

Robust and Miniaturized Interferometric Distance Sensor for In-Situ Turning Process Monitoring

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Abstract:

For in-process shape monitoring of rotating objects such as workpieces in a turning machine, contactless and compact sensors with high temporal resolution as well as high precision are necessary. For this purpose, we developed a miniaturized and robust non-incremental fiber-optic distance sensor with dimensions of only 30x40x90 mm³, which can be attached to the mount of a turning tool and therefore allows precise in-process 3D shape measurements of turning parts.

In this contribution we present the design of the miniaturized sensor supported by optical simulations as well as in-process shape measurements in a turning machine. To proof the accuracy of the measurement results, comparative measurements with tactile sensors were performed.

Introduction

In-process measurement of the diameter and the 3D-shape of fast rotating objects is an important task in production engineering, e.g. for monitoring and controlling turning or grinding processes, respectively. However, this is very challenging for metrology, since compact and robust sensors with concurrently micron precision and high measuring rate (> 10 kHz) are required.

Up to the present, tactile measurement methods are used for spot test, but they fail for in-process inspection. Optical sensors operate contactless and offer high accuracy inherent to the small laser wavelength. However, incremental sensors such as Michelson interferometers cannot measure absolute distance values, causing ambiguous measurement results if distance jumps of more than half the laser wavelength occur. Furthermore, the measuring rate of most optical techniques is fundamentally limited either by the speed of mechanical scanning (time domain OCT, focus sensing) or by the detector frame rate and minimum exposure time required (triangulation, chromatic confocal techniques, frequency domain OCT) [1, 2]. Therefore, precise and highly dynamic measurements are not possible with these sensors. Additionally, all these techniques measure only one measurand which is

not sufficient to determine the absolute shape of a rotating object without further information [3].

To solve this problem, the laser Doppler distance sensor (LDD sensor) was developed, which is able to measure concurrently the tangential velocity and the radial position of rotating objects non-incrementally [3, 4]. Thus, the diameter and the 3D-shape of rotating solid state objects can be determined with a single sensor and with micron precision [3]. In addition, a high temporal resolution can be achieved since the measurement uncertainty of this sensor is generally independent of the object speed [5]. One area of application of this new sensor is the in-situ shape measurement at metal working lathes e.g. to monitor the turning process for zero-error production. In order to integrate the sensor into the lathe, a small-sized and robust sensor head was developed which enables in-process measurements directly adjacent to the turning tool bit of the metal working lathe.

We present the results of in-process shape measurements during the turning process at a metal working lathe. Influences of present vibrations and turning swarfs flying around are discussed. Due to the feed rate during the turning process, the measuring points follow a helix along the circumference of the workpiece. Via a specific evaluation algorithm, the 3D shape of the workpiece could be determined.

Working principle of the laser Doppler distance sensor

The laser Doppler distance sensor (LDD sensor) based on laser Doppler velocimetry (LDV), where an interference fringe system with approximately parallel fringes with spacing d is generated by the intersection of two coherent laser beams. An object passing this intersection volume scatters light which is amplitude modulated with the Doppler frequency f . Thus, the transverse velocity component of the object can be calculated by $v = f d$. To obtain the axial position z of the measurement object additionally, the LDD sensor was invented [3, 5]. Two distinguishable fan-shaped interference fringe systems with contrary fringe spacing gradients were superposed to achieve an unambiguous calibration function $z(q)$, which is the inverse function of $q(z) = d_1(z)/d_2(z)$, see Fig. 1. If an object passes the measurement volume formed by the two interference fringe systems, two Doppler frequencies $f_{1,2}$ can be measured. With the quotient q of these two Doppler frequencies

$$q(z) = \frac{f_2(v, z)}{f_1(v, z)} = \frac{v(z)/d_2(z)}{v(z)/d_1(z)} = \frac{d_1(z)}{d_2(z)} \quad (1)$$

and the calibration function $z(q)$, the distance z can be calculated. Additionally, the velocity v can be calculated using the local fringe spacings $d_{1,2}(z)$. Thus, the distance z and the

transverse velocity v of scattering objects can be determined independently and simultaneously, see Fig. 1.

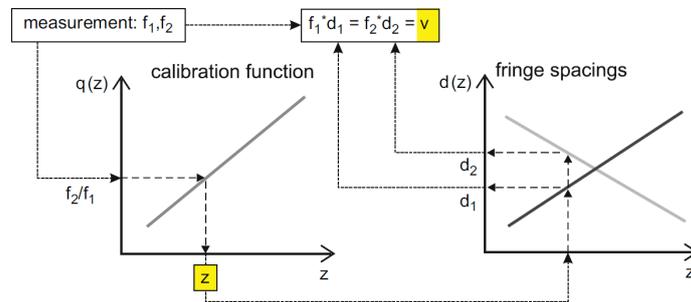


Fig. 1: Principle functionality of the laser Doppler distance sensor [6].

Miniaturization

In order to integrate the sensor into a metal working lathe, a modular sensor setup consisting of a light sending unit, an all-passive sensor head and a detection unit was chosen, see Fig. 2. The three units are connected to each other via optical fibers. This modular setup allows that all active components are spatially separated from the lathe. Consequently, only the sensor head has to be small-sized and robust.

To integrate the sensor head into the lathe, a miniaturized fiber-optic sensor head was necessary. Performing optical simulations using the optical system design software *ZEMAX* a minimal sized optical setup was found which did not affect the sensor performance. Additionally, the simulation results are used for the mechanical design. Finally, a sensor head with an overall size of only 30x40x90 mm³ was developed, which is about 10 times smaller than previous sensor setups, see Fig. 2 [5]. Hence, in-process measurements at the turning machine with the miniaturized LDD sensor are possible.

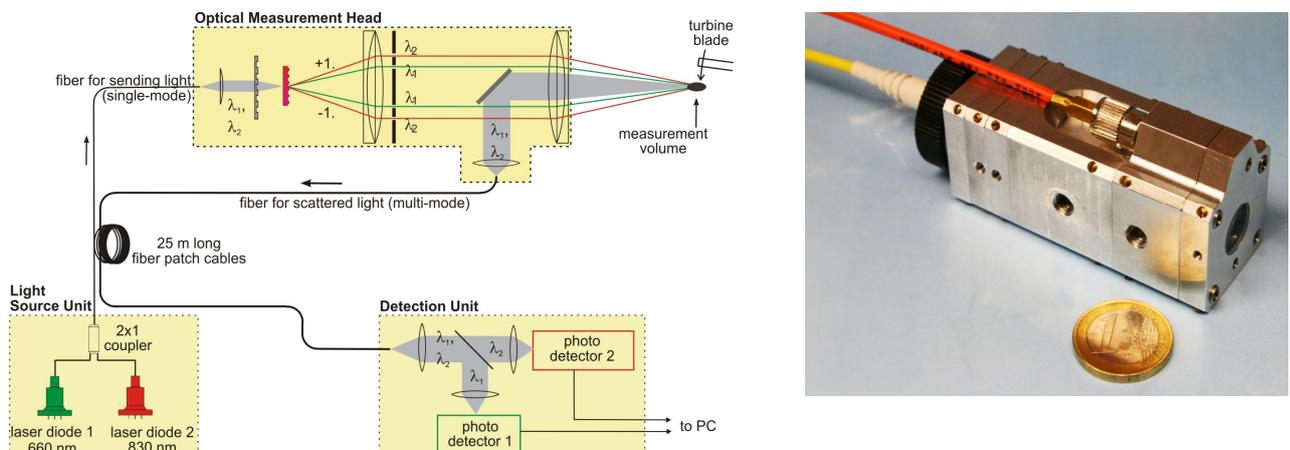


Fig. 2: Modular setup of the laser Doppler distance sensor (left) [5] and miniaturized all-passive sensor head (right).

Experimental setup and signal processing

All measurements were carried out with nearly the same processing parameters. Approximately 100 measuring points per revolution and a rotation frequency of about 1200 rpm of the workpiece result in a measuring rate of about 2 kHz. The feed rate has been adjusted to be about 0.060 mm/revolution. Cylindrical aluminium objects have been mounted to the turning machine for in-process measurement of the 3D-shape and the absolute diameter. The miniaturized sensor head was attached directly to the turning tool mount and aligned perpendicular to the surface of the test object, as illustrated in Fig. 3. Thus, in-process measurements of the shape of the workpieces could be achieved.

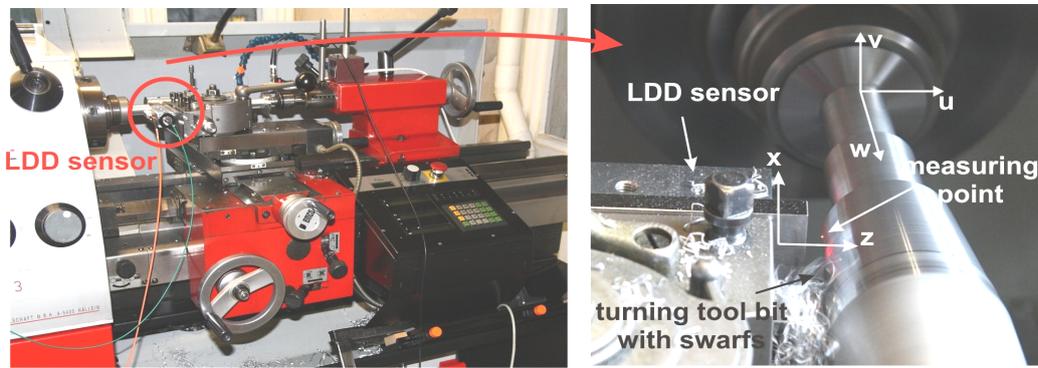


Fig. 3: Experimental setup at the metal working lathe.

As described before, the LDD sensor is able to measure the transverse velocity as well as the axial distance. Thus, the tangential velocity v and the radial change ΔR of rotating objects can be measured simultaneously [3]. Furthermore, if the rotation frequency f_{rot} and the feed rate v_w are known, the absolute 3D shape can be determined by the following procedure.

With the measured mean tangential velocity $\langle v_x \rangle$ and the mean rotational frequency $\langle f_{rot} \rangle$ the mean radius $\langle R \rangle$ can be determined by [3]:

$$\langle R \rangle = \frac{\langle v_x \rangle}{2\pi \langle f_{rot} \rangle} \quad (2)$$

Taking into account the additionally measured radius deviation $\Delta R(t)$, the time resolved radius can be determined by means of $R(t) = \langle R \rangle + \Delta R(t)$. The integration of the angular velocity $\omega(t)$ results in the actual rotation angle $\varphi(t)$ of the measurement object [3]:

$$\varphi(t) = \int_0^t \omega(\tau) d\tau = \int_0^t \frac{v_x(\tau)}{R(\tau)} d\tau \quad (3)$$

Hence, the 3D shape of the rotating object can be calculated taking into account the feed rate v_w by:

$$\begin{pmatrix} u(t) \\ v(t) \\ w(t) \end{pmatrix} = \begin{pmatrix} R(t) \cdot \cos(\varphi(t)) \\ R(t) \cdot \sin(\varphi(t)) \\ t \cdot v_w(t) \cdot f_{rot}(t) \end{pmatrix} \quad (4)$$

Results

The first measuring object was a rotational symmetric aluminium workpiece which has been manufactured in advance with a defined radial step of 250 μm . In this case, the measurement has been performed directly at the running turning machine but lathing has been avoided. This has been realized by a slightly displaced working tool mount in radial direction (in-situ measurement). Hence, possible effects to the measurement results induced by the turning tool can be neglected. Fig. 4 shows the 3D-shape of the above described object whereas the absolute radius is color-coded.

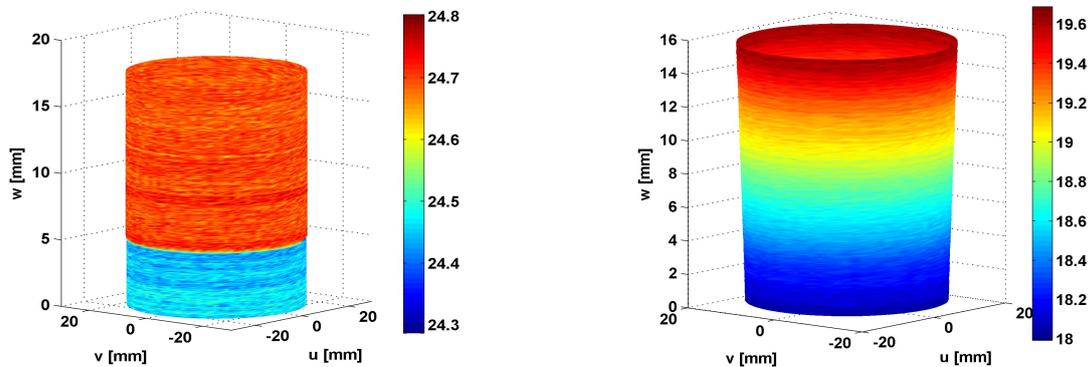


Fig. 4: 3D-shape of the cylinder with a radial step of a 250 μm step (left) and the in-process measurement of the cone (right); both measured with the miniaturized LDD sensor.

For the next measurement a cone was fabricated in the metal working lathe with an angle of about 6°. This time, the LDD sensor measured the 3D-shape of the workpiece in-process (see Fig. 4). Thus, all possible effects which can occur at the turning process are considered in this measurement.

Table 1: Comparison of the results measured with the miniaturized LDD sensor and the results of the tactile reference.

step height [μm]	LDD sensor	tactile methods
mean value	250.8	251.6
standard deviation	3.1	1.8
measurement condition	in-situ	static
cone angle [$^{\circ}$]	LDD sensor	tactile methods
mean value	5.897	5.909
standard deviation	0.015	0.018
measurement condition	in-process	static

Conclusions

In this contribution we present the results of in-process shape measurements during the turning process at a metal working lathe using a miniaturized LDD sensor. Due to the rotation and the feed rate at the turning process, the measuring points follow a helix along the circumference of the workpiece allowing the determination of the absolute 3D-shape of the turning workpiece by a specific evaluation algorithm.

The measured results are in good agreement with the comparative measurements. Specific details to the measurement uncertainty will be given in the talk. Consequently, the miniaturized LDD sensor opens up new perspectives for in-process monitoring of turning or grinding processes. This is essential for zero-error production which increases the production efficiency.

Acknowledgement

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