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Load carrying capacity of misaligned hydrodynamic water-lubricated plain journal bearings with rigid bush materials

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ABSTRACT

This paper analyzes the ultimate hydrodynamic load carrying capacity of water-lubricated plain journal bearings with rigid bush materials under misalignment effect, aiming to help designers find appropriate design parameters. The relationships between the ultimate load carrying capacity and the misalignment angle for bearings with different relative clearances, different length-to-diameter ratios are gained. Bearings with different diameters and different rotational speeds are also studied to determine how the ultimate hydrodynamic load carrying capacity changes with diameter and rotational speed. Finally, a method is provided for determining the appropriate radial clearance and length of misaligned water-lubricated rigid plain journal bearings.

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1. Introduction

Water-lubricated bearings have been applied in Navy ships, boats, submarines, pumps and hydroelectric turbines due to its simplified design, environmental sustainability, low cost and energy saving [1–4]. Misalignment effect, which can be caused by shaft deformation under heavy load, non-central loading, manufacturing errors or improper installation, exists in most of these applications. The misalignment effect lowers the load carrying capacity of the bearing, increases the friction torque and sometimes even leads to seizure failure [5]. To design the bearing with high reliability, it is necessary to investigate the load carrying capacity of water-lubricated journal bearings under misaligned conditions.

In recent years, Litwin et al. [5–13], Yin et al. [14–17], and Pai et al. [2,18–20] have done many researches on water-lubricated journal bearings respectively, but most of the publications are about the operating properties of water-lubricated bearings with various bush materials or structure parameters under aligned condition, few have considered the effect of misalignment. Mallya et al. [19] investigated the steady state characteristics of a misaligned water-lubricated journal bearing with a L/D ratio of 4 and three circumferentially equispaced axial grooves in 2014. In the work, the influence of misalignment on load capacity, friction coefficient and side leakage for different eccentricity ratios was analysed. Litwin et al. [13] carried out a comparative analysis of the load carrying capacity of typical rigid and polymer bearings under both aligned and misaligned conditions using an elastohydrodynamic lubrication (EHL) model. This paper drew the conclusion that rigid bearings have greater hydrodynamic capacity than elastic bearings for the same minimum film thickness, but there is a serous risk of rapid wear which might lead to significant shaft and bush damage if loss of lubricating film occurs; for elastic bearings, in case of substantial shaft misalignment mixed friction takes place which in time leads to running in. Litwin [5] pointed out that elastic bearings well tolerate non-coaxial work as they undergo large deformations and in consequence their load is distributed over an area greater than that in rigid bearings. In Ref. [11], Litwin and Olszewski assessed the possible application of water-lubricated sintered brass slide bearings for marine propeller shaft. Once again the authors concluded that water-lubricated bearings with metal bush have important merits such as low resistance to motion, long service life or stability of form, but their large value of elasticity module can lead to local stress concentration at the bush edges in the case of non-axiality of bush and shaft axes. Thus, rigid bearings such as bronze bearings and ceramic bearings are greatly sensitive to shaft misalignment, and this limits their promotion. To provide references for designing such bearings, this paper studies the load carrying capacity of misaligned water-lubricated bearings with rigid bush materials.

There have been a large number of researches working on misaligned oil-lubricated journal bearings since 1922. Pierre [21] and Bouyer and Fillon [22] have given an overview of the literature in the 20th century in the introduction parts of their papers. In recent 15 years, several new studies on misalignment effects on journal bearing performance have been published. In 2000, Guha

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Nomenclature

c	radial clearance $=R_b$-R_j
C, C_1, C_2	journal centre at the midplane, front end and rear end of bearing
D	journal diameter
e	eccentricity orientation
e_0	steady-state eccentricity at the midplane of bearing ($z=0$)
e'	magnitude of the projection of the axis of the misaligned journal on the midplane of the bearing
F	load carrying capacity
h_{min}	minimum film thickness
L	bearing length
M	misalignment moment
N	rotational speed of journal
O_b	bearing centre
p	static pressure
p_s	specific pressure $=F/(DL)$
R	journal radius
$\vec{v}$	velocity vector
ε_0	central eccentricity ratio $=e_0/c$
ε'	non-dimensional projected distance of the journal $=e'/c$
θ	angular coordinate
μ	fluid dynamic viscosity
ρ	fluid density
α	misalignment direction, i.e., angle of the projection of journal front centreline (CC_1) on the midplane
β	misalignment angle, i.e., angle between journal axis and bearing axis $=e'/L$
γ	angle between F and M vector
ϕ_0	central attitude angle
ψ	relative clearance $=c/R$
ω	angular velocity of journal $=2\pi N$

[23] studied the steady-state performance characteristics of a misaligned journal bearing with $L/D=1$ for various values of isotropic roughness parameter, eccentricity ratio and degree of misalignment using finite difference method. In 2002, Gómez-Mancilla and Nosov [24] analysed the pressure field of a misaligned short journal bearing theoretically and presented analytical expressions to calculate three additionally generated force and moments due to angular misalignment. Bouyer and Fillon [22] undertook an experimental analysis of misalignment effects on hydrodynamic plain journal bearing performances. Hydrodynamic pressure and temperature fields in the mid-plane of the bearing, temperatures in two axial directions, oil flow rate, and minimum film thickness for various operating conditions and misalignment torques were shown. Later, in 2004, Boedo and Booker [25] investigated the transient and steady state behaviour of misaligned plain journal bearings using finite element method. Sun and Gui [26–28] investigated the hydrodynamic lubrication characteristics of an oil-lubricated journal bearing with misalignment caused by shaft deformation by both numerical calculation and experiments. Pierre et al. [21] studied the thermohydrodynamic (THD) behaviour of misaligned plain journal bearings using a THD model validated with measurements. The influences of misalignment torque and misalignment direction on pressure field, temperature field and shaft position in the bearing for two different loads were revealed. In 2005, Bouyer and Fillon [29] analysed the effects of mechanical and thermal deformation on misaligned bearing performance using a thermoelastohydrodynamic (TEHD) model. Nikolakopoulos and Papadopoulos [30] investigated the friction coefficient of worn misaligned journal bearings in 2008. Later, in 2010, Nikolakopoulos et al. [31] proposed an engineering approach for the elastohydrodynamic (EHD) analysis and optimisation of the steady operation of intact, worn and misaligned journal bearings. In 2012, He et al. [32] analysed the effects of journal misalignment on a journal bearing caused by an asymmetric rotor structure; Li et al. [33] studied the 3D transient flow field of a misaligned journal bearing using the CFD method based on fluid-structure interaction (FSI) technique; Thomsen and Kilt [34] investigated the improvement of journal bearing operation at heavy misalignment using bearing flexibility and compliant liners by a TEHD model. In 2013, Zhang et al. [35] studied the TEHD behaviour of misaligned plain journal bearings. In 2014, Sun et al. [36] studied the effect of surface roughness, viscosity-pressure relationship and elastic deformation on lubrication performance of misaligned journal bearings. In 2015, Xu et al. [37] provided a comprehensive analysis on the static and dynamic characteristics of misaligned journal bearings considering the turbulent and THD effects by solving the generalised Reynolds equation and energy equation.

The above studies mainly focused on the operating properties such as pressure and temperature distribution, minimum film thickness, friction coefficient, and dynamic characteristics of misaligned journal bearings. Beodo and Booker [25] studied some limiting cases of misaligned journal bearings and found that misaligned bearings had infinite load and moment capacity as the endplane minimum film thickness approaches zero under transient journal squeeze motion and under steady load and speed conditions. Elastic deformation, thermal effects, surface roughness and pressure–viscosity variations were not taken into account in their analysis. Actually, the load and moment capacity is limited due to these ignored factors. In 1980s, some researchers studied the seizure of journal bearings [38–41], but most of them focused on seizure mechanism. Landhere et al. [42] constructed a transition diagram for plain journal bearings, but they did not consider the misalignment effect and the results were about a specified oil-lubricated bearing with $D=50$ mm, $L=50$ mm, $c=150$ μm. There is still no studies giving a comprehensive investigation on the ultimate load carrying capacity of misaligned water-lubricated journal bearings. The present work focuses on this subject.

With the rapid development of computer technology, a few researchers have used commercial computational fluid dynamics (CFD) programs which are based on the full Navier–Stokes equations to study the performance of misaligned bearings [33]. CFD programs provide a convenient design service, but the design process is generally time-consuming. Thus it is necessary to summarise the results from such programs to develop the reference for designing water-lubricated plain journal bearings [14,15]. This work studies the ultimate load carrying capacity of misaligned hydrodynamic water-lubricated rigid plain journal bearings using CFD method. As the load carrying capacity and temperature rise of water-lubricated bearings are small [43], elastic deformation and thermal effects are not taken into account in this work. Considering the differences between the physical properties of water and oil, the cavitation effect of water is taken into account via the Zwart–Gerber–Belamri Cavitation Model.

In this research, firstly a misaligned hydrodynamic water-lubricated plain journal bearing 80 mm in diameter is fully studied. The ultimate hydrodynamic load carrying capacity of the bearing with $D=80$ mm is defined as the load carrying capacity of

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