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Mechanisms of incursion accommodation during interaction between a vibrating blade and an abradable coating

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ABSTRACT

Abradable materials are used as inner coatings in aeronautical compressors. In the event of blade–casing interaction, the abradable coating accommodates the incursion of the blade tip in order to protect the blade and the casing from severe damage. In this study, an experiment was conducted in conditions representative of the full-scale situation in terms of velocity, temperature and the dynamical characteristics of blades. The mechanisms of incursion accommodation were investigated based on dynamical data and a *post mortem* analysis of the coating and the wear debris. First, dynamical blade tip incursion was estimated by considering blade vibrations and coating waviness. The tip incursion was found to be significantly different from the measured displacement of the blade foot. Next, a *post mortem* analysis of the coating was performed at the surface and sub-surface. Four mechanisms were identified, namely debris release, surface shearing, compaction and reversible deformation. Care was taken to provide orders of magnitude for the different mechanisms relating to residual thickness loss of the coating.

1. Introduction

Minimizing the in-service clearance between rotating blades and the surrounding casing has been shown to improve the efficiency of aeronautical compressors. In fact, it may well be critical to blade and casing integrity in the event of contact between the two. Indeed, during engine operation, the rotor–stator interface is subjected to centrifugal rotor loadings, differential thermal expansions between the rotor and the stator as well as accelerations arising from aircraft maneuvering and vibrations. Abradable materials are used for the inner coatings of casings in order to accommodate blade incursions. Blade strikes lead to coating wear and blade vibrations, which occur simultaneously. Experimental investigations on full-scale compressors have demonstrated the existence of an association between the excited blade modes and the wear profile of abradable coatings [1] that leads to blade failure. In order to predict the vibratory response of blades induced by rubs against the casing, a large number of numerical models have been developed [2–6]. In other models, wear laws have been implemented to simulate the behavior of the abradable material when rubbed by the blade [7–10]. Different basic assumptions are made in these models. Marscher [7] has proposed a model based on the presence of a shear mix layer at the blade–coating interface. In the model by Williams [8], the wear depth is considered to be zero below a certain load and proportional to the radial load above this threshold. In their model, Legrand et al. [9] consider that the behavior of the abradable material is controlled by a two-region constitutive law that includes both elastic and plastic parameters. Salvat et al. [10] developed a model based on an analogy between abradable removal and milling, in which wear has been modeled as the removal of chips. In order to validate these wear models or define their scope of validity, experimental research is required.

Different kinds of experiments have been developed to identify the wear mechanisms pertaining to abradable materials. The test rig at Sulzer-Innotec [11,12] is capable of generating interactions for a wide range of tangential speeds (up to 400 m s^{-1}) and temperatures (up to 1000 °C). Dadouche et al. [13] studied the effect of speed, incursion rate and temperature on rubbed surfaces and correlated these parameters with the tangential cutting force. More recently, Fois et al. [14,15] investigated the relationship between incursion rates, wear mechanisms and interaction forces for an abradable AlSi-hBN coating at relative velocities of 100–200 m s^{-1}. The authors highlighted two main mechanisms, namely cutting

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Nomenclature

x	coordinate along the normal direction (mm)
y	coordinate along the tangential direction (mm)
V_T	tangential speed of the abradable coating (m s^{-1})
T_a	temperature of the abradable coating (°C)
V_e	electrical pulse sent to the actuator (V)
Φ	angular position of the coated cylinder (°)
R	radius of the coated cylinder (mm)
D_N	apparent incursion (displacement of the blade foot in the normal direction) (μm)
Δ_N	variation of apparent incursion (blade foot stroke during interaction) (μm)
D_T	blade bending displacement (mm), measured at 17.5 mm from the blade tip
f_N/f_N^{max}	normal component of the blade–coating interaction force (–)
f_T/f_T^{max}	tangential component of the blade–coating interaction force (–)
δ	incursion of the blade tip into the abradable coating (μm)
p_b	position of the blade tip (μm)
p_a	position of the abradable coating (μm)
L	blade length (mm)
α_1	modal amplitude of the first blade bending mode (mm)
Z_1	mode shape of the first blade bending mode (–)
w	coating waviness (μm)
R_f	radius of the median filter used for image post-processing (px)
S	threshold used for image post-processing (gray level)
p	percentage of porosity in the abradable coating (–)
p_0	initial percentage of porosity in the abradable coating (–)
Δe	variation of thickness due to coating compaction (μm)
l_d	debris length (μm)
Δl_d	variation of debris length (μm)
h_d	average thickness of wear debris (μm)
e_d	coating thickness evacuated as debris (μm)

(high incursion rate) and adhesive transfer (low incursion rate). The coating-to-blade tip transfer was investigated by means of a stroboscopic imaging technique, that enabled the transfer growth to be recorded during the interaction. *Post mortem* observations showed an association between adhesive transfer and grooving of the coating, which is consistent with Borel's analysis on worn service parts [16]. These test rigs and experiments [11,13–15] can provide wear maps of abradable coatings, in which the dominant wear mechanisms are generally expressed as a function of the tangential blade speed and incursion rate.

However, in the quoted studies, the wear analysis of abradable coatings is often confined to macroscopic observations and descriptions of worn surfaces, which limits the possibilities for developing physical wear laws in the abovementioned numerical models. The interpretation of interaction scenarios is complex since wear mechanisms are analyzed after many blade rubs. Cuny et al. [17] developed a test setup that uses a gas gun to launch an abradable AlSi-polyester specimen into interaction with a cutting tool. Single-pass incursions were generated, but the wear mechanisms were not investigated and only room-temperature experiments were conducted. On the whole, the test rigs have been designed with small rigid blades and therefore do not investigate the relationships between blade vibrations and abradable coating wear.

The present paper aims to propose a different experimental approach for studying the accommodation of blade incursion in an abradable coating. The test rig, presented in papers [18–20], is capable of reproducing very short blade–seal interactions. The blade–seal configuration has been simplified with respect to the full-scale case to enable comprehensive instrumentation. The experiments are representative of low-pressure compressor conditions in terms of the materials used (abradable AlSi-polyester material, titanium blade), the relative rotor–stator speed (up to 95 m s^{-1}), the abradable coating temperature (up to 300 °C) and the dynamical characteristics of the blade. In this study, we did not investigate a wide range of interaction conditions but instead concentrated our efforts on performing a detailed analysis of a single-pass interaction between a vibrating blade and an abradable AlSi-polyester coating. This involved estimating the interaction force and blade tip incursion by taking into account the blade vibrations. Additionally, the mechanisms of incursion accommodation were investigated at the surface and sub-surface by means of high-speed imaging, SEM and X-ray microtomography.

2. Blade–coating interaction

2.1. Test rig

The configuration and instrumentation of the test rig, developed at ONERA, the French Aerospace Lab, have been discussed in detail in previous papers [19,20]. As shown in Fig. 1a, the test rig consists of a rotating cylinder (300 mm in diameter) whose external surface is coated with an abradable material. The relative blade/coating speed V_T is generated by spinning the cylinder. The interaction is generated by translating the blade toward the abradable coating. In order to do this, the titanium blade is fastened to a small rigid unit, which is moved in direction x by means of a piezo-electric actuator (Fig. 1b). The translation of this small rigid unit (i.e. translation of the blade foot) is defined as the apparent incursion D_N. The blade used in this study has a simplified geometry but with flexural characteristics representative of compressor blades [20]. In order to reach in-service compressor temperatures, the coating is heated by an induction heating system (Fig. 1a). The surface temperature T_a of the abradable coating is monitored via an infrared pyrometer that is properly calibrated to take into account the emissivity.

The instrumentation has been chosen to capture the dynamics of blade–seal interactions of a few milliseconds. The apparent incursion D_N, which results from the electrical command sent to the actuator and the interaction force, is measured with laser displacement sensor 2 (Fig. 1b). A second sensor, displacement sensor 1, measures the blade bending displacement D_T (in direction y) at 17.5 mm from the blade tip. D_T is used to estimate the tangential component of the interaction force at the blade tip, f_T. A piezoelectric force sensor is placed between the actuator and the small rigid unit to measure the incursion force in direction x. The acceleration of the small rigid unit in direction x is measured by means of two accelerometers. The output signals of the force sensor and the accelerometers are post-processed to estimate the normal component of the interaction force f_N. The method used to estimate the interaction force has been described previously in [20]. Images of the interaction are recorded using a high-speed camera placed on one side of the test rig. The blade bending motion and the ejection of wear debris are both captured by the camera at 12 500 frames/s with a resolution of 1024 × 1024 pixels. On the opposite side of the incursion cell, a third sensor, laser displacement sensor 3, is used to record the circumferential profile of the coating. Two types of acquisitions are performed