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Assessment of Substrate and TBC Damage Effects on Resonance Frequencies for Blade Health Monitoring

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ABSTRACT

The reliability of critical aircraft components continues to shift towards onboard monitoring to optimize maintenance scheduling, economy efficiency, and safety. Therefore, the present study investigates changes in dynamic behavior of turbine blades for the detection of defects, with focus on substrate cracks and TBC spallation as they relate to vibration modes 1 to 6. Two-dimensional and three-dimensional finite element simulation is used. The results indicate that TBC spallation reduces natural frequencies due to the ensuing hot spot and overall increase in temperature, leading to drops in blade stiffness and strength. Cracks cause even larger frequency shifts due to local plastic deformation at the crack that changes the energy dissipation behavior. Mode 1 vibration shows the largest shifts in natural frequencies that best correlate to the size of defects and their position. As such, it may be most appropriate for the early assessment of the severity and location of defects.

KEYWORDS

Blade Damage, Blade Health Monitoring, Damage Detection, Defect Location, Defect Size, Resonance Frequencies, Resonance Vibration, TBC Loss, Vibration Mode

INTRODUCTION

The reliability of critical aircraft components continues to heavily rely on regular maintenance at pre-determined intervals. In addition, more difficult to inspect parts are often replaced independent of their damage state at the end of a pre-set service life. While achieving an unparalleled level of safety, this approach can lead to conservative maintenance schedules, unnecessary shutdowns, high maintenance costs and unforeseeable failures. Therefore, there is great need and growing drive to shift to more efficient maintenance through onboard monitoring in order to timely detect or replace damaged components while the defects are still at their incipient stage. In this context, the current study aims at conducting a comprehensive analysis of blade substrate and coating defects, together with the ensuing changes in blade temperature and properties, as they relate to shifts in blade natural frequencies. This is achieved by completing a series of FEA models, each with varying severity and location of damage, and comparing the results to those of the undamaged blade.

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BACKGROUND

The highly conservative approach currently used to ensure the safety of key aerospace components has led to parts, such as turbine blades, being among the most commonly rejected or replaced components (Carter, 2005). Therefore, current efforts primarily focus on detecting potential damages before they reach a critical size for rapid growth and component failure. However, most previous literature reports have focused on crack size and location, without accounting for the ensuing local hot spot and overall increase in blade substrate temperature. Moreover, little is reported on the effect of TBC coating loss or spallation on the resonance behavior of turbine blades. Operating in an extreme environment, turbine blades can be subject to a variety of damage mechanisms including: chattering, high cycle fatigue (HCF) from high frequency engine vibrations, low cycle fatigue (LCF) from extreme cold and hot phases, creep, corrosion, and foreign object damage (FOD), among others. To improve the performance and durability of turbine blades, advanced coating technologies have been developed and used for decades. Thermal barrier coatings (TBCs) are among the most performant protective systems (Padture et al., 2002; Sankar et al., 2019, Dhomne & Mahalle, 2016). Current turbine blade substrates are generally metal base, such as nickel base superalloys, and have lower temperature and corrosion resistance than TBCs. Therefore, substantial substrate temperature increases resulting from potential TBC loss can cause failure of the component within relatively few operational cycles. TBC damage mechanisms are complex and ultimate failure can result in the spallation of the top coat (Ali et al., 2018; Evans et al., 2001; Schlichting et al., 2003).

To further improve safety and economy efficiency while reducing downtimes, a great deal of efforts are currently being deployed to develop more robust, compact and efficient onboard monitoring systems (Yildirim & Kurt, 2018; Roemer & Kacprzynski, 2000; Mevissen & Meo, 2019). The goal is to continuously evaluate residual strength or health and to estimate the remaining service life of components (Boyd-Lee et al., 2001). Ongoing research efforts are making critical advances in monitoring approaches and sensing technology (Borovik & Sekisov, 2020; Sunar & Al-Bedoor, 2008; Ranjan, 2016). Non-contact sensors are favoured for the monitoring of turbine blade parameters to avoid interference with aerodynamic and structural performance (Procházka & Vank, 2011; Devi et al., 2021). Resonance vibrations are highly dependent on the design, microstructure, materials properties and damage state of blades (Efe-Ononeme et al., 2018; Pridorozhnyi et al., 2019; Prasad et al., 2017). As such, they are among the most reliable indicators of blade health. Particularly, shifts in resonance frequencies can be readily measured for the detection of potential blade damages (Djaidir et al., 2017; Madhavan et al., 2014; Atiyah & Falih, 2019; Rani et al., 2019). Therefore, the current study is based on a solid foundation of achievements realized so far. However, the work goes beyond blade cracks. It expands to not yet sufficiently studied aspects such as the effect of TBC damage on the dynamic behavior of turbine blades and how the impact of defects relates to specific mode shapes.

MATERIALS AND METHODS

System, Materials and Loading Conditions

The Pratt and Whitney PW-100 engine is used as reference in this study. Its inter-turbine temperature before the power stage is approximately 785°C and the exhaust temperature is between 565-600°C. Its further characteristics and main operation parameters are described in detail in the 2000 Pratt and Whitney Canada Large PW100 Series Training Manual and in earlier publications (van Dyke & Nganbe, 2021; Hosking et al., 1999; Saravanamuttoo, 1987). Cruise loading condition at 85% of the maximum propeller shaft rotation speed of 1200 rpm is taken as basis for the simulation. Waspaloy IN713LC is considered as blade substrate (Donachie & Donachie, 2002) with temperature dependent elastic modulus and strength.

In a first step of modelling, elastic-plastic material behavior is considered and the blade is modelled as a two-dimensional solid of 100 mm height and 10 mm thickness. A first partition is added for a

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