Laser-Doppler-Distance-Sensor using phase evaluation for position, shape and vibration measurements

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Abstract

In this article we present a novel optical sensor allowing simultaneous measurements of axial position and tangential velocity of moving solid state objects. An extended laser Doppler velocimeter setup is used where two interference fringe systems are superposed slightly tilted. The axial position of moving solid state surfaces is determined via a phase evaluation. The phase laser Doppler distance sensor offers a position resolution up to 150 nm. In contrast to conventional measurement techniques, such as triangulation, the position uncertainty is independent of the lateral surface velocity. This feature enables precise distance and shape measurements of fast rotating solid state surfaces.

1. Introduction

Distance, shape and vibration measurements of rotating objects, e.g. to analyze dynamic rotation processes, are an important task in the field of process control and production measurement. While monitoring the production process, zero-error production becomes possible, which will increase the production efficiency. Additionally, a higher durability and reliability of the technical equipment can be achieved. Hence, optical measurement techniques became more and more important in production metrology. Compared to tactile measurement techniques, which are commonly used up to now, optical measurement techniques are fast and contactless, which is important for sensitive and fast moving surfaces. Due to these advantages, a lot of optical sensors are applied depending on the measurement problem, e.g. triangulation [1], low coherence interferometry [2], absolute distance interferometry [3], time-of-flight or laser Doppler techniques [4, 5].

Triangulation, a widely used technique for distance measurement and low coherence interferometry offer low measurement uncertainties down to the sub-micrometer range. Nevertheless, due to necessary scanning processes or because of using a position sensitive detector, the measurement rate is restricted to some kHz. Additionally, the measurement uncertainty increases with increasing object velocity due to decreasing averaging time.

Laser Doppler vibrometers offer a resolution of some nanometers and a high measurement rate in the MHz range. However, they are restricted by their incremental measurement method, which can cause errors at rough surfaces if phase jumps higher than half the wavelength occur. In this case, the displacement can not be determined unambiguously.

Additionally, the majority of optical measurement methods determine only one measurand, e. g. distance or velocity, which is not enough to determine the absolute shape of a rotating object. The laser Doppler distance sensor overcomes this drawback by measuring the position and velocity of a moving object simultaneously.

2. Sensor Principle

Laser Doppler velocimeters (LDV) are based on the evaluation of scattered light signals which are generated from measurement objects passing the interference fringe system in the intersection volume of two coherent laser beams. These scattered light signals exhibit an amplitude modulation with the Doppler frequency f. Thus, the measurement object velocity v can be calculated by [6]:

$$v = f \cdot d \, , \tag{1}$$

where d is the mean fringe spacing due to the sensor setup. Conventionally, an average of the velocity over the measurement volume is obtained and the position resolution is as large as the length of the measurement volume along the optical axis.

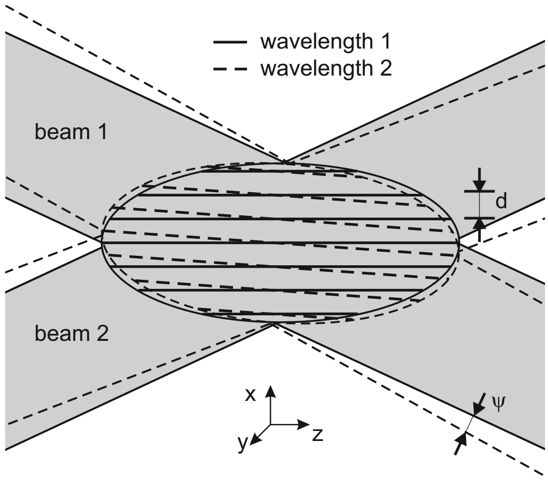

Figure 1: Principle of the phase laser Doppler distance sensor. Superposition of interference fringe systems with approximately constant and equal fringe spacing d, which are tilted towards each other by an angle ψ [7].

For simultaneous measurements of position and velocity af a moving solid state surface an extended LDV setup with phase evaluation is used. Its measurement volume is formed by two interference fringe systems of different laser wavelengths. These interference fringe systems with approximately equal fringe spacing are superposed slightly tilted towards each other, see Fig. 1.

When a scattering object crosses this measurement volume, two distinguishable scattered light signals result. These two signals exhibit a phase difference φ depending on the axial position z of the scattering object. Assuming plane wavefronts, this phase difference can be described as:

$$\varphi = s \cdot z + \varphi_0 \,, \tag{2}$$

where s is the slope of the phase difference function $\varphi(z)$ and φ_0 the phase offset in the center of the measurement volume (z = 0). By evaluating the phase difference, the position z inside the measurement volume can be determined using the inverse function of Eq. (2). With the known working distance D_0 between sensor front face and the center of the measurement volume, also the distance $D = D_0 + z$ of the measurement object with respect to the sensor can be determined. So, only the position z is considered in the following.

With the known axial position z, the local fringe spacing can be taken into account allowing a more precise velocity determination compared to a conventional LDV. Thus, Eq. (1) can be transformed to:

$$v = f_1(v,z) \cdot d_1(z) = f_2(v,z) \cdot d_2(z). \tag{3}$$

To achieve a low measurement uncertainty, the slope s of the calibration curve φ should be as high as possible (see section 4). However, for an unambiguous determination of the position, the calibration curve has to be bijective. Therefore, the range of the phase difference inside the measurement volume has to be restricted to 2π. Therefore, an optimum slope s_{opt} exists, which is given in [7, 8]:

$$s_{opt} = \frac{2\pi}{l_z}, \tag{4}$$

where l_z is the length of the measurement volume in z-direction, see Fig. 1.

For a lower measurement uncertainty, the slope of the calibration function $\varphi(z)$ can be inceased easily by increasing the tilting angle ψ between the two interference fringe systems. However, when using a higher slope than s_{opt}, the determination of the position is no longer unambiguous within the whole measurement volume. Hence, one additional information is needed, which can be obtained by a further interference fringe system. The third interference fringe systems has to be adjusted in such a way, that in addition to the steep phase function $\varphi_1(z)$ one bijective phase function $\varphi_2(z)$ is obtained, see Fig. 2. Thus, it is possible to determine the object position first roughly via the calibration function $\varphi_2(z)$ and secondly very accurate via the steeper calibration function $\varphi_1(z)$. Consequently, a more precise position measurement is possible. Nevertheless, the requirement of a third laser wavelength demands a higher technical effort in practice.

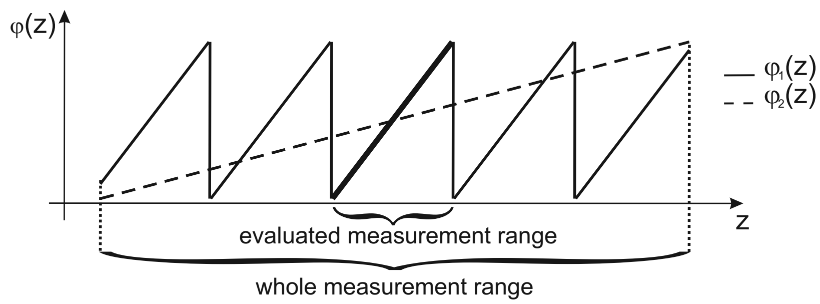

Figure 2: Sensor setup with two calibration functions, one ambiguous and one unambiguous phase function, to achieve a lower measurement uncertainty.

3. Sensor setup

The experimental setup was arranged with an optical bench, see Fig. 3. Two laser diodes, a red one (660 nm) and an infrared one (785 nm), were used as light sources. The two laser beams were combined via a dichroic mirror and focused onto a transmission phase grating, which acts as beam splitter. The first positive and negative diffraction orders were used as partial beams, all other orders were blocked by beam stops. A Keplerian telescope behind the grating, consisting of two achromatic lenses, focused the partial beams into the measurement volume, see Fig. 3. Since lenses with low chromatic aberration for the red and near-infrared wavelength were employed, a good overlap of the two interference fringe systems was achieved. The length of the measurement volume in z-direction, i.e. the position measurement range, was about 800 µm. The lateral diameter of the measurement volume is equal to the spot size at technical surfaces and was 60 µm with this setup.

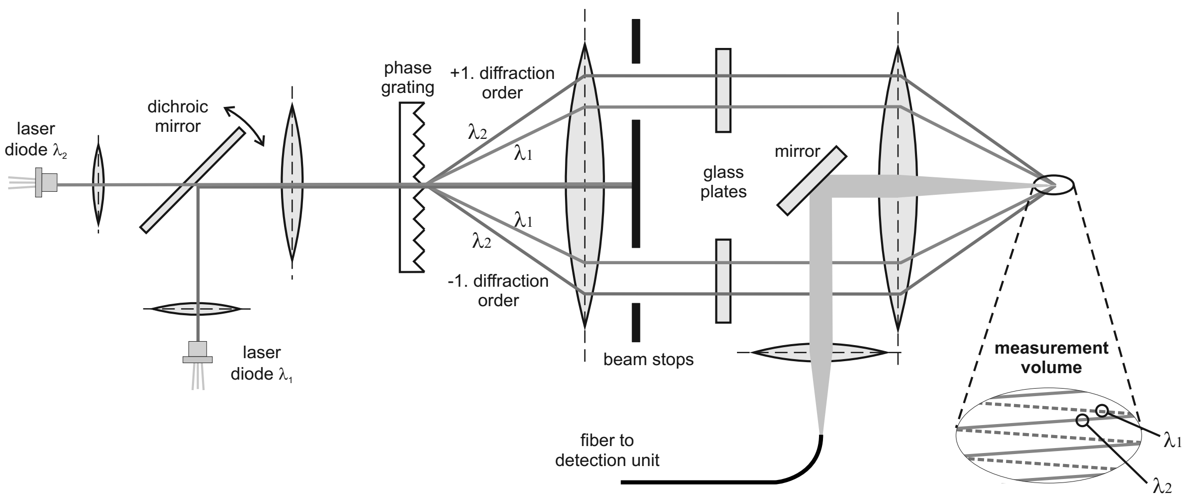

Figure 3: Experimental setup of the phase laser Doppler distance sensor [7].

There are two possibilities of adjusting the relation between the phase difference φ of the two scattered light signals and the position *z* inside the measurement volume. Tilting the dichroic mirror results in a change of the angle between both interference fringe systems. Consequently, the slope *s* of the calibration function φ can be tuned appropriately. The phase difference offset φ_0 can be changed by tilting the glass plates inside the Keplerian telescope [8, 9].

The bi-chromatic scattered light from the measurement object was detected in backward direction. Collimated by the front lens, the scattered light was coupled out by a small mirror between the partial beams inside the Keplerian telescope. With a subsequent lens the light was coupled into a multimode fiber patch cable and guided to the detection unit. At this point, the bi-chromatic light was split into the two different wavelengths by a second dichroic mirror and focused onto two photo detectors. The electrical photo detector signals were sampled simultaneously by an A/D converter card installed in a standard PC. Further signal processing and evaluation was done by a MATLAB program. Thereby, the Doppler frequencies $f_{1,2}$ where calculated with a least square fit of the fast Fourier transformed photo detector signals. For phase estimation, the cross-correlation function of the two photo detector signals was calculated. Via a cosine least square fit, the time shift of the maximum of the cross-correlation function was determined, which is proportional to the phase difference φ.

4. Theoretical measurement uncertainty

The statistical position uncertainty which is defined as the standard deviation σ_z of repeated measurements at a fixed axial position of the measurement object can be described using Eq. (2) by:

$$\sigma_z = s^{-1} \cdot \sigma_\varphi . \tag{5}$$

Assuming that the two scattered light signals have equal Doppler frequencies, the minimum standard deviation of the phase difference estimation is given by the Cramer-Rao Lower Bound (CRLB) [6]. With Eq. (5) the minimum position uncertainty for the sensor assuming noisy single-tone signals with constant amplitude can be written as:

$$\sigma_z > s^{-1} \cdot \frac{\sqrt{2}}{\sqrt{SNR} \cdot \sqrt{N}} , \tag{6}$$

where SNR is the signal-to-noise ratio and N the number of statistically independent sampling points. Hence, the position uncertainty depends not directly on the object velocity, which is an important advantage of the laser Doppler distance sensor compared to other distance sensors.

In order to estimate the phase difference φ, the two Doppler frequencies $f_{1,2}$ have to be equal. Therefore, both interference fringe spacing functions $d_{1,2}$ have to be identical ($d_1(z) \equiv d_2(z)$). Since a diffraction grating is used for beam splitting with sin $(\alpha_1)/\lambda_1$ = sin $(\alpha_2)/\lambda_2$, the minimum fringe spacings at the center of the measurement volume, i.e. z = 0, are equal [9]. However, due to the different wavelengths, the fringe spacing curves differ outside the center of measurement range resulting in a phase drift $\Delta\varphi$ during the measurement time. If the beam waists $w_{01,2}$ of the two laser wavelength $\lambda_{1,2}$ match with [8]:

$$w_{02} \approx \sqrt{\frac{\lambda_1}{\lambda_2}} \cdot w_{01} \tag{7}$$

the systematic deviation due to the phase drift $\Delta\varphi$ can be neglected in practice [7].

In addition to the position z, also the velocity of an object can be determined. Based on Eq. (3) the relative measurement uncertainty for the velocity σ_v/v can be calculated using the Gaussian uncertainty propagation and assuming the statistical independence of fringe spacing d and Doppler frequency f. The minimum measurement uncertainty can be achieved in the center of the measurement volume and is [7]:

$$\frac{\sigma_v}{v} \approx \frac{\sigma_f}{f} . \tag{8}$$

Hence, the minimum relative velocity uncertainty is approximatelly equal to the relative Doppler frequency uncertainty. Due to the independence on the fringe spacing deviation, this sensor allows more precise velocity measurements than conventional LDVs.

5. Experimental results

Experiments were carried out with test objects of steel and aluminum exhibiting different but defined roughnesses with R_a-values (arithmetical mean deviation of the roughness profile) between of 0.1 µm and 3.6 µm. These objects were moved trough the measurement volume with a defined velocity and at defined axial positions by a motor with a stabilized rotation frequency and a motorized translation stage. So, measurements at defined axial positions and with well known object velocities can be accomplished. At each position 25 individual measurements were carried out to obtain the statistical uncertainties. Thereby, the Doppler frequencies $f_{1,2}$ and the phase difference φ were calculated from the whole time domain signals corresponding to an averaging over the 12 mm broad tip of the metal objects.

At first, a sensor setup with a bijective phase function within the whole measurement range was applied showing that it is in principle possible to determine the position of rough solid surfaces via phase evaluation. Subsequently, a sensor setup with a slope of s = 5.5 °/µm was arranged corresponding to a bijective range of 65 µm to achieve a higher position resolution. The first measurements with this second setup were carried out only for the bijective range around z = 0 to limit the technical effort, see Fig. 2.

As an example, the measurement results for one test object with R_a = 0.2 µm measured with the second setup are presented in Fig. 4. A minimum statistical position uncertainty σ_z = 140 nm was achieved within the measurement range of 65 µm. Due to the speckle effect at random surface structures the maximum systematic position deviation Δz_{max} = 1.5 µm is significantly higher than the statistical uncertainties.

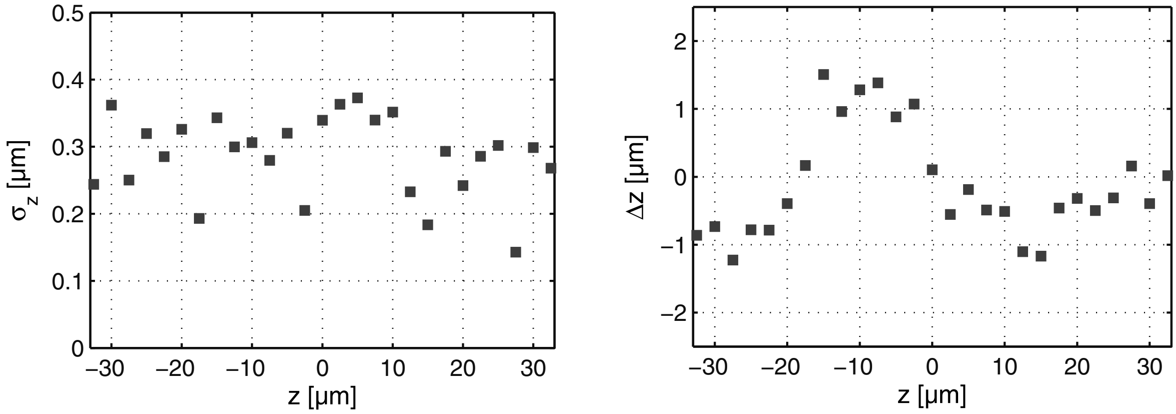

Figure 4: Measurement results of the position evaluation: statistical uncertainties (left) and systematic deviations (right) of the sensor setup with s = 5.5 °/µm [7].

In order to analyze the dependence of the position uncertainty on the velocity, measurements on a rotating brass wheel with one tooth of 2 mm width and a radius of 40 mm were accomplished. At varying circumferential speed *v*, the tooth tip position was measured simultaneously by the phase laser Doppler distance sensor with *s* = 5.5 °/µm and two commercial triangulation sensors manufactured by *Micro-Epsilon*, with measurement rates of 2.5 kHz (TS_1) and 20 kHz (TS_2). The latter one exhibit an elliptical laser spot to reduce the influence of the speckle effect on the measurement result. Both triangulation sensors have a measurement range of 2 mm. Referring Fig. 5, the position uncertainty of both triangulation sensors worsens with increasing velocity *v* of the brass tooth, which is due to the decreasing averaging time. Due to the higher measurement rate and the special shape of the laser spot, the measurement uncertainty and the dependence on the object velocity of the triangulation sensor TS_2 is significantly lower. In contrast to the triangulation sensors, the position uncertainty σ_z of the phase laser Doppler sensor remains nearly constant at σ_z = 500 nm over the whole velocity range proving that its position uncertainty is indeed independent of the object velocity, see Fig. 5.

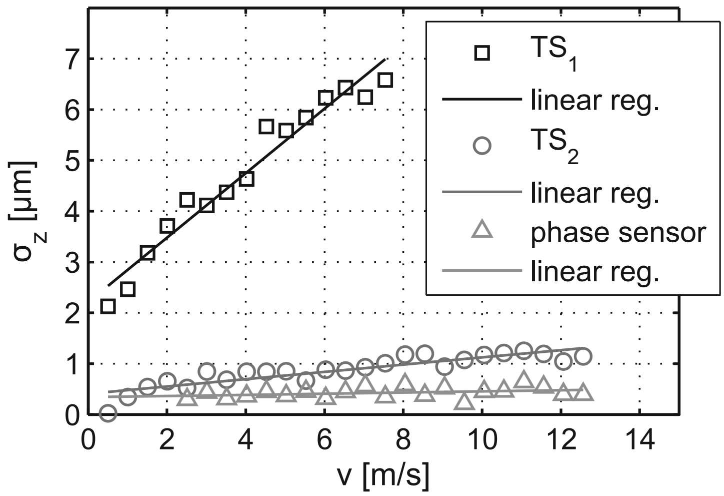

Figure 5: Measured statistical position uncertainties σ_z in dependence on the object velocity v for the phase laser Doppler distance sensor and the two triangulation sensors (TS) [7].

Due to the simultaneous measurement of axial position and tangential velocity, the diameter and thus the two-dimensional shape of rotating solid state objects can be calculated by a time-resolved analysis of the scattering light signals as described in [10]. By generating these two-dimensional shapes at several positions along the rotation axis of the measurement object its three-dimensional shape can be calculated, see Fig. 6.

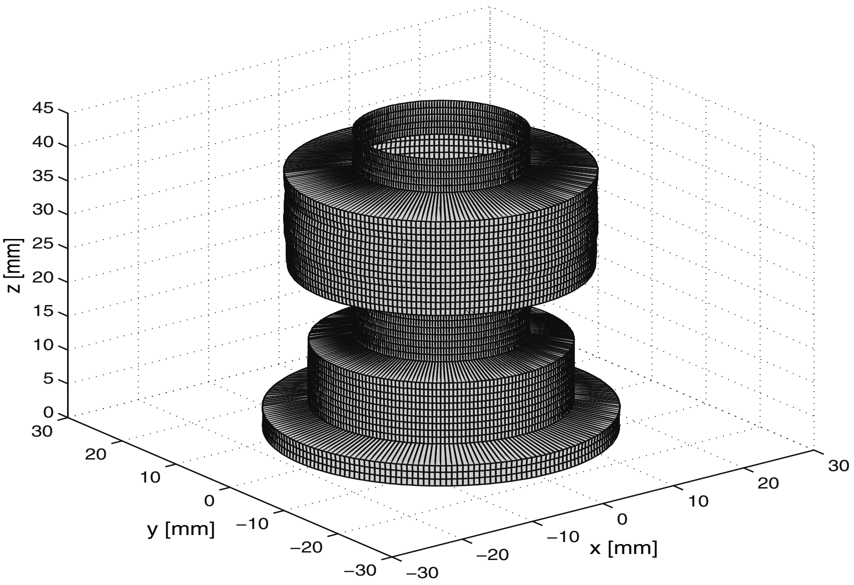

Figure 6: three-dimensional shape of a rotationally symmetric solid state object.

6. Conclusions

This article presents a novel laser Doppler distance sensor using two tilted fringe systems and phase evaluation which allows simultaneous measurement of position and velocity of moving solid state objects. While using a high slope of the phase difference function, a minimum position resolution of σ_z = 140 nm within a measurement range of 65 µm was achieved. In the future, this measurement range can be extended without increasing the measurement uncertainty significantly by using a third interference fringe system. It was shown that the absolute radius and thus the two-dimensional shape of rotating objects can be calculated due to the simultaneous measurement of position and surface velocity. Furthermore, it was demonstrated that the position uncertainty is independent of the object velocity, which is an important advantage compared to many other optical sensors, such as triangulation.

Acknowledgments

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