Applied Mathematical Modelling 39 (2015) 2539–2553

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

Flutter analysis of bending–torsion coupling of aero-engine compressor blade with assembled clearance

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ARTICLE INFO

Article history:
Received 28 June 2013
Received in revised form 13 July 2014
Accepted 23 October 2014
Available online 21 November 2014

Keywords:
Compressor blade
Assembled clearance
Bending–torsion coupling flutter
Limit cycle oscillations
Amplitude jumping phenomenon

ABSTRACT

In this paper, the flutter of a compressor blade is investigated to explore the fracture failure mechanism of the blade with an assembled clearance, cubic structural nonlinearity and aerodynamic forces. Firstly, the stability of the linearized system is studied in the neighborhood of an equilibrium point and the threshold speed of the linear flutter of the blade is obtained. Then the response equations of limit cycle oscillations (LCOs) are deduced by using the averaging method, and the stability of LCOs is analyzed based on the first-order approximate theory. Comparisons with the results from the fourth-order Runge–Kutta scheme are carried out, and the accuracy of the first-order approximation of the averaging method is discussed. Finally, the influence of clearance parameter, bending stiffness and torsional rigidity on the flutter characteristics of the blade is analyzed.

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1. Introduction

Compressor blades are the key mechanical components in aero-engine. These blades are often exposed to extremely severe vibration, such as flutters. Therefore, the reasons of a blade fracture failure caused by vibrations have attracted lots of interest from scientific research personnel. Vibrations of a compressor blade are divided into forced vibration and aero-elastic stability (flutter). The flutter is one of the main reasons of the fracture failure.

The compressor rotor blade and its hub are connected with a dovetail joint which is one of the main types of assembly in the current aero-engine (shown in Fig. 1). Such a joint leads to the assembled clearance between the tenon and mortise. Compared with fixed welding joint, the former joining approach weakens the root constraint of the blade and also changes the modal parameters and the vibration characteristics of the blade.

So far, there are already several reported solutions of the nonlinear dynamic problems in bladed disks for localized contacts in special devices [1–7], such as friction dampers, root joints, or blade shrouds. These studies had only focused on the influences of a single nonlinear factor rather than combination of several nonlinear factors on the dynamical response of a blade.

However, up to now, the theoretical and experimental studies of dovetail joints [8–10] are focused mostly on the analysis of contact stresses and stresses in areas close to the contact interfaces, which have influences on fretting fatigue and crack propagation of the blade root. The main purpose of these works is the analysis of contact stresses but not the dynamic response for a blade with dovetail joints.

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http://dx.doi.org/10.1016/j.apm.2014.10.051
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Nomenclature

a_h	non-dimensional distance from airfoil mid-chord to elastic axis
c_h, c_α	damping factors in bending and in torsion
I_α	mass moment of inertia about elastic axis
K_h, K_α	stiffness in bending and in torsion
r_α	non-dimensional radius of gyration about the elastic axis
$\bar{\omega}$	frequency ratio (ω_h/ω_α)
ω	frequency of limit cycle oscillations
V	freestream velocity relative to blade
m	mass per unit span of blade
δ	semi-clearance distance
$\Phi(\tau)$	Wagner's function
$A_i(\tau)$	harmonic amplitudes
$\theta_i(\tau)$	harmonic phase angles
x_α	non-dimensional distance from the airfoil elastic axis to the centre of mass
ζ_h, ζ_α	viscous damping ratios in bending and in torsion
S_α	static mass per unit span about elastic axis
ω_h, ω_α	uncoupled natural frequency in bending and in torsion
b	semi-chord
ρ	air density
t	time
τ	non-dimensional time
β	nonlinear torsional rigidity coefficient
μ	mass ratio of blade
λ	eigenvalue
$\{\dot{}\}$	differentiation with respect to t
$\{'\}$	differentiation with respect to τ

Some researchers also investigated the effects of structure parameters and aerodynamic parameters on the flutter boundaries using the typical section model. Bendiksen and Friedmann [11–13] did a series of work to investigate the typical section model of a flat cascade in incompressible flow, and supersonic flow with subsonic leading-edge locus. Bendiksen and Friedmann [11] determined the aeroelastic stability boundaries of a flat cascade with aerodynamic, inertial, and structural coupling between the bending and torsional degree of freedom. The obtained results illustrate that the bending–torsion interaction has a pronounced effect on the cascade flutter boundary. Bendiksen and Friedmann [12] studied the effects of bending–torsion interaction on the flutter boundaries of a supersonic cascade based on a computationally efficient solution of the unsteady supersonic flow using dual integral equation formulation, which agrees with results obtained previously by the authors for the incompressible flow. The obtained results indicate a potential instability in the bending mode even in the absence of strong shocks. Bendiksen and Friedmann [13] examined the effects of bending–torsion interaction on the flutter boundaries of fan and compressor blades in two different speed regimes (incompressible flow, and supersonic flow with a subsonic leading edge locus). Although some data from the earlier works [11,12] by the authors is used, the emphasis in the literature [13] is on illustrating the practical consequences of the results in the design and flutter prediction of fans and compressor rotors. Bendiksen and White [14] analyzed the aeroelastic stability of titanium and composite blades over a range of

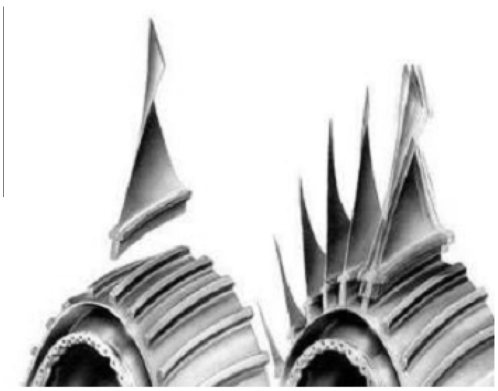

Fig. 1. Dovetail joint of a blade.

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