3D VIBRATING PROBE FOR MEASURING MICROFEATURES WITH NANOMETER UNCERTAINTY

M.C.J.M. van Riel (martijn.vanriel@xpresspe.com)[1,2]
E.J.C. Bos (edwin.bos@xpresspe.com)[1]

[1] Xpress Precision Engineering, The Netherlands
[2] Eindhoven University of Technology, The Netherlands

ABSTRACT

Existing high precision 3D tactile microprobes such as the Gannen XP by Xpress Precision Engineering perform excellent in measurement repeatability and uncertainty. Considering measurements on the micro scale there are however some effects that limit the performance of these probes. The stiffness of the stylus poses a limitation in scanning measurements and measurement sensitivity and the smallest probe tip that can be used limits the smallest detail that can be resolved. In this article a vibrating probe is suggested which will be able to overcome these limitations. The measurement principle of the vibrating probe is explained and it is shown how the a vibrating probe deals with the limitations present in existing tactile probes.

Index Terms – 3D vibrating microprobe, tactile microprobe, micro- and nanometrology

1. INTRODUCTION

Reducing component size offers many advantages in both industrial as well as consumer applications. Besides the obvious benefit of size reduction other advantages of miniaturization include lower mass, less energy consumption, more functionality per unit volume and cost reduction. As components become smaller, the need for low uncertainty 3D characterization increases. In the last decade various high precision 3D measurement probes have been developed and are currently commercially available. An extensive overview of probes used in dimensional (nano)metrology is given by Weckenmann et al [1,2]. Currently, the use of tactile probes on the micro scale is limited by various effects originating from interactions between probe tip and workpiece [3]. In this work some limitations of tactile probes are discussed and a vibrating probe is proposed to overcome these limitations.

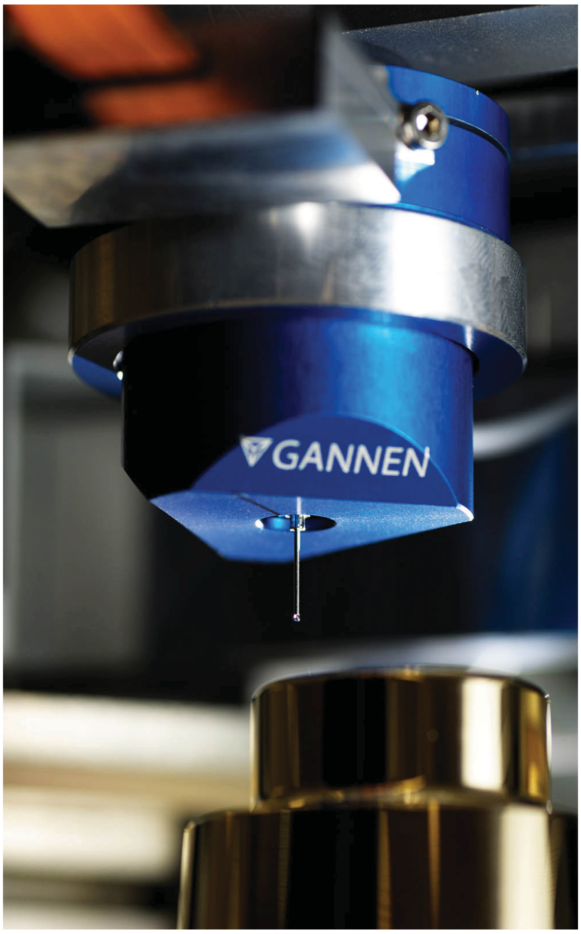

Figure 1 *Gannen XP probing system mounted in a coordinate measuring machine.*

2. GANNEN PROBES

Among the high precision 3D probes that are available today are the Gannen probes by Xpress Precision Engineering. Based on research by Pril, Haitjema and Schellekens at the Eindhoven University of Technology [4,5], the Gannen probes were further developed by Bos [6]. The probes consist of a silicon membrane with three slender rods. On the central, moving platform of this chip a stylus is attached with at its end the probe tip. Displacement of the probe tip leads to an elastic deformation of the three slender rods. This deformation is measured using piezo-resistive strain gauges that are integrated in the slender rods. Incorporating lithographic manufacturing procedures in the design results in a probe with a low moving mass of 25 mg, including stylus and probe tip.

The flagship probe of the Gannen series is the Gannen XP, which is typically outfitted with a stylus of 6,8 mm. In this configuration the probe has an isotropic stiffness of 480 N/m and equal measurement sensitivity for every direction. Moreover, the use of integrated piezo-resistive strain gauges results in hysteresis below 0,05% and a standard deviation in repeatability of 2 nm over its entire measurement range and in any direction. Finally the 3D probe uncertainty of the Gannen XP amounts to 10 nm (k=3) [7].

3. LIMITATIONS OF TACTILE MICROPROBES

Despite the excellent specifications of the Gannen XP and other existing tactile 3D measurement probes, there are still some factors that limit their operation. In particular interactions on the micro scale between probe tip and workpiece pose limitations on the performance of the probes [3]. In the paragraphs below three effects are mentioned that limit the operation of tactile microprobes.

3.1. **Stylus stiffness – scanning measurements**

A first limitation of tactile microprobes is found during scanning measurements. Friction between probe tip and surface of the workpiece limits the smallest measuring step that can be performed. As the length of the stylus increases and its diameter is reduced, the stylus stiffness decreases. In combination with the increase of surface forces on the micro scale, the stick-slip effect will increase, according to [3]:

$$\Delta y = \mu\left(\Delta x + \frac{F_{sf}}{c_t}\right) \qquad (1)$$

In which Δy represents the stick-slip distance, μ the coefficient of friction, Δx the probe deflection, F_{sf} the surface forces and c_t the stiffness of the probe at the probe tip. From this equation it can be seen that the stick-slip distance will increase as surface forces or probe stiffness (including stylus stiffness) increase, respectively decrease. From a probe point of view it can be concluded that an increase in aspect ratio of the stylus will negatively affect the smallest measurement step that can be performed during scanning.

3.2. **Stylus stiffness – measurement sensitivity**

The sensitivity of the probing system is reduced when the stiffness of the stylus decreases with respect to the stiffness of the probe suspension. In most tactile probes the stylus connects the probe tip with the probe measurement system, i.e. the stylus is part of the metrology loop. As a result the sensitivity of the probe decreases if the stiffness of the stylus is in the same order of magnitude as that of the probe suspension [3]. Figure 2 shows simulations of the sensitivity of the Gannen XP probe as a function of the radius of the measuring part of the stylus. With the measuring part of the stylus, the thinner part of the stylus directly below the probe tip is indicated. This part of the stylus determines the overall stylus stiffness. From figure 2 it can be concluded that for a stylus radius larger than 70 µm, the sensitivity of the Gannen XP does not change, e.g. the stylus stiffness is large compared to the stiffness of the probe suspension. For comparison purposes the sensitivity at this stylus radius is taken as 100% and consequently, the sensitivity for smaller radii is shown as a percentage of this value. It can be seen that for a stylus radius smaller than 40 µm the sensitivity, and consequently the signal-to-noise ratio, decreases significantly. It can be shown that for the Gannen XP styli with a ratio of 45 between the length and the radius of the measuring part of the stylus can be obtained.

By decreasing the stiffness of the probe suspension less stiff styli, e.g. higher aspect ratio styli, can be used. This is indicated in figure 2 by the Gannen XM, a probe with a specifically designed lower suspension stiffness compared to the Gannen XP. This will result in a stylus with a ratio of 80 between the length and radius of the stylus. However, this decrease in probe suspension stiffness comes at a cost. The stiffness of the Gannen XM is no longer isotropic; 10 N/m in x and y direction and 50 N/m in z direction and the repeatability and 3D probe uncertainty increase to respectively 4 nm and 24 nm (k=3) [7].

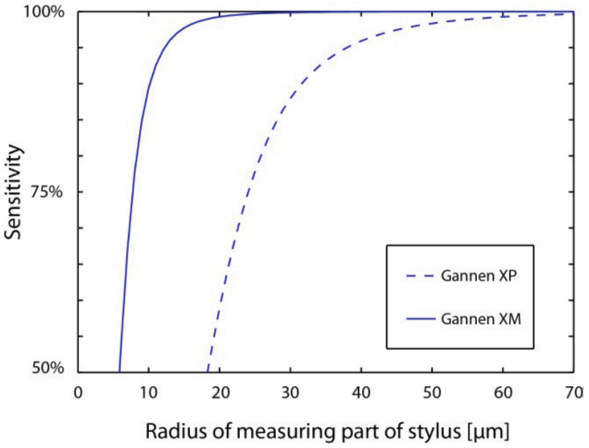

Figure 2 *Sensitivity in xy-direction for the Gannen XP and XM as a function of the stylus radius [4].*

3.3. **Probe tip diameter**

As measured features become smaller, the tip of the probe also needs to decrease in size. As a probe tip is mounted on the measuring part of the stylus, the measuring part of the stylus needs to have a smaller diameter than the tip itself. This to ensure that walls parallel to the stylus can be measured without the risk of contact between stylus and wall. From the previous two paragraphs it can be concluded that the diameter of the stylus cannot be reduced without a cost, i.e. an increase in stick-slip during scanning measurements and a reduction in measurement sensitivity. The limits on stylus stiffness therefore also limit the diameter of the probe tip that can be used. Moreover, at the current state of technology, it is very difficult to produce spheres with a diameter below approximately 50 µm that are of sufficient quality in shape and roughness to be used as probe tips.

4. VIBRATING MICROPROBE

In order to overcome the limitations of tactile probes mentioned above, a 3D vibrating microprobe is proposed. The measurement principle of the vibrating probe is based on changes in its dynamic response as it interacts with the surface of a workpiece. The probe is excited close to or at its natural frequency. Due to probe tip-surface interactions the oscillation amplitude, phase and resonance frequency change. These changes are registered and used as measurement signals. This is displayed schematically in figure 3, on the left the probe oscillates freely and on the right the probe interacts with the surface. Also shown in this figure are the corresponding magnitude and phase response plots. As can be seen from the magnitude and phase responses, upon interaction these two responses shift, which is used as the measurement signal. This change in the dynamic response of the system can be registered with very high sensitivity around the natural frequency. At this frequency the magnitude and phase responses respectively show a steep peak and a steep slope which can be used for measurements with a high sensitivity. Many high sensitivity measuring instruments make use of this principle, foremost among them are the atomic force microscopes with demonstrated sub-nanometer resolutions.

4.1. **Scanning measurements**

Compared to tactile probes, a vibrating probes offers some solutions to reduce the limitations that are present in tactile probes and discussed earlier in this paper. A vibrating probe can interact with the surface of the workpiece in two ways, which are denoted by terms used in atomic force microscopy: the so-called intermittent or tapping contact mode and the non-contact mode. When operated in tapping mode, the vibrating probe touches (taps) the surface at each oscillation. In non-contact mode, the tip of the probe interacts via surface forces with the surface of the workpiece. No mechanical contact exists between probe-tip and workpiece in this mode.

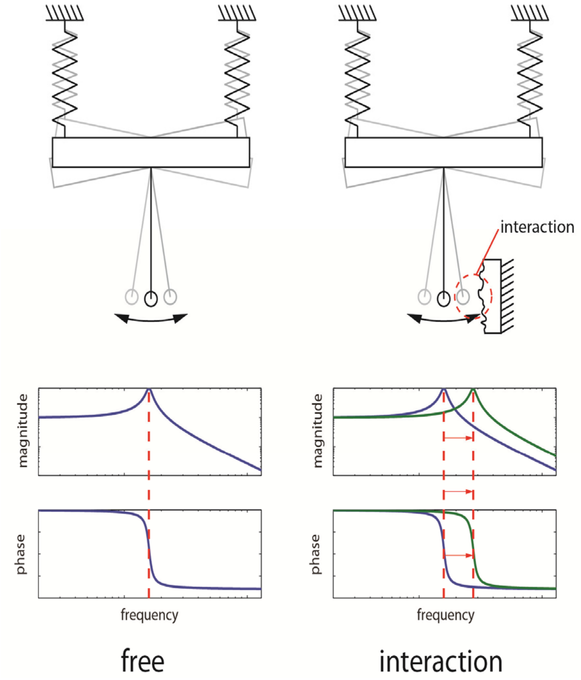

Figure 3 *Operating principle of a vibrating probe, on the left the probe oscillates freely and on the right the probe interacts with the measured surface. Corresponding magnitude and phase response plots are shown.*

In tapping contact mode, the vibrating probe is only in contact with the workpiece for an instant every oscillation. As the frequency of oscillation is high (~1 kHz) and the speed with which the probe scans the surface is rather low (~0,1 mm/s) no stick slip-effect will be observed. For the non-contact mode of operation it is obvious that in the absence of mechanical contact no stick-slip effect can occur. It can therefore be concluded that for a vibrating probe the stick-slip effect will not pose no limitations on the smallest measuring step during scanning.

4.2. **Measurement sensitivity**

In a tactile probe the stylus stiffness compared to the probe suspension stiffness affects the sensitivity of the probe. In a vibrating probe it is not just the stiffness of both the probe suspension and stylus but rather the dynamic behavior of these two components that affects the sensitivity. To illustrate this, the dynamic response of the vibrating probe was simulated using the model shown in figure 4. The model consists of two masses m_p and m_s, which represent respectively the equivalent mass of the probe and equivalent mass of the stylus. These masses are connected to some structure (such as a coordinate measuring machine) via the probe suspension stiffness, k_{ps}, to each other via the stylus stiffness, k_{st}, and to the workpiece via

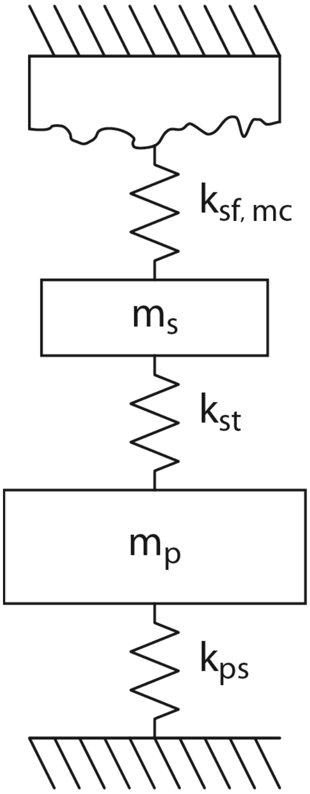

Figure 4 *Dynamic model of a vibrating probe.*

the stiffness of the surface forces or mechanical contact $k_{sf,mc}$. Note that the modeling of the surface forces or mechanical contact by a single linear spring is incomplete but will serve for the purpose of this illustration.

In the simulation the probe is excited via a force acting on the probe mass. The displacement of the same mass is the response signal. As the surface forces interact with the stylus the response of the probe mass will change as is indicated schematically in figure 3. This change is used as the measurement signal. As the stiffness of the stylus is lowered, less information can be transmitted through the stylus to the probe mass and, as a result, the response of the probe mass will be different. The masses and stiffnesses of the modeled vibrating probe correspond to the masses and stiffnesses of the Gannen XP probe.

In figure 5 the sensitivity of the model of the vibrating probe is displayed in the same manner as in figure 2. The sensitivity obtained with a measuring part stylus with a radius of 70 µm is set at 100% and changes in sensitivity due to a decreasing radius are related to this 100%. In this figure the sensitivity of the Gannen XP is also shown for comparison.

Figure 5 shows that the sensitivity of the vibrating probe does not change significantly for smaller radii up until a radius of about 7 µm. For smaller radii, the sensitivity drops rapidly. Compared to the sensitivity of the Gannen XP, the vibrating probe can use thinner styli and still be able to perform measurements with a high sensitivity. Furthermore, it should be noted that the model of the vibrating probe is based on a Gannen XP, a probe that is not designed to be used as a vibrating probe. As a consequence, the difference in sensitivity for thinner styli between the Gannen XP and a vibrating probe will be even larger if the masses and stiffnesses of the vibrating probe are optimized.

4.3. **Probe tip diameter**

The smallest probe tip that can be used on a tactile probe is determined by the radius of the measuring part of the stylus. The probe tip diameter needs to be larger than the diameter of the measuring part of the stylus, this to ensure that walls parallel to the stylus can be measured without the risk of contact between stylus and wall. As the vibrating probe is able to make use of thinner styli, consequently smaller probe tips can be used. Furthermore, the vibrating probe rotates about a point that lies somewhere at the bottom of the stylus as it measures in the xy plane, as can be seen in figure 3. As a result the lateral displacement of the probe tip is larger than the displacement of the stylus, making it less likely that the probe would touch the workpiece with its stylus instead of its probe tip.

Manufacturing spheres with a diameter smaller than 50 µm and with a high quality in shape and surface roughness is also a limiting factor in vibrating probes. This last limitation might be circumvented due to the fact that the vibrating probe is actuated. By utilizing a well defined probe tip, but not a sphere, such as the tip of an AFM cantilever and moving it in space, a (part of a) virtual probe tip can be created. This might solve the problem of low quality microspheres but will most likely pose challenges in other technical areas.

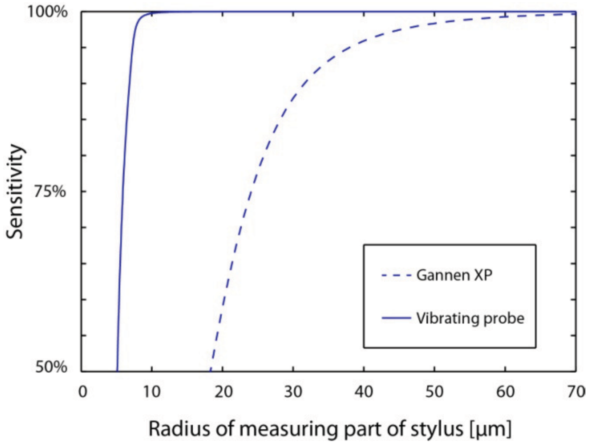

Figure 5 *Sensitivity of a vibrating probe with similar dynamic properties as the Gannen XP and the sensitivity of the Gannen XP as a function of the radius of the measuring part of the stylus.*

5. CONCLUSION

At present, there are a number of high precision 3D tactile microprobes commercially available. One of these is the Gannen XP by Xpress Precision Engineering. The measurement repeatability and accuracy of these probes are excellent, the Gannen XP for example is capable of performing measurements with a repeatability and 3D accuracy of 2 nm and 45 nm, respectively. Despite these specifications, there still are some limitations concerning the performance of these probes on the micro scale. The stiffness of the stylus limits the scanning behavior and measurement sensitivity and the diameter of the probe tip is limited by the diameter of the stylus on which the probe tip is attached. A vibrating microprobe will be able to overcome these limitations, thus resulting in a probe that is capable of performing measurements on micro-sized features, such as holes with a diameter below 60-80 μm, and with nanometer uncertainty and repeatability.

6. ACKNOWLEDGMENTS

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