Precision Engineering 38 (2014) 492–498

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Performance evaluation of a new taut wire system for straightness measurement of machine tools

Oleg Borisov*, Simon Fletcher[1], Andrew Longstaff[1], Alan Myers[2]

Centre for Precision Technologies, TC/10 CPT Research Office, University of Huddersfield, Queensgate, Huddersfield, West Yorkshire HD1 3DH, United Kingdom

ARTICLE INFO

Article history:
Received 24 May 2013
Received in revised form 13 January 2014
Accepted 15 January 2014
Available online 31 January 2014

Keywords:
Straightness
Taut wire
Optical sensors

ABSTRACT

This paper describes evaluation of a method of measuring the straightness of motion of machine tool axes using a taut wire and an optical sensor head mounted at the tool point location. In contrast to commonly used taut wire instruments, straightedges or laser-based methods, this solution combines low cost, simplicity of setup and automated data capture while achieving state of the art accuracy suitable for application on precision machine tools. A series of tests are discussed which examine the performance of the new sensing head and different wires which highlight the suitability of the taut wire properties as a straightness reference. Experimental results obtained on a production machine tool are provided with respect to the accuracy and repeatability of both the proposed taut wire system and a laser interferometer operated under the same conditions. The reference errors of wires made of different materials are compared and the wire catenary is separated from the measurement results. The uncertainty budget for taut wire and laser systems is presented and expanded uncertainty of 4 μm obtained for both. During the experiment, the method showed excellent repeatability with two standard deviations of 1.5 μm over a measuring range of 1.5 m; this performance matches that of a commercial laser interferometer-based straightness reference to within 0.1 μm.

1. Introduction

Straightness errors, along with positioning and angular errors, are present in every linear motion system [1]. According to the international standard ISO230 part 1 [2], the straightness of a moving stage can be determined by measuring lateral displacements of the stage while it moves. In order to do this, a straightness reference and a displacement indicator are required. In practice, this gives rise to a variety of straightness methods utilizing straightedges, taut wires or laser interferometers. Each method has its own advantages and disadvantages depending on such factors as required accuracy, measuring range, ease of use, speed and cost.

Straightness measuring methods using a straightness reference intrinsically depend on the straightness of the reference and how this changes under different measuring conditions. While the effects of support, temperature variation, vibration, etc. must all be taken into consideration, the effects are generally exacerbated by increase in axial range. This is particularly important since every machine tool has moving axes and those machines with long axes, required to increase the machine tool's functional capability, are often susceptible to higher levels of errors. Thus, the error needs to be measured over longer distances where straightness-measuring solutions become less accurate.

The reason for such a dependency is the physical contradiction between different requirements of the straightness reference: it must be long, stable and straight, ideally two-dimensional and, which is particularly important, capable of being placed at any area of the machine's workspace to represent the desired tool point path. Finding such an artefact presents a significant challenge that ultimately leads to a compromise between the factors. At present, material artefacts like straightedges or optical devices (mostly lasers) are used to create a reference line from a solid structure or a light beam against which the axis straightness should be measured.

Being simple and easy to use straightedges are limited by their own dimensions, allowing measurements within their lengths only. Partial overlapping introduced by Pahk et al. [3] extends the potential measuring range but the speed of process, accuracy and uncertainty of measurement can be compromised by the size and quantity of overlaps.

Another approach utilizes laser-based techniques relying on a highly coherent light beam, having long axial ranges suitable for most machine tools and a high quoted level of accuracy. The Renishaw XL-80, a popular measurement instrument, has a stated

* Corresponding author. Tel.: +44 01484 472413.
E-mail addresses: briarmains@gmail.com, o.borisov@hud.ac.uk (O. Borisov), s.fletcher@hud.ac.uk (S. Fletcher), a.p.longstaff@hud.ac.uk (A. Longstaff), a.myers@hud.ac.uk (A. Myers).
[1] Tel.: +44 01484 472413.
[2] Tel.: +44 01484 473660.

0141-6359/$ – see front matter
http://dx.doi.org/10.1016/j.precisioneng.2014.01.003

accuracy for measurement of straightness on short (up to 4 m) axes of ±0.5% ±0.5 ±0.15M^2 μm (where M = measured distance in metres). The accuracy decreases to ±2.5% ±5 ±0.015M^2 μm when using long range optics over lengths exceeding 4 m. This is because the angle of the reflecting optic, called a Wollaston prism, is smaller for the long-range kit, making the system more sensitive to inhomogeneity of the air. Estler et al. [4] in their review of long range measurements showed that the beam unpredictably bends while passing through the air. Magalini and Vetturi [5] carried out experiments which also demonstrated a high level of uncertainty due to the environment, using a Hewlett Packard laser interferometer. Measuring the straightness of a centre lathe axis, they calculated an uncertainty of 4 μm rising up to 16 μm (calculated on the basis of a 95% confidence interval) over 8.5 m when laboratory conditions are changed to a productive department. Comparing a precision level and taut wire microscope combination with an HP5519A laser interferometer, the authors concluded that laser interferometry did not enable lower uncertainties than that caused by the first two methods.

Other optical methods not employing interferometry have also been developed, aiming to address the issues of cost, speed and environmental effects. Most of them concentrate on consideration of cost and simplicity of setup. Fan and Zhao [6] used a different layout of the measurement system where the laser beam emitted at one end of the measured axis faces a four quadrant photo detector instead of a mirror. That principle halved the beam length compared to conventional interferometers and was found to have an accuracy of 0.3 μm within a ±100 μm measuring range and 0.5 μm repeatability on 100 mm axial range. While not setting a new level of accuracy, the method is potentially lower in cost since it does not require any matched optics (prisms, reflectors).

Lin [7] integrated a double straightness reflector, Wollaston prism and a traditional reflected layout to achieve repeatability of 1 μm over the range of 200 mm. The same reflected layout but with a single-mode fibre-coupled laser was tested by Feng et al. [8] and Kuang et al. [9]. In that case a longer axis of 1.35 m is measured against a dual frequency laser interferometer with the result of matching to within a few micrometres for a straightness error having a magnitude of 160 μm.

Chen et al. [10] combined a dual-frequency laser with two Wollaston prisms, aiming to compensate air disturbances on the range of 16 m in laboratory conditions. The system was stated to provide a high measurement stability of 3.6 μm while the actual comparison test result did not show a value lower than 20 μm. Also, it was admitted that the two alternative methods have very large uncertainty making it difficult to quantify the accuracy of the proposed system.

The aforementioned approaches successfully reduce the effect of environmental stability of the laser beam but do not eliminate it completely and in some cases require optical arrangements that may not be practical or economical. The stability remains proportional to the propagation distance as it has been proved by Magalini and Vetturi [5]. Alternative straightness references do exist and in particular physical references are successfully applied, using reversal techniques to improve accuracy, but these are generally limited in their measuring range.

In this paper, a taut wire and specially designed sensing head is proposed as an effective solution. The combination of the wire's availability, flexibility, lightweight and proximity to two-dimensional structure gives an excellent example of a physical straight line. As it will be shown, diameter inconsistency and gravitational sag of the wire, affecting its own straightness, do not significantly change its reference property because the former is shown not to be significant and does not increase with wire length, and the latter can be predicted and compensated at the calculation stage. The findings in this paper are considered novel because,

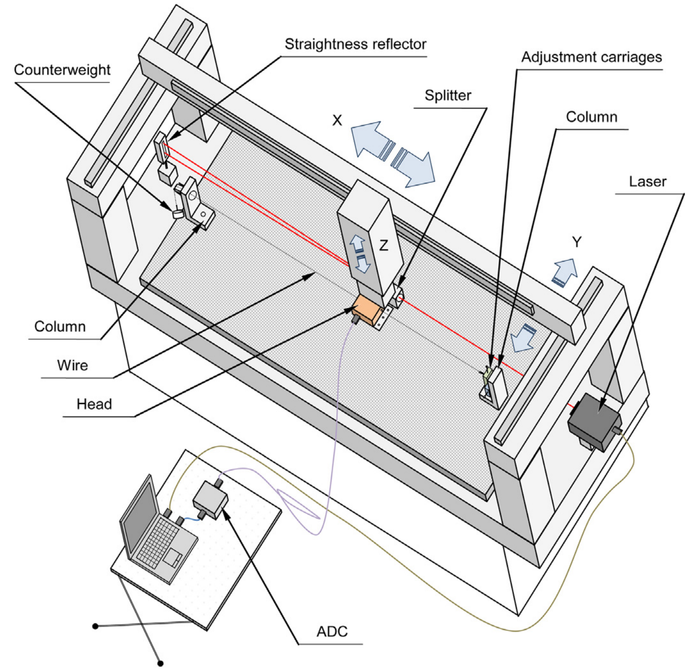

Fig. 1. Taut wire system and laser interferometer used for evaluation setup on the machine.

despite being a well-known reference for measuring straightness [1,4,11], a detailed analysis of the taut wire measurement for long-range measurement has not been the subject of published research.

2. Method

This paper describes performance evaluation of a sensor head [12] applied to the measurement of 1.5 m long machine tool axis. The main attention paid to the effects of measuring length, dynamics of the machine and overall uncertainty budgeting.

The system includes taut wire mounted on two vertical stands along the measured axis (Fig. 1). One end of the wire is fixed on the first column while the other end is passed through a hole on the second column, over a wheel and attached to a freely suspended counterweight which provides a constant stretching force. The moving stage has the measuring head attached to it so that the wire passes through its optical sensors capturing lateral displacements of the head at every point of axis travel. The signals from the sensors are fed into an analogue to digital converter where they are transformed into straightness measurement data.

The measuring head (Fig. 2) has four sensors, two each in the vertical and horizontal orientations. The vertical sensors provide data for the straightness measurement while one horizontal sensor enables fine positioning of the head relative to the wire for slope error removal. In case of measuring straightness in horizontal plane, signal from one of the vertical sensors provides positioning data and combined signal from horizontally orientated sensors – measured error.

Precise alignment of the wire and the axis can be achieved through manual operation of fine adjustment carriages attached to the right column. Adjustment is only required at one end of the wire, making the process very simple and efficient.

Apart from sensors, the head carries electronic circuits for powering the sensors and regulation unit with four potentiometers for fine adjustment of sensor sensitivity. Everything is mounted on an angled plate which can be attached to the moving carriage or a spindle either directly or using a magnetic base. The assembly plate holds a plastic cover with slotted holes to allow the wire to pass

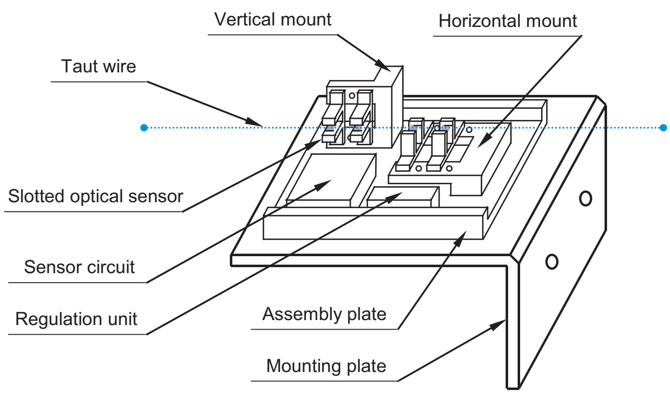

Fig. 2. Measuring head without cover.

through it. The cover is important because it protects the components and also blocks ambient light that can affect the sensors.

The basic principle of device operation consists of light beam emitted and received within each sensor. When the wire enters the working area of each, it reduces the amount of light received which changes electric output of the sensor. This change is monitored in real time, transformed into digital form and converted to micrometres of lateral displacement of the head relative to the wire fixed on the machine table.

3. Test setup

The system was set up on a 5-axis milling machine to measure the straightness of its longest horizontal axis in the vertical plane. Both wire support columns were mounted on the machine's table with a distance of 2.2 m between them. The counterweight was chosen so that the stretching force was as close to the maximum the wire could withstand according to its specification, ensuring the wire remained as stable and straight as possible. The sensor head was mounted on the spindle carrier together with optical splitter from Renishaw XL-80 laser interferometer kit, both representing desired tool point location. The laser itself was set up at a position to measure the same axis without any movement of the machine except along the measured axis. The separation between the laser beam and the wire was approximately 100 mm.

The catenary, or sagging of the wire, becomes significant on vertical measurements on horizontal axes when a distance between the wire mounting points is 1.5 m or greater, resulting in 1–2 μm of systematic error. This effect can be estimated as a parabolic [13] deflection depending on the tension, wire weight and length (Fig. 3). It was automatically subtracted from the measurement data. The associated uncertainty in is provided in Section 6.

4. Test conditions

The machine is located in a workshop having no special environmental control and is therefore susceptible to the usual airflow, temperature gradients, etc. caused by open workshop doors (the doors of the machine itself were shut), neighbouring working machinery, operators moving around, etc.

Both measurement systems were left idle for 20 min to complete the warm up stabilization stage. Bi-directional tests were performed at least three times to reduce the effects of random error sources. Axis movement speed was set to 5 mm s^{-1} for all measurement runs. Each measurement was taken with the machine nominally stationary at a discrete step of 20 mm. The laser was set to long term averaging mode (rolling average with 4 second window); the wire system output had a two sample rolling average applied.

The progressive slope, common to straightness measurements due to misalignment of the straightedge with the axis under test was always reduced to less than 3 μm and therefore did not affect the measurement. In the case of the taut wire, this slope was minimized in both planes. The wire chosen was DAIWA Sensor Monofil 0.26 mm diameter which is a high quality fishing wire and was found by experimentation to be most suitable for measurement purposes.

Fig. 4 shows some measurement results for different wire materials. Variation in the material used and the manufacturing process for metallic wires introduces different reference errors. However, the specified type of fishing wire was found to perform repeatably without strict limitation of size and quality.

5. Performance evaluation

The *X*-axis of the 5-axis machine tool used for evaluation had horizontal (EYX) and vertical (EZX) straightness errors of 4 μm and 5 μm respectively over a 1.5 m travel range, as measured using a Renishaw XL-80 laser system. The first test aimed to ensure the taut-wire system does not suffer from any “crosstalk” effect which could be the case when using the optical sensors. Two EYX measurements were completed with different misalignment (slope error) of 150 μm and 5 μm in the vertical direction. The result, presented in Fig. 5, shows a very low effect on measured straightness.

The next step was to measure the axis with the same laser interferometer and short range straightness optics to determine the repeatability in such strict conditions of low straightness error, low slope error (which could affect the interferometer) and 1.5 m axis. Six tests were performed sequentially (Fig. 6).

Analysis of the result obtained from the laser had a calculated spread of two standard deviations of better than 2 μm in optimal test conditions. In order to reduce the random influences,

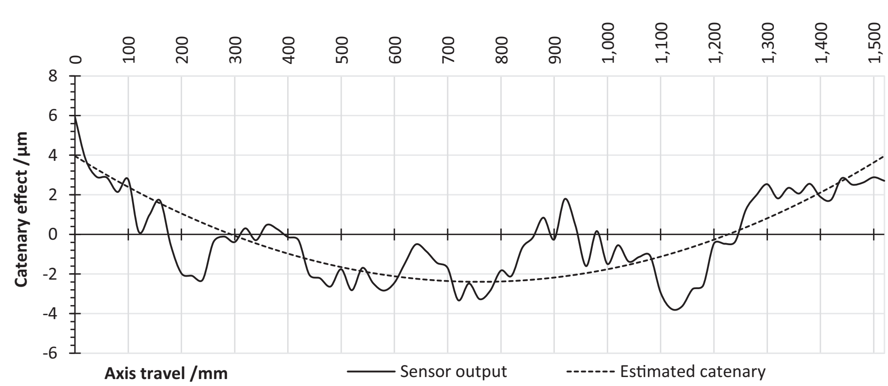

Fig. 3. Estimated catenary effect caused by gravity.

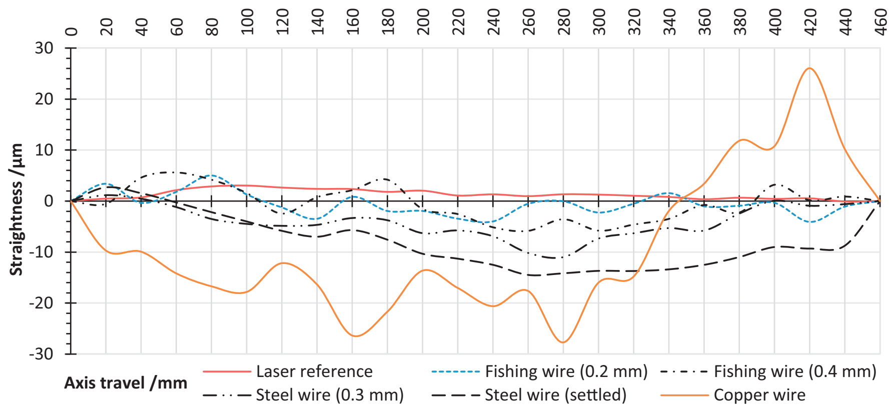

Fig. 4. Test of different wires.

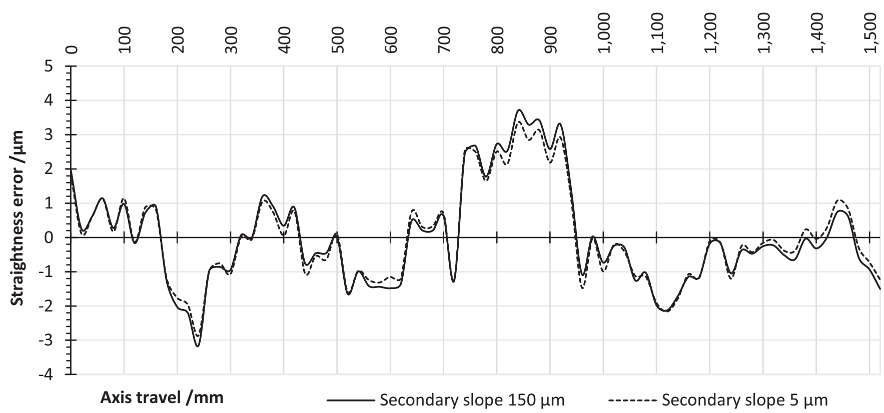

Fig. 5. Vertical straightness error dependency on horizontal error of the same axis using the wire.

averaging of multiple runs was required to get the best reference data against which the new sensor could be compared. This took additional time during which the thermal distortion of the machine could begin to have an effect. The machine's repeatability can be visually estimated from Fig. 7 (combined with the repeatability of the wire) and is considerably higher than the one of the laser setup.

Considering the taut wire system, the repeatability is affected by the systematic error of the reference (installed wire piece). Fig. 8 illustrates the difference between different pieces of the same type of wire. In this case straightness references are different but their results still close to each other. However, this is the largest contribution to measurement uncertainty for the system as described in Section 6. Due to the efficiency of the system, it is feasible to complete additional tests to enable averaging of the results from different wire pieces for wire error reduction.

As suggested, an average of these three different pieces of wire was used to provide the measurement shown in Fig. 9 for comparison with the average from the laser system. There is a good correlation in magnitude and shape, confirming that the systematic error of the wire is either significantly lower than the measured error or/and can be reduced by increasing the number of measurements.

In addition to standard measuring tests, static tests were also carried out to confirm the stability of both measurement methods independently of the machine. This eliminated any variability introduced by the machine's drives and axes to isolate the stability

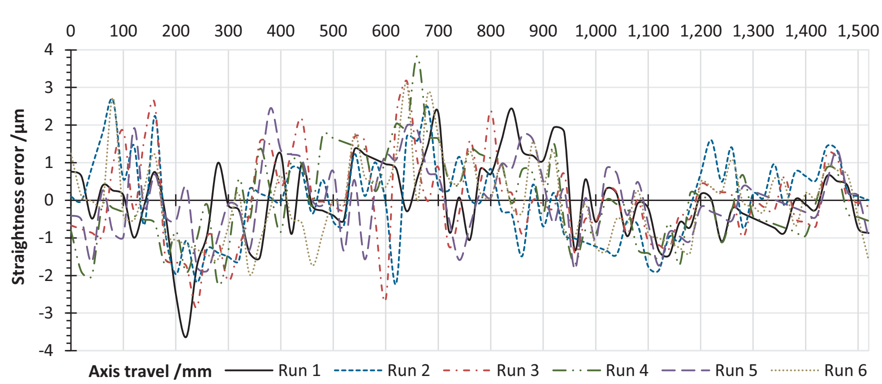

Fig. 6. Straightness error measured six times using the laser.

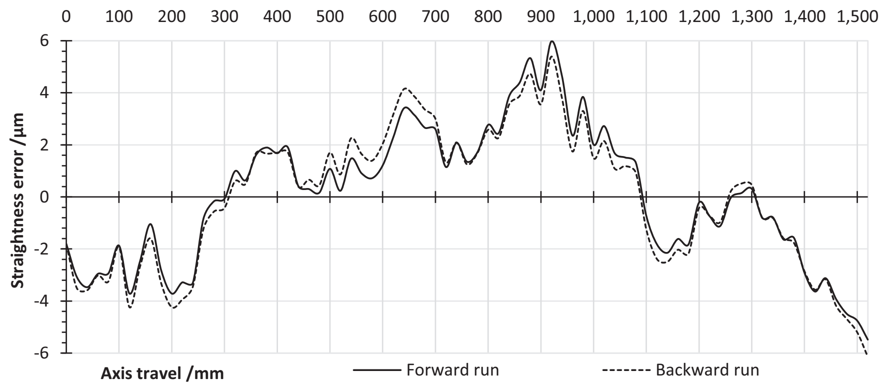

Fig. 7. Combined repeatability of the machine and the wire system.

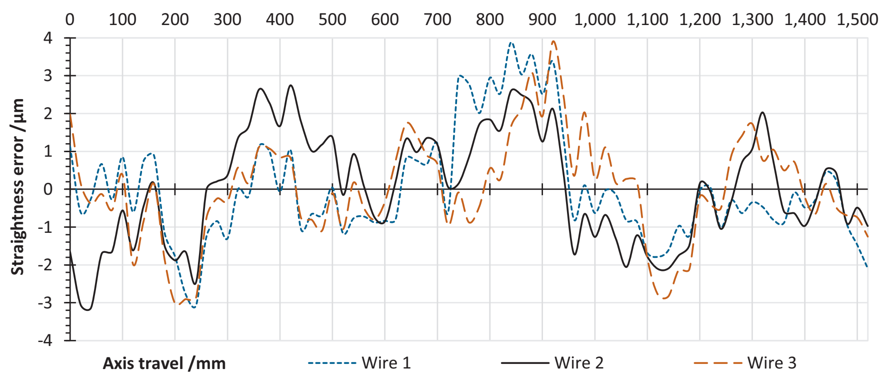

Fig. 8. Straightness error measured several times using different wire pieces.

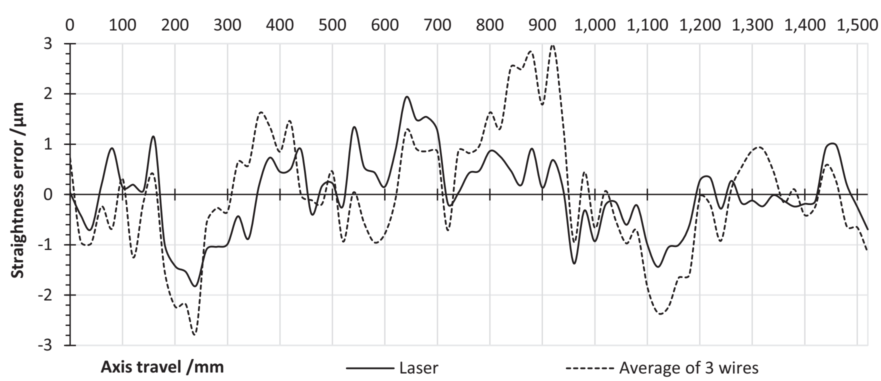

Fig. 9. Straightness error measured using the laser and the taut wire.

of each method in typical environmental conditions with respect to axial range. ISO230 part 1, section 6.3.3 [2] recommends that the sampled data should not exceed 10% of the tolerance of the specified test.

According to the same standard laser interferometer and optical sensor head were positioned in the middle of the normal axis travel range; this is theoretically the least stable position along the taut wire. Readings were taken every four seconds during a five-minute interval, similar to the capture pattern for the pseudo-static test described above. Each sample was subject to the averaging methods used for the other tests.

Fig. 10 shows more than one order of magnitude difference in output stability between both methods (standard deviations 0.43 µm and 0.04 µm, respectively). This suggests the combination of taut wire and non-contact optical measuring system is suitable for typical machine axis measurement.

6. Uncertainty analysis

Measurement uncertainty U was determined according to the method presented in the technical report ISO230 Part 9 [14], using basic equations applied to uncertainty budget contributors listed in Table 1. The conditions included a 1.5 m axis, measured for straightness in vertical plane over a 15-minute period using the wire specified earlier (Section 4). All contributors were deemed to be uncorrelated. Their distribution was assumed rectangular because no specific knowledge of them is available and therefore possible overestimation of corresponding uncertainties was considered reasonable. Standard uncertainty of each contributing component was given as:

$$u_i = \frac{a^+ - a^-}{2\sqrt{3}} \tag{1}$$

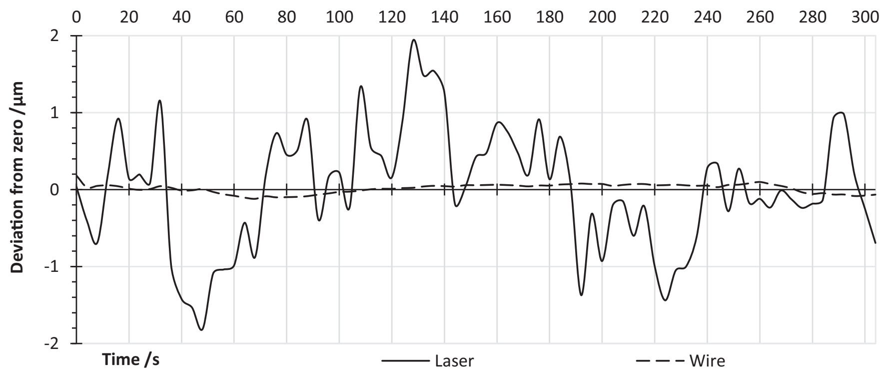

Fig. 10. Static stability of the laser and the taut wire.

where a^- and a^+ are lower and upper limits of distribution, respectively. Combined uncertainty u_c was derived as a sum of its contributors:

$$u_c = \sqrt{\sum u_i^2} \tag{2}$$

And with coverage factor k, derived from total degrees of freedom, expanded measurement uncertainty U was calculated as:

$$U = k \cdot u_c \tag{3}$$

The table above describes factors contributing towards measurement uncertainty. The first three represent angular deviations of the axis during its linear motion. These were measured by tilting the spindle and then separating the vertical lateral displacement from the measured value. It was necessary to quantify the sensitivity of the measuring system to the unwanted rotational movements of the axis during the test runs. All three effects change the position of the wire within the optical sensor slightly moving it forward/backwards (pitch and yaw) or left/right (roll). Horizontal alignment is the uncertainty due to slope in the corresponding plane (Fig. 5). The wire catenary estimation has an error due to wire length (2.2 m between stands) and weight measurement. Electronic noise together with drift as measured while the axis was stopped at its end, minimizing the effect of wire movement. The next two parameters characterize properties of the wire, measured during idle tests. The sensor calibration error represents sensor non-linearity approximation during system calibration when the axis moves known intervals incrementally in a vertical direction.

Sensitivity coefficients were obtained from the combined sensitivity value of the optical sensors, which was 16 mV/µm. Degrees of freedom were estimated as the number of repeated measurements ($n = 4$) less one.

The total value of degrees of freedom was derived using a Welch–Satterthwaite equation:

$$\upsilon = \frac{\left(\sum u_i^2/n_i\right)^2}{\sum (1/(n_i - 1))(u_i^2/n_i)^2} \tag{4}$$

This gives $\upsilon = 3.41$ which corresponds to coverage factor $k = 3.31$. The resulting $U_{wire} = 4$ µm could not be compared directly with the accuracy specification of a Renishaw XL-80 laser interferometer, which is 0.86 µm. Knapp in his paper [15] provides an uncertainty budget for laser interferometer, the same contributors were calculated to obtain combined uncertainty for our laser system (Table 2).

This gives $U_{laser} = 4$ µm which is somewhat lower than the value quoted by Knapp (6 µm) and is similar to the wire system result mentioned above. The actual results obtained on the machine (Figs. 6 and 8) have two standard deviations of 1.5 µm for both the laser and taut wire systems. This confirms good performance correlation between both systems.

Table 1
Uncertainty budget for straightness measurement using taut wire system.

Contributor	Average value	Unit	Sensitivity coefficient	Effect, µm		Uncertainty, µm	Degrees of freedom
				a^-	a^+	u	
Axis pitch	–	mV/deg	0.063	0.01	0.02	0.003	3
Axis roll	–	mV/deg	0.063	0.10	0.50	0.115	3
Axis yaw	–	mV/deg	0.063	0.15	0.80	0.188	3
Horizontal alignment	30	µm/m	0.01	0.20	0.60	0.115	3
Catenary estimation error	0.15	µm/m	2.2	0.2	0.4	0.058	3
Electric noise	1.26	mV	0.063	0.07	0.10	0.009	3
Electronic drift	0.7	mV/h	0.063	0.10	0.20	0.029	3
Wire profile variation	–	µm	1	1.00	5.00	1.155	3
Wire profile drift	1.7	µm/h	0.25	0.25	0.45	0.058	3
Sensor calibration error	–	µm	1	0.02	0.50	0.139	3

Table 2
Uncertainty budget for straightness measurement using laser interferometer.

Contributor	Average value	Unit	Sensitivity coefficient	Effect, µm		Uncertainty, µm	Degrees of freedom
				a^-	a^+	u	
Laser device	2.5	µm	1	0.50	4.50	1.155	3
Thermal drift	1.2	µm	1	1.00	1.40	0.115	3
Air disturbance	0.6	µm	1	0.50	0.70	0.058	3
Δ surface temperature	2	°C	0.4	0.40	1.20	0.231	3

As can be seen from Figs. 4 and 8, the main contributor to the taut wire system uncertainty was the unique profile of each piece of wire installed. Consequently, the straightness value depends on the quality of the wire, which normally does not exceed 4 μm and does not depend on wire length being limited by its diameter inconsistency. This allows high stability of the system installed on longer axes to be assumed despite environmental effects normally having a pre-emptive contribution to the uncertainty of other methods. As shown before (Figs. 8 and 9), taut wire system uncertainty can be further decreased by the averaging of different wire results in the same conditions at the expense of additional time spent on wire reinstallation and repeated measurement runs.

7. Conclusions

The performance of a new measuring system has been evaluated for measurement of machine tool axis straightness. It is based on an existing taut wire reference, which has been implemented using new materials, precise optical sensors and new measurement methodology. The system was tested in real manufacturing workshop conditions and compared to a typical alternative commercial system, namely a laser interferometer system. The profile of the machine axis was reproduced by both systems with just 1 μm difference. A detailed analysis of factors affecting measurement uncertainty has been performed with an expanded uncertainty of 4 μm and good correlation between both systems. Additionally, statistical analysis on various data sets showed two standard deviations of 1.5 μm.

Stability and repeatability were tested with respect to the measured axis length. Experiments proved excellent stability of the taut wire and optical sensor head when compared to the interferometer system during typical measurement durations. This shows the high potential of the method in terms of stability.

The first practical advantage of the taut wire system is its suitability for long range measurements. Environmental effects have very little random influence with correct tension in the wire, while systematic error due to wire diameter inconsistency is not significant and was not found to depend on the length of the wire and therefore on the length of the axis being measured. According to six different wires tested, DAIWA Sensor fishing wire is considered to be the most suitable for straightness measurement. The catenary effects on the wire can be calculated and removed from the systematic error by subtraction of a parabolic curve.

From these results, the system developed is shown to provide an efficient solution for measuring axes up to 1.5 m. Due to the characteristics, it is anticipated that advantages in stability will benefit longer axes as well where the performance of alternative methods degrades substantially.

Acknowledgement

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding of the EPSRC Centre for Innovative Manufacturing in Advanced Metrology (Grant Ref: EP/I033424/1).

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