XIX IMEKO World Congress
Measurement of Geometrical Quantities
September 6–11, 2009, Lisbon, Portugal

LASER DOPPLER DISTANCE SENSOR FOR FAST SHAPE MEASUREMENTS AT ROTATING OBJECTS

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Abstract – For monitoring the shape of fast rotating objects such as turbo machine rotors, contactless and compact sensors with a high measurement rate as well as high precision are required. We present a novel laser Doppler distance sensor for shape measurements of rough technical surfaces. This novel sensor offers concurrently high distance resolution in the micron range and high temporal resolution in the microsecond range. Especially the distance measurement uncertainty is, in principle, independent of the lateral object velocity. In order to prove its operational capability shape measurements of fast rotating objects are demonstrated in comparison with conventional sensors.

Keywords: optical distance measurement, real-time shape measurement, tip-clearance of turbo machines.

1. INTRODUCTION

In-process measurement of position and shape as well as dynamic deformations and vibrations of fast moving and especially rotating objects, such as turning parts, gear shafts and turbine blades, is an important task both in production engineering and process control. However, this is a big challenge for metrology, since non-incremental and contactless measurement techniques with high position resolution and concurrently high temporal resolution are required.

For example, 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 turbo 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 online determination of the tip clearance is therefore indispensable for an optimized and safe operation. For example, active clearance control systems [1] for high pressure turbines, which are currently under way, will require tip clearance sensors with an accuracy of about 25 µm and a measurement rate of about 50 kHz.

Many sensing principles have been used for tip clearance measurements [2]. Usually capacitive or inductive probes are employed because they are robust and low cost. However, they offer a moderate accuracy of around 50 µm in practice. Eddy current sensors have the advantage that they can measure through nonferromagnetic casing walls, but the sensor response strongly depends on the thickness and the material of the turbo machinery casing [3]. Moreover, capacitive as well as eddy current probes will fail at latest developments of turbo machinery towards lightweight construction employing blade materials like fiber-reinforced composites or ceramics, which do not conduct electricity.

Optical measurement techniques overcome this drawback and also offer higher accuracy. However, incremental sensors such as Michelson interferometers or laser Doppler vibrometers often are not suitable, because their measurement results become ambiguous if jumps of more than half the laser wavelength occur. Furthermore, the measurement rate of most optical techniques is fundamentally limited either by the speed of mechanical scanning (time domain optical coherence tomography (OCT) [4], conventional auto-focus sensing) or by the detector frame rate and minimum exposure time (triangulation, chromatic confocal sensing, Fourier domain OCT). Furthermore, at rough surfaces the measurement uncertainty of triangulation is fundamentally limited by coherent speckle noise and also shading is a major problem [5]. In order to overcome these problems on the temporal resolution, a new kind of laser Doppler technique will be presented.

2. LASER DOPPLER DISTANCE (LDD) SENSOR

The idea is to generate two superposed fan-shaped interference fringe systems with contrary fringe spacing gradients inside the same measurement volume (see Fig. 1). The fringe spacings are monotonously increasing and decreasing functions $d_{1,2}(z)$ with respect to the axial position z, i. e. the distance. A wavelength-sensitive detection of the two resulting Doppler frequencies $f_{1,2}$ yields the quotient function

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

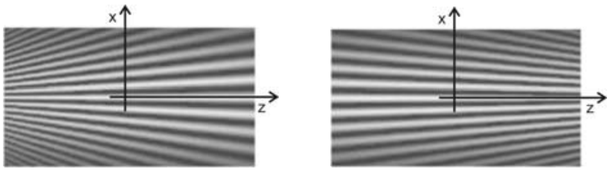

Fig. 1: Two fan-like interference fringe systems of different wavelengths and with opposite gradients are generated in the same measurement volume of the laser Doppler distance (LDD) sensor. The position, i.e. distance z and also the velocity v in x-direction are precisely measured with high temporal resolution.

The quotient q(z) allows to determine the axial position, i.e. distance *z* of a scattering object inside the measurement volume. With the known *z*-value, the actual fringe spacings d_1 and d_2 can be identified via the known fringe spacing curves $d_{1,2}(z)$. As a result, the velocity *v* can be calculated precisely according to $v = f_1 \cdot d_1 = f_2 \cdot d_2$ (see Fig. 2).

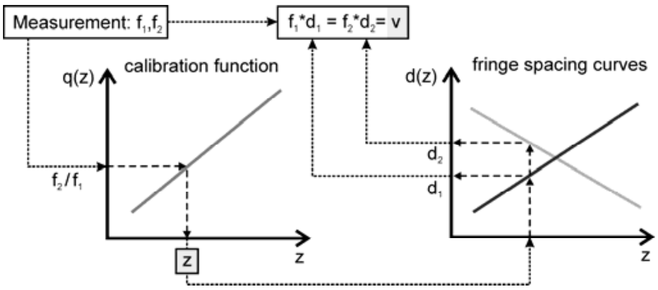

Fig 2: Functional principle of the laser Doppler distance (LDD) sensor.

Together with the known working distance A from the sensor to the measurement volume (Fig. 3) it yields the distance D = A + z from the sensor to the measurement object. For practical reasons distance and position will not be differentiated in the following.

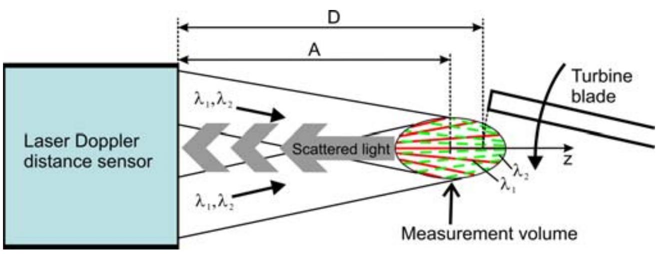

Fig. 3: Application of the laser Doppler distance (LDD) sensor e. g. for tip clearance measurements of turbo machines. Fundamental mode laser diodes of optical powers of some mW and emission wavelengths of 658 nm and 830 nm are employed.

The achievable distance measurement error of the LDD sensor can be investigated by using the law of error propagation [6]. In the center of the measurement volume it can be approximated by

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

Due to this equation, the position uncertainty only depends on the steepness of the quotient 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 [6] and the relation for the Doppler frequency $f = v/d$, equation (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 $k = \sqrt{3}/\pi$. Consequently, besides the steepness of the quotient function, the distance measurement uncertainty σ_z depends on the actual fringe spacing *d*, on the averaging length on the object surface Δx (e. g. blade width), on the *SNR* of the measured signals and on the number *N* of recorded samples per signal. However, the object velocity *v* cancels out and, thus the distance uncertainty is independent of the velocity of the measurement object. Therefore, precise position measurements can be carried out also at extremely fast moved objects, e.g. turbine blades.

The experimental verification of the briefly presented theory was accomplished by a calibration setup (fig. 4). Fig. 5 shows the resulting statistical measurement error in dependence of the tangential velocity of the wheel. Fig. 6 presents a velocity independent measurement error of the distance also at high velocities of turbo machines.

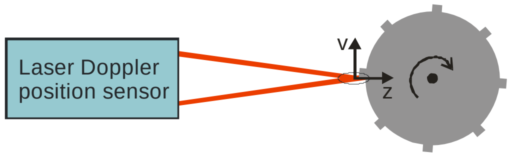

Fig. 4: Calibration arrangement using a rotating brass wheel with teeth of known size.

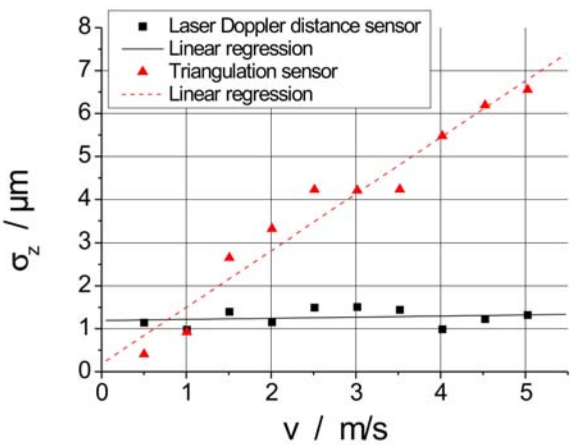

Fig. 5: The statistical uncertainty of the laser Doppler distance (LDD) sensor is independent of the lateral surface velocity v_x in contrast to triangulation sensors.

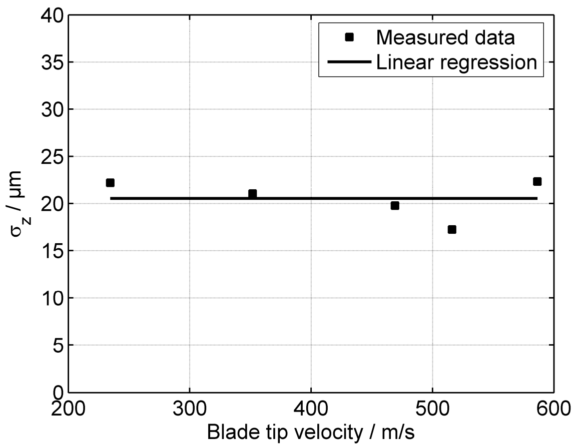

Fig. 6: Systematic measurement uncertainty of the laser Doppler distance (LDD) sensor in dependence of the velocity of the turbo machine blade tip. Due to the speckle effect at rough surfaces the unknown systematic measurement uncertainty occurs.

The LDD sensor features a low distance uncertainty down to the sub-micrometer-range (150 nm [7]), a low relative uncertainty of the velocity of typically $5 \cdot 10^{-4}$ [6] and a high measurement rate up to the Megahertz range. The LDD sensor based on the measurement principle described above has the following unique features:

1. The optical Doppler effect is used to perform a non-incremental position measurement with high temporal resolution. This is due to the employment of fast single photo detectors with high bandwidth.
2. According to equation (3) the measurement uncertainty of the distance is independent of the lateral object velocity [7]. Fig. 5 shows the statistical measurement uncertainty of the LDD sensor. At lateral velocities higher than about 1 m/s the LDD sensor exhibits a lower uncertainty than typical triangulation sensors. Fig. 6 demonstrates the independence of the distance uncertainty on the lateral velocity also at high speeds.
3. In addition to the distance, the lateral velocity component is determined as well. This can be used to measure the diameter and shape (characteristic parameters like eccentricity, ellipticity, etc.) of rotating workpieces even during processing. Beyond that, all three velocity components can be measured using more multiplexing channels. Also three dimensional shape measurements can be accomplished using array detectors.

3. SPAPE MEASUREMENT OF ROTATING WORKPIECES

Precise on-line shape and vibration measurements of fast rotating objects are an important task in manufacturing metrology. First part quality of the geometry of workpieces is one goal. During manufacturing the diameter of rotating cylindrical objects has to be controlled. In general, for dynamic distance, deformation and vibration measurements optical methods gain increasing importance.

The laser Doppler distance sensor allows lateral velocity and distance measurements of rough surfaces simultaneously. This feature allows the measurement of the workpiece diameter by only one sensor. It makes an easy integration into a machine tool possible. Since the measurement uncertainty is independent of the rotation speed fast turning and grinding processes can be controlled.

The shape measurement is based on time resolved evaluation of the Doppler signal frequency using a sliding fast Fourier transformation (FFT) [6]. Figs. 7 and 8 show the time resolved distance and lateral velocity of the rotating object.

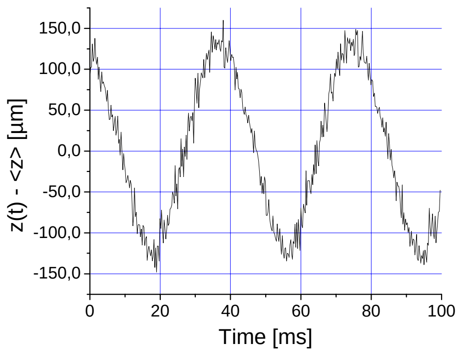

Fig. 7: Temporal variation of the distance z(t) from the sensor to the object surface.

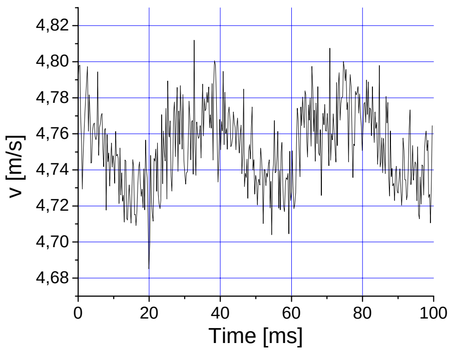

Fig. 8: Temporal variation of the lateral velocity v(t).

The Fourier transformation of the radius function r(t) = z(t) - <z> results in the mean value of rotation frequency $\langle f_{Rot} \rangle$. Together with the average velocity <v> the mean value of the radius can be calculated as [6]:

$$\langle R \rangle = \frac{\langle \mathrm{v} \rangle}{2\pi \cdot \langle \mathrm{f}_{\mathrm{Rot}} \rangle} \quad . \tag{4}$$

The measured angular velocity ω(t) results in the time resolved angle of the measurement point on the surface of the workpiece [6]:

$$\varphi(t) = \int_0^t \omega(\tau) d\tau = \int_0^t \frac{\mathrm{v}(\tau)}{\langle R \rangle + r(\tau)} d\tau \, . \tag{5}$$

The two dimensional shape of the workpiece yields to [6]:

$$\vec{r}(t) = \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = [\langle R \rangle + r(t)] \cdot \begin{pmatrix} \cos(\varphi(t)) \\ \sin(\varphi(t)) \end{pmatrix} \, . \tag{6}$$

Fig. 9 shows the rotating workpiece inside a turning machine. During the turning process the shape of a rotating cylindrical work piece was measured [6]. With each turn of the object its cross-sectional shape at the measurement position was recorded accordingly to equation (6) completely. Moving the sensor along the rotation axis yields the entire three dimensional shape of the rough surface (Fig. 10). Hence, diameter and shape can be measured in-process. By comparing the results with a default radius a closed-loop control of the abrasion can be realised.

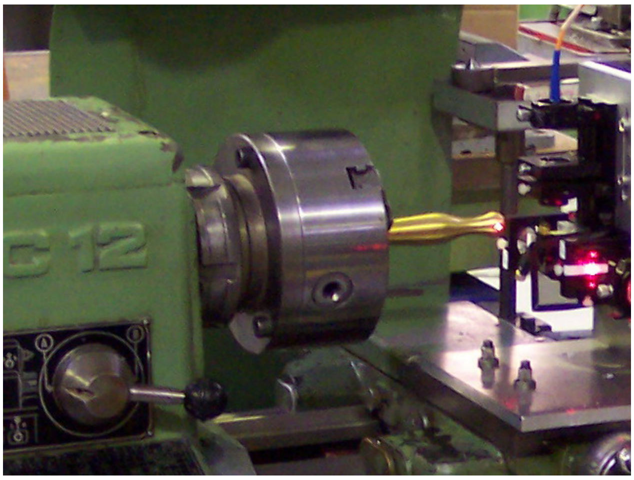

Fig. 9: Photography of the cylindrical workpiece inside a turning machine (cooperation with Prof. H. K. Tönshoff, University of Hannover, Germany).

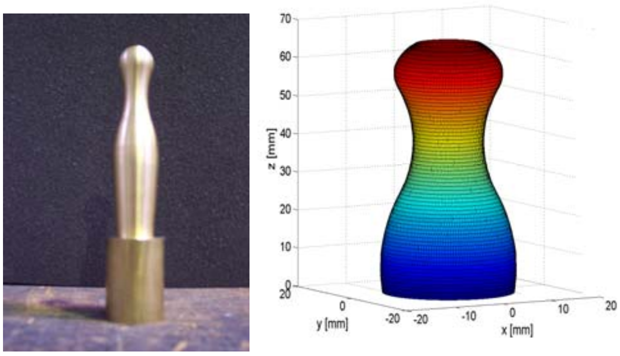

Fig. 10: Photography of the workpiece (left). The measurement result is presented as 3d shape (right). The rotation axis is along the z-direction. Here a scanning process was applied in order to get the three dimensional (3d) shape. In the future simultaneous array-measurements will be accomplished.

4. TIP CLEARANCE MEASUREMENTS OF A TRANSSONIC TURBO MACHINE

The experiments were carried out at a transonic centrifugal compressor test rig in the German Aerospace Center (DLR) in Cologne [8]. The optical measurement head of the LDD sensor was attached to the compressor casing (see fig. 11) and the beams were directed onto the turbine blades through a 6 mm thick optical access window. It was mounted flush with the inner contour of the turbine casing. For safety reasons, the light source unit, the detection unit and the PC were set up in a control room adjacent to the test rig.

The rotor had a radius of 112 mm and was equipped with 26 blades of 1.7 mm thickness 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 stray light signals. No special treatment of the tip surfaces was necessary. A maximum rotary frequency of 50,000 rpm (833 Hz) could be set, which corresponds to a blade frequency of 21,667 Hz and a circumferential blade speed of 586 m/s at the measurement position. During operation the compressor temperature rose up to 280°C. The water cooling of the measurement head worked effectively keeping its temperature stable at about 18°C. Also no distracting contamination of the glass window could be observed.

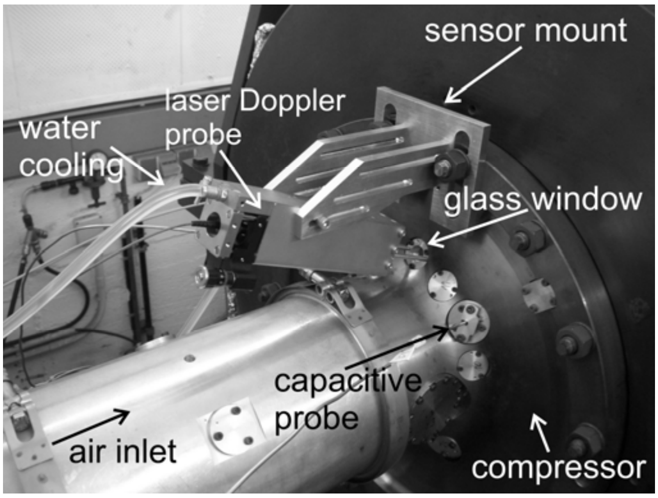

Fig. 11: Compressor section of the test rig at the German Aerospace Centre (DLR) in Köln (Germany) with the mounted laser Doppler distance probe (cooperation with Dr. R. Schodl) [8].

Fig. 12 shows the measured positions of a single rotor blade for 65…85 consecutive revolutions and at different rotary frequencies between 30,000 and 50,000 rpm. No significant blade position variations are visible for rotary frequencies smaller than 45,000 rpm (fig. 13, upper three plots).

The constant spectral power densities shown in fig. 13 represent white noise processes, which correspond to the stochastic fluctuations of the distance. They result in the measurement uncertainty of the LDD sensor, see fig. 6. According to equation (3) the measurement uncertainty depends on the spatial averaging interval Δx, which is given by the blade width of 1.7 mm. Since also the other parameters of equation (3) are constant no dependence of the blade velocity occurs.

However, 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. 12 and 13, lower two plots). These periodic variations are occurring at all 26 rotor blades above 45,000 rpm. It is in good agreement with measurement results of the capacitive probes, where also periodic oscillations in the tip clearance at a frequency of 1/3 of the actual rotary frequency were detected above 45,000 rpm (see fig. 13, lower two plots). Consequently, the LDD sensor is capable of detecting rotor vibrations due to its high temporal resolution in the microsecond range. The blade passage time duration, i.e. the measurement time, was about 3 µs at the maximum speed of the turbo machine.

It has to be pointed out that conventional laser Doppler vibrometers can not be used for the presented task. Due to their ambiguity range of half the laser wavelength no mutual measurements of different blade passages is possible.

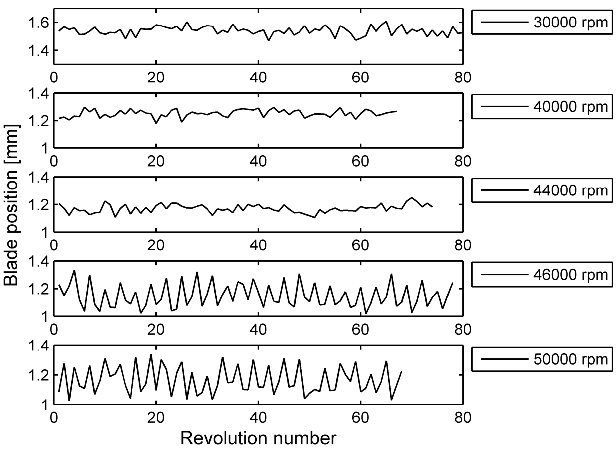

Fig. 12: Time series of the blade positions at different rotation frequencies [8].

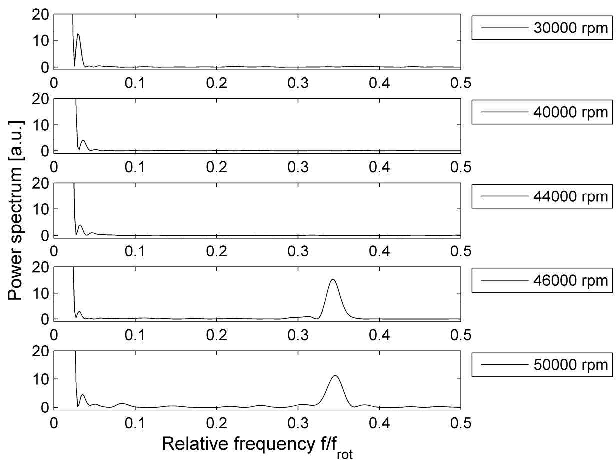

Fig. 13: Fourier power spectra of the time series from fig. 12.

In order to eliminate disturbances from thermal expansions of compressor casing and sensor mount, a further test series was performed at constant rotary frequency of 50,000 rpm. Before starting the measurement, the compressor was kept running at 50,000 rpm for about half an hour in order to reach thermal equilibrium. During the test series, the tip clearance was successively increased by throttling the compressor and, thus, reducing the effective mass flux and increasing the pressure ratio between inlet and outlet. Measurements have been carried out at six different settings of the throttle valve.

In fig. 14, the results of LDD sensor and capacitive measurements are compared. The individual data points represent the tip clearances measured with the LDD sensor averaged over the 5 rotor blades with highest SNR and 65 revolutions in dependence of the tip clearances measured with the capacitive reference probe. The error bars mark the measured standard deviations for the LDD sensor. For comparison, the solid curve indicates the tip clearance measured with the capacitive probe (identity) including an uncertainty interval, which was assumed to be ± 50 µm. An excellent agreement occurs between the data of both sensors. An average standard deviation of only 22 µm could be obtained, which represents the measurement uncertainty of the LDD sensor (compare with Fig. 6). It is considerably better than the accuracy of capacitive probes of about 50 µm. Consequently, the fiber-optic LDD sensor presented in this contribution has proven to be capable of precise tip clearance and vibration monitoring at transonic turbo machines.

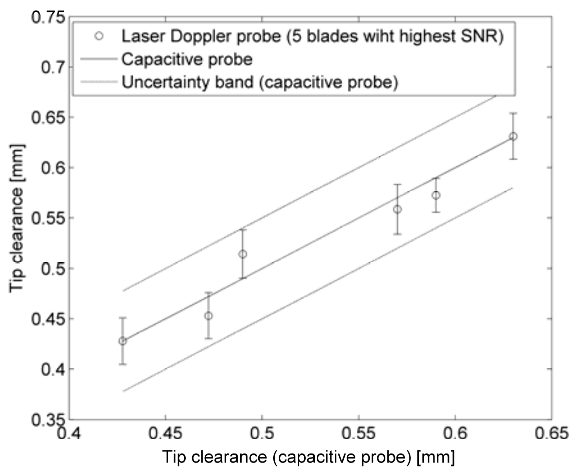

Fig. 14: Tip clearances measured with the laser Doppler probe (LDD sensor) in comparison with the data from the capacitive probes [8]. The laser sensor data were averaged over the 5 rotor blades with highest signal-to-noise-ratio (SNR). The dashed lines indicate the uncertainty interval for the capacitive probes.

5. SUMMARY

A novel laser Doppler distance (LDD) sensor was applied for real-time shape measurements of rotating workpieces as well as turbo machine single blade tip clearance measurements under operational conditions. It has been shown that the distance uncertainty of the LDD sensor is in principle independent of the object velocity. Thus, in contrast to other measurement techniques, the novel LDD sensor offers high temporal resolution and high distance resolution simultaneously.

ACKNOWLEDGMENTS

This work was funded by the German Research Foundation (DFG) by project Cz 55/19-1.

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