XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

LASER INTERFEROMETRY FOR STRAIGHTNESS MEASUREMENTS IN A WEAKLY CONTROLLED ENVIRONMENT

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Abstract: Straightness measurements for the geometrical inspection of machining tools have been operated in a weakly controlled environment (concerning temperature, pressure, humidity and induced mechanical vibrations) with reference to industrial manufacturing departments.

Measurements have been performed by means of a Wollaston prism laser interferometer.

A first experimental characterization of this instrumentation has been operated by repeatability tests conducted in controlled and not controlled environments, considering different relative positions for the interferometer and the laser head. Then a calibration diagram has been constructed, assessing the accuracy and the instrumental uncertainty in the case of displacement measurements in a plane perpendicular to the laser beam direction.

In a second stage a suitable method has been developed to estimate the uncertainty level associated to straightness measures operated by the laser interferometric technique and also by traditional instrumentation, such as taut-wire and microscope and precision level. Measurement uncertainty is estimated by means of the Monte Carlo Method and according to standards.

Measures obtained by the laser interferometric method prove to be affected by higher levels of uncertainty than those coming from traditional approaches.

Keywords: straightness, interferometry, uncertainty, Monte Carlo

1. INTRODUCTION

In the industrial field of the production and selling of machining tools the internal inspection phase constitutes a crucial step, due to the economical intrinsic value of the goods. Specifically, the geometrical inspection phase proves to be critical, since the contractually imposed tolerance specifications tend to be dramatically narrow and to be accepted by producers in order to remain competitive on markets. As a consequence, the measurement uncertainty associated with inspection measuring operations has to be suitably narrow to allow the verification of the imposed tolerances, as it is explained in [1].

In the industrial field of the production of large dimensions machining tools (where the linear extension of components can reach even 30 m), it is commonly considered that measurement methodologies based on laser interferometry allow inspection operations on the mechanical constituting elements of these, offering suitable low measurement uncertainty levels.

Since the seventies laser based measurement techniques have been adopted in the mentioned industrial field, with the aim to increase repeatability in positioning measurement and control [2]. Nowadays it is commonly accepted that laser interferometry guarantees low uncertainty affected measures for positioning measurements and also for dimensional or geometrical verifications if used in controlled environments (in terms of temperature, pressure, humidity and induced vibrations). By contrast, if it is adopted for measurements in manufacturing departments such performances can not be assured. This is the case of the inspection of the constituting mechanical elements of large machining tools, which are directly inspected in the production department, due to their dimensions.

Geometrical and dimensional inspection is conducted with reference to [3]. Keeping into account straightness measurements, two different methods can be adopted: displacements measurement or angles measurement. The inspection instruments proposed by standards are, among the others: the taut-wire and microscope, the electronic precision level and Wollaston prism laser interferometry [4].

2. PURPOSE

This work is aimed at experimentally characterizing the performances (in terms of accuracy and uncertainty) offered by Wollaston prism laser interferometry for straightness measurements, when these are conducted within the industrial productive departments, where parameters influencing measurements can not be controlled.

Results obtained by this instrumentation are compared with those measured by a taut-wire and microscope and by a precision level on the same mechanical components.

3. METHODS

3.1. Straightness definition and measurements

As stated by standards [3], a profile located in a plane is considered straight when it is completely contained between two straight lines, which are parallel to the general profile direction (representative line). This one is defined to minimize the straightness deviation (defined as the distance between the two lines) and it can be obtained by the least squares method or by choosing two points near the ends of the profile.

Two different approaches are proposed by standards [3] for straightness measurements and tolerances verifications.

The first method consists in performing length measurements (Fig. 1). A practical straightness reference is defined and deviations from this (in terms of distance) are measured in different positions along the profile to be verified.

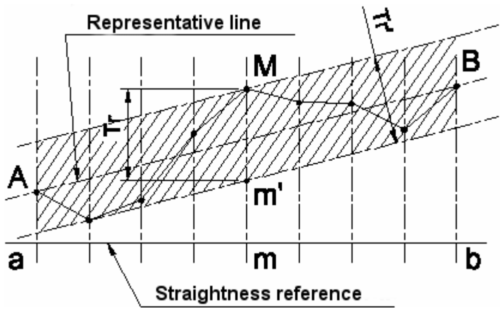

Fig. 1. Length measurements method.

The second method consists in performing angular measurements (Fig. 2). Angular deviations from the straightness reference are measured on consecutive segments on the profile.

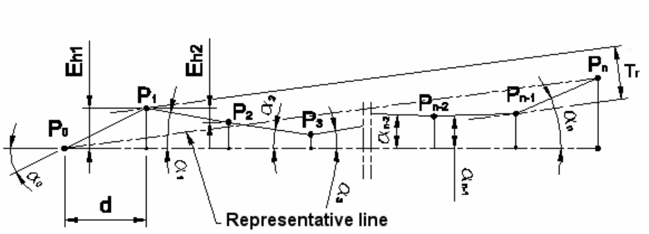

Fig. 2.-Angular measurements method.

In both cases straightness deviation is estimated as the distance (T_r) between the two straight lines parallel to the representative line and passing thorough the upper and lower points of deviation.

In this work, according to standards [3]: a taut-wire and microscope method has been adopted to asses straightness deviation thorough length measurements in the horizontal plane; straightness evaluation in the vertical plane has been performed thorough angular measurements by means of a precision level.

3.2. Laser interferometric method

Also laser interferometric techniques are proposed by standards [3] to perform straightness measurements thorough the two aforementioned approaches.

The adopted instrumentation is constituted by: a laser head (HP5519A), a Wollaston prism interferometer (HP10691A) [4], a reflecting V-shape mirror (HP55292A); it has been used to perform length measurements for straightness evaluations in both the vertical and the horizontal planes.

In the adopted configuration the laser head and the reflecting mirror are set in fixed positions and the interferometer is movable on the profile to be measured (Fig. 3).

As it is explained in [4,5,6] a laser beam, having two orthogonal components, is originated by the laser head and is sent as an input beam to the Wollaston interferometer.

Here the beam is split into two divergent output beams (a,b). These are incident on the V-shape reflector, which reflects them into the interferometer and then to a receiver, which is placed in the laser head structure.

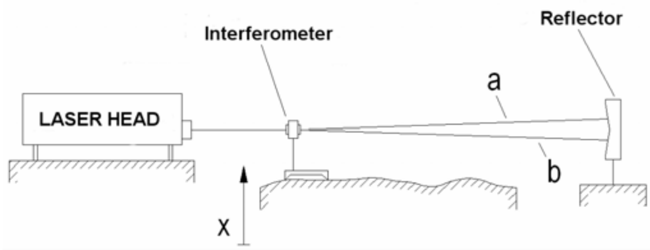

Fig. 3. Laser-interferometer configuration.

When the interferometer is moved along the profile to be measured, interference phenomena are generated in the signal coming back to the receiver, because the two beams (a,b) recombined by the interferometer are subjected to paths of different length, as consequence of the profile geometry. Analyzing the originated fringes pattern, displacements of the interferometer with respect to a straightness reference (given by the laser beam projected by the head), as moved along the stage, are estimated, and so the straightness deviation T_r can be calculated.

Although other methods have been proposed [7,8,9], laser interferometric techniques, based on the described configuration, are still widespread in industry because of some advantages such as: high signal to noise ratio, high linearity, high resolution, relatively small size.

3.3. Preliminary characterization

Preliminary experimental tests have been undertaken on the laser interferometric instrumentation, performing length/displacement measurements.

Firstly experimentation has been conducted to assess the effects of the operating conditions on measures. Specifically, the laser head, the interferometer and the reflector have been set in fixed relative positions; in this condition the interferometer and the reflector are not subjected to relative displacements and so the imposed measurand value is zero (once the alignment has been correctly operated). Measurements have been conducted in both the metrological laboratory (environmental controlled conditions) and the industrial productive department (environmental weakly controlled conditions), considering different distances between the interferometer and the reflector and choosing different values for the acquisition duration.

A second experimental stage has been undertaken to construct a calibration diagram for the adopted measurement system, when used in a weakly controlled environment for length/displacement measurements, considering different operating conditions in terms of interferometer-reflector distance and acquisition time.

The calibration procedure involved the adoption of a micrometric screw, by which known values of displacement have been imposed on the interferometer with respect to the reflector. Verification on the imposed displacements has been performed by means of a dial gage, which was a factory standard employed in the in-house calibration department and so has been considered as a reference instrument. The calibration diagram has been constructed starting from the collected experimental points, according to standards [10] and as explained in [11].

3.4. Measurement uncertainty assessment

In straightness measurements, the measurand is given by the straightness deviation value T_r, defined in 3.1. This quantity results as a function of the measures obtained by the aforementioned methods in terms of displacements or angles. According to [10] the model of measurement can be defined by the functional relationship reported by Equation 1.

$$T_r = f(X_1, X_2, ..., X_i, ..., X_N) \qquad (1)$$

In Equation 1 each X_i quantity represent the measure (displacement or angle) obtained on the considered profile at the *i-th* position. The f function resume the procedure needed to calculate the T_r quantity, once the x_i values are known, including the definition of a representative line and of the two parallel lines of minimum reciprocal distance containing the acquired profile. Each X_i measure is affected by uncertainty; propagating all the N uncertainty contributions thorough the model given by Equation 1, also the uncertainty affecting T_r can be estimated.

Due to non-linearity of the measurement model and to the presence of reciprocal correlation for measures X_i (in the specific case of angular measurements), the approach proposed by [10] and adopted by [12] cannot be successfully applied for uncertainty propagation, since the method proposed by such documents assume a linear model and the absence of correlation for the input quantities X_i.

The proposed method is based on the Monte Carlo numerical technique [13], which is used for the uncertainty propagation as proposed by [14,15], in order to estimate a probabilistic distribution of values for T_r and so to calculate its uncertainty. According to this method, each input quantity X_i as well as the output quantity T_r are treated as random variables and the propagation of the probability distribution functions assigned to all the X_i is numerically operated thorough the model f, by means of a sampled approach as follows.

1. A suitable probability distribution function (*pdf*) $g(X_i)$ is assigned to each X_i. In the case of length measures operated by the laser-interferometer instrumentation this *pdf* is given by a Gaussian distribution whose standard deviation is defined according to the calibration diagram constructed during the preliminary characterization. The *pdf* adopted in the case of the taut-wire and microscope or the precision level instruments is defined according to calibration data reported by their data sheets (B category evaluation [10]). The mean value for each distribution is given by the obtained measurement reading concerning the displacement or the angle measured at the *i-th* position along the considered profile.
2. For each X_i variable M x_{ij} values are generated according to the $g(X_i)$ function. By this way M vectors of possible values for the X_i variables are defined, defining M possible shapes for the measured profile.
3. For each one of the M possible profiles the straightness deviation value T_{rj} is estimated, and so a sample of M values for the T_r variable is constructed.
4. A confidence interval is constructed for T_r starting from the M sampled values and so uncertainty affecting the T_r measure is estimated.

4. RESULTS

4.1 Preliminary characterization

The preliminary characterization of the laser interferometric instrumentation, conducted according to what explained in 3.3, has pointed out that environmental conditions as well as the distance between the interferometer and the reflector strongly influence the repeatability of measures. By contrast it has been noted that the acquiring time for each displacement measure does not affect results.

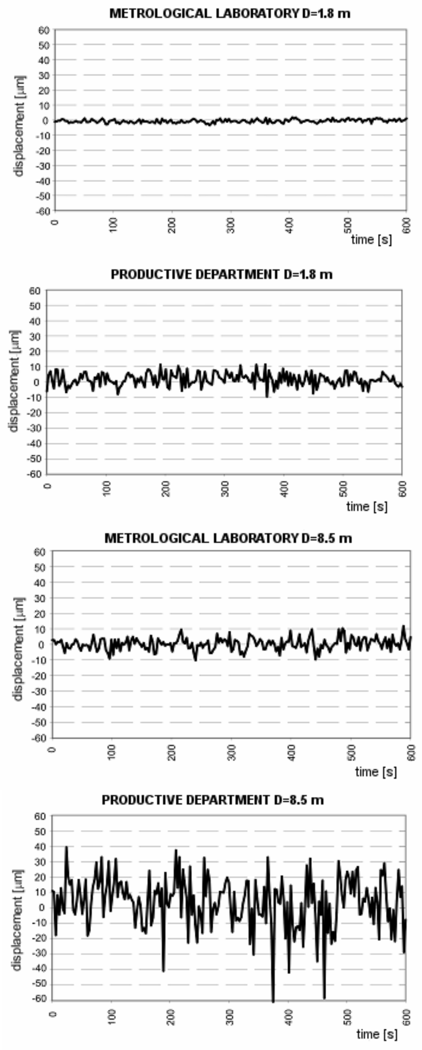

Fig. 4-Repeatability tests.

In Fig. 4 four diagrams are reported, concerning measures obtained in the metrological laboratory and in the productive department, considering two distances D for the interferometer-reflector couple: 1.8 m and 8.5 m. 200 values have been acquired at a time interval of 3 seconds, for a whole acquiring duration of 600 seconds.

A standard deviation σ has been calculated to estimate the variability of the acquired data. Then a 95 % confidence interval for σ has been constructed. As it is reported by Fig. 5, σ and the amplitude of its confidence interval increase linearly on the distance D. σ values are lower in the case of environmental controlled conditions.

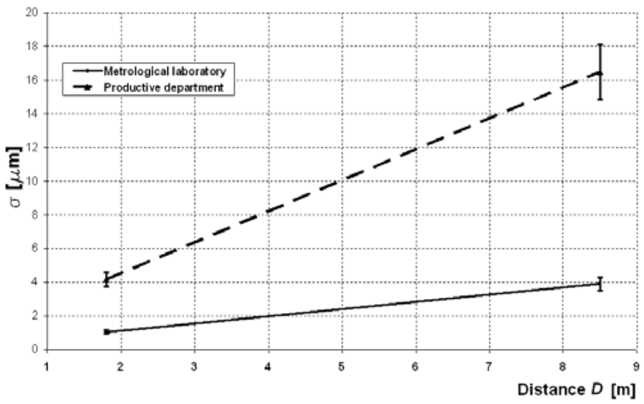

Fig. 5-Effects of operative conditions on measures variability.

As explained in 3.3, a calibration diagram has been constructed for the laser interferometric instrumentation, when used in the productive manufacturing department. Different values for the D distance have been considered. It has been proved that, varying the D value, different uncertainty levels for the diagram have to be taken into account, while a single linear calibration curve can be adopted. One of the resultant calibration diagrams (for D = 8.5 m) is shown in Fig. 6.

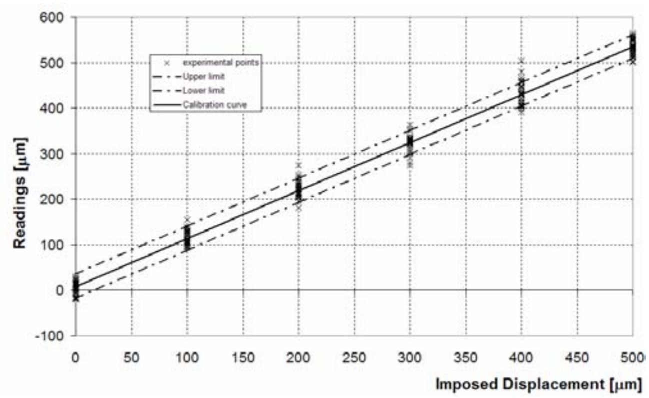

Fig. 6- Calibration diagram.

The shown calibration diagram has been obtained considering a constant level of uncertainty on the whole explored measuring range. The variations of the instrumental extended uncertainty U (calculated on the basis of a 95% confidence interval) on the D value are reported by Tab. 1.

Table 1. Instrumental uncertainties.

D [m]	U [μm]
1.8	1.2
5.15	6.7
8.5	14.7

The calibration curve allows to estimate the accuracy of the laser-interferometer system in the above mentioned operative conditions; accuracy results to be 5.4 %.

4.2 Comparisons

A measurement session has been undertaken on a long guide (13 m) of a center lathe. Measurements have been operated by the laser technique and then compared to results obtained by the taut-wire and microscope and the precision level for straightness inspection in the horizontal and in the vertical planes respectively.

The experimental configuration for measurements performed thorough laser-interferometry is shown in Fig. 7.

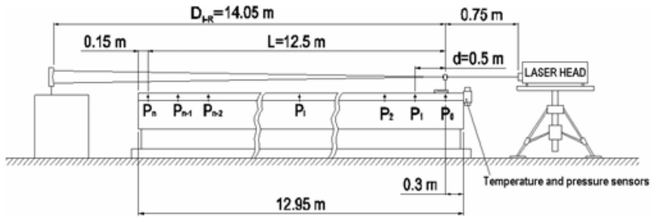

Fig. 7-Laser-inteferometer configuration.

Here a comparison is proposed for measurements in the vertical plane considering the laser-interferometric system and the precision level. Fig. 8 shows the profile of the long guide as measured by the two instruments. In ordinate displacements expressed in μm are indicated with respect to the considered straightness reference element; the whole length of the guide is considered (abscissa x [m]). It can be noted that the two measurements are compatible, but the measurement uncertainty associated to the use of the laser technique results wider.

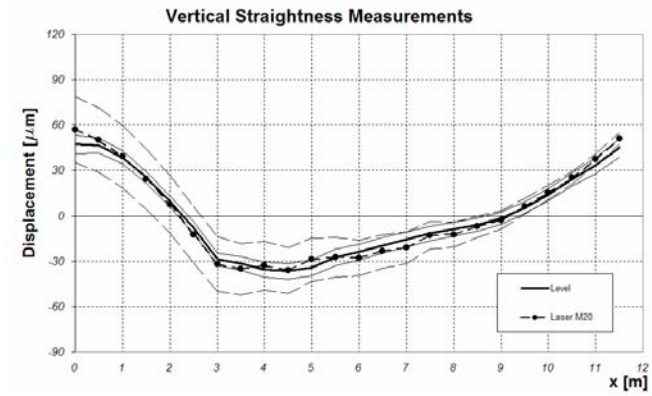

Fig. 8-Measured profiles comparison.

In Fig. 9 the sampled probability distribution functions of T_r calculated by means of the Monte Carlo technique are represented for the laser equipment (a) and also for the precision level (b).

According to Fig. 9, the indicated mean denotes the mean of the found distribution while upper and lower limits denote the extreme values defining a 95 % confidence interval, constructed on the obtained sample. Extended uncertainty (calculated as half the amplitude of this interval) affecting straightness deviation measures (Tr) results to be 9 μm for the precision level and 20 μm for the laser interferometer.

It is worthwhile to note that, nevertheless the *pdfs* assigned to the Xi input quantities were symmetric

(Gaussian or Uniform distribution functions) the resulting distribution for the output quantity *Tr* results to be asymmetric, due to the intrinsic non-linearity of the measurement model.

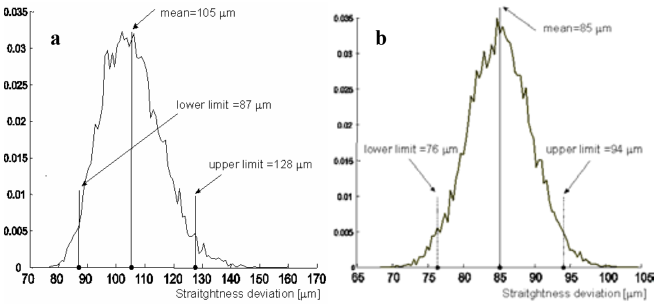

Fig. 9-Sampled probability distribution functions for straightness deviation *Tr*: laser equipment (a) and precision level (b).

The same kind of analysis has been performed for straightness measurements in the horizontal plane, comparing results obtained by the laser technique and the taut-wire and microscope equipment. In this case the extended uncertainty results to be 7 μm for the microscope and 22 μm for the laser-interferometer.

5. DISCUSSION

Results in terms of accuracy (estimated in 5.4%) agree with those reported in [16] concerning to the field of particles accelerator structures inspection, where accuracy, for an interferometer-reflector distance higher than 3 m, is estimated in 5%. These values are worse than those reported in [5], where accuracy is indicated in 2%; still, this value is given for a Wollaston interferometer coupled with a corner cube to increase performances and no details are given about the control conditions on the measuring environment. Further in [5] it is stated that repeatability in straightness measurements results to reach extremely low values (1.0 μm), which does not agree with the uncertainty values here reported. However, it has to be noted that several authors [16,17] report on the high effective influence of environmental conditions variability on measurement results obtained by laser interferometric methods and so, reasonably, the mentioned discrepancy can be explained taking into account this aspect.

Concerning the uncertainty evaluation method here proposed, it has to be noted that, typically, as it is stated in [15], a huge number of Monte Carlo trials *M* is needed to find out reliable results in the computation of the sampled probability distribution function to be assigned to the output random variable. Nevertheless in this case it has been proved that 1000 trials give satisfactory results, since, increasing this value, results do not considerably change.

6. CONCLUSION

The laser interferometric technique based on the use of a Wollaston prism has been characterized and tested for straightness measurements on components of large dimensions machining tools in a non-controlled environment, specifically in the production department of INN.SE Berardi (Brescia, Italy).

Results obtained in terms of uncertainty associated to straightness measurements prove that this instrumentation does not allow measurements with lower uncertainties than traditional techniques (such as the taut-wire and microscope and the precision electronic level), if used in weakly controlled environments. This conclusion could be explained taking into account atmospheric effects on the laser beam [17]. Furthermore it has to be noted that the estimated measurement uncertainty for the described laser-equipment would not allow, in the inspection operations, to perform tests of conformance with straightness tolerance specifications on the considered components. In fact according to [18] the prescribed straightness tolerance interval for a guide of less than 15 m length is 50 μm, while, with reference to the case described in 4.2, the instrumental uncertainty is 20 μm for vertical plane straightness measurements; from these data it descends that a conformance verification would give origin to a wide ambiguity interval (20 μm each side) and to a narrow acceptance interval (10 μm) [1]. It is clear that, since the tolerance specifications to be verified tend to be more and more restrictive (beyond prescriptions reported by standards) as consequence of people' confidence on performances offered by laser based techniques in geometrical and dimensional inspection, the conformance test by the presented equipment results to be unfeasible.

However, it cannot be concluded that absolutely laser-interferometric techniques cannot be adopted for straightness measurements in non controlled atmospheres: other authors report very low uncertainty for different experimental configurations [5,7,16,19] (still very few indications are given about environmental control conditions in the cited works).

ACKNOWLEDGMENTS

The authors wish to thank INN.SE Berardi S.p.A. (Brescia, Italy), Dr. G. Gelmi and Dr. F. Benini.

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