euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020
www.euspen.eu

# Error identification and compensation for on-machine measurement using a laser displacement sensor

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**Abstract**
Faced with many turned parts on a lathe, the profile inspection usually relies on coordinate measuring machine, which is an off-line method and may introduce repositioning or reclamping errors. Then, an accurate and efficient on-machine measuring method of integrating a laser displacement sensor on a numerical control lathe has been proposed, which can inspect the profile of the workpiece without taking it off from the machine tool system. Based on the measuring process, a deviation model is constructed after analysis of the error sources. To improve the accuracy of the measurement, the deviations are identified by several other related inspection methods, which are employed to compensate the measured values. Subsequently, an additional experimental test is conducted to verify the effectiveness of the proposed methodology. Results have shown that the positive and negative deviations in the static measurement are +4.4 µm and -2.7 µm, respectively. Then, to improve the measurement efficiency, the dynamic process is adopted, in which the workpiece rotates at the optimized parameters. Although the measuring deviations enlarge to +6.3 µm and -3.1 µm partially, the time consumption is reduced to 10% to that of the static mode. The confidence interval analysis implies that the probability of 95% of the authentic values will fall into the calculated intervals.
**Keywords:** laser on-machine measurement, measuring process, error compensation, measurement accuracy, numerical control lathe.

## 1. Introduction

Intelligent manufacturing is a general concept that covers a range of digitalization, networkization and intelligentization technologies in the manufacturing industry [1], then as an advanced and efficient measurement technology, the on-machine measurement has attracted a lot of attention. Nowadays, on-machine measuring technology with a laser displacement sensor has started being utilized in the dimensional measurement of components [2-4], which has the advantages of high speed and accuracy. Compared with the mechanical probe, the laser displacement sensor is considered as a better choice for the lathe, which is more convenient for assembly and more efficient in measurement. Many researchers have established the volumetric errors model based on the homogeneous transformation matrix and rigid body dynamics [5-9]. And the laser on-machine measurement system have been presented for surface metrology and process monitoring to improve the machining accuracy and efficiency [10-11].

This paper attempts to propose a laser on-machine measuring methodology with high accuracy and efficiency integrated on the NC lathe, through the model construction, error identification and compensation. Firstly, the fundamental measuring process using the laser displacement sensor is introduced. Then, various sources of deviation found in the measurement results are analyzed, with the measuring errors identified and compensated. Some measurement results and related discussion are also provided.

## 2. Details of measurement conduction

Parts of rotary structure on the NC lathe can be measured by the laser displacement sensor, with the parts clamped by the chuck and the sensor installed in the turret. Then the measuring program is transferred to drive the transition of the sensor, realizing the collection of the parts profile information, as shown in Figure 1(a).

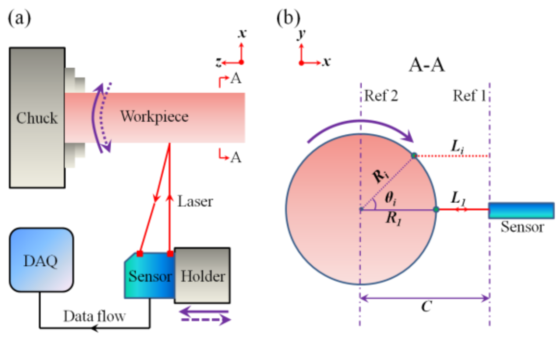


**Figure 1.** (a) The schematic of laser on-machine measurement on the NC lathe (b) Measuring process of rotary structural part.

The instantaneous radius at different position can be measured and calculated by revolving the parts, with the section characteristic of the circle, as shown in Figure 1(b).

## 3. Identification and compensation of measurement errors

### *3.1. Sensor position errors*

The position deviations can be adjusted by the calibration function in the calibration process, with which the measured values are compensated and revised before measuring.

### *3.2. Kinematic motion errors of the lathe*

Errors of the lathe have an obvious influence on the measuring accuracy, such as $\delta x(\theta)$, $\varepsilon y(\theta)$ and $\delta x(z)$, which should be recognized and compensated for the measurements to obtain the precise radius according to ISO 230-2:2014. The redial run-outs reach a maximum of 43 µm with the repeatability of 2 µm, and the straightness in the X direction is approximately 2.2 µm.

### *3.3. Alignment deviation of the part*

Additionally, the random clamping error of the workpiece exists certainly, which is difficult to be compensated by the effective theoretical expression. Hence, the compensated and registered point cloud is imported into the self-developed software, and then the deviations are analyzed through the comparison with the model which is measured by the coordinate measuring machine, thus reducing the measurement randomness.

## 4. Results and discussion

A cylinder was adopted to verify the effectiveness of the proposed methodology, five positions of which were measured by the coordinate measuring machine of TESA micro hite 3D and the laser sensor of LK-G80 respectively. The cylinder was ground with the tolerance of 9 μm according to ISO-1101-2017 and the reference value can be obtained with the uncertainty of 3 μm. In the static measuring process, the deviations before compensation are -0.0322 mm ～+0.0416 mm. Then after the compensation, the deviations reduce to -0.0133 mm ～+0.0199 mm. Later the fitting alignment and registration are conducted, resulting in the further reduction of the deviations, which range from -0.0027 mm to +0.0044 mm. After the error identification, compensation and registration, the measurement accuracy has been significantly improved, greatly exceeding the precision of the NC lathe itself.

When faced with large-scale uncomplicated parts, the efficiency requirements are difficult to appease, resulting in the consideration of the dynamic measurement. The amplitudes at different rotary speeds are respectively Amax = +0.0229 mm, Amin = -0.0337 mm, Bmax = +0.0201 mm, Bmin = -0.0191 mm, Cmax = +0.0171 mm, Cmin = -0.012 mm, the absolute values of which gradually decrease. The higher the rotary speed of the chuck, the more similar the radial run-out is to the sinusoidal function, with the amplitude decreasing.

In summary, the accuracy and efficiency of the laser on-machine measurement are respectively analyzed in detail, with the recommended parameters range provided (S ≥ 360 r/min, F ≤ 1200 mm/min). In terms of measurement efficiency, the time consumption of static mode is 10 min, while that of dynamic mode is 1 min. To evaluate the measurement certainty, five positions are distributed uniformly on the standard cylinder, where the radius are measured and calculated, as shown in Figure 2.

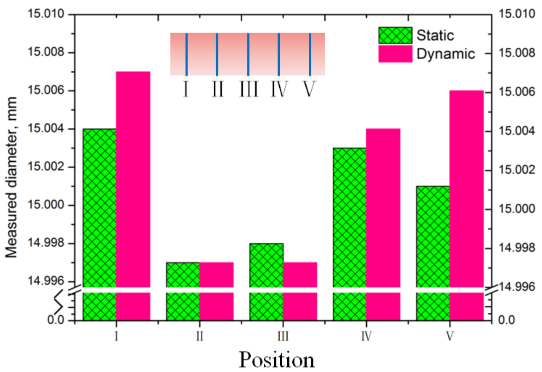


**Figure 2.** Measured and calculated radius at different positions of the workpiece.

The radius deviations of the static and dynamic measurements are differentially -0.003 mm ～+0.004 mm and -0.004 mm ～+0.007 mm, which are similar to the error analysis of the software. Additionally, the measurement system can detect other collisionless features by transforming one-dimensional distance to three-dimensional points cloud based on algorithm, which is calibrated through the self-configured process.

To analyze the reliability of the measured values, which are submit to the normal distribution X～N (μ, $\sigma^2$), the confidence interval is calculated. On account of the specimen, the interval [θ1, θ2], which makes P{θ1 ≤ θ ≤ θ2}=1-α, is achieved from the given confidence level.

$$\left[\bar{X} - z_{\frac{\alpha}{2}}\frac{\sigma}{\sqrt{n}}, \bar{X} + z_{\frac{\alpha}{2}}\frac{\sigma}{\sqrt{n}}\right]$$

When the confidence level is set as α = 0.95, the $z_{0.025}$ = 1.96 and n = 5 are obtained through the look-up table. Then due to the standard deviations of the static and dynamic are respectively 0.005 and 0.0062, the confidence intervals are calculated partly as [14.9962, 15.005] and [14.9968, 15.0076], implying that the probability of 95% of the authentic values will fall into the confidence intervals, that is, the reliability of the measurements is certain.

## 5. Conclusion

A laser on-machine measuring methodology on the NC lathe is proposed, which aims at improving the accuracy and efficiency by the error identification and compensation. Firstly, the deviation model of laser on-machine measurement is constructed and simplified, with the errors recognized by means of related detection methods, and then three-dimensional coordinates of the measuring points are calculated based on the measuring process. After error compensation and registration, the positive and negative deviations in the static mode are +4.4 μm and -2.7 μm, with high accuracy and slightly insufficient efficiency. However, in the dynamic measurement, when the feed rate is invariant, the deviations decrease with the rise of the rotary speed, as the tendency slows down. Then, the deviations are less affected by the feed rate as the rotary speed is definite, which grow larger until the parameters of S = 360 r/min, F = 5 mm/r. At S = 360 r/min and F = 120 mm/min, the deviation appears least, with the values of +6.3 μm and -3.1 μm differentially. Additionally, the time consumption of the dynamic mode is 10% to the static mode. Thus, in the process of laser on-machine measurement, if the workpiece is complicated or the demand of measuring accuracy is strict, the static mode is employed, while the dynamic mode is considered to be a preferred choice as the simple part or the high efficiency, with the parameters recommended as S ≥ 360 r/min and F ≤ 1200 mm/min, for reference only. Furthermore, the confidence interval analysis implies that the probability of 95% of the authentic values will fall into the calculated intervals.

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