

FIBER OPTIC LASER DOPPLER PROBE FOR IN-SITU TIP CLEARANCE AND VIBRATION MONITORING AT TURBO MACHINES

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Abstract: We report about a novel optical method based on laser Doppler techniques for shape and vibration monitoring of fast rotating objects. Tip clearance and vibration measurements on a transonic centrifugal compressor performed during operation at up to 50,000 rpm and 586 m/s blade tip velocity are presented. The results are in excellent agreement with those of capacitive probes and the achieved accuracy was about 20 μm .

Keywords: shape and vibration monitoring, laser Doppler techniques, tip clearance.

1. INTRODUCTION

Precise shape and vibration measurements of fast rotating objects are an important task in manufacturing metrology and process control. 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.

Many sensing principles have been used for tip clearance measurements [1]. Usually capacitive probes are employed because they are robust and low cost. However, they offer only 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 [2]. 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 principles based on e.g. triangulation [3], optical coherence tomography (OCT) [4] or time-of-flight measurements [5] overcome this drawback. However, at most optical techniques the measurement rate is limited either by the speed of mechanical scanning (OCT) or by the detector frame rate and minimum exposure time (triangulation). Furthermore, at rough surfaces the

measurement uncertainty of triangulation is fundamentally limited by coherent speckle noise and also shading is a major problem. At time-of-flight, the resolution is limited due to the limited time resolution of the signal processing.

In the following we will introduce a new fiber coupled laser Doppler tip clearance probe, which is based on laser Doppler velocimetry (LDV). In contrast to other optical sensors, the laser Doppler probe offers high temporal and high spatial resolution simultaneously [6,7]. Real-time measurements of quickly passing objects are possible, since this sensor does not contain any mechanically moved parts and because high bandwidth photo detectors are employed. In addition, this sensor is not strongly influenced by coherent speckle noise and shading is reduced unlike triangulation [6]. An all passive fiber optic measurement head makes the sensor flexible and immune against temperature influences and electrical disturbances.

2. SENSOR PRINCIPLE

LDV is a well-established technique for measuring velocities of point-wise scattering particles in fluid flows and also of moved solid-state surfaces. It evaluates the scattered light from measurement objects passing a measurement volume, which is formed by interference fringes in the intersection volume of two coherent laser beams. Taking into account the spacing d of the interference fringes, the velocity v of the measurement object is calculated by means of $v = f d$, with f denoting the measured Doppler frequency.

The novel laser Doppler probe presented in this paper is an extension of a conventional LDV. Here, two superposed fan-like interference fringe systems with contrary fringe spacing gradients are generated inside the same measurement volume using wavelength division multiplexing (see fig. 1) [6,7]. The fringe spacings are monotonously increasing and decreasing functions $d_{1,2}(z)$ of the axial position z . A wavelength-sensitive detection of the Doppler frequencies $f_{1,2}$ yields the quotient function [6]:

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

which is also monotonously varying and does not depend on the velocity v . It can therefore be used to determine the axial position z of a scattering object inside the measurement volume.

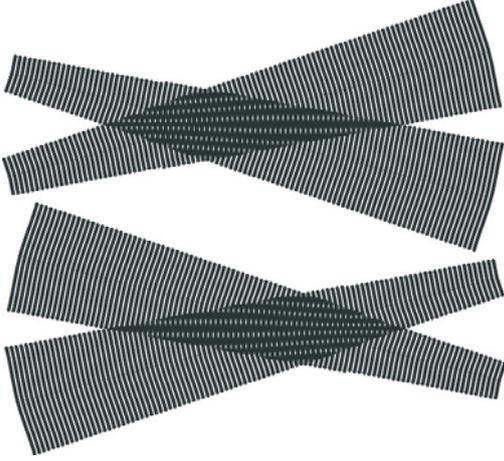


Fig. 1: Two interference fringe systems with monotonously increasing (top) and decreasing (bottom) fringe spacing in axial direction, which are superposed in the same location in practice.

This feature allows the sensor to measure not only velocities but also distances to moved objects like turbine blades. Thereby, precise position measurements can be carried out at extremely high object velocities, because the position accuracy is independent of the object velocity since the position measurement is attributed to a velocity measurement. The velocity is calculated by $v=f_1d_1=f_2d_2$. The sensor was already applied successfully for measuring flat-plate boundary layers in fluid flows [7] and also for shape and excentricity measurements of rotating cylinders with micrometer spatial resolution [6,8].

3. SENSOR SETUP

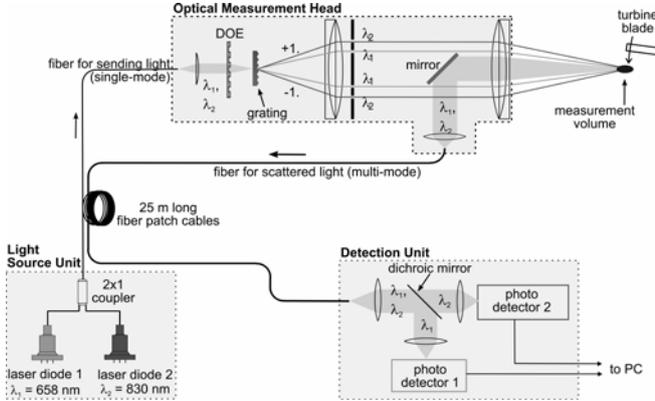


Fig. 2: Experimental setup. The passive optical measurement head is connected via fiber patch cables to light source unit and detection unit.

The fiber optic laser Doppler probe consisted of three different units: A light source unit, the passive optical measurement head and the detection unit (see fig. 2). The passive measurement head was connected to light source unit and detection unit via 25 m long fiber patch cables resulting in a modular and flexible setup.

The fiber optic measurement head was all passive and equipped with radiator coils for water cooling making it immune against temperature influences and electrical disturbances. In order to obtain a compact and robust sensor head with a minimum number of adjustment elements, a special design using a diffractive lens was employed, which

is explained in detail in [9,10]. The outer dimension of the measurement head were 200 x 82 x 54 mm³.

The light source unit contained two pigtailed single transverse mode laser diodes (660 nm and 830 nm wavelength) combined by means of a 2x1 fused fiber coupler to one single mode fiber. The detection unit split the received scattered light from the measurement object into the two different wavelengths by a dichroic mirror and focused it onto two high bandwidth photo detectors. The detector signals were fed via a 14 Bit A/D converter card into a standard PC for further processing.

4. MEASUREMENT ACCURACY

The position uncertainty of the sensor, i.e. the statistical measurement error in the position can be described by the standard deviation of the measured positions σ_z for a fix position of the measurement object. This error can be derived analytically using the law of error propagation [7]. For the center of the measurement volume it can be approximated by

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

Due to this equation, the position uncertainty only depends on the steepness of the quotient function $\partial q/\partial z$ and on the relative uncertainty of the frequency measurement σ_f/f . Inserting the Cramer-Rao lower bound (CRLB) for the frequency measuring error of noisy single-tone signals [11] and the relation for the Doppler frequency $f = v/d$, equation (2) can be rewritten as [12]

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

with k denoting a constant term. Consequently, besides the steepness of the quotient function, the position uncertainty σ_z depends on the actual fringe spacing d , on the averaging length on the object surface Δx (here: blade tip thickness), 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 position 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).

Experimentally a statistical measurement error of $< 3 \mu\text{m}$ was determined over the whole measurement range of the sensor of 1.8 mm [12]. Due to the random structure of rough solid state surfaces an additional systematic measurement error occurs, which did not exceed $22 \mu\text{m}$. Compared to these errors, temperature and pressure influences from the turbo machine can be neglected [12]. Consequently, the measurement accuracy of the novel laser Doppler probe is better than $25 \mu\text{m}$ for a measuring range of 1.8 mm. This is considerably superior to conventional tip clearance sensors (e.g. capacitive or eddy current probes), which have an accuracy of only (50...100) μm .

5. CENTRIFUGAL COMPRESSOR TEST RIG

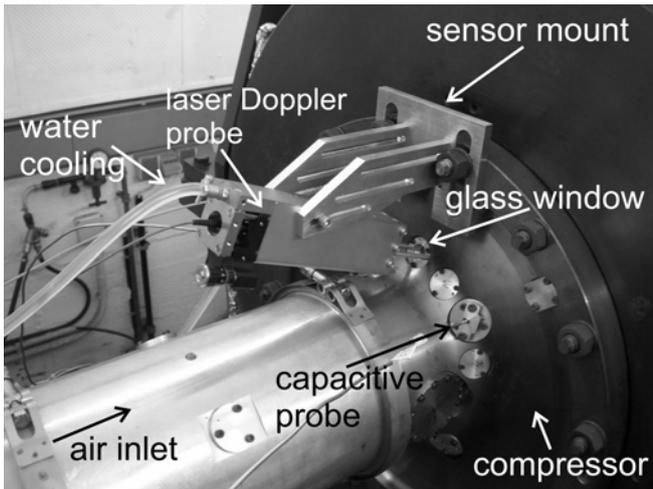


Fig. 3: Compressor section of the test rig at the German Aerospace Centre (DLR) in Köln with the mounted laser Doppler probe.

The experiments were carried out at a transonic centrifugal compressor test rig in the German Aerospace Center (DLR). The optical measurement head of the laser Doppler probe was attached to the compressor casing (see fig. 3) and the beams were directed onto the turbine blades through an optical access window, which was mounted flush with the inner contour of the turbine casing. The light source unit, the detection unit and the PC were set up in the 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 tips was necessary. A maximum rotary frequency of 50,000 rpm (833 Hz) could be achieved, which corresponds to a blade frequency of 21,667 Hz and a circumferential 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 contamination of the glass window could be observed.

The compressor casing was additionally equipped with three capacitive probes equally distributed on the perimeter (see fig. 3). These capacitive reference probes were used to determine the tip clearance at the beginning of each test series. Since the laser Doppler probe measured only displacements and the absolute position of the inner casing wall was not known, a constant value was added to the outcomes of the laser Doppler sensor such that the first data point of each test series coincided with the mean value from the capacitive probes. Thus, the tip clearance curves measured with the different sensors could be compared. For future works, the position of the inner casing wall can be determined by an appropriate calibration and, thus, the tip clearance can be measured directly by the laser Doppler position sensor.

6. SIGNAL PROCESSING

The data acquisition card of the PC recorded time domain signals of 16 mega samples (MS) length per channel at a maximum sampling rate of 200 MS/s, which corresponds to up to 100 revolutions of the rotor depending on the rotary frequency. A trigger signal from a revolution transducer allowed starting data acquisition every time at the same rotor blade. The individual rotor blades provoked nearly rectangular signal bursts on both measurement channels with an amplitude modulation by the Doppler frequency on top (see fig. 4). Thus, the actual rotary frequency f_{rot} could be determined as fundamental frequency of the spectrum of the downsampled time domain signals.

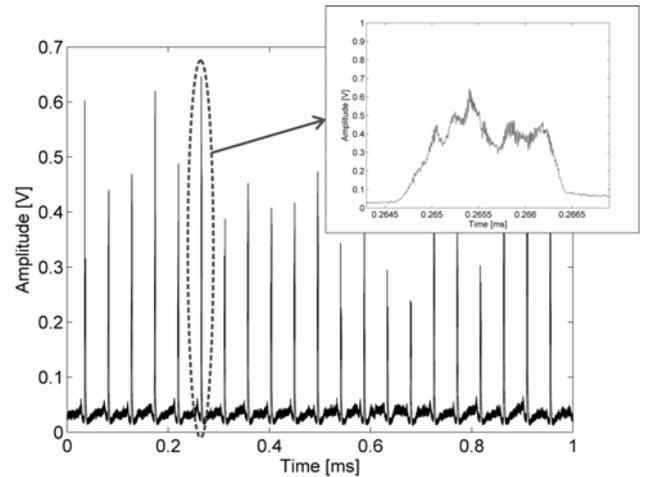


Fig. 4: Extract of one recorded time domain signal at 50,000 rpm and enlarged signal section corresponding to the passage of one rotor blade with Doppler frequency amplitude modulation on top.

For further evaluation, the signal bursts corresponding to the individual rotor blades were cut out of the time domain signals using a suitable amplitude threshold. Afterwards, these signal bursts were high pass filtered in order to extract the high frequency part containing the Doppler modulation and to remove the DC pedestal. By applying a Fast-Fourier-Transform (FFT) and fitting Gaussian curves to the spectra, the two Doppler frequencies $f_{1,2}$ were determined for each blade passage. The ratio of these two Doppler frequencies was used to calculate the positions of the individual blade tips by means of equation (1). Despite the high blade frequency of up to 21.7 kHz, the positions of the individual rotor blades could be measured for each revolution.

From the blade tip positions of all consecutively measured rotor revolutions the mean value and the standard deviation were calculated, where the latter defines the measurement uncertainty (position resolution). A validation procedure was implemented in order to discard signals whose SNR fell below a certain level. Also an average tip clearance can be specified by averaging over the mean positions of all blades.

7. MEASUREMENTS DURING POWERING UP AND SHUTTING DOWN THE COMPRESSOR

First, tip clearance measurements were performed during powering up and shutting down the compressor. The rotary

frequency was increased step-by-step from 20,000 rpm to 50,000 rpm and turned down to 20,000 rpm again over a period of about one hour. Thereby, the tip clearance changed due to the thermal expansion of casing and rotor and because of the varying pressure conditions inside the machine. The measured tip clearances with capacitive and laser Doppler probes are shown in figure 5 as a function of the rotary frequency. All data points represent average values over 65...85 revolutions of all 26 rotor blades.

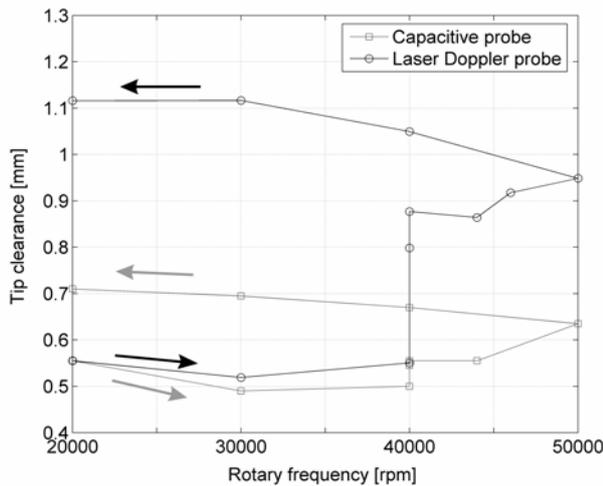


Fig. 5: Tip clearances measured during power up and shut down of the compressor. Starting point and direction of both curves are indicated by arrows [12].

At both measurement curves, the tip clearance is decreasing towards a minimum at 30,000 rpm and, afterwards, it is constantly increasing exhibiting a hysteresis (fig. 5). The hysteresis emerges due to the fact that the thermal expansions of casing and rotor are proceeding much slower than the temperature changes in the air flow. Therefore, casing and rotor are still expanding despite the rotary frequency has already been decreased again.

However, especially around 40,000 rpm, the increase in the tip clearance measured with the laser Doppler probe is much stronger than for the capacitive probe. This is because of the thermal expansion of the sensor mount and of the outer part of the compressor casing, where the sensor mount was fixed (see fig. 3). The laser Doppler sensor registered this thermal expansion in addition to the actual tip clearance variation. In contrast, the capacitive probes were implemented closer to the rotor axis, where temperature changes and resulting thermal expansions were very small. Finite element method (FEM) simulations and measurements with a dial gauge confirmed that the position of the laser Doppler probe can change by up to 0.5 mm with respect to the rotor position during power up. This value matches very well with the measured difference of about 0.4 mm at the end of the test series (see fig. 5). For future experiments an improved sensor mount should be used in order to avoid such interference.

For determining the measurement uncertainty of the laser Doppler probe, the standard deviations σ_z of the measured blade tip positions over all 65...85 revolutions

were calculated for each rotor blade. The result is shown in figure 6 in dependence of the rotary frequency for a single rotor blade. Below 45,000 rpm, the standard deviations are between 17 μm and 26 μm resulting in an average measurement uncertainty of only 20.6 μm . This is much better than the accuracy of capacitive probes of about (50...100) μm and it agrees very well with the results from section 4. Above 45,000 rpm, the standard deviation σ_z increases strongly. However, this increase is due to occurring axial vibrations of the compressor rotor.

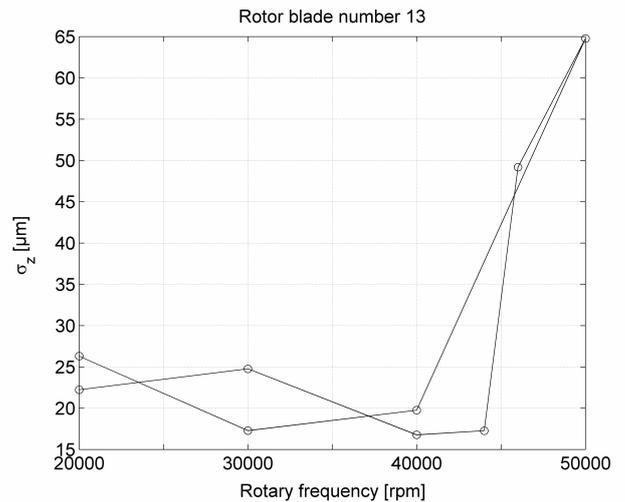


Fig. 6: Mean standard deviation of the position σ_z for rotor blade number 13 in dependence of the rotary frequency [12].

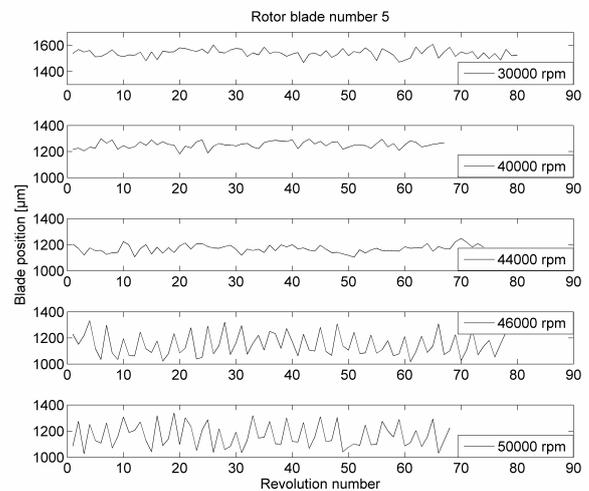


Fig. 7: Positions of a single rotor blade measured with the laser Doppler probe at 65...85 consecutive revolutions for five different rotary frequencies between 30,000 and 50,000 rpm.

Figure 7 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. 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 fig. 7, lower two plots). These periodic variations are occurring at all 26 rotor blades above 45,000 rpm [12]. This 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 [12].

Consequently, the laser Doppler tip clearance probe is capable of detecting rotor vibrations due to its high temporal resolution. These vibrations are responsible for the strong increase in the standard deviation σ_z above 45,000 rpm (fig. 6). However, the actual measurement uncertainty of this sensor can be assumed to be the same as for lower rotary frequencies. This can be verified by applying an appropriate lowpass filter to the blade position signals for removing the oscillations, which are physically generated by axial rotor vibrations and which do not represent a measurement error of the laser Doppler position sensor (see section 8).

8. MEASUREMENTS AT 50,000 RPM

In order to eliminate interference 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 several minutes 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.

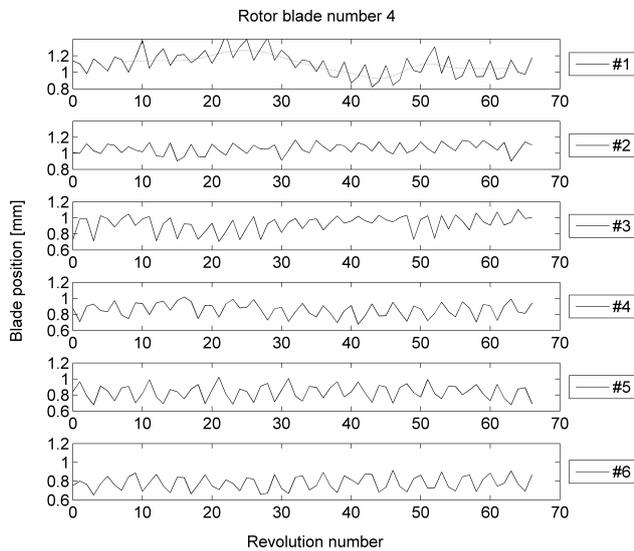


Fig. 8: Blade position curves of a single rotor blade for the six successive measurements with different throttle settings (#1-6) measured with the laser Doppler probe.

Figure 8 shows the measured positions of a single rotor blade for the different throttle settings over 67 consecutive revolutions. In consistency with the former measurements (see section 7) and in agreement with capacitive probes, also here periodic oscillations with a period length of about 3 revolutions and with an amplitude of about 200 μm (peak)

appear in all measurement curves. These oscillations are physically effected by axial rotor vibrations, because they were observed at all blades and at all measurements above 45,000 rpm in the same way. Thus, they do not represent measurement errors of the laser Doppler probe and have to be removed for determination of the measurement uncertainty. Therefore, a second order lowpass filter was applied to the measured blade position curves of all rotor blades and for all six measurements in order to remove these oscillations at 1/3 of the rotary frequency [12].

The resulting average standard deviations for all six measurements with different throttle settings are depicted in figure 9. On average over all 26 rotor blades, the resulting measurement uncertainty was between 27 μm and 37 μm . By averaging only over the five blades with highest SNR, values between 17 μm and 25 μm could be obtained. These results demonstrate that, above 45,000 rpm as well as for lower rotary frequencies, the measurement uncertainty of the laser Doppler tip clearance probe is approximately 20 μm .

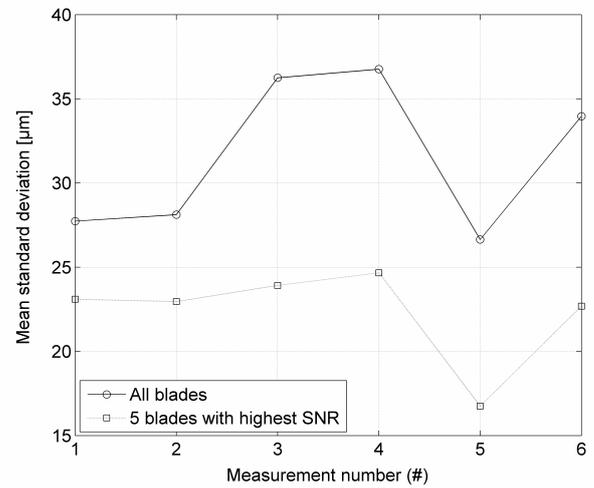


Fig. 9: Standard deviations of the measured tip clearances for the six different throttle settings, averaged over all blades and over the 5 blades with the highest SNR, respectively [12].

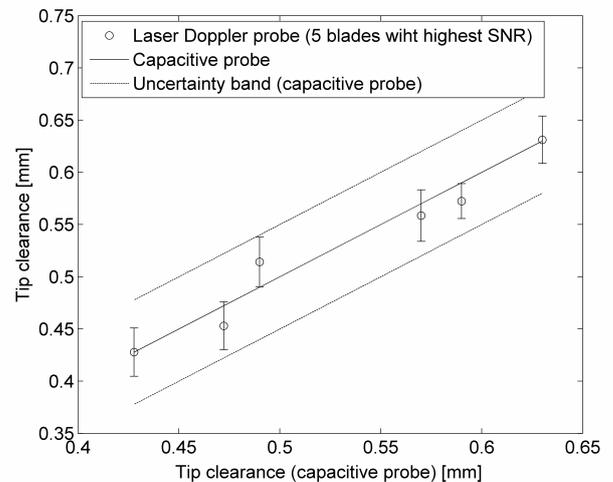


Fig. 10: Tip clearances measured with the laser Doppler probe averaged over the 5 rotor blades with highest SNR in comparison with the data from the capacitive probe. The dashed lines indicate the uncertainty interval for the capacitive probes [12].

In figure 10, the results of laser Doppler and capacitive measurements are compared. The individual data points represent the tip clearances measured with the laser Doppler probe averaged over the 5 rotor blades with highest SNR and 65 revolutions in dependence of the tip clearances measured with the capacitive probe. The error bars mark the measured standard deviations for the laser Doppler probe. For comparison, the solid curve indicates the tip clearance measured with the capacitive probe (identity) including an uncertainty interval, which was assumed to be $\pm 50 \mu\text{m}$. An excellent agreement occurs between the data of both sensors. No significant systematic measurement errors emerged. An average standard deviation of only $22 \mu\text{m}$ could be obtained, which is equal to the accuracy of the laser Doppler probe due to the absence of systematic measurement errors. This value is in good agreement with the results from section 4 and it is considerably better than the accuracy of capacitive probes of only $(50 \dots 100) \mu\text{m}$.

Consequently, the fiber-optic laser Doppler probe presented in this paper has proven to be capable of tip clearance and vibration monitoring at turbo machines.

9. CONCLUSIONS

A novel fiber optic laser Doppler probe based on an extended laser Doppler velocimeter was developed and applied for the first time to turbo machine single blade tip clearance and vibration measurements under operational conditions. It has been shown that the position uncertainty of this sensor is in principle independent of the object velocity. Thus, in contrast to other measurement techniques, the novel laser Doppler probe offers high temporal resolution and high position resolution simultaneously. An all-passive fiber coupled measurement head makes the sensor robust, flexible and immune against temperature influences and electrical disturbances.

The experiments were carried out at a transonic centrifugal compressor test rig of the German Aerospace Center (DLR). Measurements of tip clearance and rotor vibrations during power up and shut down of the compressor as well as at maximum rotary frequency of 50,000 rpm (833 Hz) corresponding to 21.7 kHz blade frequency and 586 m/s blade tip velocity were presented. All measurement results are in excellent agreement with those of capacitive probes. However, the measurement uncertainty of the laser Doppler probe was only around $20 \mu\text{m}$ on average and, thus, considerably superior to conventional tip clearance probes, which have an accuracy of only $(50 \dots 100) \mu\text{m}$. Due to the high temporal resolution of this sensor, individual rotor blades could be resolved even at maximum speed of 50,000 rpm. Hence, also axial rotor vibrations could be detected in good agreement with capacitive probes.

Consequently, the novel fiber optic laser Doppler probe presented in this paper has great potential for in-situ tip clearance and vibration monitoring at metallic and non-metallic turbine blades with high precision. It opens up new perspectives in the field of real-time production metrology and process control and for future developments of turbo machines.

ACKNOWLEDGMENTS

The authors thank M. Beversdorff, H. Fischer and J. Schlappa for their technical support at the compressor test rig and P. Becker for calibrating the sensor. Also the financial support from the Deutsche Forschungsgemeinschaft (FKZ: Cz 55/15-1) is greatly acknowledged.

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