Multifunctional, Laserinterferometric Measurement Systems

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Abstract:

The trend in many fields of enabling technologies, such as microelectronics, communications, microsystems, and micromechanics, toward imposing increasingly stringent demands upon precision continues. Those types of technologies allow creating micromechanical components having dimensions of a few micrometers that have to be accurately measured, positioned relative to one another, and assembled. In that conjunction, laser-interferometric metrology provides unique opportunities that combine measurements over large ranges at extraordinarily fine resolutions with traceability of measurement results to international length standards. Laser-interferometric metrological systems may be used for measuring displacements ranging from subnanometers to several meters, without need for reconfiguring the optical or electronic systems involved or their component devices.

1. Introduction to Homodyne Interferometers

Homodyne interferometers are based on comparisons of the values of the parameters to be determined to light wavelengths and allow attaining ultraprecise, nanometer-scale resolutions. A metrological analysis of the metrological method involved indicates the opportunities they afford and the metrological limits of laser-interferometric systems. For that purpose, consider a Michelson interferometer, the basic type of interferometer involved, and assume that the laser light source employed emits plane waves that are split into a pair of coherent, partial waves and interfere through superposition. The intensity distribution in the image plane will then be give by Eq. 1:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\gamma + \frac{2\pi}{\lambda_0} \cdot n \cdot i \cdot s), \quad (1)$$

where I is the intensity, I_1 is the intensity of partial wave 1, I_2 is the intensity of partial wave 2, γ is the phase angle of the measurement, λ_0 is the source vacuum wavelength, n is the refractive index of the transmitting medium, i is the interferometer factor (the optical interpolation factor), and s is the displacement to be measured.

From Eq. 1, it follows that

$$s = \frac{\delta \cdot \lambda_0}{i \cdot n} \quad , \quad (2)$$

where δ is the order of interference, from which the smallest, resolved displacement-quantization unit, s_q, may be derived as

$$s_q = \frac{\lambda_0}{e \cdot i \cdot n}, \quad (3)$$

where e is the electronic interpolation factor.

Eq. 3 shows that Michelson interferometers are capable of attaining extraordinarily fine resolutions. Resolutions extending down to 0.1 nm are attainable, even over large displacement ranges, using precision interferometers and the current state of the art in electronic signal-processing equipment.

2. Fiber-Coupled Homodyne Interferometers

The homodyne interferometers presented here are Michelson interferometers. Fig. 1 depicts such an interferometer, configured in the form of a plane-mirror interferometer.

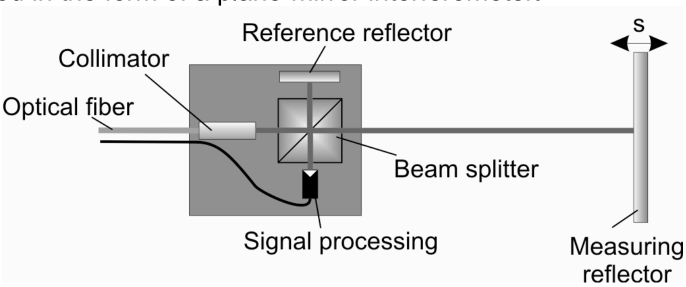

Fig. 1: The layout of a miniature, plane-mirror interferometer.

Both the laser light source and power-supply/signal-processing unit are separated from the measurement head. Light from the frequency-stabilized He-Ne laser is transmitted to the measurement head on a single-mode fiberoptic lightguide, which allows keeping heat sources well away from the location where measurements are conducted. The advantage of the metrological method presented here is based on transmitting just a single beam that is retroreflected by the moving mirror per measurement axis, which allows configuring the metrological setup such that there will be a well-defined point of contact with the object being measured and that the laser beam will remain accurately aligned on the measurement axis, which, in turn, means that the configuration of an Abbé comparator will be maintained. Abbé errors, a typical error source, will thus be minimized or totally eliminated. A plane mirror, or an arbitrary optical surface, is utilized as the moving mirror, where surfaces having reflectances of less than 1 % will be sufficient. Such interferometers have nanometer precisions and excellent linearities over displacements of up to 2 m.

Figs. 2 and 3 depict modifications of the miniature, plane-mirror interferometer in the forms of differential interferometers.

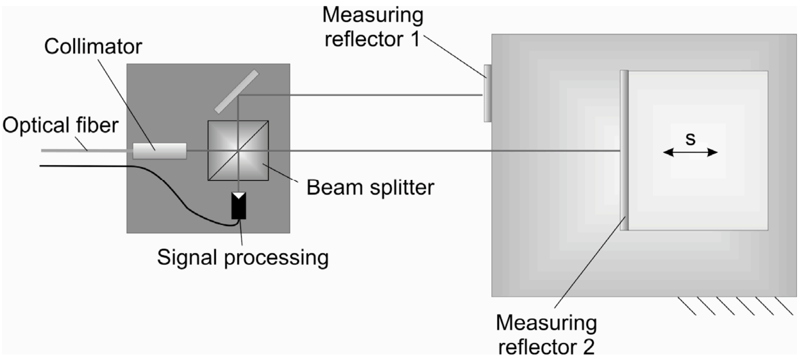

Fig. 2: A miniature, differential-plane-mirror interferometer employing parallel beams.

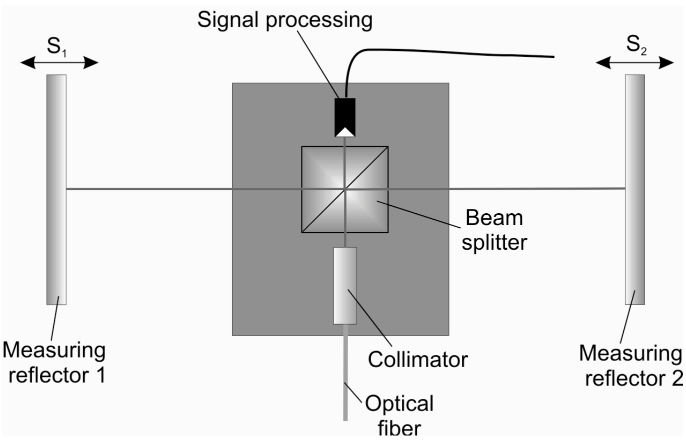

Fig. 3: A miniature, differential-plane-mirror interferometer employing antiparallel beams.

All of those interferometers have length resolutions of 0.1 nm over displacements of up to 2 m. Plane-mirror interferometers may also be configured in the form of double-beam or triple-beam interferometers. The layout of such a double-beam interferometer is depicted in Fig. 4.

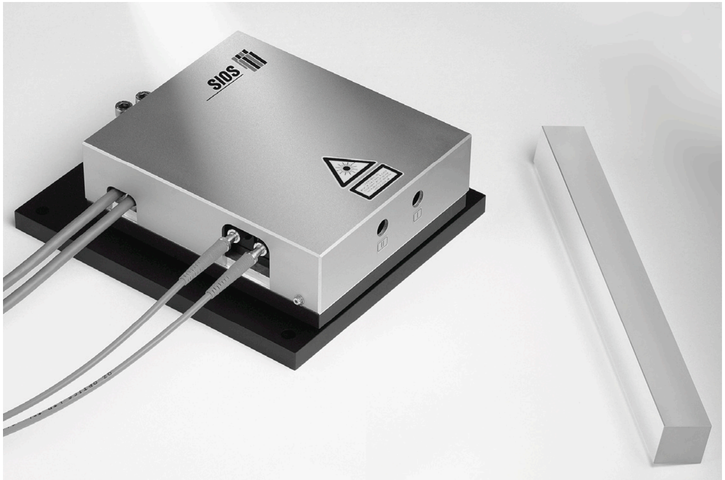

Fig. 4: A miniature, double-beam plane-mirror interferometer.

The double-beam, miniature interferometer shown has a pair of independent interferometer channels and a length resolution of 0.1 nm over an angular resolution of 0.001 arcsec or better, for a baseline beam separation of 25.4 mm.

Employment of a pair of parallel measurement beams allows accurately acquiring two pathlengths simultaneously. The tilt angle is determined from the difference in the two pathlengths and the calibrated, lateral separation of the pair of beams. The mathematical relation involved is

$$\tan\alpha = \frac{\Delta s}{a}, \qquad (4)$$

where α is the angle to be determined, Δs is the pathlength difference, and a is the baseline, lateral separation of the pair of measurement beams (cf. Fig. 5).

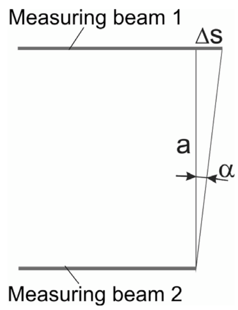

Fig. 5: Determining angles from pathlength differences and beam lateral separations

The application areas of double-beam interferometers range from laser-interferometric measurements on measurement, microscope, or translation stages, coordinate-measuring machines, or machine tools, to bending or strength-of-materials studies or calibration of angle-measurement instrumentation.
Figs. 6 and 7 illustrate some of their typical applications.

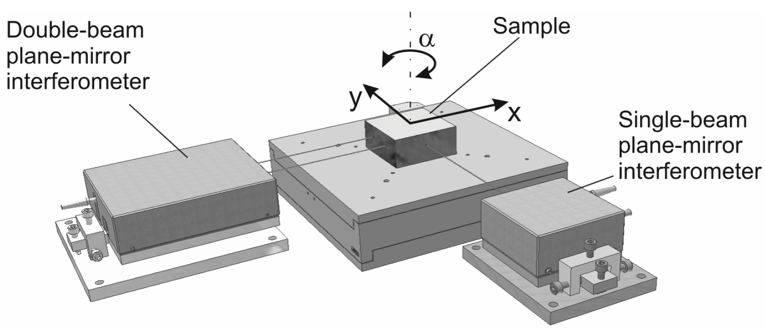

Fig. 6: Interferometric measurements on a plane table.

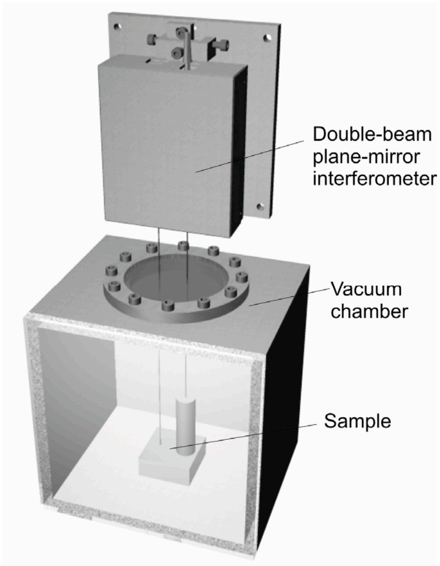

Fig. 7: Dilatometric measurements using a dual-beam interferometer.

Triple-beam interferometers are metrological instruments intended for incorporation into systems that are supplied by a single laser and process three, separate, interferometer channels. Particular attention is devoted to providing a totally symmetric optical configuration. Three pathlengths may be simultaneously determined with nanometer precisions. The associated angles may be extremely accurately determined from the respective differences, Δs, in pairs of pathlengths and the associated beam separations. All systems feature synchronous data transfers on all metrological channels.

Thanks to their extremely compact designs, triple-beam interferometers used for ultraprecise length and angle measurements may be readily adapted to suit widely varying types of metrological tasks. Their employment of fiberoptic lightguides for transmitting light from their laser source eliminates heat sources in their sensor head and allows their flexible arrangement and simple, rapid alignment. Angular resolutions of 0.002 arcsec may be achieved for length resolutions of 0.1 nm.

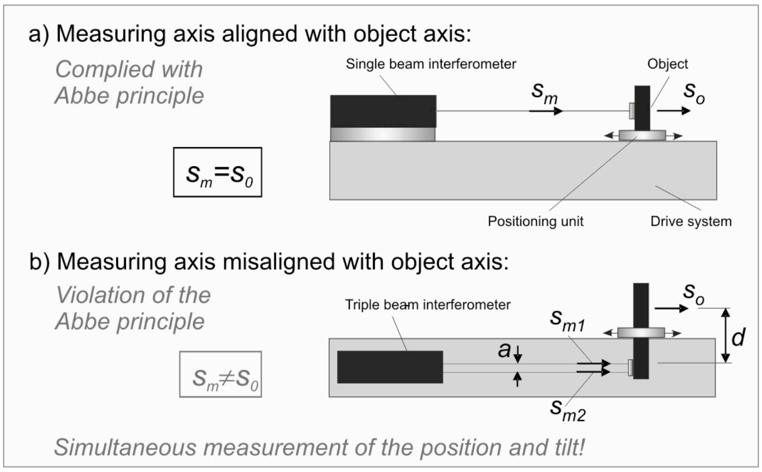

Fig. 8: Example of a measurement on linear guides.

The major metrological characteristics of triple-beam interferometers may be summarized as follows:

pathlength range on each axis: 2 m,
best length resolution attainable: 0.1 nm,
range of pitch and yaw angles measurable: ± 2 arcmin,
best angular resolution attainable: 0.002 arcsec,
vertical and horizontal beam separations: 12 mm is standard.
moving-mirror translation rate: 800 mm/s,
operating temperature range: 15°C to 30°C.

3. Laser-Interferometric Vibrometers

The metrological system to be described here is a Michelson interferometer, modified for conducting noncontacting measurements of vibrations. Reflection of its measuring beam at an industrially rough surface causes multiple diffractions that form a speckle pattern. Superimposing that speckle pattern on the reference beam generates the same interference pattern for every speckle that would result from superimposing a pair of plane waves. The best signal/noise ratios will thus be obtained using an interferometer configuration, for which just one speckle will be analyzed, which may be achieved by suitably designing its sensor head. The intensity distribution that results from superimposing a single speckle on the reference beam is given by

$$I \cong I_{ref} + I_S + 2 \cdot \sqrt{I_{ref} \cdot I_S} \cdot \cos\left(\delta_{ref} - \delta_S\right), \tag{5}$$

where I_{ref} and δ_{ref} are the intensity and phase of the reference beam, respectively, and I_s and δ_s are those for the speckle involved. The phase difference is proportional to the displacement of the object being measured, and thus represents the measured quantity. Fig. 9 depicts the vibrometer's layout

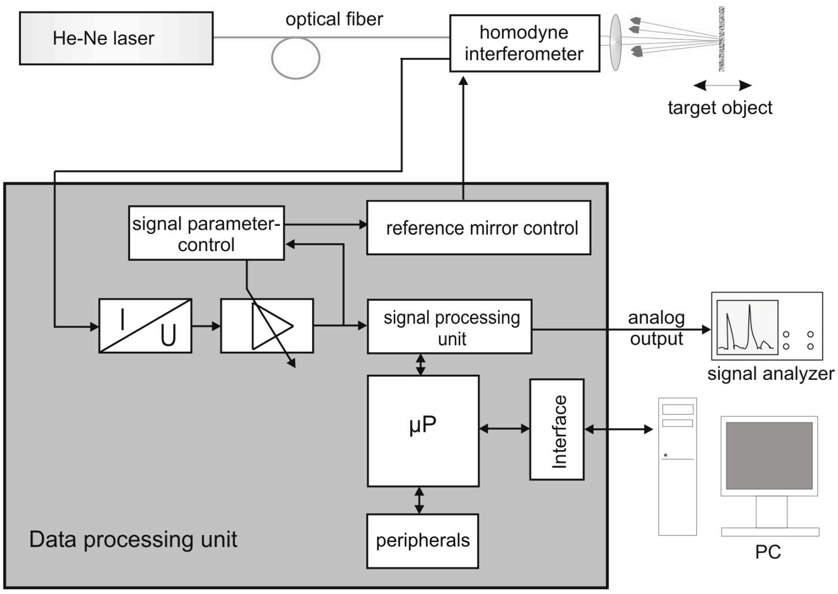

Fig. 9: Layout of a homodyne vibrometer.

Laser-interferometric vibrometers are ideal instruments for making accurate, noncontacting determinations of temporal changes in the positions of objects or surfaces having arbitrary roughnesses. They are capable of detecting mechanical vibrations at frequencies ranging from 0 to 2 MHz with subnanometer resolutions of better than 0.1 nm.

Fig. 10 illustrates an application of that vibrometer in combination with a microscope.
The vibrometer's measuring beam transits the microscope's optical train, yielding a spot diameter of about 2 µm. A combination of a microscope and an x-y translation stage that supports the object being measured allows extremely accurately positioning the measuring beam on small components, which allows conducting vibration measurements on MEMS, AFM-cantilevers, and other micromechanical components. Typical cantilever resonant frequencies fall in the low MHz-range and may be acquired by the vibrometer, thanks to its frequency range of some MHz.

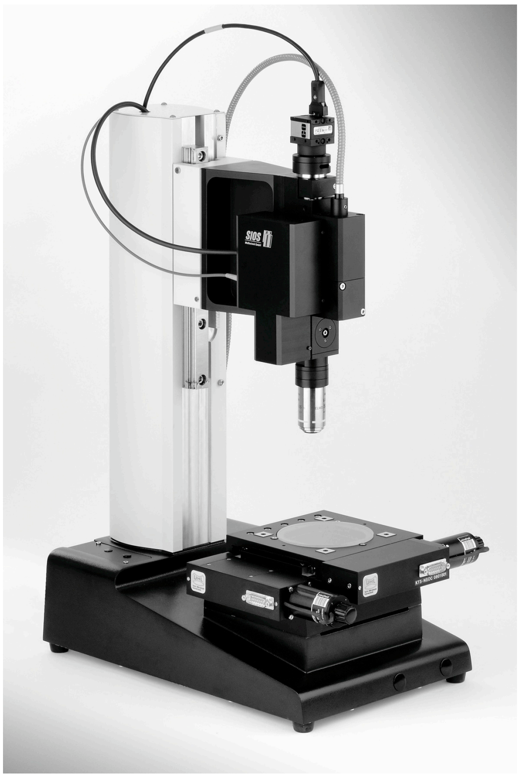

Fig. 10: A homodyne vibrometer installed on a microscope.

4. Summary

Recent advances in SIOS Meßtechnik GmbH’s homodyne interferometers have been in two areas. One is that their metrological parameters have been improved. In addition to their reduced metrological errors, their length resolutions of ≤ 0.1 nm are demanded by many applications. The other is that further advances that significantly extend the application areas of homodyne interferometers have been developed. Homodyne interferometers are thus now capable of highly flexibly covering new applications involving ultraprecise length and angle measurements in industry and research.

5. Acknowledgements

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6. References

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