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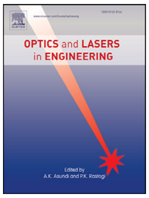

Miniaturized interferometric 3-D shape sensor using coherent fiber bundles

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ABSTRACT

Mach-Zehnder interferometer based sensors for simultaneous distance and velocity measurement allow for absolute 3-D shape measurements of rotating workpieces for instance in cutting lathes. The achievable shape uncertainty is limited to around one micron due to the speckle effect and temperature drifts, however. In this paper, a laser Doppler distance sensor with phase evaluation (P-LDD sensor) with a camera based scattered light detection is investigated. A novel speckle separation technique and in-situ fringe distance calibration method are realized to reduce the measurement uncertainty. A coherent fiber bundle is employed to forward the scattered light towards the camera. This enables a compact and passive sensor head with keyhole access. Compared with a photo detector based sensor, the camera based setup 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.

1. Introduction

Absolute shape measurements of rotating workpieces are important for process monitoring and process control for instance at metal cutting 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. This also makes the measurement process susceptible to mounting tolerances. 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.

With the advantages of non-contact and fast measurements, optical measurement techniques [2–9] 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 workpiece is missing.

One approach to measure the mean diameter of the workpiece is to measure the tangential velocity of the surface during rotation with a known frequency, additionally. Thus, a simultaneous measurement of position and tangential velocity at the same position enables absolute shape measurements. While lubricants and coolants might prohibit the application of optical sensors during the cutting process, due to light distortion, the approach allows for in-situ shape measurements directly after cutting or even in-process measurements for dry machining. Furthermore, the simultaneous velocity and distance measurement enables other applications at rotating machinery such as tip clearance and tip vibration measurements in turbo machinery, deformation measurements of high speed rotors [10] or spindle vibration measurements.

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 with key-hole access [11]. The measurement principle is based on the evaluation of the Doppler frequencies of the scattered light signals and thereby on speckles [12]. 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 of only one pixel [13]. This results in an increased surface velocity uncertainty and distance uncertainty, and therefore in an increased uncertainty of the measured shape. Furthermore, temperature drifts result to a systematic uncertainty of the interference fringe distance, which increases the shape uncertainty further [14].

The aim of this article is to introduce a sensor to be employed in rotating machines for example for the in-situ, absolute 3-D shape measurement of rotating workpieces in cutting lathes. A setup with a camera based scattered light detection is proposed to evaluate the speckles individually and to achieve an in-situ fringe distance calibration, thereby

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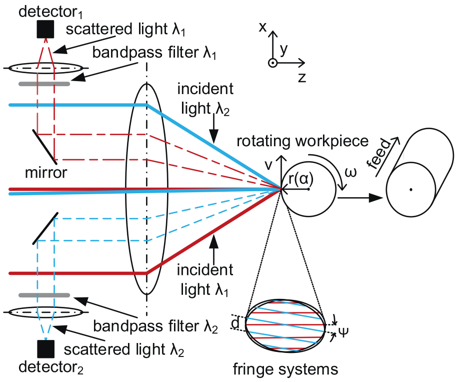

Fig. 1. Principle of P-LDD sensor: superposition of two interference fringe systems with constant and equal fringe spacing d, which are tilted towards each other by an angle ψ. The scattered light from each fringe system is detected with a photo detector.

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 cameras. The measurement principle of the P-LDD sensor and the measurement uncertainty budget are described in Section 2. Since the speckle and fringe distance related measurement uncertainties are dominant, the camera based methods and the respective image processing for the reduction of these measurement uncertainties are proposed in Section 3. Finally, the coherent fiber bundle based scattered light signal transmission is presented in Section 4.

2. Principle and setup

As shown in Fig. 1, the P-LDD sensor is based on a laser surface velocimeter using interference fringe patterns [15,16].

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}. Determining the fringe distance d by a calibration and measuring the Doppler frequency with the Fast Fourier Transform (FFT), the particle velocity v perpendicular to the fringe system can be calculated by

$$v = f_{\mathrm{D}} \cdot d. \tag{1}$$

In order to measure the axial distance z simultaneously, two mutually tilted interference fringe systems with equal fringe distances and the tilting angle ψ are superposed by wavelength multiplexing. This leads to a position dependent lateral offset between both fringe systems. Thus, z is calculated with the measured phase difference φ between both light signals by

$$z = \varphi \cdot s^{-1}, \tag{2}$$

where the s is the slope of the calibration function $\varphi(z)$. By evaluating the surface distance and the surface velocity of a rotating workpiece, the absolute shape $r(\alpha)$ can finally be evaluated by [11]

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

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. 1. The dominant contributors to the shape uncertainty σ_r and their resulting shape uncertainties have been derived experimentally and are listed in Table 1. Note that, the contributors can be distinguished between uncertainties resulting from the sensor and uncertainties resulting from the machine, namely the spindle rotation speed and spindle vibrations. The spindle rotation speed can be measured precisely with angular encoders or by speckle correlation with the P-LDD sensor. It has a negligible influence towards the total shape uncertainty. Spindle vibration superposes the position signal and potentially increases the uncertainty of the angle dependent radius deviation. Its impact strongly depends on its amplitude and spectral properties and can be decreased by averaging, filtering or multi-step separation techniques [17]. In this paper we concentrate on reducing the uncertainties resulting from the sensor system.

In order to analyze the measurement uncertainty, the scattered light signals are modeled. The detected signal of a single particle that crosses the measurement volume perpendicular to the interference fringes can be described by a sinusoidal modulation:

$$b(t) = Ae^{-\frac{2f_{\mathrm{D}}^2 \cdot (t/f_{\mathrm{s}} - t_{\mathrm{a}})^2}{t_{\mathrm{w}}^2}} \cos\left(2\pi f_{\mathrm{D}} \cdot (t/f_{\mathrm{s}} - t_{\mathrm{a}})\right), \quad t = 1, 2, \ldots, N, \tag{4}$$

with the Doppler frequency f_{D} and a gaussian envelope with the amplitude A. Whereas f_{s} is the sampling frequency, t_{a} describes the arrival time of the particle and t_{w} the temporal $1/\mathrm{e}^2$ width of the envelope which results from the geometrical width of the measurement volume and the particle velocity. For scattered light signals from rough surfaces the speckle effect has to be considered. Former investigations showed, that each speckle exhibits the same Doppler frequency f_{D} but random amplitudes A_k and arrival times t_{a_k}. Thus, the detector signal from K speckles reads [18]

$$s(t) = \sum_{k=1}^{K} b_k(t), \quad t = 1, 2, \ldots, N, \tag{5}$$

which results in a distortion in the scattered light signal. The distortion depends on the speckle effect and therefore on the surface micro geometry. Thus, the measurement uncertainties caused by the speckle effect cannot be reduced by repetitive measurements of the same surface.

In order to reduce the measurement uncertainty, the speckle signals should be processed and evaluated separately. In fluid measurements a temporal separation based on Hilbert transform [19], Empirical Mode Decomposition [20], or Wavelet transform [21] can be applied to separate consecutive burst signals. These approaches are not feasible for surface measurements, because several speckles occur simultaneously.

Meanwhile, the total measurement uncertainty is also limited by the relative fringe distance uncertainty which is influenced by thermal effects [22]. The uncertainty of the fringe distance due to thermal effect should be eliminated by an in-situ fringe distance calibration method which enables the calibration at any moment when the temperature changes.

For separating the individual speckle as well as to measure the fringe distance, we propose a matrix camera based approach, cf. Fig. 2. We employ one camera (Basler piA640-210gm, maximum frame rate of 210 Hz, resolution of 648 px × 488 px, and a photoelement size of 7.4 µm × 7.4 µm) for each fringe system. Two interference fringe systems are generated by two pairs of laser beams with wavelengths 656 nm and 686 nm, respectively. The light of the fringe systems is scattered at a metallic specimen with a plane, rough surface, which is mounted on a moving stage. The stage is moved laterally in steps of 1 µm. Both cameras are synchronized by a function generator.

In the experiments of this paper, the velocity of the moving stage, the sampling frame rates of the cameras and the used areas of the CCDs amount to 200 µm/s, 200 Hz, and 200 px × 200 px, respectively. The measurement uncertainties result from 10 random segments on the specimen surface. Please note that the applied velocity is several magnitudes lower than the common surface velocity inside of cutting lathes and limited due to the framerate of the CCDs. However, camera speeds will further increase in the coming years and can already be increased by reducing the pixel number. In our experiments, a high camera resolution is employed to investigate the feasibility of the approach. A second prob-

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