Design of a Tactile Measuring Probe for Coordinate Measurement

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Abstract: Probes are major components of coordinate measuring machines. They contribute to a large extend to measurement uncertainty of the CMM. In this paper a new low cost design is presented. The moving element of the probe head consists of the stilus and a tripod as intermediate body with a small aluminium enhanced mirror at each end. The intermediate body is suspended on three sping made of berillium-copper folies. The displacement of the probe tip is calculated of the from the displacement of the three mirrors measured by modified optical pick-ups and rotation The static and dynamic behaviours of the probe is discussed. The theoretical results are experimentally verifyed.

Keywords: measuring probe, optical sensing, submicron resolution, coordinate measurement

1 Introduction

As technology advances, the requirement for parts and product quality becomes more and more stringent. Measurement uncertainty in the nanometer range was first introduced in 3D coordinate measurement of micromechanical elements. The was recognized that the uncertainty is mainly determined by the accuracy of the sensing probe, thermal drift of the probing point and the metrological frame. The development of probes with a measuring uncertainty far below 0,1 μm will be an important contribution to the above mentioned goal.

The probe performance is effected by a number of factors, which have to be taken into account in the design process. Geometric errors are inherent to manufacturing and assembly. Due to the limited accuracy of these processes, the probe can show inaccuracies. A typical example of the limited manufacturing accuracy is the deviation from the sphericity of the probe tip. Typical assembly error is the misalignment of the transducers. Due to finite stiffness. the probing force causes a bending of the stylus. Probing force also causes elastic deformation of the surface sensed and the tip ball due to Hertzian stress. The extent of the deformation depends on the materials, micro- and macrogeometric forms and the force.

Internal and environmental influences can introduce thermal distortion, which in turn, effect the probe accuracy. Drift is a typical example of such an error. Also the location of the stylus tip can seriously change due to thermal expansion of the stylus. Deflection resulting from thermal destortion can be avoided by designing thermally symmetric structures.

Displacement of the probe tip can be determined either by measuring the deformation of the probe suspension using strain gauges, or by measuring the the gap using capacitive distance sensors. Strain gauges glued to the stressed surface, that may show hysteresis and creep, which results in measurement uncertainty. Strain gauges integrated into the suspension by microelectrinic technology show anisotropy and sensitivity to temperature variation.

An other solution is given by the usage of capacitive displacement sensors. Their advantage is that they provide nanometer resolution on a relative large – 100µm – range. The disadvantages are their environmental dependence, their tilt and target form sensitivity and the connected high costs.

An alternative solution is provide by optical sensors eliminating the majority of the disadvantages described in the previous paragraphs. The most costeffective solution is based on the autofocusing probe applied in commercial products as CD and DVD drives. That was the reason that we have decided to use it in our probe. The working principle is described in one of the subsequent paragraphs.

Hysteresis is a residual error that occur when the load on a loop of structural components is increased and decreased in a cyclic way. It is caused by friction between the components and by internal material properties. Because the force due to measurement is not of cyclic nature hysteresis errors can not be predicted, so they should be avoided. Usage of flexures is advantages because they exibit neglectible hysteresis.

2 Probe Construction

In the last year a number of various probe constructions has been built in order to investigate their properties under different circumstances. One of them is the tripod structure described subsequently. The flexture structure is made from tungsten carbide tubing (intermediate body) and beryllium-copper strips as given in Figure 1. This construction is stiff and light. The moving part weights only 500 mg. The suspension is isotropic and its stiffness is 10 N/m.

The probe has a measuring uncertainty is 50 nm. The probe was designed to operate with a standard probing force of 0,2 mN, corresponding to a pin deflection of 10 µm. The resolution of the probe is determined by the resolution of the optical pick-up.

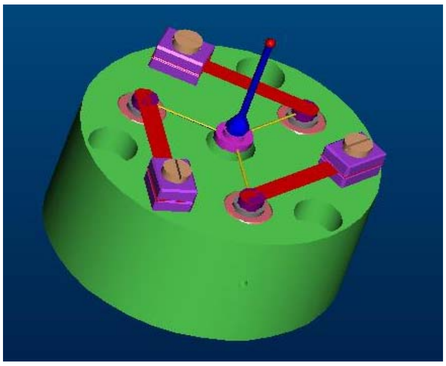

Figure 1
The tripod probe

The subsequent relationship describes the translations measured by the sensors, gathered in a vector M, when the probe tip is moved over a distance X_{tip} with r_s is the radius of the intermediate rods and l_{st} is the length of the stylus:

$$\overline{M} = \begin{pmatrix} \frac{r_s}{l_{st}} & 0 & 1 \\ -\frac{1}{2}\frac{r_s}{l_{st}} & \frac{1}{2}\sqrt{3}\frac{r_s}{l_{st}} & 1 \\ -\frac{1}{2}\frac{r_s}{l_{st}} & -\frac{1}{2}\sqrt{3}\frac{r_s}{l_{st}} & 1 \end{pmatrix} \overline{X}_{tip} \qquad (1)$$

The relationship between the tip displacement and the sensing force is given by equation (2).

$$\overline{F} = \begin{pmatrix} \frac{3}{2}(k_{sxx} + k_{syy} + c_{szz}x_s^2 + 2ck_{szx}y_s + c_{szz}y_s^2)l_{st}^{-2}X_{tipx} \\ \frac{3}{2}(k_{sxx} + k_{syy} + c_{szz}x_s^2 + 2ck_{szx}y_s + c_{szz}y_s^2)l_{st}^{-2}X_{tipx} \\ 3c_{szz}X_{tipz} \end{pmatrix} = \begin{pmatrix} c_{xy} & 0 & 0 \\ 0 & c_{xy} & 0 \\ 0 & 0 & c_z \end{pmatrix} \overline{X}_{tip}$$

Where

$$c_{xy} = \frac{3}{2}\frac{E_s w_s t_s^3}{l_s l_{st}^2}\left(\frac{1}{2(1+\nu_s)}\left(\frac{1}{3} - 0{,}21\frac{t_s}{w_s}\left(1 - \frac{1}{12}\frac{t_s^4}{w_s^4}\right)\right) - \frac{y_s}{l_s} + \frac{y_s^2}{l_s^2} + \frac{x_s^2}{l_s^2} + \frac{1}{3}\right)$$

$$c_z = 3\frac{E_s w_s t_s^3}{l_s^3} \qquad (3)$$

and $$c_{xx} = \frac{Ew_s^3 t_s}{l_s^3} \quad c_{yy} = \frac{Ew_s t_s}{l_s} \quad c_{zz} = \frac{Ew_s t_s^3}{l_s^3} \quad (4)$$

$$ck_{xz} = \frac{1}{2}\frac{Ew_s^3 t_s}{l_s^2} \quad ck_{zx} = -\frac{1}{2}\frac{Ew_s t_s^3}{l_s^2}$$

$$k_{xx} = \frac{1}{3}\frac{Ew_s t_s^3}{l_s} \; k_{yy} \approx \frac{Gw_s t_s^3}{l_s}\left(\frac{1}{3} - 0{,}21\frac{t_s}{w_s}\left(1 - \frac{1}{12}\frac{t_s^4}{w_{4s}^4}\right)\right) \; k_{zz} = \frac{1}{3}\frac{Ew_s^3 t_s}{l_s}$$

where

- E is Young's modulus of the spring material
- G is the sliding modulus
- w_s stands for width of the spring
- t_s is the thickness of the spring
- l_s is it's length

The disadvantages of this construction are that due to parasitic translations of the rods when they are translated out of the xy-plane, the probe will rotate around the z-axis when moved in vertical direction. Additionally, when probe tip is not exactly on the z-axis, it will move over a small predictable distance in x- or y-direction when moved in the vertical direction.

3 The Measurement System

For measuring the displacement at the end of the berillium-coper strips a commercial compact disk/versatile disk optical pick-up is used (see Fig. 2).

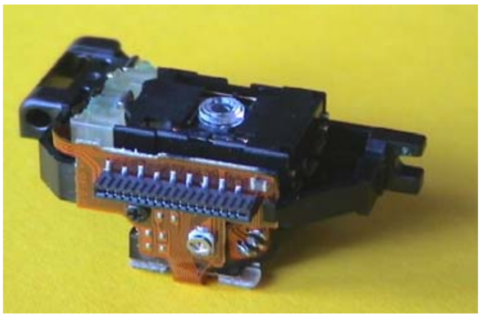

Figure 2

A commercial optical pick-up head

Inside a CD/DVD optical pickup a laser beam emitted from a laser diode is first diffracted and collimated into three beams, which are then focused on the optical disk surface. The distance of the focusing lens is controlled by a voice coil motor. The reflected beam is passing through an asigmatic element, impinge onto a sis split photo detector. The detection of the laser beam focusing condition is based on the astigmatic method, using a cylindrical beamshaping lens. When the beam is perfectly focused on the surface the spot on the four quadrant diode is circular.

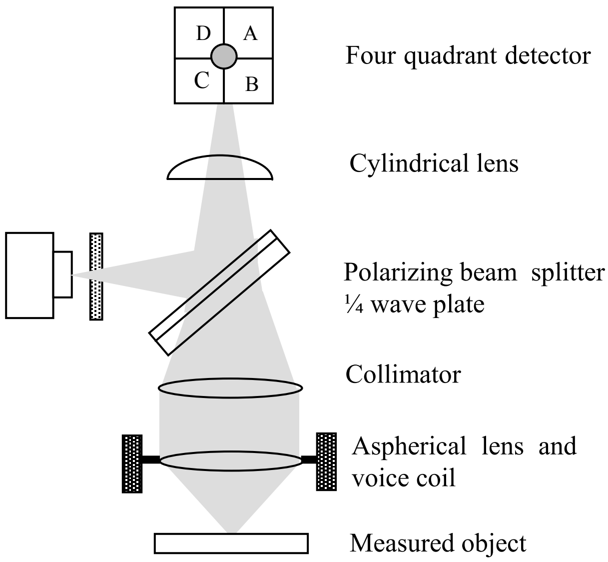

Figure 3
Configuration of the pick-up head

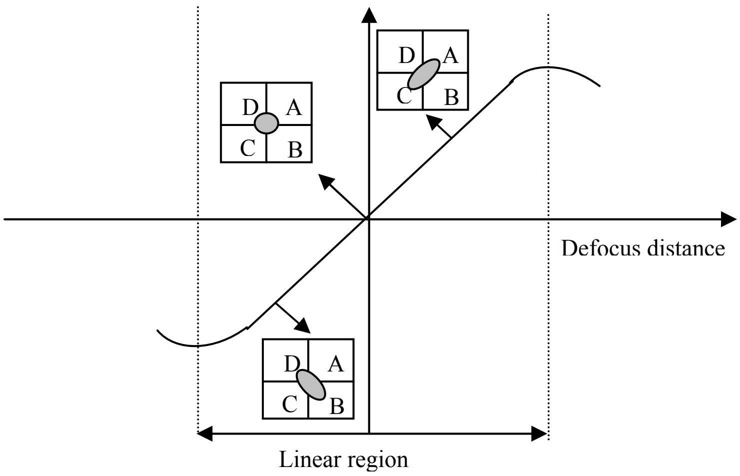

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Figure 4
Laser spot shape and the S-curve

If the surface is out of focus he spot on the quadrat sensors appears more eloganted. The shape change can be detected using simple arithmetic; $(V_A+V_C)-(V_B+V_D)$ where V_A- V_D are the preamplifier output voltages of the photosensors. The focus error signal vs. Vertical surface distance shows an S-curve, with a linear region of ~6μm. Measuring the focus error signal the voice coil motor can drive the objective lens into a position at which the focal point returned to the surface of the measured object. In such a way the displacement of the mirrors at the end of the tungsten carbide tubing can be measured with nanometer resolution.

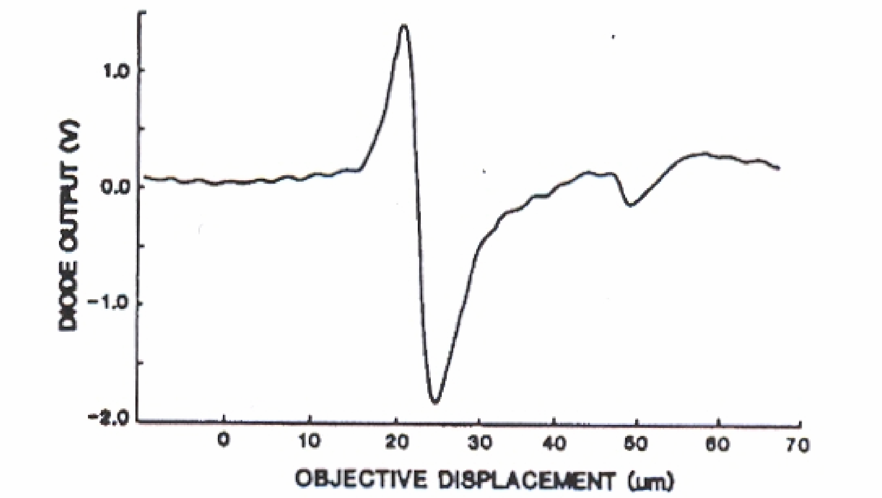

Figure 5
Four quadrant diode signal vs focus error

4 Error Sources and Their Compensation

The measuring uncertainty of the probe is mainly determined by the resolution of the optical pick-ups, which according to literature data is the order of one nanometer or less depending on the wavelength of the laser and the optical system used.

In the calculation given in Section 2. it was assumed that the tungstan carbide tubing and the stylus form a rigid body. However this is not case in practice. As the probe stylus is an elastic body, its deformation must also be taken into account when calculatig the displacement. The stylus can be considered as a a cantilever beam. Assuming that the deformation in the z-axis direction can be neglected the deformation in the x-y plane can be computed in the possesion of the material constants exact knowledge. However as equations (2) and (3) show directional variation, the results of this calculation depend both on the magnitude and the direction of the tip deflection.

As the probe body is made out of Invar a very low thermal expansion material and the construction was kept symmetrical from the thermal point of view, temperature variation can influence the measurment accuracy if the material of the interchangible stylus differs from that of the intermediate body.

At a number of places in the thermal loop parts were glued together because there was not alternative. However glue layers can introduce unwanted effects, like hysteresis or creep. To minimise these effects a thin layer was used. As very small forces act on the tip and the required time span for stability is limited problems of this nature are not expected.

5 Experimetal Setup and Measurement Results

The measuring capabilities of the probe were determined using the experimental set-up given in Fig. 5. The tip of the probe was displaced using a three-axis Nanopositioner. The displacement values of the nanopositioner were in turn measured by a short distance plane mirror interferometer. The signals generated by the translation and the 2D rotation were processed by a signal procesing circuit and the collected and converted into digital form by a data aquisition card.

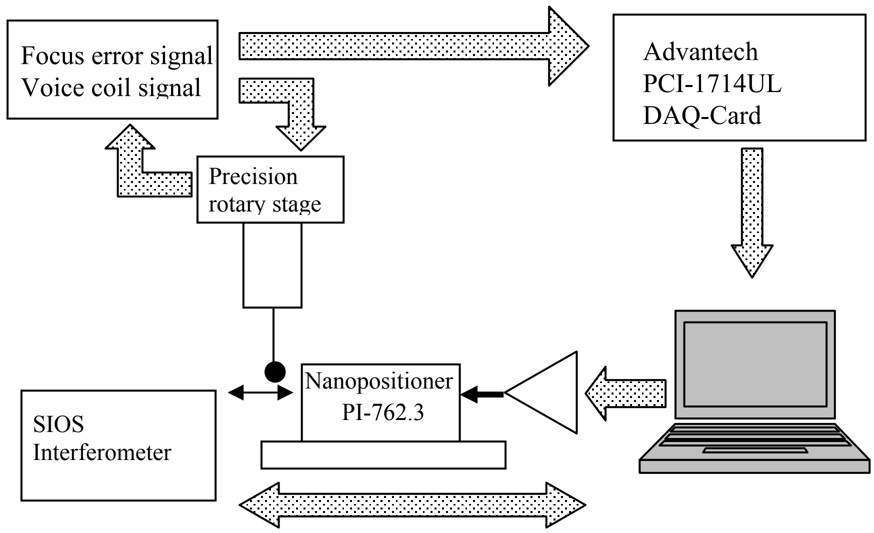

Figure 6

Experimental set-up for determining the measuring capabilties

The set-up enables the calibration of probes to 10 nm uncertainty with 1 nm resolution.

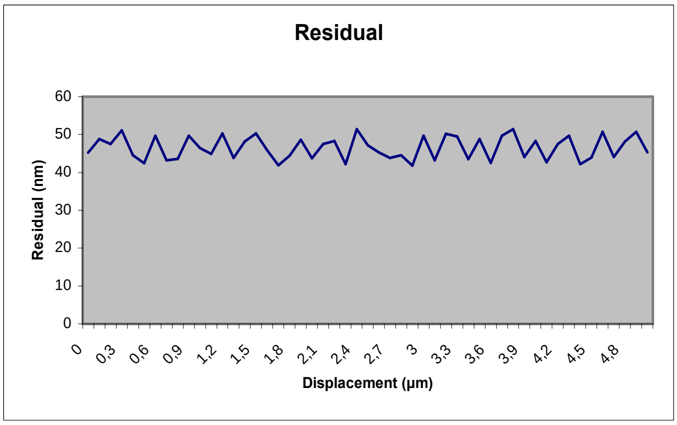

Figure 7
Difference between displacement as measured by interferometer and displacement calculated from optical sensor's output

All experiments presented here were carried out on a granite table on vibration demping foots, at a room temperature 20ºC and relative humidity of 60%.

Conclusions

With the increasing application of micromechanical elements co-ordinate metrology faces a new challenge. The paper presented a low cost high precision probe construction adequate for sensing these tiny and accurate objects. The probe can be manufactured by conventional technologies and adequate resolution can be reached using sensory technology applied in consumer electronics.

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