SUMMARY We present a smart steering wheel that detects the gripping position and area, as well as the distance to the approaching driver’s hands by measuring the resonant frequency and its resistance value in an LCR circuit composed of the floating capacitance between the gripping hand and the electrode of the steering, and the body resistance. The resonant frequency measurement provides a high sensitivity that enables the estimation of the distance to the approaching hand, the gripping area of a gloved hand, and for covering the steering surface with any type of insulating material. This system can be applied for drowsiness detection, driving technique improvements, and for customization of the driving settings.

key words: drowsiness detection, gripping position, gripping area, body resistance, driving position

1. Introduction

Various types of sensors are being developed to detect driver drowsiness because it is a major cause of accidents. The steering wheel in a vehicle is important for detecting a driver’s conditions because the driver is always gripping the steering wheel, while driving. If a sensor can detect the location on the steering wheel that the driver is gripping or is going to grip and the tightness of the driver’s grip, this information can reveal the level of the driver’s fatigue and the car can alert the driver to wake up. In addition, the data can be used for improving driving techniques, for learning safe driving, and for customizing the driving settings of the car.

We have developed a sensing system that can detect these driver’s motions on the steering wheel by employing a capacitive touch sensing technology that has been developed in the field of touch panels. Capacitive touch sensing is a cost-effective and easy-to-install technology. In this study, we have developed a special detection circuit based on a technique called swept frequency capacitive sensing (SFCS), proposed by Sato [1]. A similar detection system was proposed by Hu using the high-Q oscillation of the installed inductor as a 3D gesture-sensing system [2]. The circuit developed by us has a TX/RX system combined with an SFCS that enables the steering wheel to detect the driving motion sensitively.

2. Sensing Principle

Figure 1 shows the schematic view of the electrodes installed on a steering handle and its equivalent circuit. The two electrodes, TX and RX, are covered with a thin insulator layer. By employing TX/RX structure, we can obtain not only a capacitance value, but also a skin resistance value.

These electrodes are connected electrically with a mutual capacitance, $C_m$ and a leakage resistance, $R_l$, by placing them close to each other. When a driver grips the steering handle with the TX and the RX, floating capacitances, $C_{f, TX}$ and $C_{f, RX}$, are created by the electrodes, respectively. In addition, the skin resistance, $R_s$, of the driver’s hand is also to be taken into account [2], [3]. A frequency-scanned sine-wave voltage is applied to the TX through the inductor, $L$ and the displacement current from the RX to the ground is measured. The total impedance, $Z$, is defined as the value of the sine-wave voltage divided by the obtained AC current.

Figure 2 illustrates the spectrum of the absolute value of $Z$ that has a minimum value owing to the LC resonance. When the steering has no grip, resonance occurs owing to $C_m$. The resonant frequency is given by the following equation:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{R_l^2 C_m - L}{R_l^2 C_m^2 L}},$$

and the impedance value is given by:

$$Z_{\text{min}} = \frac{L}{C_m} \frac{1}{R_i}.$$

Fig. 1  Schematic view of the steering sensor and the basic equivalent circuit of touch sensing system.
When the driver grips the steering or his/her hand approaches the steering, floating capacitances $C_{f,tx}$ and $C_{f,rx}$ are created resulting in the shift of $f_r$ to a lower frequency according to the following equations:

$$f_r = \frac{1}{2\pi \sqrt{\frac{1}{C_f L}}}.$$  \hspace{1cm} (3)

where $C_f$ is given by

$$C_f = \frac{C_{f,tx} C_{f,rx}}{C_{f,tx} + C_{f,rx}},$$  \hspace{1cm} (4)

and the impedance value is given by:

$$Z_{\text{min}} = \frac{1}{R_s},$$  \hspace{1cm} (5)

under the conditions where the current mainly follows through the $R_s$ path.

When the steering is gripped more tightly, $C_f$ value increases because the contacting area to the electrodes increases, so that, $f_r$ shifts to a lower frequency.

But in an actual circuit, we should consider the current which flows into a body. Figure 3 shows the actual equivalent circuit taking the current into account. We assumed the body has a resistance, $R_b$, and is connected to the ground with the parasitic capacitance, $C_p$, which is usually large enough not to be neglected even if the ground is placed near the body because the human body has huge surface.

3. System Setup

Figure 4 shows the images of our sensing system installed on a steering wheel. One electrode for the RX and four elec-

![Fig. 2](image1)

Fig. 2 Spectrum of the circuit impedance

![Fig. 3](image2)

Fig. 3 Equivalent circuit of the touch sensing system on the steering

![Fig. 4](image3)

(a) (b)

Fig. 4 Pictures of the steering wheel with the embedded frequency-scan touch sensing system

![Fig. 5](image4)

Fig. 5 Block diagram of the entire system
trodes for the TX were placed on the handle as shown in Fig. 4(a). A conductive tape composed of urethane film, silver paste, and adhesive was employed for the TX and RX electrodes with a width of 1 cm and a space of 2 mm. A custom designed PCB was installed at the center of the wheel as shown in Fig. 4(b).

Figure 5 shows the block diagram of the sensing system. A frequency-scanned sine-wave voltage is applied sequentially to the TX, revealing the position of the hands gripping the wheel. The voltage to the TX is applied by a programmable frequency scanning waveform generator (Analog Devices Co., AD5932) that scans from 1–3 MHz in frequency. A 4:1 analog multiplexer, aMux, for scanning the TX is introduced before the resonant inductor, \( L \), to reduce the effect of the parasitic capacitance in the multiplexer. The sine-wave current from the RX is transformed to voltage with a current-voltage amplifier, \( I/V \) and its amplitude is detected by an envelope detector. Then, the amplitude change is read by an analog-digital converter, A/D, in a microcomputer, (Microchip Co., dsPIC30F3013) that controls the wave generator and sends the data to a Bluetooth® chip. The data are then transferred to PC in real time with the Bluetooth® technology by wireless and processed by a software in the PC.

4. Results

4.1 Change of \( Z_{\text{min}} \) and \( f_r \)

The results obtained with our system are shown in Fig. 6 by the approach of the hand to the steering and by increasing the gripping area. The simulation results were obtained from an analog circuit simulation on the circuit shown in Fig. 3, using the parameters in Table 1 and changing the values of \( C_{f,TX} \) and \( C_{f,RX} \), equally, from 0 – 1 nF. A good agreement of the results in Fig. 6 indicates the validity of the equivalent circuit in Fig. 3.

When the hand approaches to the steering, two current paths will be created. One is a path through the body, i.e., \( R_b \) and \( C_p \) to the ground, and the other is through the skin of the hand, i.e., \( R_s \) and \( C_{f,RX} \) to the RX. \( R_b \) in the measurement frequency range is in several kilo-ohms in our measurements. The body is connected to the ground by \( C_p \) that is relatively large, even if an actual capacitance is connected because the human body has a considerable surface that forms a capacitance through air. In our measurements, it is more than 1 pF, even if the body is totally insulated electrically from the ground. \( R_b \) and \( C_p \) are varied in a large range depending on the body state. When the body is facing the ground in a large area, \( C_p \) increases and when the facing position is close to the TX, \( R_b \) decreases. This feature enables the detection of a driver’s state such as determining whether the driver’s leg is on the brake pedal or not.

4.2 Gripping Area Sensing

In Fig. 7, \( C_r \) is approximately proportional to the touched area indicating that the gripping area can be estimated by the resonant frequency. The capacitance value was calculated using the resonant frequency according to the following equation:

\[
C_r = \frac{1}{(2\pi f_r)^2 L},
\]

where \( C_r \) is mainly composed of \( C_f \), but is affected by other capacitances such as the \( C_b \). The electrodes of the TX and RX on the steering used in this work have the same widths,

Table 1  Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance, ( L )</td>
<td>180 ( \mu )H</td>
</tr>
<tr>
<td>Skin resistance, ( R_s )</td>
<td>20 k( \Omega )</td>
</tr>
<tr>
<td>Leakage resistance, ( R_l )</td>
<td>20 k( \Omega )</td>
</tr>
<tr>
<td>Mutual capacitance, ( C_m )</td>
<td>17 pF</td>
</tr>
<tr>
<td>Body resistance, ( R_b )</td>
<td>5 k( \Omega )</td>
</tr>
<tr>
<td>Body parasitic capacitance, ( C_p )</td>
<td>50 pF</td>
</tr>
</tbody>
</table>

Fig. 6  Minimum impedance change depending on the distance to the hand or on the gripping area

Fig. 7  Results of area sensing
hence, the same gripping areas on the TX and RX are expected. Therefore, the capacitance value calculated by $f_r$ is expected to be approximately half of $C_{f,TX}$ because $C_{f,TX}$ and $C_{f,RX}$ are connected in series.

4.3 Driving Posture Sensing

Figure 8 shows the results of the capacitance values calculated from the resonant frequency depending on the driving posture. The steering handle was gripped with a single hand. The measurements were not done in an actual car, but in a laboratory, so that the driver could stand from the sheet. We put an imitated shift leveler on the desk, which was made of metal and grounded. When $C_f$ is not large enough, so that, $f_r$ is located from 1 to 2.5 MHz, some current flows through the body, which means that $f_r$ and $Z_{\text{min}}$ are affected by $C_p$ and $R_b$. Therefore, $C_r$ is changed by the driving posture. When the driver’s foot is floated from the accelerator pedal, the parasitic capacitance decreases. On the other hand, when the driver grips the shift lever, the parasitic capacitance increases.

4.4 Hand Distance Sensing

In Fig. 6, $Z_{\text{min}}$ is slightly increasing with approaching the hand, but the increase is quite small, which indicates that the detection of the distance to the approaching hand is difficult. In order to enhance the sensitivity for the approaching the hand, we changed the width ratio of RX to TX, $RR$. We employed the electrode configuration with small $RR$ as shown in Fig. 9. The $RR$ value was 0.1. This electrode configuration enables a more sensitive detection of $R_b$ and $C_p$ than that with $RR = 1.0$. The $Z_{\text{min}}$ values change more depending on a distance to the hand. In addition, the $C_r$ change also becomes sensitive to the driving posture because the larger current flows through the body.

Figure 10 shows the simulation results of the spectrum $|Z_{\text{min}}|$ based on the equivalent circuit of Fig. 3 in cases of $RR = 0.1$ and $RR = 1.0$. The increase of $Z_{\text{min}}$ from the value at no touching clearly enhanced in case of $RR = 0.1$, which shows the high sensitivity for approaching hand.

Figure 11 shows the impedance change depending on the distance between the hand and the steering. The change of the impedance from the value at no touching, $\Delta |Z|$, decreases inversely with increasing the approaching distance.

4.5 Improved Posture Detection

The electrode configuration with $RR = 0.1$ can also improve
the sensitivity for the driving posture detection as mentioned before. As shown in Fig. 12, the capacitance change depending on the driving posture gets larger comparing with Fig. 8, which means that the sensor became more sensitive for the posture detection.

4.6 Developing Application Software

Figure 13 is a graphical window of the application software that we had developed on a PC for displaying the sensing results in real time. As the software, can be installed in a tablet PC and the data can be transferred by wireless, the system can be easily installed in an actual car, as shown in Fig. 14.

5. Conclusion

We have developed a smart steering system that measures the resonance frequency and its minimum impedance in the circuit including the floating capacitance created between the TX/RX electrodes and the hand, the skin resistance of the hand, the body resistance, and the body parasitic capacitance to the ground. The system was able to detect the gripping position and the area, the distance to the approaching hand, and the driver’s posture that are useful for detecting the driver’s drowsiness, improving the driving techniques, and for customizing the car driving settings.

References


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