A self - mixing laser sensor for the real - time correction of straightness/flatness deviations of a linear slide

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ABSTRACT

The development of a contactless sensor based on the Laser-Self-Mixing effect for the simultaneous measurement of linear and transverse degrees-of-freedom (DOFs) of a moving target is described in this paper. The sensor is made of three laser diodes with integrated monitor photodiodes, and a properly designed reflective target attached to the moving object. The proposed technique exploits the differential measurement of linear displacements by two identical self-mixing interferometers (SMIs) and makes the system more compact and easier to align with respect to traditional interferometric systems, thus providing an effective low-cost motion control system. The feasibility of the proposed sensor is experimentally demonstrated over a range of 1 m for linear motion and ± 6 mm for transverse displacements, with resolutions of 0.7 μm and 20 μm, respectively.

Keywords: Self-mixing, optical feedback, interferometry, metrology, straightness, flatness, multi-DOFs measurements, laser diode.

1. INTRODUCTION

The real-time monitoring of transverse deviations of a slide moving along a linear guideway is a common problem in a great variety of scientific and industrial applications, i.e. precision metrology [1], lithography [2], calibration system for large-scale structures [3], and accelerator structures [4]. In fact, a slide linearly moving in a specific direction inevitably deviates in the transverse plane because of geometric defects of guideways, mechanical imperfections or thermal deformation of its structural components.

If the direction of the linear motion is assumed to be the x – axis, deviations in the xy plane or in the xz plane are commonly referred to as straightness and flatness errors, respectively, although their amplitude is expected to be much smaller than the working range of the main linear displacement.

Several optical sensors have already been used for measuring such deviations in real time. For example, the straightness of a laser beam onto the active surface of a position sensitive detector as a four-quadrant photodetector or a CCD camera, is frequently exploited in both free-space [5] or fiber medium [6]. Alternatively, the transverse estimation can be provided by the differential reading of two quadrant detectors at either ends of the guideway, where a collimated light beam is partially obscured by a knife-edge mounted onto a slide [7]. The resolution of this technique is determined by the quality of knife-edge, the beam profile uniformity and the detector sensitivity, eventually reaching the submicron range in case of short tracks and getting worst if long linear displacements have to be monitored. This drawback can be overcome by exploiting the transverse displacement of a laser beam back-reflected by a retroreflective target[8], preserving resolution of tens of microns almost independently on the length of the linear track. Nevertheless, the presence of position sensitive detectors requires an analogical treatment of the detected signal.

A digital signal approach is typical of optical interferometers, which are themselves unable to measure transverse displacements because it does not introduce any optical path difference with respect to the reference arm. This hindrance can be overcome by projecting a component of the transverse motion along the direction of the laser beam. This goal is usually achieved by attaching a Wollaston prism at the moving target [9], for separating and then recombining the laser beam reflected by a retroreflector fixed at the far end of the optical path. When the Wollaston prism is moved along with the stage, a difference in the optical path occurs in case of transverse motion with respect to the original laser beam and the number of interferometric fringes detected by an external receiver is used to measure the straightness of the stage. The measurement resolution (typically some micrometers) depends on the divergence angle of the Wollaston

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prism, which cannot be easily changed due to fabrication constraints. A sub-micrometric resolution can be achieved by the insertion of additional optical elements [10] - [12]. In any case, these approaches require expensive setups and are not easily extended in a multi – DOF measuring system because of the presence of a fixed elements beyond the movable stage, which strictly limits the compactness of the apparatus.

In this paper, we present a compact interferometric system capable of tracking the target displacement along the longitudinal axis with sub-micron resolution over 1 meter range, and along the transverse axis with 20 microns resolution over about 6 mm range. The proposed technique is entirely based on the differential measurement of linear displacement by three identical self-mixing interferometers (SMI), each made only by a laser diode package with integrated collimated lens and monitor photodiode, and a plane mirror target. The first SMI_1 is aligned with the main longitudinal x-axis, whereas the remaining two SMIs are properly tilted in order to make the compound system able to measure both longitudinal and transverse motion.

The paper is organized as follows: methodology is described in Section 2; experimental results are presented in Section 3 and conclusion are drawn in Section 4.

2. METHODOLOGY

2.1 Laser-Self-Mixing interference

Laser interferometry is one of the most disseminate and performing phase sensitive techniques for metrological measurements. Besides the traditional "external configuration" needing one or more external detectors, the LSM approach, which is based on an "internal configuration" since the superposition between the incident and the retroreflected field takes place inside the non linear laser cavity, has been established in the last two decades [13-14].

The LSM interference takes place when a portion of the light emitted by a laser source is reflected back into the laser cavity by an external reflector, such as a mirror or a diffusive target, and interferes with the standing wave inside the laser cavity, causing the amplitude and frequency modulation of the output laser beam [15-16]. If the relative feedback power is kept below a certain threshold (the moderate feedback regime), the output power swings from a maximum to a minimum every $\lambda/2$ displacement of the external reflector, depending on the back - reflected phase Φ via a distorted cosine – type relation. The most suitable solution, in order to optimize the measuring setup, consists in the detection of the amplitude modulation of the laser output power by means of the photodiode integrated into the laser package for feedback control.

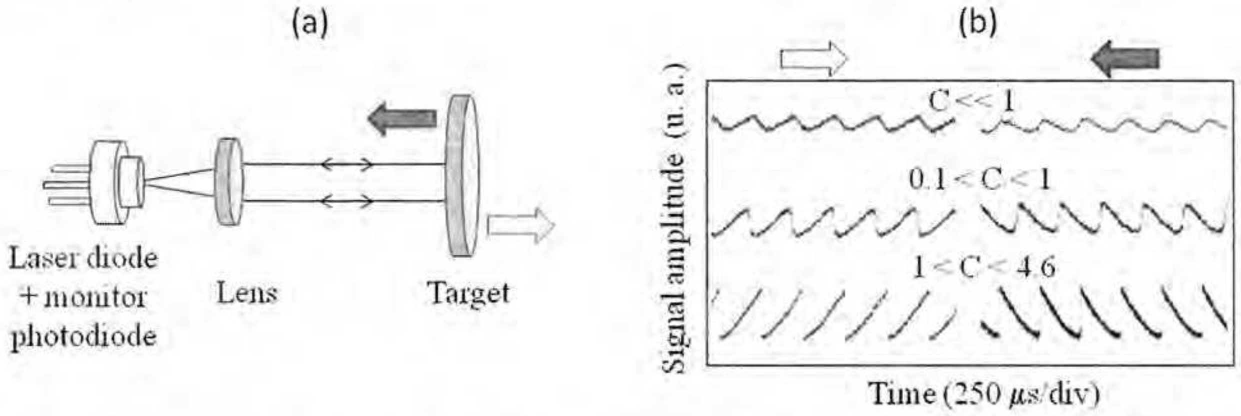

Fig. 1. (a) Schematics of the LSM setup, with the target moving backward (gray arrow) or forward (white arrow) with respect to the laser source. (b) Experimental oscilloscope waveforms obtained for different feedback regimes in presence of a linear continuous displacement of the target at a speed of 1 mm/s in forward (traces at the left) and backward (traces at the right) direction with respect to the laser source.

The useful features of this scheme with respect to the traditional interferometric one are the reduction of the number of required optical elements (such as the beam splitter and the reference mirror), a much simpler optical alignment since there is no external reference arm, and a reduced cost due to the absence of the external detector. The basic setup, sketched in Fig. 1 (a), is thereby made only of a laser source, a collimating lens, a neutral attenuator for the adjustment of feedback power, and a remote target. Actually, this setup can be considered as an evolution of the Michelson interferometer with the reference arm folded on itself toward the laser source, whose output coupler serves as the beam splitter.

Another peculiarity is that the feedback regime, i.e. the relative amount of light coupled back into the laser, directly affects the characteristics of the output signal in a non linear way, allowing for the identification of the sign of the displacement by means of a single quadrature reading. A useful classification of the feedback regimes for metrological purposes can be performed by adopting the C – value as the selective parameter [17], where C is the feedback parameter [18] defined as follows:

$$C = \varepsilon \sqrt{\frac{R_3}{R_2}} (1 - R_2) \sqrt{1+\alpha^2} \frac{L}{l \cdot n_{eff}} \tag{1}$$

Expression (1) depends on a combination of laser dependent parameters (R_2 is the output coupler reflectivity, l is the laser cavity length, n_{eff} is the effective refractive index of the active medium, α is the linewidth enhancement factor) and system adjustable parameters (R_3 is the target reflectivity, L is the external cavity length, and $\varepsilon < 1$ is a constant referred to as the mode matching factor).

With reference to the oscilloscope waveforms produced during a linear displacement of the target and reported in Fig. 2 (b), when $C \ll 1$ (very weak feedback regime), the output waveform is represented by a sine function as in classical interferometry. In this regime the laser behavior is quite unperturbed with respect to solitary laser operations, and the symmetry of the waveform requires the duplication of the measurement channel or a phase shifting modulation of the signal in order to recover the direction of the target displacement. When $0.1 < C < 1$ (weak feedback regime), the waveform becomes progressively distorted as C approaches unity, with an asymmetry related to the direction of motion of the external reflector. When $1 < C < 4.6$ (moderate feedback regime), the laser becomes bi-stable and the waveform is visibly sawtooth-like, with sharp switching every time the phase changes by 2π. Lastly, for $C > 4.6$ (strong feedback regime, not represented in Figure 2 b), the system becomes multi-stable producing waveform instabilities.

2.2 Measurement of linear displacements

On the basis of the above classification, operation in the moderate feedback regime represents the most convenient solution for displacement measurements along the longitudinal x-axis, since the module of the displacement can be simply recovered by the count of the total number of produced fringes, whereas the direction of displacement can be recovered via the sign of the sharp transitions in the sawtooth-like signal. More in details, the standard analysis in the self-mixing configuration consists of the AC signal amplification by a trans-impedance amplifier, followed by the time-derivation of the output signal, which converts the sawtooth-like fringes in a series of positive and negative spikes, whose sign depends on the direction of the motion of the target. Finally, the net number of counts N = N+ - N-, given by the algebraic sum of the positive (N+) /negative (N-) counts, returns the linear displacement Δx as:

$$\Delta x = N \cdot \lambda / 2 \tag{2}$$

where N and λ are the net number of fringes and the wavelength of the laser.

Operations in the moderate feedback regime is usually achieved and controlled by means of a variable attenuator placed along the optical path. The attenuation of the feedback intensity is always required in presence of reflective target and collimated semiconductor lasers. In order to avoid the insertion of the filter, either the target should be changed or the collimating condition can be properly modified. In the first case, a diffusive target can be employed to reduce the back - scattered radiation re – entering the laser source; however, this solution implies a signal fading over long-distances due to the speckle effect. The alternative choice is represented by the reduction of the distance between the laser diode and the collimating lens, in order to obtain a divergent laser beam whose power losses through the finite aperture optical elements (lens and diode facet) will compensate the linear increase of the feedback parameter C with the target distance with no need of attenuation filter along the optical path [19].

2.3 Measurement of transverse displacements

With reference to the two self-mixing interferometers illustrated in Fig. 2 (a), SMI_1 is able to detect purely linear displacement Δx along the x-axis whereas it is totally blind to any off-axis motion. A second interferometer SMI_2, placed at a distance d_y from the first and rigidly tilted by a small angle α with respect to the x-axis in the xy plane, identifies a new optical axis x'. This expedient makes the interferometer sensitive to displacements along both the linear (x) and transverse (y) axis, since both cause a change $\Delta l_2 = \pm N_2 \times \lambda_2 / 2$ of the optical path length along x'.

Only SMI_2 is thus needed for measuring a pure Δy displacement, whereas a combined linear / transverse displacement requires the comparison of the two SMI_i (i=1,2) readings in order to be properly measured. The same considerations apply for the measurement of flatness, via a third interferometer SMI_3, placed at a distance d_z from SMI_1 and tilted by an angle β with respect to the x – axis in the xz plane (see Fig.2 b). In terms of number of interference fringes, the measurement displacements can thus be written as:

$$\begin{cases} \Delta x = N_1 \cdot \lambda_1 / 2 \\ \Delta y = N_2 \cdot \lambda_2 / [2\sin(\alpha)] - N_1 \cdot \lambda_1 / [2\tan(\alpha)] \\ \Delta z = N_3 \cdot \lambda_3 / [2\sin(\beta)] - N_1 \cdot \lambda_1 / [2\tan(\beta)] \end{cases} \quad (3)$$

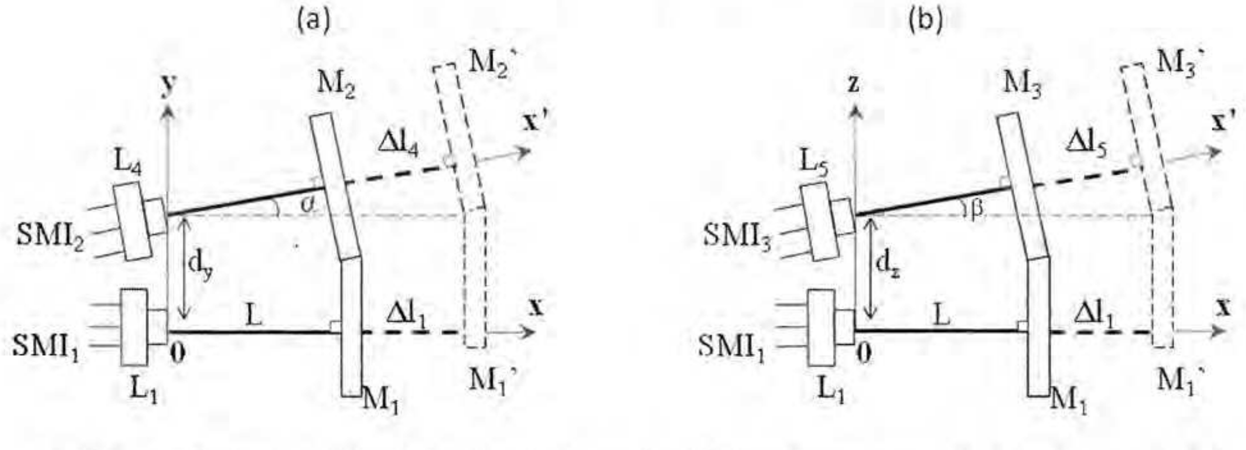

Fig. 2. Schematic geometry of the setup for the straightness (a) and flatness (b) measurement. Each interferometer SMI_i (i = 1,2,3) is made up by a laser diode L_i, and a plane mirror M_i as target. M_i' is the position of the target after the displacement.

2.4 System performance: resolution and accuracy

Given the intrinsic linear resolution $R_x = \lambda / 2$ of the self-mixing technique, the straightness/flatness resolution can be derived by Eq. 3 by assuming null the counter N_1 and unitary the counter $N_{2/3}$, resulting in $R_y = \lambda / [2 \cdot \sin(\alpha)]$ and $R_z = \lambda / [2 \cdot \sin(\beta)]$ For example, a straightness resolution of 1 μm can be achieved with a wavelength λ of 0.8 μm and an angle α approximately equal to 25°. However, such a large angle is not practical if medium – long linear displacement (some centimetres up to some meters) are allowed along the x – axis, since the drift of the spot of the tilted laser $L_{2/3}$ in the yz plane would increase proportionally to Δx. Accordingly, the tilt angle, and the resolution, will be constrained by the dimensions of the system: given the maximum allowed size of the target (h × h) and its maximum longitudinal distance from the lasers x_{max}, $\alpha \le \tan^{-1}(h / x_{max})$. Our choice to limit h ≈ 50 mm and to allow for $x_{max} \approx$ 1.5 m resulted in α ≈ β ≈ 2° and an expected theoretical resolution of about 20 μm for a laser wavelength of 1.3 μm.

The estimated measurement accuracy σ, that is the deviation between the measured and the actual displacement, can be obtained by applying the error propagation formula to Eq. (3) in terms of number of interference fringes N_1 and N_2 as:

$$\begin{cases} \sigma_x = \sqrt{\left(\frac{\partial l_i(N,\lambda)}{\partial N}\right)^2 \sigma_N^{\ 2}} = \frac{\lambda}{2}\sigma_N \\ \sigma_y = \sqrt{\left(\frac{\partial y(N,\lambda,\alpha)}{\partial N}\right)^2 \sigma_N^{\ 2} + \left(\frac{\partial y(N,\lambda,\alpha)}{\partial \alpha}\right)^2 \sigma_\alpha^{\ 2}} \approx \sqrt{\frac{1}{2}\left(\frac{\lambda}{\alpha}\right)^2 \sigma_N^{\ 2} + \left(\frac{y}{\alpha}\right)^2 \sigma_\alpha^{\ 2}} \end{cases} \tag{4}$$

where we have assumed that $\lambda = \lambda_1 \approx \lambda_2$. The error in the fringe count is $\sigma_{N1} = \sigma_{N2} = 2$, since each electronic channel for the positive/negative fringe count is affected by an intrinsic uncertainty of ± 1 count. The assessment of the tilt angle of the target and its uncertainty were obtained by means of a preliminary calibration against a reference meter. The result is $\alpha = 2.1°$ with a corresponding uncertainty of $\sigma_\alpha \approx 0.1°$. Consequently a linear accuracy $\sigma_x \approx 1.3$ μm and a maximum transverse accuracy $\sigma_y \approx 69$ μm for a straightness $\Delta y = 1$ mm can be achieved with a laser of wavelength $\lambda = 1.3$ μm.

The measurement error due to wavelength fluctuations has been neglected in the above system, since the wavelenght was continuously monitored by a wavelength meter allowing a relative accuracy $\Delta\lambda/\lambda = 10^{-6}$. A more detailed formulation of the measurement accuracy in a SMI including the effect of wavelength fluctuations can be found in [20].

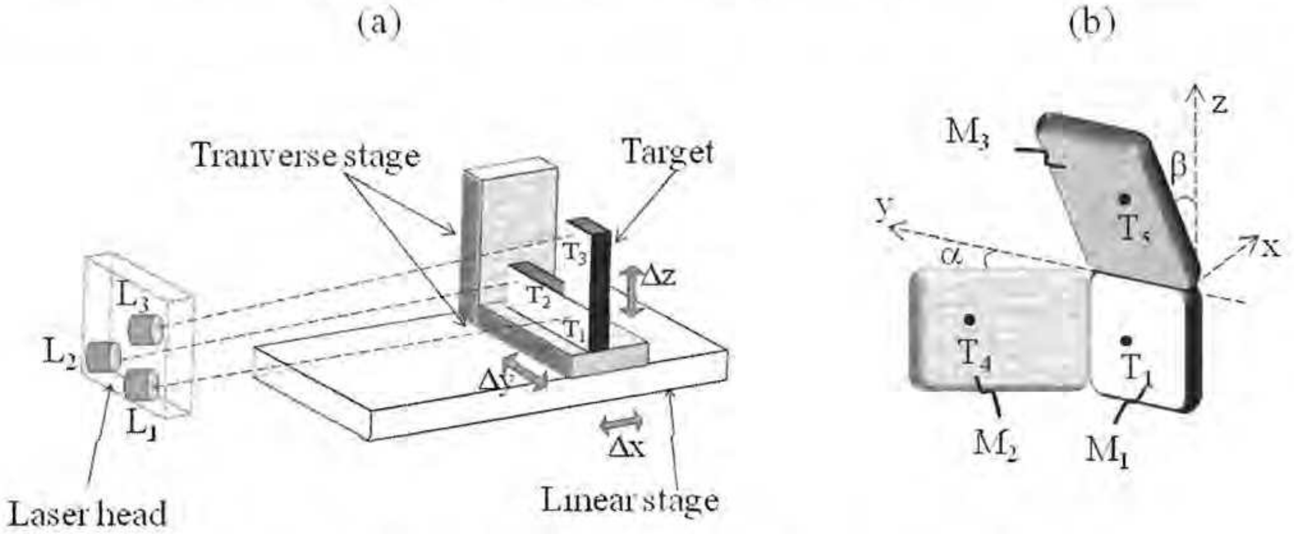

Fig. 3.(a) Schematics of the set-up for a linear/transverse measuring system; (b) details of the complex target.

3. EXPERIMENTAL SETUP AND RESULTS

3.1 Setup description

The prototype of the sensor is schematically illustrated in Fig. 3 (a). It is composed of a laser head, which consists of three laser diodes mounted side-by-side in a "L"-like configuration, and a reflective target. The sources are Distributed-Feedback (DFB) diode lasers with nominal wavelength of 1310 nm and current threshold I_{th} = 12 mA. In our experiments the lasers are driven by a current I = 23mA. Each laser is equipped with a collimating lens (numerical aperture NA = 0.5 and nominal focal length f = 8 mm) and a monitor photodiode, whose photocurrent is firstly AC-coupled to a transimpedance amplifier (gain $=10^5$ V/A), and then fed into the signal processing board of a computer. In order to avoid the presence of a variable attenuator, the moderate feedback condition has been achieved by properly defocusing the laser source.

The moving target consists of three reciprocally tilted mirrors (Fig. 3 b): M_1 is a squared mirror of side 10 mm lying in the plane yz, M_2 is a rectangular mirror of dimension 40 mm × 10 mm, tilted at angle $\alpha = (2.1 \pm 0.1)°$ around the z – axis, M_3 is a rectangular mirror (10 mm × 40 mm) tilted at angle $\beta = (1.8 \pm 0.1)°$ around the y - axis. The target was mounted on a y-z translational stage fixed to a 1 m linear stage along the x-axis. The minimum distance between the target and the laser head was 15 cm.

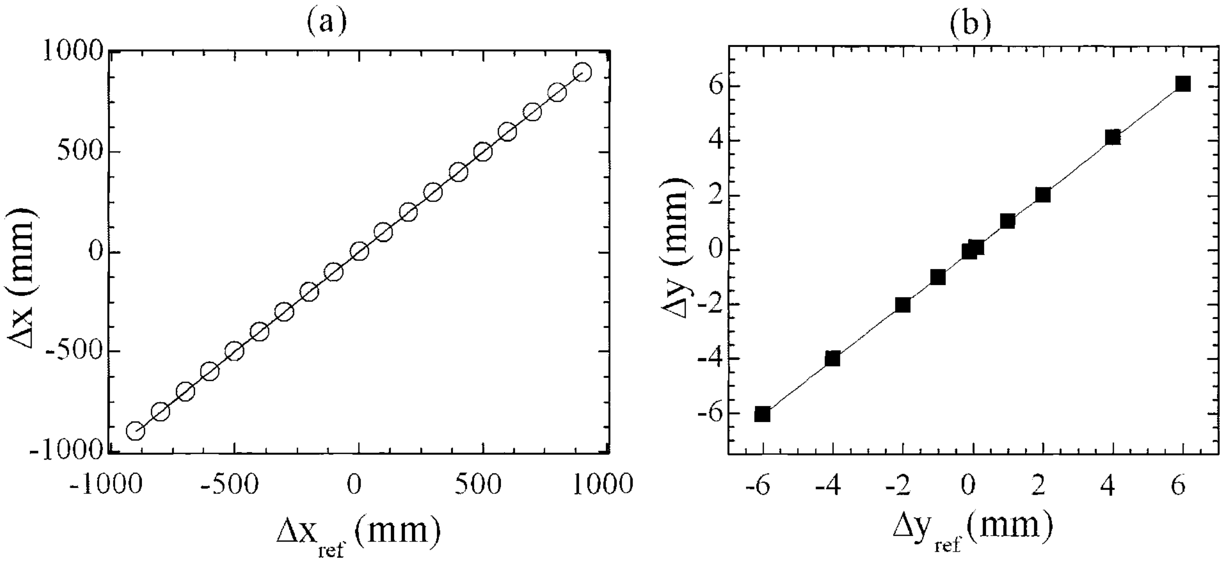

Fig. 4.(a) Target displacement Δx measured by the linear interferometer SMI_1, where positive (negative) values are related to forward (backward) linear displacements. (b) Straightness Δy measured by the interferometer SMI_2 at a fixed distance laser – target L=120 cm. The error bars are always smaller than the symbol size.

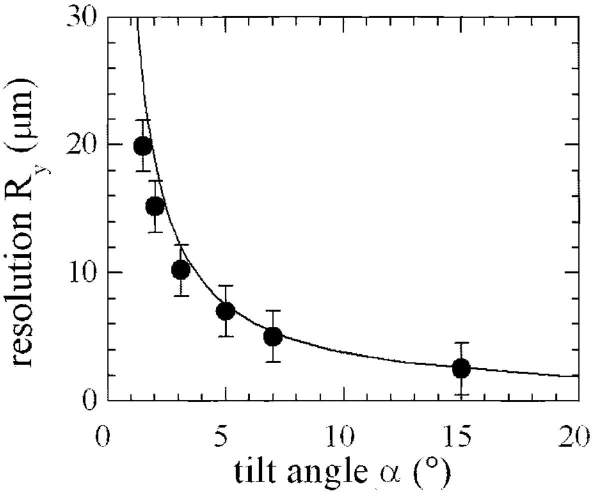

Fig. 5. Experimental (full marks) and theoretical (continuous line) straightness resolution R_y, as a function of the tilt angle of SMI_2.

3.2 Experimental results

Fig. 4 (a) shows the measured linear displacement Δx up to 1 m at a speed of 10 mm/s, as compared with the nominal displacement given by the translational stage. The system response is linear over a linear dynamic range of six orders of magnitude. The maximum continuous displacements was only limited by the length of the linear stage. However, the existence of the sawtooth-like signal was observed over a continuous range up to 2 m. To validate the proposed system as a transverse displacement sensor, the interferometers SMI_2 was tested for displacements Δy in the range $2\times10^{-3} \div 6$ mm (Fig. 4 b) at a fixed distance laser/ target L = 1.2 m. The linearity of the response is guaranteed over the full measurement range. Analogous results are achievable for the flatness by using the interferometers SMI_3 [20].

As discussed in Sec. 2.4, the performance of the system in terms of resolution, that is the minimum straightness able to produce one interference fringe, improves by increasing the SMI_2 tilt angle α as reported in Fig. 5. The 15° required to achieve a resolution of 3 μm restricted the longitudinal range to $\Delta x \leq 150$ mm for the chosen mirror size of 40 mm.

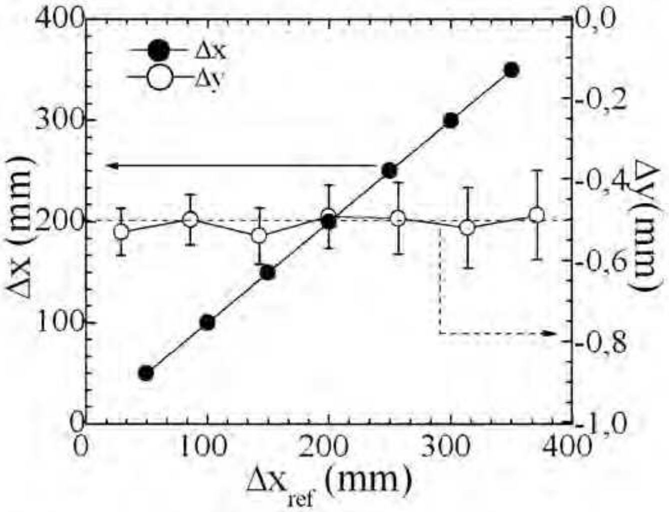

Fig. 6. Simultaneous measurement of a linear displacement in the range 20 – 400 mm with a fixed straightness Δy = -0.5 mm, pointed out by the dotted line.

Most practical applications require a real – time control of a small straightness/flatness deviation of a moving target along the main x – axis. The simultaneous measurement of the linear and transverse motion is reported in Fig. 6, where a given Δy (Δz) displacement of - 0.5 mm was imposed to the target during its linear translations Δx in the range 0 ÷ 400 mm. The results shows that the combination of linear and transverse motion can be handled consistently by SMIs without a significant loss of accuracy.

4. CONCLUSIONS

A three-DOFs optical system based on the LSM effect has been described in this paper. The proposed sensor simultaneously measures linear and transverse displacements (straightness and flatness) of a moving target, over a measurement range greater than 10^3 mm and 6 mm with linear and transverse resolutions of 0.7 μm and 20 μm, respectively. This result has been achieved by the differential readings of couples of identical LSM interferometers, properly tilted with respect to the longitudinal axis in order to recover both the linear and the transverse information.

The feasibility of the measurement technique has been demonstrated by implementing a prototype experimental setup, made of three DFB laser sources, each equipped with monitor photodiode and collimating lens, and an innovative target consisting of three reciprocally tilted mirrors attached to the moving object. Straightness measurements have been performed in both pure or combined 2-DOFs displacements, thus confirming the suitability of the proposed methodology.

Interestingly, the same experimental approach entirely based on the LSM interference has been recently exploited in a compact 3-DOFs system, capable of tracking the longitudinal displacement of the target simultaneously with yaw and pitch rotations up to ± 0.45° [21], thus suggesting a further extension of the demonstrated sensor toward a 5-DOFs optical system for the real-time measurement of three translations and two rotations of a remote target.

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