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Research Paper

Friction power analysis and improvement for a tilting-pad journal bearing considering air entrainment

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HIGHLIGHTS

- Air entrainment plays an important role for the tilting-pad journal bearing.
- In the unloaded area, the high air volume fraction leads to the low friction power.
- Closing oil inlet holes of the unloaded area can remarkably decrease friction loss.

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ABSTRACT

This paper analyses the effects of air on oil–air distribution and energy characteristics of a tilting-pad journal bearing via computational fluid dynamics. With a gaseous cavitation model, air entrainment from an outlet boundary is analysed for the TPJB at a 3000 rpm rotation speed under a 180 kN load. The simulated bearing friction power is consistent with the experimental data, which indicates that the air entrainment from the outlet boundary is near the actual working conditions. According to the analyses, the shear stress of the loaded area is mainly influenced by velocity gradient in the normal direction to the rotor-side wall, whereas the shear stress of the unloaded area is mainly influenced by air volume fraction. With air cavitation and entrainment, the air volume fraction increases and affects the viscosity of a mixture considerably, thereby eventually influencing the shear stress on the rotor-side wall and bearing friction power. On the basis of this relationship, an improvement, which closes two oil inlet holes of the unloaded area whilst increasing the oil-supplied pressure of the loaded area, is proposed to remarkably decrease the bearing friction power whilst keeping load capacity. Simulation results validate the effectiveness and feasibility of the improvement.

1. Introduction

With high dynamic stability and long service life, titling-pad journal bearings (TPJBs) are widely used in rotating machineries [1]. Given the improved efficiency of the machinery, the rotating speed is increased and the bearing friction power becomes increasingly proportionate to the entire mechanical loss. Especially for large steam turbine, the friction power of a titling-pad journal bearing can be as high as several hundred kilowatts. Therefore, the improvement of decreasing the friction power is worth investigating. In order to obtain the improvement, the flow characteristic of the bearing should be understood firstly, because it is the main factor that influences friction power, and is complex for high-speed TPJBs given cavitation and air entrainment.

Bearing oil cavitation has been widely studied in recent years, and various cavitation models have been developed to predict the cavitation process accurately. On the basis of Jakobsson–Floberg–Olsson (JFO) condition which is a flow pattern observed by an experiment, numerous JFO-type cavitation models, such as Kumar and Booker's algorithm [2] and Elrod's algorithm [3], have been developed. These models adapt to the Reynolds equation which is a simplified equation from Navier–-Stokes equations based on the assumptions of bearing oil film, rather than computational fluid dynamics (CFD).

Recently, the mechanism of bearing oil cavitation and its corresponding models have gained considerable attention. In general, cavitation is subdivided into vaporous and gaseous. Vaporous cavitation occurs when the pressure in a liquid drops to its vapour pressure and then the liquid phase changes into vapour. To describe vaporous cavitation, the Rayleigh–Plesset equation has been proposed under the assumption of spherical symmetry [4]. This equation is generally studied [5–9], and then successfully applied for bearing oil films [10,11].

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Nomenclature

f	volume fraction
F	force
h	material static enthalpy
p	pressure
Sc	Schmidt number
T	temperature
t	time
u	flow velocity
V	volume
y	distance to the nearest wall

Greeks

δ	solubility
λ	thermal conductivity
μ	kinetic viscosity
τ	shear stress
ν	velocity
ρ	density

Superscripts

T	transpose
$+$	dimensionless

Subscripts

air	air including the released air and backflow air
*air*1	released air from the bearing oil
*air*2	backflow air from the bearing outlet boundary
cavoil	cavitation oil
l	laminar
local	local situation
oil	oil
surround	surround situation
t	turbulence
w	wall
x	x direction
y	y direction

Gaseous cavitation occurs when the pressure drops to air-dissolved pressure and then air emitted. For a bearing, gaseous cavitation seems more common and important than vaporous cavitation because the vapour pressure of lubricating oil is low and rarely reached. Therefore, a gaseous cavitation model is proposed on the basis of the air solubility in bearing oil lubricant [12,13]. This model adapts to the Reynolds equation and CFD, and has been applied to many complex simulations, such as analysing the non-equilibrium dissolution effect in thrust bearings [14–17].

Ambient air may backflow into the bearing from the outlets because cavitation produces pressure that is lower than the working environment; this process is called air entrainment. In recent years, air entrainment has played an important role in the behaviour of floating bush bearings [18,19] and squeeze film dampers [20]. It may also be important for TPJBs [21].

Therefore, in the present work, air entrainment in a TPJB is considered with the gaseous cavitation model to provide a proper low-pressure area by CFD. The present work focuses on the detailed oil–air distribution of the entire bearing and their effects on reduced friction power. On the basis of the understanding of the flow characteristic, a feasible improvement for the TPJB is provided to decrease friction power remarkably whilst maintaining load capacity.

The remainder of this paper is outlined as follows. In Section 2, the governing equations of the homogeneous mixture model are presented. Section 3 introduces the TPJB. The simulation results of the basic bearing characteristics, friction power and oil-air distribution are illustrated in Section 4. In Section 5, two bearing improvements for decreasing the bearing friction power are provided and compared to select a feasible improvement. Section 6 provides the conclusions drawn from this work.

2. Governing equations

2.1. Cavitation model

In the present work, a gaseous cavitation model is built on the basis of the air solubility in lubricant oil [12] and is adjusted for air backflow from the bearing outlet. The surrounding pressure and temperature are set to 101.325 kPa and 313.15 K, correspondingly, on the basis of the working condition of the oil box. The standard status of the released air from the bearing lubricant oil is set to $T_0 = 273.16$ K and $p_0 = 101.325$ kPa. Under this status, the released air volume can be calculated as follows:

$$\widetilde{V}_{air1} = (\delta_{surround} - \delta_{local})V_{oil} \tag{1}$$

In accordance with the unit volume of the solvent, the Bunsen solubility of air can be calculated by [22]:

$$\delta_{surround} = e^{-2.476+\frac{250.8}{T_{surround}}}\frac{p_{surround}}{p_0} \tag{2}$$

Considering that the local condition for air is different from the standard status, the local air emission volume can be calculated using the standard volume as follows:

$$V_{air1} = \frac{p_0}{p_{local}}\frac{T_{local}}{T_0}\widetilde{V}_{air1} \tag{3}$$

On the basis of the abovementioned equations, the air emission volume fraction can be expressed as:

$$f_{air1} = \frac{V_{air1}}{V_{air1} + V_{oil}} = \frac{A}{A+1} \tag{4}$$

where $A = \max\left[\frac{T}{T_0}\left(e^{-2.476+\frac{250.8}{T_{surround}}}\frac{p_{surround}}{p} - e^{-2.476+\frac{250.8}{T}}\right), 0\right]$.

The lubricant oil and the air it releases are considered to be mixed fully. Thus, for simplicity, the lubricant oil and the air it releases can be calculated as a mixture, called cavitation oil. The density, laminar viscosity and enthalpy of the cavitation oil can be calculated as:

$$\rho_{cavoil} = (1 - f_{air1})\rho_{oil} + f_{air1}\rho_{air} \tag{5}$$

$$\mu_{l,cavoil} = (1 - f_{air1})\mu_{oil} + f_{air1}\mu_{air} \tag{6}$$

$$h_{cavoil} = (1 - f_{air1})\rho_{oil}h_{oil} + f_{air1}\rho_{air}h_{air} \tag{7}$$

2.2. Navier-Stokes equations

To reflect air entrainment, the boundary condition of air backflow is adopted. The backflow air and cavitation oil are considered two phases, and the homogeneous mixture model is used. In the mixture model, the cavitation oil and backflow air phases are calculated separately. Assuming that the cavitation oil and backflow air share a common flow field and the two-phase flow is homogenous, $\overrightarrow{v_{air}} = \overrightarrow{v_{cavoil}}$ and the pressure field is common. The continuity and momentum equations for the two-phase homogeneous mixture model can be written as follows.

For the backflow air phase, the continuity equation is: