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# Finite length floating ring bearings: Operational characteristics using analytical methods

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ABSTRACT

The floating ring bearings widely used in high-speed applications are usually incorporated in rotordynamic algorithms under short bearing approximation or by using numerical solutions. In an effort to improve both the accuracy and evaluation time of the pressure distribution in a floating ring bearing, a recently developed exact analytical solution is applied to finite-length floating-ring bearings. The main design characteristics and operational parameters such as ring speed ratio, eccentricities, and friction coefficient are presented for various cases of operation under the exact analytical solution and they are compared with approximating or numerical bearing models and experimental measurements when possible.



## 1. Introduction

Floating ring bearings are a type of hydrodynamicaly lubricated journal bearing with special applications, usually in high-speed rotating systems. In this type of bearings, a ring is inserted between the bearing casing and the rotating journal and floats in the lubricant after obtaining a certain percentage of the rotating speed of the journal. In normal operating conditions, the ring is fully separated from the journal and the casing by the lubricating films that are both capable of receiving load [1].

The operational characteristics of floating ring bearing present both advantages and disadvantages. The contribution of the outer fluid film in additional damping to the system is considered very beneficial especially in applications of high-speed systems, e.g. turbosystems, where the occuring instability response can be sufficiently damped, allowing the system to operate without compromised integrity. The generated heat is less than in a plain cylindrical journal bearing and the thermal distortion does not result in severe shape deformation of the cylindrical surfaces. Additionally, floating ring bearings present lower frictional losses compared to fixed sleeve bearings. However, the existence of two clearances in the radial direction can yield poor shaft centring [2]. Furthermore, the demand of supplying lubricant in two fluid films and the potential demand for an unloaded start up may discard floating ring bearings from some applications.

The fundamental theory for the operation of floating ring bearings has been widely investigated in the past [1, 3–5] and recent literature [6–17]. Computational power nowadays allows the application of very accurate numerical solutions for floating ring bearings in rotordynamic algorithms. Approximate analytical solutions, usually considering short bearing geometry, may be sufficient for certain applications of floating ring bearings. However, in rotordynamic case studies for the design of high-speed systems, the proposal of fast and accurate analytical solutions for floating ring bearings can be still of interest. An accurate analytical model for floating ring lubrication offers the ability to formulate the nonlinear dynamics of such systems in a complete analytical concept and thus further investigations can be performed regarding the dependence of e.g. instability thresholds and other design parameters on the bearing geometry. The bearing geometrical configuration does not always correspond to a short bearing. Given these considerations, a recent analytical solution for plain finite-length cylindrical bearings [18–20] is applied in this paper to the concept of floating ring bearings.

This paper details the solution of the Reynolds equation for the lubrication of finite length floating ring bearings, in analytical closed-form expressions. The fluid film pressure distribution, the impedance forces and some important operational characteristics are evaluated analytically for various cases of bearing operation and parameters of the solution. Bearing eccentricity, the friction coefficient, and the ring speed ratio are evaluated for various

Abbreviations: ADI, Alternating Direction Implicit; NFD, Number of Finite Differences; CFD, Computational Fluid Dynamics; ODE, Ordinary Differential Equation; FDM, Finite Difference Method; PSM, Power Series Method; NDF, Numerical Differentiation Formula; SLP, Sturm–Liouville Problem

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## Nomenclature

| | |
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| $\mathbf{A}$ | matrix for the definition of the system $\mathbf{A}\times\boldsymbol{\sigma}=[0]$ for the Power Series Method solution |
| $\delta_j$ | constants used in the evaluation of the pressure distribution, $j=1,2,\ldots$ |
| $\varepsilon_i$ | eccentricity ratio of the journal in the inner oil film of the 1st and the 2nd bearing respectively |
| $\varepsilon_o$ | eccentricity ratio of the ring in the outer oil film of the 1st and the 2nd bearing respectively |
| $\eta_j$ | constants used for the normalization of eigenfunction used in the pressure distribution evaluation, $j=1,2,\ldots$ |
| $\theta$ | coordinate at the circumferential direction of each oil film |
| $\vartheta$ | angle of rotation of the floating ring |
| $\Lambda_i$, $\Lambda_o$ | load criterion for the inner and the outer film correspondingly |
| $\mu$ | Lubricant dynamic viscosity; used for bearing global analysis |
| $\nu$ | Lubricant kinematic viscosity; used for bearing global analysis |
| $\rho$ | Lubricant density; used for bearing global analysis |
| $\mu_i,\mu_o$ | dynamic viscosity of the lubricant at the inner and outer oil film respectively |
| $\boldsymbol{\sigma}$ | Vector matrix with the unknown constants $\sigma_j$ included in the definition of Power Series |
| $\tau_i$ | shear stresses in the inner oil film |
| $\tau_o$ | shear stresses in the outer oil film |
| $\varphi_i$ | attitude angle of the inner oil film |
| $\varphi_o$ | attitude angle of the outer oil film |
| $\Phi_i$ | particular solution of the Reynolds equation defined at the inner oil film at the circumferential direction |
| $\Phi_o$ | particular solution of the Reynolds equation defined at the outer oil film at the circumferential direction |
| $\chi$ | coordinate at the axial direction of each bearing |
| $\Omega$ | rotating (spinning) speed of the shaft |
| $\Omega_r$ | rotating (spinning) speed of the floating ring |
| $\Omega_{\text{eff}}$ | effective rotational speed in a fluid film; used for global bearing analysis |
| $\Omega_{\text{eff},i}$ | effective rotational speed at the inner oil film |
| $\Omega_{\text{eff},o}$ | effective rotational speed at the outer oil film |

*Latin letters*

| | |
|---|---|
| $c$ | radial clearance; used for bearing global analysis |
| $c_i$ | radial clearance at the inner oil film |
| $c_o$ | radial clearance at the outer oil film |
| e | Euler's number |
| $e$ | eccentricity of the journal in the inner oil film; used also for bearing global analysis |
| $e_r$ | eccentricity of the ring in the outer oil film |
| $f(\theta)$ | homogenous solution of the Reynolds equation at the circumferential direction |
| $F_r$ | resulting force of the inner oil film at the journal, at the “r” direction |
| $F_{r,i}$ | resulting force of the inner oil film at the inner surface of the ring, at the “r” direction |
| $F_{r,o}$ | resulting force of the outer oil film at the outer surface of the ring, at the “r” direction |
| $F_t$ | resulting force of the inner oil film at the journal, at the “t” direction |
| $F_{t,i}$ | resulting force of the inner oil film at the inner surface of the ring, at the “t” direction |
| $F_{t,o}$ | resulting force of the outer oil film at the outer surface of the ring, at the “t” direction |
| $F_Y$ | resulting force of the inner oil film at the journal, at the vertical direction |
| $F_{Y,i}$ | resulting force of the inner oil film at the inner surface of the ring, at the vertical direction |
| $g$ | gravity acceleration |
| $g(x,\theta)$ | homogenous solution of the Reynolds equation |
| $h$ | oil film thickness |
| $\mathbf{J}$ | Jacobian matrix of the nonlinear system of equations for the equilibrium of the journal and the floating ring |
| $K$ | Number of eigenfunctions used for the analytical solution of the Reynolds equation |
| $F_r$ | resulting force of the inner oil film at the journal, at the “r” direction |
| $L$ | Length of bearing; used for bearing global analysis |
| $L_i$ | effective length of the inner fluid film |
| $L_o$ | effective length of the outer fluid film |
| $N$ | number of Power Series terms |
| $P$ | lubricant pressure |
| $\underline{P}$ | dimensionless lubricant pressure, $\underline{P}=c^2/\mu\Omega R^2$ |
| $P_i$ | developed pressure of the oil in the inner film |
| $P_o$ | developed pressure of the oil in the outer film |
| $R$ | radius of the journal; used also for bearing global analysis |
| $Re$ | Reynolds number; used for bearing global analysis. $\mathcal{R}e=\boldsymbol{\rho\Omega Rc/\mu}$, $\mathcal{R}e=\boldsymbol{\rho\Omega Rh/\mu}$ (local Reynolds number) |
| $R_i$ | inner radius of the floating ring |
| $R_o$ | outer radius of the floating ring |
| $Ta$ | Taylor number; used for bearing global analysis. $Ta=\sqrt{c/R}Re$ |
| $T$ | lubricant temperature; used for bearing global analysis |
| $T_i$ | resulting torque of the inner oil film to the inner surface of the ring |
| $T_o$ | resulting torque of the outer oil film to the outer surface of the ring |
| $u(x,\theta)$ | particular solution of the Reynolds equation |
| $W$ | bearing load; used for bearing global analysis |
| $y$ | vertical displacement of the journal |
| $y_r$ | vertical displacement of the ring |
| $z$ | horizontal displacement of the journal |
| $z_r$ | horizontal displacement of the ring |

values of the load criterion (Sommerfeld number) and compared among the proposed exact analytical solution for the finite length bearing, a numerical solution for the finite length bearing and an analytical solution under the short bearing approximation. The ring speed ratio – a parameter that significantly influences the thresholds of instability in high-speed systems – is presented with differences among the aforementioned solutions. Loading capacity and frictional losses may also differ among the solutions for various operational conditions of the bearing. The evaluation time needed for the exact analytical solution, together with its accuracy and simplicity, encourages its application in rotordynamic algorithms for high-speed systems.