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From the Doppler Effect to Ultrafast Distance Metrology

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Abstract:
The fast inspection of technical processes gains increasing importance. Time resolved distance and shape measurements of the dynamic deformation of high speed rotating objects are challenging. The measurement rate of conventional distance sensors is limited, since their uncertainty strongly increases with the surface velocity of the inspected object. In contrast, the recently developed laser Doppler distance sensor exhibits a distance measurement uncertainty which is independent of the lateral surface velocity. This unique measurement feature allows ultrafast inspection of high-speed objects such as rotors of turbo machines.

1. Introduction

The Doppler effect is often involved in laser metrology. Measuring the Doppler frequency allows to determine the velocity of objects. This well known principle is employed at established interferometric instruments for velocity measurements such as laser Doppler velocimeters and laser Doppler vibrometers. They offer contactless velocity measurements with high temporal and spatial resolution.

In contrast, the Doppler effect has not been used to measure the distance of objects so far. If we consider a Mach-Zehnder interferometer, the diffraction of the laser waves results in a complementary relation of the measurement uncertainties between the velocity and the distance. For precise velocity measurements, preferably, planar optical wavefronts and small diffraction divergence are required, but then no distance information is gained. On the other hand, the Doppler technique is very interesting for high-speed distance measurements due to its inherently high temporal resolution. The question is how this potential advantage can be transferred to distance metrology.

The idea sounds unconventional: Optical diffraction effects have to be enhanced. Instead of employing collimated beams with almost planar wavefronts, strongly focused beams with great curvature of the wavefronts are used. Concave and convex wavefronts generate converging and diverging fringe systems, respectively, see Fig. 1. These distorted fringe systems result in Doppler frequencies, which depend on both velocity v_x and distance z. The individual evaluation of one Doppler frequency does not allow precise determination of these measurands. But the measurement of two Doppler frequencies at the same time and space changes the situation dramatically. By these coincident Doppler frequency measurements, both measurands, i.e. velocity v_x and distance z, can be determined beyond diffraction limit.

In the next sections, the principle, the measuring features, and one example of the multiple applications of the novel laser Doppler distance (LDD) sensor will be presented.

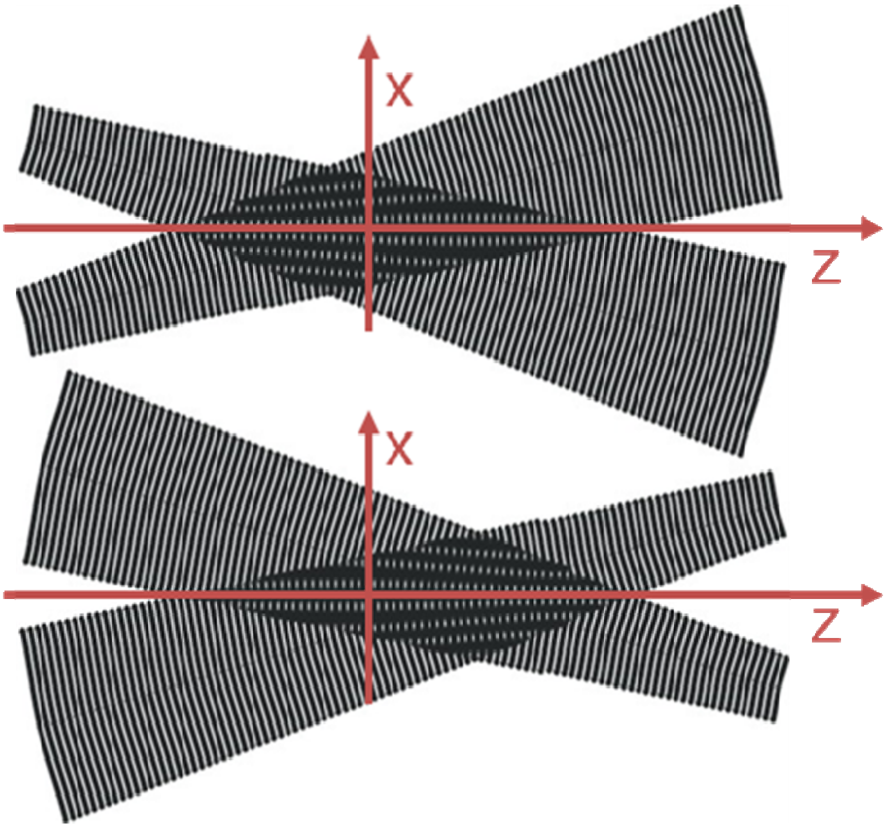

Fig. 1: Diverging and converging interference fringe systems are generated in the measurement volume. The resulting Doppler frequencies can be distinguished by applying multiplexing techniques such as employing different light wavelengths. As a result, the distance z and the velocity v_x are determined beyond the diffraction limit

2. Principle and advantages of the laser Doppler distance (LDD) sensor

Superposed diverging and converging interference fringe systems of different optical wavelengths are generated inside the same measurement volume (see Fig. 1). A wavelength-sensitive detection of the resulting Doppler frequencies $f_{1,2}$ yields the calibration function [1]

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

The axial position z of a scattering object is calculated based on this calibration function. With the determined z-position, the actual fringe spacings d_1 and d_2 can be identified via the calibration. As a result, the velocity v_x can be calculated precisely according to $v_x = f_1 \cdot d_1 = f_2 \cdot d_2$. Together with the known working distance A from the sensor to the center of the measurement volume (see Fig. 2), the distance D = A + z from the sensor to the measurement object is determined. For practical reasons, distance and position will not be distinguished in the following.

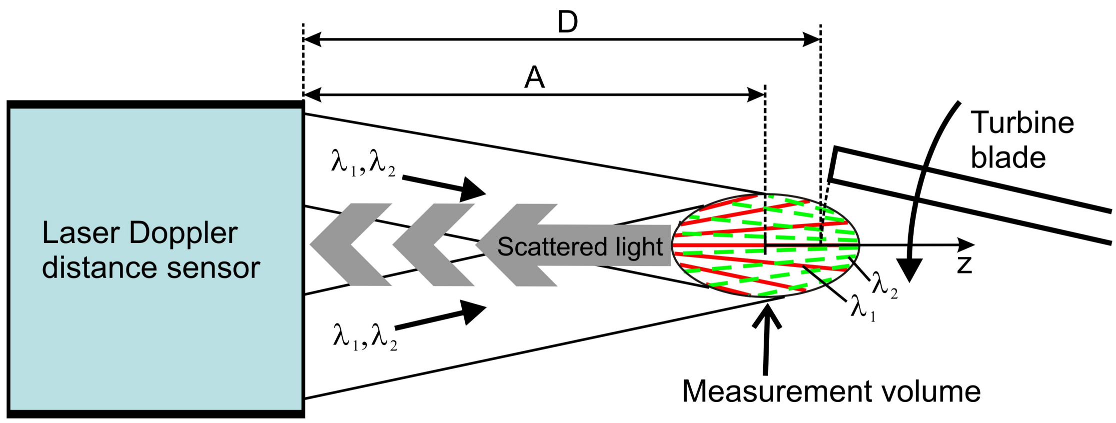

Fig. 2: Laser Doppler distance (LDD) sensor: Diverging and converging interference fringe systems corresponding to different optical wavelength are generated inside the measurement volume. Based on a monotonous calibration function, the velocity v_x and the position z (c.f. distance D), e.g. of the turbine blade tip, are measured simultaneously.

In the following the measurement features will be evaluated. The distance measurement uncertainty of the LDD sensor was investigated by using the law of error propagation. In the center of the measurement volume, the measurement uncertainty (standard uncertainty) approximately yields

$$\sigma_z \approx \sqrt{2}\left|\frac{\partial q(z)}{\partial z}\right|^{-1}\frac{\sigma_f}{f} \quad . \tag{2}$$

The distance measurement uncertainty only depends on the steepness of the calibration function $\partial q/\partial z$ and on the relative frequency uncertainty σ_f/f. Inserting the Cramer-Rao lower bound (CRLB) for the frequency measuring error of noisy single-tone signals and the relation for the Doppler frequency $f = v_x / d$, Eq. (2) can be rewritten as

$$\sigma_z \approx \sqrt{2}\left|\frac{\partial q(z)}{\partial z}\right|^{-1}\frac{k\cdot \mathrm{v}/(\Delta x\cdot\sqrt{SNR\cdot N})}{\mathrm{v}/d} = \sqrt{2}\left|\frac{\partial q(z)}{\partial z}\right|^{-1}\frac{k\cdot d}{\Delta x\cdot\sqrt{SNR\cdot N}}, \tag{3}$$

with $k = \sqrt{3}/\pi$ [2, 3]. The distance measurement uncertainty σ_z depends on steepness of the quotient function, the fringe spacing *d*, the averaging length on the object surface Δx (e. g. blade width of a turbo machine rotor), the signal to noise ratio (*SNR)* of the measured signals and the number *N* of recorded samples per signal.

It is important to notice that the distance measurement uncertainty is independent of the lateral velocity of the measurement object surface. This has been validated experimentally too (see Fig. 3). Thus, precise distance and shape measurements can be carried out also at high speed moving objects, e.g. turbine rotors.

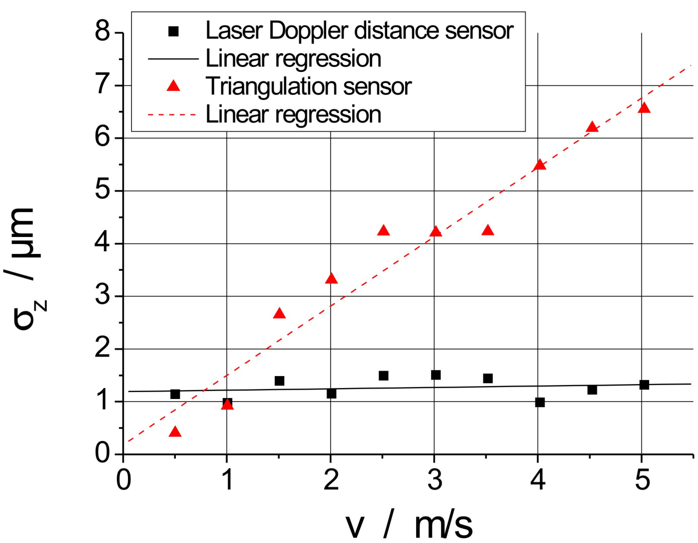

Fig. 3: The statistical measurement uncertainty of the laser Doppler distance (LDD) sensor is independent of the lateral surface velocity v_x in contrast to a laser triangulation sensor. A rotating brass wheel with one teeth of known height was used as a test object here.

The LDD sensor is based on a non-incremental interferometric principle. It features measurements with a small statistical uncertainty down to the submicrometer range, a low relative uncertainty of the velocity of around $5 \cdot 10^{-4}$ as well as a high measurement rate up to the Megahertz range.

3. Application of the laser Doppler distance (LDD) sensor

In-process measurements of distance and shape of fast moving objects such as turning parts, gear shafts, rotors and turbine blades are a big challenge. Robust in-situ measurements with high spatial and temporal resolution are required in particular at turbo machines [4 - 8]. The LDD sensor fulfils these requirements and provides advantages compared to conventional sensors. Since the distance is determined by the evaluation of Doppler frequencies, an unique measurement feature results: The measurement uncertainty of the distance does not depend on the lateral velocity of the object, see Eq.(3). Thus, dynamic deformations of high speed rotors can be evaluated with high temporal resolution [9,10].

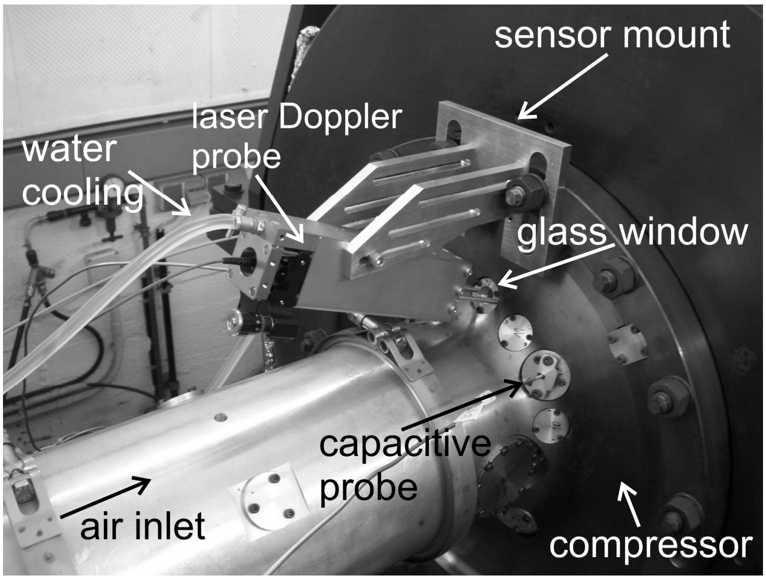

Fig. 4: Compressor section of the test rig at the German Aerospace Centre (DLR in Köln, Germany) with the mounted LDD sensor [3]. At harsh environments, in-situ inspections of the rotor blades have been performed. An optical access through a small glass window was used.

One important application of the LDD sensor is the monitoring of turbo machines. The efficiency of turbo machines can be optimized by minimizing the distance between blade tip and casing in order to reduce leakage flows. However, during operation, the tip clearance is changing due to mechanical forces caused by varying temperature and pressure conditions inside the machine and by vibrations of rotor blades and casing. In order to prevent fatal damage, it has to be assured that the rotor will not touch the casing in any case. An accurate and real-time determination of the tip clearance is therefore indispensable for an optimized and safe operation. For enabling tip clearance measurements at turbo machines under operational conditions, such as high vibrations and temperatures of up to 300°C, a robust measurement system with an all-passive fiber-coupled sensor was realized, see Fig. 4.

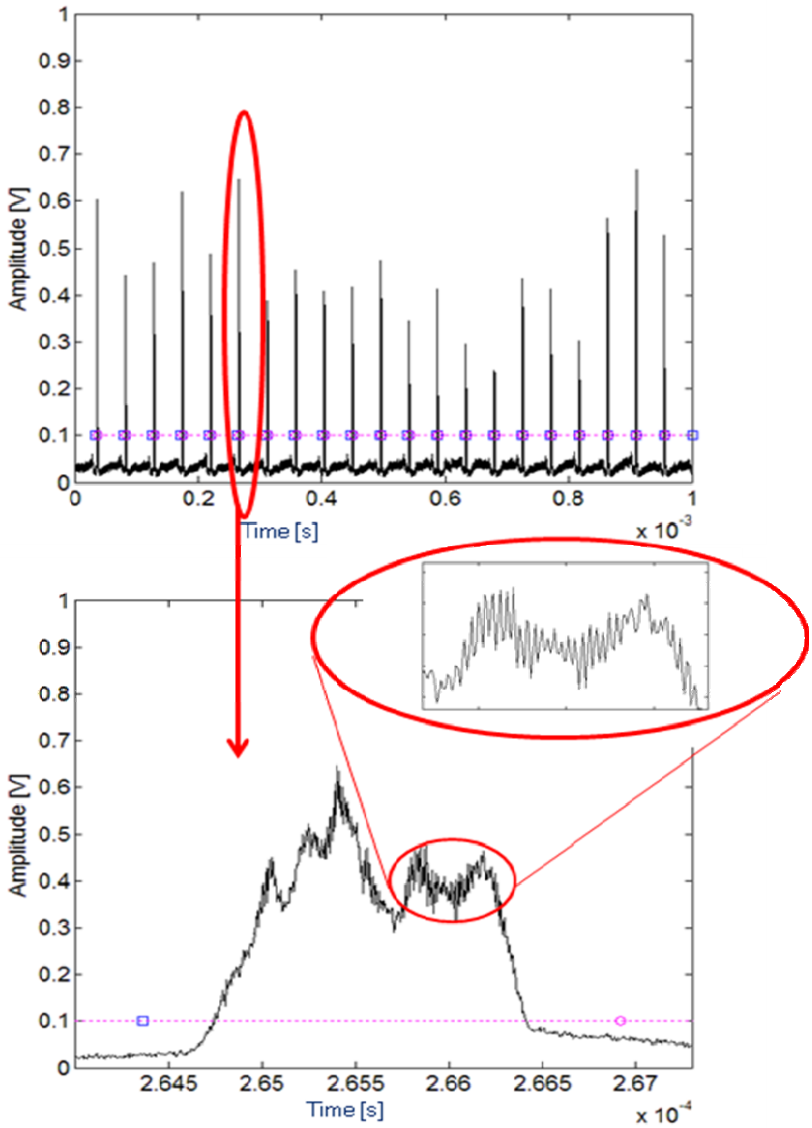

Fig. 5: Measurement signals of the LDD sensor acquired during operation of the turbo machine at 50,000 rpm [3] Above: Signals of multiple blades with a frequency of 21.667 kHz. Below: Signal of a single blade with a duration of only two microseconds. The magnification shows the Doppler modulation of the interference signal.

The rotor of the turbo machine had a radius of 112 mm and was equipped with 26 blades of a thickness of 1.7 mm at the tip. The measuring point was located at the outermost radial part of the rotor blades, which is the exit for the compressed air. The blade tip roughness was sufficient to generate Doppler modulated scattered light signals. No special treatment of the tips was necessary. A maximum rotary frequency of 50,000 rpm (833 Hz) could be set, which corresponds to a blade frequency of 21.667 kHz and a circumferential speed of 586 m/s at the measurement position. Fig. 5 shows the acquired measurement signal with duration of about 2 microseconds. As shown in session 2, the LDD sensor exhibits a distance measurement uncertainty which is independent of the lateral surface velocity, see also Eq. (3). This unique advantage allows precise measurements of high-speed moving objects. The measurement resolution yields to only few microns also at velocities of several 100 m/s. This allows studying vibration processes of fast rotating turbine blades.

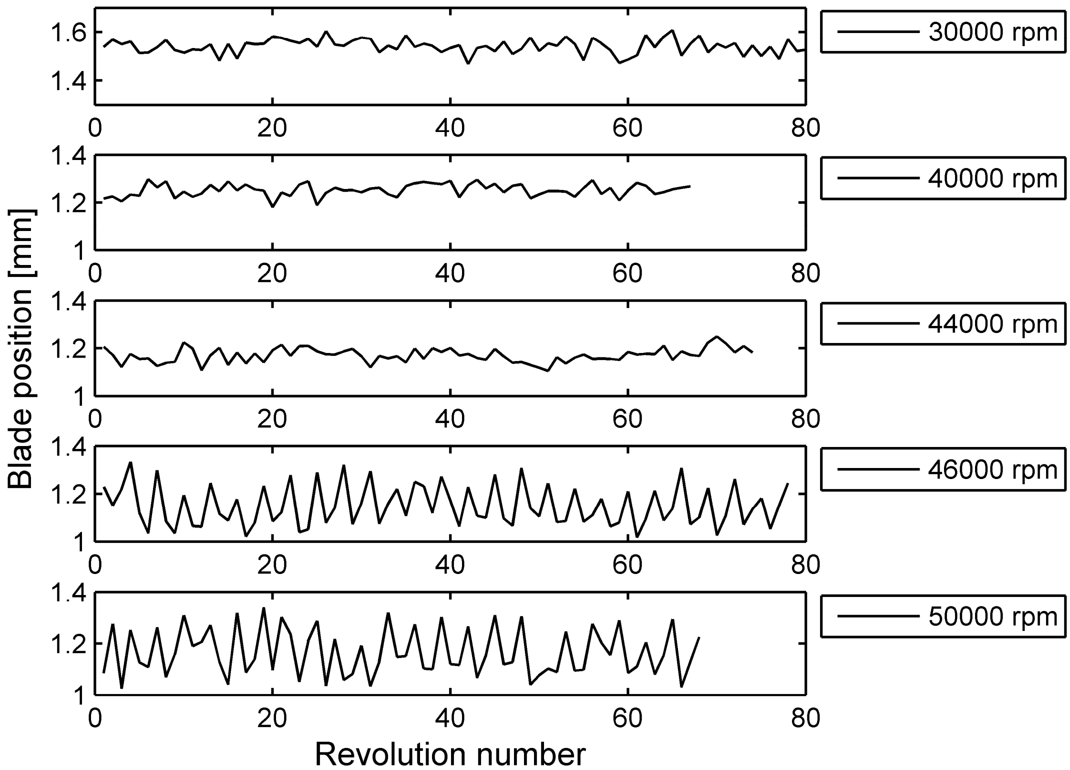

Fig. 6: Time series of the position of one specific rotor blade at different rotation frequencies of the turbo machine [3].

Position time series (Fig. 6) and corresponding Fourier spectra (Fig. 7) of a single rotor blade have been measured with the LDD sensor for five different rotational frequencies between

30,000 rpm and 50,000 rpm [3]. No significant blade position variations are visible for rotary frequencies smaller than 45,000 rpm (Figs. 6 and 7, upper three plots). Above 45,000 rpm, periodic variations in the measured blade positions with a period length of about 3 revolutions corresponding to a frequency of 1/3 of the rotary frequency and with an amplitude of about 200 µm (peak-peak) appear (see Figs. 7 and 8, lower two plots). These periodic variations are occurring at all 26 rotor blades above 45,000 rpm revealing occurring rotor vibrations at this speed.

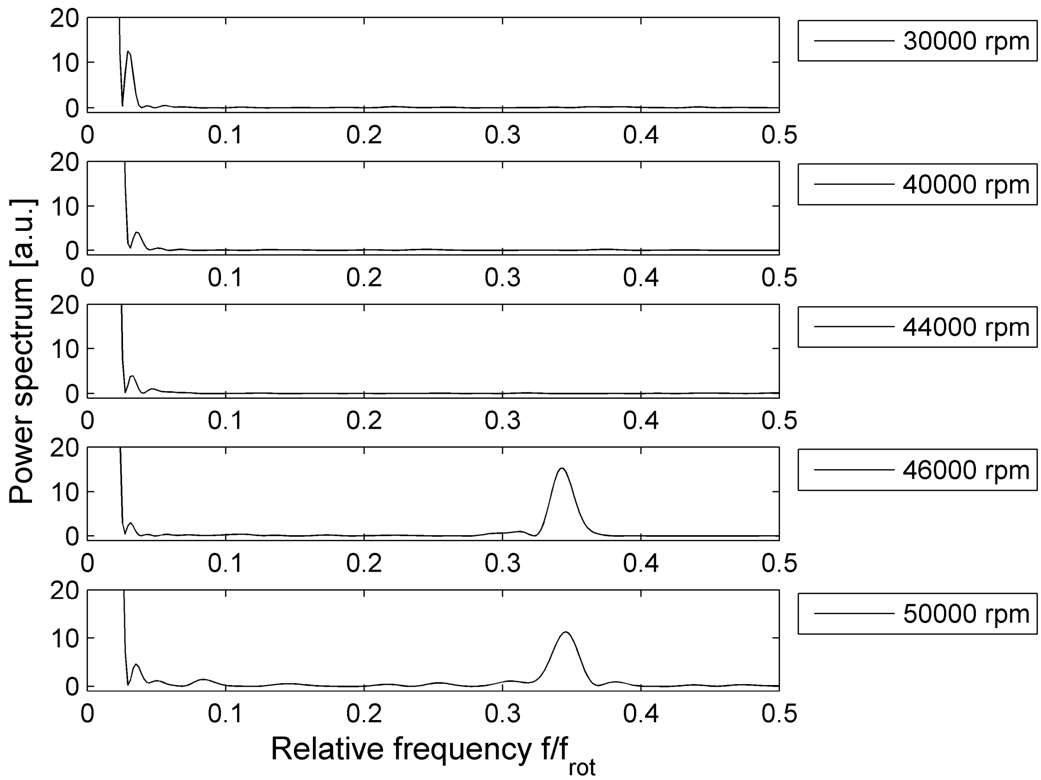

Fig. 7: Spectral power density of one specific rotor blade at different rotation frequencies of the turbo machine.

4. Conclusions

The novel laser Doppler distance (LDD) sensor offers high temporal resolution and high distance resolution simultaneously. In particular, the measurement uncertainty of the distance is independent of the lateral velocity of the object. This unique advantage has been demonstrated at turbo machines by ultrafast distance measurements at the microsecond scale.

Acknowledgement

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