Design of readout circuit for high sampling miniaturized MEMS wall shear force sensor

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Abstract. Wall shear stress is one of the important measurement parameters in wind tunnel experiments. In the shock wind tunnel, the duration of the flow field is very short, usually a few milliseconds. To ensure measurement accuracy, the sampling rate should not be less than 1kHz. Due to the limitation of model volume and experimental environment, it is necessary to design a miniaturized readout circuit with high precision and high sampling rate, which is highly integrated with the MEMS wall shear stress sensor. The circuit includes a micro capacitance detection module integrated with the sensor head and a host computer signal processing and display module. Aiming at the complex measurement environment of the shock tunnel, to ensure the measurement accuracy, stability, and anti-interference ability of the weak capacitance detection circuit, a miniaturized ceramic substrate circuit is fabricated by a microstrip circuit process. The test results show that the resolution of the micro capacitance of the circuit can reach 20fF at the detection frequency of 3kHz, which can meet the measurement requirements of Shock tunnel, and realize the real-time measurement and display of wall shear stress signal.

1. Introduction
Wall shear stress is the viscous resistance produced by the fluid passing through the object's surface. It is an important physical quantity to evaluate the performance of any fluid engineering equipment and the distribution of surface friction. The measurement of high-precision wall shear stress has a wide range of applications in aerodynamic research [1], industrial process control, biomedicine [2], and other fields [3]. At present, there are three kinds of wall shear stress measurement technologies: oil film interference technology [4], liquid crystal coating technology, and sensor technology based on micromachining (MEMS) [5]. The first two are indirect measurement techniques, which need to be combined with other directly measured physical parameters to obtain the wall shear stress to be measured through indirect calculation. The sensor technology based on MEMS is a direct detection technology, which uses electrical and optical methods to detect the displacement of floating elements. The displacement is converted into a current or voltage that can be processed directly by a photoelectric conversion device, and its detection accuracy is high. According to different measurement principles, the shear stress sensors used for direct measurement can be divided into piezoresistive, capacitive, and optical types. Among them, capacitive sensors have the advantages of high sensitivity, strong overload capacity, good
dynamic response characteristics, and strong adaptability to harsh conditions such as high temperature, and radiation, so they are widely used [6].

At present, there is no mature experience and technology in the readout circuit design of capacitive MEMS wall shear stress sensors. Wang Xiong of China Aerodynamics Research and development center [7] designed a differential capacitive MEMS wall shear stress sensor. The measuring range of the sensor is 0 ~ 100Pa, the change of capacitance is 0 ~ 1pF and the resolution is 0.1Pa. However, the maximum detection frequency of the readout circuit of the above sensor can only reach 20Hz. For special measurement environments, such as shock tunnels, the duration of the flow field is very short, usually at the millisecond level, and the detection frequency of the sensor readout circuit can not meet the detection requirements of such scenes. To solve the above problems, a micro capacitance readout circuit that can work at the detection frequency of 3kHz is designed, which can realize the rapid measurement and graphical display of the signal of capacitive wall shear stress sensor, and the resolution of capacitance transformation can reach 20fF. The circuit has the characteristics of small size, high integration with the sensor head, and strong anti-interference ability.

2. Detection principle
The capacitive sensor is a capacitor with variable parameters. Its capacitance changes very little, Usually at the pF level. The internal capacitance of MEMS differential capacitive wall shear stress sensor is a "pendulum" differential capacitance, and the internal structure of the sensor head is shown in Figure 1.

![Figure 1. (a)Differential capacitance detection principle. (b)Integral header structure.](image_url)

The grounded plates act as the fixing plates of the capacitance. When no external force is applied, the upper and lower plates are parallel and in a balanced state, $C_1=C_2$. When the fluid flows through the surface of the flat plate, the shear stress generated will cause the capacitive plate to offset on the floating head, which will cause the $C_1$ and $C_2$ capacitance values to change simultaneously. Using capacitance difference $\Delta C$ to calculate the wall shear stress measured by the sensor.

In the application of shock tunnel, the measurement frequency of the sensor usually reaches more than kHz (the duration of the flow field is usually tens of milliseconds). Pcap01 micro capacitance detection chip is a highly integrated capacitance digital conversion chip with the data processing unit. It adopts the measurement principle of a high-resolution time digital converter [8]. Its measurement principle diagram is shown in Figure 2, which can realize the detection of single capacitance and differential capacitance of pF order. Its highest detection frequency can reach 500KHz.
Figure 2. Pcap01 internal measurement schematic diagram.

From the figure above, it can be seen that the reference capacitance \( C_{\text{REF2}} \) and the capacitance \( C_1 \) to be measured are connected to the same discharge resistance to form the RC charging and discharging circuit. Four different resistance values are provided here, and the appropriate discharge resistance is chosen according to the maximum capacitance value in the design. There are four switches. Switches PC0 and PC1 are responsible for controlling whether capacitance is connected, while switches \( S_{\text{CHG}} \) and \( S_{\text{DISCH}} \) control charging and discharging. During measurement, the reference capacitance and the capacitance to be measured are charged to the voltage \( V_{dd} \) of the power supply, then discharged to the threshold voltage \( V_{th} \) by the discharge resistance, and then recharged, repeatedly. The discharging time is recorded by the time digital converter TDC inside the chip [9][11].

Since the reference capacitance \( C_{\text{REF2}} \) and the capacitance \( C_1 \) to be measured are discharged by the same discharge resistance, the ratio of \( C_{\text{REF2}} \) to \( C_1 \) can be calculated by discharging time \( t_0 \) and \( t \) of the two capacitors, and formula 1 is as follows:

\[
\frac{t}{t_0} = \frac{C_1}{C_{\text{REF2}}} \rightarrow C_1 = C_{\text{REF2}} \frac{t}{t_0}
\]

The final output value of Pcap01 is the discharge time ratio of 24bit (unsigned fixed point number with 3-bit integer and 21-bit decimal), which needs to be converted to decimal decimal (divided by \( 2^{21} \)) multiplied by the reference capacitance value to reach the final capacitance value to be measured, as shown in Formula 2.

\[
C_1 = \left( \frac{C_1}{2^{21}} \right) \cdot C_{\text{REF2}}
\]

The \( C_1 \) is the ratio output of Pcap01.

3. Hardware circuit design

The hardware circuit takes the Pcap01 chip and its peripheral circuit as the design core detects the differential capacitance at the same time, collects the capacitance change value in real-time, and outputs the corresponding digital signal through internal conversion. PC0 port of Pcap01 connects reference capacitance, PC1, PC2 port connects differential capacitance to be measured, the peripheral connection of micro-decoupling bypass capacitance reduces noise interference and establishes a connection with a single-chip computer through 4-line hardware SPI communication mode. Its communication bus frequency can reach 24MHz, which ensures the complete and high-speed transmission of measurement data.

ARM Cortex-M4 32-bit core STM32F411CEU6 single-chip computer is selected as the core controller. Its working frequency can reach up to 100 kHz. It is responsible for controlling the working state of Pcap01 and receiving the real-time captured capacitance scale value of Pcap01 and sending the collected value to the upper computer for subsequent processing.

Aiming at the complex environment of shock tunnel, to ensure the measurement accuracy, stability, and anti-interference ability of weak capacitance detection circuit, a miniaturized ceramic substrate circuit is fabricated by microstrip circuit process. The overall size of the hardware circuit is 2.1cm ×
1.6cm, which can be highly integrated with the sensor head. The schematic diagram of the overall readout circuit and the circuit diagram of the ceramic substrate is shown in Figure 3 and Figure 4.

Figure 3. Schematic diagram of readout circuit

Figure 4. Ceramic physical circuit

When designing a hardware circuit, the selected capacitance value is as close as possible to the measured capacitance. Because the measured capacitance value is the product of the capacitance ratio and the reference capacitance value, it is very important to select a high precision reference capacitance for the detection performance of the circuit. The difference capacitance to be measured is about 8pF. Therefore, the readout circuit is selected with a size of 7.5pF, and the capacitance precision error is less than 0.05pF. In addition to the reference capacitance being a necessary design consideration, it is also important to note that the parasitic capacitance at the micro-capacitance input is as small as possible and that the line between the measured capacitance and the input port of the reference capacitance distance detection chip needs to be short enough [12].

4. Software Design

The software design of the readout circuit includes the readout circuit software control program based on C language and the LabVIEW upper computer program of graphical programming. The software design flow chart of the readout circuit is shown in Figure 5.
Finally, the capacitance measurement value should be displayed in real-time on the upper computer (PC) and processed in the follow-up, and the follow-up design should be completed by using LabVIEW. Through the design of the visa communication module in the LabVIEW acquisition system, good communication with the sensor readout circuit is established. After receiving the capacitance ratio sent by the single-chip microcomputer, the upper computer obtains the capacitance value to be measured through the data processing operation through the above formula 2, and finally displays it through the real-time graphical curve on the front panel, and can save the measured capacitance value as an excel file for subsequent data processing. The upper computer test interface is shown in Figure 6.

![Figure 6. Upper computer measurement display interface.](image)

5. Measurement experiment and analysis

5.1. Readout circuit precision experiment

After the overall design of the interface circuit is completed, the ceramic circuit is integrated with the sensor head to measure the output of the sensor under no-load conditions. Under the condition of different sampling frequencies, the capacitance acquisition value is obtained from the Excel data file saved by the upper computer, as shown in Figure 7. The measurement results show that under the detection frequencies of 1kHz, 2KHz, 3kHz, and 4kHz, the static differential capacitance output by the interface circuit is 0.013pF, 0.016pF, 0.02pF, and 0.035pF respectively. Through conversion, the resolution of the corresponding minimum wall shear stress at the detection frequency of 1 ~ 4kHz is about 10Pa, 16Pa, 21Pa, and 30Pa respectively.

![Figure 7. Static differential capacitance measurements at different detection frequencies.](image)

As the detection frequency increases, the resolution of the readout circuit to the micro capacitor becomes worse. The relationship between the resolution of the unloaded capacitor under different detection frequencies is shown in Figure8. For measurement scenes such as shock tunnels, the experimental time is very short, usually from a few milliseconds to tens of milliseconds. To ensure the measurement accuracy of experimental data, the sampling frequency should not be less than 1kHz (the resolution is about 10fF).
Combined with the requirements of the shock wind tunnel experiment, to obtain more sampling data (at least 3 groups of measurement values need to be obtained within 1 millisecond), the measurement error is reduced. The detection frequency of the readout circuit is determined to be 3kHz. At this detection frequency, the resolution of the readout circuit to the micro capacitor is about 20fF.

![Figure 8. Relationship between different detection frequencies and resolution.](image)

5.2. **Output characteristic experiment of MEMS Capacitive wall shear stress sensor**

After the readout circuit is assembled with other parts of the sensor, the working performance of the readout circuit is tested by using the static calibration device of the wall shear stress sensor. Fix the sensor on the turntable of the centrifuge and simulate the wall shear stress through the centrifugal force in the vacuum environment, as shown in Figure 9. The effect of changing the wall shear stress can be simulated by controlling the speed. The experimental test data are shown in Figure 10.

![Figure 9. Performance test diagram of wall shear stress sensor.](image)

![Figure 10. Performance test curve of interface circuit.](image)

It can be seen from the above figure that the wall shear stress increases with the increase of rotating speed, and the capacitance difference also increases accordingly. The curve steps in the figure are obvious and stable, and each independent step corresponds to a corresponding wall shear stress, which further verifies the practical measurement feasibility of the readout circuit. Through calculation, the
resolution of the readout circuit to the micro capacitance is about 20fF at the sampling frequency of 3kHz. At this time, the resolution of the MEMS capacitive sensor to the wall shear stress is about 20Pa (the shear stress range of the shock wind tunnel is usually 100 ~ 1500Pa). In the later stage, the resolution of shear stress can be further improved by optimizing the design of the sensor head.

6. Conclusion

The readout circuit of MEMS Capacitive wall shear stress sensor based on pcap01 capacitance detection chip is designed, and the integrated package of readout circuit and header structure is realized, which can be used for the measurement of model wall shear stress with high precision and high sampling frequency in a shock tunnel. The readout circuit has the characteristics of small volume, high integration, and strong anti-interference ability. Under the detection frequency of 3kHz, the resolution of the readout circuit to the micro capacitor can reach 20fF.

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