Miniature Interferometers for Precise Distance Measurements

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1. INTRODUCTION

Not all tasks encountered in the field of laser interferometric distance measurement technology in industry and research can be solved using conventional laser interferometers. In many cases, they are too unhandy, too bulky and also too expensive. Therefore, small sensor systems are necessary whose measuring range, resolution, precision and measuring speed can be adapted because of their modular structure.

This paper presents a miniature laser-interferometric measuring system designed for making precision measurements in the field of microtechnology, nanotechnology, and macrotechnology. Resolutions of 1 nm and an accuracy of a few nanometers may be achieved over dynamic ranges as large as 5 m. The particular advantages offered by these fiberoptic-coupled miniature laser interferometers will be discussed, based on selected practical applications.

These miniature interferometer systems for precision distance measurements have the following major features:

- modular design,
- easy adaptation to a variety of tasks,
- compactly designed interferometer modules,
- complete coupling via optical fibres,
- nanometer resolution and accuracy for measuring ranges of 5 m, and
- comparatively low costs.

2. METROLOGICAL ANALYSIS

The following metrological analysis is intended to elucidate the capabilities and limitations of laser interferometry. The Michelson interferometer (cf. Fig. 1), which serves as the basis for all other types of interferometers, is thus the ideal basis for such analyses [1]. It will be assumed that the laser light source employed emits plane waves that are split into two coherent partial waves that interfere when superimposed on one another. The intensity distribution in the interferometer's image plane will then be given by Eq. 1:

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

where

γ is the phase angle of the incident beam,
λ_0 is its vacuum wavelength,
n is the refractive index of the ambient medium (air),
I is the interferometer factor, and
s is the path length to be measured.

From Eq. 1, if follows that:

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

where δ is the order of interference.

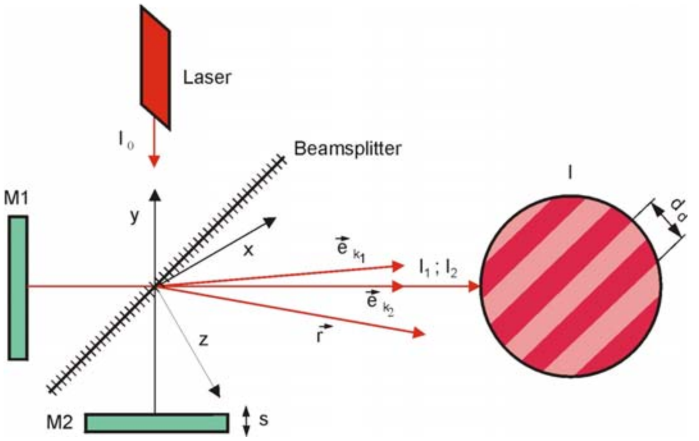

Fig. 1: A schematized Michelson interferometer.

Resolution

The smallest resolvable path-length increment, s_q, may be computed using Eq. 3:

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

where e is an electronic interpolation factor.

Eq. 3 shows that extraordinarily fine resolutions are attainable. The current state of the art in electronic signal-analysis equipment allows resolutions of << 1 nm. Such high resolutions, which are achieved using precision interferometers, are also attainable over large path lengths, s, which allows reaching relative resolutions much better than those attainable using any other metrological method (e.g., for s = 10 m and s_q = 1 nm, the relative resolution will be 10^{-10}).

Precision

Various factors that limit the precision of laser-interferometric length measurements must be taken into account in determining the precision and accuracy of the method. Eq. 2 may be used to compute the effects of such factors on the results of length measurements, s.

The refractive index, n, of air is a function of the ambient temperature, barometric pressure, and absolute humidity. The extent to which these factors affect the results of length measurements may be seen from Table 1. Corrections may be made if these parameters are measured.

The stability of the wavelength, λ_0, of the laser light source employed is a second major factor affecting metrological precision. Table 2 lists the relative wavelength stabilities of various laser light sources. In order to determine the absolute modal wavelength of a frequency-stabilized He-Ne-laser, it must be slaved to an iodine-vapor-stabilized He-Ne-laser that is linked to the cesium atomic clock of a national standards institute. The number of increments (counter pulses) is the product of the order of interference, δ, involved and the electronic interpolation factor, e. The electronic interpolation factor, e, thus specifies the number of pulses into which a signal period is subdivided. The resultant interpolation errors should also be taken into account.

$\frac{\Delta n}{n} = -0.929 \cdot 10^{-6} K^{-1} \cdot \Delta\delta$,	where $\Delta\delta$ is the change in ambient temperature,
$\frac{\Delta n}{n} = +2.682 \cdot 10^{-9} Pa^{-1} \cdot \Delta p$,	where Δp is the change in barometric pressure,
$\frac{\Delta n}{n} = -3.84 \cdot 10^{-10} Pa^{-1} \cdot \Delta p_F$,	where Δp_F is the change in water-vapor partial pressure.

Table 1: The effects of ambient temperature, barometric pressure, and humidity on the refractive index of air, n.

Laser light source	± $\Delta\lambda_0/\lambda_0$
Unstabilized single-frequency He-Ne-lasers	$\approx 10^{-6}$
Unstabilized dual-frequency He-Ne-lasers	$\approx 3 \times 10^{-7}$ (for max. path-length differences < their resonator length)
Stabilized He-Ne-lasers (for the case of equal mode intensities)	$\approx 10^{-8}$
Iodine-vapor-stabilized He-Ne-lasers	$\approx 10^{-12}$
Diode lasers	$\approx 10^{-5}$ 10^{-6} short-term stability

Table 2: The relative wavelength stabilities of various types of laser light sources.

The fact that the aperture of the interferometer's illumination system also affects the accuracy of the results of length measurements is frequently overlooked. The following correction for that aperture should be applied:

$$\Delta s_A = -\frac{r^2}{4f^2} \cdot s\,, \qquad (4)$$

where

Δs_A is the correction to measured lengths be applied,
r is the radius of the aperture stop or of the core of the fiberoptic lightguide employed,
f is the focal length of the collimator employed, and
s is the measured path length.

If the laser beam is not normally incident on the moving mirror, M2 (cf. Fig. 1), then yet another systematic measurement error will have to be taken into account:

$$\Delta s_\alpha = -s \cdot (1 - \cos\alpha)\,, \qquad (5)$$

where α is the angle between the incident beam and the normal to the reflective surface of M2.

Systematic measurement errors will also occur if the axis along which the moving mirror, M2, is translated is not parallel to the normal to its reflective surface:

$$\Delta s_\beta = -s \cdot (1 - \cos\beta)\,, \qquad (6)$$

where β is the angle between its translation axis and the normal to its reflective surface.

3. LASER-INTERFEROMETRIC GAUGING PROBES

Fig. 2 depicts a laser-interferometric gauging probe that utilizes a fiberoptic-coupled miniature interferometer equipped with a retroreflector as its internal metrological system. This gauging probe has a motor-drive on its spindle that exerts an adjustable, constant, force on objects being measured over its full dynamic range. The technical data for this laser-interferometric gauging probe are as follows:

- Dynamic range: 20 or 50 mm
- Resolution: 1 nm
- Relative metric precision: $\leq 10^{-6}$
- Applied force: adjustable over the range 0.5 N to 1.5 N
- Fiberoptic-coupling of the gauging probe to the interferometer

Application areas of this laser-interferometric gauging probe include:

- thickness measurements on optical or mechanical components,
- measuring the thicknesses of foils,
- calibrating gauge blocks, and
- calibrating dimensional reference standards, precision metrological instruments, and sensors.

Working in collaboration with the Physikalisch-Technische Bundesanstalt (PTB), Brunswick, Germany, and Ilmenau Technical University, Ilmenau, Germany, we have developed a new type of gauge-block calibration system based on a laser-interferometric gauging probe that allows reducing the total number of gauge blocks required to around one-tenth of that normally necessary, while maintaining ultrahigh metric precisions.

Employing the laser-interferometric gauging probe as the upper gauging probe increased the dynamic range from the former few micrometers for the case of an inductive sensor to 20 mm, while maintaining the same, or better, metric precision, which allowed making more efficient gauge-block calibrations and cutting gauge-block recalibration costs. Fig. 3, below, depicts the metrological setup employed.

Fig. 2: View of a laser-interferometric gauging probe.

Fig. 3: View of a gauge-block calibration system equipped with a laser-interferometric gauging probe.

4. EMPLOYING MINIATURE INTERFEROMETERS AS MODULAR COMPONENTS OF METROLOGICAL SYSTEMS

Miniature interferometers are manufactured in versions equipped with retroreflectors and plane-mirror reflectors. Although both types of system have common metrological characteristics, their applications differ.

Their major technical data may be summarized as follows:

Parameter	Miniature interferometer equipped with a retroreflector (cf. Fig. 4)	Miniature interferometer equipped with a plane-mirror reflector (cf. Fig. 5)
Dynamic range	≤ 5 m	≤ 2 m
Resolution	1.24 nm	1.24 nm
Relative metric precision	$\leq 1 \times 10^{-6}$	$\leq 1 \times 10^{-6}$
Moving-mirror translation rate	≤ 600 mm/s	≤ 600 mm/s
Max. tilt of moving mirror relative to measuring beam	± 3°	≤ 2’ for distances from the sensor head of 0.5 m or less

Fig. 4: View of a miniature interferometer equipped with a retroreflector.

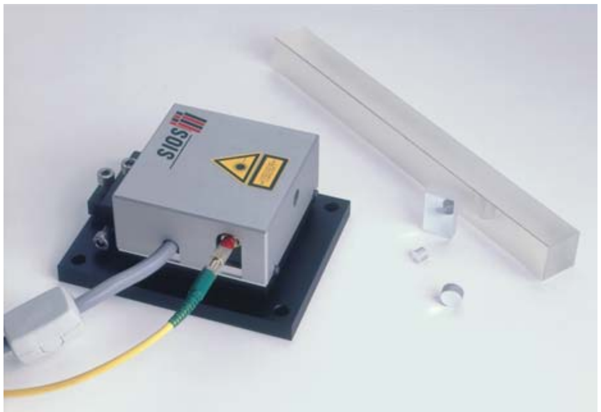

Fig. 5: View of a miniature interferometer equipped with a plane-mirror reflector.

Miniature interferometers are used as modular components of

- machine tools,
- metrological systems and measuring microscopes,
- coordinate-measuring machines,
- hardness testers, and
- materials-testing equipment,

as well as equipment for calibrating other types of length-measurement instrumentation and as precision length-measurement systems for use in research and development work.

5. MICROINTERFEROMETERS

Microinterferometers (cf. Fig. 6) operate on the same principle as miniature interferometers equipped with retroreflectors and are noted for their compact designs, fiberoptic coupling, and simple alignment. Among other applications, they are used on position controllers, hardness testers, materials-testing equipment, multi-axis translation stages, and calibration systems.

Their employment of fiberoptic coupling and discrete micro-optical components and their layout and interconnection hardware allow achieving extremely compact sensor-head dimensions of 28 mm x 25 mm x 15.5 mm and a sensor-head weight of just 35 g. Their employment of the wavelength of a frequency-stabilized He-Ne-Lasers as their dimensional reference standard and their inclusion of corrections for the refractive index of air as standard equipment, guarantee excellent metrological characteristics. A dynamic range of 5 m and resolution of 1.24 nm are also standard equipment. The maximum translation rate of their moving mirror is 0.6 m/s.

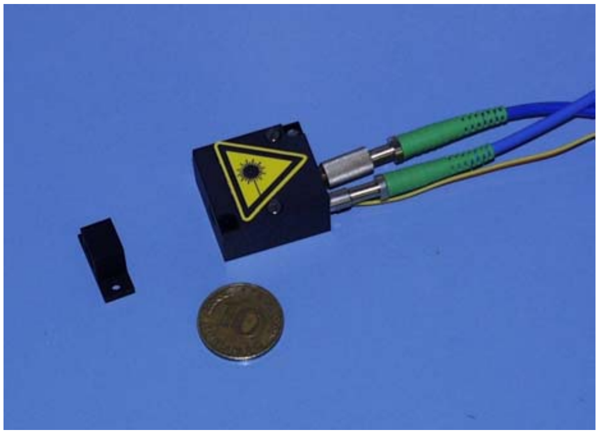

Fig. 6: A view of the interior of the microinterferometer's sensor head, showing the latter's moving retroreflector.

6. VIBROMETERS

Vibrometers equipped with miniature plane-mirror interferometers are employed in vibrational analysis. Their measuring beam is focused on the object whose vibrations are to be measured. Measurements are totally noncontacting. The surface finish of the object whose vibrations are to be measured is arbitrary, as long as it yields a reflectance of 5×10^{-4}, or better. The minimum resolvable vibrational amplitude is 0.3 nm. Fig. 7, below, presents plots of vibrational-amplitude resolution versus vibrational frequency for two vibrometer models (SM 01 and SM 02).

Analyzing the resultant vibrometer data using FFT-software allows performing vibrational measurements, including spectral analyses, at frequencies up to 500 kHz. Fig. 8 depicts the vibrometer units involved.

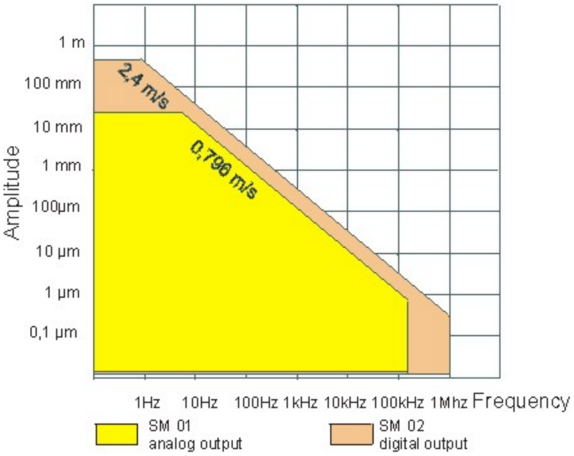

Fig. 7: Plots of vibrometer vibrational-amplitude resolution as a function of vibrational frequency.

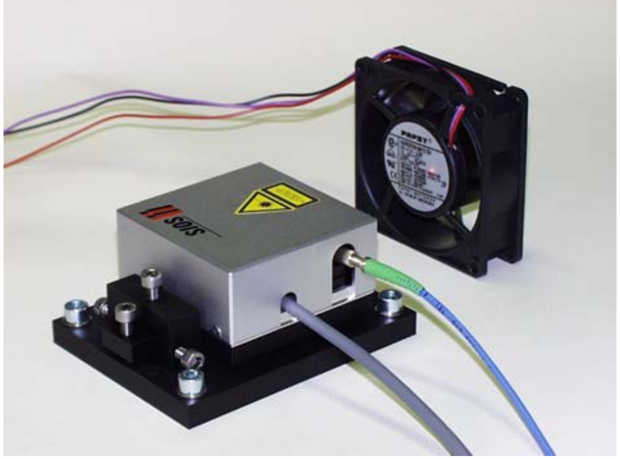

Fig. 8: A view of the vibrometer units involved.

7. ACKNOWLEDGMENTS

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8. LITERATURE

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