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Forced response of rotating bladed disks: Blade Tip-Timing measurements

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ABSTRACT

The Blade Tip-Timing is a well-known non-contact measurement technique currently employed for the identification of the dynamic behaviours of rotating bladed disks. Although the measurement system has become a typical industry equipment for bladed disks vibration surveys, the type of sensors, the positioning of the sensors around the bladed disk and the used algorithm for data post-processing are still not standard techniques, and their reliability has to be proved for different operation conditions by the comparison with other well-established measurement techniques used as reference like strain gauges. This paper aims at evaluating the accuracy of a latest generation Tip-Timing system on two dummy blisks characterized by different geometrical, structural and dynamical properties. Both disks are tested into a spin-rig where a fixed number of permanent magnets excite synchronous vibrations with respect to the rotor speed. A new positioning for the Blade Tip-Timing optical sensors is tested in the case of a shrouded bladed disk. Due to the presence of shrouds, the sensors cannot be positioned at the outer radius of the disk pointing radially toward the rotation axis as in the most common applications, since the displacements at the tips are very small and cannot be detected. For this reason a particular placement of optical laser sensors is studied in order to point at the leading and trailing edges' locations where the blades experience the largest vibration amplitudes with the aim of not interfering with the flow path. Besides the typical Blade Tip-Timing application aimed at identifying the dynamical properties of each blade, an original method is here proposed to identify the operative deflection shape of a bladed disk through the experimental determination of the nodal diameters. The method is applicable when a small mistuning pattern perturbs the ideal cyclic symmetry of the bladed disk.

1. Introduction

Vibrations in turbomachinery could reduce the blades fatigue life by increasing the risk of crack formation. In this frame the blade health monitoring represents an important challenge in order to prevent unexpected blade failures. Traditionally, the rotor blade vibrations have been detected using the strain gauges that still represent nowadays the most reliable measurement system. However, the main disadvantage in using the strain gauges is that they cannot be used in the engine in service since they need to be stuck on the blade airfoil. For this reason in the last years of blades monitoring, the non-contact measurement technique, the Blade Tip-Timing (BTT), has gained ground. The BTT technique is based on the analysis of the arrival times of the rotating blade under a set of stationary sensors [1,2]. In the most common applications the BTT sensors are mounted on the casing so that they are radially oriented towards the blade tips, in order to detect the greatest vibration amplitudes [3]. Besides of being non-contact and usable on

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working engines, the main advantage of the BTT system lies on the fact that it can monitor all the blades together during their rotation. It is therefore possible to identify if one blade vibrates more than the others as in the case of typical mistuning problems. The latest generation industry-standard BTT systems process the arrival times by using indirect [4–7] or direct [5,8–10] identification methods, in order to determine the modal parameters characterizing the vibrating blade. A verification on the correctness of the obtained parameters represents a due step in order to consider the BTT measurements as reliable. Different authors have demonstrated a good correlation between the BTT and strain gauge measurements for both real [3] and controlled [11] operation conditions, in the case where the displacements are measured at the blade tip using the standard radial sensors positioning.

The present paper explores the capability of the BTT technique as a measurement method useful not only for the evaluation of the maximum vibration amplitude and the corresponding resonance frequency of each single blade, but also for the identification of the deformed shape of the measured mode. In this frame an extensive experimental campaign was performed on two disks. The first is a dummy disk with a simple geometry of a flat plate, characterized by blade bending vibration modes in the disk axial direction. The second is a dummy disk designed to simulate a dynamic behaviour closer to a real turbine disk where the blades are connected to each other at the tips by an outer ring.

Two main issues are described throughout the paper. The first concerns the validation on both the dummy disks of the BTT measurements performed by using a new sensors placement named *beam shutter* configuration. This sensors arrangement is particularly suitable for measurements on shrouded bladed disks as in the case of [12] and requires only one set of optical laser sensors working both as senders and receivers of the reflected laser beam. The BTT measurements were then validated by the comparison to those acquired by the strain gauges that were glued only to few blades. The second issue is the proposal of an original method to identify, from the response data of all the blades, the nodal diameter number characterizing the dominant response mode of the disk. The method does not work when the mistuning is so large to completely destroy the ideal cyclic symmetry of the disk, but appears reliable only when a small mistuning is present. It is proved, in fact, that a small mistuning pattern induces a particular modulation of the blades response amplitude. It is shown in different cases, both experimental and simulated, that the number of wave-lengths (WLs) of this modulation is related to the number of the nodal diameter of the dominant response mode of the disk.

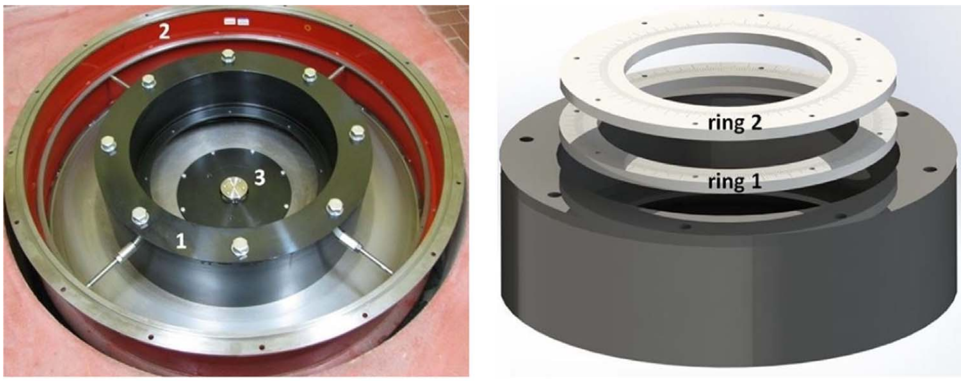
2. The spinning test rig

The two dummy disks were tested in a laboratory spinning rig at room temperature under vacuum conditions [13]. As shown in Fig. 1(a) the test rig has a vertical axis with two cylindrical protective structures (1 and 2) coaxial to the rotating shaft that is positioned under the floor. At the top of the shaft a flange allows the disk accommodation (3). The cylinder 1 also supports two static rings (Fig. 1(b)): the ring 1 keeps in a fixed position a set of permanent magnets that are used to excite the rotating disk, while the ring 2 holds the BTT laser sensors.

2.1. The dummy disks

The dummy disk 1 (Fig. 2(a)) is an aluminium disk with a simple geometry of a flat plate where each blade has the shape of a cantilever beam. The dummy disk 1 has 12 identical blades whose length and width are 150 mm and 25 mm respectively. The thickness and the outer diameter of the disk are 5 mm and 400 mm. A cylindrical magnet with a 5 mm diameter and 5 mm height is glued in a housing drilled at the tip of each blade.

The dummy disk 2 (Fig. 2(b)) was designed to have a dynamic behaviour closer to a real turbine disk. The blades are connected to each other at the tips by an outer ring as in the case of shrouded bladed disks. It is a single piece made of the ferromagnetic steel AISI 460, in order to allow the magnetic interaction between the permanent magnets and the blade airfoils. It has 32 real profiled blades



(a) (b)

Fig. 1. The spinning rig (a) and the supporting rings for the magnets and laser sensors positioning (b).