement of single-point force in biomedical or mechanical fields; and such sensor supplies a kind of new method for developing single-point force measurement equipment. The developed sensor is thin and flexible and flat and implantable.

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