Effects of Targeting Spherical Surfaces with Capacitive Displacement Sensors

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1 Introduction

Within the field of precision engineering, capacitive sensors are used to sense fine motion, measure positioning error (e.g., straightness, squareness, and ball bars), and inspect workpieces (e.g., roundness, cylindricity, sphericity). Capacitive sensors present a relatively inexpensive, robust, and easy-to-use solution to these and other measurement challenges.

A common realization of the capacitive sensor is a sensing electrode and guard ring enclosed within a grounded sensor body. Fig 1 shows this configuration in a commercial sensor used in precision applications. The sensor is positioned perpendicular to a target electrode formed by a conductive surface in a workpiece, machine, or instrument. In many cases the target surface is flat, but other applications common in machine and workpiece metrology require curved target surfaces. For example ASME standards for evaluating machine tools [1,2] describe several tests to measure errors with capacitive sensors targeting spherical or cylindrical surfaces. Another example is the ultra-precision measurement of spindle error motion, which is usually made with capacitive sensors and lapped spherical artifacts [3,4].

It is standard practice for commercial capacitive sensors to be factory calibrated with flat target surfaces. This paper shows how measurements taken with sensors targeting spherical surfaces lead to four sources of error if the sensors are calibrated with flat targets. First, the sensitivity of the sensor increases resulting in exaggerated displacement measurements. Furthermore, the sensing range is both decreased and shifted towards the target. Finally, the otherwise linear output of the sensor system becomes increasingly nonlinear for targets of decreasing diameter.

To investigate the severity of these effects, a capacitive sensor (Fig 1) is evaluated with spherical targets having diameters less than 25.4 mm. Complexities in this sensor preclude a simple analytical model so an approach using the finite element method is used. The results from the finite element analysis are validated experimentally by comparing the output of two capacitive sensors, one targeting a flat reference surface and another targeting a spherical surface. The excellent agreement of the finite element and experimental results suggest that either approach is valid for quantifying these effects. The output of the sensor with larger spheres is easily corrected with apparent sensitivities, but the nonlinear effects with small spheres become so significant that accurate measurements are not achieved.

2 Capacitance as a Function of Gap and Target Diameter

The dimensions, geometry, and materials of a modern capacitive sensor may not measure a
capacitance that agrees with analytical solutions. However, finite element analyses (FEA) can determine the capacitances even when sensors are constructed with multiple electrodes, complex geometry, complex boundary conditions, or multiple dielectric materials. This section therefore describes an FEA procedure for capacitive sensors; although the details of the geometry are sensor specific, the procedure is general. The results of the FEA procedure are the lumped capacitance between the sensing electrode and spherical target as a function of two variables, the gap and the target diameter.

Capacitance values for many combinations of electrode gap and target diameter are necessary to reveal nonlinearities, so the analysis was conducted in ANSYS with a set of scripts that repeatedly model the geometry and calculate capacitance [5]. The 3D geometry of the cylindrical commercial sensor targeting a spherical electrode is reduced to 2D axisymmetric geometry to significantly reduce the number of finite elements and calculation time. The axis of symmetry coincides with the centerline of the sensor and the center of the spherical target. This analysis primarily uses a 2D quadrilateral element. Special quadrilateral elements are used at the perimeter of the geometry to accurately model infinite boundary conditions. Both types of elements have one degree of freedom at their nodes, voltage, used to calculate the potential function in the non-conductive volumes of the model.

The geometry of the model includes the sensing electrode, guard ring, body, target, epoxy insulators, and the air between the sensor and target. Only the areas for the dielectric material (epoxy and air) are meshed since there is no change in potential within the conductive electrodes. The density of the mesh was evaluated and adjusted to achieve reliable convergence with acceptable solution time. The density of the mesh is highly concentrated in the regions near the sensing element, with relatively large elements at the perimeter of the axisymmetric geometry.

An exemplary result from an electrostatic finite element analysis is shown in Fig 2. This contour plot shows the electric potential within the dielectric epoxy and air when a fixed potential is applied to the sensing area and guard ring while the housing and target are grounded. It is important to observe the potential gradients in the air gap between the sensing electrode and target and also in the epoxy that separates the sensing electrode from the guard ring. These gradients indicate the fringing of the electric field beyond the sensing electrode.

![Figure 2. Voltage potential within non-conductive volumes.](image)

Although the distribution of electric potential is of some qualitative interest, the capacitance between electrodes is more meaningful for assessing the effect of a spherical target. The three electrodes in the sensor and the single target electrode lead to four self-capacitances and six capacitances between electrodes. ANSYS provides the CMATRIX macro for determining the lumped capacitances in problems with multiple electrodes, and Smith [5] thoroughly demonstrated how this macro is used to determine the ten capacitances in the present problem. Since the electronics of the commercial sensor detect displacements by monitoring only changes in the capacitance between the sensing electrode and target, only one of these calculated values is necessary for this analysis.

The capacitance is calculated for spherical targets with diameters of 6.35, 9.53, 12.70, 15.88, 19.05, 22.23, and 25.40 mm. For comparison, the lumped capacitance is also calculated as a function of the gap for a flat target. The lumped capacitance is calculated with gap increments of 5.1 µm for the low sensitivity and 1.016 µm for the high sensitivity. Twelve to fifteen increments of the gap are analyzed for each spherical diameter. Capacitance values are not calculated for a spherical diameter of 6.35 mm and the high sensitivity since the required sensing range was unreasonably close to the target. A listing of the computed values for capacitance is available from Smith [5]. The values of capacitance for the low sensitivity range between 0.217 pF and 0.526 pF. The capacitances for the high sensitivity range between 0.593 pF and 1.822 pF.
3 Effects of Spherical Targets

The computed values for the lumped capacitance between the sensing electrode and target reveal four effects of spherical targets. As the diameter of the target is reduced, the sensing range decreases and the sensing range shifts towards the target. Furthermore, the apparent sensitivity and nonlinearity increase, which is more important to the accuracy of measurements. All of these effects become more pronounced when sensors have high sensitivity and the diameter of the target is small.

Fig. 3 shows plots of the inverse of the lumped capacitance between the sensing electrode and target as a function of the gap distance and the diameter of the target. For an ideal sensor, each curve should be a straight line with positive slope; recall that the sensitivities are defined as negative values, which changes the sign of the slope. Vertical lines show the minimum, nominal, and maximum gaps for a flat target, reflecting these lines onto the ordinate gives the inverse capacitances that correspond to the minimum, nominal, and maximum gaps for a flat target.

Using the data plotted in Fig. 3, the output voltage from the sensor’s electronics can be predicted. The output voltage is proportional to the difference between the inverse capacitance at the gap distance and a reference internal capacitance. Fig. 4 shows the predicted output voltage for various target diameters in the high sensitivity case. The change in slope of the curves indicates increasing values in the sensor’s sensitivity $S$, which results in exaggerated displacement measurements.

4 Experimental Validation

The finite element models described in the previous section can be experimentally validated using capacitive sensor systems and targets of varying diameter. The experimental hardware used for this validation allows comparison of the output from two capacitive sensors while minimizing the influence of off-axis motion and thermal gradients through thoughtful design.

Fig. 5 shows the hardware used to validate the finite element models. The two sensors are held in the same bracket so that any relative motion between one sensor and its target is equal and opposite to the relative motion between the second sensor and its target. The testing is performed on a precision Moore No. 3 Universal Measuring Machine with collinear sensors in accordance with the Abbe Principle to minimize the effects of any off-axis motions. The sensor bodies are aligned to within 20 arc-seconds of the axes of travel. During testing, the machine table is moved in the direction along the sensor axes.

The first (left hand) sensor always targets a precision-ground flat reference surface while the second (right hand) sensor targets either a flat surface for calibration or spheres of varying diameter. During calibration with two flat target surfaces the sensor output repeats within 20 nm and matches the manufacturer’s calibration data within 0.25%, which is negligibly small compared to the effects observed due to target diameter. This result confirms the accuracy of the sensor alignment, and the insensitivity of the experimental hardware to vibration, noise, and thermal drift.
Prior to testing, the importance of sensor centering and perpendicularity to the spherical target was explored experimentally. In practice, this is equivalent to finding the “high spot” on the target sphere. This geometric effect is not included in the axisymmetric finite element model and is difficult to completely eliminate in the actual hardware. By checking the repeatability of the comparative sensor output with different amounts of deliberate decentering, it was found that the effect is negligible for sensor centering within 50 micrometers of the high spot. It is straightforward to find the high spot to within 25 micrometers or better using the three axes of the Moore measuring machine, thereby satisfying this requirement. Once the highest point on each sphere is found, both capacitive sensors are adjusted axially in the sensor bracket such that each sensor is within one micrometer of the middle of its sensing range (nominally zero Volts from the sensors’ electronic output).

During each test, the machine is slowly actuated while both sensors measure several full cycles of motion over the sensing range. When the two sensors target flat surfaces, the output is linear over the range of travel. However, the relationship becomes nonlinear when a spherical target replaces the second reference flat. As predicted by the finite element results, the comparative sensor output shows a nominally linear relationship with additional higher-order behavior. The data show both the apparent sensitivity of the spherical target (the linear portion) and the nonlinear residual. The experimental results show excellent agreement with the finite element models. The maximum discrepancy between model and experiment was less than 2% for the -0.394 V/micrometer sensor system less than about 8% for the -1.969 V/micrometer sensitivity.

The experimental measurements with flat targets show residuals consistent with the manufacturer’s calibration data sheet. The experimental results with spherical targets show increasing nonlinearity with decreasing sphere diameter, again consistent with theoretical results.

5 Conclusion

Capacitive displacement sensors for precision manufacturing and metrology are often used with spherical targets despite being calibrated with flat surfaces at the factory. This paper elucidates four effects of this standard practice. First, the sensitivity of the sensing system increases, which tends to exaggerate actual displacements. Second, increases in the sensitivity reduce the size of the sensing range. Third, as the diameter of the target electrode decreases, the sensing range shifts closer to the target electrode. Fourth and perhaps most important when striving for accurate measurements, the relation between the output voltage and displacement becomes increasingly nonlinear as the diameter of the spherical target decreases.

The finite element analysis and the experimental approach described in this paper prove to be equally valid techniques for quantifying these effects in a particular capacitive displacement sensing system. For a representative sensor, these approaches indicate that the error in sensitivity may be as much as 150% and that the nonlinearity may prevent accurate measurements with small diameter targets. Furthermore, the sensing range can shift so near the target that it becomes essentially impossible to even make measurements.

Since these effects lead to measurement error, precision manufacturing and metrology applications requiring the highest accuracy should correct the output of the sensor or use sensors factory calibrated with a particular spherical target. For all but the smallest targets, sufficiently accurate measurements are obtainable with corrected sensitivities. For the smallest spheres where nonlinearities are significant, a higher order correction is likely necessary. Alternatively, using a sensor with a smaller sensing area can reduce the error, and this aspect can be investigated in future work.

6 References


