Research on Cable Surface Condition Sensing Technology Based on High-Precision Array Flexible Sensing Units

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Abstract: This study introduces a novel cable surface condition sensing technology that employs a high-precision array of flexible sensing units to detect minor changes such as deformation, pressure, and damage on the cable surface in real-time. The manufacturing process of the flexible capacitive tactile sensors, including the preparation of PVDF films and the assembly of Ni-PU films, was elaborated. The experimental results demonstrated the sensor's rapid response and high sensitivity, meeting the requirements for cable surface state monitoring. The innovation of this paper lies in its comprehensive and real-time monitoring capability, which is crucial for early warning and health surveillance of cable damage, thereby enhancing the intelligent and detailed management of power systems. The original contribution is the application of flexible sensing arrays for early detection and health monitoring of cable damage, providing significant support for cable maintenance and replacement decisions.

Keywords: Cable Surface Condition; Flexible Sensing Units; High-Precision Monitoring; Intelligent Tactile Sensing

1. Introduction

With the acceleration of urbanization and the continuous expansion of power grid scale, cables, as an important medium for power transmission, have become particularly important for monitoring and assessing their operational status [1]. Traditional cable monitoring technologies mostly rely on regular manual inspections, a method that is not only inefficient but also difficult to achieve real-time monitoring of cable conditions [2]. Therefore, it is of significant importance to develop a technology capable of monitoring the surface condition of cables in real-time and with accuracy.

2. Technology Introduction

2.1 Overview of Flexible Sensing Technology

With the rapid development of flexible electronics, nanotechnology, and artificial intelligence technologies, new types of sensors have attracted increasing attention. Among them, flexible pressure sensors are particularly noteworthy, as they can effectively convert external physical signals into various forms of electrical signals [3]. Specifically, they can transform pressure signals into different types of sensor signals, such as piezoresistive, capacitive, triboelectric, and piezoelectric [4].

2.2 Sensor Fabrication Process

This paper describes the production process of flexible capacitive tactile sensor in detail, including the preparation of [5] of PVDF film, the cutting and packaging of Ni-PU film, which provides the process basis for the mass production of sensors.

(1) Put PVDF powder and N-methyl pyrrolidone (NMP) solution into a beaker according to the mass ratio of 1:10, at room temperature of 22℃, use ultrasonic washer ultrasonic shock for 40min, so that PVDF powder and NMP solution evenly mixed evenly for backup;

(2) The clean glass substrate is horizontally fixed on the rotating table of the homogenizer. Draw 1ml from the prepared mixed solution and drop it evenly on the glass substrate;

(3) Turn the glass sheet at a constant speed of 1000 r/min for 5s, so that the PVDF / NMP mixture is evenly coated on the surface of the glass sheet under the action of centrifugal force;

(4) Leave the PVDF film in step (3) at room temperature for 22℃ for 6h, then peel the PVDF film with a thickness of 40 μm and set aside;

(5) The PVDF film and conductive polyurethane sponge are cut to an appropriate

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size and packaged into a flexible capacitive tactile sensor with an area of 1.52cm2 and a total thickness of 0.65 mm;

(6) Different speeds can be set in step (3), such as 900,800,500 and 200 r/min respectively spin-coated PVDF films of 70,100,200 and 300 μm, then repeat steps (4) and steps (5), finally encapsulated into flexible capacitor tactile sensors with total thicknesses of 0.68,0.71,0.81 and 0.91 mm, respectively. The schematic diagram of the production process of the flexible capacitive tactile sensor is shown in Figure 1.

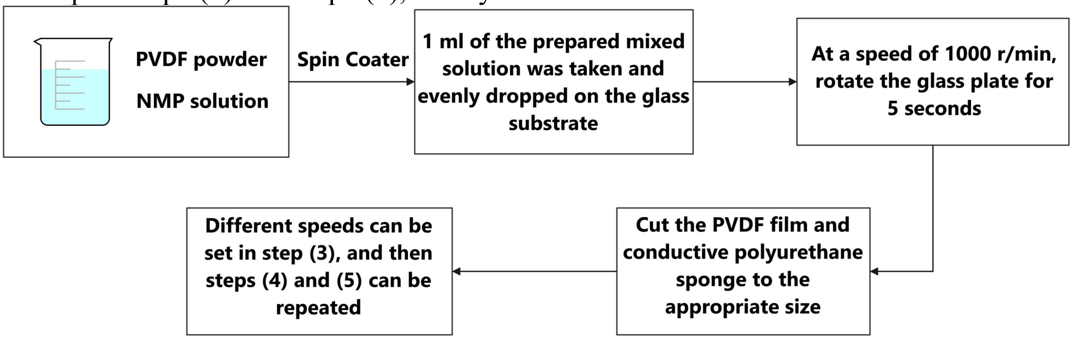

Figure 1. Fabrication Process of Flexible Capacitive Tactile Sensor

3. Experiments and Results

3.1 Normal Pressure and Bending Force Experimental Platform Setup

A normal pressure and bending force experimental platform [6] was set up for testing the sensing characteristics of flexible capacitive tactile sensors under normal pressure and bending force environments. The normal pressure experimental platform, as shown in Figure 2, is designed to generate normal pressures of different frequencies and magnitudes, and to collect the capacitive signals of the tactile sensor in real-time. First, the waveform parameters are set in the signal generator to produce the corresponding waveform signals, which are then transmitted to the power amplifier. After receiving the signal, the power amplifier amplifies the signal's power and converts it into a driving signal to drive the linear motor. The linear motor's end is fixed with a force sensor, and the pressure signal during the contact between the force sensor and the capacitive tactile sensor is transmitted to the pressure acquisition system via a 16-channel acquisition card. The capacitive signal of the flexible capacitive tactile sensor is collected in real-time by an LCR impedance meter. By recording and comparing the variation of the capacitive signal with the normal pressure signal in real-time, the sensing characteristics of the flexible capacitive tactile sensor are tested. The linear motor in the normal pressure experimental platform has an effective travel of 90 mm and can provide a maximum normal pressure of 100 kPa.

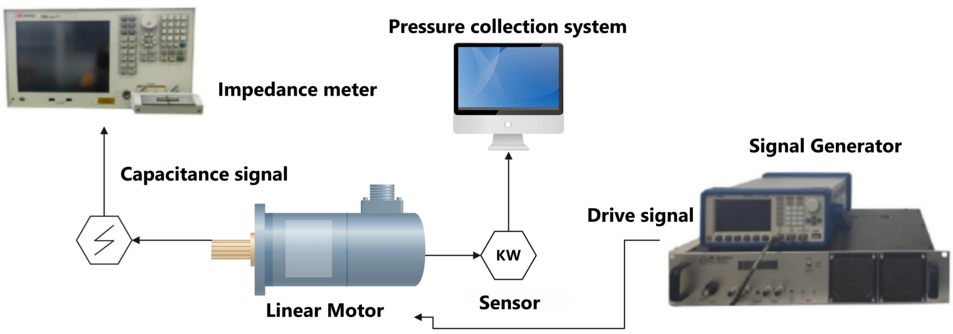

Figure 2. Test Process

3.2 Test Result Analysis

Response speed is an important parameter for measuring whether a flexible capacitive tactile sensor can obtain external information in real-time [7]. In this paper, a rapid touch and pressure was applied to the surface of the flexible capacitive tactile sensor with a finger, and a capacitive change cycle was selected to test the sensor's response speed. A stable capacitive response signal was obtained during the loading-unloading process by quickly pressing and then quickly removing the finger from the sensor surface. The results are shown in Figure 3. The change rate of the sensor when the finger touches it once is about 130%. When the sensor surface is rapidly pressed twice and three times, the response amplitude of the sensor is approximately consistent. This indicates that the sensor can respond quickly and accurately to multiple touches in a short time. The capacitive change waveform of the sensor during a single loading-unloading cycle was selected, and the results are shown in Figure 3. The sensor shows a short response time in a single loading-unloading cycle, which are 36 ms and 73 ms respectively, indicating that the sensor has a fast response speed and can obtain external information in real-time. The longer unloading recovery time is caused by the convex microstructures on the Ni-PU surface.

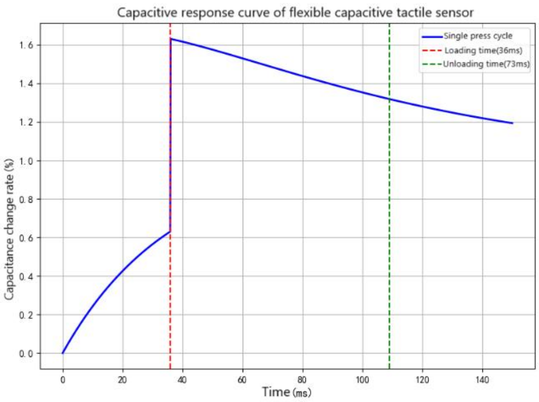

Figure 3. Test Results of the Flexible Capacitive Tactile Sensor

4. Cable Surface Condition Monitoring

In this paper, we use the sensors made above and establish the data-driven model [8], which uses the above sensors to predict the relative position variables of cable deformation and moving parts by using multi-sensor data. The advantage of this approach is that it avoids the complexity of traditional analytical modeling while also reducing the need for a deeper understanding of material properties. In terms of sensor selection, although fiber grating (FBG) sensors can detect signals such as deformation and pressure through optical wavelength measurement, they perform poorly in terms of stretching and have the challenge of real-time signal demodulation. Therefore, this paper uses a capacitive sensor, which is known for its high sensitivity (0.1 PF), stretchability (50%), and strong stability. The deformation-capacitance curves of the capacitive sensors show a high degree of linearity, which gives them a significant advantage in measurement accuracy.

To further illustrate the performance of the capacitive sensor, a diagram is provided, and the relationship between the shape variable and the capacitive value is shown in Figure 4. The horizontal axis represents the shape variable in mm (mm), ranging from 0 to 30, while the vertical axis represents the capacitance value in pifara (pF), ranging between 100 and 170. The blue points in the figure represent the sample data points collected in the experiment. Although these points are relatively scattered, they show an upward trend on the whole. The red fitted curves smoothly connect these data points, revealing a nonlinear relationship between the shape variables and the capacitance values. With the increase of the shape variable, the capacitance value first increases rapidly, and then the growth rate slows down until it approaches saturation. This trend is crucial for understanding the behavior of the material under different shape variables, helping to make more accurate predictions and optimization in the design and application.

Moreover, the high sensitivity and stretchability of capacitive sensors enable it to provide stable and reliable performance in various application scenarios. Their linearity and stability further enhance the accuracy of the prediction model, which is important for engineering and scientific research. With this data-driven approach, researchers are able to more effectively analyze and predict the relative positions of cable deformation and moving parts, thus enabling more efficient design and monitoring in materials science and engineering applications.

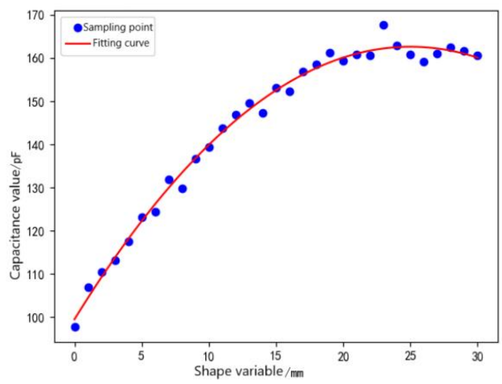

Figure 4. Sensor Strain Variable - Capacitance Value Relationship

At present, the measurement equipment of many flexible sensors is large and expensive, and even if the corresponding cheap supporting measurement circuit [9] is designed, its measurement circuit is generally rigid printed circuit board (PCB), and there is a strong sense of separation between the sensor and the measurement circuit. Therefore, this paper designs a flexible circuit board (FPC), combining the electrode with the measurement circuit into a whole. Figure 5 is the relevant dimensions of the sensor array. According to the drawing of the flexible sensor array of pressure sensitive component part, and the final product can be seen that the sensor is better flexible and can fit a more complex environment.

Figure 5. Sensor Finished Product Image

In order to observe the display effect of the sensor array, a program capable of displaying the magnitude and position of force was designed and developed based on Matlab. First, the lower-level machine collects pressure signals through pressure sensors and converts them into electrical signals, which are then transmitted to the upper-level machine via a Bluetooth module. The upper-level machine then converts these electrical signals into images.

In order to verify the stability of the sensor array and program [10], 20g of water bottle is placed on the sensor, and the result shows that the pressure part of the sensor, which means that the pressure sensor unit can detect the pressure and the spatial distribution of the sensor. Similarly, there is a small response around the water bottle, because the resistance sensor uses a whole, and when part of it is pressed, the entire sensor array creates crosstalk.

Currently, flexible sensing arrays are not used in sensing systems of a machines. However, from the preliminary test, the self-designed and flexible sensor array has the basic identification ability. In the subsequent research, the measured data needs to be more refined and complete the measurement task better from both qualitative and quantitative aspects.

5. Conclusion

The cable surface state sensing technology based on high-precision array flexible sensing units proposed in this paper has been experimentally verified for its effectiveness and accuracy in cable condition monitoring. The designed flexible capacitive tactile sensor has high sensitivity, fast response, and strong stretchability, enabling real-time detection of small pressure, deformation, and damage changes on the cable surface, meeting the high-precision requirements of the power system for cable condition monitoring. Compared with traditional monitoring methods, this technology has significant advantages in monitoring accuracy, real-time performance, and deployment flexibility, especially in early warning and health monitoring of cable damage, with a wide range of application prospects.

Through the effective integration and testing of the sensor array, this paper has proven its ability to achieve comprehensive perception and dynamic monitoring of cable conditions, providing strong support for the intelligent management of power systems. Future research will further optimize the layout scheme of the sensor array, enhance its adaptability and stability in complex environments, and explore more efficient data processing methods, promoting the transformation of this technology into practical applications, and aiding in the preventive maintenance and safe operation of power facilities.

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