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SAW signal conditioner-based dynamic capacitive sensor for high-speed gap measurement

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ABSTRACT

High-speed gap measurement in the nano/micrometer range presents unique engineering challenges. A signal conditioner is required for capacitive sensors to amplify, denoise, and restrict the bandwidth. In this work, a capacitive sensor was used in combination with a SAW device that serves as a signal conditioner. The proposed system provides 2.75 MHz bandwidth through amplitude modulation using the center frequency of the SAW device as a carrier signal and has outstanding signal conditioning capabilities. Construction and characterization of a SAW-based capacitive gap sensor to measure a 200 Hz gap frequency are described.

1. Introduction

The need for high-speed and high-precision gap measurements has become an important engineering issue. Currently, optical or capacitive sensors are used for high-speed gap measurements. Optical sensors are not affected by magnetic field and have excellent sensitivity, resolution, and bandwidth. By these characteristics, optical sensors have been applied in a various technologies like information storage, magnetic bearing, organ systems [1–4], but require a special optical path for the reflection of light. Also, the surface of measure object has to be a light reflective material. Moreover, the high cost and complexity of the signal processing hinders their widespread use. On the other hand, the capacitive method has several advantages in terms of configuration simplicity, power consumption, and low cost. Although the resolution and sensitivity of capacitive methods are very good, they are not as good as optical methods. Capacitive methods are also widely used in various high-precision technologies like positioning system, MEMS applications, droplet detection, etc. [5–9] and they can be realized using various configurations [10,11], but the noise level increases as the size decreases [10]. As a result, special signal-conditioning electronics are required, and this causes problems related to the measurement bandwidth and complexity and the use of lumped or semiconductor elements for denoising and amplification. By these characteristics, the capacitive sensors were mainly used to the static or quasi static measurements.

In this work, a surface acoustic wave (SAW) device was used as a signal conditioner to help eliminate some of the disadvantages of capacitive methods. A SAW device is mainly comprised of inter-digital transducers (IDTs) and a delay line and has the characteristics of a bandpass filter plus a delay. In the past, the main applications of SAW devices have been high-frequency bandpass filters in wireless communication systems [12]. However, they are now also used as bio or chemical sensors, in which the main sensing factor is the center frequency or phase shifting due to the contact between a substrate and working fluids [13–15]. When a SAW device is used as a signal conditioner with an external impedance Z_L attached to an output IDT, as shown in Fig. 1, it measures the amplitude response at SAW input frequency from the impedance change between the source impedance R_S and the external impedance Z_L and the overall signal flow of measurement system is shown in Fig. 2.

Through this application, denoising and delay effects are provided with simple electronics [16]. Additionally, the device can be easily expanded to wireless sensors. Using these characteristics, SAW devices have been applied to gap sensor, pressure sensor, torque sensor, and so on [16–19]. At this time, the response is shown as amplitude modulated signals with the SAW input signal as carrier frequency in time domain with low noise. And it enables the measurements of dynamic frequencies lower than

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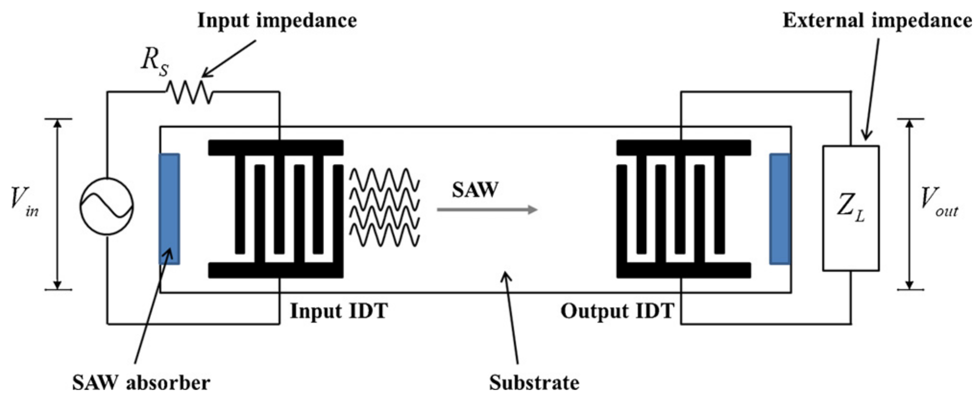

Fig. 1. Structure of the SAW device used as a signal conditioner with an external impedance Z_L.

SAW input frequency in real time. However, almost all previous research has also focused on static or quasi-static measurements likewise the capacitive sensor application. Even, the calibration of the sensing element to compensate for amplitude decrement during contact due to the existence of parasitic resistance has not been considered. To improve on previous researches, static and dynamic gap measurements were performed in the present study, along with calibration of the amplitude decrement due to parasitic resistance.

For this research, the electrodes of the capacitive sensor attached to the SAW device were configured as parallel plates whose configuration is very simple and measurable distance is larger than other structures. First, theorems for capacitive sensor impedance and electro-acoustic equivalent circuit models for the SAW response with external loads were considered for the case of static and dynamic gap changes. Static gap measurements were then obtained by substituting the capacitive impedance into the electro-acoustic equivalent circuit model and compared with experimental results. And measurable bandwidth from the sapling data and center frequency was calculated. The calibration method used for the sensing element was also treated through a variable capacitance technique. And dynamic gap measurements were obtained and compared for several harmonic frequencies. Finally, minimum data sample time for measure frequency was calculated considering measurement noise level.

2. Theory

2.1. Capacitive sensor

The configuration of the parallel-plate capacitive sensor is shown in Fig. 3. The capacitance can be calculated by the following equation:

$$C = \varepsilon \frac{A}{d} \tag{1}$$

where ε, A, and d are the dielectric coefficient, electrode area, and distance between two plates, respectively.

$$Z = -j\frac{1}{2\pi f C} \tag{2}$$

Because the capacitive sensor used to measure the gap detects an impedance change with the gap distance d, the impedance Z was rearranged with respect to d and is mathematically written as Eq. (2). If d is a function of time, Z is also a function of time:

$$Z(t) = -j\frac{d(t)}{2\pi f \varepsilon_0 A} \tag{3}$$

Therefore, if the equivalent circuit model of the overall system is known, the effect of $d(t)$ can be determined by substituting Eq. (3) into the circuit model.

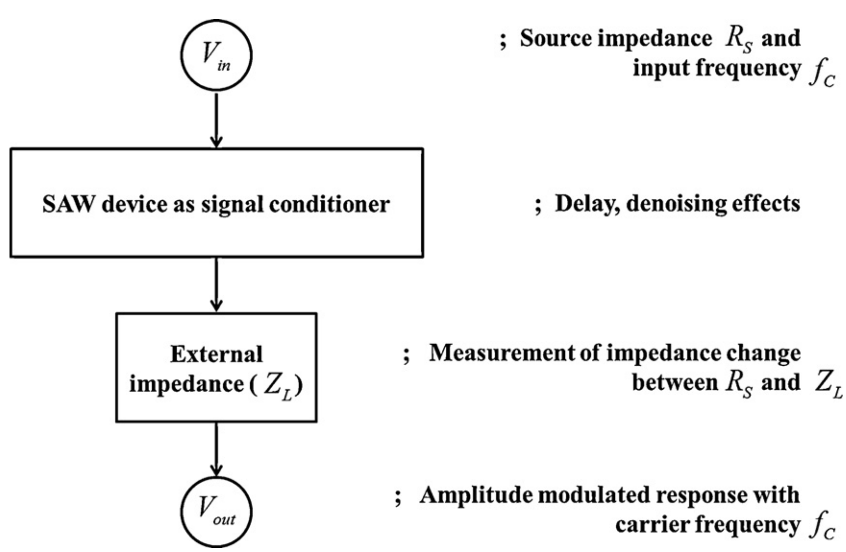

Fig. 2. Overall signal flow of measurement system.