COMBINED EXPERIMENTAL-NUMERICAL APPROACH FOR THE 3D VIBRATION ANALYSIS OF ROTATING COMPOSITE COMPRESSOR BLADES: AN INTRODUCTION

T. Wollmann[1], M. Dannemann[1], A. Langkamp[1], N. Modler[1], M. Gude[1], L. Salles[2], N. Hoffmann[2,3] and A. Filippatos[1]

[1]Institute of Lightweight Engineering and Polymer Technology, Technische Universität Dresden,
Holbeinstraße 3, 01307 Dresden, Germany
Email: tino.wollmann@tu-dresden.de, Web Page: http://tu-dresden.de/mw/ilk
[2]Department of Mechanical Engineering, Imperial College London,
Exhibition Road, London SW7 2AZ, UK
Email: l.salles@imperial.ac.uk, Web Page: http://www.imperial.ac.uk
[3] Department of Mechanical Engineering, Hamburg University of Technology,
21073 Hamburg, Germany
Email: norbert.hoffmann@tuhh.de, Web Page: http://www.tuhh.de/dyn

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Abstract

As compressor blades are subjected to highly dynamic loads, there is a particular interest in determining their modal properties under operating condition. Furthermore, intensive research is conducted for the development of fibre-reinforced epoxy blades due to the high specific stiffness and strength as well as the high damping of composite materials. Traditional modal analysis techniques are state of the art to determine the vibration behaviour of non-rotating/stationary blades, where some new approaches show the vibration analysis of rotating blades. These approaches for rotating structures have the disadvantage, that either the excitation or the measurement method are influencing the dynamic behaviour of the investigated structure or the method itself cannot be applied for composite materials. Other techniques do not allow a continuous or full-field measurement of the rotating structure. To determine the vibration behaviour of rotating composite compressor blades, a combined experimental-numerical approach is introduced. Therefore, an experimental system for the vibration excitation and a 3-dimensional determination of the vibration behaviour of rotating components are presented. An overview of the main addressed research topics is given.

1. Introduction

There is a particular interest in determining the modal properties of compressor blades under operating condition, as they are subjected to highly dynamic loads during operation. Furthermore, intensive research is conducted for the development of fibre-reinforced epoxy blades due to the high specific stiffness and strength as well as the high damping of composite materials [1, 2].

1.1. Motivation

During the development of new turbomachinery components, the behaviour of these structures under operating condition is of particular interest. Especially for rotating structures the influence of centrifugal forces plays an important role as the load distribution cannot applied in a tensile test in simplified form. To determine the realistic vibration behaviour at different rotational velocities, an experimental approach with rotating components is necessary. This approach would furthermore allow a validation of numerical models for different rotational velocity and the corresponding pre-stress.

1.2. State-of-the-art

Traditional modal analysis techniques are state of the art to determine the vibration behaviour of non-rotating/stationary blades, where some new approaches show the vibration analysis of rotating blades, e.g. [3, 4]. These approaches for rotating structures have the disadvantage, that either the excitation (e.g. piezoelectric actuators [5, 6]) or the measurement method (e.g. strain gauges [7]) influence the dynamic behaviour of the investigated structure or the method itself cannot be applied for composite materials (e.g. electromagnetic excitation [8]). Other techniques do not allow a continuous or full-field measurement of the rotating structure [9].

Specifically, Laser Doppler Vibrometery is a non-contact method for modal analysis, offering high accuracy in diverse applications. A Laser Doppler Vibrometer (LDV) uses the Doppler Effect on scattered laser light to measure the axial velocity at one point. To obtain full-field measurements, multiple points along a surface can be measured in series, hence the term Scanning Laser Doppler Vibrometer (SLDV) is used [10]. The measurement of rotating structures have e.g. been shown through the use of a continuous tracking SLDV [8] or the use of an SLDV in combination with an optical derotator [11].

Digital image correlation (DIC) is an image processing technique which also has the capability of full-field measurements without influencing the dynamic behaviour. Displacement fields are calculated based off the change in position of each correlated subset. The spatial density and radii of these subsets are parameters for the analysis, and should be selected with considerations to speckle size and camera resolution [12]. With the framerate higher than the Nyquist frequency, sufficiently high eigenfrequencies can be extracted from the frequency-domain displacement signal, obtained through the FFT [13]. For rotating structures problems occur by recording reproducible images because of triggering issues with the release of the high speed camera to the rotating structure at the same position [14] as well as motion blur and depth of field issues at complex geometries [15].

2. Methodical approach of the 3D vibration analysis of rotating blades

To determine the vibration behaviour of rotating composite compressor blades [16], a combined experimental-numerical approach is introduced. In this context, the individual elements of an experimental system for the vibration excitation and a 3-dimensional (3D) determination of the vibration behaviour of rotating components are presented. Recent improvements in Digital Image Correlation techniques [17] and Laser Doppler Vibrometry [18] offer novel possibilities for non-contact 3D modal analyses. These two methods for modal analysis will be adapted and used for the estimation of the dynamic behaviour of rotating components. An overview of the main addressed research topics is shown in Figure 1.

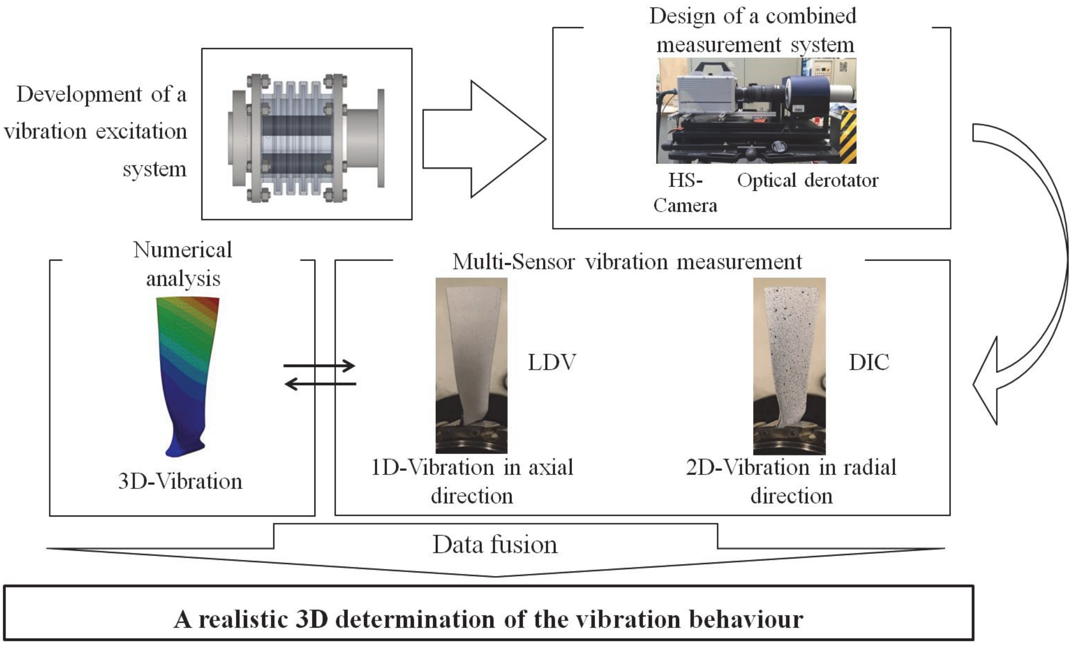

Figure 1. Overview of the main components required for a non-contact 3D modal analysis.

2.1. Development of a vibration excitation system

Several experimental methods exist for the excitation of components. For example, impulse excitation using chopped air, electromagnetic and impact methods can be used to excite the structure. Nevertheless, not all methods can be used in certain environments or for rotating composite components. Air excitation for example can be difficult in a low pressure environment (technical vacuum) and electromagnetic excitation can only be used for ferromagnetic materials [8]. Further piezoelectric methods can be applied, whereas the application of piezoelectric patches on the surface of a single blade or the integration of this patch into a blade from composite material [19] would influence the structural behaviour and is therefore tried to be avoided. A different and the here applied method is the excitation of the complete rotor by integrating piezo stack actuators between the shaft of the spindle and the rotor. In Figure 2 the principle concept of the excitation system is shown [20].

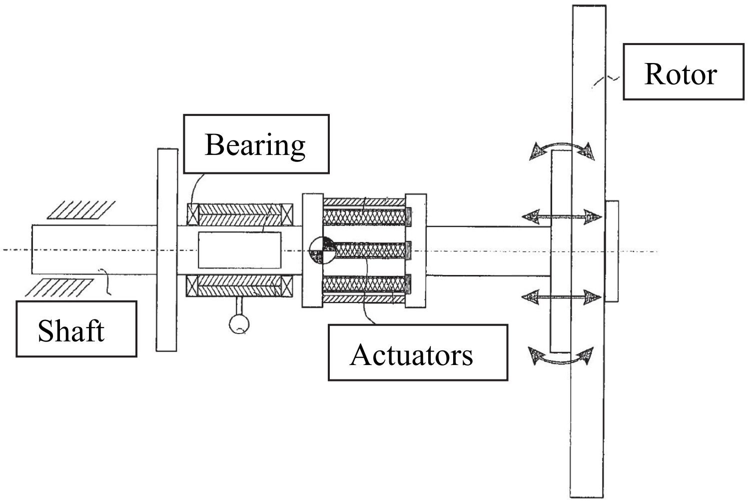

Figure 2. Principle concept of the excitation system [20].

2.2. Design of a combined measurement system for in-plane and out-of-plane displacements

For the proposed measurements of the 3D vibration behaviour, the experimental set-up consisting of a spin rig, an optical derotator [11], a SLDV and a high speed camera. Two measurements have to be conducted in parallel using a mirroring system behind the derotator or subsequently using the same experimental parameters.

Although no devices have to be applied for measurement or excitation, the composite blades have to be prepared for the optical measurement methods. In Figure 3, the unprepared composite compressor blade (left), prepared for SLDV measurement (middle) and prepared for DIC measurement are presented. The blades are prepared with reflective foil as well as with an stochastic speckle pattern. The SLDV measurements are then performed to determine the out-of-plane deflections and the DIC measurements are used for the determination of the in-plane deflections.

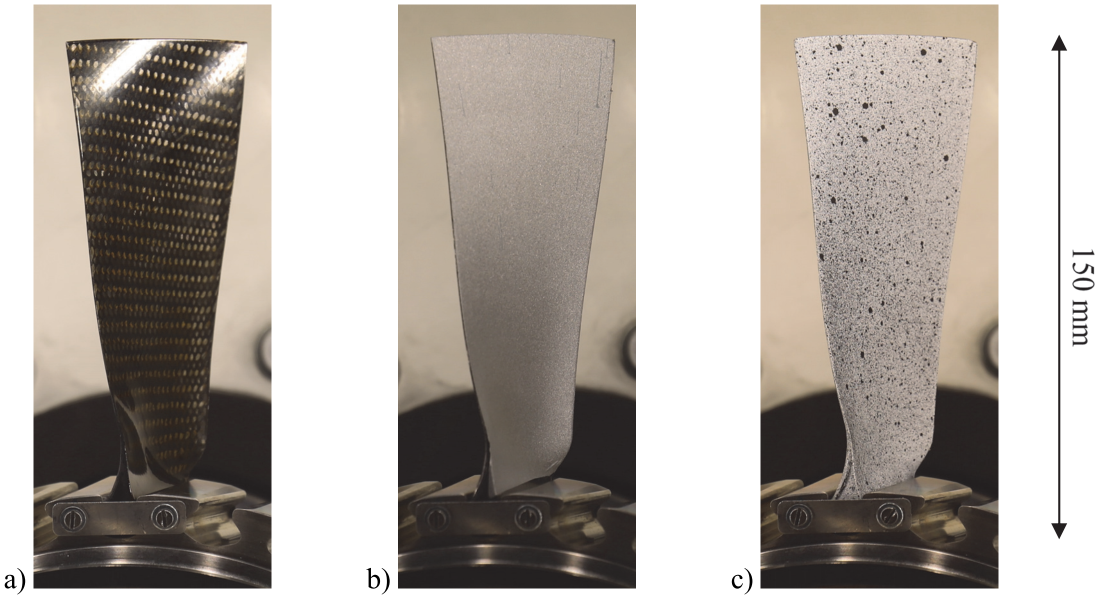

Figure 3. Illustration of the composite compressor blade (a), with reflective foil for the SLDV (b) and with a stochastic speckle pattern for the DIC measurement (c).

3. Experimental set-up for the combined measurements

The experimental set-up for both measurement systems and selected results are presented within this chapter.

3.1 Out-of-plane vibration measurement

For the investigation of the composite compressor blades, the vibration excitation system was mounted in the test chamber together with the bladed disc. As shown in Figure 4, an optical derotator was positioned in front of the test rig aligned with the axis of rotation. A modal analysis was afterwards performed under a technical vacuum and at a rotational velocity up to 1,500 RPM. For the presented results, the setting parameters for the modal analysis were defined as following. All of the measurement points were measured three times for 320 ms after the excitation. Frequencies up to 6.4 kHz were measured with a resolution of 3.125 Hz and three channels were recorded. Namely the output signal for the voltage, the signal for the reference single point laser and the signal for the laser scanning head. The performed modal analyses have proven that the vibration excitation system is capable of exciting the composite blade though the disk and the bladed disc dovetail contact.

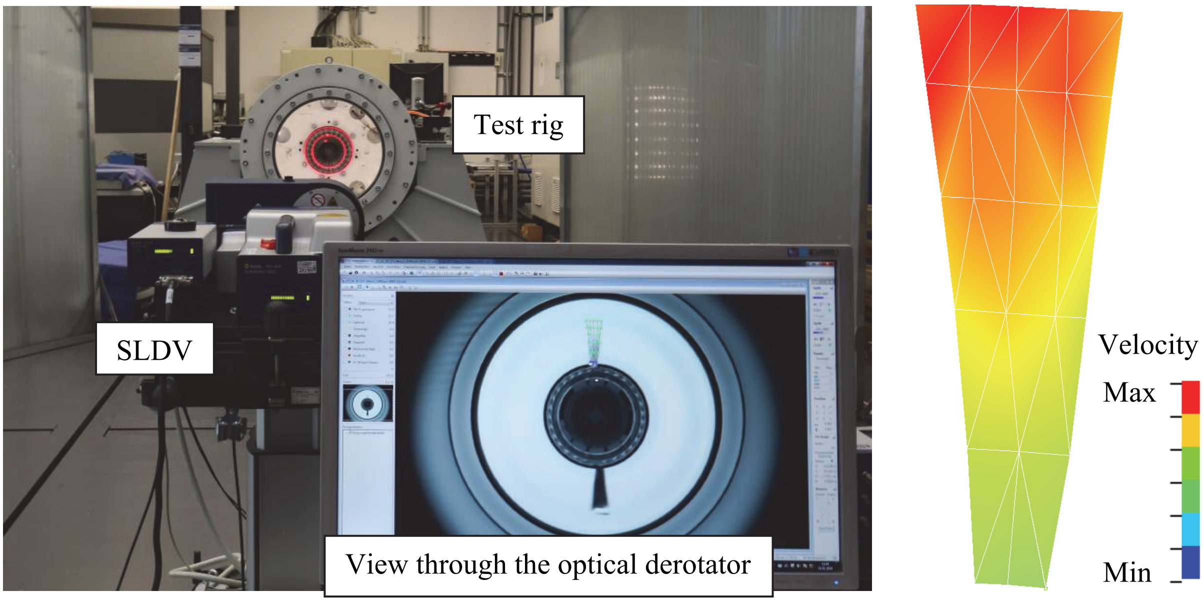

Figure 4. Experimental set-up for the SLDV-measurements using the optical derotator (left) and the measured mode shape of the 1st natural frequency at 1,000 RPM (right).

3.2 In-plane vibration measurement

A high speed camera is mounted on the optical derotator for the in-plane vibration measurements, as shown in Figure 5. Using the same alignment of the optical derotator as presented in the previous chapter, a suitable lens for the high speed camera and an additional illumination system, the camera is able to record high speed images without motion blur issues. Subsequently, a modal analysis can be performed and evaluated with a proper DIC software.

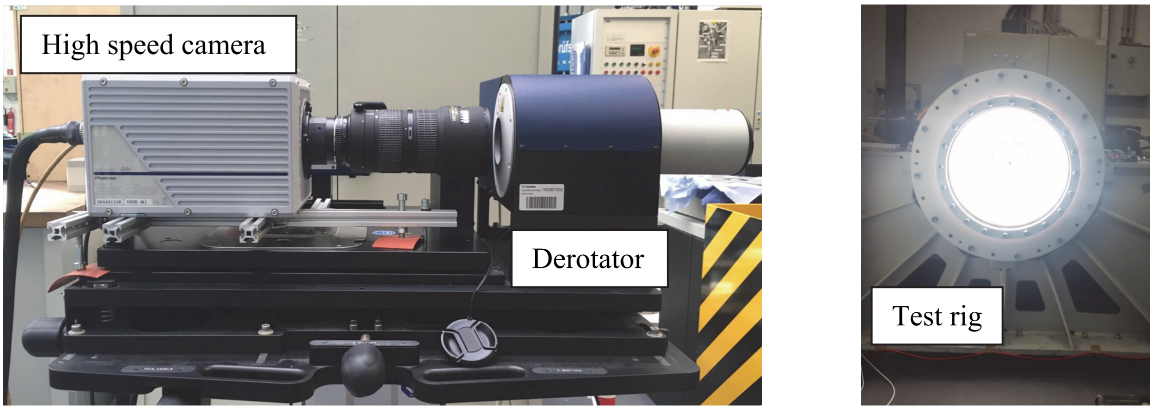

Figure 5. A high speed camera *Photron SA4* mounted on an optical derotator *Polytec PSV-A-440* (left) and illuminated test rig (right)

4. Fusion of experimental data and their comparison with numerical results

The out-of-plane SLDV measurements and in-plane DIC measurements are combined for a 3D dynamic analysis using MATLAB. The combined 3D results can be compared with the numerical results to determine the accuracy of the models, as shown in Figure 6. They can further be used to validate the first measured modal parameter and extend the overall understanding by generating numerical results which exceed the experimental results. The in-house code FORSE [21] developed in Imperial College permits to add the effect of the friction at the interface. The measured frequency response function can be compared with the numerical results in terms of amplitude of vibration, which allows to validate the numerical method. The SLDV-measurements using the optical derotator permits to compare the numerical results obtained in rotating frame and to validate the software in real operating condition.

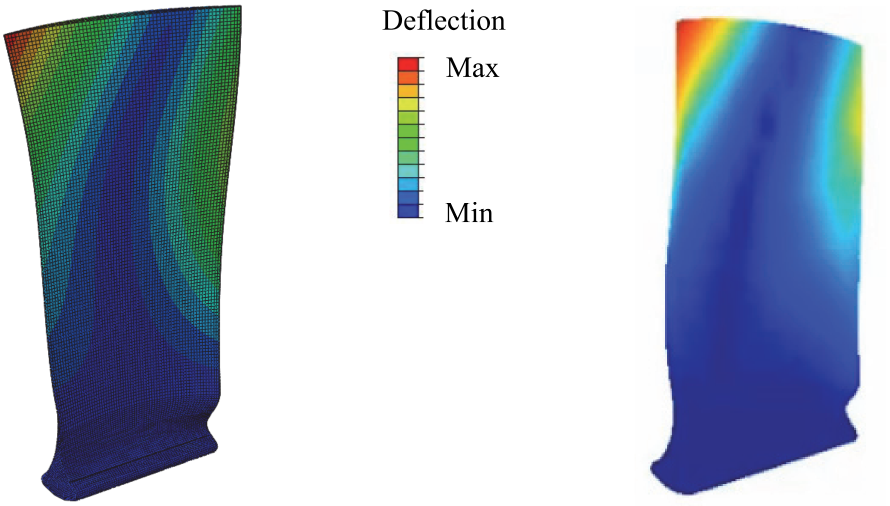

Figure 6. Illustration of the numerical results from the simulated 3D-discplacement (left) and the corresponding fused experimental results (right) for the 3rd natural frequency at non-rotating condition.

5. Conclusions

The main research topics for a combined experimental-numerical approach for the 3D vibration analysis of rotating composite compressor blades have been introduced. First successful results for the vibration measurement of composite compressor blades using a Scanning Laser Doppler Vibrometer have been presented, showing that the vibration excitation system is capable of exciting the composite blade though the disk and the bladed disc dovetail contact. The combination of novel excitation systems together with high-end measurements systems presented here can be a sound basis for further developments in the field of experimental testing of composites under realistic loading and operational conditions.

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