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Dynamics modeling of CMM probing systems

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Abstract

The probing system dynamics is important for coordinate measuring machine (CMM) performance, particularly when probing in scanning mode. This is a typical situation e.g. in gear metrology, where the flanks are typically scanned. This may occur even without full awareness of the user, who may accept default values or choose with little understanding. This work presents a modelling of a contouring probe. The model is based on the characteristics of real probes; more specifically, continuous passive systems are considered, resulting essentially in second order 3D systems. The theoretical model is validated experimentally by scanning suitable surfaces exhibiting a range of slopes. The separation between static and dynamic effects is achieved by repeating the experiments at varying scanning speed, so that a same geometrical slope results in different temporal slopes – which the probing system dynamics is sensitive to. The model is oriented to define a good trade-off between the scanning speed and the measurement uncertainty.

Keywords: CMM, probe dynamics, drivetrain, form and size measurements, large ring segment

1. Probe dynamics working area

Coordinate measuring machines (CMMs) are increasingly used for dense gauging of complex shapes like gear tooth profiles. Even for simpler profiles with large dimensions, like large ring bearing for high-end wind turbines, dense gauging is requested to characterize tolerances and waviness for the wearing prediction of such mechanical parts. However, the probing system is the dominant dynamic contributor in gear metrology because the CMM carriage accelerations required in gear measurement are usually well borne by the structure. The probing system is not the only component inputting dynamic effects in coordinate measurement: the CMM itself does with its mechanical structure. This work presents a modelling of a contouring probe. The model is identified using the characteristics of real probes and it is oriented to define a good trade-off between the scanning speed and the measurement uncertainty.

When the probe is subject to a small mechanical impulse, it behaves like a traditional second order oscillating system [1] and it exhibits a damped oscillation. All details of model identification are given in the section "probe model". Probe dynamics can be essentially defined by its natural oscillating frequency ω_0. From this model, it follows that the contribution to the measurement uncertainty increases rapidly approaching ω_0. Since the frequencies of probe motion depend both on the scanning speed and the waviness of the mechanical part under measure, a convenient way to display the CMM scanning speeds is the plot in **Figure 1**. This plot shows an area (green shaded) where the influence of the natural oscillating frequency of the scanning probe is negligible. This area (working area) contains all the pairs of waviness-scanning speeds with such characteristic. Each curve in the plot represents the points where a probe of a CMM moving at the speed read from the X-axis on a surface with a waviness read from the Y-axis oscillates at a constant frequency.

Specifically for a CMM Leitz PMM with a B4 controller and a TRX probe head (

Figure *4*) the measured natural oscillating frequency is ω_0 = 8,55 Hz (red curve) [1]. Assuming a buffer zone of 20% of ω_0, the area below the green curve can be considered as a good working area, since it has a low contribution to uncertainty coming from the probe dynamics.

In this plot, two points (red and black dots) representing the scan speed and the measured waviness of a ring segment are also reported (**Figure 2**) [2]. The plot shows that the points fall in the good working area.

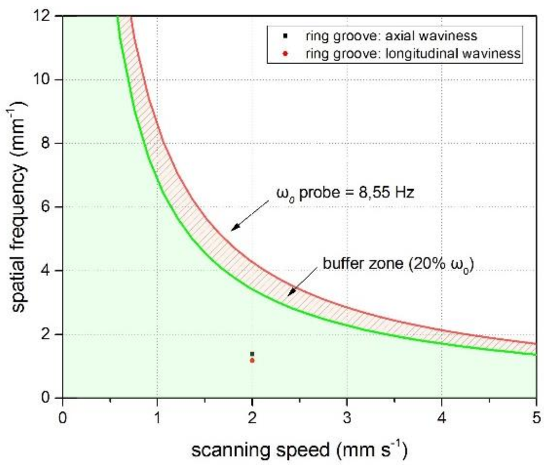

Figure 1. Working area for surface scanning according to probe mechanical characteristics

The waviness of the two points in **Figure 1** are taken from the *RSm* parameter of the axial and longitudinal roughness plots shown in **Figure 2**. The *RSm* parameter represents the main harmonic component of the roughness profile acquired by a profilometer. The measured values are, respectively, 722,53 μm and 848,71 μm for axial and longitudinal directions.

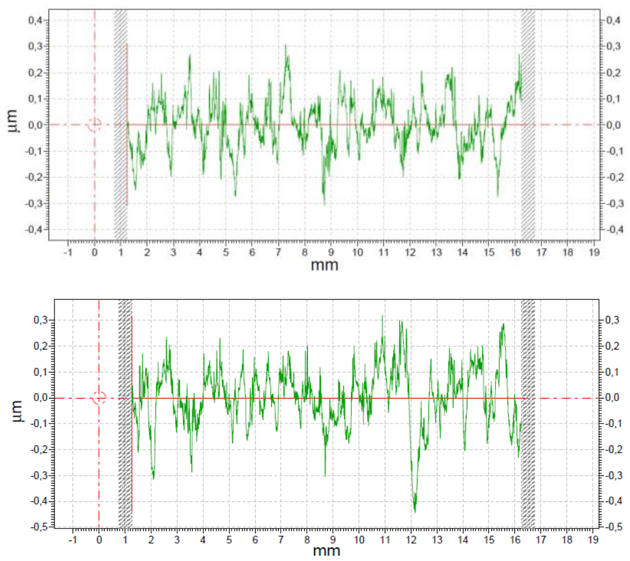

Figure 2. Roughness plots of ring segment. Axial roughness (upper). Longitudinal roughness (lower)

2. Probe model

Damping is always present in mechanical systems. Modelling the CMM probe like a classical spring-mass-dashpot system, by inputting an impulse to it, we can consider the second order differential equation for the displacement (along one axis):

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0$$

whose underdamped ($0 < \xi < 1$) solution is

$$x(t) = e^{-\xi\omega_n t}\left\{\left[\frac{\xi}{\sqrt{1-\xi^2}}x(0) + \frac{1}{\omega_d}\dot{x}(0)\right]\sin\omega_d t + x(0)\cos\omega_d t\right\}$$

where ω_n and ω_d are, respectively, the natural frequency and the damped natural frequency. When the initial velocity is set to zero, at two different moments the ratio between two oscillation amplitudes is

$$\frac{x_1}{x_2} = \frac{e^{-\xi\omega_n t_1}}{e^{-\xi\omega_n(t_1+T)}} = \frac{1}{e^{-\xi\omega_n T}} = e^{\xi\omega_n T}$$

Calculating the logarithmic ratio of succeeding amplitudes x_1 , x_2, that is the

$$\text{logarithmic decrement} = \xi\omega_n t = \frac{2\pi\xi}{\sqrt{1-\xi^2}}$$

it is possible to obtain the damping ratio ξ :

$$\xi = \frac{\frac{1}{n-1}\left(ln\frac{x_n}{xn}\right)}{\sqrt{4\pi^2 + \left[\frac{1}{n-1}\left(ln\frac{x_1}{x_n}\right)\right]^2}}$$

from which to derive, finally, ω_d and ω_n [3].

2. CMM dynamics

We also tried to characterize the CMM global dynamics, apart from probe dynamics. For such a purpose, a "datum sphere" (with a diameter of 30 mm) was measured with different probe speeds (ranging from 1 mm s^{-1} to 10 mm s^{-1} on the sphere, along a path 45 mm long). From preliminary results, the deviation of measured data from the ideal fitted profile exhibits an oscillating frequency of ≈1 Hz that we assume as the global natural frequency of the CMM. **Figure 3** shows the same waviness/probe speed plot as **Figure 1,** with the addition of the ω_0 CMM curve (black curve). This curve introduces a low limit to the good working area at the lower frequencies.

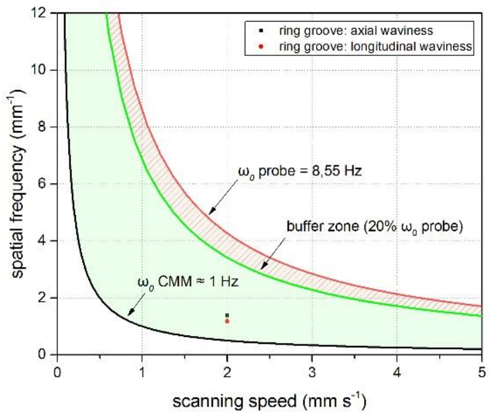

Figure 3. Same working area as in previous figure, with CMM capabilities at low frequencies added

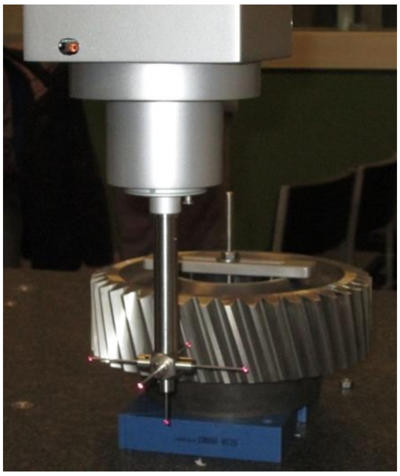

Figure 4. CMM probing system of a CMM Leitz PMM with a B4 controller and a TRX probe head

4. Conclusions

This work presents a method to select the right scanning speed versus the waviness (working area) of the measurement object, taking into account both the probe dynamics and the CMM global dynamics. In such area there is a low contribution to uncertainty coming from the probe dynamics and CMM global dynamics.

References

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[3] Katsuhiko Ogata, *System Dynamics 4th ed.*, Sec. 8-3, Prentice Hall, 2003.