PRECISION MEASUREMENT OF SMALL DIAMETER HOLE IN A METALLIC OBJECT

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INTRODUCTION

There are a number of industrial applications such as in the aerospace and disk drive industries, which require precision measurement of small diameter holes with high aspect ratio. Some of the standard measurement systems, such as optical techniques, while capable of characterizing holes on the surface of the work piece, would face difficulties in characterizing the interior of a hole especially if the latter is a non-through hole. A novel vibroscanning method has demonstrated the possibility measurement of a 125um micro hole with level of precision better than 0.5um [1,2]. However, this technique requires a special probe, which is not widely available. Because of this, CMM using mechanical probe is still commonly used in industry. However, using CMM for small hole measurement has certain drawbacks. It is expensive, time consuming, and is a contact measuring technique. Also it is difficult to use CMM for the measurement of very small diameter holes. Therefore it is desirable to develop an alternative, more widely available cost effective precision approach.

Capacitance sensor may be a good solution as it is cost effective, widely available, and has been used for measurement of fastening holes for the aerospace industry [3]. It is the objective of this paper to refine this technique for the measurement of small diameter high aspect ratio holes. It is also the objective of this paper to see the level of precision of measurement which can be achieved using the capacitance sensor.

There is a challenging issue facing the capacitance measurement system for a small diameter hole with high aspect ratio. As the hole is small and deep, it is not practical to make the capacitance sensor much smaller than the diameter of the hole. As a result, the capacitance sensor inside the hole has the tendency to pick up signals from various regions of the hole. Therefore, an efficient way of deciphering the integrated capacitance signal for the profile of the hole is necessary. Different types of capacitance sensors have been designed, and the test results have been compared. These test results have also been compared with CMM measurement. Our preliminary result shows that the level of precision of 0.1um can be achieved by this technique. This level of resolution is more than an order of magnitude better than the small measurement technique using CMM. It is also more than an order of magnitude of improvement over the previous recorded result [3].

CAPACITIVE SENSING METHOD

In order to determine the physical geometry of a conductive work piece, the capacitance between a sensor probe and the work piece can be applied and correlated to its dimensions.. Simply speaking, for an ideal two plate capacitor, the capacitance depends on the size and shape of electrodes, distance between the two electrodes and the dielectric medium between them. If the size and shape of electrodes and the dielectric medium can be kept constant, distance variation between the probe and work piece can be interpreted.

The principle of capacitive sensing method for a small hole measurement is just applying the same concept to determine the small hole diameter from the capacitance between a cylindrical sensor probe and a small hole. In theory, the capacitance between a hole and a centering cylinder is given by

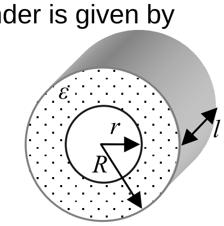

Figure 1. Coaxial cylinders.

$$C = \frac{2\pi\varepsilon l}{\ln(R/r)} \quad (1)$$

Taking a 2.8mm hole with a 2.4mm sensor probe as an example, the capacitance versus hole sensor probe is plotted in *Figure 2*.

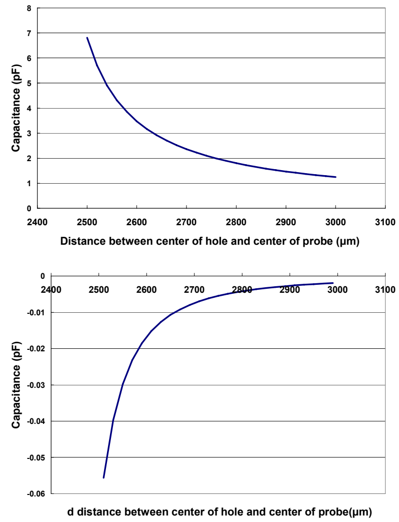

Figure 2. (Top) Capacitance signal distribution inside a hole for different hole diameters. (Bottom) Sensitivity of capacitance change with hole diameter.

Comparing the capacitance signal with the sensitivity of the capacitance change, the capacitive method in measuring hole diameter is feasible and a 6pF range with 16 bit resolution capacitance meter (less than 1fF resolution), which is common and easily found in the market (like Lion Precision and HP), can be used for this purpose. In this research, a simple, self-developed and low cost capacitance to voltage meter was used and a good performance was still achieved.

There are quite a few advantages in selecting the whole center capacitance for calculating the diameter. First, it is easy to find. Only one measuring point is needed during measurement. Fast throughput of the machine can be reached. Second, the capacitance change within the center region is quite flat (*Figure 3*). This implies that a simple alignment mechanism is good enough for the probe alignment. In a more robust case, for an eccentric cylinder configuration, the formula of capacitance can be determined as

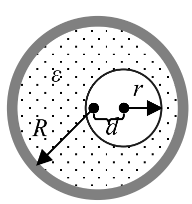

Figure 3. Eccentric cylinders of the same length l.

$$C = \frac{2\pi\varepsilon l}{Cosh^{-1}\left(\frac{R^2 + r^2 - d^2}{2Rr}\right)} \qquad (2)$$

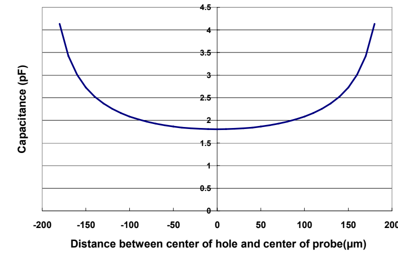

Figure 4. Capacitance signal distribution inside hole for a different probe location.

In this paper, the diameter of hole is calculated from the centered probe capacitance signal which is the minimum capacitance location between the probe and a hole. No matter how large or small the hole, there must be a minimum capacitance location. Thus, a universal reference between a hole and the probe can be found and the complexity of equipment setup can be simplified.

PROTOTYPE EQUIPMENT

To prove the practical applicability of this method, prototype equipment was built and actual measurements were carried out. The whole system architecture is as follows:

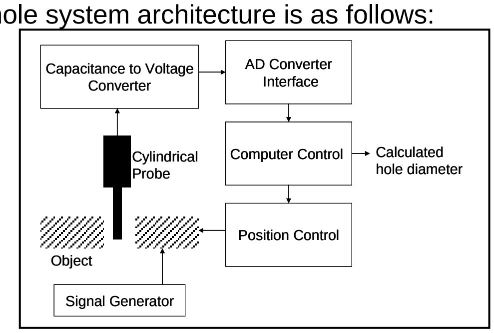

Figure 5. System Flow of the prototype equipment.

There is a basement for mounting all the equipment on it. This mounting bed is used for mounting the sample and the capacitive probe in position for the experiment. The hole sample is mounted in the X & Y direction stage which is controlled by two computer-controlled actuators for the centering of the probe. The cylindrical capacitive probe is mounted on the L stage for hole insertion. In the experiment, when the sensor probe is inserted to the hole, the computer controlled x, y stage will search the minimum capacitance position automatically. Within 10 seconds (depends on the speed of the actuator), the minimal capacitance was recorded by the computer. Figure X shows the experimental set-up.

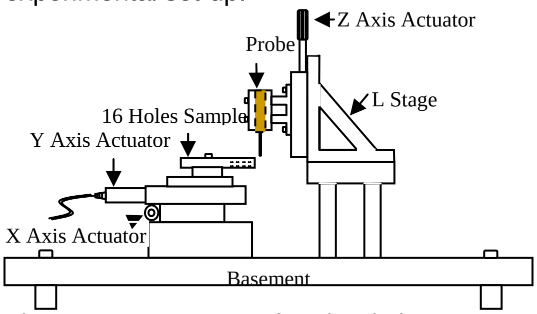

Figure 6. Component for the hole measurement systems setup.

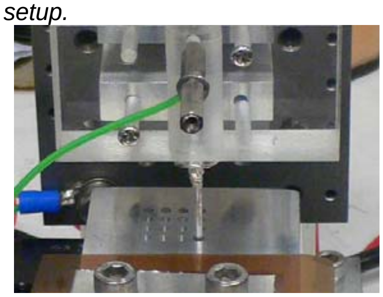

Figure 7. Sensor Probe is inserted into the hole of the sample.

EXPERIMENTAL RESULTS

In the first preliminary experiment, a 16-hole sample was used for calibration and measurement. The holes was drilled by CNC machine and the size of holes start from 2.6mm to 2.9mm with 20um difference each.

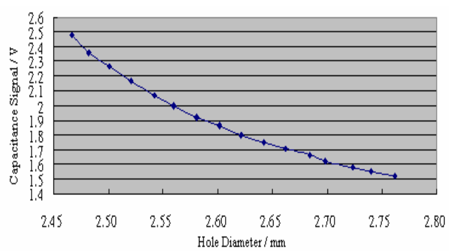

Figure 8. Experimental result for the capacitance to hole diameter.

From the experiment, a clear relation between the capacitance and hole diameter was found. From the *Figure 8*, the sensitivity of hole diameter (delta Capacitance / delta hole diameter) is equal to 0.028pF/um. With reference to our capacitance measuring equipment, less than 1fF resolution of capacitance can be detected. This implies that a less than 0.03um resolution of hole diameter can be achieved through this system configuration.

However, in practical situations, there is a difficulty to reach this high resolution for a rod sensor probe. When the probe is inserted into the hole, the capacitance is accumulated due to the increase in sensing area. The capacitance change is not as flat as the change in horizontal movement. From *Figure 9*, the capacitance between probe and hole keeps increasing when the probe is entering the hole (~1000fF/micron). As a result, if the height alignment of the sensor probe is not repeatable, there will be a large deviation of the measurement in hole diameter.

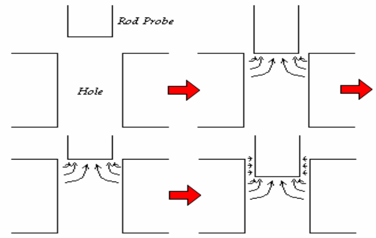

Figure 9. Rod probe is inserted into a hole.

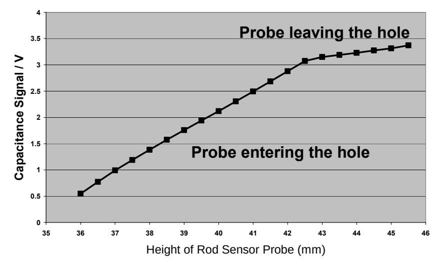

Figure 10. Rod probe signal with different height level.

On the other hand, rod probe can only be used to measure the average hole diameter of upper hole or the whole through-hole. The measurement of hole diameter at different heights level cannot be measured. Due to this reason, a disk probe (*Figure 11*) was developed for improvement.

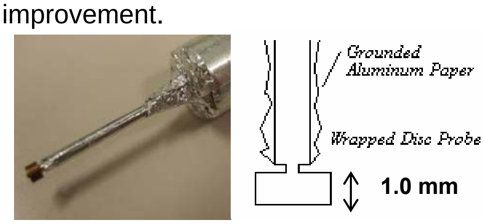

Figure 11. Design of a disk shaped ground shielded probe.

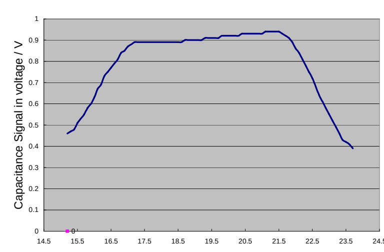

Figure 12. Effect of capacitance change for disk probe with different probe Z level.

By using the disk probe configuration, the error due to Z axis alignment is reduced by 60 times. Although the signal strength of the probe is reduced by 5 times (<0.15um resolution), the reduction in Z alignment error can compensate the loss.

TABLE 1. Effect of capacitance change for rod and disk probe with different probe Z level.

Probe	Cylindrical	Shielded Disk
Sensitivity Z level	1000 fF/um	16 fF/um
Error in diameter	0.035um/um	0.008um/um

With the help of the ground shielding disk probe, the high resolution of diameter measurement can be easily achieved by low resolution and cheap Z axis actuator. The hole diameter in different high levels can also be measured. Even for holes with 2 or more arms like *Figure 13*.

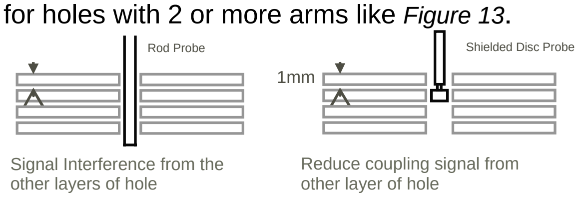

Figure 13. Effect of capacitance change for rod and disk probe with different probe Z level.

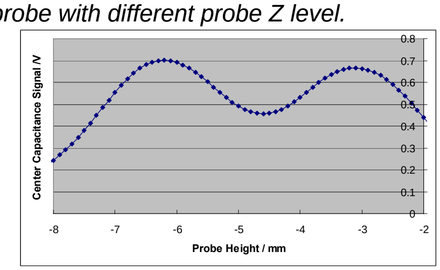

Figure 14. Effect of capacitance change for two holes in different Z level.

Within the +/- 200 um in the peak capacitance value, the slope of capacitance is limited to +/- 0.1 pF/mm (0.1fF/um). In comparing with the sensitivity of disk probe, 2fF/um, the error caused by Z level is acceptable.

CONCLUSIONS

Capacitive sensing method proved an opportunity for the industry to use low cost equipment to achieve a considerably high resolution performance. For some hole measurement applications, the circularity and the profile of a hole may not be interesting. Capacitive sensing method would be a sensible choice. In practice, cost is always in a consideration. In capacitive measuring systems, probe and circuit board are easily acquired a low prices (less than US$1,000 for a probe and circuit) by mass production.

Two types of probe are shown in this extended abstract, the rod probe and disc probe. Generally speaking, A disc probe is much better than a rod probe as the measurement results have fewer errors caused by misalignment of probe height. However, both probe designs can perform their best by being applied in different situations. Rod probe is best used to measure very small, thin through holes (low aspect ratio) with thicknesses of 1 – 2 mm. The probe can be inserted through the hole. The entire signal received by the probe comes from the thin hole. The effect of the depth of the probe position is reduced. The disk probe can be used to measure hole diameters at different height. Moreover, for a series of holes like a disk drive actuator, the disc probe performs well.

In comparing with the cycle time for measuring a hole, capacitance probe measurement measures much faster in compared with the traditional CMM probing. Using CMM requires quite a number of sample points so as to determine the average diameter of a hole. It takes at least one or a few minutes to find out the result. By using capacitance method, only the time for center searching is needed. As proved in the previous paragraph, the position of centering does not need to be accurate and line scanning would be even possible.

ACKNOWLEGEMENTS

The work described in this paper was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKUST6001/06E)

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