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3D shape measurements with a single interferometric sensor for in-situ lathe monitoring

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ABSTRACT

Temperature drifts, tool deterioration, unknown vibrations as well as spindle play are major effects which decrease the achievable precision of computerized numerically controlled (CNC) lathes and lead to shape deviations between the processed work pieces. Since currently no measurement system exist for fast, precise and in-situ 3d shape monitoring with keyhole access, much effort has to be made to simulate and compensate these effects. Therefore we introduce an optical interferometric sensor for absolute 3d shape measurements, which was integrated into a working lathe. According to the spindle rotational speed, a measurement rate of 2,500 Hz was achieved. In-situ absolute shape, surface profile and vibration measurements are presented. While thermal drifts of the sensor led to errors of several μm for the absolute shape, reference measurements with a coordinate machine show, that the surface profile could be measured with an uncertainty below one micron. Additionally, the spindle play of 0.8 μm was measured with the sensor.

Keywords: interferometry, phase measurement, speckle, process monitoring and control, rough surface, shape measurement, in-situ

1. INTRODUCTION

1.1 State of the art

Currently the achievable precision of high-speed turning lathes is limited by temperature drifts, tool wear, spindle vibration and axle play. These effects are being compensated in part. For instance temperature compensation¹ and measurement, prediction and compensation of tool wear^{2,3} can be employed. However, in order to guarantee shape deviations below 1 μm , 3d shape measurements are required. The most versatile and precise tools are tactile coordinate measurement machines (CMM), but they allow no in-situ measurements. Therefore the testing with CMM is slow and susceptible to mounting tolerances, because the specimen has to be reclamped in a separated machine for shape measurements. Furthermore the measurement process itself is time consuming due to its tactile nature and to prevent scratching of the specimens surface. In order to increase the possible sample size, a first progress was achieved by performing tactile measurements inside the lathe. However, the required time for testing still exceeds the production time. Therefore non-contact measurement techniques such as optical techniques are required, which offer higher measurement rates of several kHz and therefore will allow a hundred percent process monitoring. Employing shadow projection for instance, allows for scanning the 3d shape of a shaft in just a few seconds.⁴ However, shadow projection is unable to resolve concave profiles and the shadow projection systems are too bulky to easily fit into a lathe, since sending and detection unit of the system are on opposing sides of the specimen. Thus, optical techniques with keyhole access are required, such as triangulation, chromatic confocal sensing or absolute distance interferometry. All of these techniques enable sub-micron precision as well as measurement rates of several kHz and can be employed for surface profile measurements. Stand-alone, however, none of these techniques is able to measure the 2d shape i.e. the angular resolved radius of the work piece, since exact knowledge of the distance to the rotational axis is necessary additionally to the measured distance between sensor and surface. For this reason, tumbling, vibrations, eccentricity and drifts of the rotational axis

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will lead to measurement errors. Consequently, a fast, precise, in-situ, 3d shape monitoring with keyhole access is required for a hundred percent process monitoring in high precision lathes, which is insusceptible to errors due to the changing position of the rotational axis.

1.2 Aim and outline of the paper

The aim of this paper is to apply the laser Doppler distance sensor with phase evaluation (P-LDDS) for in-situ, 3d, absolute shape measurements in a computerized numerical controlled (CNC) lathe for the first time and to characterize the achievable measurement uncertainty. The measurement approach is to measure the distance between sensor and specimen as well as the circumferential velocity of the specimen simultaneously with a single sensor, which is described in section 2.1. The interferometric principle for the simultaneous velocity and distance measurement with the P-LDDS is then explained in section 2.2. In order to fit the sensor into the lathe, it was miniaturized for the first time. The miniaturized sensor setup is presented in in section 2.3. For characterizing the P-LDDSs performance, several experiments considering mainly the influence of surface roughness and material were performed in a CNC lathe. The respective experimental setup and measurement procedure are described in section 3, and the measurement results, i.e. the determined measurement uncertainties, are finally presented in section 4.

2. MEASUREMENT AND SENSOR PRINCIPLE

2.1 3d shape measurement with keyhole access

The 3d shape of an object can be described by its radius with respect to polar coordinates $r(\alpha, \tilde{z})$. Since the exact position of rotational axis is unknown in practice, an indirect shape measurement has to be performed. For this purpose the shape is separated in the mean radius of the object

$$R = \frac{1}{2\pi \cdot l} \int_0^{2\pi} \int_0^l r(\alpha, \tilde{z}) d\tilde{z} d\alpha \quad , \quad (1)$$

with the length of the object l and the respective deviations from the mean radius

$$\Delta r(\alpha, \tilde{z}) = r(\alpha, \tilde{z}) - R \quad . \quad (2)$$

The radius deviations Δr can be measured directly with optical distance sensors, which offer sufficient uncertainties below $1 \mu\text{m}$ and measurement rates of several kHz. The radius deviation from the object mean radius is obtained from n distance measurements $z(\alpha, \tilde{z})$ over multiples or at least one revolution of the object with the mean measured distance Z by

$$\Delta r(\alpha, \tilde{z}) = -(z(\alpha, \tilde{z}) - Z) \quad \text{and} \quad Z = \frac{1}{n} \sum_{i=1}^n z(\alpha, \tilde{z}). \quad (3)$$

Note that according Fig. 1, the r - and z -axis point in opposite directions. However, a direct measurement of the mean radius R by the distance measurements is affected by the unknown distance $\tilde{x}$ between the sensor and the rotational axis, cf. Fig. 1. For this reason, any uncertainty in the alignment between sensor and axis, for instance due to thermal or temporal drifts, directly increases the measurement uncertainty of the shape measurement. Therefore we propose a novel approach for the absolute shape measurement, which is based on a surface velocity measurement in addition to the distance measurement. By evaluating the surface velocity, the mean radius R can be measured without cross-sensitivity to $\tilde{x}$. Considering the angular velocity ω of the object as constant and known, R can be measured by the mean surface velocity V according to

$$R = \frac{V}{\omega} = \frac{1}{\omega \cdot n} \sum_{i=1}^n v(\alpha, \tilde{z}) \quad . \quad (4)$$

Now combining the results 3 and 4 of the distance and the velocity measurements, respectively, the absolute shape is finally obtained by

$$r(\alpha, \tilde{z}) = \frac{V}{\omega} + \Delta r(\alpha, \tilde{z}) = \frac{V}{\omega} + Z - z(\alpha, \tilde{z}) \quad . \quad (5)$$

Figure 1. Schematic of measurement principle. The tangential velocity v and the surface distance z of the rotating work piece are measured simultaneously and result in the angular resolved radius. Feeding the sensor along the $\tilde{z}$ -axis enables a 3d shape measurement with key hole axis.

Note that this measurement approach is independent of sensor and axle misalignment. Whereas the rotation of the work piece within the lathe enables the angular resolved radius measurement (2d shape), feeding the sensor along the $\tilde{z}$ direction finally offers a 3d shape measurement.

2.2 Laser Doppler distance sensor with phase evaluation

The measurement principle of the laser Doppler distance sensor with phase evaluation (P-LDDS) allows for the simultaneous measurement of lateral velocity and position of moving, optically rough surfaces. Hence, it meets the requirements of the novel measurement approach presented in section 2.1. The measurement principle of the P-LDDS is based on laser surface velocimetry (LSV).⁵ LSV uses an interference fringe pattern formed in the intersection of two coherent laser beams. In order to calculate a surface velocity, the measured Doppler frequency of the scattered light signal f_d and the calibrated fringe spacing d are evaluated:

$$v = f_d \cdot d \quad . \quad (6)$$

In order to measure the surface distance simultaneously, the P-LDD sensor superposes mutually tilted interference fringe systems with the same fringe spacing.⁶ In Fig. 2 the fringe pattern and resulting scattered light signals are depicted schematically. The fringe systems exhibit a position dependent phase shift

$$\phi = z \cdot s \quad , \quad (7)$$

with the slope s of the phase shift with respect to the position z , cf. Fig. 2. The slope s depends on the tilting angle ψ between the fringe patterns and the (equal) fringe distance d according to the formula

$$s = 2\pi \frac{\tan \Psi}{d} \quad . \quad (8)$$

As a result, evaluating the Doppler frequencies as well as the position dependent phase shifts allows for an axial distance measurement *and* a lateral velocity measurement.

Figure 2. Two mutually tilted interference fringe systems of a P-LDDS (left), and scattered light signals from a particle (right). The velocity is coded in the frequency f_D , the position in the phase difference ϕ .

Figure 3. All passive, interferometric sensor head. The trichromatic light is introduced via the sending fiber. Grating and Keplerian telescope generate the 3 fringe systems. The mirrors forward the scattered light into the detection fibers.

2.3 Sensor setup

The developed setup combines an increased dynamic range, utilizing 3 interference fringe systems,⁷ and a reduced distance uncertainty, utilizing receiving optics matching,⁶ in an all passive sensor head. The sensor employs three fiber coupled laser diodes with $\lambda_1 = 638 \text{ nm}$; $\lambda_2 = 658 \text{ nm}$ and $\lambda_3 = 685 \text{ nm}$, which are coupled into the same sending fiber, see Fig. 3. This reduces the active components from the sensor head. The three chromatic light is collimated and split spatially by a blazed transmission diffraction grating. A narrow band stop filter (NF) blocks the +1. diffraction order (DO) from λ_2 and a narrow band pass filter (BP) blocks the -1. DO from λ_1 and λ_3 . The remaining ± 1 . and 0. DO are superposed by a Keplerian telescope and form the interference fringe systems in their intersection. The wavelength difference between λ_1 and λ_3 results in a slight tilt between the corresponding interference fringe systems, due to different diffraction angles. The tilting angles between the interference fringe systems and, thus, the slopes s_{12} and s_{31} can be scaled by the magnification factor of the Keplerian telescope f_2/f_1 and the grating constant g . Two mirrors forward the light through the respective filters onto fiber-coupled photo detectors. The electronic detector signals are then finally analyzed on a computer using MATLAB for measuring the Doppler frequencies and the phase shift, cf. section 2.2.

3. EXPERIMENTAL SETUP AND IN-SITU CALIBRATION

The P-LDDS is mounted onto the tool revolver of the lathe, see Fig. 4. It is positioned by the same program used for the specimen production. For testing, shafts with different roughness are manufactured. Due to the open design of the sensor head, dry machining is employed. First, a measurement on a cylindrical shaft with a length of 100 mm and a diameter of 47 mm was conducted as a proof of concept. The cylinder was measured in the lathe directly after its production. For the measurement the rotational frequency was set to $f_{rot} = 25 \text{ Hz}$ and the feed velocity to $v_{feed} = 60 \text{ mm/s}$ resulting in a measurement time of 100 s. With a measurement rate of 2.5 kHz $n = 250,000$ data points with a spacing of approximately 1.5 mm (circumference) $\times 40 \mu\text{m}$ ($\tilde{z}$) resulted. The results for the radius variation measurement are depicted in Fig. 5 and compared to measurements with a coordinate measurement machine (CMM) for reference. As a result, the measurement of the radius variation is within the measurement uncertainty of the CCM of 1 μm . However, the measurement of the absolute radius showed a significant deviation towards the reference. Whereas the relative standard deviation of a single velocity measurement was 0.3%, which results in a random error for the radius measurement with a standard deviation of only $\sigma_r = 0.3\% \cdot r / \sqrt{n} = 280 \text{ nm}$, an absolute deviation of 170 μm occurred. This is attributed to a misalignment of the optics within the sensor head during operation in the lathe caused by heating within the machine, which resulted in a shift of the calibration function for the velocity measurement. The results of this experiment are therefore used to recalibrate the sensor for the following experiments inside the lathe, resulting in absolute diameter deviation $< 1 \mu\text{m}$.

Figure 4. The sensor head is mounted onto the tool revolver. This allows for a free positioning.

Figure 5. Measurement of radius variation with the P-LDDS (in-situ) and a coordinate coordinate measurement machine.

4. EXPERIMENTAL RESULTS

Since the P-LDDS measurement depends on the speckle effect,⁸ the influence of the surface roughness towards the measurement uncertainty was investigated. For this purpose cylindrical probes with different roughness profiles were manufactured, by using different materials and by varying the feed motion v_{feed} between 2 and 2,000 mm/min during production. This leads to roughnesses between $R_a = 100$ nm and $R_a = 10$ μm. Fig. 6

Figure 6. Measurement uncertainties of position and velocity in dependency of the surface roughness R_a , material and feed motion.

shows the standard deviation σ_z of the position measurement and the standard deviation σ_v/v in dependency of

the surface roughness. The results show that the standard deviations for aluminum and brass are comparable. Furthermore, no significant difference between feed motions with $v_{feed} = 1 \text{ mm/s}$ and $v_{feed} = 17 \text{ mm/s}$ are apparent. Regarding the surface roughness, $\sigma_z \approx 200 \text{ nm}$ and $\sigma_v/v \approx 0.3\%$ is achieved for $100 \text{ nm} < R_a < 1 \mu\text{m}$, whereas σ_z and σ_v/v increase for $R_a > 1 \mu\text{m}$. Thus, the sensor system is well suited for different materials, allows high scanning speeds, and in contrast to conventional laser optical distance sensors, performs well on optically rough surfaces as well.

In addition to the experimental assertion of the measurement uncertainty, the spindle play (periodical movement of the rotational axis) of approximately $0.8 \mu\text{m}$ could be measured, see. Fig. 7. The spindle play resulted in a sinusoidal position variation at the rotational frequency. Being able to resolve the spindle play is especially important, because the spindle play is a key issue for minimizing the achievable tolerances of production with lathes.

Figure 7. Measured surface position in dependency of position and time. A sinusoidal variation with the rotation frequency $f_{rot} = 25 \text{ Hz}$ indicates spindle play with an amplitude of $0.8 \mu\text{m}$.

5. CONCLUSION AND OUTLOOK

A new approach for in-situ 3d shape monitoring for lathes was presented, by evaluating axial position and lateral velocity of the workpiece surface. As optical sensor, the P-LDDS allows the simultaneous measurement of both quantities and also offers keyhole access. The sensor was applied in a lathe and its performance regarding the surface roughness (micro-geometry) was investigated. It was shown, that the sensor achieves a standard deviation of the position measurement of approximately 200 nm and a standard deviation of the relative velocity measurement of 0.3% . This resulted in an uncertainty below $1 \mu\text{m}$ of the absolute shape measurement. Systematic errors in the velocity measurement, which resulted in systematic errors of the absolute diameter, were eliminated by in-situ calibration. The measurement rate is only limited by the rotational frequency and feed velocity of the lathe. The shape measurement of a 100 mm long shaft, with 47 mm in diameter took 6 s . Furthermore, the sensor system was applied to measure the spindle play with an amplitude of $0.8 \mu\text{m}$, simultaneously to the 3d shape measurement.

As an outlook, a more robust sensor head design with respect to thermal effects as well as an online signal processing are currently setup for industrial application. The online signal processing will provide the measurement data in real-time to allow a direct control of the production process, enabling zero-error production. Furthermore, the influence of coolants on the surface towards the measurement uncertainty is to be investigated, in order to improve near-dry machining as well as dry machining.

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