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Long duration blade loss simulations including thermal growths for dual-rotor gas turbine engine

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Abstract

This paper presents an approach for blade loss simulation including thermal growth effects for a dual-rotor gas turbine engine supported on bearing and squeeze film damper. A nonlinear ball bearing model using the Hertzian formula predicts ball contact load and stress, while a simple thermal model estimates the thermal growths of bearing components during the blade loss event. The modal truncation augmentation method combined with a proposed staggered integration scheme is verified through simulation results as an efficient tool for analyzing a flexible dual-rotor gas turbine engine dynamics with the localized nonlinearities of the bearing and damper, with the thermal growths and with a flexible casing model. The new integration scheme with enhanced modeling capability reduces the computation time by a factor of 12, while providing a variety of solutions with acceptable accuracy for durations extending over several thermal time constants.

1. Introduction

The design trend for high-performance rotating machinery such as gas turbine engines is to pursue high power output and high efficiency. It requires lighter and more flexible rotors, which may operate above bending critical speeds. Modern commercial aircraft gas turbines are usually designed as dual-rotor machines that require complex analytical models composed of two rotors rotating at different speeds and interacting through intermediate bearings. Blade loss simulations are always necessary to verify the reliability and safety of a design.

Novel squeeze film damper designs [1–3] are introduced to reduce the severe nonlinearity due to highly eccentric rotor motion during blade loss event when a squeeze film damper clearance is almost lost. A porous squeeze film damper [1], which is made of a permeable sintered porous metal material, was proposed and modeled using a rigid Jeffcott rotor for a blade loss simulation. In Refs. [2,3], a chambered porous damper

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was designed, and blade loss experiments were conducted using a rotor operating above its first bending critical speed.

Stallone et al. [4] developed an analytical method based on the modal synthesis to predict the transient dynamic response of an aircraft engine when a fan blade is lost and they validated theoretical results with test data. Alam and Nelson [5] used a shock spectrum procedure to estimate the peak displacement response of a flexible rotor under high imbalance, however only a linear support model was used. Lawrence et al. [6] applied the pitch and yaw moments of inertias as a function of speed to consider the non-axisymmetric bladed disk and examined the effects of those moments on the rotor/disk response with a spooldown rate, and they [7] then proposed a new blade/casing interaction model and compared it with the existing contact models. Using this contact model Gallardo and Lawrence [8] derived explicit expressions of the stability boundary in terms of the whirling frequency and the required damping. Sun et al. [9] conducted blade loss transient simulations using a flexible dual-rotor engine mounted on detailed bearing and squeeze film damper models. The present research makes significant improvements of the blade loss simulation model over Ref. [9] by including the thermal effects and the staggered integration scheme as follows: (1) since the oil viscosity of squeeze film damper decreases as the viscous power loss in the oil film causes the temperature to go up, the resulting damping force is considerably decreased as the blade loss event goes on, (2) the staggered integration scheme significantly saves the computation time for blade loss simulations with local nonlinearities, while providing a variety of solutions with acceptable accuracy.

In this research, a flexible dual-rotor gas turbine engine including detailed support models is utilized for blade loss simulations. The nonlinear ball bearing model is capable of predicting the maximum contact load and stress between ball and race using Hertzian formula, while the viscous damping forces are obtained from the pressure profile in the annular oil film using finite element analysis. Furthermore, a simple thermal model estimates the thermal growths of bearing components due to rotor/rub ring friction and bearing drag torque and the resulting thermal expansions. Blade loss causes the bearings and squeeze film dampers to heat up, and the bearing clearance and the viscosity of oil film change slowly with time. The slow variation of the vibrations requires a very long total simulation time and in addition, the numerical integration time step must be kept very short because of the nonlinearities, especially the rub effect that includes an intermittently activated high stiffness. A modal truncation augmentation method combined with a staggered integration scheme provides a way to reduce the dimensionality and yet retain computational accuracy. The simulation results show that the proposed approach is an efficient tool for simulating blade loss dynamics and thermal growths over durations extending over several thermal time constants.

2. Blade loss simulation models

2.1. Dual-rotor gas turbine engine

Fig. 1 depicts a typical two-spool gas turbine engine [10]. The basic engine consists of an inner core rotor called the power turbine and an outer core rotor called the gas generator turbine, which has two stages driving an axial compressor. The power turbine rotor is supported by two main bearings located at the shaft extremities, #0 and #5, while the gas generator rotor is supported principally by rolling-element bearings at four locations: #1–#4. There are two intermediate differential bearings connecting the power turbine and gas generator rotors. The squeeze film dampers are installed at the bearing locations to provide ample viscous damping and to reduce the vibration amplitude and transmitted dynamic force.

The flexible gas turbine engine model shown in Fig. 2 is based on Ref. [10] and has a total of 38 lumped masses with the power turbine divided up into 22 nodes and the gas generator into 16 nodes. Each node has 6 degrees-of-freedom, i.e., 3 translational and 3 rotational motions, and the system has a total of 228 degrees-of-freedom. Polar moments of inertia of the rotors only at the turbine and compressor stages are considered. The gas generator rotor is connected to a flexible casing model [11] composed of the total of 118 elements with 342 degrees-of-freedom. The casing model consists of 104 solid elements (8 nodes/element, 3 degrees-of-freedom/node), 8 beam elements (2 nodes/element, 6 degrees-of-freedom) and 6 longitudinal spring-damper elements. The elements have many shared nodes in a way that the total degrees-of-freedom of the casing model are 342. The total degrees-of-freedom of the dual-rotor gas turbine engine model for the blade loss simulation are 691