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New low cost sensing head and taut wire method for automated straightness measurement of machine tool axes

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ABSTRACT

This paper describes a novel method to measure straightness error of an axis of motion with a system utilising taut wire, optical sensor and reference error cancellation technique. In contrast to commonly used taut wire, straightedge or laser-based methods it combines simplicity of setup and low cost with high levels of automation, accuracy and repeatability. An error cancellation technique based on two-point method is applied for the first time to a versatile reference object which can be mounted at any place of machine's working volume allowing direct measurement of motion straightness of a tool point. Experimental results on a typical machine tool validate performance of the proposed taut wire system with a commercial laser interferometer operating in the same conditions is used as a reference. The proposed method shows highly repeatable results of better than ±0.25 μm over the range of 0.48 m and measurement accuracy comparable to the interferometer of ±0.5 μm.

1. Introduction

The performance characterisation of machine tools is prevalent in modern manufacturing industry where component accuracy is crucial. Straightness in two orthogonal planes, along with positioning error and three angular deviations, often referred to as roll, pitch and yaw, represents six components of error of any nominally linear motion system [1]. On machine tools having multiple axes, those geometric errors combine and affect the accuracy of produced components. It is important, therefore, that all geometric errors including straightness are known (measured) to understand capability and ideally reduced to a minimum to maintain highest accuracy of machining.

Unlike other geometric errors, straightness error measurement involves detection of lateral displacements along the direction of axis travel. Most direct straightness-measurement systems consist of a straightness reference and a displacement indicator [2]. There is always a great difference in values of straightness error compared to the distance along which they are measured. It is approximately 10^5 and so the straightness reference should be—long and flat at the same time. Here lies the main problem of straightness measurement in space—finding a suitable reference object. Measurement of straightness typically involves material artefacts (straightedges) or various optics (from telescopes to lasers) or even levels using earth gravitation as a horizontal reference for angular displacements to be converted to the lateral ones.

Because straightness measurement cannot be split over the distance along the axis, straightedges are limited by their own dimensions allowing measurements within their lengths only. An attempt to solve this issue by Pahk et al. relies on multiple measurements with partial overlapping [3]. Increased range comes at a cost of reduction in accuracy which is highly dependent on the number of overlaps and overlapped length.

Telescopes and autocollimators, which have been the first optical methods [4], with time advanced to numerous laser-based techniques where a highly coherent laser beam was used as a straightness reference [5–7]. Conventional Helium–Neon laser interferometers manufactured by companies such as Agilent and Renishaw have set a high level of measurement accuracy (Agilent 55283A ±0.2% of measured value, Renishaw XL-80 ±0.5%) but did not put an end to research in the straightness area. Being relatively expensive, slow, complicated and susceptible to disturbances over longer ranges, laser interferometers gave way to numerous alternatives and advancements aiming to overcome those well-known disadvantages.

Fan and Zhao introduce a simple laser test for measuring straightness using a four-quadrant photo detector [8]. The method does not depend on expensive matched optics and uses a shorter laser beam to improve its stability, demonstrating 0.5 μm repeatability on a 100 mm range. This result is not validated against other methods; the system is only calibrated

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with a laser interferometer which can still leave systematic errors of the system unknown. To increase sensitivity of a conventional laser (HP5518A) using more sophisticated optics, Lin [9] shows a possible advancement in accuracy achieving repeatability of 1 μm over 200 mm.

A solution to avoid using more stable (and more expensive) dual-frequency lasers is described by Feng et al. [10] and Kuang et al.[11]. A single-mode fibre-coupled laser produces a beam which strikes into a corner reflector mounted on the moving spindle and reflects back to a photodetector. Like all laser-based methods, this one suffers from beam pointing stability issues which get worse with distance. Moreover, the method involves a laser interferometer for calibration and relies on quality of the beam which leads to further expense related to a powerful laser emitter. Internal setup of the measuring unit requires space, numerous adjustments and laboratory conditions.

Measuring angular displacements instead of linear ones using a different optic setup is presented by Zhu [12]. Similar to previous laser method in terms of setting up, this one claims to provide a higher accuracy once again taking advantage of improved and more complicated optics. The same time the system remains sensitive to measurement distance.

Chen et al. [13] describe a dual-frequency laser with two Wollaston prisms to compensate air disturbances over a very long range of 16 m. An experiment, carried out in laboratory conditions, claims to show high measurement stability of 3.6 μm. This, however, not necessarily means the corresponding level of accuracy because only overall 230 μm-high V-shape of the measured profile was reproduced when its details fell into the area of measuring system repeatability of 20 μm.

All the improvements mentioned above might not be sufficient to solve the issue with lasers where accuracy is compromised over the measuring range as it is affected by the refraction index of air turbulence and, for some systems, beam pointing stability. Estler [14] in his comprehensive review of long range measurements, where he describes all the factors affecting a laser beam propagating in the air, shows that the beam actually bends and this happens rather randomly which can make modelling and compensation of such error a challenge.

To overcome the limitations of methods using a beam of light or solid artefacts a different physical reference object together with a different measurement setup is required. The first one needs to be flexible in length yet solid which mean range flexibility and low environmental susceptibility. The second one needs to be range-independent and non-contact to maintain high measurement accuracy over the range. A technique that would fit into those requirements is straightness measurement using a taut wire. It provides the overall desired physical setup but its accuracy and efficiency issues are yet to be addressed.

2. Method

The taut wire is a known reference for measuring straightness [1,14,15]. A length of the wire, stretched between two points, gives a straight line assuming catenary effects are negligible, eliminated or subtracted. The wire can have long lengths (The wire may begin to sway with lengths greater than 15 m) and any orientation in space needed to make it nominally parallel to an axis of motion, such as on a machine tool. Step by step misalignment comparison of wire and axis nominal travel trajectory allows calculation of straightness of one relative to another. The main reasons why this method is not widely used at present are its low accuracy and inefficient data gathering methods. The accuracy is compromised by both variability of the wire reference and typical wire detection methods such as microscope or electrical contact. Even commercial non-contact implementation with the use of laser diode [16] has stated precision of ± 5 μm. All of those methods require manual intervention leading to a time-consuming process and involve relatively high levels of measurement uncertainty. Fig. 1 shows the proposed solution to overcome those issues:

Each of the key features of the method is described below:

1. nylon fishing wire is readily available in any length; it is lightweight, portable and easily-mountable. Its diameter variation depends on wire quality, stretching force and settling time and normally lies within 2–20 μm between the lowest and highest point. A wire made of steel, like string on a musical instrument is successfully used in fixed-length straightedges [15], but it is less suitable for long ranges because of its limited availability and poor dimensional quality. Thin wires provide low sensitivity when using an optical detector and require more effort when choosing the right stretching force (to get the wire as straight as possible while avoiding breakage).
2. slotted optical sensors like those manufactured by Omron are primarily designed for automation applications to detect the presence of a non-transparent object between the fixed wavelength emitter and receiver. Bench testing has proved that they have sensitivity and stability enough for detection of objects even on a sub-micron level. For this work an Omron sensor, shown in Fig. 2, is used as it provides good balance between sensitivity and range and can be easily mounted. These are low cost, portable, and mass-manufactured so are readily available and have provided an excellent solution for measuring lateral displacements of a stretched wire passing through the sensing area.
3. fine adjustment carriages are used for precise alignment of the wire with the measured axis within a travel range of several millimetres. Adjustment of the carriages can be checked very quickly using feedback from the sensors without the need of additional equipment. Removal of slope between the wire and 0.5 m axis typically takes 5 min while alignment of the laser beam can take 7–10 min.
4. the technique of the reference error cancelation during step by step straightness measurements (also referred as “two-point method”) was first published in 1979, applied to a machined steel plate [17,18]. Error in the reference was taken out of calculation by using data from an additional displacement

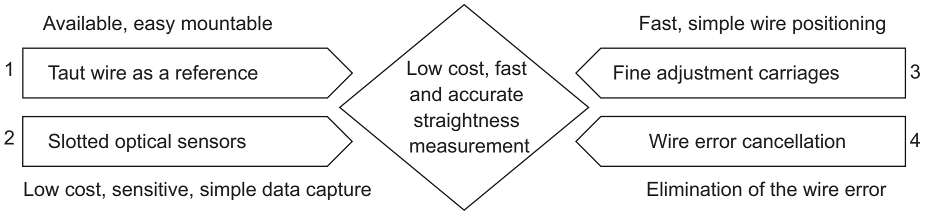

Fig. 1. Measurement principle.

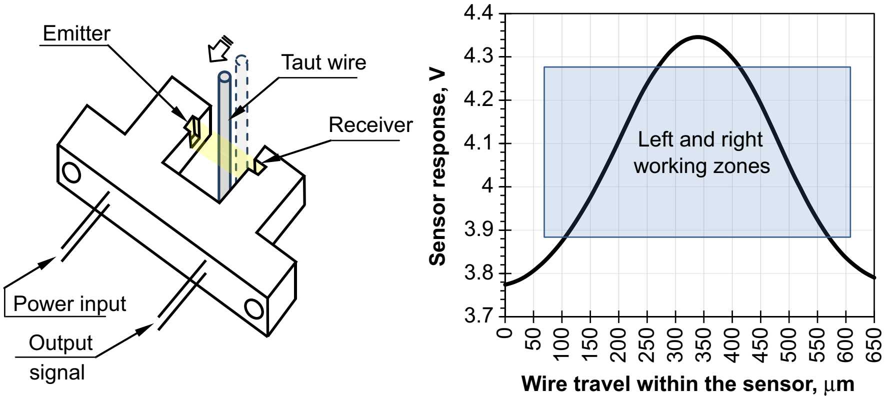

Fig. 2. Omron photomicrosensor and its sensitivity graph.

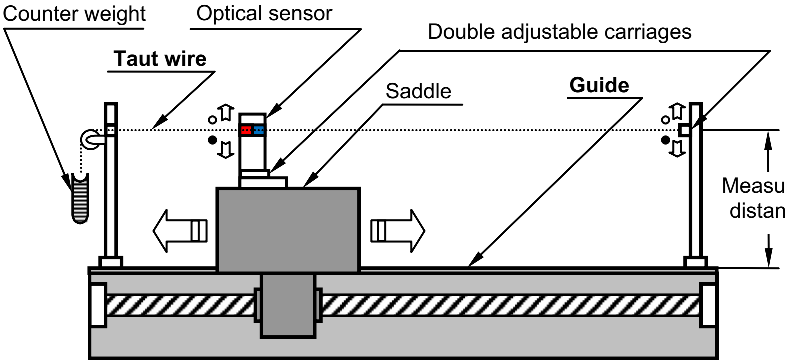

Fig. 3. Taut wire measurement system mounted on a machine tool.

> sensor. If the distance between a pair of sensors is equal to the increment of axis travel, they both can be used together to measure relative displacement at every point. Adding each value to the sum of the previous reading, starting from zero, gives a separated lateral error of measured axis.

This approach was successfully tested on a 7 m long boring machine, when the error was measured along 5 m range with 100 or 200 mm increments [15] showing its high potential. Gap sensors (sensitivity 5 μm/mV) provided good correlation with a laser interferometer measuring an error of 40 μm.

The improvements that followed [19,20] still rely on a solid 3-dimensional straightness reference, requiring consideration of its pitch error which had to be measured separately. Another issue is a large accumulated error—negligible on the first step, its amount soon exceed the measured value. To prevent that, a larger step size and calculation of intermediate values have been proposed [20]. More recent applications of two-point method (even expanded to three-point) are in topography and surface profile measurements [21–23] where the reference error of a moving stage is separated achieving sub-micron accuracy levels using capacitive sensors.

All those developed methods represent a good use of error cancellation principle applied to straightness measurement of machined parts whether it is a precision guide, cylinder or a flat surface. Application of those methods to machine tool's axes can be challenging because the straightness reference needs to be specially positioned and have a variable length if it is to be useful on a wide range of machines.

On the other side, straightness of an axis guide way can be very different from the straightness of motion of the tool or workpiece point due to the error magnification by other axes forming a kinematic chain between them. Therefore it is not sufficient to measure the guide or attached artefact (for example, using capacitive sensors), a direct measurement between the tool/workpiece interface is necessary to ensure high accuracy.

Here we introduce an alternative use of the error cancelation technique when the straightness reference is a stretched wire. Unlike a straightedge, the wire can be considered to be a 2-dimensional reference as its cross-section is round. This means only one wire error, its change in diameter, needs to be eliminated and the only measured lines are axis and wire surfaces belonging to the same plane. The wire is a simple object which can be easily placed at any part of machine's working volume to measure straightness of corresponding axes directly, without estimation which can be a source of measurement error like it is the case with laser interferometry.

The taut wire setup shown in Fig. 3 consists of: two stands, the distance between which covers the full measured axis; the wire itself stretched between them; the new optical sensing head mounted on the moving component of the machine using a post having the same length as a typical tool so that systematic and random (vibrational) effects from linear and rotational error components will be representative of those in operation. Position of the wire can be adjusted using the aforementioned dual axis carriage. Measurement of the axis straightness is based on the following conditions:

1. both the wire and the measured machine axis have time-invariant (at least for the duration of the test) surface profiles (straightness values over the range) i.e. repeatable systematic errors dominate over non-repeatable and random errors.
2. straightness error of the first point of the measured surface has zero value. Upon completion of the measurement, least-squares fitting eliminates any residual slope while not changing its shape.

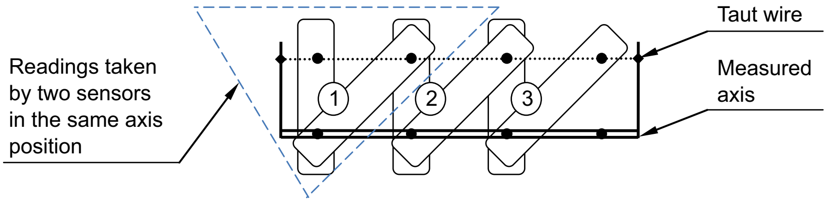

Fig. 4. Dual sensor measurement.

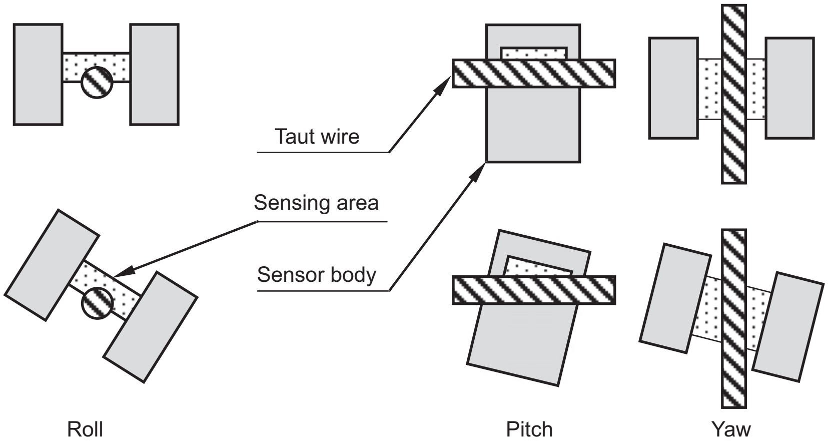

Fig. 5. Rotational components of motion affecting the system.

3. measurement time is sufficiently short so that no change in straightness of the machine axis can occur.

These conditions enable separation of the wire surface profile from the profile of measured axis. In case of single sensor measurement they both combine and the total reading at every point represents the sum of both errors. If wire error greatly dominates the straightness error of the axis, measurement fails.

Along with wire error caused by deviation of its diameter, there are random errors caused by wire movement due to airflow, vibration and stretching force.

Fig. 4 shows the order of measuring: every time the machine stops, current axis error combined with error of the wire on current and the subsequent steps are measured. This way every time readings are taken from both sensors. Because the distance between the sensors matches the axial increment (the method to achieve that is described at the end of this section), the first sensor takes position of the second one on the previous step and measures the same error on the wire but combined with different error of the axis. On the figure it is shown by pairs of rectangles (pairs of readings): 1, 2, 3… The following subtraction of second reading of the first pair from the first reading of second pair (both have the same amount of wire error) gives the difference between axis errors which is between the first and the second steps. Accumulation of those numbers obtained from full number of steps (starting from 0) gives the straightness error of the axis on every step.

When two sensors are used simultaneously and readings are taken at every two adjacent points of the wire, and the distance between those points is the same as the machine movement increment, the following calculation [17] separates axis and wire errors (including some random ones) from each other:

$$x_i = x_{i-1} + s_i - c_{i-1} = \sum_{1}^{i} (s_i - c_{i-1}) \tag{1}$$

Where$x$—axis error on step i, c—combined (measured) error from the first sensor, s—combined error from the second sensor.

According to the first condition $x_1 = 0$, all the other values of x are calculated using Eq. (1).

This equation confirms that the calculated axis error is not influenced by the wire error (including slope) at all as long as it and the machine positioning is repeatable. This error separation enhances the accuracy of straightness measurement regardless of the distance and error amount, though importance of the wire and machine repeatability increases with the length of measured axis and number of sampling points as the positioning error accumulates. To control the accumulation, all tests were carried out as multiple bi-directional runs and the difference between corresponding results has proven to be very small, typically less than one tenth of a micron during all of the validation tests.

Error cancellation reduces only the systematic part of measurement error; random contributors like errors in the sensors themselves, including electrical fluctuations, remain. Because those measurement errors are cumulative, even such small effects could become problematic over longer axes. The method can therefore be expanded to a third sensor to provide averaging at each measurement point. Due to the cost and availability of the sensors, this does not degrade the practicality of the solution at all.

Separation of the sensors in the measuring head is determined once by using a piece of opaque tape attached to the wire. Detection of the edge of the tape while slowly moving the machine axis gives each sensor a clear change in readings taken and the difference in machine coordinates of both points gives the measured step size. Uncertainty using this simple method comes from accuracy of the axis, shape of the tape, speed of motion, etc. It is generally in order of 10 μm which is sufficient because rate of change in diameter of the fishing wire is very small, typically stays within a tolerance of 0.1 μm/1 mm (i.e. just 0.001 μm over 10 μm).

3. Measurement error

The proposed combination of taut wire and multiple optical sensors used together cancelling the reference error, is subject to certain systematic errors limiting the method's accuracy. The two-point method itself, as a basic principle is perfect and the error appears on the stage of its practical implementation. In case of profile measurements with capacitive sensors, the main error factors reported are zero-difference [20] and pitch error [22] which need to be measured separately and the system calibrated accordingly.

This system uses multiple optical sensors which have different and non-linear outputs but this difference is relatively small and the output is fairly linear in the range of 200 μm (Fig. 2). After simple calibration described in Section 5 all outputs are linearised into one straight line with a permanent sensitivity value for all sensors.

Rotational components of a measured axis of motion have a negligible effect on the optical sensors because rotation of the wire within the sensing area does not change the amount of light blocked by the wire and consequently the sensor output is not affected (Fig. 5).

The sensors are sensitive to linear displacements in one direction only, i.e. errors in the transverse directions resulting from the machine's kinematic chain and length of the post consisting of both linear and rotational components do not contaminate the reading. Similarly, change in the relative orientation of the sensor to the wire does not affect the reading because the result is negligible change in the amount of light blocked by the sensor.

4. Physical system

A system diagram and the new measurement device itself are shown on Fig. 6. Raw voltage from the optical sensors passes through low pass (≈ 3 Hz) filters before undergoing analogue to digital conversion for calculation of the measured error using Eq. (1).

The device is assembled on a steel plate carrying optical sensors, stabilized power circuit and individual sensitivity controls for every sensor. Possible potentiometer drifting proved to have a negligible effect on the measurement accuracy because only power going to light emitting diodes can change and therefore does not change sensitivity of the sensors. Manual adjustment moves the working zone vertically within the sensing area (shown on Fig. 2) allowing better intersection between sensors to increase straightness measuring range.

The present design has three sensors mounted horizontally. This works in several different measurement schemes: using first and second sensors as a pair for error cancelation; using second and third in the same way; using both pairs simultaneously and taking the average of them to reduce the total uncertainty; take the first and third pair when longer step size is required (to reduce the time of long range measurements); use the first, second and third separately or all three separately (for single sensor measurement with averaging when the reference error is negligible compared to the axis error). Orientation of the device determines the straightness error to be measured. Spare space is available for a set of vertically mounted sensors for simultaneous straightness measurement in both perpendicular planes.

Dynamic data capture, when the machine moves continuously, is also possible with axis feed rate not exceeding 150 mm/min (in the current implementation of the sensing head). This speed depends on the maximum speed of sensor power circuit and can be determined experimentally finding a maximum feed rate value which does not change the measured straightness value compared to the one obtained with a lower speed.

5. Validation

The system was validated on a machine tool axis that was 0.5 m long and horizontally orientated. Straightness in the vertical plane was measured using a Renishaw XL-80 laser interferometer having stated straightness measuring accuracy of ± 0.5 μm over 0.48 m. Shortly after, measurement was done using the proposed taut wire (DAIWA Sensor Monofil 0.26 mm diameter) with minimal Abbe offset to eliminate effects of angular errors on the axis. In both cases the straightness profile was obtained with step size of 19.956 mm, equal to the actual distance between two optical sensors. All data readings were taken with four second dwell interval to allow the long term averaging of the interferometer system to stabilise. For new system, the same dwell time was used during which averaging of 40 readings was used to reduce the amount of noise and small random errors. Every test run was bi-directional to ensure random error detection. Slope errors on both planes were eliminated prior to measurement using double adjustable carriages (Fig. 3). Both optical sensors were calibrated using a high accuracy (<3 μm over full 12 mm range) digital dial test indicator so that the linear sensitivity was established with a magnitude of 1.6 mV/μm.

In the case of the laser, an average of three sequential bi-directional tests was obtained for comparison with the wire. To include in the validation consideration for the fact that every piece of wire has its own unique surface profile, three different pieces were tested and on each of those three runs were also

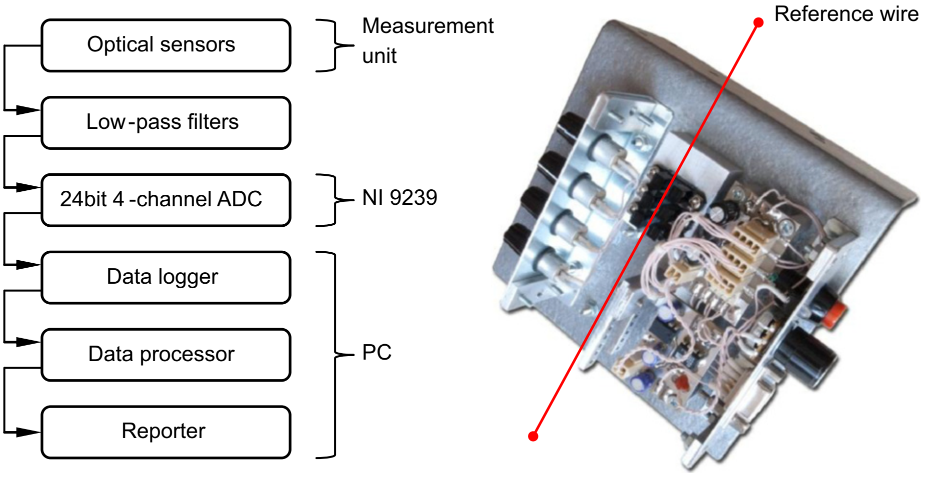

Fig. 6. The system dataflow diagram and measurement device.

completed. Prior to measuring, the wire was left to settle for approximately five minutes. Normally such time period is enough for good quality fishing wire to stabilise: during that time it is continuously changing its diameter becoming thinner as it stretches. Stabilisation time is individual for every wire material, thickness and stretching force. Finding the minimal period while the wire cannot be used for measurements is a simple procedure of logging measurement data while the machine is not moving, assuming relatively stable thermal conditions.

Fig. 7 shows averaged (here and after—least square fitted to remove residual slope) results of measuring straightness using the same piece of wire. Three bidirectional tests performed one after another show repeatability within 0.2 μm.

After three tests were completed, the wire was replaced, a new wire piece left to settle and measured. Then again replaced, settled, measured. The results are shown in Fig. 8, with non-repeatability across all nine measurements never exeeding 0.5 μm.

Fig. 9 contains results of a single-sensor measurement of three wire pieces for comparison. It is clearly visible that without error cancellation the taut wire is poor as a straightness reference giving a non-repeatability of up to 4 μm and no obvious common profile which can not be obtained by averaging.

Fig. 10 confirms a good correlation to within 1 μm between averaged laser and average of three wires measurement results. Taking into account a very low value of measured error and fundamenal differences between measuring methods, certain output discrepancy should be considered normal.

To find out the actual measurement capability of both methods in terms of random error, idle mode (the machine is nominally stationary) tests were carried out. The laser was set to long term averaging mode, all tests were sequential, with a few minutes time between them, all in normal workshop conditions including airflow and vibrations. The results, shown in Figs. 11 and 12 demonstrate one order of magnitude difference. The stability of the wire setup output is significantly higher than that of laser at less than 0.1 μm over the duration representing typical measurement tests. This is particularly important because the test was done under representative manufacturing conditions including working machinery in close proximity, airflow from people moving around, temperature gradients, vibration, dust and dirt. Two positions of the reader head were tested for stability; the middle of the wire and close to the end where the wire is mounted. No noticeable difference was detected.

It is important to note that Fig. 12 contains the accumulated error of almost a hundred sequential readings yet maintains excellent stability. Overall, the proposed system appears to be highly resistant to environmental effects, which gives reason to expect good results from measuring longer axes.

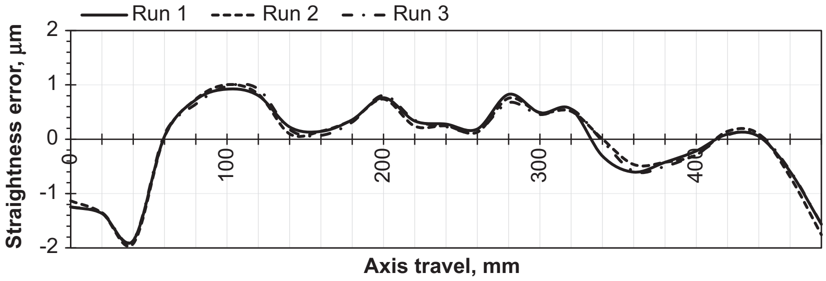

Fig. 7. Repeatability within one piece of the wire.

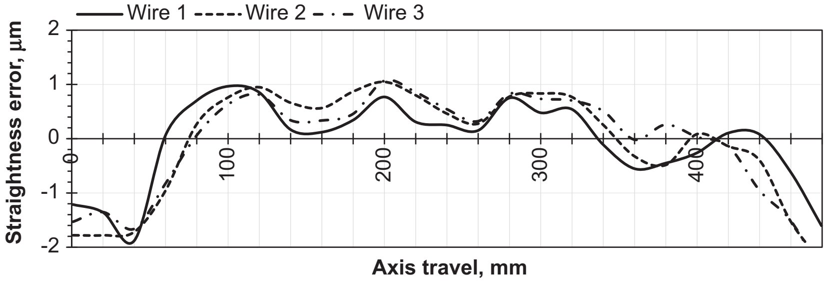

Fig. 8. Wire repeatability within three pieces.

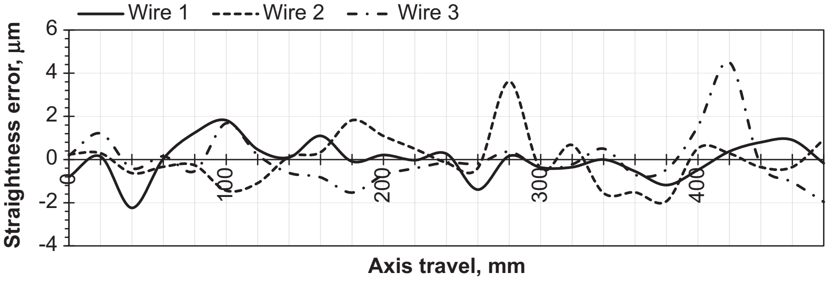

Fig. 9. Wire repeatability within three pieces (single-sensor test).

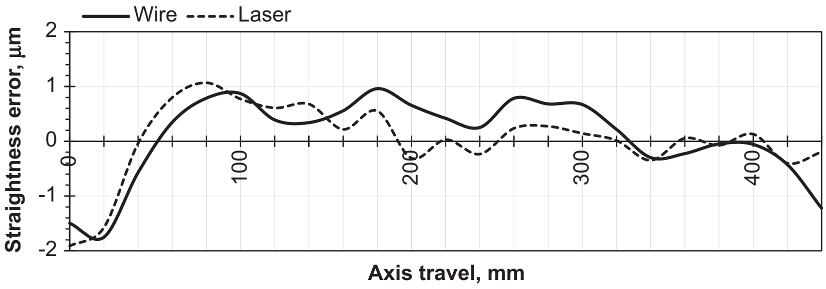

Fig. 10. Wire against the laser.

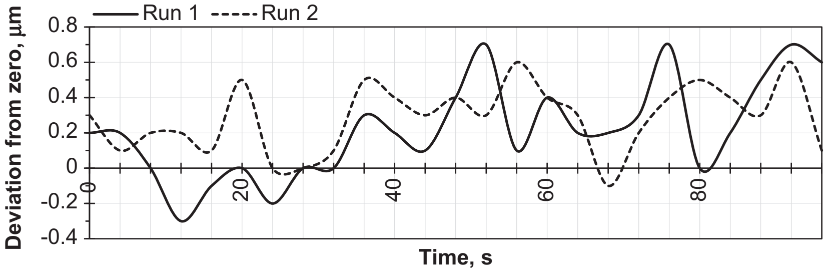

Fig. 11. Laser interferometer idle stability.

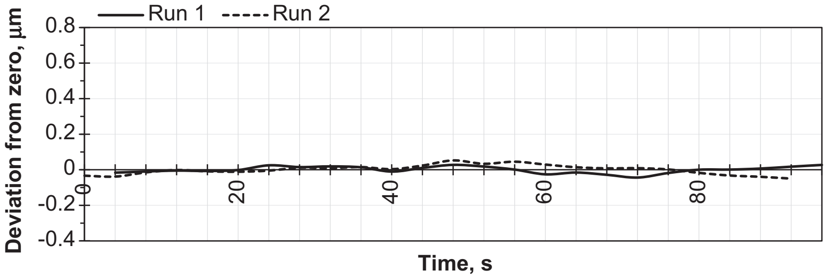

Fig. 12. Wire idle stability.

6. Conclusions

A novel straightness measuring system comprising ultra-low cost optical sensor unit, taut wire (with fine adjustment carriages) and error cancellation technique is proposed. The system is capable of eliminating the inherent random wire error and demonstrates similar accuracy level of ±0.25 µm compared to a conventional laser interferometer and superior repeatability over a measuring range of 0.48 m. A quick and simple wire setup allows measurement of an axis in any position and in principle, both coordinate planes at once. The method has been successfully tested over a 0.48 m distance which validates the newly designed sensing unit and methodology. In contrast to the laser interferometry method, the wire setup does not become more difficult with the distance as sensitivity of reference adjustment does not change. Practically it can mean a considerable difference in set-up time increasing with the length of measured axis. In this case the system can be used as a supplement to laser interferometer, increasing the efficiency of its industrial application. Experimental results presented confirm that the output does not depend on actual wire superficial straightness or variation in diameter after its error is eliminated using the double sensor measurement method. Finally, the result is shown to be stable and accurate, providing an excellent opportunity of reducing the time and cost of straightness measurements.

The aforementioned low cost nature of the solution also makes it a candidate for permanent installation either as a live sensor on a structure or available locally for efficient normal or quick check axis measurement to feed into SPC. Further development will concentrate on longer axes measurement and on adding a second set of sensors for simultaneous capture of straightness profiles in two planes decreasing test time without any appreciable increase of associated costs.

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