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In-process, non-destructive, dynamic testing of high-speed polymer composite rotors

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ABSTRACT

Polymer composite rotors are lightweight and offer great perspectives in high-speed applications such as turbo machinery. Currently, novel rotor structures and materials are investigated for the purpose of increasing machine efficiency and lifetime, as well as allowing for higher dynamic loads. However, due to the complexity of the composite materials an in-process measurement system is required. This allows for monitoring the evolution of damages under dynamic loads, for testing and predicting the structural integrity of composite rotors in process. In rotor design, it can be used for calibrating and improving models, simulating the dynamic behaviour of polymer composite rotors. The measurement system is to work non-invasive, offer micron uncertainty, as well as a high measurement rate of several tens of kHz. Furthermore, it must be applicable at high surface speeds and under technical vacuum.

In order to fulfil these demands a novel laser distance measurement system was developed. It provides the angle resolved measurement of the biaxial deformation of a fibre-reinforced polymer composite rotor with micron uncertainty at surface speeds of more than 300 m/s. Furthermore, a simulation procedure combining a finite element model and a damage mechanics model is applied. A comparison of the measured data and the numerically calculated data is performed to validate the simulation towards rotor expansion. This validating procedure can be used for a model calibration in the future. The simulation procedure could be used to investigate different damage-test cases of the rotor, in order to define its structural behaviour without further experiments.

1. Introduction

1.1. Motivation

The combination of increasing economic demands and high-performance requirements in various branches leads to design solutions containing extremely loaded, lightweight components. In such applications, the usage of polymer based fibre-reinforced composite materials became the state of the art in the last few years. Particularly in the case of complex

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loading conditions, which are typical for wind turbines and high-speed rotor components, fibre-reinforced composites with adjustable mechanical properties represent an advantageous alternative to conventional monolithic materials [1,2].

However, due to the complexity of the composite materials their behaviour under dynamic loads is difficult to predict, especially for complex rotor geometries. For rotor design, measurements are necessary in order to calibrate and verify models simulating the rotor behaviour under dynamic loads. Furthermore, damages within the composite rotor can evolve slowly and unnoticed in process. These can reduce the load capacity significantly. Consequently, testing and predicting the structural rotor integrity is important, in order to prevent unexpected rotor failure. As a result, non-invasive, in-process monitoring of the rotor is required.

1.2. State-of-the-art

Ultrasonic testing is the most widely used non-destructive inspection method for the position resolved examination of structures. However, at composites the applicable frequency is below 5 MHz due to the increasing attenuation of the material for higher frequencies. This results in a low resolution and, thus, a low detection accuracy of small damages. Furthermore, an on-line ultrasonic testing method for high-speed moving rotors has not yet been reported [3].

In order to test and monitor the integrity of the rotor structure Young's modulus of the rotor before and after loading can be compared. The standard approach for determining Young's modulus of a certain material are tensile tests [1]. However, tensile tests are static and offer only little information about the dynamic behaviour of the structured rotor. Furthermore, they do not replicate the dynamic, radius dependent, radial forces applied on a rotating bladed rotor, especially for anisotropic materials. Additionally, the composite rotor has to be dismounted from the machine for tensile tests, making the procedure time consuming.

For testing a rotor under dynamic loads a rotor test rig can be used for burst trials. However, this provides only the maximum applicable rotational speed of the rotor under a specific dynamic loading. Using high-speed cameras to monitor the burst process gives additional information about weak points in the rotor [4]. However, such a method does not give any information regarding the damage evolution and in any case this test leads to the destruction of the specimen.

In order to monitor the dynamic behaviour of the composite rotor without destruction, strain gauges can be applied [5]. Strain gauges mounted on the rotor can rip off at higher rotation frequencies prior to the damage initiation. Integrated strain gauges are invasive. This can lead to negative structural effects, e.g. stress concentrations or local reduction of adhesive forces, alter the stress and strain fields and therefore change the dynamic behaviour of the rotor. Furthermore, an expensive telemetry system is necessary and every single rotor has to be equipped with several gauges which is both time and cost consuming.

A non-invasive, in-process approach is to determine the radial expansion at different rotor frequencies. Electrical sensors such as capacitive, inductive or eddy current probes can be used for metallic rotors and are well established [6]. However, they fail at composite rotors due to the low magnetic permeability and electrical conductivity of the material.

A non-invasive, optical measurement system is proposed to be applied at composite rotors. In order to achieve a high angular resolution at high surface speeds, a measurement rate of several 10 kHz is needed. Furthermore, micron uncertainty is desired. Several optical measurement techniques such as triangulation [7], low coherence interferometry [8], laser Doppler vibrometry [9], absolute distance interferometry [10] or chromatic confocal sensing [11] can fulfil at least one of these requirements under ideal conditions. However, material properties, such as surface roughness, high optical transmittance or absorption of the used composite in combination with the high surface speed of several 100 m/s, increase the measurement uncertainty of these conventional optical measurement techniques significantly.

In contrast, a laser Doppler distance sensor is well suited for measurements of fast moving, rough surfaces, since its distance measurement uncertainty is nearly independent from the surface velocity. The sensor measures the surface distance with micron uncertainty and was already applied for metallic rotors at velocities of around 600 m/s [12]. Concerning metallic rotors, its capability of measuring the radial expansion with a measurement rate of several 10 kHz was already demonstrated [13]. At composite rotors the laser Doppler distance sensor was already used for monitoring blade vibrations [14].

In the recent years extensive investigations have been performed in the theoretical prediction of progressive failure of 3-dimensionally stressed laminates until final failure [15] and in the development of phenomenological damage models capable of predicting different diffuse and discrete damage phenomena [16]. A combination of such damage mechanics models with the Finite Element theory has been introduced for the numerical analysis of the dynamic behaviour of composite rotors and some first qualitative results have been presented [17,18]. Until now however, a comparison and validation of the simulation procedure with experimental data has not yet been performed to the authors' knowledge.

1.3. Aim and outline of the paper

The aim of this paper is to apply the laser Doppler distance (LDD) sensor, developed by TU-Dresden, for in-process, non-destructive testing of the structural integrity of high-speed composite rotors. Furthermore, the experimental results are compared with numerical results to validate a simulation procedure. A multi-sensor measurement system was set up in order to monitor the expansion of a composite rotor, which was accelerated stepwise up to an angular velocity of 200 Hz, leading to surface speeds above 300 m/s. At first the investigated composite rotor is described briefly in Section 2.1. In order