Tribology International 96 (2016) 326–348

Contents lists available at ScienceDirect

Tribology International

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

Static and dynamic performances of refrigerant-lubricated bearings

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ARTICLE INFO

Article history:
Received 20 August 2015
Received in revised form
23 November 2015
Accepted 28 December 2015
Available online 4 January 2016

Keywords:
Gas bearing
Two phase flow
Turbulence
THD

ABSTRACT

For years now, gas bearings are successfully used over a large panel of turbo-machineries. Some of these systems are bound to be run in controlled environments such as refrigerating gas. In this work we present a theoretical and numerical model which takes into account the vapor/liquid lubricant transition, the laminar/turbulent flow transition and both temperature and viscosity 3D variations in the fluid and the solids for both static and dynamic situations. This model involves: the resolution of the generalized Reynolds equation for compressible fluids with 3D variable viscosity, the description of the turbulence effects by the phenomenological approach of Elrod, using a 3D eddy viscosity field, the resolution of a non-linear equation of state for the lubricant, able to describe the vapor/liquid transition and a local thermal approach to obtain a 3D estimation of the fluid temperature, thanks to the thin-film energy equation. The thermal effects in solids are also taken into account. In this study, we showed the importance of an accurate description of the film parameters, which variations largely influence the bearing behavior. Among the principal theories, there are: compressible lubricant, with an appropriate non-linear behavior when close to the vapor/liquid transition, vapor/liquid transition and calculation of the mixture equivalent parameters, turbulent flow for high-speed GFBs with a 3D eddy viscosity mode, a 3D behavior for viscosity, particularly the cross-film variations, (temperature dependent)and a 3D behavior for temperature, particularly in cross-film direction in order to be consistent with viscosity, but also in the axial direction in order to account for potential temperature gradient which considerably modifies the bearing 3D temperature profile. Both static and dynamic behaviors of GFBs are analyzed.

1. Introduction

The reduction of on-board masses and volumes is a central issue regarding transports, particularly in aeronautics. ACM are classified as high-speed turbomachines and nowadays, most of the ECS on civil and military aircrafts and vehicles use Gas Foil Bearings (GFBs) in the ACM [1]. If the lubricating gas and the one in the environment are the same, a separate lubricant feeding system becomes unnecessary. Hence, GFBs solve both lubricant supply and bearing environment pollution problems at the same time. In some cases, GFBs can be used in an environment different from air, like refrigerants in the ECS. A realistic solution in refrigerant environment is refrigerant lubricated GFBs. Over the last 20 years, a significant number of studies have shown GFBs were the best options for a consequent range of applications, such as oil-free turbomachinery [2]. However, there are still problems when one tries to implement GFBs into new systems, particularly in refrigerant environments. Studies in this domain already exist but they are either experimental [3] or analytical but without specific lubricant behavior analysis [4]. Refrigerant lubricated GFBs require a specific ThermoHydroDynamic (THD) theoretical and numerical model [5]. In this paper, static and dynamic GFBs' behavior are investigated when running in refrigerating gas. A THD approach is used in conjunction with gas constitutive equation to describe pressure, density, viscosity and temperature. It involves the use of a GRE (Generalized Reynolds Equation) for turbulent flow, a non-linear cubic EoS (Equation of State) for two-phase flow and a 3D turbulent thin-film energy equation and 3D thermal equations in solids. Journal bearings' global parameters are calculated for steady state and dynamic conditions.

2. Hydrodynamic lubrication

In bearings, for compressible gas, the pressure is related to density, temperature and viscosity. This relation is often described by the ideal gas law. The main assumption of the ideal gas theory is that density remains dependent on pressure and temperature. However, when pressure is close enough to the vapor pressure, which is value for which the vapor/liquid transition occurs, this assumption becomes invalid. Two-phase flow has been observed experimentally under specific conditions when refrigerant is introduced into GFBs' lubrication system. Therefore we use a non-linear EoS able to

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http://dx.doi.org/10.1016/j.triboint.2015.12.035

Nomenclature

C_b	Bearing assembling clearance (m)
C_L	Bearing manufacturing clearance (m)
C_i, $i=1,3$	Phenomenological constants in Clapeyron's formula
c_p	Heat capacity (J kg^{-1} K^{-1})
R_s	Shaft radius (m)
R_h	Housing radius (m)
R_L	Sector radius (m)
L	Bearing axial length (m)
F_0	Viscosity integral coefficient F_0 (m^2 s kg^{-1})
F_1	Viscosity integral coefficient F_1 (s)
F_2	Viscosity integral coefficient F_2 (m s)
h	Film thickness (m)
N_d	Dissipation number
p_{sat}	Vapor pressure (bar)
Pe	Peclet number
$\Re_L$	Local Reynolds number
a_ρ	EoS temperature-dependent coefficient
c_{min}	Minimal speed of sound in the mixture (m s^{-1})
c_v	Minimal speed of sound in the vapor (m s^{-1})
B	EoS constant coefficient (for a given fluid)
M	Molar mass (kg mol^{-1})
k, k_-, k^-	Thermal conductivity (W m^{-1} K^{-1})
h_-	Global coefficient of exchange (W m^{-2} K^{-1})
m_ρ	EoS constant coefficient (for a given fluid)
p	Pressure (Pa)
p_c	Critical pressure (Pa)
Pr^t	Prandtl number
R	Ideal gas constant (J mol^{-1} K^{-1})
T, T_-	Temperature (K)
T_{amb}	Ambient temperature (K)
T_c	Critical temperature (K)
Ta_c	Critical Taylor number
Ta_L	Local Taylor number
u,v,w	Circumferential, radial and axial velocity components (m s^{-1})
x,y,z	Circumferential, radial and axial coordinates (m)
$y+$	Dimensionless distance from the wall
Su	Sutherland number
E	Young's modulus (Pa)
t_h	Bump thickness (m)
S	Bump pitch (m)
l	Bump radius (m)
Q_E	Flow rate at the entry of sector (m^3 s^{-1})
Q_S	Flow rate at the exit of sector (m^3 s^{-1})
Q_A	Flow rate in the axial direction (m^3 s^{-1})
W, W_-	Load (N)
k_i	Stiffness coefficient in the local coordinates (x,y,z) (N m^{-1})
K_i	Stiffness coefficient in the global coordinates (r,t,z) (–)
c_i	Damping coefficient in the local coordinates (x,y,z) (N s m^{-1})
C_i	Damping coefficient in the global coordinates (r,t,z) (–)
t	Time (s)
M_c	Critical mass (kg)
K_{eq}	Equivalent stiffness (N m^{-1})

Greek symbols

Λ	Bearing number
Ω	Shaft rotational speed (R.P.M)
ρ, ρ_-	Fluid mass density (kg m^{-3})
ϕ_e	Local attitude angle
ϕ	Global attitude angle
α	Volume expansivity at constant pressure (K^{-1})
α_f	Heat transfer diffusivity
δ_L	Thickness of the laminar sublayer (m)
ε_i	Eccentricity ratio of sector
ε_b	Eccentricity ratio of bearing
γ	Adiabatic index
κ	Von Karman constant
μ, μ_-, μ^-	Dynamic viscosity (Pa s)
ω_ρ	EoS acentric factor
τ	Stress tensor (kg m^{-1} s^{-2})
λ	Mixing coefficient
υ	Poisson's ratio
α_t	Bump compliance
γ_c	Whirl frequency (Hz)
ω_t	Deflection of the foil (m)

Subscripts, superscripts

$\cdot^*$	Exponent for the sum of the laminar and turbulent parameter values
$\cdot^t$	Exponent for the turbulent regime
$\cdot_0$	Subscript for the reference value
$\cdot_l$	Subscript for the liquid phase
$\cdot_v$	Subscript for the vapor phase
$\cdot_s$	Subscript for the shaft
$\cdot_h$	Subscript for the housing

describe the density variation as a function of pressure and temperature, as well as the vapor/liquid transition. Density and pressure are strongly coupled and both the GRE and the EoS have to be solved simultaneously. Viscosity is also linked to the temperature and to the fraction of liquid in the fluid. We choose a modified Peng–Robinson EoS [6], whose dimensional formulation is written as follow:

$$p=\frac{R\,T}{\left(\frac{M}{\rho}\right)-B}-\frac{a_\rho}{\left(\frac{M}{\rho}\right)\left(\frac{M}{\rho}+B\right)+B\left(\frac{M}{\rho}-B\right)} \tag{1}$$

with

$$\begin{cases} R=8.314462175\ \left(\mathrm{J\ mol^{-1}\ K^{-1}}\right) \\ a_\rho=0.457135528921\frac{R^2T_c^2}{p_c}\left[1+m_\rho\left(1-\left(\frac{T}{T_c}\right)^{0.5}\right)\right]^2 \\ m_\rho=0.378893+1.4897153\omega_\rho-0.17131848\omega_\rho^2+0.0196554\omega_\rho^3 \\ B=0.0777960739039\frac{RT_c}{p_c} \end{cases} \tag{2}$$

where p is the pressure, R the ideal gas constant, T the local temperature, B and m_ρ are EoS constant coefficients (for a given fluid) whereas a_ρ is an EoS temperature-dependent coefficient. The molar mass M, the critical pressure p_c, the critical temperature T_c and the acentric factor ω_ρ are among the fluid characteristics which can be found in REFPROP or any other fluid database. The only lack of accuracy of the EoS prediction is due to bad prediction of the vapor pressure, for which the transition occurs. In order to cope with this, we use the Clapeyron formula to predict the vapor/liquid transition. Thanks to the Dupre approximation, one only needs three couples (T_i, p_{sat} (T_i)) (for a given gas) to predict the vapor pressure at any given temperature [7]:

$$ln\left(p_{sat}(T)\right)=C_1-\frac{C_2}{T}-C_3 ln(T) \tag{3}$$

C_1, C_2, C_3 are three phenomenological constants (for a given gas) which values can be obtained thanks to three couples (T_i, p_{sat}