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Novel capacitive displacement sensor based on interlocking stator electrodes with sequential commutating excitation

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A B S T R A C T

A novel capacitive displacement sensor is proposed. The stator consists of a pair of interlocking comb-type electrodes, driven by two consistent high frequency voltage sources with opposite phase. The mover consists of double sensing channels with electrical orthogonal relationship. Through capacitive coupling, a relative displacement between the mover and the stator is converted to quasi sine/cosine signals, featured with direction identification and instantaneous displacement interpolation. Theoretical analysis indicates that the physical resolution of the studied sensor is the same as the electrode unit's width. And also, the interchannel's amplitude ratio and phase difference keep stable in a wide range of air gap size. Hence the performance of displacement detection can be enhanced by amplitude normalization and interpolation. Using a Printed Circuit Board (PCB) fabricated prototype, the proposed scheme was experimentally tested. Typical coupling statuses were captured. Main sensing characteristics and performance were investigated, such as the responding of air gap variation, the displacement sensitivity, and the measurement uncertainty.

1. Introduction

Displacement detection with high resolution and accuracy is essential for micro-electronic technology, precision fabricating, biological engineering, etc. Kinds of strategies have been developed in these fields. In which, the well known methods include laser interferometry, laser triangulation, grating interferometry, and capacitive coupling [1–4]. However, capacitive displacement transducers based on variable air gap have been long restricted in small-scale usages [5–9], even though this kind of schemes has shown outstanding characteristics, such as simple structure, high sensitivity, and especially the prominent dynamic response.

Through the utilization of comb-type electrode structure, recently developed periodic area-varying capacitive sensors have been studied for large-scale displacement measurement [10–13]. Fig. 1 illustrates the theory of a periodic area-varying capacitive displacement sensor. The stator and the mover share the same comb-type electrode structure. In situation of the mover electrode units facing the stator electrode units in parallel direction with constant air gap, a horizontal movement of the mover generates a periodic variation of coupling capacitance between the two buses. Hence the displacement of the mover can be detected by processing the capacitance variation signal, and the measurement scale can be easily expanded by increasing the electrode units on the stator. Yet, there are some unsolved problems left for the comb-type electrode structure. One of the critical issues is the identification of each component contained in the capacitance variation signal, because not only the horizontal movement, but also the air gap change, the overlapping deviation, and the dielectric constant drift may contribute to the capacitive coupling process.

To improve the displacement detection performance, Kang et al. [14] proposed an interlocking sensing electrode structure; alignment deviation was treated as a common interference and suppressed efficiently. But the drift of offset capacitance and the instantaneous displacement measurement have not been accounted. To reduce air gap influence, Kim et al. introduced a contact-type capacitive displacement sensor with dielectric coating technology [15,16]. However practical problems including friction, thermal effect, and wear must be considered. Moreover, it is a general tend to employ slimmer electrode unit for higher physical resolution, which certainly will lead to a deterioration of signal-to-noise ratio (SNR) of effective capacitance variation signal relative to the drift of offset capacitance. Thus the interference of offset capacitance, as well as the air gap fluctuation must be taken into account carefully for such comb-type electrode sensing schemes.

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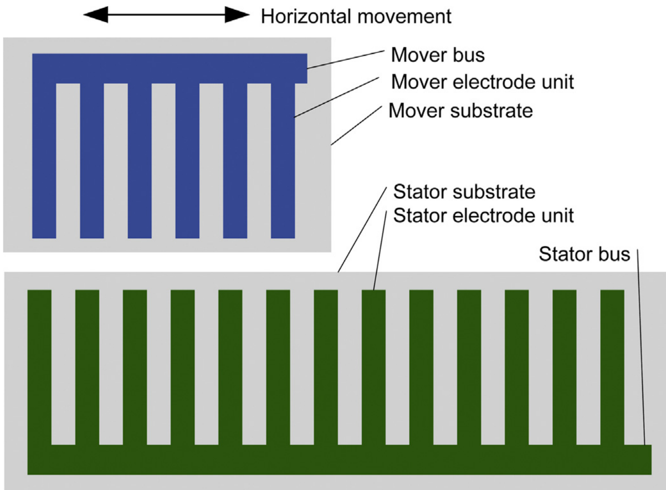

Fig. 1. Theory of a periodic area-varying capacitive displacement sensor.

In this study, we present a novel capacitive displacement sensing strategy. By employing an interlocking comb-type structure, all electrode units on the stator are marked with high frequency voltage source, features with consistent amplitude but sequentially opposite phase. Hence the influence of offset capacitance can be eliminated for each sensing electrode unit. Moreover, through the design of double sensing channels with electrical orthogonal relationship, horizontal movement of the mover can be converted to quasi sine/cosine signals. Main common mode interferences such as air gap fluctuation, overlapping deviation, and dielectric constant drift can be effectively suppressed.

2. Theory and modulation function

Fig. 2a shows the equivalent circuit of the presented interlocking stator electrodes capacitive displacement sensor (ISECDiS). For the stator, electrode unit's width and spacing size are equal as w_p. Two high frequency voltage sources with consistent amplitude but opposite phase, E_1 and E_2, are applied to drive the interlocking electrodes, namely the odd-numbered units and the even-numbered units. Thus the sequential commutating excitation of all the stator electrode units is fulfilled.

For the mover, the electrode units of the double sensing channels, CHA and CHB, are designed with a horizontal offset of $5w_p$, hence to maintain an electrical orthogonal relationship, which will be proved through the following analysis. The original coupling signal of each sensing channel is first enhanced by a high impedance buffer. Then with the band-pass filter, and the bipolar demodulation circuit, quasi sine/cosine signals are outputted during mover scanning process.

Fig. 2b illustrates the capacitive coupling model of sensing CHA, where C_1 to C_{4n} indicate the coupling capacitors of CHA sensing unit with each stator unit. R_{in} and C_{in} indicate the input impedance of the buffer. Defining high frequency voltage sources E_1 and E_2 in time domain as

$$\begin{cases} e_1(t) = u_e \sin(\omega_e t) \\ e_2(t) = u_e \sin(\omega_e t + \pi) \end{cases} \quad (1)$$

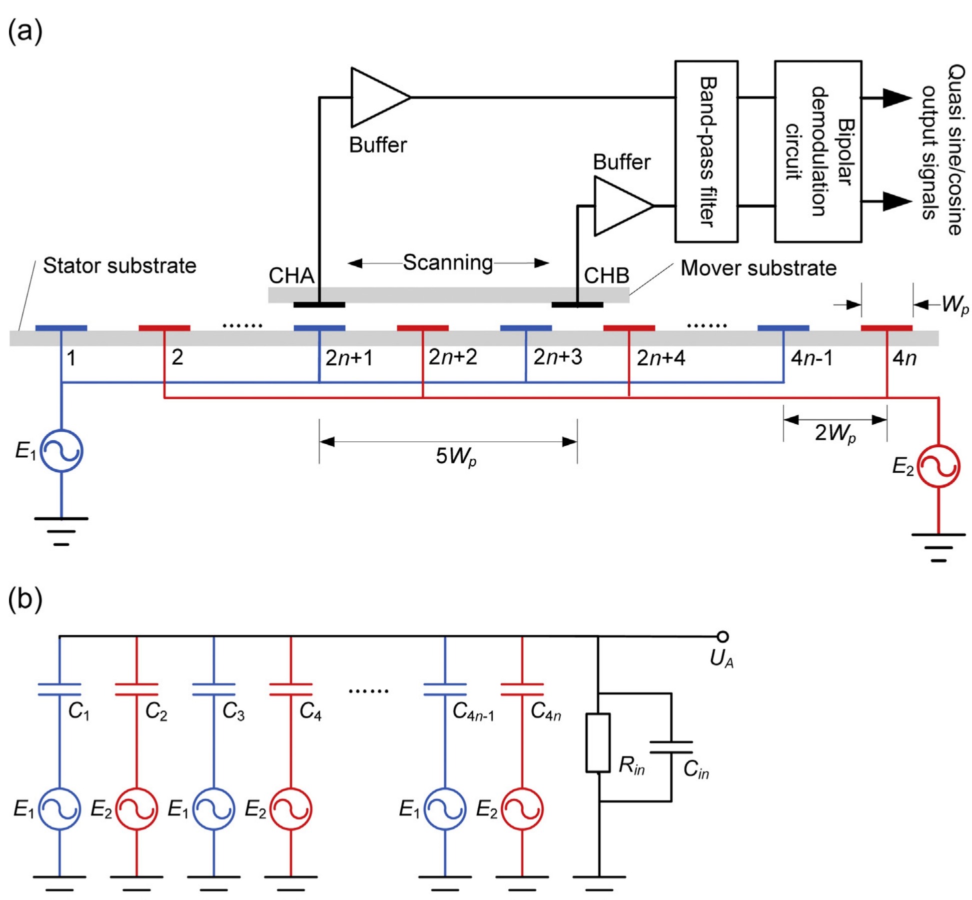

Fig. 2. Theory of the ISECDiS. (a) Equivalent circuit of the stator and the mover. (b) Capacitive coupling model of CHA.