

Deformation Monitoring of High-Speed Rotors using a Non-Incremental Interferometric Measurement System

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Abstract:

We present a non-incremental interferometric measurement system for in-process monitoring of the dynamic behaviour of high-speed rotors, which is essential for improving safety and energy efficiency of motors and turbo machines, such as aircraft engines. The measurement system is based on the novel laser Doppler distance sensor which exhibits the unique feature that its measurement uncertainty of some microns is independent of the velocity of the device under test. This allows precise measurements of rotor deformations and blade vibrations even at high rotor speed. By aligning three sensors equally spaced by angles of 120° along the circumference of the rotor, dynamic deformations such as radial expansion and tumbling motions of the rotor can be measured simultaneously. Due to the robust fiber-optic sensor design, measurements can be carried out under vacuum condition and at high temperatures too.

Introduction

In order to improve the safety and the lifetime as well as the energy efficiency of motors and turbo machines, the dynamic behaviour of the rotor has to be monitored and optimized. This includes analyzing vibrations and tumbling motions of the rotor provoked by, e.g., temperature variations, rotor unbalance or mechanical stress. In addition, elastic and plastic deformations occur in particular at high rotor speed. Their measurement is of huge interest especially for testing the robustness and the stiffness of lightweight rotors made of fiber reinforced composites, whose nonlinear and anisotropic behaviour is too complex to be calculated reliably.

It is a big challenge for metrology to measure rotor deformations and vibrations at high speed, since contactless and non-incremental measuring methods are required offering both micron position resolution and microsecond temporal resolution. Generally, optical sensors allow non-contact and precise shape measurements. However, incremental sensors such as interferometers or laser scanning vibrometers are out of question, because their measurement results become ambiguous if distance or radius jumps of more than half the

laser wavelength occur, e.g. at rough surfaces. Furthermore, the measurement 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 (triangulation, chromatic confocal techniques, frequency domain OCT). Therefore, precise and highly dynamic measurements are not possible with these sensors. Furthermore, the measurements have to be performed under vacuum condition quite often.

To solve this problem we developed a novel interferometric laser Doppler distance sensor (LDD sensor), which enables non-incremental position and shape measurements of moving and especially rotating objects [1-2]. Remarkably, its measurement uncertainty of some microns is independent of the test object velocity in principle [2]. This unique feature allows precise measurements of rotor deformations and blade vibrations even at high rotor speed [2,3]. Furthermore, a compact and robust fiber-optic sensor head has been realized employing diffractive optics [2-4]. Thus, measurements are possible even under harsh environmental conditions such as high temperatures occurring at turbo machines [2,3] as well as under vacuum condition [5].

In the following, the functional principle of the LDD sensor is explained at first. Afterwards, the experimental setup is described and the measurement results are presented. Finally, the most important results are summarized.

Functional principle of the LDD sensor

The LDD sensor is based on laser Doppler velocimetry (LDV) which is a well-established technique for measuring velocities of point-wise scattering particles in fluid flows and also of moved solids. 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. However, due to the wave front curvature of Gaussian laser beams, the fringe spacing d is not constant but varies along the axial position z . This limits the achievable velocity measurement accuracy of conventional LDV sensors fundamentally since the object position z is not known.

The basic idea of the LDD sensor is to enhance this parasitic position dependency of the fringe spacing $d(z)$ significantly and to utilize it for determining the axial position z of the measurement object in addition to its tangential velocity v [1-2] (Fig. 1). For this purpose, two superposed fan-shaped interference fringe systems with contrary fringe spacing gradients are generated inside the same measurement volume using wavelength division multiplexing

(see Fig. 1, top). The fringe spacings $d_{1,2}(z)$ are monotonously increasing and decreasing functions 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 [1-2]

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

which is also monotonously varying and does not depend on the object velocity v . Therefore, this quotient $q(z)$ can be used to determine the axial position z of a scattering object inside the measurement volume non-incrementally and independently of its transverse velocity $v = v_x$. With the known position z , the actual fringe spacings d_1 and d_2 at the position of the measurement object can be identified via the calibrated fringe spacing curves $d_{1,2}(z)$. As a result, the velocity v can be calculated precisely according to $v = f_1 d_1 = f_2 d_2$. Thus, axial position z and tangential velocity v of scattering objects can be determined simultaneously.

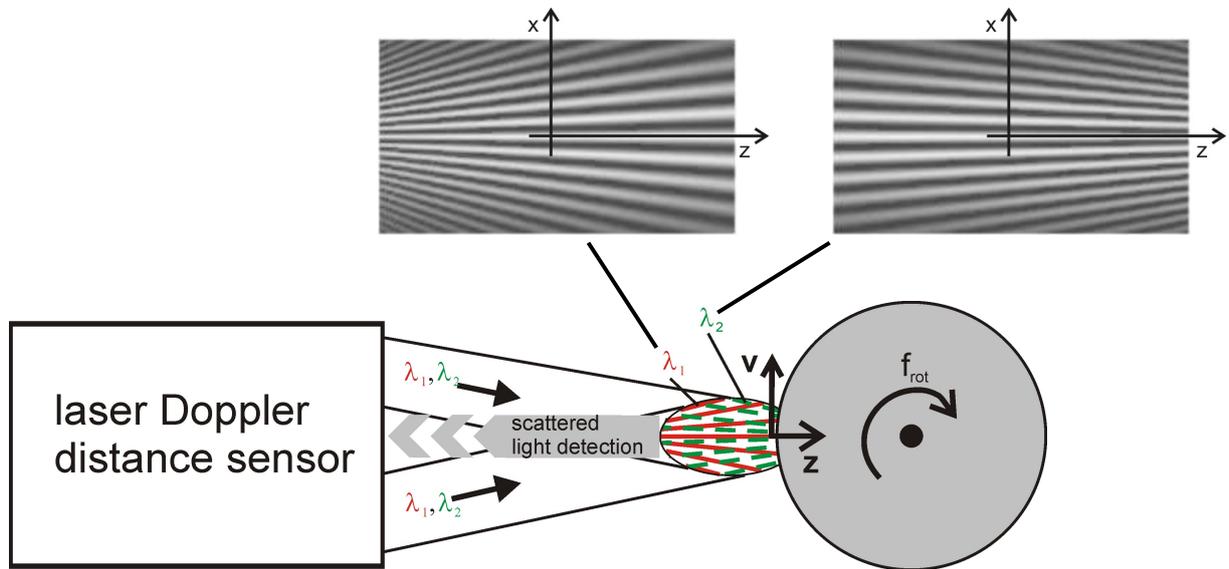


Fig. 1: *Bottom*: LDD sensor that comprises a measurement volume with two superposed fan-shaped interference fringe systems distinguishable via wavelength coding (λ_1, λ_2) for measuring simultaneously axial position z and tangential velocity v of a rotor. *Top*: Enlarged interference fringe systems with monotonously increasing (left) and decreasing (right) fringe spacing in axial direction z , which are superposed in the same location inside the measurement volume.

Experimental setup

At the Institute of Lightweight Engineering and Polymer Technology of the Technische Universität Dresden, a special high-speed rotor test rig exists, where research on the robustness and on the dynamic behaviour of rotors is accomplished (Fig. 2). The rotors

under investigation can be accelerated up to 250,000 rpm. The test rotors are mounted only unilaterally to the top cover of the test rig (see Fig. 2 (c)) which provokes tumbling motions. To measure simultaneously dynamic rotor deformations and tumbling motions, a 3-point LDD sensor measurement system is required (see Fig. 2) [5]. The three sensors are arranged at the same object height but at different angular positions along the object circumference with offsets of 120° against each other. Furthermore, all three sensors are directed to the rotation axis which coincides with the center of mass assuming a cylindrical rotor. The measured position values of the three sensors are corresponding to three points in a plane, which are unambiguously defining a circle representing size and position of the cylindrical rotor. Assuming that the mean object radius is much larger than the radial expansions ΔR caused by speed or temperature as well as much larger than the amplitude of occurring tumbling motions, the radial alignment of the sensors with respect to the rotation axis will be always maintained in good approximation.

Here, as a test object, a cylindrical rotor out of steel was used exhibiting a diameter of 190 mm, a height of 300 mm and a mass of about 60 kg (see Fig. 2). For safety reasons, the rotation speed was restricted to a maximum of 12,000 rpm corresponding to a maximum surface speed of around 120 m/s. All measurements were accomplished both at normal atmospheric air pressure of 1 bar and at low vacuum pressure of 5 mbar ($= 5 \cdot 10^{-3}$ bar).

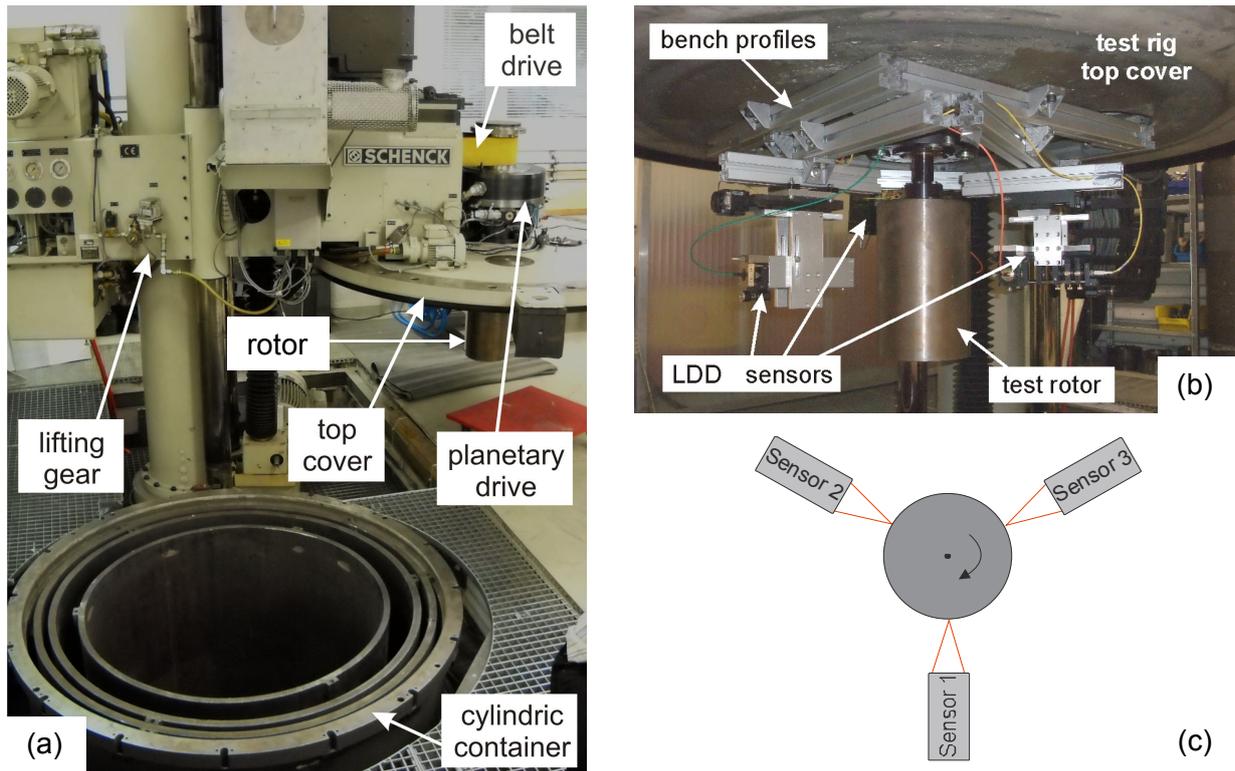


Fig. 2: (a) Vacuum high-speed rotor test rig; (b) enlarged picture of the test rig top cover with the test object (steel cylinder) and the three LDD sensors attached to it; (c) configuration of the 3-point LDD sensor measurement system.

Results

Fig. 3 depicts the measured variation in time of the center of mass in x_c - and y_c -directions for a rotation speed of 2000 rpm as well as the corresponding two-dimensional map for the tumbling motion. For better visibility of the tumbling, regression curves were fit to the raw data. The peak-to-peak amplitude of the tumbling in x_c - as well as in y_c -direction amounts to about 200 μm at maximum. Furthermore, the wobbling is not stationary which is clearly visible in the two-dimensional map shown on the right side of Fig. 3.

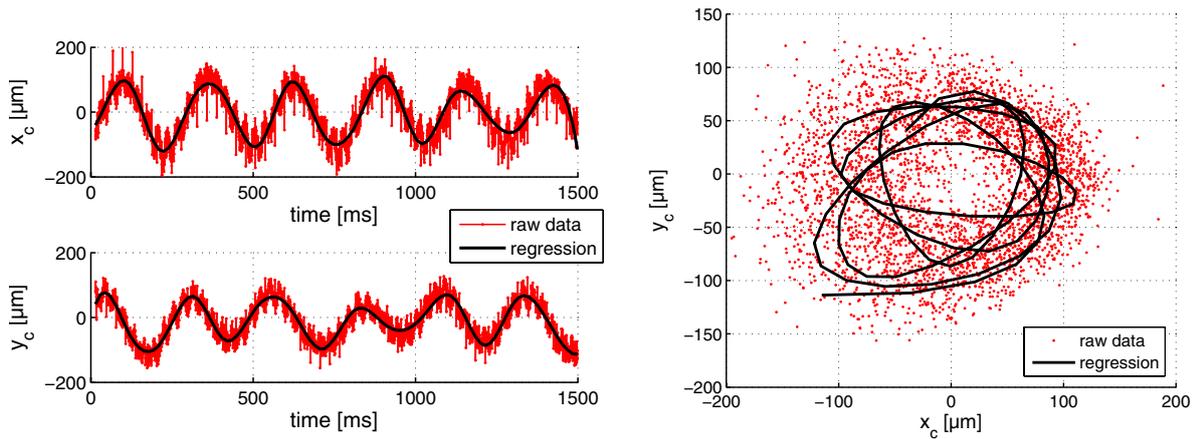


Fig. 3: Measured dynamic displacement of the center of rotation, i.e. the center of mass, $(x_c, y_c)^T$ of a cylindrical steel rotor over time (left) and corresponding two-dimensional map of the tumbling motion (right). The black lines represent regression curves [5].

For a quantitative analysis of the dependency of the wobbling magnitude against the rotation speed, the standard deviations of the displacements of the center of mass were calculated according to

$$\sigma_{center\ of\ mass} = \sqrt{\sigma_{x_c}^2 + \sigma_{y_c}^2} . \quad (2)$$

As a result, it can be seen in Fig. 4 that the tumbling amplitude is maximal at a rotational speed of 2000 rpm representing a resonance point and that it is strongly decreasing towards higher rotor speed. Furthermore, there are no significant differences between the measurements under normal atmospheric air pressure and under low vacuum.

In addition, the radial expansion ΔR of the test rotor has been evaluated in dependence of the rotational speed f_{rot} . According to theory, the radial rotor expansion is directly proportional to the square of the rotation speed, i.e. $\Delta R \sim f_{rot}^2$ [5]. The obtained measurement results agree very well with this theory as indicated by the quadratic regression curve included in Fig. 5. The radius measurement uncertainty is only 2 microns, see error bars in Fig. 5.

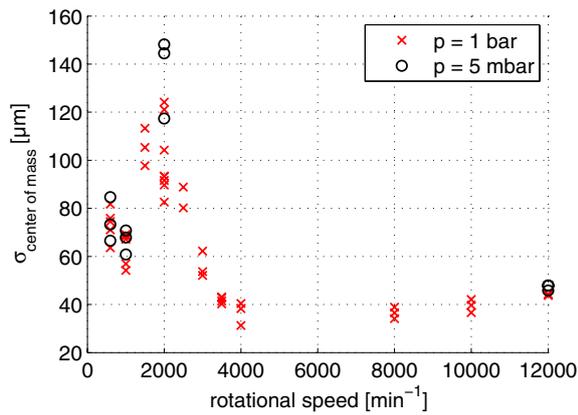


Fig. 4: Tumbling magnitudes in dependence on the rotational speed.

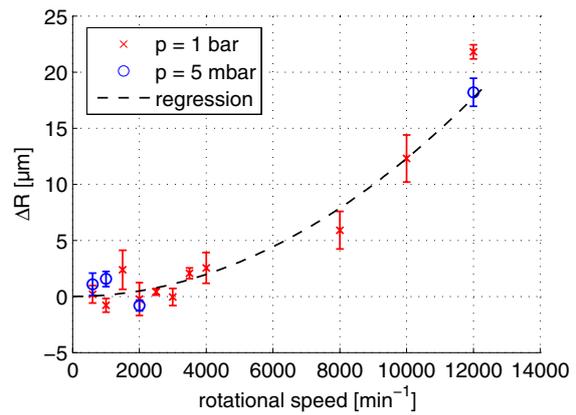


Fig. 5: Measured radial rotor expansion as a function of the rotational speed.

Conclusions

The presented experimental results demonstrate that dynamic deformations (radial enlargement) and tumbling motions of rough solid rotors can be measured simultaneously and independently using a multi-point LDD sensor measurement system. Due to the velocity independent measurement uncertainty of the LDD sensor, these measurements can be carried out also at high rotor speed. Furthermore it was shown that this measurement system can be applied under varying pressure conditions including vacuum.

Currently, also composite rotors are studied. Furthermore, tip clearance changes and blade vibrations of bladed rotors can be measured [2]. Details about that will be given in the talk.

Consequently, the novel multipoint LDD sensor measurement system opens up new perspectives for in-process monitoring of the dynamic behaviour of high-speed rotors. This is essential for improving lifetime and energy efficiency of motors and turbo machines, such as aircraft engines.

Acknowledgement

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