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Dynamic probe calibration up to 10 kHz using laser interferometry

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Abstract

This paper describes two systems for dynamic probe calibrations which are in use at the Van Swinden Laboratory of the Netherlands Measurements Institute (NMi-VSL). The systems have in common that they enable both static and dynamic probe calibration using a laser interferometer. The displacements are generated using piezoelectric devices. Measurements are shown which illustrate the capabilities of the systems to characterize and calibrate fast-moving probes. © 1998 Elsevier Science Ltd.

Keywords: Dynamic calibration; Laser interferometer; Stylus instrument

1. Introduction

The probes of roundness- and roughness-testers are usually calibrated in a static or quasi-static way. In practice, however, a probe will respond to a signal which behaves randomly in time and which consists of high and low frequency components. A major question for these systems is: to what extent the static calibration results remain valid for real, dynamic circumstances?

Systems for dynamic probe calibrations are sometimes referred to as "moving table" systems, of which some examples can be found in the literature [1,2]. Factors which affect the performance of such a system are the stability, amplitude, bandwidth and the resolution and sampling frequency of the measuring system. This paper describes two "moving table" systems with different performance characteristics.

2. The laser interferometer

A HP laser interferometer system, type 5529A, has been used as the length standard for all measurements. The laser interferometer measures the displacement with a resolution of 5 nm, a maximum sampling frequency of 33 kHz and a relative accuracy of better than 1×10^{-6}. Some checks on the performance of this instrument were carried out:

- the laser frequency was calibrated against an iodine-stabilized He–Ne laser;
- the interpolation error was checked for static circumstances with a digital piezo translator, as described in the literature [3];
- the sampling frequency was checked by measuring a piezo displacement driven by a function generator with a defined frequency.

These tests indicate that the system's accuracy is better than 5 nm. The accuracy of the internal timebase is of the order of 10 μs which is sufficient for our applications.

3. The closed-loop piezo system

This system is based on a Queensgate digital piezo translator (DPT) type DPT-C-S. This translator can be moved very reproducible ($s = 0.2$ nm) up to 15 μm with a maximum frequency

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of about 100 Hz; with a reduced maximum displacement the maximum frequency is about 500 Hz. The properties and use of this system are described elsewhere [3,4]. A gage block acts as a flat reference for a moving probe and simultaneously as an optical flat for a HP 2529A laser interferometer which records the movement of the gage block while it is scanned by the probe. The tilt is about 5″ and shows hysteresis when the gage block is moved up or down. This implies an error of about 0.2% for each millimeter off-axis adjustment or movement. As two laser-beams are positioned symmetrically around the probe, the system corrects for Abbe-offset errors apart from a small off-axis probe movement. The set-up is schematically depicted in Fig. 1.

4. The open-loop piezo system

This system was designed to achieve higher frequencies and to have a more flexible probe attachment than the closed-loop system, at the expense of somewhat less repeatibility and much less linearity of the generated mirror movement. This system is based upon the same "standard" flat-mirror optical arrangement for laser interferometers as the closed-loop system, but here the in- and outcoming beam from the laser interferometer overlap. In one of the interferometer arms a flat mirror is attached to a piezo tube. This mirror is cut out of a Tungsten carbide gage block by a spark-erosion process. The flat mirror thickness is 2 mm and the diameter is 8 mm. To achieve a maximum bandwidth, an open-loop HV piezo tube (PI, 5 mm inner diameter) is used while the weight of the mirror is kept at a minimum. The attachment of the mirror on the tube and the tube on the basement requires some care, as not only the tube length, but also the tube diameter increases when a voltage is applied. The insulation on both sides of the tube consists of three small ceramic cilinders (1.5 mm diameter) which are glued in-between the tube and the mirror on one side and the tube and the basement on the other side. The glue also pre-loads the mirror to the tube. The laser optics is mounted under the piezo tube so all types of probes have easy access on the upper side. The set-up is sketched in Fig. 2. By varying the output voltage of the HV amplifier (PI, type P-270) from 0 to 1000 V, a displacement of 10 μm is generated. Figure 3 shows the amplitude of sinus-signals which are generated when a sinus-generator is connected to the HV amplifier. At its maximum amplitude of 5 μm the bandwidth is about 8 kHz; for smaller amplitudes an oscillation, which indicates the bandwidth limit, appears at 12 kHz. The tilt is 19″ when the mirror is moved over its full range of 10 μm and is proportionally less for smaller movements. This implies an error of 1% for each millimeter off-axis adjustment or movement.

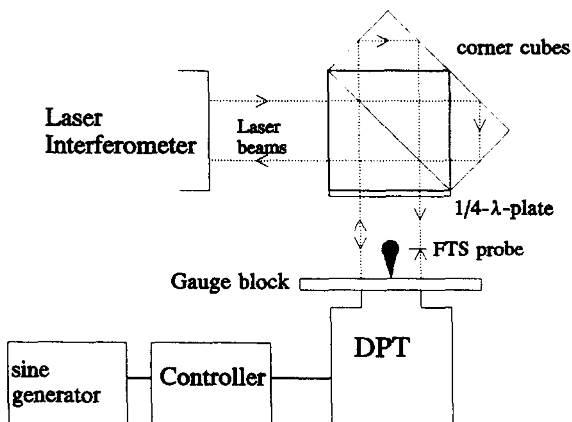

Fig. 1. Sketch of closed-loop system.

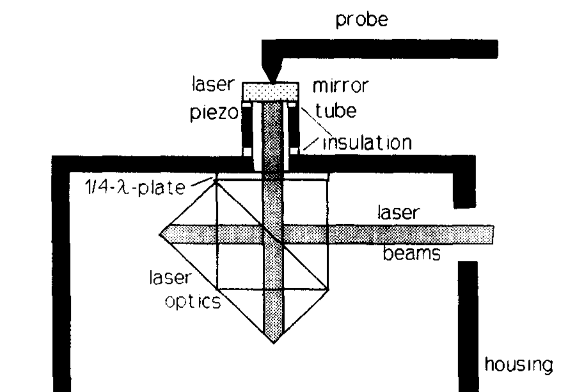

Fig. 2. Sketch of open-loop system.

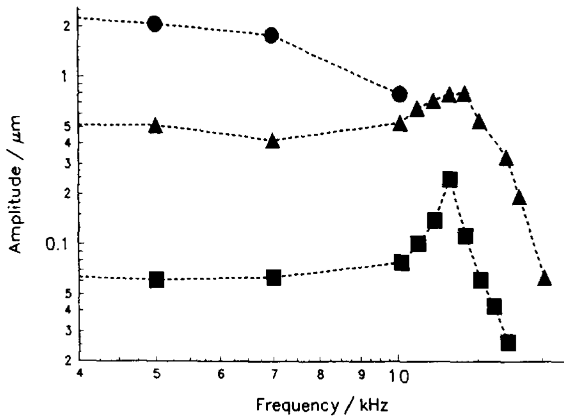

Fig. 3. Frequency response of open-loop system.

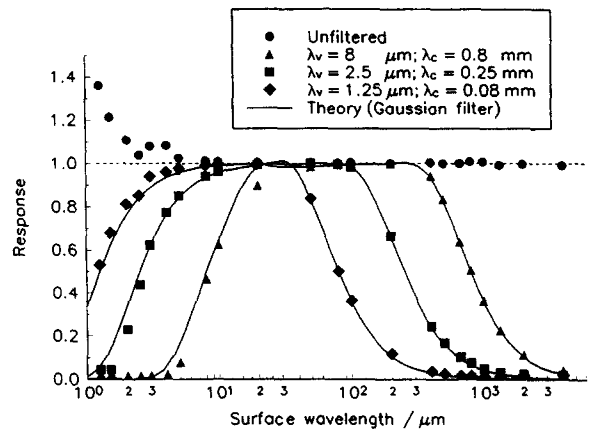

Fig. 4. Low-frequency response function of the FTS.

5. Calibration of a roughness tester for moderate frequencies

With the closed-loop system the response function of a Rank–Taylor Hobson Form Talysurf Series 120L roughness tester (FTS), equipped with its standard probe, was measured. Sine-shaped signals simulate surface waves using the constant velocity of the probe (485 µm/s). Such signals with an amplitude of 0.3 µm and a frequency which corresponds to wavelengths between 1 µm and 4 mm have been applied to the probe. The signals were measured both unfiltered and filtered with the instruments software with short-wavelength cut-offs λ_c of 1.25; 2.5 and 8 µm and long-wavelength cut-offs λ_c of 0.08; 0,25 and 0.8 mm. The roughness parameter R_q measured by the FTS was compared to the standard deviation of the displacement as was measured by the laser interferometer system. The unfiltered data give information about the probe behavior itself: ideally the response should be independent of the measured surface wavelength. From the filtered data it can be derived whether the system (probe + software) behaves according to the defined filter characteristics. The results are depicted in Fig. 4. In Fig. 4, also the theoretical filter characteristics are drawn based on ISO 11562 [5]. The graph shows that the nominal filter characteristics are followed very well for the longwavelength cut-offs and fairly well for the short-wavelength cut-offs. The unfiltered data show a flat response for wavelengths >4 µm. For shorter wavelengths, deviations occur which cannot be fully measured because of the limited bandwidth of 500 Hz which corresponds to 1 µm wavelength for the FTS probe speed (485 µm/s). This limitation is a disadvantage of this system, as is also the space which is needed for the laser beams. These problems are overcome with the open-loop system which is used in the next section.

6. Calibration of a roughness tester for higher frequencies

With the open-loop system the transfer function of the FTS was measured for frequencies from 250 Hz up to 1.3 kHz (wavelengths from 0.35 to 2 µm) and an amplitude of 0.05 µm. At higher amplitudes or frequencies the stylus was lifted inside the measured frequency range. The result is given in Fig. 5. Because of the lower amplitude, a somewhat different response in the 1–2 µm region is measured as in Fig. 2. A significant oscillation is found at a wavelength of 0.6 µm. Note that the effect of this oscillation is limited in practical measurements because of the filtering effect of the probe tip diameter of 2 µm and, if used, the software filtering. However when measuring sharp edges this effect is clearly noticed in unfiltered measurement.

A similar measurement was carried out on a Perthen type PRK roughness tester with a C5D read-out system. The roughness tester was used in

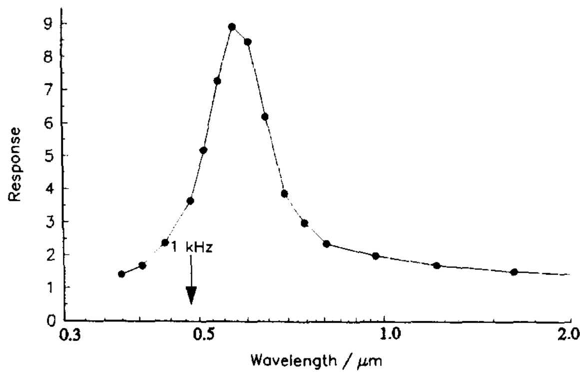

Fig. 5. High-frequency response function of the FTS.

its settings for fine surfaces: 80 μm cut-off and a velocity of 100 μm/s. The R_{max} parameter was compared to the peak–peak value measured by the laser interferometer in the same time interval. The results for an amplitude of 0.1 μm and frequencies up to 2 kHz are depicted in Fig. 6. In this figure, also the theoretical filter characteristics is drawn based on ISO 11562 [5] with $\lambda_s = 0.25$ μm and $\lambda_c = 80$ μm.

The deviations near $\lambda = 80$ μm are due to the analog 2RC characteristics of the Perthen. The high frequency cut-off, which significantly deviates from the theoretical line, corresponds to 500 Hz with a 2RC characteristics and proved to be independent of other settings (cut-off, velocity 0.1 mm/s or 0.5 mm/s). This will give deviations when measurements are compared with measurements taken with instruments having the correct filter characteristics, especially for fine surfaces.

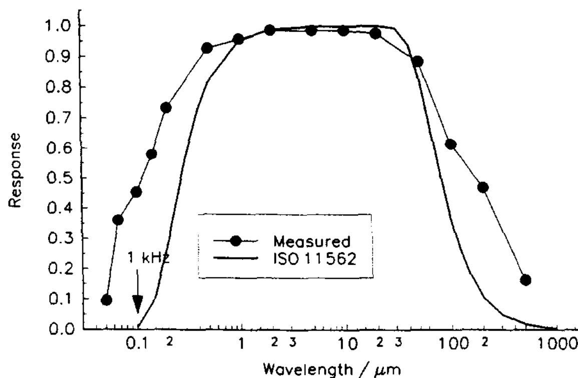

Fig. 6. Response function of Perthen C5D roughness tester.

Because of this internal analog filter, the oscillation frequency for this probe could not be measured and it will be larger than 1.5 kHz. The stylus was lifted from the surface at 1 kHz at an amplitude of 1 μm. This is a much better figure than the 0.1 μm measured for the FTS probe which will be due to the higher (inertial) mass of the FTS probe.

These examples show that the designed dynamic probe calibration systems can measure all significant dynamic probe characteristics of roughness measuring instruments.

7. Calibration of a roundness tester for harmonic components

For a ball manufacturer, an SKF roundness tester type MWA 160 B, was calibrated. This roundness tester is specifically designed to measure the dominant harmonic roundness components of balls. The balls to be measured are fixed at one position and cannot be further centered. This leads to a de-centering of about 2 μm for each measurement. The output of the instrument consists of a centered roundness diagram, the excentricity, the LSC-out of roundness and the three dominant harmonic components except the first, which corresponds to the excentricity. The rotation speed can be varied; for this calibration 4 rpm was used and a sampling frequency which leads to 1024 points/revolution. The probe of this instrument was calibrated by taking the probe off the roundness tester and attaching it to the open-loop piezo system. To this system, a signal was fed which corresponds to a practical measurement. An excentricity of 2 μm was simulated by a sinus-signal with an amplitude of about 2 μm and a frequency corresponding to the rotation frequency of the table; in this case 0.066 Hz (4 rpm). To this signal a second sinus-signal was superimposed which corresponds to the frequency and amplitude of the harmonic component to be calibrated.

The output of the roundness tester was taken as if a normal roundness measurement was made; the laser-interferometer took 8192 samples in 15 s. The laser-interferometer data were analyzed using the fast Fourier-transform (FFT) algorithm, for the

roundness probe its own evaluation system was used.

As an example which visualizes the obtained data, we give the result for a 50 upr signal with a 1.5 μm amplitude. The signal imposed to the probe is given as a roundness diagram together with its amplitude spectrum in Fig. 7. In the spectrum, higher harmonics are present due to non-linearities in the piezo. The values as measured by the roundness tester are also indicated: the excentricity (first harmonic) and the three other dominant harmonic components at 49, 50 and 100 upr.

The somewhat different distribution of the harmonic components over the 49, 10 and 51st will be due to a not perfectly constant speed of the roundness tester.

The amplitude of the harmonic component at 50 upr as measured by the roundness tester is 1.26 μm while the reference value as it is measured by the laser interferometer is 1.44. This is consistent with other measurements which indicate a filtering-effect with a cut-off corresponding to 70 upr, even when the roundness tester gives "unfiltered" results. The larger harmonic component measured at 100 upr must be due to a non-linearity of the roundness tester probe which is confirmed by measurements at different amplitudes. In this way, similar to the calibration of a roughness tester, filtering characterisitics can be calibrated also.

The repeatability (standard deviation) was about 0.5 nm +0.1% of the generated amplitude for the open-loop piezo system; for this roundness tester it was about 1 nm +0.5% of the measured amplitude.

8. Conclusions

We have shown two systems which enable dynamic calibrations which are traceable to a laser wavelength. It is shown that the systems can comprehensively characterize the dynamic properties of roughness and roundness measuring systems.

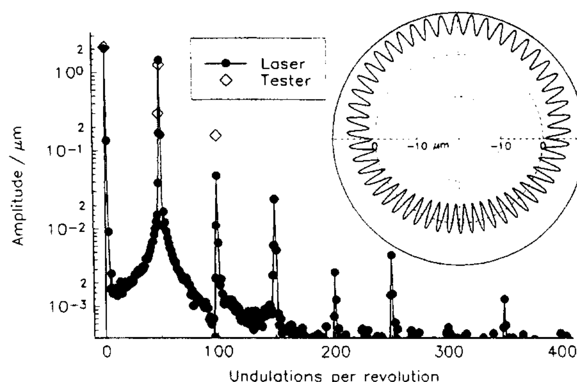

Fig. 7. Display of a roundness diagram and the corresponding amplitude spectrum as it was generated using the open-loop system. Measurements on this signal of the roundness tester are also shown.

Acknowledgements

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