Development of a Strain Sensor using an Oscillator Circuit*

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(Received November 26th, 2013)

A new type of strain sensor using a CMOS inverter oscillator circuit has been developed. This sensor does not require an amplifier because a counting device measures the frequency changes in the circuit voltage output caused by the resistance changes in the strain gauge. The characteristics and measurement accuracy of the sensor that consists of an oscillator circuit and a strain gauge are confirmed by static tensile tests of specimens. The test results reveal that the same level of accuracy as that of a conventional sensor is achieved by using a simple compensation factor assuming the existence of an internal resistance on the circuit.

Key Words: Strain, Oscillator Circuit, Wheatstone Bridge

1. Introduction

The measurement of structural strain is an essential part in development and operation phases, and it is performed in various fields. In the field of aviation, strain is measured in airframe development tests such as material tests, static strength tests and fatigue tests. Sensor systems combining strain gauges and Wheatstone bridge circuits are widely used for strain measurement1) (Fig. 1). These devices measure strain by capturing resistance changes in the strain gauge attached to a structure upon a change in the voltage of the Wheatstone bridge circuit. These sensors excel in terms of reliability, accuracy and cost, and have a performance record of many years. On the other hand, strain gauges require wiring to a Wheatstone bridge circuit and an amplifier, and large-scale strain measurement (extending to thousands of points in aircraft development testing) requires an enormous amount of effort to set up. The existence of wiring also significantly restricts the measurements of movable structures such as rotors. The reasons that make it difficult to develop wireless sensors include the fact that the requirements of amplifiers, A/D converters and low-pass filters for the amplification of the microvoltage changes in the Wheatstone bridge circuit makes miniaturization difficult and reduces the benefits of making wireless sensors. Sensor systems with an amplifier and a power supply that perform wireless transmission of measured strain data also exist,2–7) but these are difficult to miniaturize and cannot solve the problems and restrictions of large-scale strain measurement or the measurement of movable structures. On the other hand, a measurement system has been developed8) to achieve a simple wireless system through the application of an oscillator circuit. This is a method that uses a specimen as a capacitor and measures the strain through changes in capacitor capacitance.

However, because of the specimen constraints, the strain measurement accuracy is not verified. If strain measurement is possible with a wireless system, it is not only extremely easy to set it up for large-scale strain measurements, but it also facilitates the application to, for instance, the strain measurement of movable structures and that inside pressure containers, thus substantially extending the range of application.

For the present study, a measurement sensor (Fig. 2) with few specimen constraints is developed9,10) negating the need for an amplifier by combining a strain gauge and a CMOS inverter oscillator circuit, and its strain measurement accuracy is verified. This sensor uses a method where changes in resistance in the strain gauge when strain develops in an object are captured through frequency changes in the oscillator circuit. With this method, a pulse counter is required to measure frequency changes, but as the circuit configuration of a CMOS inverter oscillator circuit is simple and no amplifier is used, an A/D converter or low-pass filter is required, and the simplification and miniaturization of the sensor system becomes possible. The present measurement sensor is therefore extremely promising for the creation of wireless systems in the near future. Another benefit is that the pulse counter design is considerably simpler than the design of an A/D converter and a low-pass filter.

We first developed a sensor combining a semiconductor strain gauge and a CMOS inverter oscillator circuit and confirmed the sensor’s functionality. A semiconductor strain gauge is used because of its high gauge factor. The resistance change and the changes in the frequency output increase when the gauge factor is high, and thus, the resolution increases. On the other hand, semiconductor strain gauges
have issues such as their high temperature dependence, narrow measured strain range, and high price, which are considerable shortcomings in comparison to generic strain gauges (resistance wire strain gauges). From the perspective of practical application, generic strain gauges, although they have a low gauge factor, are convenient. Therefore, we subsequently developed a strain gauge applying a generic strain gauge and evaluated the sensor performance. In this paper, we report the results of this evaluation and those of strain sensors using a semiconductor strain gauge.

2. Strain Sensor using an Oscillator Circuit

With the newly developed sensor, changes in resistance through strain are measured as changes in oscillating frequency in the oscillator circuit. Here, we outline the principles of the proposed strain gauge.

2.1. Circuit and oscillating frequency

Circuits that have two states, Hi and Lo, are termed multivibrators, and they can be divided into three types depending on the number of stable states (i.e., states that are maintained as long as there is no external input), namely astable, monostable and bistable multivibrators. The astable multivibrator has no stable state, and is a circuit that, even when there is no specific external input, switches between two states. The fact that no external input is required makes the astable multivibrator a suitable circuit for the strain gauge developed in the present study. Various types of astable multivibrators exist, but we have opted for the CMOS inverter oscillator circuit,\(^{11}\) which has a comparatively simple circuit as well as a highly stable oscillating frequency. Figure 3 represents the circuit diagram for the CMOS inverter oscillator circuit. A circuit consists in principle of two CMOS converters, one capacitor and one resistor. When the oscillator circuit is activated, the voltage output that changes at a constant frequency can be obtained as the output. Here, we discuss the oscillating frequency for the CMOS inverter oscillator circuit. State transitions for the oscillator circuit are as illustrated in Fig. 4, and as state transitions are “initial state → state 1 → state 2 → state 1 → state 2 ...” when voltage is applied to the circuit, the circuit output oscillates through the repetition of states 1 and 2. Figure 4 shows each state immediately following the transition. Figure 5 shows the output waveforms for the oscillator circuit. If the oscillator circuit resistance value is \(R\); capacitor capacitance, \(C\); the CMOS inverter threshold voltage, \(V_{th}\); and the applied voltage, \(E\), then the stored charge in the capacitor \(q\) is expressed by the following equation.

\[
q(t) = CE - Ze^{\frac{1}{C}}
\]

\[Z\] denotes the coefficient determined under the initial conditions. Because \(q(0) = 0\) is in the initial state, it follows that \(Z = CE\).

\[
q(t) = CE\left(1 - e^{\frac{1}{C}}\right)
\]

As the charge is stored in the capacitor, the voltage potential difference in the capacitor increases, and therefore, the input voltage in the CMOS inverter 1 drops. When the input volt-

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[Fig. 1. Strain gauge (bridge circuit).]

[Fig. 2. Strain gauge (oscillator circuit).]

[Fig. 3. CMOS inverter (oscillator circuit).]

[Fig. 4. Oscillator circuit (state transitions).]
The voltage potential difference between the resistor terminals is \( E - V_{th} \), and the following equation is derived.

\[
V_{th} = (E + V_{th})e^{\frac{q}{CR}}
\]

Consequently, the time taken for the transition from state 2 to state 1 can be obtained.

\[
t_{2 \rightarrow 1} = -CR \ln \frac{V_{th}}{E + V_{th}}
\]

Therefore, the oscillating frequency of the CMOS inverter oscillator circuit can be expressed with the following equation.

\[
f = \frac{1}{t_{1 \rightarrow 2} + t_{2 \rightarrow 1}} = \frac{1}{CR \left[ \ln \left( \frac{2E - V_{th}}{E - V_{th}} \right) + \ln \left( \frac{E + V_{th}}{V_{th}} \right) \right]}
\]

### 2.2. Strain measurement methods

Strain sensors make use of the characteristic that when the resistance elements in a CMOS inverter oscillator circuit are replaced with a strain gauge and the resistance values change, the oscillating frequency calculated in Eq. (11) changes.

We outline the relationship between the amount of frequency change in the oscillator circuit and the strain. If in Eq. (11), the capacitor capacitance, applied voltage and the threshold voltage are constant the following equation is easily derived. Further, it is found that product \( A \) of the resistance and the frequency is constant.

\[
R \times f = A
\]

When a strain gauge is applied to the resistance, strain \( \varepsilon \) and resistance value change \( \Delta R \) can be expressed with the following equation using gauge factor \( K \) and gauge resistance value \( R \).

\[
\frac{\Delta R}{R} = K\varepsilon
\]

The relationship between the oscillator circuit frequency change \( \Delta f \) and strain can be obtained from the following equation from Eqs. (12) and (13) if the second-order terms are ignored.

\[
\varepsilon = -\frac{\Delta f}{K \cdot f}
\]

In other words, if a strain gauge can be affixed to the object to be measured, and the amount of change in the oscillating frequency in the oscillator circuit can be measured, then this can be converted into a strain value using Eq. (14).

### 3. Strain Sensor Properties

#### 3.1. Specimen and strain measurement test

A static tensile test is performed to confirm strain gauge behavior and examine the measurement accuracy. The specimens are an A2024-T351 sheet conforming to ASTM
E8M-04, with a semiconductor strain gauge for use in oscillator circuits affixed at the back in the center, and for the sake of comparison, a generic strain gauge for use in Wheatstone bridge circuits (Fig. 6). As the considered semiconductor strain gauge is normally used for measuring microstrain, the strain limit (the point where the strain error exceeds 10%) is 0.3% at room temperature, the gauge factor is $K = 166$, and the resistance value is approximately 1 kΩ. For the generic strain gauge, the gauge factor is $K = 2.07$ and the resistance value is 120 kΩ. The reason for using the abovementioned semiconductor strain gauge is the high level of frequency change that can be obtained. It is self-evident from Eq. (14) that, with the same amount of strain, the frequency change increases as the gauge factor increases. A K-type thermocouple for measuring temperature is affixed to the front of the specimen, but as the semiconductor strain gauge is likely to be affected by temperature, this is to monitor the specimen temperature.

Using a 100-kN servohydraulic load frame, we increase the tensile load on the specimen in 1-kN increments during the test (load increase speed: 1 kN/6 s); further, for each load, we measure the output frequency of the oscillator circuit with a frequency counter (Fig. 7) while measuring the strain with a Wheatstone bridge circuit. The specimen is placed on each chuck within the environmental chamber under controllable temperatures (we will touch upon the subject of temperature later). Figure 8 shows the experimental setup. The strain gauge in the photograph is an example of the several types of sensors that were developed.

3.2. Test results

Figure 9 shows the relationship between the frequency output by the oscillator circuit at room temperature and the strain in a bridge circuit. It shows that the oscillating frequency changes through the changes in strain and that the oscillator circuit is functioning. Figure 10 shows a graph comparing results where these data have been converted to physical quantities on the basis of Eq. (14) with the strain measurement results using a bridge circuit. Although the strain measurements through a bridge circuit have a comparatively high accuracy and the accuracy is high for the range of these strain values, merely converting the oscillator circuit output into physical quantities results, as can be seen from the graph, in differences of more than two times the strain values and in substantially decreased accuracy.
4. Error Cause and Corrected Measurement Results

4.1. Impact of circuit temperature
It was speculated that a possible cause for the poor accuracy is the fact that the temperature increases because of the heat generated by the continuously operating circuit and that the properties of the elements of, for instance, the CMOS inverter change. Therefore, to examine the effect of the circuit temperature, we performed a test by fixing a thermocouple to the circuit board and increasing the circuit board temperature to 65 degrees by using the environmental chamber (the temperature of the specimen at this point was approximately 50 degrees). Furthermore, to differentiate between the temperature impact of the strain gauge and the temperature impact of the circuit board, only the specimen is set at approximately 50 degrees, and the test is performed with the circuit board at room temperature. The measurement results are shown in Fig. 11, and the strain measurement results show hardly any discrepancy in the output between the specimen at room temperature and that at 50 degrees. Further, there is no impact of the temperature of the strain gauge. On the other hand, when the circuit board temperature is set at 65 degrees, some effect on the strain values is observed. However, compared with the substantial strain errors for the bridge circuit and the oscillator circuit, this impact is low. Moreover, the heat generated by the circuit board does not cause the errors.

4.2. Impact of the sensor’s internal resistance
As another cause for the error, we speculated that the sensor’s internal resistance may have a large impact. For instance, the resistance of the lead wires of the strain gauge or of the terminals that connect the lead wires to the circuit acts as the internal resistance. Therefore, we investigated the effects of the internal resistance on the measurement results. As outlined previously, product $A$ of the resistance and the frequency in Eq. (12) is constant. However, in addition to the strain gauge resistance $R_{\text{gauge}}$, we consider the internal resistance $R_{\text{internal}}$. Therefore, the overall strain value $R$ is calculated according to the following equation.

$$R = R_{\text{gauge}} + R_{\text{internal}}$$  \hfill (15)

Then, when substituting Eq. (15) for Eq. (12), product $A'$ of the gauge resistance and the output frequency is obtained as follows.

$$A' = R_{\text{gauge}} \times f = A - R_{\text{internal}} \times f$$  \hfill (16)

It is clear from this that when internal resistance exists, $A'$ is a linear function of the frequency. Figure 12 shows the results obtained for $A$ values by actually connecting 19 types of fixed resistors from 0.6 to 1.5 kΩ to the oscillator circuit and measuring the output frequency. If no internal resistance exists, the $A$ values are independent of frequency and are constant, but the test results indicate that they are a linear function of frequency and that when internal resistance exists, the measurement results are affected.

4.3. Impact of other circuit properties
The parasitic capacitance and the parasitic inductance existing in the circuit also impact the output frequency and are possible causes of error. However, as mentioned earlier, the impact of the internal resistance is thought to be particularly significant on the present circuit.

4.4. Correction methods and correction results
Internal resistance, parasitic capacitance, and parasitic inductance vary for each circuit board and are affected by temperature. Internal resistance considerably impacts the present circuit, and under constant environmental conditions for the same circuit board, $A$ is a linear function of frequency. To obtain the linear function data for making corrections immediately before the strain measurement, three types of fixed resistors ($R = 817, 998, 1196 \Omega$) are embedded beforehand in the strain sensor circuit board, and a mechanism was set up that allows for its exchange with a strain gauge. Using this mechanism, we measured the oscillating frequency for each fixed transistor immediately before taking the present measurements. Further, from this relationship between the resistance value and the oscillating frequency, the linear function is obtained with the least squares method, and $A$ is corrected and converted into strain. The strain values thus obtained with this correction method are shown in Fig. 13. Accuracy is found to have improved substantially through this correction, and the results are in no way inferior to the values obtained from the bridge circuit.
5. Application of a Generic Strain Gauge

Although semiconductor strain gauges have the benefit of a high gauge factor, they are used for particular applications and have issues such as high temperature dependence and a narrow measured strain range. The ability to apply a generic strain gauge to a strain sensor is desirable for the implementation of the sensor. Therefore, we perform a strain measurement test by changing the oscillator circuit capacitor capacitance and the fixed resistors for use in corrections to the generic strain gauge resistance values (approximately 120 Ω). The test is performed with the same method as described earlier, and for both a generic strain gauge and a semiconductor strain gauge, the test is performed up to 23 kN; i.e., near the elastic strain limit.

The test results with a generic strain gauge applied to the oscillator circuit are shown in Fig. 14. During the conversion of the measured oscillating frequency into strain, strain values varied significantly from the bridge circuit, but by using the correction method outlined in the previous section, we obtained almost identical values to the strain values from a bridge circuit. However, it is found that where the load exceeded 13 kN, the linearity deteriorated slightly and some errors occurred. The cause for this is thought to be the fact that because of a low gauge factor, the frequency change to strain is small and a noise impact is likely. In particular, as a current that vibrates with the oscillating frequency flows in the 2-m lead wire connecting the oscillator circuit and the strain gauge, it is found that a function as an antenna is likely to be impacted by noise and affects the oscillating frequency if the lead wire is near any electronic equipment such as a computer.

The measurement results obtained using a semiconductor strain gauge applied to the oscillator circuit are shown in Fig. 15. It is confirmed that although the post-correction results match well with the bridge circuit results of up to approximately 3,000 με (0.3% strain), the error increases when the strain increases further, and the semiconductor strain gauge properties are reflected unchanged in the measurement results.

6. Conclusion

We developed a strain sensor without the need for an amplifier, using an oscillator circuit. The results of the strain values obtained by measuring the oscillating frequency through tensile tests combining a semiconductor strain gauge and an oscillator circuit were found to be substantially different from strain values obtained using a Wheatstone bridge circuit. The verification of the cause for this phenomenon was found to be the following: The impact of temperature on the strain gauge and the circuit board was low and there was a high possibility of an impact of circuit property measurements (particularly internal resistance). Taking circuit properties into account, corrections were carried out for the measurement results, and it was found that these results were in no way inferior to those acquired using a bridge circuit.

Semiconductor strain gauges have a high gauge factor but have the problem of a high temperature dependence and a narrow measured strain range. Therefore, we developed a strain sensor that applies a generic strain gauge to the oscillator circuit. The test results showed that by applying corrections in the same way to a semiconductor strain gauge, virtually identical values can be obtained as the results...
acquired through a bridge circuit. Further, we ascertained that, as the strain limit is higher than for a semiconductor gauge, higher strains can be measured with good accuracy. On the other hand, it was found that because of the low gauge factor, frequency changes through strain changes were small and easily affected by noise. One cause for the noise is the susceptibility to the surrounding noise of the lead wire from the strain gauge to the oscillator circuit. However, the strain sensor using an oscillator circuit developed in the present study can be miniaturized because of its simple circuit configuration. Therefore, an integration of the strain gauge and the circuit will make lead wires unnecessary, and hence, the impact of noise will decrease.

As the efficacy of the strain gauge with an oscillator circuit has been confirmed, and aiming at future implementation, we plan to study further not only miniaturization and the realization of a wireless system but also how to enable a stable and highly accurate measurement in any environment as well as methods to eliminate and correct the effect of noise. In particular, we intend to study correction methods, taking not only the effect of internal resistance but also that of parasite capacitance and parasite inductance into consideration for more accurate corrections.

Acknowledgments

Part of this study was carried out using a Grant-in-Aid for Scientific Research (C) (22560705).

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