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3D interferometric shape measurement technique using coherent fiber bundles

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ABSTRACT

In-situ 3-D shape measurements with submicron shape uncertainty of fast rotating objects in a cutting lathe are expected, which can be achieved by simultaneous distance and velocity measurements. Conventional tactile methods, coordinate measurement machines, only support ex-situ measurements. Optical measurement techniques such as triangulation and conoscopic holography offer only the distance, so that the absolute diameter cannot be retrieved directly. In comparison, laser Doppler distance sensors (P-LDD sensor) enable simultaneous and in-situ distance and velocity measurements for monitoring the cutting process in a lathe. In order to achieve shape measurement uncertainties below 1 μm , a P-LDD sensor with a dual camera based scattered light detection has been investigated. Coherent fiber bundles (CFB) are employed to forward the scattered light towards cameras. This enables a compact and passive sensor head in the future. Compared with a photo detector based sensor, the dual camera based sensor allows to decrease the measurement uncertainty by the order of one magnitude. As a result, the total shape uncertainty of absolute 3-D shape measurements can be reduced to about 100 nm.

Keywords: shape measurement, interferometry, coherent fiber bundle, in-situ, image processing, speckle

1. INTRODUCTION

Absolute shape measurements of workpieces are important for process monitoring and process control at working lathes. Currently, as the state of the art, coordinate measurement machines (CMM) allow absolute shape measurements with submicron precision.¹ However, the measurement process of the workpiece is slow compared to the workpiece processing time in the lathe, due to the time required for setting up the measurement and due to the tactile nature of conventional CMMs. Furthermore, the measurement is usually performed ex-situ and after the processing. This means that an immediate control of the workpiece processing is not possible. For this reason, an absolute shape measurement is required inside of the lathe.

Optical measurement techniques such as triangulation,² low coherence interferometry,³ conoscopic holography,⁴ absolute distance interferometry,⁵ laser tracker,⁶ mode-locking external cavity laser sensor,⁷ dispersive white-light interferometry⁸ and wavelength scanning heterodyne interferometry⁹ can enable high measurement rates and submicron distance uncertainties. Thus, they can be employed to measure the surface profile of the workpiece, either by scanning or by employing the inherent rotation of the workpiece inside the lathe. However, at high surface or scanning velocities the measurement uncertainty of these techniques increases, due to the decreasing averaging time and the speckle effect, which occurs at rough surfaces. Moreover, all these techniques offer only one measurand, the distance. As a result, the absolute diameter of the work piece is missing.

One approach to measure the diameter of the workpiece is to measure the tangential velocity of the surface during rotation, additionally. For instance, the laser Doppler distance sensor with phase evaluation (P-LDD sensor) enables simultaneous velocity and distance measurements and is well equipped to measure at fast moving rough surfaces as well. Therefore, it enables an absolute, in-situ shape measurement inside of a lathe cf. Fig. 1.¹⁰ The measurement principle is based on the evaluation of the Doppler frequencies of the scattered light signals and thereby on speckle.¹¹ For the conventional setup, the scattered light is detected with photo detectors. Therefore, several speckles oscillating with equal Doppler frequency but random phases are superposed on the detector.¹² This results in an increased surface velocity uncertainty and therefore in an increased uncertainty of the measured shape.

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Figure 1. A photo detector based P-LDD sensor is integrated into a cutting lathe for an in-situ measurement.¹⁰

The aim of this paper is to introduce a dual camera based scattered light detection, to evaluate the speckles individually and thereby reducing the measurement uncertainty. In order to realize a compact and robust sensor for in-situ measurements, a coherent fiber bundle is used to transmit the scattered light signal from the sensor head to the camera. The measurement principle of the P-LDD sensor is described in Sec. 2. Since the speckle related measurement uncertainty is dominant, the camera based method and the respective image processing for the reduction of this measurement uncertainty is proposed in Sec. 3. Finally, the coherent fiber bundle based scattered light signal transmission is presented in Sec. 4.

2. 3-D SHAPE MEASUREMENT WITH P-LDD SENSOR

As shown in Fig. 2, the P-LDD sensor is based on a Mach-Zehnder velocimeter using interference fringe patterns. It is easily described for single scattering particles passing the measurement volume with a certain velocity. The amplitude of the scattered light is then modulated with the Doppler frequency f_D . With the interference fringe distance d and the particle velocity v perpendicular to the fringe system, the Doppler frequency f_D results to

$$f_D = v/d. \quad (1)$$

Determining the fringe distance by a calibration and measuring the Doppler frequency thus allow a velocity measurement.

Figure 2. Principle of P-LDD sensor: superposition of two interference fringe systems with constant and equal fringe spacing d , which are tilted towards each other by an angle ψ . The scattered light from each fringe system is detected with a photo detector.

In order to measure the axial position z simultaneously, two mutually tilted interference fringe systems with

equal fringe distances and the tilting angle ψ are superposed. This leads to a position dependent lateral offset between both fringe systems, resulting in a position and velocity dependent delay τ of the two scattered light signals cf. Fig. 3. The two light signals can be distinguished by wavelength multiplexing. In order to eliminate the velocity dependency, the position dependent phase difference $\varphi = 2\pi\tau/f_D$ is determined to calculate

$$z = \varphi \cdot s^{-1}, \quad (2)$$

where the s is the slope of the calibration function $\varphi(z)$.

Figure 3. (a) Two scattered light signals from a single scattering particle. The phase difference dictates the distance z . (b) Scattered light signals from a rough surface: the distortion of amplitude and phase results from the speckle effect.

By evaluating the surface distance and the surface velocity of a rotating workpiece, the absolute shape can finally be evaluated by

$$r(\alpha) = R + \Delta r(\alpha) = \frac{\bar{v}}{\omega} - (\bar{z} - z(\alpha)). \quad (3)$$

The mean radius R of the workpiece can be estimated by the mean velocity $\bar{v}$ of the surface and the angular velocity ω , which is constant and known. The angle dependent deviation $\Delta r(\alpha)$ of the workpiece radius from the mean radius is obtained from the difference of the mean value $\bar{z}$ and the angle resolved distance $z(\alpha)$. While the rotation of the workpiece in the lathe enables the angle resolved radius measurement (2-D shape), an additional feed forward of the sensor along the rotational axis achieves an absolute 3-D shape measurement, cf. Fig. 2.

3. CAMERA BASED SIGNAL DETECTION

As shown in Table 1, the total measurement uncertainty for an absolute shape measurement results to $\sigma_r \approx 1 \mu\text{m}$ and is currently limited by the relative velocity uncertainty $\sigma_{v,\text{speckle}}/v$ and the distance uncertainty $\sigma_{z,\text{speckle}}$ due to the speckle effect. This is caused by multiple speckles with equal modulation frequency (Doppler frequency f_D) but random phase are interfering on the detector surface¹³ shown in Fig. 4, which results in a distortion in the scattered light signal cf. Fig. 3(b).

Table 1. Measurement uncertainty budget for a 3-D shape measurement containing the most significant contributors. The numerical values are derived experimentally. The uncertainties are calculated for a representative 3-D shape measurement with stepwise scanning along the height of the workpiece with $M = 10^4$ (10^2 measurement points per revolution $\times 10^2$ scanning steps along the y direction, cf. Fig. 1), $N = 10^5$ ($M \times 10$ revolutions per scanning step), the mean radius of the workpiece $R = 20 \text{ mm}$ and a temperature variation of $\Delta T = 1 \text{ K}$. Averaging length X_L is the displacement of the workpiece surface, while sampling a time series of the scattered light signal for one measurement point.

description	value	resulting shape uncertainty in μm
3-D shape uncertainty		
$\sigma_r = 1 \mu\text{m}$		
relative velocity uncertainty due to speckle	$\sigma_{v,\text{speckle}}/v = 4 \times 10^{-3}/\sqrt{X_L/\text{mm}}$	0.8
distance uncertainty due to speckle	$\sigma_{z,\text{speckle}} = 0.2 \mu\text{m}/\sqrt{X_L/\text{mm}}$	0.2
relative uncertainty of fringe distance	$\sigma_d/d = 1.5 \times 10^{-5} \times \Delta T/K$	0.2
distance uncertainty due to detector noise	$\sigma_{z,\text{noise}} = 0.2 \mu\text{m}/\sqrt{X_L/\text{mm}}$	0.06
relative velocity uncertainty due to noise	$\sigma_{v,\text{noise}}/v = 0.5 \times 10^{-3}/\sqrt{X_L/\text{mm}}$	0.03
relative uncertainty of angular velocity	$\sigma_\omega/\omega = 10^{-6}$	0.02

Figure 4. The scattered light intensity on the detector surface for a P-LDD sensor at four consecutive time steps. The step size is one half of the fringe spacing. Therefore the images for $n = 1$ and $n = 3$ look almost identical but slightly shifted, since the surface movement equals exactly one fringe spacing. The same holds for the images $n = 2$ and $n = 4$. However, the images for $n = 1$ and $n = 2$ are totally different, because complete different surface positions are illuminated. As an example, note the fluctuation of the intensity of a dominant speckle (red box), which occurs with the Doppler frequency. Note further that the grayscale is inverted for a distinct show.

In order to reduce the measurement uncertainty due to the speckle effect, a speckle separation technique employing a line camera has been presented in Ref. 14. It achieves a reduction of the measurement uncertainty of the velocity by $\sqrt{S}$ cf. Fig. 5(a) (green curve), whereas S is the number of independent scattered light signals that are detected simultaneously. Thus, S is limited by the number of camera pixels and by the speckle size. In order to decrease the uncertainty further, a matrix camera based speckle separation is proposed. The speckles can be separated by employing a modified particle image velocimetry algorithm¹⁵ and by exploiting the fact that each speckle has the same velocity on the camera surface. Averaging the amplitude spectra of each speckle yields a seemingly undisturbed gaussian function from which the Doppler frequency can be calculated cf. Fig. 5(a) (red curve). Compared to the photo detector based sensor, $\sigma_{v,\text{speckle}}/v$ can be decreased by a factor of 40 to $1 \times 10^{-4} \times \sqrt{X_L/\text{mm}}$. Thus, the contribution of $\sigma_{v,\text{speckle}}/v$ towards the shape uncertainty is reduced to 20 nm.

Figure 5. (a) Determined amplitude spectrum with the matrix camera based approach (red curve), where the amplitude spectra are determined for each speckle signal. For comparison, the formerly resulting amplitude spectra with the line camera (green curve) and the photo detector (integration over all camera pixels, blue curve) are shown. The uncertainties are given for scattered light signals with an averaging length of $X_L = 1$ mm. (b) The normalized distance uncertainties $\sigma_{z,\text{speckle}} \times \sqrt{X_L/\text{mm}}$ with dual camera based and photo detector based P-LDD sensors.

For reducing the distance uncertainty, two coaligned cameras are employed to capture two scattered light signals. The corresponding speckle signals on both camera surfaces should exhibit the same time delays, i.e. the same phase difference. Thereby, by using speckle separation and averaging each phase difference between corresponding speckle signals, the distance uncertainty can be reduced by $\sqrt{S}$ in theory. To verify this, the scattered light signals from a 100 mm long surface is acquired with the cameras and with the photo detectors. In order to calculate $\sigma_{z,\text{speckle}}$ the distances are calculated for different averaging lengths. $\sigma_{z,\text{speckle}}$ then results from the standard

deviation of the measured distances of 10 consecutive surface segments.

In theory, the distance uncertainty reduces directly proportional to the square root of the averaging length.¹⁶ Thus, $\sigma_{z,\text{speckle}} \times \sqrt{X_L/\text{mm}}$ should remain constant. The calculated $\sigma_{z,\text{speckle}}$ is depicted in Fig. 5(b). While $\sigma_{z,\text{speckle}} \times \sqrt{X_L/\text{mm}}$ should remain constant, it increases with increasing X_L . This is attributed to out-of-flatness deviations of the surface, i.e. surface roughness and waviness, which superposes the calculated $\sigma_{z,\text{speckle}} \times \sqrt{X_L/\text{mm}}$. For the photo detector based measurement it can be seen, that $\sigma_{z,\text{speckle}} \times \sqrt{X_L/\text{mm}}$ remains constant for $X_L < 1$ mm. Thus, $\sigma_{z,\text{speckle}} \times \sqrt{X_L/\text{mm}} = 0.2 \mu\text{m}$. For the camera based sensor no saturation can be seen. Therefore, only an upper boundary for the measurement uncertainty can be given $\sigma_{z,\text{speckle}} \times \sqrt{X_L/\text{mm}} < 80$ nm.

After reducing $\sigma_{v,\text{speckle}}/v$ and $\sigma_{z,\text{speckle}}$, the shape uncertainty is now limited by the relative uncertainty of the fringe distance σ_d/d . The fringe distance can be unstable due to temperature effect cf. Table 1. However, with the matrix camera based approach, the fringe pattern of the interference fringe system can be obtained by averaging the signal images over time and thus eliminating the speckle effect on the averaged image cf. Fig. 6(a). By utilizing the Fast Fourier Transform, an in-situ and real-time calibration of the fringe distance d can be achieved. Thus, the influence of the temperature variation on d can be eliminated. Applying this approach $\sigma_d/d \approx 10^{-4}/\sqrt{X_L/\text{mm}}$ is determined. With $X_L = 1$ mm and the total sample number $M = 10^4$, $\sigma_d/d \approx 10^{-6}$ results for the shape uncertainty presented in Table 1. The contribution of σ_d/d towards the shape uncertainty is reduced to 20 nm. As a consequence, by using dual camera based P-LDD sensor, the 3-D shape uncertainty is reduced to about 100 nm.

Figure 6. (a) The fringe pattern of the interference fringe system obtained by camera based signal detection (b) The fringe frequency $1/d$ is evaluated by the Fast Fourier Transform.

4. COHERENT FIBER BUNDLE BASED SIGNAL TRANSMISSION

In order to realize in-situ measurements inside of a lathe, a small and robust sensor is required. Formally, this was achieved by employing multi-mode fiber coupled photo detectors.¹⁰ Using multi-mode fibers is not possible here because the spatially resolved speckle images are required while multi-mode fibers distort these images due to mode-mixing.¹⁷

Therefore, the possibility to use a coherent fibre bundle (CFB) is investigated. CFBs are used in endoscopy to transmit images coherently, meaning that the relative distance and angle between each pixel remains constant.¹⁸ For a first experiment, one CFB (Edmund Optics Standard Flexible Fiberscope) with 6000 fiber cores and $3 \mu\text{m}$ core diameter is employed to forward the scattered light of one fringe system towards one camera cf. Fig. 7. A camera with 200×200 px is used to detect the image of the scattered light field at the distal end of the CFB. Thus, we employ around 7 camera pixels per fiber core. For a comparison, an experiment without CFB (direct camera detection) is done under the same experimental environment.

Figure 7. Camera based P-LDD sensor with coherent fiber bundle scattered light detection

In order to investigate the influence of the number of fiber cores and camera pixels, camera signals for differently sized areas are processed and the relative velocity uncertainty due to speckle $\sigma_{v,\text{speckle}}/v$ is calculated. As shown in Fig. 8, $\sigma_{v,\text{speckle}}/v$ with CFB is reduced to 7×10^{-4} . This is a factor of 6 smaller compared to the photo detector based sensor, meaning that CFB can indeed be used to transmit the speckle patterns in a P-LDD sensor. However, the reduction is lower than the number of 40000 camera pixels (without CFB) whose value is 1×10^{-4} (reduced by factor 40) would suggest. This has several reasons. First, the number of independent signals is limited by the number of camera pixels as well as by the number of fiber cores, which is only 6000. Second, the CFB uses a common cladding, thus optical cross talk reduces the effective number of fiber cores further.¹⁹ Third, each fiber core is multi-mode which results in a distortion of the imaged signals. Lastly, no matching of the speckle size to the fiber spacing is applied. Thus the number of independent signals is decreased further. The impact of each of these contributors will be investigated in the future.

Figure 8. Camera based relative velocity uncertainty due to speckle with and without coherent fiber bundle scattered light detection. The result is as a function of the number of fiber cores (camera pixels). For a single photo detector with only one pixel, i.e. a single fiber core (green circle), the relative velocity uncertainty is maximal and amounts to 4×10^{-3} .

5. CONCLUSIONS AND OUTLOOK

A dual camera based speckle separation method is presented for the speckle noise reduction of Doppler frequency based velocity and distance sensors. Experiments are performed for validating the proposed dual camera based approach. By evaluating the Doppler frequency of each speckle separately, the velocity uncertainty decreases with the square root of independent speckles. Thus, a reduction by a factor of 40 for the velocity uncertainty is achieved in comparison to a photo detector based signal detection. Similarly, a reduction for the distance uncertainty by a factor of 3 is achieved. Furthermore, employing cameras allows for an in-situ calibration of the fringe distance. Thus, an absolute shape uncertainties of below 100 nm can be achieved for an in-situ shape measurement, for instance in turning lathes. In comparison, CMMs allow 3-D shape uncertainties of around 1 μm

and do not support an in-situ measurement. A coherent fiber bundle has been employed for signal transmission to demonstrate the capability of realizing a robust, all passive sensor head. As an outlook, the second coherent fiber bundle will be used for dual fiber bundle based signal transmission. The possibility to employ single mode fiber bundles and matching the core number to the speckle number will be investigated. To demonstrate shape measurements, a high speed camera with a speed of 1 MHz will be employed to sample the signal images. Based on a tactile internet, the sensor can be used for monitoring the cutting process by remote control. As a broad prospect, the camera based speckle separation method also can be applied in other optical sensors that are limited by the speckle effect and do not use matrix cameras yet, such as triangulation sensors or interferometers.

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