Miniaturized non-incremental fiber-optic sensor using diffractive optics for simultaneous distance and velocity measurement

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We use diffractive optics for miniaturization of a fiber-coupled interferometric sensor that allows for simultaneous measurements of distance and velocity. We show in-situ application of this sensor in a rotor test-rig for integrity studies of fiber reinforced polymer rotors under vacuum condition. Rotor deformations identified at high rotational speed prove the high potential of the sensor.

1 Introduction

The in-process observation of composite rotors of fiber reinforced polymer is very important as state-of-art simulations of these materials are not reliable. Thus measurements are necessary for improving both simulations and the quality of the rotors and for optimizing the materials towards light-weight, durable, cost-effective rotors with high efficiency [1]. Such measurements have to be performed in rotor test-rigs and their behavior has to be monitored on-line. The position of the rotor is a very important measurand in rotor characterization, as it enables tracking the behavior during rotation and identifying e.g. widening, tumbling or wobbling. The search for an appropriate sensor that is capable of measuring the surface position of such rotor with high accuracy is challenging. Common sensors like capacitive or inductive ones are not usable with composites, as they require metallic surfaces. Optical sensors also reach their limits, as the measurement uncertainties strongly increase at the high rotational speeds necessary for testing.
Laser Doppler based techniques proved to be capable of measuring both velocity and position simultaneously at high surface velocities of hundreds m/s with an uncertainty in the micron range [2]. Hence they overcome the limitations of common optical sensors but consist of too bulky setups for in-situ measurements.
We present a miniaturized optical sensor head based on diffractive optical elements that is perfectly suited for in-situ measurements of all kinds of rotors, including composites.

2 Setup

The used sensor is based on the laser Doppler distance sensor (LDDS) introduced in [2]. The modular setup allows separating the illumination and detection from the passive measurement head. The illumination-unit illuminates the measurement head by a single-mode fiber with light of two laser diodes (λ_1=658 nm and λ_2=830 nm). The task of the measurement head is to create the measurement volume and to collect the light that interacted with the object.

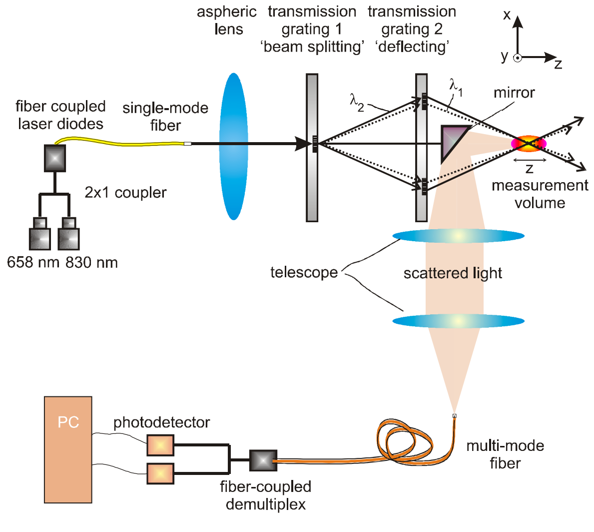

***Fig. 1** Experimental setup of the miniaturized sensor.*

The measurement volume consists of two spatially overlapping fringe systems which are created by two mutually interfering beam pairs of the two used wavelengths. Using a diverging and a converging fringe system with contrary fringe spacing gradients, a spatial coding across the measurement volume is achieved, which allows measuring the velocity and the position of the object simultaneously. These special fringe geometries are created using dispersion, introduced by an aspheric lens

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which creates the beam-waists in-front and behind of the measurement volume for the two-wavelengths. The miniaturization is mainly achieved by the usage of diffractive optical elements located on glass-substrates, which allow minimizing the number of optical elements used to form a simple and robust Mach-Zehnder interferometer [3], as shown in Figure 1. An object that passes the fringes scatters light which is coupled into a multi-mode fiber using a telescope. The detection-unit demultiplexes the signals for the two wavelengths and two Doppler frequencies $f_{d1}(z)$ and $f_{d2}(z)$ are obtained. These allow determining the position at which the object crossed the volume, using the quotient of the two Doppler frequencies q(z)

$$q(z) = \frac{f_{d2}(z)}{f_{d1}(z)} \quad . \qquad (1)$$

3 Results

The test object is a rotor-disc of fiber reinforced polymer with a diameter of d=50 cm. The disc is mounted in an evacuated rotor test-rig and is accelerated to 100 Hz, which corresponds to a surface velocity of about 160 m/s. The sensor monitors the edge of the rotor-disc that crosses the measurement volume and scatters the light. Figure 2 illustrates the configuration. The effective measurement rate is about 12 kHz. One revolution corresponds to 122 sampling points, with a mean averaging length for each point on the surface of the rotor of 12 mm.

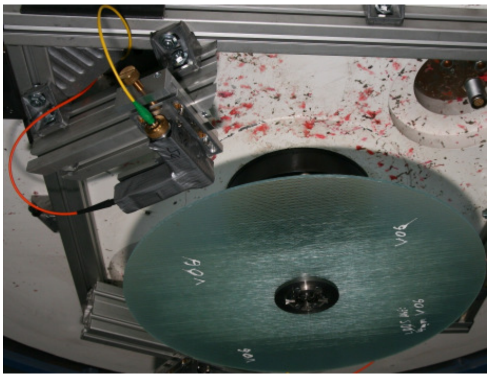

Fig. 2 *The passive sensor head monitors the edge of the rotor disc within the test-rig. The cracks visible on the surface of the disc originate from damages that occurred at high-speed*

At high rotation frequencies the rotor starts widening which is monitored by the sensor as a distance change. The deformation for f_{rot}=100 Hz is shown in figure 3 in a radial plot. The widening is elliptical as the rotor has different longitudinal and transversal tensile moduli. The mean standard deviation for each point of the angle resolved position is about $\sigma_r \approx 25$ µm. Using averaging the mean uncertainty for the expansion can be calculated to $\sigma_e \approx 1$ µm.

4 Conclusion

Using diffractive optical elements we miniaturized an optical sensor that is capable of measuring the position of a fast rotating rotors in-process. The sensor is flexible as it is usable at metallic and composite rotors. Changes in the position due to e.g. widening can be tracked and allow analyzing and comparing the integrity of rotors of different kinds of material and composition.

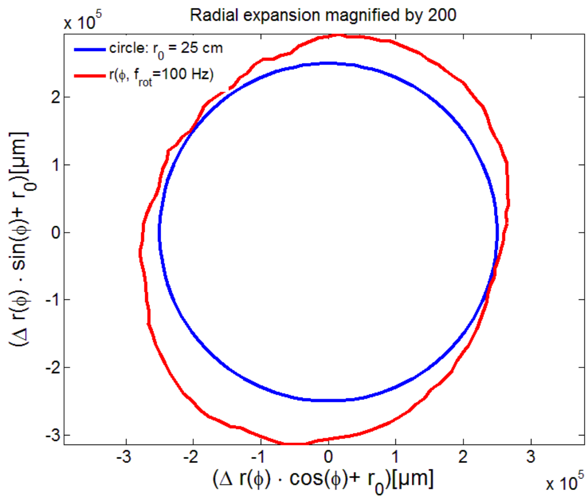

Fig. 3 *Angle resolved radial expansion of a composite rotor at a rotation speed of 100 Hz. The blue curve corresponds to an ideal circle, while the red curve shows inhomogeneous expansion creating an elliptical profile.*

Ongoing development promises sensors of this kind to be usable at high-temperatures up to 600°C and at high ambient pressure. This is important for in-process monitoring of turbo machines which is essential for improving lifetime and efficiency.

5 Acknowledgement

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