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Ultraprecision 3D probing system based on spherical capacitive plate

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ABSTRACT

In order to make ultraprecision dimensional and profile measurement of small structures with large aspect ratio possible, a 3D probing system based on a spherical capacitive plate is proposed for use in making 3D non-contact probing at nanometer resolution. A spherical capacitive plate with identical sensing characteristic in any arbitrary spatial direction is used to convert the micro gap between the plate and the part being measured into a capacitive signal. Most of the electric lines of force of the spherical capacitive plate concentrate within a small region between the plate and the part being measured, so that the properties of 3D non-contact probing, isotropy characteristics, approximate point sensing and measurability of small structures with large aspect ratio are effectively combined in one probing system. Experimental results indicate that when a 3 mm probing head is used, the probing system has a resolution of better than 5 nm. With nonlinearity corrected, the residual nonlinear error is less than 10 nm in the full-range. The proposed system can therefore be used for submicron measurement of small structures with dimension larger than 3 mm and depth down to 100 mm.

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1. Introduction

More and more small structures with large aspect ratio, such as holes with diameters in the range of 3–10 mm and aspect ratio above 10 are used in aviation, aerospace and automotive industries in recent years. These precision machined structures have aspect ratios up to several tens and even several hundreds. And so, they present challenges to the measurement precision and measurable depth of existing probing systems.

With a long stylus or extension rod, a spherical contact probe can go deep into an industrial part. However, unavoidable stylus bending and contact deformation of probing head and part being measured make the stylus aspect ratio of a high precision contact probe hardly exceed 5:1. Especially when the diameter of a spherical probing head is below 1 mm, the influence of contact deformation on the measurement precision is very serious. Probing forces of the low force 3D probe developed by Kung et al. [1] and the pneumatic ball probe developed by Takamasu et al. [2] can reach mN order, but high precision and large stylus aspect ratio cannot be obtained at the same time. A patented "Tip Sensing" technique [3] has been proposed to compensate the stylus bending due to probing force and inertia. However, the contact deformation of the probing head and the part being measured cannot be compensated.Non-contact probing techniques, especially optical probing techniques are promising to make a breakthrough in measurement precision and measurable depth. And so, many precision measuring instrument manufacturers tried hard to develop non-contact probes. However, existing non-contact probes based on principles of magic eye, eddy current [4], capacitance sensing [5] or pneumatic sensing [6] usually have low precision and principle shortcomings of average effect and so on. High resolutions can be obtained with some optical probes [7,8] such as confocal probes, but their sensing characteristics can be easily influenced by the surface finish and/or material characteristics of the part being measured. With quick development of MEMS and micro/nano metrology techniques, a variety of micro and nano probes [9–11] with nanometer resolution and large stylus aspect ratio have been proposed. However, they are usually used for ultraprecision measurement of microstructures on millimeter or micrometer scale, and their measurable depth is usually limited to millimeter order.

It can be seen that existing probing systems can hardly meet the requirement of ultraprecision measurement of small structures with large aspect ratio in measurability, precision or measurable depth. So an ultraprecision 3D probing system based on a spherical capacitive plate is proposed, in which the properties of 3D non-contact probing, isotropy characteristics and approximate point sensing are effectively combined, and measurement of small structures with aspect ratio above 10 is made possible.

2. Principle

The proposed ultraprecision 3D probing system is based on a technique we are now applying for patents [12]. As shown in Fig. 1, micro gap δ is between the spherical probing head and the part

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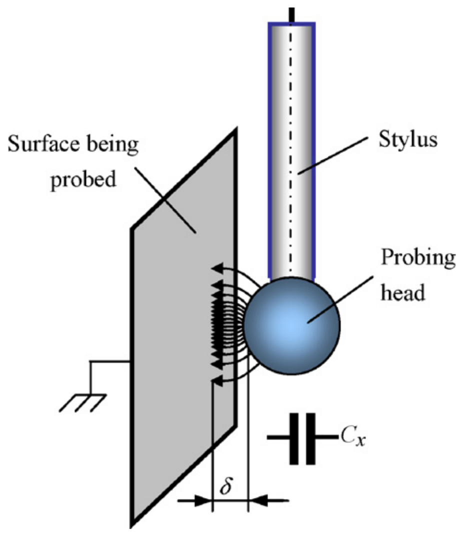

Fig. 1. Principle of spherical capacitive plate.

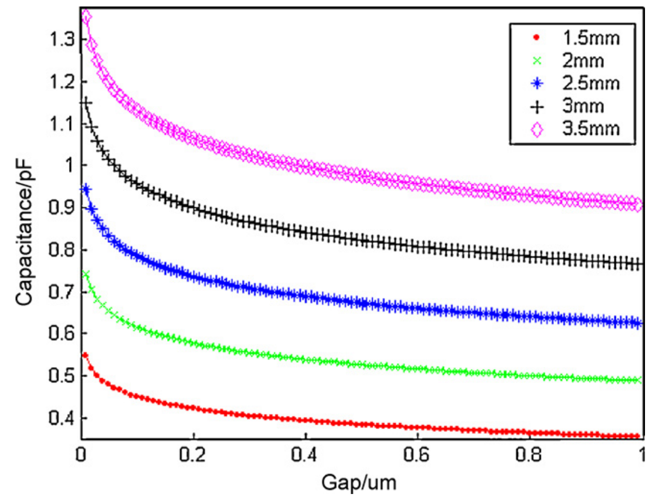

Fig. 3. C_x–δ curves of spherical capacitive plates.

being measured which is earthed, and capacitance C_x is formed between the spherical capacitive plate over the surface of the probing head and the part being measured. For the electric field between the spherical capacitive plate and the part being measured is a non-uniform 3D spatial field, it is difficult to calculate the distribution of electric field by solving Laplace equation. So electrical image method [13] is used here to calculate the value of C_x.

As shown in Fig. 2, the diameter of spherical capacitive plate is D, and the center of sphere is O. Assuming the distance between O and the surface being probed is d, then $d= D/2+\delta$. According to electrical image method, when charge $+q_1$ is set at O, the image charges which are successively generated are $-q_1$, $\pm q_2$, $\pm q_3$, $\pm q_4$, ..., and the distances between charges $+q_1$, $+q_2$, $+q_3$, $+q_4$, ... and O are l_1, l_2, l_3, l_4, ... respectively:

$$\begin{cases} l_1 = 0 \\ l_n = \dfrac{D^2}{4(2d - l_{n-1})} \\ q_n = \dfrac{D}{2(2d - l_{n-1})} q_{n-1} \end{cases} \tag{1}$$

Assuming the potential of the spherical plate is φ, then φ is determined only by $+q_1$:

$$\varphi = \frac{q_1}{2\pi\varepsilon D} \tag{2}$$

where ε is the dielectric constant of air.

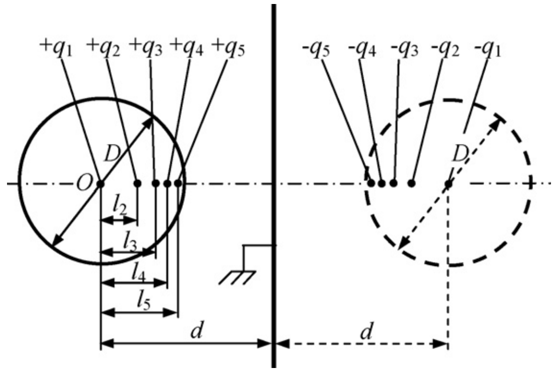

Fig. 2. Charge series in electrical image method.

According to the definition of capacitance:

$$C_x = \frac{q}{\varphi} = \frac{\sum_{n=1}^{\infty} q_n}{\varphi} = 2\pi\varepsilon D\left(1 + r + \frac{r^2}{1-r^2} + \frac{r^3}{1-2r^2} + \frac{r^4}{1-3r^2+r^4} + \frac{r^5}{1-4r^2+3r^4} + \ldots\right) \tag{3}$$

where $r = D/4d$.

The sensitivity of C_x to micro gap δ can be obtained by differentiating equation (3): $S_x = \partial C_x/\partial\delta$. It can be seen from Figs. 3 and 4 that: (1) the sensing characteristics of the probing system are theoretically nonlinear, and the nonlinearity needs to be corrected during signal processing; (2) the measurement of a capacitive signal of 0.1aF or even weaker needs to be achieved to obtain a nanometer resolution, so there is a requirement for the anti-stray capacitance performance of the probing system.

On one hand, the sensing characteristic of the spherical capacitive plate is identical in any arbitrary spatial direction, so that the sensing characteristic and measurement precision will not be influenced when the probe is re-mounted and/or the depth being measured is changed, and structures with very large aspect ratio can be probed. On the other hand, most of the electric lines of force of a spherical capacitive plate concentrate within a very small region between the plate and the part being measured, which

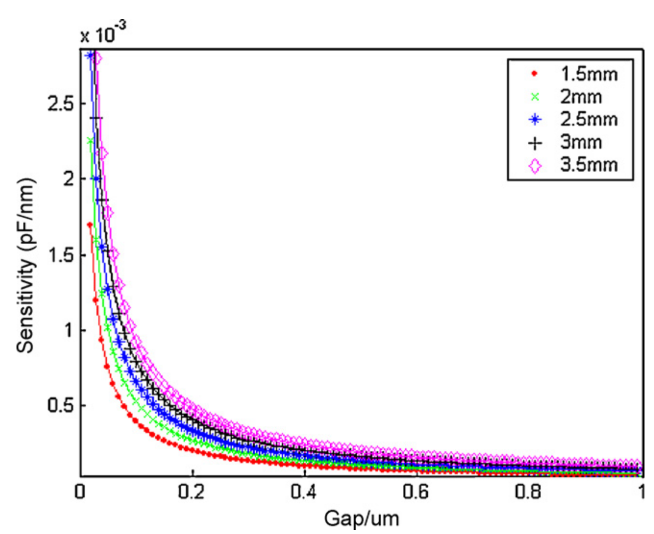

Fig. 4. S_x–δ curves of spherical capacitive plates.

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