Mechanical Systems and Signal Processing 30 (2012) 306–322

Contents lists available at SciVerse ScienceDirect

Mechanical Systems and Signal Processing

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

Nonlinear effects caused by coupling misalignment in rotors equipped with journal bearings

Paolo Pennacchi *, Andrea Vania, Steven Chatterton

Department of Mechanical Engineering, Politecnico di Milano, Via La Masa, 1, I-20156 Milano, Italy

A R T I C L E   I N F O

Article history:
Received 10 March 2011
Received in revised form
23 November 2011
Accepted 24 November 2011
Available online 16 December 2011

Keywords:
Coupling misalignment
Hyperstatic rotors
Journal bearings
Rotordynamics
Nonlinear effects

A B S T R A C T

Misalignment is one of the most common sources of trouble of rotating machinery when rigid couplings connect the shafts. Ideal alignment of the shafts is difficult to be obtained and rotors may present angular and/or parallel misalignment (defined also as radial misalignment or offset). During a complete shaft revolution, a periodical change of the bearings load occurs in hyperstatic shaft-lines, if coupling misalignment between the shafts is excessive. If the rotating machine is equipped with fluid-film journal bearings, the change of the loads on the bearing causes also the variation of their instantaneous dynamic characteristics, i.e. damping and stiffness, and the complete system cannot be considered any longer as linear.

Despite misalignment is often observed in the practice, there are relatively few studies about this phenomenon in literature and their results are sometimes conflicting. The authors aim at modeling accurately this phenomenon, for the first time in this paper, and giving pertinent diagnostic information. The proposed method is suitable for every type of shaft-line supported by journal bearings. A finite element model is used for the hyperstatic shaft-line, while bearing characteristics are calculated by integrating Reynolds equation as a function of the instantaneous load acting on the bearings, caused also by the coupling misalignment. The results obtained by applying the proposed method are shown by means of the simulation, in the time domain, of the dynamical response of a hyperstatic shaft-line. Nonlinear effects are highlighted and the spectral components of the system response are analyzed, in order to give diagnostic information about the signature of this type of fault.

1. Introduction

In her comprehensive book about Rotordynamics, Muszyńska [1] observed that rotor misalignment could be considered as the second most common malfunction after unbalance. She remarked also that this interesting topic was not object of much attention by researchers.

The authors of this paper share her position and want to contribute by presenting a paper aimed at explaining the reason of the presence of superharmonic components, i.e. of nonlinear behavior, in rotor vibration spectrum as a consequence of rigid coupling misalignment, owing to wrong assembly or imperfect flange machining, of an hyperstatic shaft-line equipped with journal bearings. The method is suitable to be applied to every type of shaft-line.

* Corresponding author. Tel.: +39 02 2399 8440; fax: +39 02 2399 8492.
E-mail address: paolo.pennacchi@polimi.it (P. Pennacchi).

0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2011.11.020

Nomenclature

Symbols

$[\mathbf{C}]$	damping matrix of the complete system (rotor+ bearings+ foundation)
$[\mathbf{C}^{(f)}]$	damping matrix of the foundation
$[\mathbf{C}^{(r)}]$	internal damping matrix of the rotor
$[\mathbf{C}^{(rr)}]$, $[\mathbf{C}^{(rf)}]$, $[\mathbf{C}^{(fr)}]$, $[\mathbf{C}^{(ff)}]$	damping coupling matrices that are due to oil-film forces
$c^{(b)}_{rs_i}$	damping coefficient of ith bearing between r and s direction
e	Euler's number
$\mathbf{F}^{(bf)}_{b_i}$	dynamic forces of the oil-film of the ith bearing on the foundation
$\mathbf{F}^{(br)}_{b_i}$	dynamic forces of the oil-film of the ith bearing on the journal
$\mathbf{F}_C$	equivalent force caused by the coupling misalignment
$\mathbf{F}_u$	unbalance force
$[\mathbf{G}^{(r)}]$	gyroscopic matrix
g	gravitational acceleration
h	oil-film thickness in the bearing
I_c	set of the indexes of the rotor nodes corresponding to a journal bearing
i	index
i	imaginary unit
j	index
j_C	index of the coupling node
$[\mathbf{K}]$	stiffness matrix of the complete system (rotor+ bearings+ foundation)
$[\mathbf{K}^{(f)}]$	stiffness matrix of the foundation
$[\mathbf{K}^{(r)}]$	stiffness matrix of the rotor
$[\mathbf{K}^{(r)}_{cc}]$	part of the rotor stiffness matrix corresponding to the d.o.f.s of the constrained nodes in the rows and in the columns
$[\mathbf{K}^{(r)}_{cf}]$	part of the rotor stiffness matrix corresponding to the d.o.f.s of the constrained nodes in the rows and of the free nodes in the columns
$[\mathbf{K}^{(r)}_{fc}]$	part of the rotor stiffness matrix corresponding to the d.o.f.s of the free nodes in the rows and of the constrained nodes in the columns
$[\mathbf{K}^{(r)}_{ff}]$	part of the rotor stiffness matrix corresponding to the d.o.f.s of the free nodes in the rows and the columns
$[\mathbf{K}^{(rr)}]$, $[\mathbf{K}^{(rf)}]$, $[\mathbf{K}^{(fr)}]$, $[\mathbf{K}^{(ff)}]$	stiffness coupling matrices that are due to oil-film forces
$k^{(b)}_{rs_i}$	stiffness coefficient of ith bearing between r and s direction
$[\mathbf{M}]$	mass matrix of the complete system (rotor+ foundation)
$[\mathbf{M}^{(f)}]$	mass matrix of the foundation
$[\mathbf{M}^{(r)}]$	mass matrix of the rotor
m_u	unbalance mass
n_b	number of the journal bearings
n_C	number of rotor couplings
n_r	number of rotor nodes
p	oil pressure in the journal bearing
$\mathbf{R}$	vector of the static reactions on the bearings
r_u	radius of the unbalance mass
U	entraining velocity of the oil
$\mathbf{x}$	vector of generalized displacements of the system (rotor+foundation)
$\mathbf{x}^{(f)}$	vector of generalized displacements of the foundation
$\mathbf{x}^{(r)}$	vector of generalized displacements of all the rotor nodes
$\mathbf{x}^{(r)}_c$	vector of the generalized displacement of the constrained nodes
$\mathbf{x}^{(r)}_f$	vector of the generalized displacement of the free nodes
$\mathbf{x}^{(r)}_j$	vector of generalized displacements of jth rotor node
$x^{(r)}_j$	vertical displacement of jth rotor node
$y^{(r)}_j$	horizontal displacement of j^{th} rotor node
$\mathbf{W}$	weight force
W	relative velocity
$\Delta\alpha$	magnitude of the angular misalignment
Δr	magnitude of the radial misalignment
$\Delta\mathbf{x}$	generalized displacements imposed by coupling misalignment on the shaft
$\Delta\mathbf{x}_{jC}$	generalized displacements imposed by coupling misalignment on the d.o.f.s corresponding to the j_Cth coupling node
ζ	coordinate along the axial direction of the journal bearing
η	oil viscosity
θ	angular position of the rotor
$\vartheta^{(r)}_{x_j}$	rotation about horizontal direction of jth rotor node
$\vartheta^{(r)}_{y_j}$	rotation about vertical direction of jth rotor node
ξ	coordinate along the sliding direction of the journal bearing
φ_α	phase of the angular misalignment with respect to rotor phase reference
φ_r	phase of the angular misalignment with respect to rotor phase reference
φ_u	phase of the unbalance with respect to rotor phase reference
Ω	rotational speed

Subscripts

C	coupling
c	constrained
f	free
i	index
j	index
r	radial misalignment
α	angular misalignment

Superscripts

(b)	bearing
(f)	foundation
(r)	rotor