The Influence of Electric-Field Bending on the Nonlinearity of Capacitive Sensors

Xiujun Li, Gerben de Jong, and Gerard C. M. Meijer, *Member, IEEE*

***Abstract*—Three-layered electrode structures are often employed in multiple-electrode capacitive position sensors. Even when advanced algorithms and well-designed guarding electrodes are used, the electric-field-bending effect is still one of the major contributors to the nonlinearity of capacitive position sensors. In this paper, the effects of electric-field bending on linearities of five capacitive linear-position sensors have been studied based on a physical model of the capacitive sensor. It is shown that the effect of electric-field bending on linearities strongly depends on the sensor structures, and that it is significantly reduced when advanced sensor structures and algorithms are used. The results are very useful for optimizing the sensor structure according to its application.**

***Index Terms*—Capacitive sensor, electric-field-bending, multiple electrodes, nonlinearity.**

I. INTRODUCTION

CAPACITORS are often used as sensing elements in position sensors, having the attractive features of a low energy consumption and a simple structure. In previous papers [1]–[5], it has been shown that, with capacitive sensors, a rather high accuracy and resolution can be obtained. The remaining inaccuracy is mainly caused by the electric-field-bending effect and mechanical errors. The use of guarding electrodes is very important as these reduce the influence of the electric-field-bending effect and also reduce the effect of external disturbing signals [1]–[5]. However, the guarding electrode cannot eliminate the influence of electric-field-bending effect completely. Even when well-designed guarding electrodes are used, the electric-field-bending effect is still one of the major causes of the nonlinearity of capacitive position sensors.

In this paper, the effects of electric-field bending on linearities of five capacitive linear-position sensors with three-layered electrode structures have been studied, based on a physical model of the capacitive sensor. It is shown that the effect of electric-field bending on linearities depends strongly on the structure of the sensor electrodes. The result of this study can be used to optimize the sensor electrode structure according to its application.

II. MULTIPLE-ELECTRODE CAPACITIVE SENSORS

In accurate capacitive sensor systems with a large measurement range, the capacitive sensing elements are implemented as multiple-electrode elements [4]–[9]. The advantages of multiple-electrode elements are as follows:

- a large measurement range;
- high accuracy;
- reduction of the electric-field-bending effect;
- reduction of the mechanical errors;
- small nonlinearity.

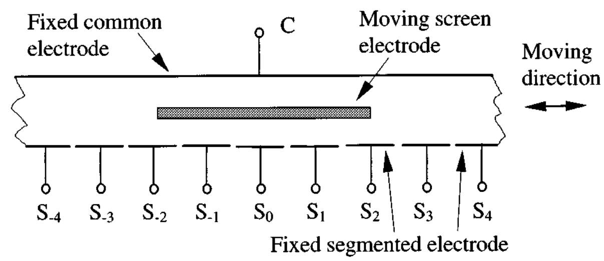

Fig. 1. Three-layered electrode structure.

A structure of the capacitive sensing element used often with multiple electrodes is a three-layered electrode structure [6], [7], [9]. Fig. 1 shows such a structure. The segmented (multiple) electrode and the common electrode are fixed. The moving screen electrode which is grounded, shields the segmented electrode from the common electrode and so decreases the capacitance between the two fixed electrodes. The multiple capacitors, which are formed between the common electrode and the segments, carry the position information of the moving screen electrode.

Based on the sensor structure shown in Fig. 1 and the retrieving algorithm described in [6], Fig. 2 shows five sensing element structures for the linear position. The differences of these structures pertain to the widths of the screen and the gap of the moving electrodes with respect to the fixed segmented electrodes.

For these five sensor structures, the relations of the measured position x_m and the capacitances can be represented by the following equations:

$$\frac{x_m}{x_s} = \frac{C_1 - C_3}{2(C_1 + C_3 - 2C_2)} \quad (1)$$

$$\frac{x_m}{x_s} = \frac{C_2 - C_4}{2(C_1 - C_3)} \quad (2)$$

$$\frac{x_m}{x_s} = \frac{C_4 - C_2}{(C_2 + C_3 + C_4 - 3C_1)} \quad (3)$$

$$\frac{x_m}{x_s} = \frac{(C_1 + C_2) - (C_4 + C_5)}{2(C_1 + C_5 - C_2 - C_4)} \quad (4)$$

$$\frac{x_m}{x_s} = \frac{(C_5 + C_6) - (C_2 + C_3)}{2(C_4 - C_1)} \quad (5)$$

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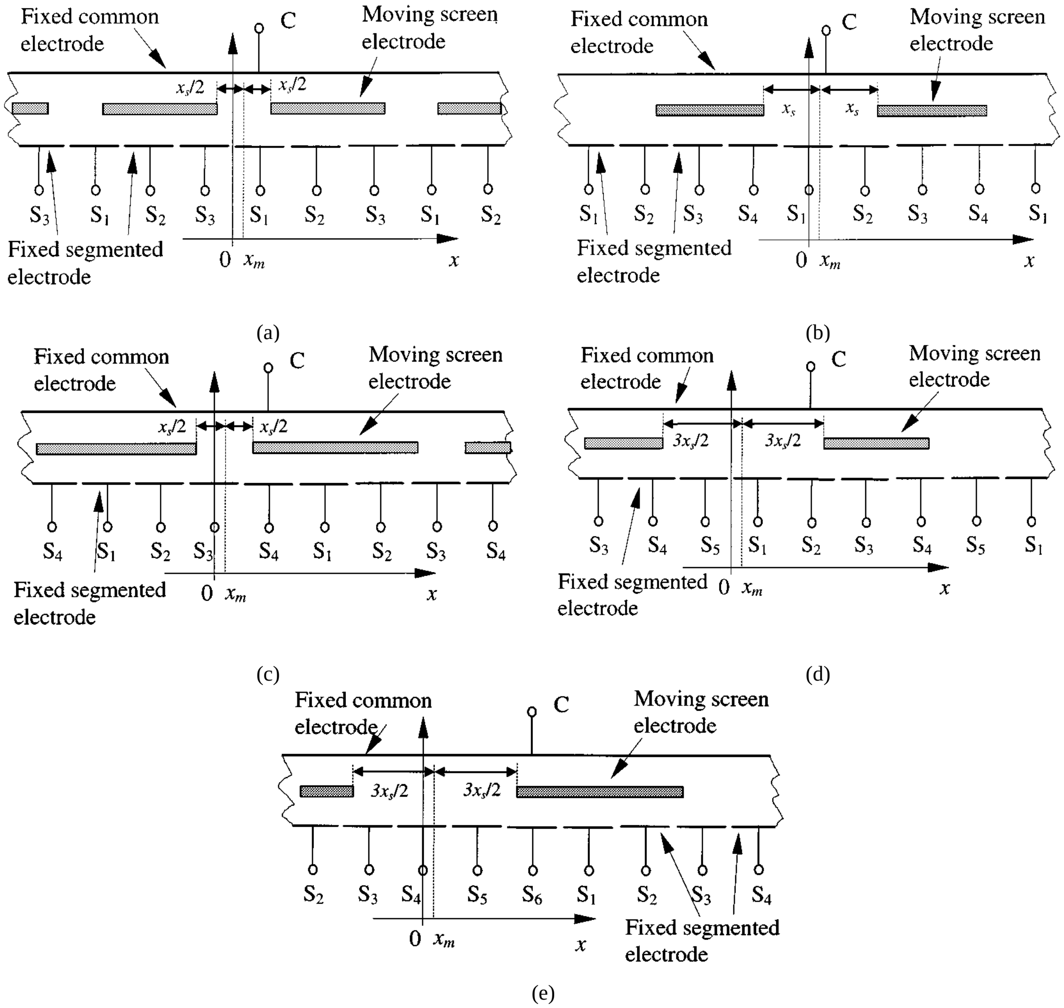

Fig. 2. Five sensing element structures for the linear position.

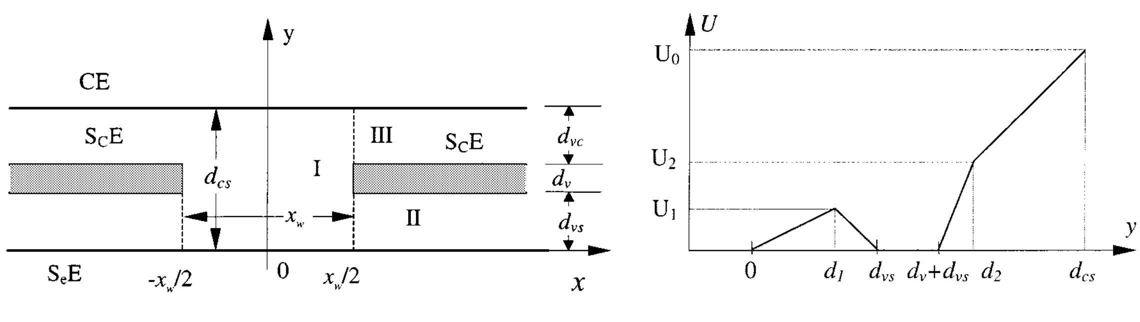

Fig. 3. (a) Crossview of a part of the sensor. (b) Piecewise linear approximation for the potential at $x = x_w/2$.

TABLE I
GEOMETRICAL PARAMETERS OF THE SENSOR

Parameters	Notation	Unit	Values
electrode distance	d_{cs}	mm	2.0
thickness of the screen electrode	d_v	mm	0.2
position of the screen electrode	d_{vc}/d_{vs}	-	1.0
length of the segment electrode	l_s	mm	15.0
width of the segment electrode	x_s	mm	4.0

respectively, where x_s is the width of one segment, and C_i $(i = 1 \cdots 6)$ are the capacitances between the common electrode and the segmented electrode, respectively. The validity of these formulas is limited to the measurement range of one segment width (x_s). Outside this range, other appropriate capacitors are selected.

III. Physical Model of the Capacitive Sensor

Generally, it is difficult to find an analytic solution for a three-dimensional electrostatic-field problem. However, if the lengths of the segmented and common electrodes are much larger than their electrode distances, $d_{\rm cs}$ [see Fig. 3(a)] and larger than the widths of the electrodes, we can get a simplified two-dimensional model as shown in Fig. 3(a) for

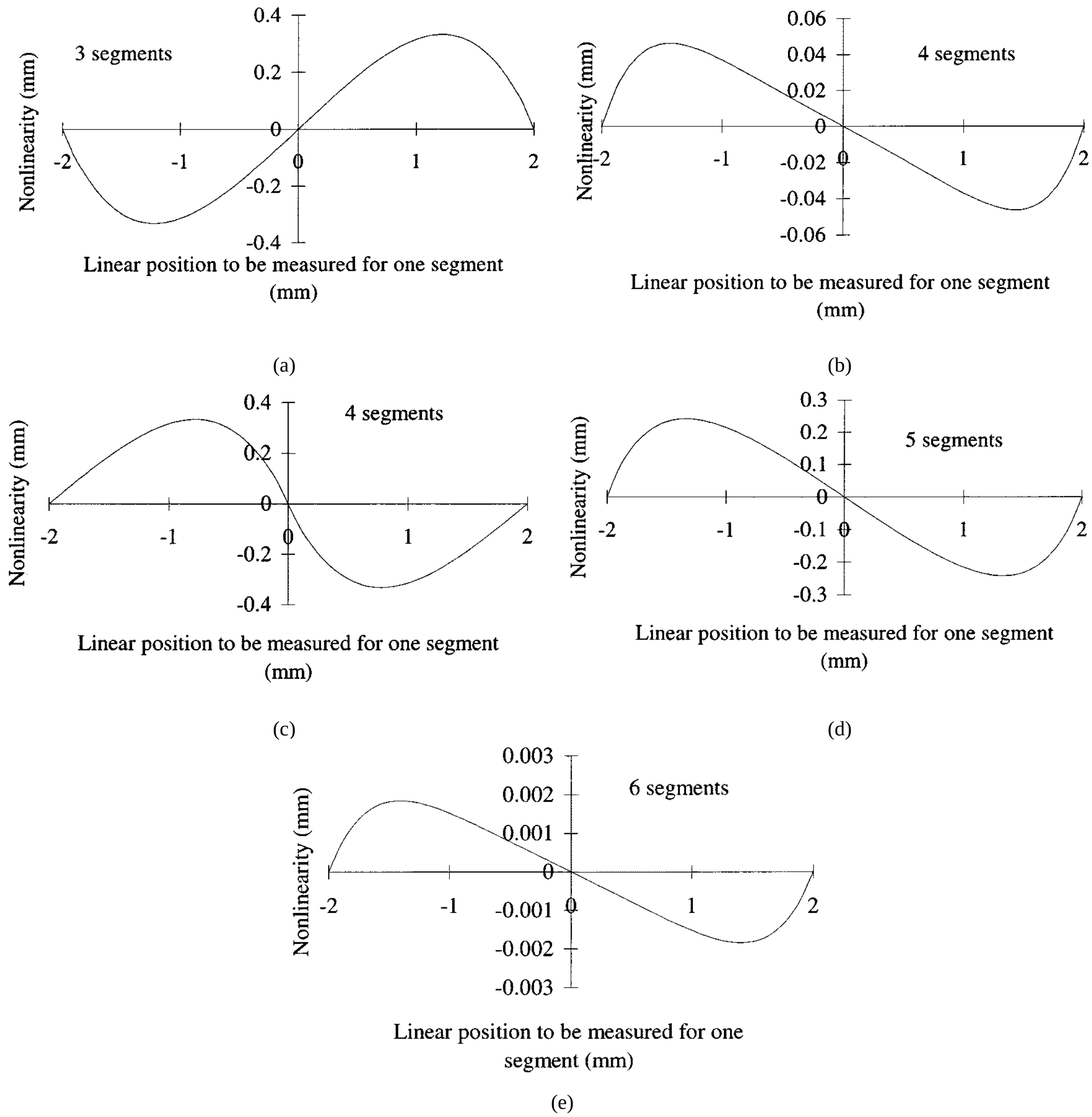

Fig. 4. The simulated results for effects of electric-field-bending on sensor linearity.

the structure shown in Fig. 1, which is symmetrical along the y-axis [8], [9].

In this figure, x_w is the width of the screen windows, d_{cs} the distance between the common and the segmented electrodes, d_v the thickness of the screen electrode, d_{vs} the distance between the screen and the segmented electrodes, and d_{vc} the distance between the common and the screen electrodes.

For $x = x_w/2$ and $x = -x_w/2$, and $0 < y < d_{\mathrm{cs}}$, we assume that the potential is a continuous piecewise-linear potential, taken as a basic triangular-shaped function. The accuracy of this approximation is verified by means of the numerical calculation described in [8], [9]. This potential function is shown in Fig. 3(b).

In this model, the potential U_0 represents the potential of the transmitting (common) electrode. The potentials U_1, U_2 and positions d_1, d_2 are auxiliary variables which are determined by the potential U_0, the geometrical parameters ($d_{\mathrm{cs}}, d_v, d_{\mathrm{vs}}$, and d_{vc}) and the width of the screen windows x_w [8], [9]. The segmented and moving electrodes are grounded.

IV. The Influence of the Electric-Field-Bending Effect on the Linearity

Based on the physical model of the capacitive sensor described above, the nonlinearities caused by the electric-field-bending effect are calculated numerically for the multiple-electrode capacitive sensors shown in Fig. 2. The used geometrical parameters are listed in Table I.

Fig. 4 shows the calculated effects of the electric-field-bending on the sensor linearity. These results correspond to the sensor structure shown in Fig. 2, respectively.

From these simulations it can be concluded that the structure with six segments shows a much better linearity than the other ones. The simplest structure is that of Fig. 2(a), because in this case only three segments have to be measured. However, the linearity amounts to ± 0.4 mm for a measurement range of ± 2 mm. On the other hand, even when the same segmented electrode structure is used [see Fig. 2(b) and (c)], the nonlinearity can be improved by means of advanced screen electrode and the algorithm [see Fig. 4(b) and (c)].

V. CONCLUSION

The effects of electric-field bending on linearities of five capacitive linear-position sensors have been studied based on a physical model of the capacitor. Analyzed results showed that the effect of electric-field bending on the linearities is strongly reduced when an advanced sensor structure with six read-out segments and a corresponding algorithm are used. In this case the nonlinearity amounts to $\pm$ 0.046% for a measurement range of 4 mm. The result of this study can be used to optimize the sensor electrode structure according to its application with respect to simplicity, accuracy, and measurement speed.

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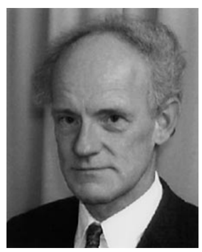

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