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Experimental and numerical simulation of a rotor/stator interaction event localized on a single blade within an industrial high-pressure compressor

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A B S T R A C T

This contribution addresses a confrontation between the experimental simulation of a rotor/stator interaction case initiated by structural contacts with numerical predictions made with an in-house numerical strategy. Contrary to previous studies carried out within the low-pressure compressor of an aircraft engine, this interaction is found to be non-divergent: high amplitudes of vibration are experimentally observed and numerically predicted over a short period of time. An in-depth analysis of experimental data first allows for a precise characterization of the interaction as a rubbing event involving the first torsional mode of a single blade. Numerical results are in good agreement with experimental observations: the critical angular speed, the wear patterns on the casing as well as the blade dynamics are accurately predicted. Through out the article, the in-house numerical strategy is also confronted to another numerical strategy that may be found in the literature for the simulation of rubbing events: key differences are underlined with respect to the prediction of non-linear interaction phenomena.

1. Introduction

The need for the improvement of modern aircraft engines efficiency motivates designers to consider reduced clearances between rotating and stationary components. As a counterpart, structural contacts between these components may occur more frequently and must now be accounted for as part of nor- mal engine running conditions in non-accidental configurations. Subsequent vibratory phenomena may involve a single blade—it is then usually referred to as rubbing [1–3]—a full bladed disk and the surrounding casing—with possible modal coincidence yielding very high amplitudes of vibration [4,5]—or precessional shaft motions such as backward or forward whirl motions [6–9]. A usual strategy employed by engine manufacturers in order to mitigate such vibratory phenomena involves the deposition of an abradable coating along the casing contact surface [10,11]. This coating acts as a sacrificial material that is worn out in the case of blade/casing contacts. However, even when this coating is employed, interaction phenomena leading to blade failure have been reported [1].

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Nomenclature

Δt	duration of a rubbing event	φ	angle of rotation along axis x
$\delta\Omega$	angular speed step between two simulations	ψ	angle of rotation along axis z
$\delta\theta$	angular shift of the wear lobes	1B	first bending mode of the blade
μ	friction coefficient	1T	first torsional mode of the blade
$\Omega^*_{c,a}$	actual numerical critical angular speed	2B	second bending mode of the blade
Ω_c	experimental critical angular speed	LE	leading edge
Ω^*_c	predicted numerical critical angular speed	MC	middle of chord
		TE	trailing edge

Because they may threaten the engine components structural integrity, these interactions have been the focus of many recent studies, both numerical and experimental.

In this contribution, the focus is made on an experimental test bench set-up in Snecma facilities. It features a full-scale high-pressure compressor stage and aims at simulating contact induced interactions between one of the blades (slightly longer than the other ones) and the surrounding abradable coating that is deposited along the casing circumference. For this experimental set-up, it is found that the witnessed interaction involves a single blade—thus it should be analysed as a sequence of rubbing events—, more specifically its first torsional mode, which is its second free-vibration mode. The numerical simulation of rubbing events has been the center of attention in a significant number of recent publications [2,12,13,14]. Several strategies may be employed to simulate such occurrences:

- a *brute-force approach* using a commercial finite element software with full 3D finite element models for the rotating components [15] is sometimes considered. This approach advantageously allows for a very precise modeling of the problem (possibly featuring nonlinear deformations, centrifugal and gyroscopic effects…) but inevitably yields very long computation times and only a handful of rubbing events—at most—may be numerically simulated,
- a *phenomenological approach* that first aims at characterizing the contact forces during the sequence of rubbing events before applying it on the blade tip as a function of time [2,3]. This approach is also commonly used for the modeling of machining operations such as cutting and milling [16,17]. Using this phenomenological approach, a very long sequence of rubbing events may be simulated but the restriction of rubbing induced contact forces to a pulse load [2,3] fully known a priori filters contact related nonlinearities thus making it impossible to predict some potentially critical interaction phenomena. Additionally, when a pulse load is considered, strong assumptions are often made on the way the load is applied along the blade tip,
- *simplified analytical models* are also frequently used for the simulation of rubbing events [18,14,19]. In this case, contact conditions are typically treated by a penalty law: on one hand residual penetrations are tolerated and wear removal cannot be physically accounted for but on the other hand, sophisticated bifurcation analyses may be carried out under the assumption that interaction motions are periodic, and interesting qualitative results may be obtained in order to characterize the nature of interaction phenomena,
- a *reduced-order model based* [13,20,21] approach, which is used in this article, is the last known method to simulate rubbing events. It combines the use of precise 3D finite element models of the rotor with a full 3D contact treatment procedure with no a priori assumptions on the rubbing forces. This quantitative approach aims at providing accurate results but remains more computationally costly than the use of simplified analytical models for instance. This strategy has already been applied to the simulation of a bend-ing induced interaction [1] for the last stage of a low-pressure compressor [20]: the critical numerical speed, wear lobes as well as blade dynamics were accurately predicted. It advantageously accounts for abradable coating removal and contact treatment is based on a Lagrange multiplier computation [22] thus no residual penetrations can occur between the structures.

So far, there is no existing comparison between these methods and only a few of them have been calibrated or confronted with experimental observations. In the context of this article and the numerical simulation of several hundreds of rubbing events for a given blade, both the brute-force approach and the use of simplified analytical models seem irrelevant: the former is not admissible due to the cumbersome computation times it would imply while the latter can not capture accurately the blade dynamics. Accordingly, this article gives the opportunity to confront the phenomenological approach with the reduced-order model based approach. Beside of the presentation of experimental and numerical results, different sections of this article focus on the distinction between these two strategies.

The first section of the article describes the test bench and the targeted interaction scenario, it also provides details regarding the blade instrumentation: the type of gauges used during the experiment is briefly exposed. Experimental results and observations are then listed in the second section of the article. In particular, the second section also contains an in-depth analysis of the stress signals retrieved on the longer blade during distinct phases of the interaction.

Following sections are related to the numerical investigations carried out in order to numerically predict the experimental results. The third section recalls the key points of the reduced-order model based strategy and the focus is made on