Highly flexible ionic liquid capacitive sensor for aerodynamic pressure measurement

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Abstract

A flexible microfluidic super-capacitive pressure sensor is developed to measure the aerodynamic pressure on the surface of aircraft. The innovative sensor contains a filter paper filled with ionic liquid, and coated with two indium tin oxide polyethylene terephthalate (PET/ITO) films on the top and bottom, respectively. When external pressure applies on the top PET/ITO film of sensor mounted on the surface of aircraft, the capacitance between the two PET/ITO films will change due to deformation of top PET/ITO film. The external pressure will be determined according to the change of the capacitance. Comparing to traditional pressure sensor, the developed sensor provides a high sensitivity up to \(108.2 \text{ nF/Kpa}\) and rapid dynamic responses for pressure measurement. In addition, fabrication process of the proposed sensor is also developed.

1. Introduction

Typically, the measurement of the aerodynamic pressure distribution include three main methods: discrete pressure hole method [1-7], pressure sensitive coating technology (PSP) [8, 9] and computational fluid dynamic (CFD) [10-13]. So far, there are still many problems in the experimental measurements and theoretical analysis methods. The discrete pressure hole method is both mechanically complex and computationally intensive. Meanwhile the measurement hole also affect the aerodynamic shape of the aircraft [2]. PSP technique is a relatively new technique for measuring global aerodynamic pressure. However, the PSP technique can only used in wind tunnel experiments [8]. CFD simulation also has some disadvantages, such as that numerical calculation method will lead to distortion, resulting in a pseudo-physical conclusion [12, 13]. So it is of great importance to develop a new method to measure the real-time aerodynamic pressure acting on an aircraft in flight, which can further help us explore the aerodynamic shape possessing great properties [12].

Recent years have seen the rapid rise and development of flexible electronic sensors with a high degree of deformability and conformability, including piezoelectric, resistive and capacitive [14-22]. The capacitive sensors are arguably one of the most popular due to its long-term drift stability, high electrical sensitivity, low power
consumption, fast response time and simple device construction as compared to piezoelectric and resistive sensors [23-25]. An ionic skin through ionic hydrogel, developed by Suo [26, 27], can measure changes in strains from 1% to 500%, and pressure as low as 1KPa with small drift over many cycles. In addition, Pan et al have developed an ionic liquid sensor using ionic hydrogel as sensing medium to achieve ultra-high sensitivity and flexibility pressure measurement [25,28-30]. However, the fabrication procedure of hydrogel is complex and the phase transition of hydrogel at high temperature will lead to the sensor failure.

In the present study, a flexible ionic liquid super-capacitive sensor is developed to measurement the aerodynamic pressure. The fabrication process of the proposed sensor is given. Several experiments are carried out to illustrate the relationship between capacitance change and pressure.

2. Experimental

2.1 Materials and apparatus

In the course experiments, Advantec filter papers (No. 1, Toyo Roshi Kaisha., Ltd., Japan) were used. Ionic liquid 1-butyl-3-methylimidazolium bis-(trifluoromethyl) -imide (Shanghai Chengjie Chemical Co. Ltd.) was chosen as the sensing material. Polyethylene terephthalate (PET) coated with 100 nm thick layer of indium tin oxide (ITO, Mianyang prochema Commercial Co.) was used for electrode layer. A WK6500B (Shenzhen wenke Electronics Co., Ltd.) impedance analyzer was utilized for capacitance measuring. A KD-II 10/100 N (Shenzhen Kaiqiangli Technology Co., Ltd.) mechanical testing apparatus was used for precisely controlling the pressure applied on the sensor.

2.2. Sensor design and implementation

The flexible ionic liquid super-capacitive sensor contains a filter paper with a thickness of 0.15mm filled with ionic liquid, and two polyethylene terephthalate films, coated with a 100nm thick layer of indium-tin-oxide (PET/ITO), on the top and bottom of filter paper, respectively. The sensing chamber was fabricated by double-sided adhesive type. Figure 1 illustrates the fabrication process of the ionic liquid super-capacitive pressure sensor.
Figure 1. Schematic illustration of the fabrication of the flexible ionic liquid super-capacitive pressure sensor. (a) The naked PET/ITO film. (b) Double-sided adhesive type attached on the electrode to make a sensing chamber. (c) Transferring the ionic liquid filter paper to the sensing chamber. (d) Sealing the sensing chamber with another PET/ITO film.

In principle, the presented sensor is based on a deformability-dependent capacitance sensing mechanism as shown in Figure 2. Under external pressure, the PET/ITO film experiences a minute compressive deformation, and the capacitance between the two PET/ITO films will change due to deformation of the top PET/ITO film. The external pressure will be determined based on the change of the capacitance. As the top PET/ITO film contact with the ionic liquid paper immediately, the capacitance lies on the formation of an electrical double layer (EDL) resulting from electrons on the electrode and counter ions from the ionic liquid at nanoscopic distance.

Figure 2. Working mechanism of the flexible ionic liquid super-capacitive sensor. (a) The change of capacitance is 0 when no pressure applied on the sensor. (b) The capacitance changed follows the external pressure applied on the sensor.

3. Results and discussion
3.1 Device testing

For measurements, the pressure sensor was fixed at a acrylic plate. The force controlled by the mechanical testing apparatus was applied on a plate to make a uniformly pressure on the sensor. The pressure was calculated by dividing the force over the area of the membrane. When the external pressure applied on the sensor, the capacitance was detected by the impedance analyzer. We choose the driving frequency from 20 Hz to 1.5 KHz at 0.5 AC voltage. Figure 3 shows the capacitance change as a function of the driving frequency at 0 Pa and 10 KPa. The results show that the capacitance decreases with higher frequency and the capacitance has maximum change at 20 Hz. Considering energy consumption and actual measure situation, an 20 Hz driving frequency at 0.5 AC voltage was chosen for the testing mentioned hereafter.

![Figure 3. The capacitance changes with driving frequency sweep from 20Hz to 1.5 KHz at 0 Kpa and 10 Kpa.](image)

3.2 Pressure response

Figure 4(a) illustrates the capacitance changes with different pressures applied on the sensor, given the thickness of PET/ITO films at 50 µm and sensing area at 10mm * 10mm. As the mechanical testing apparatus applied pressure on the sensor, the capacitance of the sensor was measured by the impedance analyzer in real-time. Figure 4(a) shows the relationship between the capacitance change and the actual pressure applied on the sensor, and the slope rate was defined as the sensor sensitivity. It is clear that the capacitance change depends on the pressure, and the sensitivity increases first and then decrease with the increase pressure. The reason can be explained as follows. Firstly, when a pressure is below 7 KPa, the PET/ITO film does not contact with the ionic liquid filter paper, the capacitance increase according to the distance narrowing between top PET/ITO film and ionic liquid filter paper. The sensitivity is 1.5 nF/KPa, as shown in figure 4(a)-A. when the pressure is more than 7 KPa, the device sensitivity is 108.2 nF/KPa. Due to the elastic contact between the PET/ITO film and the ionic liquid
filter paper, an electrical double layer (EDL) as a huge capacitance is formed on the electrode and the counter ions from the ionic liquid at nanoscopic distance. Continue to increase the pressure, the sensitivity decreases due to the reduced mechanical deformation of the PET/ITO film in response to a large pressure which is caused by the small deformation limit has been exceeded.

The pressure sensor was also compressed repeatedly with a prescribe maximum pressure of 10KPa at frequency 0.05 Hz, while the capacitance and the pressure were recorded (Figure 4(b)). The capacitance-pressure curves were stable over 1000 cycles. As shown in previous results, the pressure of 10 KPa is enough to make the top PET/ITO film contact with the ionic liquid filter paper. It can be seen that once the pressure is applied on the sensor, the top PET/ITO film contact with the ionic liquid filter paper and the capacitance increase immediately. And when withdraw the pressure, the capacitance returning to the original value. Therefore, it can be concluded that the present sensor has a good response to the dynamic pressure.

![Figure 4](image)

**Figure 4.** (a) Relative rate of change in capacitance of the sensor as a function of different pressure. The inset shows that the relative rate of change in capacitance under low pressure. (b) The relationship of pressure and capacitance of the sensor cyclically compressed by 10 Kpa.

## 4. Conclusions

This study has developed a flexible super-capacitive sensor with a simple architecture and high sensitivity. The developed flexible sensor was tested at static and dynamic pressure and was aproved to have a good sensitivity, linearity and repeatability. Comparing to the traditional pressure sensor, the developed sensor can provide a high sensitivity (up to 108.2 nF/Kpa) and rapid dynamic responses for pressure measurement.

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