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The investigation of the coupled vibration in a flexible-disk blades system considering the influence of shaft bending vibration

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ABSTRACT

The continuum model of flexible shaft-disk-blades coupling system is established to investigate the coupling vibration among shaft-bending, shaft-torsion, disk-transverse and blade-bending. The influence of shaft bending rigidity, disk transverse rigidity and rotational speed on natural frequencies and mode shapes are particularly researched. The present paper discovers that when shaft bending is negligible, there are three types of coupling modes, shaft torsion-disk transverse-blade bending (TDB), disk transverse-blade bending (DB) and blade bending-blade bending (BB). As shaft goes further flexible, the shaft bending-disk bending-blade bending (SDB) mode occurs. What's more important is that shaft bending only couples with disk's 1-nodal diameter mode. Then the influence of disk transverse on coupling vibration is studied. With the decrease of disk's transverse rigidity, the repeated BB modes bifurcate into BB and DB modes, TB (shaft torsion-blade bending) and SB (shaft bending-blade bending) modes shift to TDB and SDB modes, respectively. Besides, disk's n-nodal ($n \geq 2$) diameter modes always couples with blade bending when $\beta \neq 0°$. At last, the effect of rotational speed on the frequencies is investigated, concluding that shaft flexibility and disk flexibility can significantly affect the critical speeds of the system.

1. Introduction

In the compressor/turbine engineering equipment, the blade, the disk and the shaft are assembled together by a certain connecting structure, forming a blade-disk-shaft system with some coupling characteristics. The coupling vibration among shaft, disk and blades could become significant if the shaft is flexible and blade's stagger angle varies. With the development of scientific research, many scholars in this field have carried out a lot of researches on the coupling vibration of the blade-rotor system. However, the coupling vibrations among shaft bending, shaft torsion, disk transverse and blade bending are seldom considered together. The present research focuses on coupling vibration of the shaft-disk-blades system under the influence of shaft's bending and shear.

Shaft-disk assembly is the key element in many mechanical applications, such as gas turbine, aircraft engine and centrifugal compressor. And the flexible shaft-rigid disk model is the most popular analytical model for such system firstly. In another aspect, the dynamic characteristics of disk flexibility have been investigated for years. Lamb and Southwell [1]

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Nomenclature

ρ_s	material density of the shaft
L_s	length of the shaft
A_s	cross-section area of the shaft
J_{ps}	the polar moment of inertia for shaft
J_{ds}	cross-sectional moment of inertia for shaft
E_s	Young's modulus for shaft
I_s	shaft's cross-section area moment of inertia
G_s	shear elastic modulus of the shaft
κ_s	shear correction factor of the shaft
ρ_D	material density of the disk
h_D	thickness of the disk
R_D	radius of the disk
m_D	mass of the disk
E_D	Young's modulus of the disk
υ_D	Poisson's ratio
J_{dd}	diametral moment of inertia for disk
J_{pd}	polar moment of inertia for disk
ρ_b	blade mass density
L_b	blade length
A_b	cross-section area of the blade
E_b	Young's modulus of blade
I_b	area moment of inertia of the blade
x	shaft's transverse displacements with respect to the X axis
y	shaft's transverse displacements with respect to the Y axis
θ_x, θ_y	bending angle of shaft at arbitrary position
u_D	disk's transverse displacement
u	blade displacements with respect to the x_b axis
v	blade displacements with respect to the y_b axis
A_0, A_1, A_2	the transformation matrix from local coordinate system to the global coordinate system
$\boldsymbol{X}$	the mode shape vector of the bending shaft respect to the X axis
$\boldsymbol{Y}$	the mode shape vector of the bending shaft respect to the Y axis
$\boldsymbol{\Phi}$	the mode shape vector of the shaft torsion
$\boldsymbol{U}, \boldsymbol{V}$	the mode shape vector of the blade
$\boldsymbol{q}_\theta, \boldsymbol{q_u}, \boldsymbol{q_v}$	generalized vector
Ω	rotational speed
TDB	shaft torsion-disk transverse-blade bending coupling mode
SDB	shaft bending-disk transverse-blade bending coupling mode
DB	disk transverse-blade bending coupling mode
BB	blade bending-blade bending coupling mode
TB	shaft torsion-blade bending coupling mode
SB	shaft bending-blade bending coupling mode

Subscripts

$()_b$	blade
$()_D$	disk
$()_s$	shaft bending
$()_\theta$	shaft torsion

derived the frequency equations and mode shapes, initiating the study on the vibration of a spinning disk. Parker and Mote [2] predicted natural frequencies of stationary annular or circular plates with a perturbation solution, and they discussed the mode split of the repeated natural frequencies. Kim et al. [3] reported that significant changes could occur to its natural frequencies and modes when a structure deviates from axisymmetry because of circumferentially varying model features. Iii and Mote [4] evaluated experimentally the validity of the standard models of the membrane stress boundary condition at the clamping collar. Shen [5] studied forced vibration response of rotating disk/spindle system consisting of multiple flexible circular disks clamped to a rigid spindle supported by two flexible bearings. Dopkin and Shoup [6] studied the influence of disk's flexibility on natural frequencies by a transfer matrix method.

As the rotating systems become lighter and more flexible with higher operating speed for higher productivity and economical design, the flexible shaft-rigid disk model cannot accurately predict the vibration characteristics of the system.