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Phenomenological modeling of abradable wear in turbomachines

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ABSTRACT

Abradable materials are widely used as coatings within compressor and turbine stages of modern aircraft engines in order to reduce operating blade-tip/casing clearances and thus maximize energy efficiency. However, rubbing occurrences between blade tips and coating liners may lead to high blade vibratory levels and endanger their structural integrity through fatigue mechanisms. Accordingly, there is a need for a better comprehension of the physical phenomena at play and for an accurate modeling of the interaction, in order to predict potentially unsafe events. To this end, this work introduces a phenomenological model of the abradable coating removal based on phenomena reported in the literature and accounting for key frictional and wear mechanisms including plasticity at junctions, ploughing, micro-rupture and machining. It is implemented within an in-house software solution dedicated to the prediction of full three-dimensional blade/abradable coating interactions within an aircraft engine low pressure compressor. Two case studies are considered. The first one compares the results of an experimental abradable test rig and its simulation. The second one deals with the simulation of interactions in a complete low-pressure compressor. The consistency of the model with experimental observations is underlined, and the impact of material parameter variations on the interaction and wear behavior of the blade is discussed. It is found that even though wear patterns are remarkably robust, results are significantly influenced by abradable coating material properties.

1. Introduction

Abradable coatings have long been used by aircraft engine manufacturers as sacrificial materials in order to reduce operating clearances between the bladed disk and the casing in both compressor and turbine stages. These coatings advantageously mitigate potential parasitic leakage flows from a stage to the next one by geometrically adapting their profile in case of contacts with a blade thus preventing potentially hazardous structural damages [20]. The nature of the coating and its mechanical properties are adjusted depending on where it is implemented in the engine: as an example, a coating sprayed on the casing of a low-pressure compressor does not require the same thermal resistance as its counterpart sprayed in the high-pressure turbine. Accordingly, a wide variety of abradable coatings such as ceramics, aluminum/silicon alloys or nickel/graphite composites to name a few [26] might be employed. These materials may be sprayed, sintered or even

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deposited with a honeycomb structure on the casing [26]. As a direct consequence, during blade-tip/abradable coating unilateral contact occurrences, distinct physical mechanisms may be at play. Understanding these mechanisms is important because while an isolated blade/abradable contact does not threaten the blade integrity by itself, repeated contacts could lead to unwanted vibratory resonances of the blade [20]. Hence the need for a better understanding of the interaction [19] both through experiments and numerical simulations able to predict the interaction for different blade geometries, blade-casing configurations and abradable material behaviors. Several investigations on the static characterization of abradable coatings [23,11] as well as abradability investigations carried out statically, or at very low speed, are available [32,31] in addition to a few scratch tests [15,16]. Recently, experimental investigations on the dynamic characterization of abradable coatings within a simulated turbo-machinery environment were reported with respect to: a high relative interaction speed (from 100 m/s to 500 m/s) [5,28], elevated temperatures (up to 600 °C) [6] as well as a combination of high interaction speeds and elevated temperatures [17,22]. While the influence of thermal conditions has long been explored [21], experimental works carried out by manufacturers are rarely published.

Concerning the numerical aspects, various blade/casing interaction models were developed over the recent years. Analytical models with simplified contact and no wear [27,14] as well as more sophisticated Finite Element simulations able to accurately reflect the blade geometry and model the abradable coating removal [20] were developed. The main restrictions are the modeling of abradable wear and the computational cost of the overall simulation, hence limited to a few blade revolutions. Very few quantitative models of abradable wear exist in the literature to overcome these problems. A phenomenological model was proposed by Marscher [18], based on observations that were not confirmed in latter experiments. A few qualitative models of abradable wear based on experimental observations were proposed by Schmid [26]. A Finite Element micro model of the bulk material without contact was proposed in [8]. Finally, two abradable coating models in the context of full three-dimensional simulations were suggested with a focus on the numerical efficiency rather than on the physical relevance of wear phenomena [13,29].

A crucial ingredient for the quantitative study of the blade displacement is to accurately capture the interaction behavior between the tip of the blade and the coating. In this context, a simplified macro-scale model of the interaction is presented in this paper, based on the phenomenology and physics of abradable wear. A model depending only upon experimentally measurable material quantities is targeted. It has been implemented in the numerical framework introduced in [2]. First a synthesis of abradable phenomenology is presented, then a blade/coating interaction model is proposed from the resulting classification. Two studies are then explained: (1) the simulation of an experimental test rig with a fixed blade and a rotating cylinder coated with abradable material [17] and (2) the interaction of a blade with the casing and its abradable coating in a real aircraft engine low pressure compressor.

For the sake of brevity, several key notions related to the analysis of rotor/stator interactions are not recalled in this article. An in-depth literature review about these notions may be found in [10].

2. Phenomenology of abradable wear

2.1. Interaction parameters

With respect to contact dynamics, blade/coating interactions depend on three main parameters [26]: tangential velocity at the blade tip, temperature and incursion.

In this contribution, attention is paid to blade/coating interactions in aircraft engine low-pressure compressors where typical velocities at the blade tip range from 100 m/s to 600 m/s. Most experiments stand within this range or slower [1,5,17,28]. Temperature varies from 0 °C to 600 °C.

Contrary to tangential velocity and temperature, the incursion, also called bite-per-blade in the literature, cannot be measured precisely during the experimental simulation of an aircraft engine interaction. It may only be estimated from the final wear profile and the number of blade revolutions. Schmid [26] considers various cases with nominal incursions ranging approximately from 0.001 μm to 20 μm. Other experiments [1,5,17,28] operate on ranges from 10 μm to 100 μm. Note that in a vast majority of cases, rotating test rig experiments typically control the bite-per-blade only through the incursion velocity [26,3]. Nevertheless, from the material standpoint, the incursion velocity is completely negligible and only the bite-per-blade is of physical significance (as noted, for example, by Schmid [26]).

Because there are several abradable materials and because the three aforementioned parameters (tangential velocity, temperature and bite-per-blade) imply different contact configurations between the blade and the coating, many different observations have been reported in the literature. In the following, a synthesis of these observations is carried out.

2.2. Phenomenology

The behavior of the abradable is quasi-brittle in traction and elastoplastic in compression. Fracture becomes more ductile with temperature [17]. Interaction with gas flux particles goes beyond the scope of the present paper, and is anyway seldom mentioned in the corresponding literature. The main area of interest regarding blade/coating interaction is the coating surface behavior, *i.e.* friction and wear. Interaction mechanisms are defined by a combination of a distinctive kinematics and a