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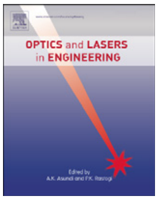

New low cost sensing head and taut wire method for automated straightness measurement of machine tool axes

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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

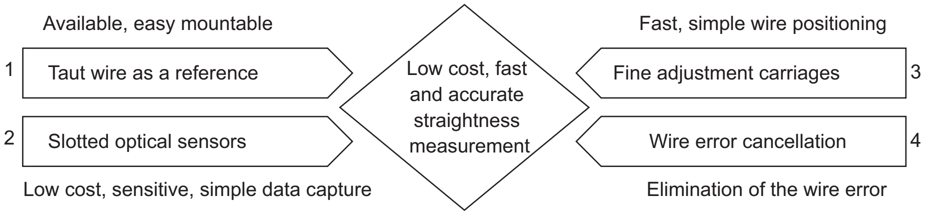

Fig. 1. Measurement principle.