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Bifurcating behaviour of a rotor on two-lobe wave squeeze film damper

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ABSTRACT

The dynamics of an unbalanced rigid rotor on squeeze film dampers with two-lobe wave bearings was examined by means of a bifurcation analysis based on numerical continuation and on the assumption of the rotor speed as bifurcation parameter. Further parameters in the study were the angular orientation of the bearing, the wave amplitude of the bearing profile and the gravity residual, while single values were given to the static unbalance and the characteristic bearing parameter. The analysis was necessarily restricted, owing to the multiplicity of quantities that affect the system dynamics. Yet, the obtained results put in evidence the way the two-lobe wave geometry influences the bifurcating behaviour of the system, modifying the length of some unstable branches and the whirling periodicity.

1. Introduction

The rotor supporting system plays a crucial role as regards the operation of rotating machinery, due to its potential to favour safe or dangerous dynamics of the equipment. Practical examples witness the severity that frequently characterizes the operating conditions of rotating systems. Speeds of several thousands of revolutions per min are the state-of-the-art in petroleum and gas industry [1]. The adoption of even lighter rotors and the structural flexibility of machinery, justified by the need of saving mass, together with the complexity and the trend to higher speeds are very often the premise to a dynamics that is both complex and potentially unsafe.

In this scenario, several options are generally possible from case to case for the support realization, recurring to traditional or innovative devices, with passive, semi-active or active behaviour. A wide class of such devices is represented by support systems of the passive type, where a lubricating oil is adopted in the core of the revolute pair (journal bearing) or to complement, thanks to its damping feature, a rigid bearing (roller bearing plus a squeeze film damper).

The research aimed at enhancing these bearings, has often focused on the use of better-performing lubricants, on the role of supply conditions and, particularly in the case of journal bearings, on the potential of clearance geometry. This last concept, shared by a significant number of solutions proposed both in the theoretical and practical field, has grown since the early works of Pinkus [2,3,4] about lobe bearings.

The studies about journal stability were particularly addressed to the enhancement of anti-whirling aptitude, encouraging the experimentation of new types of devices. According to the observation that loading the bearing turned out to be beneficial against the whirl onset, "self-loading" or "preload effect" features were pursued in these studies. This result was accomplished by displacing partial arcs (segmental pads) of the original circular bearing towards the journal, in radial or transversal direction, so that different types of multi-lobe, offset pad and pressure dam bearings were obtained.

Shaffrath [5] determined the linearized stiffness and damping coefficients about a generic static equilibrium position for multi-lobe bearings, providing examples for 2-lobe (2-LB) and 3-lobe (3-LB) bearings. Akkök and Ettles [6,7] focused their theoretical and experimental investigation on the influences of bore shapes (circular, elliptical and offset halves) and groove sizes on the oil-whirl onset. They pointed out that the destabilizing effect of greater groove sizes could overwhelm the benefits of preloading. 2-LB and 3-LB were respectively studied in the papers of Malik [8] and Flack and Lanes [9]. Choy and Halloran [10] analytically studied the stability of a double overhung pinion comparing the responses respectively obtained with an offset half-bearing, a 5-pad-tilting pad bearing and an offset half-bearing in conjunction with a hydrostatic squeeze film damper. Static and dynamic characteristics were obtained by Taylor et al. [11,12], with regard to highly preloaded 3-LB, and by Strzelecki [13], who analysed the static equilibrium positions for 3, 4 and 5-LB by means of adiabatic models of laminar and turbulent flows. A comparison between the ordinary 4-LB and a 4-LB incorporating pressure dams, with

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Nomenclature

B	dimensionless amplitude of the harmonic term in Eq. (7)
C	radial clearance, m
D	$=2R$: reference bearing diameter, m
f_S	$=-mg/k$: static deflection of the retaining spring system
f_x, f_y	$=F_{SFx}/F^*$, F_{SFy}/F^*: dimensionless film forces
f	$=\omega_B/\omega_R$: bearing parameter
F_{SFx}, F_{SFy}	components of the fluid film force, N
F^*	$=p^*RL$: reference pressure force, N
g	gravity acceleration, m/s^2
h, $\tilde{h}$, h'	film thickness and derivatives (see Eqs. (7)–(9))
k	stiffness of the SFD retaining springs
L	axial length of the damper bearing, m
m	half-mass of the rotor, kg
M, N	grid dimensions
p	pressure, Pa
p^*	$=\mu\omega(R/C)^2$: reference film pressure, Pa
$P_{i,j}$	point at i row and j column of the grid in the FD scheme
q	viscous damping factor
Q	number of unknown pressure values in the FD scheme
R	reference radius for the bearing profile (measured at δ: $\cos(2\delta+\varphi)=0$), m
t	time, s
u_1, u_2, u_3, u_4	$=x$, y, x', y': state variables
$u_{2,S}$	$u_{2,S}=y_S$: value of u_2 representing the gravity residual
U	$=\rho$ / C: dimensionless unbalance
x, y	$=\bar{x}/C$, $\bar{y}/C$: dimensionless coordinates
y_S	$=\bar{y}_S/C$: dimensionless expression of the gravity residual
$\bar{x}, \bar{y}$	coordinates of the journal centre, m
$\bar{y}_0$	vertical coordinate of the journal centre in the absence of weight, m
$\bar{y}_S$	gravity residual (Eq. (1)), m
$\dot{x}, \dot{y}, x', y'$	time derivatives
$\bar{z}$	axial coordinate, m
γ	$=p/p^*$: dimensionless pressure
γ_s, γ_o	dimensionless supply and discharge pressures
δ	angular coordinate (counterclockwise from the positive x axis)
λ	$=L/D$: axial length to diameter ratio of the damper
μ	dynamic viscosity, Pa s
ρ	rotor static unbalance, m
σ	viscous damping coefficient, Ns m^{-1}
τ	$\omega\, t$: dimensionless time
φ	angular phase in Eqs. (7) and (8)
ω	angular speed, rad/s
ω_B	$=\left(\mu RL^3\right)/\left(mC^3\right)$: bearing reference frequency, rad/s
ω_g	$\sqrt{g/C}$: angular frequency, rad/s
ω_R	$=\sqrt{k/m}$: natural frequency, rad/s
Ω	$=\omega/\omega_R$: speed parameter
ζ	$=\bar{z}/L$: dimensionless axial coordinate
$\dot{}$	derivative with respect to t
$'$	derivative with respect to τ

reference to stability problem, was reported in the work of Metha et al. [14], who assessed the better performances of the latter type. Kakoty et al. [15] carried out linear and time transient analysis about the stability of two-grooved, 2-LB, 3-LB and 4-LB in the presence of load, showing that 4-LB and 2-LB achieved better stability respectively under moderate to heavy and lighter loading conditions. Takushima [16] proved the effectiveness of an optimized 5-LB made of sintered material, in the support of a spindle motor for hard disk drives. Ghosh and Nagraj [17] investigated the performances of an orifice compensated hybrid 4-LB, operating with turbulent flow, and found that the stability was improved by increasing the offset factor with speed. Shen et al. [18] characterized the nonlinear behaviour of a rigid rotor on elliptical bearing using the free boundary theory and the variational method in the determination of fluid film forces. Rao et al. [19] studied the static characteristics of a three-taper journal bearing, commonly used in high-speed step-up gear boxes. The effect of load orientation onto linear stability was taken into account by Bhushan [20] who adopted both rigid and flexible rotor models with 3-LB. Metha et al. [21] theoretically proved the increase in the linear stability of a 3-LB, obtained by adopting an oil that was modelled as a couple stress fluid. Rahmatabadi et al. [22] studied micropolar fluid lubricated multi-LB and put in evidence that suitable orientation angles of the bearing improved the static performances.

Similarities with the above-mentioned multi-LB characterize the wave bearing (WB). Wave geometry was adopted by Dimofte for gas bearings [23,24] and successively by Dimofte et al. [25] for liquid lubricated bearings. In this device, the bearing bore is machined so as to obtain a continuous wave profile with a characteristic multi-lobe shape. Besides the investigations [23–25], several further papers have been addressed to static and dynamic characteristics of WB. In [26] Lambrulescu et al. carried out experimental and theoretical work with regard to the relation between the stability of a high-speed rotor on 3-WB and the temperature of synthetic hydrocarbon oil used for the bearing lubrication. The performances of 3-WB, for the support of a high-speed balanced rotor, were analysed by Ene et al. [27] with recourse to the linear perturbation method and numerical transient analysis. In the study, the effects of wave amplitude and oil supply pressure on the stability were examined and experimentally verified. In [28] Dimofte et al. presented a theoretical analysis of 3-WB adopted in the support of a planetary gear for turbo-fan engine, assuming operation in turbulent regime under high specific loads, with speed up to 60,000 rpm. The study made it possible to ascertain the superiority of WB against plain bearing about managing the oil temperature. Strzelecki and Socha too [29,30] carried out a broad investigation about WB, in particular assuming for the latter type a pericycloid profile of the bush section. This kind of bearing was studied in [31–33] and patented by Kaniewski [34]. In particular, Kaniewski [31] solved the Reynolds equation for a pericycloid WB, by means of Fourier series. Stasiak [32] obtained the static characteristics of a 3-lobe pericycloid WB for different feed pressures, load positions and geometries. Wierzcholsky [33] evaluated the pressure distribution for non-isothermal flow within a pericycloid WB, in the presence of surface-roughness.

The present author carried out a bifurcation analysis about an unbalanced rigid rotor on 2LWB (2 lobe-wave bearing) in a previous work [35], putting in evidence the dependence of the dynamic response on the wave amplitude and the angular position of the bearing profile. As observed in literature, in comparison to the other multi-lobe shapes, the two-lobe geometry shows the highest degree of deviation from radial symmetry. This aspect implies a significant spectrum of nonlinear responses. Thus, the consequent chance of achieving a favourable influence onto the dynamic behaviour deserves some investigation. In the mentioned