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Multi-sensor system for in situ shape monitoring and damage identification of high-speed composite rotors

K. Philipp [a,*], A. Filippatos [b], R. Kuschmierz [a], A. Langkamp [b], M. Gude [b], A. Fischer [a], J. Czarske [a]

[a] Laboratory for Measurement and Sensor System Techniques, Technische Universität Dresden, 01062 Dresden, Germany
[b] Institute of Lightweight Engineering and Polymer Technology, Technische Universität Dresden, 01062 Dresden, Germany

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ABSTRACT

Glass fibre-reinforced polymer (GFRP) composites offer a higher stiffness-to-weight ratio than conventional rotor materials used in turbomachinery. However, the material behaviour of GFRP high-speed rotors is difficult to predict due to the complexity of the composite material and the dynamic loading conditions. Consequently dynamic expansion measurements of GRFP rotors are required in situ and with micron precision. However, the whirling motion amplitude is about two orders of magnitude higher than the desired precision. To overcome this problem, a multi-sensor system capable of separating rotor expansion and whirling motion is proposed. High measurement rates well above the rotational frequency and micron uncertainty are achieved at whirling amplitudes up to 120μm and surface velocities up to 300 m/s. The dynamic elliptical expansion of a GFRP rotor is investigated in a rotor loading test rig under vacuum conditions. In situ measurements identified not only the introduced damage but also damage initiation and propagation.

1. Introduction

1.1. Motivation

Glass fibre-reinforced polymer (GFRP) composites offer high stiffness-to-weight ratios as well as adjustable directional material properties, making them an attractive alternative to conventional rotor materials [1–4]. However, the behaviour of GFRP high-speed rotors is difficult to predict due to the complexity of the composite material and the complex dynamic loading condition. In order to characterize CFRP rotors, their dynamic expansion due to the centrifugal forces is evaluated. Damage or destruction of the fibres leads to an increased expansion of the rotor radius that has to be measured preferably in situ in order to characterize the dynamic material behaviour [5]. Since the radial expansion is typically in the range from 0 to 200 μm [5] at common rotor diameters of 500 mm, a micron measurement precision is required. However, whirling motions with frequencies about 10% of the rotational frequency and amplitudes up to 150 μm [6] occur and, thus, are almost two orders of magnitude higher than the desired precision. In order to achieve the required micron measurement precision of the rotor shape, the cross-sensitivity regarding the whirling motion of the rotor has to be decreased. Typical rotational speeds of several 1000 rpm require a correction

* Corresponding author. Tel.: +49 351 463 39808.
E-mail address: katrin.philipp@tu-dresden.de (K. Philipp).

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of the whirling motion influence with temporal resolutions in the microsecond range as well as a measurement system that is able to cope with the high surface speeds of several 100 m/s. As a result, an in situ measurement system to monitor the rotor expansion at high rotational speeds with micron measurement precision is required for the characterization and prediction of the damage evolution within the rotor.

1.2. State-of-the-art

Ultrasonic testing [7–9], X-ray tomography [10] and thermography [11] are the state-of-the-art for spatially resolved inspection of fibre-reinforced structures. In order to investigate the dynamic behaviour of the rotor and the damage propagation, the rotor has to be inspected during operation. The mentioned techniques are difficult to apply at fast rotating systems, however.

The rotor behaviour with increasing rotational frequencies can be monitored using strain gauges [12]. However, they can rip of due to the high rotational speeds, before the damage propagation starts, if they are attached on the rotor surface. Integrated strain gauges are invasive and consequently can influence the dynamic material behaviour.

Measuring the dynamic expansion, i.e. the expansion dependent on the rotational frequency, enables a contact-less and destruction-free characterization of the dynamic material behaviour [5]. Electrical sensors like capacitive, inductive or eddy current probes, are well-established for measurements at metallic probes [13], but are only adaptable with restrictions for measurements at composites due to the low magnetic permeability and electrical conductivity of the material.

The radial expansion of composite rotors can be measured using several optical distance sensors along the circumference of the rotor. Well-established optical measurement techniques like chromatic confocal sensing [14], triangulation [15], absolute distance interferometry [16], laser micrometers [17] and low coherence interferometry [18] can be applied under ideal conditions. However, high surface roughnesses, translucency of the rotor material as well as the surface speeds of several 100 m/s limit the applicability of those sensors. In contrast, laser Doppler distance sensors (LDD) are inherently capable to deal with translucency of the rotor material [19] and the measurement uncertainty is hardly influenced by the surface velocity.

Dynamic expansion monitoring at metallic [6] and glass-fibre reinforced polymer rotors [5] has been conducted using a three component LDD sensor system. However, these measurements either require the assumption of a circular rotor shape [6] or a zero-average whirling motion [5]. Since the rotors to be investigated show elliptical expansion [5], which is due to the highly anisotropic fibre layup, and whirling motions do occur, which are not always zero-average [6], this approach cannot be applied in every case. Hence, the task of elliptical expansion monitoring at GFRP rotors with micron measurement precision, that is achieved by taking into account the whirling motion of the rotor, has not yet been addressed sufficiently.

1.3. Aim and outline

A four component multi-sensor system for dynamic elliptical expansion monitoring is presented. Micron measurement uncertainty is achieved by applying advanced signal processing algorithms based on the separation of the whirling motion from the radial expansion.

In Section 2 the multi-sensor system is presented as well as the measurement principle of the applied laser Doppler distance sensors. Two novel signal processing algorithms are introduced in Section 3 in order to reconstruct the rotor shape

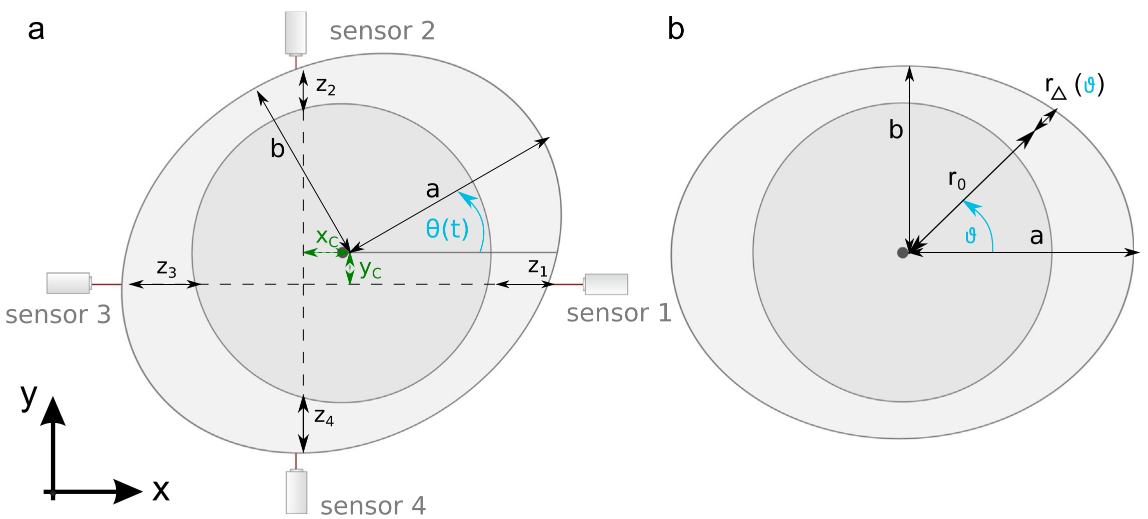

Fig. 1. Setup of the multi-sensor system consisting of four LDD sensors equally distributed along the circumference of the rotor. The sensor signals z_i contain information about the radius expansion r_Δ at the measured position as well as the whirling motion which is represented by the motion of the rotor centre position (x_c, y_c). In order to describe the measurement system, a sensor-fixed coordinate system with origin at the crossing point of the sensor axes (a) as well as a co-rotating, rotor-fixed coordinate system (b) are introduced.