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Partitioned fluid-structure methods applied to the solution of elastohydrodynamic conformal contacts

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ABSTRACT

The functional characteristics of statically-loaded journal bearings operating in the elastohydrodynamic lubrication (EHL) regime are evaluated by means of three partitioned fluid-structure coupling methods. Widely used in other areas but yet unexplored in the context of EHL problems related to journal bearings, these methods permit the use of optimized codes to solve the hydrodynamic and structural equations separately employing different techniques specialized in each type of equation. In this study, lubricant pressures are calculated using the isothermal Reynolds equation and the $p-\theta$ mass-conserving formulation is adopted for the computation of cavitation effects. An appropriate substructuring technique is applied in order to reduce the order of the bearing 3D linear-elastic finite element model. The efficiency and robustness of the partitioned fluid-structure coupling methods presented are assessed for two extreme situations of high deformation and high load conditions of a typical internal combustion engine connecting-rod big-end bearing. Numerical results evidence that partitioned fluid-structure coupling methods consist in a very efficient simulation tool for EHL journal bearing analyses.

1. Introduction

The elastohydrodynamic lubrication regime (EHL) is encountered in tribological systems whenever the intensity of the hydrodynamic pressures is high enough to produce deformations in the contact surfaces with the same magnitude order of the lubricant film clearance.

In non-conformal contacts, e.g. rolling and roll bearings, the structural deformations occur mainly due to surface compression induced by the extreme hydrodynamic pressures generated in the contact. Conversely, in conformal contacts, e.g. journal bearings and piston assemblies of internal combustion engines, the fluid pressures tend to be lower, and the surface distortions are mainly produced by the bending flexibility of the structures. In the present work, journal bearing conformal contacts are considered for the evaluation of different partitioned methods employed in the solution of the fluid structure interaction (FSI) problem developed in such systems under EHL conditions.

The coupled hydrodynamic and structural solutions of EHL problems in journal bearing systems are traditionally addressed by using either the nodal or the modal approach [1]. The modal (or mode-based) approach was introduced by [2] and is less widespread in the literature. According to this method, the nodal displacements are computed by adopting a linear combination of particular mode shapes determined from the linear elastic solution of the journal-bearing structure. On the other hand, the nodal (or node-based) approach is most predominant in publications involving EHL of journal bearing problems. In this case, the nodal displacements are determined from the direct relation between the nodal force vector and the linear compliance matrix of the elastic structure. The calculation of the compliance matrix is usually carried out by applying some reducing or substructuring technique to the complete finite element model of the entire bearing structure. Thus, only the degrees of freedom of nodes placed on the internal bearing surface are retained for the EHL solutions.

Two sub-methods of coupling can be identified for nodal approach, namely indirect or direct methods. The nodal indirect (or monolithic) methods often employ sophisticated implicit Newton–Raphson solution schemes, where the estimation of the solutions in the next steps are computed from a system of residual equations based on the perturbed Reynolds equation and on the applied external loads [3–14]. In other words, in the indirect methods all the equations involved in the EHL modeling are solved simultaneously. The nodal direct (or partitioned) methods are defined in terms of direct iterative schemes [15–16], in which the hydrodynamic and structural problems are solved separately. In that case, a coupling algorithm is required to incorporate the interaction between fluid and structure. The numerical

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Nomenclature

c	radial clearance [m]
$\boldsymbol{c}^k$	coefficients for the linear approximation of the IQN-ILS method
$[\boldsymbol{C}]$	compliance matrix
$F_{ext}^{x_b}$	external load force in the $\boldsymbol{x_b}$-axis [N]
$F_{ext}^{y_b}$	external load force in the $\boldsymbol{y_b}$-axis [N]
$\overrightarrow{\boldsymbol{F}}_{\boldsymbol{ext}}$	vector of the external load force, $\overrightarrow{\boldsymbol{F}}_{\boldsymbol{ext}} = \left(F_{ext}^{x_b},\ F_{ext}^{y_b}\right)$ [N]
h	lubricant film geometry [m]
$\overline{h}$	dimensionless lubricant film geometry, $\overline{h} = (h/c)$
L	bearing width [m]
n_s	number retained node on the bearing surface
p_H	hydrodynamic pressure [Pa]
$\overline{p}_H$	dimensionless hydrodynamic pressure, $\overline{p}_H = (p_H/\mu\Omega(R/c)^2)$
$\overline{p}_{cav}$	dimensionless limit cavitation pressure
$\overline{\boldsymbol{p}}_{\boldsymbol{H}}$	vector of the dimensionless hydrodynamic pressure
$\overline{\boldsymbol{q}}$	vector of the dimensionless rigid body position of the journal, $\overline{\boldsymbol{q}} = \left(\overline{X}_r,\ \overline{Y}_r\right)$
R	bearing radius [m]
r_{LD}	bearing width-diameter ratio (-), $r_{LD} = \left(L/2R\right)$
$\boldsymbol{r}$	residual vector
$\left[\boldsymbol{V^k}\right]$	auxiliary matrix of the IQN-ILS method
$W_H^{x_b}$	hydrodynamic load force in the $\boldsymbol{x_b}$-axis [N]
$W_H^{y_b}$	hydrodynamic load force in the $\boldsymbol{y_b}$-axis [N]
$\overrightarrow{\boldsymbol{W}}_{\boldsymbol{H}}$	vector of the hydrodynamic load force, $\overrightarrow{\boldsymbol{W}}_{\boldsymbol{H}} = \left(W_H^{x_b},\ W_H^{y_b}\right)$ [N]
$\left[\boldsymbol{W^k}\right]$	auxiliary matrix of the IQN-ILS method
X_r	rigid body position of the journal in the $\boldsymbol{x_b}$-axis [m]
$\overline{X}_r$	dimensionless rigid body position of the journal in the $\boldsymbol{x_b}$-axis, $\overline{X}_r = (X_r/c)$
$\overrightarrow{\boldsymbol{x}}_{\boldsymbol{b}}$	horizontal bearing axis
Y_r	rigid body position of the journal in the $\boldsymbol{y_b}$-axis [m]
$\overline{Y}_r$	dimensionless rigid body position of the journal in the $\boldsymbol{y_b}$-axis, $\overline{Y}_r = (Y_r/c)$
$\overrightarrow{\boldsymbol{y}}_{\boldsymbol{b}}$	vertical bearing axis
z_b	bearing axial coordinate [m]
$\overrightarrow{z}_b$	dimensionless bearing axial coordinates, $\overline{z}_b = (z_b/L/2)$

Greek Letters

δ_b	radial bearing displacements [m]
$\overline{\delta}_b$	dimensionless radial bearing displacements, $\overline{\delta}_b = (\delta_b/c)$
$\overline{\boldsymbol{\delta}}_{\boldsymbol{b}}$	vector of the dimensionless radial bearing displacements
$\tilde{\overline{\boldsymbol{\delta}}}_{\boldsymbol{b}}$	vector of the dimensionless intermediate radial bearing displacements
ε_{EHL}	tolerance error for the EHL convergence, $\varepsilon_{EHL} = 10^{-3}$
θ_b	bearing circumferential coordinate [deg]
θ	lubricant film fraction [-], $0 \le \theta \le 1$
μ	lubricant dynamic viscosity [Pa.s]
$\overline{\mu}$	dimensionless lubricant dynamic viscosity, $\overline{\mu} = (\mu/\mu_0)$
ρ	lubricant density [kg/m^3]
$\overline{\rho}$	dimensionless lubricant density, $\overline{\rho} = (\rho/\rho_0)$
ω_{EHL}	under-relaxation factor for the EHL solution
ω	rotational speed [rad/s]
$\overline{\omega}$	dimensionless rotational speed, $\overline{\omega} = \frac{\omega}{2\pi}$ [1/s]
Ω	dimensionless absolute rotational speed, $\Omega = \frac{\lvert\omega_j + \omega_b\rvert}{2\pi}$ [1/s]

Special characters

$\mathscr{H}$	solver operator of the hydrodynamic solution
$\mathscr{R}$	operator of the residual equation
$[\mathscr{R}']$	Jacobian matrix of $\mathscr{R}$
$\left[\widehat{\mathscr{R}'^{k}}\right]^{-1}$	approximation for the inverse of the Jacobian matrix $\left[\mathscr{R}'\right]$
$\mathbf{S}$	solver operator of the structural solution

Subscripts

0	reference values
b	bearing
j	journal

Superscripts

k	EHL coupling iteration

convergence of direct coupling schemes commonly used to solve flexible journal bearings systems is often difficult, especially when large deformations take place. Such numerical difficulties justify the predominance of indirect methods for the EHL solution of highly loaded bearings.

In this scenario, the aim of the present work is to propose the solution of conformal EHL contacts of statically-loaded journal bearings by means of three partitioned methods [17,22], namely Fixed Point Gauss-Seidel Method (PGMF), Point Gauss-Seidel Method with Aitken Acceleration (PGMA) and Inexact Quasi-Newton Method (IQN-ILS), and investigate their efficiency and robustness. These partitioned methods are used in a wide range of applications of fluid-structure interaction problems, such as in the analysis of flutter in wings of aircrafts and blades of turbo-machines, in the complex fluid-structure interaction of life-saving equipment such as parachutes and air bags, and even in the investigation of blood flow through arteries and heart valves [17]. The main advantage of the partitioned approach is the possibility of using optimized codes to solve hydrodynamic equations and structural equations separately. In other words, each component of the EHL problem can be solved with different techniques specialized for each type of equations. This flexibility is not verified in the implicit solutions where all equations are generally solved in the same solution framework. With such advantages in mind, another goal of this contribution is to introduce aforementioned partitioned coupling techniques in the context of tribological simulations.

2. Mathematical modeling

This section begins with a brief description of the governing equations that compose the fluid-structure interaction of EHL conformal contact typically found in static journal bearing systems, followed by comments with respect to the interpolations on the fluid-structure interface possibly needed to match different fluid and structural meshes.

2.1. Reynolds equation

The fluid-flow behavior of a typical liquid-lubricated journal bearing is described in terms of the Reynolds lubrication equation, derived from the general momentum and mass conservation equations of the