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TR2016-139 November 2016

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In this paper, we report the development of a contactless position sensor with thin and planar structures for both sensor and target. The target is designed to be a compact resonator with resonance near the operating frequency, which improves the signal strength and increases the sensing range. The sensor is composed of a source coil and a pair of symmetrically arranged detecting coils. With differential measurement technique, highly accurate edge detection can be realized. Experiment results show that the sensor operates at varying gap size between the target and the sensor, even when the target is at 30 mm away, and the achieved accuracy is within 2% of the size of the sensing coil.

IEEE Sensors

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***Abstract*—In this paper, we report the development of a contactless position sensor with thin and planar structures for both sensor and target. The target is designed to be a compact resonator with resonance near the operating frequency, which improves the signal strength and increases the sensing range. The sensor is composed of a source coil and a pair of symmetrically arranged detecting coils. With differential measurement technique, highly accurate edge detection can be realized. Experiment results show that the sensor operates at varying gap size between the target and the sensor, even when the target is at 30 mm away, and the achieved accuracy is within 2% of the size of the sensing coil.**

***Keywords*—Position sensor, inductive coupling, resonator, position switch.**

I. Introduction

Linear position sensors and switches are used to detect the position of a target structure when it is in relative motion with the sensor. The need of position sensing is desirable in many industrial applications, such robotic movement control, circuit assembly equipment, laser scanners and printers. There are many available sensing technologies that are capable of linear position sensing, such as capacitive sensor, linear variable differential transformer (or LVDT), magnetic encoder, and optical encoder [1]. Depending on the specifications of precision and reliability requirements, operating environment, and cost, different sensing schemes may be used.

In particular, it is often required to have no contact between target structure and the sensor. For such contactless sensors, there is a gap between the surface of target structure and the sensor. Therefore one challenge is to maintain the sensing range such that the sensor is effective in existence of a physical gap. While many sensors are proposed to address the problem, each solution has its own disadvantages. For example, for capacitive sensors, the size of capacitors can make their use impractical. For optical encoders, foreign matter such as dirt or grease can cause their failure with little warning; they also require very fine optical gratings for high resolution measurements. Magnetic encoders require precision housings and mechanical assembly to avoid errors caused by magnet or sensor misalignment. Inductive based sensors have advantages in reliability, cost, and susceptibility to harsh environment.

Inductive sensors detect the position of a metallic or magnetic target based on eddy current generation on the target when approaching to the sensing coil. Inductive sensors come in many different forms and shapes, and can be used as

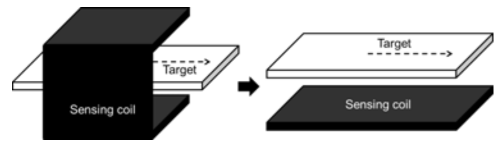

Fig. 1. Left: U-shaped slot sensor. Right: planar sensor.

position switches or as encoders for absolute position sensing. In particular, U-shaped slot sensors, are used in many systems for position sensing. A piece of metal plate is used as target structure and needs to be in the middle of the slot, as shown in Fig. 1. Such arrangement has high requirement on the movement of the target plate, as it may hit the sensing coil by accident and cause sensing error and dysfunction. It is preferred to have both sensing structure and target structure planar, and arranged facing each other, with a physical separation (illustrated on the right of Fig. 1).

The flat configuration is easier in installation and maintenance. However, it has higher requirement on the sensing range and accuracy. It is therefore important to design structures that can shape the magnetic field near the sensor to have desired pattern [2]–[4]. In particular, various planar resonator designs have been studied for multiple microwave sensing applications [5]–[7]. The quality factor of the resonator is an important factor to determine the performance of the sensor. It is desirable to have resonators with higher quality factor for sensing purpose [8], [9]. In many previous studies, the target structure has to be in close contact with the sensor, which largely limits the feasibility of these sensors.

In this paper, we propose a position sensor with flat sensing structure and target structure based small resonant coil and differential sensing, and show that accurate position detection can be realized even with a large physical gap between the target and the sensor.

II. Sensor Design

Fig. 2(a) shows a block diagram of the proposed sensor. In order to have extended sensing range with a physical separation between the target structure and sensing structure, we use resonant structures as target, and operate the sensor based on inductive coupling between sensing structures and target structure, at the resonant frequency of the target structure. The sensing structure includes a source structure, and a differential

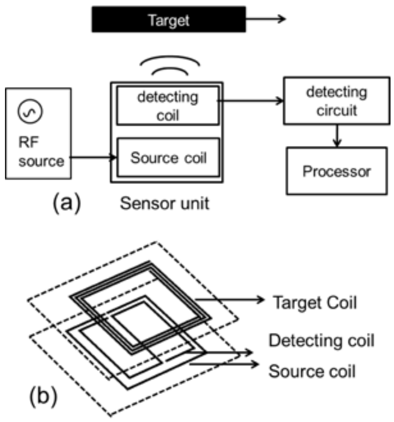

Fig. 2. (a) Block diagram of the proposed sensing system. (b) Example design of sensor structures.

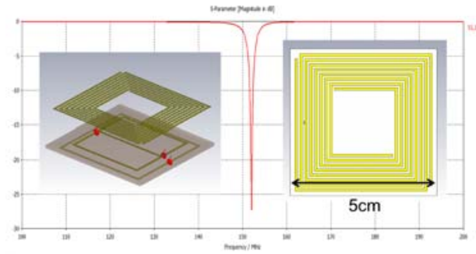

Fig. 3. Simulated reflection to the excitation port around the resonant frequency of the target coil. The structures are shown in the inset.

coil based detecting structure. The source structure is based on electric current carrying coil, and used to provide source magnetic field. The differential coil based detecting structure is used to measure the induced voltage and obtain the position information. We use differential based method in order to tolerate the change in gap size between the target structure and sensing structures.

Fig. 2(b) shows an example design of the coils. A larger rectangular loop serves as the source coil; a pair of smaller rectangular loop serves as the detecting coils; and a multi-turn spiral coil is used as target coil. The source coil and detecting coils can be build on the same circuit board, and connects to power source and detecting circuits. The passive target coil is on a separate board and can move independent of the sensing board.

We started the design process with numerical simulation (done in CST) on the resonance of the target coil. A bi-filar spiral resonator is designed instead of the mono-filar spiral, in order to have symmetric geometry with respect to the center line, and stronger magnetic response at the resonance. The geometry is shown in the inset of Fig. 3. An excitation port is applied in the gap of the source loop coil. Reflected signal is calculated as a function of frequency and plotted in Fig. 3. A sharp dip is seen around 152 MHz due to the excitation of the resonance of the target coil. The resonance can be seen from the field distribution shown in Fig. 4(a), where strong field is localized around the target coil, and is symmetric with respect to the center line of the coil when the source coil is aligned with the target. The size of the resonator is only about 2.5% of the resonant wavelength, and the quality factor (defined as $Q = f_C/\delta f$, where f_C is the resonant frequency, and δf is the 6-dB bandwidth.) is over 80, according to the simulation result.

The voltages are monitored at the excitation port, and the two ports in the detecting coils. When the target coil is missing, voltage is low at the two ports of the differential coil, while the voltage at excitation port is high, as most of the energy is reflected back. When the target coil is in the proximity, the voltage response becomes different. At resonance, energy is coupled to the target coil, with strong current oscillation in it, which generates a strong magnetic field. This magnetic field induces current in the detecting coils. The induced voltages at two ports are different depending on the position of the target.

In all the results shown, the vertical gap between the target coil and the sensing coil is fixed at $g = 15$ mm unless otherwise noted. The voltage response is calculated when the target resonator is moving with 1mm step. The differential voltage ($V_{diff} = V_1 - V_2$, where V_1 and V_2 are the voltage from two detecting coil 1 and 2, respectively.) is plotted as function of position and frequency (Fig. 4(b)). It is seen that voltage changes from positive to negative values as the target moves past zero point. Line plot is shown in Fig. 4(c) for larger position steps, where we can se the strong voltage response near resonant frequency.

Therefore we prefer to operate at a frequency close to the resonance of the target, in order to get stronger signal, and extend the sensing range. Fig. 4(d) shows the voltage as a function of target position at the frequency of 143 MHz. Two sets of results are plotted on the same scale for two different vertical gap between target coil and sensing coil. As we can see, the position of zero differential voltage is within ± 1 mm, and the voltage changes as a linear function of position. The curves are not exactly smooth, which is largely due to the accuracy in numerical simulations. This is verified in later experiments.

III. Experiment Results

Based on the design in the simulation study, a sensor was fabricated for experimental measurements. The fabrication is done using standard circuit board prototyping service. FR-4 is used as substrate material. The fabricated boards with source/detecting coils and target coil are shown in Fig. 5(a) and (b), respectively. The source coil is connected to a signal generator via a coaxial cable. The two detecting coils are connected to an oscilloscope for voltage measurements. The target coil is placed on a linear stage, with its movement is accurately controlled, while the circuit board with source/detecting coils is fixed. The two boards are arranged such that the vertical gap g in between is fixed, and the board with target coil moves in a linear fashion horizontally, as shown in Fig. 5(c).

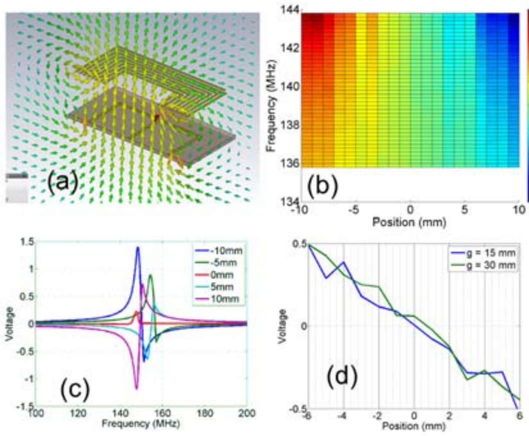

Fig. 4. Simulated results: (a) Field distrubtion at resonance; (b) Differential voltage mapping as function of target position and excitation frequency; (c) Differential voltage at different positions as function of frequency; (d) Differential voltage as function of position at fixed frequency.

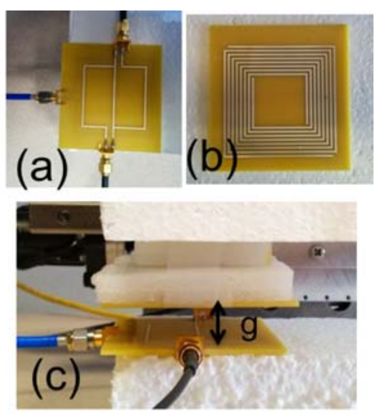

Fig. 5. Fabricated sensing and target coils, and the measurement setup.

Experiments were conducted to measure the induced voltages on the detecting coils when the target structure is at different positions. The differential voltage from the two detecting coils as function of position is plotted in Fig. 6. Two cases are plotted for vertical gap between target and sensing board $g = 15$ mm and $g = 30$ mm. In both cases, we can see that the voltage change gradually with position. When the center of the target coil is aligned with the center of the detecting coil pair, the differential voltage crosses zero. Compared with simulation results (Fig. 6(d)), the curves are much smoother, which confirms that the error in Fig. 6(d) is mainly due to numerical accuracy.

The result shows that this sensor can be used as an accurate position switch, and detect a zero position with very high accuracy. Compared with the 50 mm size of the target structure width, the accuracy of 1 mm is only 2% of its size. Moreover, the proposed sensor can be used as a short-range linear position sensor, to identify the exact position of the target. Other advantages of the proposed sensor include totally passive target structure for easy fabrication, low cost, and low maintenance.

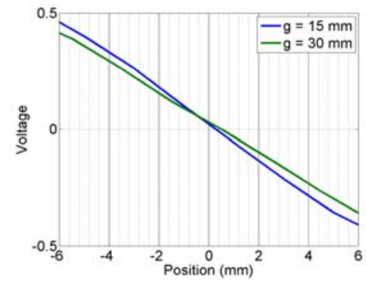

Fig. 6. Experiment measurement result of differential voltage as function of position at different gap sizes.

Moreover, multiple resonant structures can be arranged in a linear array as a target structure of the sensor, in order to extend the linear range, or improve the sensing accuracy. Similarly, multiple sensing structures can also be arrange in a linear array to have multiple channels, with increased linear position sensing range, and coding capabilities.

IV. Conclusion

In summary, we proposed a planar inductive position sensor with two key features, namely, highly resonant target structure, and differential detecting coils. With resonant target structure, the coupling between source coil and target can be greatly enhanced, therefore the sensing range is largely increased. Using a pair of detecting coils for differential measurement, a zero position can be accurately detected. The sensors have planar structures on both sensor and target and can be easily fabricated and installed. With these advantages, the proposed sensor has potential in many industrial applications.

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