CAPACITIVE SENSOR SURFACE QUALITY CONSIDERATIONS WHEN MEASURING SUB-NANOMETER DISPLACEMENT[1]

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This paper addresses the capacitive sensor surface quality issues when measuring sub-nanometer displacement. Special attention is paid to the surface roughness and its contribution to the non-linearity of the conversion: displacement-to-capacitance. Analytical approach is used for the analysis, which proves that within the limits of the model validity the vertical amplitude of the surface topology is the only factor for non-linearity error. The horizontal spatial frequency of the roughness does not directly affect the non-linearity.

With the help of the derived equations, the non-linearity error is calculated for a sensor gap from 9μm to 17μm, and a surface roughness height from 0.2μm to 1μm.

Keywords: capacitive sensor, resolution, non-linearity, surface roughness

1. INTRODUCTION

To measure displacement with capacitive sensors two conversions are needed: (i) displacement-to-capacitance conversion, and (ii) capacitance-to-electrical signal conversion. For the first conversion the mechanical design of the sensor head is important with respect to linearity, stability, volume, mechanical interfaces with the target and the reference, etc.

The best capacitive sensor configuration for measurement of very small displacements is: two parallel electrodes which move in direction to one another. The capacitance of such a configuration is

$$C = \frac{\varepsilon_r \varepsilon_o A}{d}. \qquad (1)$$

Here ε_r is the relative permittivity of the medium between the plates; ε_o is the permittivity of vacuum; A is the plate's area, and d is the distance between the plates, also called gap, which has to be measured.

The choice of a nominal value of the capacitance C, defined by the ratio A/d, has an impact on such important mechanical parameters like: mounting precision (parallelism of the two plates) and surface quality of the two plates (roughness and flatness). The smaller the ratio A/d, the more relaxed mechanical requirements, the less influence of the initial and operation tilt, and the cheaper is the sensor head. On the other hand, a smaller ratio A/d gives a smaller value of C. This leads to lower sensitivity $\Delta C/\Delta d$ and puts more severe requirements to the sensor interface electronics with respect to input noise, stability, sensitivity to interference, etc.

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Practical values of the displacement sensor capacitance are within 0.1 pF to 10 pF, and depend on the specific application requirements.

Measuring displacement in the sub-nanometer resolution range and still keeping the sensor capacitance in the above mentioned optimal range, translates into a few micrometers distance between the two electrodes. Next to the non-linearity issues related to the gap width between the active electrode and the guard ring and the initial tilt [1] [2], a very important becomes the quality of the electrode surface and especially its roughness.

In this paper we present analysis of the effect of the electrode surface roughness on the nonlinearity of the displacement-to-capacitance conversion.

2. Effect of Tilt on the Effective Gap between the Capacitive Sensor Electrodes

Let us look what is the capacitance between two rectangular plates, which are not parallel to one another, but at a certain angle φ, as presented in Fig.1.

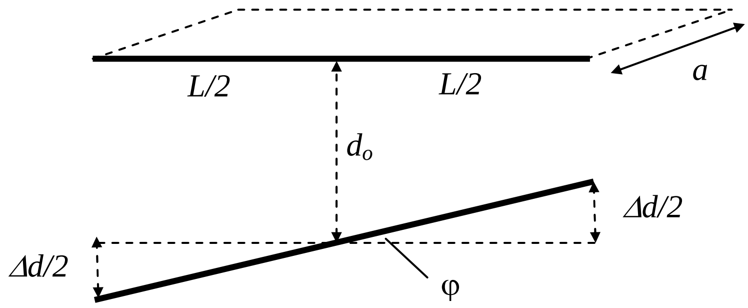


Fig.1

The capacitance is given with the integral (2), by neglecting the distortion of the parallel electric field lines due to the non-parallel plates

$$C = \int_{-\frac{L}{2}}^{\frac{L}{2}} \varepsilon \frac{a}{d_0 - l \tan\varphi} dl \qquad (2)$$

The solution of (2) is

$$C = \frac{\varepsilon a}{\tan\varphi} \ln\left(\frac{d_0 + L\tan\varphi / 2}{d_0 - L\tan\varphi / 2} \right) \qquad (3)$$

Note that if $\varphi = 0$, the solution of (2) exactly equals (1). If in (3) we replace tan(φ) with Δd/L, we achieve

$$C = \frac{\varepsilon A}{\Delta d} \ln\left(\frac{d_0 + \Delta d / 2}{d_0 - \Delta d / 2} \right) \qquad (4)$$

Comparing (1) and (4) we can define how the equivalent distance (gap) ***d*** between two rectangular flat electrodes varies, when one of the electrodes is tilted with respect to the other at angle φ = arctan(Δd/L)

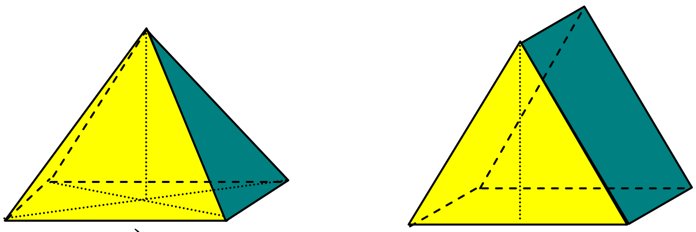
$$d = \Delta d / \ln\left(\frac{d_0 + \Delta d/2}{d_0 - \Delta d/2}\right) = \Delta d / \ln\left(\frac{1 + \Delta d/2d_0}{1 - \Delta d/2d_0}\right) \neq d_o \tag{5}$$

From (5) we can make the important conclusion that in case of tilt between two originally parallel plates, and neglecting the distortion of the parallel electric field, the variation of the equivalent distance $\boldsymbol{d}$ from its original value $\boldsymbol{d_o}$ does not depend on the electrode length $\boldsymbol{L}$.

3. Effect of the Electrode Surface Roughness on the Non-linearity

Now, let's see how we can implement the above results in estimating the influence of roughness/waviness of the sensor plate's surface on the nonlinearly of its transfer characteristics.

First we approximate one roughness component with a pyramid, as it is shown in Fig.2a.

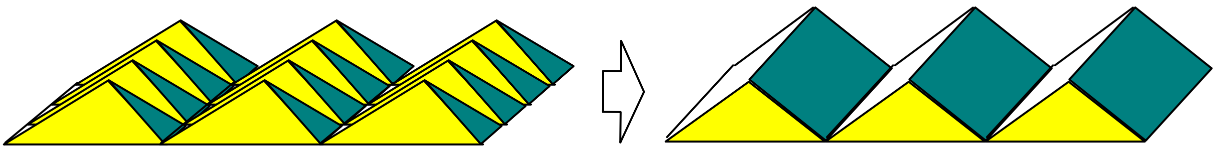


a) b)

Fig.2

The goal is to calculate what is the capacitance between such a pyramid and an ideally flat target, and how this capacitance is influenced by the height of the pyramid. Because this is not an easy task, assuming that the pyramid heigh is much smaller than the distance to the target, we modify the pyramid into a "hut"-like shape (Fig.2b). For one and the same height and the same footprint, the total surface of the side walls of the pyramid equals the surface of the tilted side walls of the "hut". The tilt angle of the pyramid walls is the same as the tilt angle of the side walls of the "hut". That is why we expect the effect of tilt on the capacitance nonlinearity to be approximately the same. Somewhat different will be only the average distance to the target d_o.

As a result of this transformation we can switch from three-dimensional to two-dimensional model of the surface topology (see Fig.3).



a) b)

Fig.3

This is possible, because in depth of Fig.3.b the cross section remains one and the same. We can look at it as many equal capacitors with tilted one electrode, just like the one presented in Fig.1. These capacitors are connected in parallel (Fig.4).

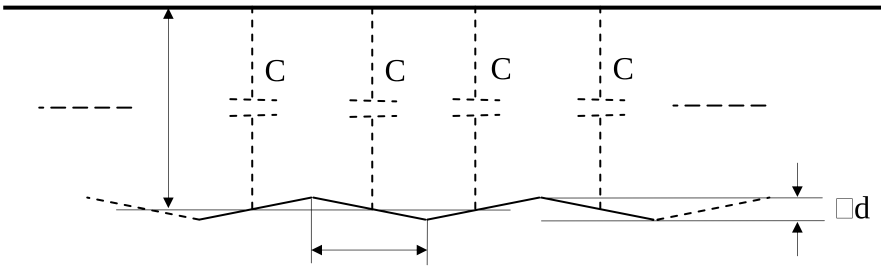


Fig.4

The total capacitance will be the sum of all parallel capacitors $C_{\Sigma} = nC$. It will have unchanged surface A (see expression (1)), defined by the surface of the target (the second electrode), and varying equivalent distance between the electrodes d (while d_o = cons.) dependant on Δd.

From the analysis so far we can conclude that the error for ***d*** does not depend on the spatial frequency of the surface variations. This is true only if we assume that the electric field lines are not distorted by the surface variations of the electrode. In case of high spatial frequency, for which the spatial period is smaller than ***Δd*** (in this case it will be more precisely to talk about roughness, rather than flatness or waviness of the electrode surface), and also much smaller than the gap $\boldsymbol{d_o}$, this assumption is not valid any more. In this case the effect of roughness is reduced considerably, because the opposite electrode "sees" only the peaks and not the valleys of the broken second electrode surface.

Fig.5 gives an idea how the gap d_o and the height variation *Δd* are transformed in case of high spatial frequency (low spatial wavelength) of the electrode surface variation. As "a rule of thumb" we can specify that when the spatial wavelength ***M*** is 10 times smaller than the gap $\boldsymbol{d_o}$, then the nonlinearly introduced by the roughness is negligible. For quantitative estimation of the same effect, an accurate quasi-static electric field simulator has to be used.

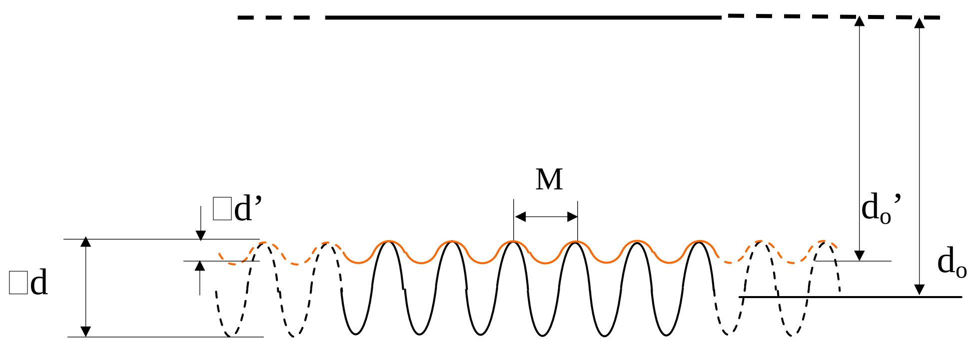


Fig.5

For the general case, with long spatial wavelength *M*, calculations were made for the relative change of ***d***: $\varepsilon = (d_o - d)/d_{o,}$ for d_o varying from 9 μm to 17 μm, and Δd varying from 0.2 μm to 1 μm,. The results are presented in Table 1, and, in a graphical way, in Fig.6.

Table 1

	$\varepsilon=(d_o-d)/d_o$				
d_o, μm	□d=1 μm	□d=0.8 μm	□d=0.6 μm	□d=0.4 μm	□d=0.2 μm
9	1.03E-03	6.59E-04	3.70E-04	1.65E-04	4.12E-05
10	8.34E-04	5.34E-04	3.00E-04	1.33E-04	3.33E-05
11	6.89E-04	4.41E-04	2.48E-04	1.10E-04	2.75E-05
12	5.79E-04	3.70E-04	2.08E-04	9.26E-05	2.31E-05
13	4.93E-04	3.16E-04	1.78E-04	7.89E-05	1.97E-05
14	4.25E-04	2.72E-04	1.53E-04	6.80E-05	1.70E-05
15	3.70E-04	2.37E-04	1.33E-04	5.93E-05	1.48E-05
16	3.26E-04	2.08E-04	1.17E-04	5.21E-05	1.30E-05
17	2.88E-04	1.85E-04	1.04E-04	4.61E-05	1.15E-05

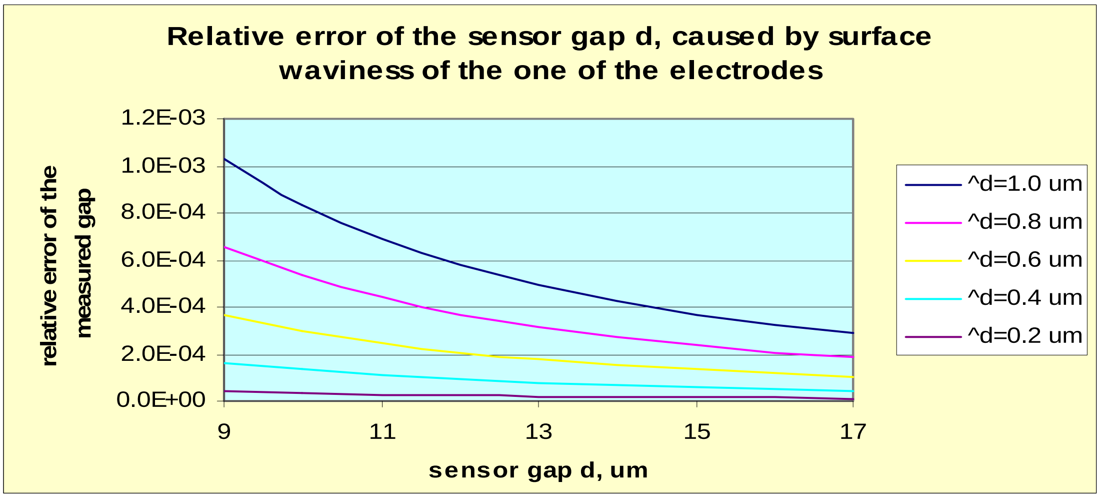


Fig. 6

4. Conclusions

- the surface waviness of the cap sensor electrode has a similar effect on the nonlinearly, as the electrode tilt;
- if the initial tilt of the sensor, due to mounting tolerances and non-parallelism, is specified to be φ (rad), the allowed height of the sensor surface waviness should be specified as $\Delta d < D.\varphi$, where *D* is the diameter of the sensing surface;

- with the increase of the spatial frequency of the roughness, the effect of its amplitude Δd is reduced due to local electric field effects. With spatial period and amplitude of the roughness 10 times smaller than the sensor gap, its effect on the nonlinearly is negligible;

5. REFERENCES

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