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Theoretical analysis of the non-linear behavior of a flexible rotor supported by herringbone grooved gas journal bearings

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Abstract

This paper studies the behavior of a flexible rotor supported by a herringbone-grooved gas journal-bearing system. A hybrid method is employed to develop a time-dependent mathematical model of the bearing system. The finite difference method is employed with the successive over relaxation technique to solve the Reynolds equation. The system state trajectories, Poincaré maps, power spectra, and bifurcation diagrams are used to analyze the dynamic behavior of the rotor and the journal center in the horizontal and vertical directions under different operating conditions. The analysis reveals a complex dynamic behavior comprising periodic and quasi-periodic responses of the rotor and the journal center. The present numerical study illustrates the relationship between the dynamic behavior of this type of system and the rotor mass and bearing number. As such, the present results provide a deeper understanding of the non-linear dynamics of gas film rotor-bearing systems.

Keywords: Herringbone grooved; Poincaré map; Bifurcation

1. Introduction

Herringbone-grooved journal bearings are regarded as excellent replacements for the ball bearings in the spindle system of a hard disk drive due to their virtually zero non-repeatable run out and reduced noise. Furthermore, the herringbone grooves cause the lubricant to be pumped inward, thereby reducing side leakage and increasing the stability of the bearing system. Additionally, bearings of this type provide high stiffness and exceptional dynamic stability against self-excited half-frequency whirl in high-speed operations. It is anticipated that the use of herringbone-grooved journal bearings will be extended to small precision motors and various other applications in the future.

A conventional analysis of a herringbone-grooved journal bearing was first performed by Whipple [1]. More extensive results for this type of bearing were later estimated by Whitely and Williams [2]. In 1967, Malanoski [3] constructed a stability map of a lightly loaded herringbone-grooved journal bearing using the small perturbation analysis method. Several researchers have analyzed the characteristics of a herringbone-grooved journal bearing in the spindle motor of a computer hard disk drive. In 1995, Zang and Hatch [4] performed a parametric study of a herringbone-grooved journal bearing. Jang and Kim [5] calculated the dynamic coefficients of a herringbone-grooved journal bearing and thrust bearing considering five degrees of freedom for the case of a general rotor-bearing system.

Castelli and Elrod [6] presented a method for solving the stability problem of self-acting gas bearings. This method involved a comprehensive set of non-linear equations, which were integrated numerically to obtain the rotor center orbits for any state of the geometrical, operational or initial conditions. If the rotor center path spirals outward with an increasing radius, the condition is

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Nomenclature

P_a	atmospheric pressure (Nt/m^2)
p	gas pressure distribution (Nt/m^2)
P	dimensionless gas pressure distribution
h	the gap between the rotor shaft and the bushing (m)
h_L, h_U	the height of the lower and upper surface, respectively (m)
H	dimensionless the gap between the rotor shaft and the bushing
μ	gas viscosity (kg/ms)
U	tangential velocity of the rotor (m/s)
K_P	stiffness of the shaft
L	Bearing length (m)
O_1, O_2, O_3	geometric center of the bearing, rotor and journal
R	radius of the rotor (m)
$\bar{x}$, $\bar{y}$	perpendicular to the radius and axial coordinates
X_{20}, Y_{20}	dimensionless initial displacement of the rotor in horizontal and vertical directions
V_X, V_Y	dimensionless velocity of the rotor in horizontal and vertical directions
V_{X0}, V_{Y0}	dimensionless initial velocity of the rotor in horizontal and vertical directions
A_X, A_Y	dimensionless acceleration of the rotor in horizontal and vertical directions
ω	rotational speed of the rotor (rad/s)
m_r	mass of the rotor (kg)
t	time (s)
τ	dimensionless time ($\tau = \omega\ t$)
C_r	the radial clearance (m)
ε	non-dimensional eccentricity ratio
f_{gx}, f_{gy}	components of the gas film force in horizontal and vertical directions
F_{gx}, F_{gy}	non-dimensional force components of the gas film in horizontal and vertical directions
Λ	bearing number

Superscripts

n	time level

Subscripts

i	grid location in circumferential direction
j	grid location in axial direction

unstable. Conversely, if the path returns to the previous equilibrium position when disturbed, the condition is stable. Although the proposed method can be used to predict the behavior of the bearing in the instability region, it is very time-consuming. Furthermore, the method does not prove that a steady state, when eventually obtained, is stable under any disturbance. Indeed, the non-linearity of the governing equations indicates the possibility of other steady states, which may or may not be stable. In other words, this form of analysis allows the prediction of instability, but does not provide proof of stability. This paper adopts the view that a gas journal-bearing shaft has a unique, stable steady-state which, under increasing load, undergoes a transition to an unstable steady state and a stable limit cycle.

In 1966, Ehrich [7] identified a sub-harmonic vibration phenomenon in dynamic rotor systems. He noted that a sub-harmonic response appears when a high-speed turbomachine is operated at, or near, twice the fundamental frequency of the rotor. Subsequently, Bently [8] reported experimental observations of second- and third-order sub-harmonic vibrations. Botman [9] observed non-synchronous vibrations at speeds greater than twice the system critical speed in a high-speed rigid rotor-damper system. In 1978, Holmes et al. [10] published a paper dealing with aperiodic behavior in journal bearings. In this study, it was concluded that moderate levels of unbalance and a high eccentricity ratio lead to aperiodic response at speeds greater than a certain threshold value. However, this aperiodic behavior is not the classic light load instability, characterized by a half-speed component and moderate eccentricity. Sykes and Holmes [11] presented experimental observations of sub-harmonic motion in squeeze film bearings and linked this to possible precursors of chaotic motion. In 1997, Sundararajan and Noah [12] proposed a simple shooting scheme, operating in conjunction with an arc-length continuation algorithm, applicable to periodically forced rotor systems. The occurrences of periodic, quasi-periodic and chaotic motions were predicted for various ranges of rotor speed. However, prior analyses have not discussed the non-linear dynamic behavior evident in the gas film of a herringbone-grooved journal bearing. Consequently, the present study analyzes the vibration of a flexible rotor supported by herringbone-grooved journal bearings. Due to the non-linearity of the gas film pressure, it is very difficult to obtain the Reynolds equation solutions. Hence, finite difference methods are employed to determine these solutions. The following section of this paper develops the mathematical model used to analyze the present herringbone-grooved journal bearing system. The simulation results are then presented and discussed. The periodic and quasi-periodic vibrations of the bearing center and the rotor center displacement are analyzed by means of dynamic system state trajectories, power spectra, Poincaré maps and bifurcation diagrams. The paper then concludes with the presentation of some brief conclusions.