

Design and Manufacture of a Capacitance Probe for Hole Metrology

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1 Introduction

As the precision requirements for machining mechanical features become more demanding and the sizes of such features are reduced, new measurement tools and metrology techniques must be developed. One such precision metrology problem is the measurement of small holes with diameters less than a few millimeters.

Current probe technologies incorporate combinations of electronics or optical sensors and miniature contact probes, the former being used to sense contact by the latter [1, 2, 3]. A hole is measured at multiple points by approaching the surface from the normal direction multiple times. This limits the wavelengths of features that can be detected in the hole surface, and decreasing the sampling distance between measurements greatly improves the ability to measure waviness and roughness within the hole surface. Therefore a continuous measurement of the complete inner surface of the hole is not typically achieved.

This paper presents the design and manufacture of an initial prototype capacitance probe for measuring the inner surface of holes approximately one millimeter in diameter in any conductive material. In this technique, the probe will sense the inner surface by using non-contact capacitance micrometry, which allows for much smaller sampling distances and many overlapping data points to be collected quickly using a rotating probe.

The typical arrangement of conductors on a capacitance sensor includes a flat, circular sensing area surrounded by a guard ring structure, both on a common plane. This geometry yields a very sensitive sensor with high linearity when targeting flat, conductive surfaces that are parallel to the sensing area. However, linearity can decrease substantially when the target surface is not flat [4, 5]. A capacitive probe for small hole metrology will naturally have a cylindrical target surface and can be designed with a cylindrical sensing window. This design described in this paper uses a section of a cylinder wall as the sensing window, minimizing the gap distance and therefore maximizing sensitivity.

The size of the sensing window, approximately 400 micrometers by 800 micrometers, is a balance between lateral resolution, depth resolution, and electronics sensitivity. The optimal probe will be only a few micrometers smaller than the hole it is measuring, therefore this design prefers a custom probe for each type of hole encountered, rather than a generic hole probe suitable for a wide variety of diameters.

For a rectangular window in close proximity to the target surface, the simplest approximation of capacitance can be used to estimate a value for the capacitance of the system. This simplified model is based on parallel plates, which are governed by Eq. (1), where ϵ_0 is the absolute permittivity of free space, ϵ_R is the relative permittivity of the dielectric medium, A is the sensing window of the probe, and d is the gap distance to the target surface.

$$C = \frac{\epsilon_0 \epsilon_R A}{d} \quad (1)$$

For a gap distance of 260 micrometers and a relative permittivity of 80, this capacitance is approximately 1.3 pF.

Three-dimensional finite element modeling helps predict the linearity and sensitivity of this probe design beyond that available by simple closed equations. With these finite element models, a specific probe design can be selected that has both sufficient lateral resolution for sensing hole features, as well as sufficient capacitance for the available electronics.

The probe is manufactured using μ EDM to both shape the probe and smooth the surface. Subsequent steps deposit an insulating layer and a conductive guard layer to the outside of this probe. A section of the dielectric and guard layers is etched away to expose the inner conductor. The conductive sensing window and guard layer must be connected to a sensitive bridge circuit to measure changes in the capacitance of the probe and target system as the inner surface of the hole is examined [6, 7].

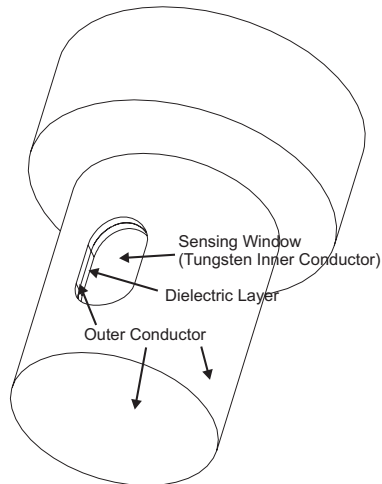


Figure 1. Capacitance Probe Design.

Because this probe can make continuous measurements of the form of the hole, several possible patterns can be tracked when mapping the interior surface. Successive, overlapping passes provide a complete, albeit averaged map of the inner surface at the resolution of the sensing window. This method, while providing limited resolution as compared with a smaller diameter contact probe, does have the advantage that the entire surface can be viewed by the probe, rather than individual, isolated points.

2 FEA Simulations of Probe Geometry

Finite element analyses (FEA) can determine the capacitances of sensors that are constructed with multiple electrodes, complex geometry, complex boundary conditions, or multiple dielectric materials. This section describes the FEA procedure applied to this capacitive hole probe; 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 window and the inner surface of an idealized cylindrical hole.

A parametric CAD model (in Pro/Engineer) was constructed of the geometry of the capacitance probe, hole surface, and dielectric between the hole and probe. Since the dimensions of the probe are determined by several parameters, the model for the probe and target surface could easily be modified as needed. These components are shown in Fig. 2, including the cylindrical probe, half of the cylindrical target surface, and a volume of dielectric connecting the two. The volume of dielectric is necessary for FEA of the space between the conductive electrodes, where the potential function and electric field are present.

Using the CAD model, the position of the probe and the target surface can be varied, and the geometry of the dielectric volume can automatically be determined for each position. This enables determination of how the capacitance varies with gap distance and eventually the

study of edge effects when the probe is near the entrance or exit of the hole.

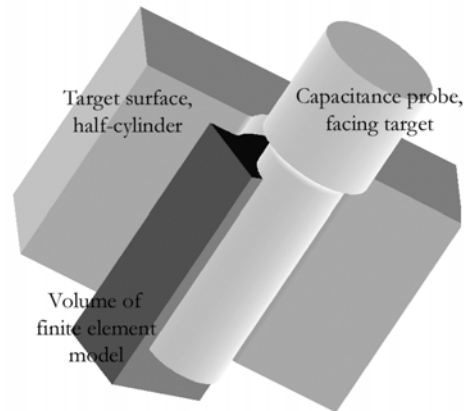


Fig. 2. Computer Model of Capacitance Probe, Target Surface, and dielectric volume.

The geometry of the dielectric volume is meshed and boundary conditions are applied in the CAD software, where it is simple to specify the sensing window and target hole surfaces. A conductive heat transfer FE model is setup in the CAD software. This is more analogous to an electrostatic analysis since the single degree of freedom, temperature, is analogous to the electric potential within the dielectric. Fixed temperatures are applied to the three conductive surfaces of the dielectric volume. These fixed-temperature boundary conditions are analogous to fixed-voltage boundary conditions in the electrostatic analysis. The volume is then meshed with quadratic tetrahedral elements. 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 edge of the sensing element, with relatively large elements elsewhere in the dielectric volume. As an example, the finite element mesh and boundary conditions for one particular gap distance (220 micrometers) is shown in Fig. 3.

The mesh is then exported for use in the FEA software (Ansys), where a wider range of element types and electrostatic analyses are available. The Ansys script generated by the ProEngineer software consists of node locations, element definitions, and boundary conditions. Since this script specifies conductive heat transfer model, the script must be revised before being imported into Ansys. The temperatures applied to the CAD model serve as placeholders to allow easy grouping of nodes by associated conductor. The modified Ansys script uses elements that have one degree of freedom at their nodes, voltage, used to calculate the potential function in the dielectric volume of the model.

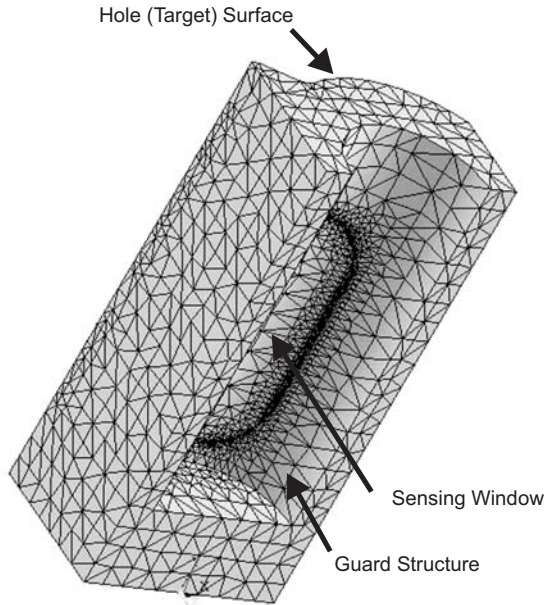


Fig. 3. Finite Element Mesh of Probe and Inner Surface of Hole.

Once the proper element type is applied to the mesh, a solution of potential values at each node is calculated by Ansys. Once such solution is shown in Fig. 4, with different grayscale levels representing different voltage potentials between the various conductors.

As described by Eq. 1, the simplest model of this system is that of infinite parallel plates. For this idealized case, the electric field is perpendicular to the conducting surfaces, and the distribution of potential is linear across the gap. In the actual system, many factors cause this potential to vary from linear, including fringe effects at the edge of the sensing window and curvature of the electric field lines due to varying gap width.

Although the distribution of electric potential is of some qualitative interest, the capacitance between electrodes ultimately needs to be determined. The two electrodes in the sensor and the single target electrode lead to three self-capacitances and three capacitances between electrodes. Ansys provides the CMATRIX macro for determining the lumped capacitances in problems with multiple electrodes, and Smith [8] thoroughly demonstrated how to use this macro to determine capacitances for sensing applications with guard rings.

The FEA is then conducted at several gap distances. Then, the inverse of the capacitance values are plotted in Fig. 5 as a function of relative displacement. As can be seen from this plot, the relationship between inverse capacitance and displacement is nearly linear. The x-intercept can be extrapolated from the data, which corresponds to an infinite capacitance, or a gap distance of zero. Because the surfaces are not precisely parallel, this crossover is considered the “effective zero.”

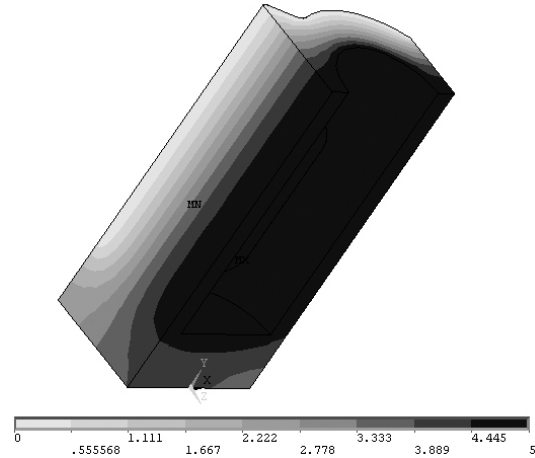


Fig. 4. Solution of Electric Field Potential Between Probe and Target.

3 Manufacture of Prototype Probe

There are four steps required in manufacturing the cylindrical probe. The first step in manufacturing a prototype probe is to apply WEDG μ EDM [9] to shape the central, cylindrical conductor to the proper diameter. The WEDG μ EDM process uses a copper wire to shape a tungsten electrode. The electrode rotates to produce axially symmetric shapes, while the wire is slowly spooled to refresh the working surface. The Panasonic MG-72 Micro Electro-Discharge (EDM) machine includes several different capacitors as well as programmable voltage in the RC circuit.

Using a multi-pass technique, the surface of the probe is first roughly shaped using capacitances and voltages that maximize the material removal rate. Subsequent passes use a lower voltage and smaller capacitance, with the result that the surface has features typically smaller than a micrometer, as demonstrated by Morgan et al. [10]. Fig. 6 shows the shape of the probe, including a larger diameter shaft where electrical connections to the capacitor are made, and the smaller shaft that includes the probe. Although this probe is about 750 micrometers in diameter, probes of 100 micrometer diameter and large aspect ratios have been achieved using the same techniques.

The surface was analyzed using a 3D surface profilometer (Zygo NewView 500) with sub-nanometer resolution, which is ideal for surface roughness measurements. A 50x objective was used, resulting in an image area of 0.11 by 0.15 mm of the smallest diameter of the probe. The larger diameter shaft, which was created using two passes of the machining wire, had an RMS value of 0.47 micrometers and an R_a value of 0.39 micrometers. The smaller diameter, which will contain the sensing window, had an RMS value of 0.28 micrometers and an R_a value of 0.22 micrometers.

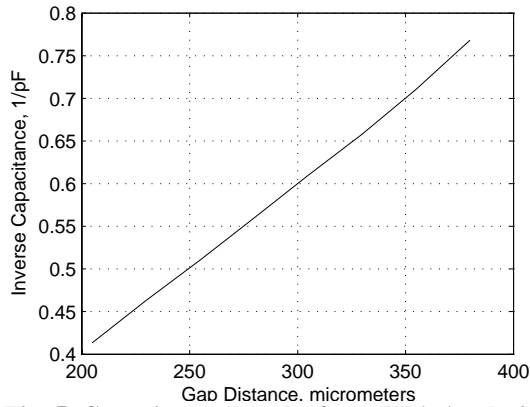


Fig. 5. Capacitance Results from FEA Analysis.

Next, a non-conductive oxide coating is deposited on the entire surface of the probe. This coating of alumina must be applied as uniformly as possible, so e-beam deposition was selected as the optimal method. The machined probe was cleaned to remove any residue of oil from the machining process using RCA1 and an acetone bath. The probe was held in a custom mount that suspends the probe vertically within the chamber.

The initial coating of alumina was applied to a probe with larger surface roughness than the subsequent probe analyzed using the Zygo interferometer. When this probe was tested for conductivity, a low resistance was measured in some areas. It is possible that the coating of approximately 2 micrometers was insufficient to cover entirely the rough surface of the probe, or the coating did not properly adhere to the probe.

The next step to be applied to the probe is to deposit gold over the entire probe, providing the same function as a guard ring in a traditional capacitance probe. Because of the expense in applying this layer of gold, the oxide coating should be improved further before this step is applied.

The final step in the manufacturing process is to use a tubular nickel mask and photolithography, to etch a small window through the gold and oxide coatings along one side of the cylinder. The mask is also machined using the Panasonic Micro EDM. This opening creates the sensing window of the capacitance probe, and it is this window that is used to profile the inner surface of the hole.

4 Conclusion

Non-contact probes have been shown to offer advantages in surface metrology in many applications. For measuring the inner surface of small diameter holes, contact probes have been used to make measurements at several points along the surface.

A new design for a capacitance probe allows the entire inner surface of the hole to be scanned. The structured of the probe is machined using μ EDM techniques developed at the University of Kentucky. Layers of additional material are added to the probe using e-beam evaporation to complete the geometry.

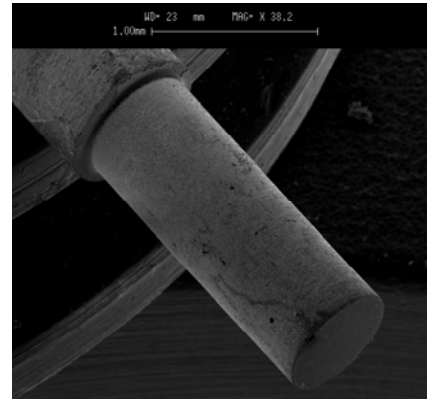


Fig. 6. Electron Micrograph of Tungsten Probe.

The probe provides an average value over the sensing window, whose shape can be optimized for a particular application. Finite element analysis can predict the performance, including linearity and sensitivity, of a probe for each individual operating condition.

5 References

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