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Linking rigid multibody systems via controllable thin fluid films

E.A. Estupiñan, I.F. Santos [*]

Technical University of Denmark, Department of Mechanical Engineering, Nils Koppels Alle, 404, Kgs. Lyngby DK-2800, Denmark

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ABSTRACT

This work deals with the mathematical modelling of multibody systems interconnected via thin fluid films. The dynamics of the fluid films can be actively controlled by means of different types of actuators, allowing significant vibration reduction of the system components. In this framework, this paper gives a theoretical contribution to the combined fields of fluid–structure interaction and vibration control. The methodology is applied to a reciprocating linear compressor, where the dynamics of the mechanical components are described with help of multibody dynamics. The crank is linked to the rotor via a thin fluid film, where the hydrodynamic pressure is described by the Reynolds equation, which is modified to accommodate the controllable lubrication conditions. The fluid film forces are coupled to the set of nonlinear equations that describes the dynamics of the reciprocating linear compressor. The system of equations is numerically solved for the case when the system operates with conventional hydrodynamic lubrication and for several cases of the bearing operating under controlled hybrid lubrication conditions. The analysis of the results is carried out with focus on the behaviour of the journal orbits, maximum fluid film pressure and minimum fluid film thickness.

1. Introduction

The feasibility of applying active lubrication to the main bearings of a hermetic reciprocating compressor is studied in this work, with the help of multibody dynamics and fluid film theory. Small-scale reciprocating compressors are of common use to compress coolant gas in household refrigerators and air conditioners. This type of compressors have pistons that are driven directly through a slider-crank mechanism, converting the rotating movement of the rotor to an oscillating motion, as illustrated in Fig. 1. The performance of the bearings affects key functions of the compressor, such as durability, noise, and vibrations. Therefore the study and optimization of the dynamic behaviour of reciprocating compressors, taking into account the hydrodynamics of bearings, can be of significant importance for the development of new prototypes. Several studies related to the modelling of small reciprocating compressors can be found in the literature [3,4], however, only a few of them have incorporated in their models the dynamics of the fluid films. For instance, a study that includes the coupling of fluid–structure dynamics to analyse the dynamics of the piston is described in Ref. [5]. In the work of Ref. [6], a model of the coupled dynamic behaviour of the piston and crankshaft is developed and some comparisons between a finite-width bearing model and a short-width bearing approach are included in the study. In contrast to previous studies, in this work a multibody dynamic model that represents the dynamics of the main mechanical components of a reciprocating compressor is coupled to the dynamics of the fluid film bearings, and the analysis is focused on the performance of the upper bearing working under hydrodynamic and hybrid (controllable) lubrication conditions. In a reciprocating machine, the lubricant films surrounding the main bearings commonly have to support inertial loads, crankshaft unbalance forces and the reciprocating forces coming from the gas pressure dynamics. The behaviour of these forces is quasi-periodic, since some changes in magnitude and frequency can occur from one cycle to the next, depending on the operating conditions. It causes that the centre of the journal bearing does not conserve a steady position, generating unwanted vibrations of the journal. The most common approach used for the analysis of dynamically loaded bearings is the mobility technique, which was developed more than 40 years ago [1]. Other methods involving bearing flexibility and thermal effects have been developed in the last two decades [2], however they are characterized by a higher computational complexity. In this study, the fluid film theory based on hydrodynamic lubrication conditions has been used to describe the governing equation of the fluid pressure distribution along the bearing surface, since the analysis is more focused on studying the feasibility of actively modifying the hydrodynamic fluid films through radial oil injection (controllable hybrid lubrication), than in the estimation of the elastic deformations of the system. One refers to hybrid lubrication when the hydrostatic and the hydrodynamic lubrication are simultaneously combined in a journal bearing. When part of the hydrostatic pressure is dynamically modified, one refers to active lubrication [7]. Besides the operational conditions, the performance of a hybrid

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[*] Corresponding author. Tel.: +45 45256269; fax: +45 45931475.
E-mail address: ifs@mek.dtu.dk (I.F. Santos).

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Nomenclature

a_b	axial land (m)
$\bar{a}_b$	axial land width ratio, $\bar{a}_b = a_b/l_b$
A_p	transversal area of the piston (m^2)
c_b	clearance of bearing (m)
d_o	diameter of orifices (m)
e_c	mass eccentricity of the crank (m)
FB	finite-width journal bearing
$\mathbf{f}$	vector of reaction forces (N)
$\mathbf{f_b}$	vector of journal bearing forces (N)
$h(\varphi, t)$	oil film thickness (m)
l	length (m)
l_b	width of bearing (m)
LJB	long-width journal bearing
m_c	mass of the crank (kg)
m_{cr}	mass of the connecting rod (kg)
m_p	mass of the piston (kg)
P_g	gas pressure inside the cylinder (Pa)
$p(\varphi, z, t)$	fluid film pressure distribution (Pa)
P_{inj}	injection pressure (Pa)
r	radius (m)
SJB	short-width journal bearing
$\mathbf{T_i}$	transformation matrix in the angle i
U	tangential velocity (m/s)
α	rotation angle of the connecting rod (rad)
ε	eccentricity ratio
λ	bearing aspect ratio, $\lambda = l_b/2r_b$
μ	oil film viscosity (Pa s)
ϕ	attitude angle (rad)
Ω	angular velocity of the rotor (rad/s)
ρ	fluid density ($\mathrm{kg/m}^3$)
τ_z	motor shaft torque (N m)
θ	rotational angle of the crank (rad)
Θ	angle measured from X axis (rad)

Subscripts

A, B, C	relative to the points A, B or C, respectively
B_i	relative to the i-th moving reference frame
b	relative to the bearings
c	relative to the crank
cr	relative to the connecting rod
I	relative to the inertial reference frame
j	relative to the journal
o	relative to the orifices

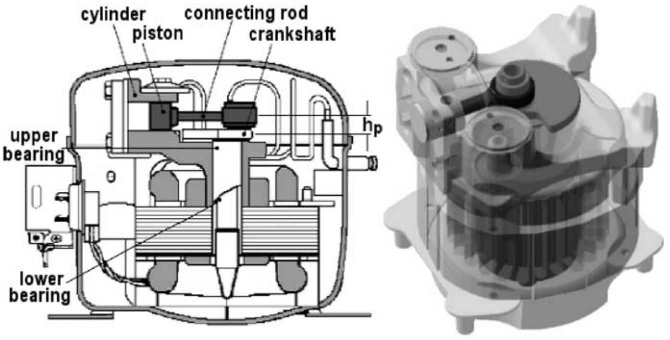

Fig. 1. Schematic draw and general view of a hermetic reciprocating compressor.

journal bearing depends on several geometric parameters, such as position and diameter of the orifices, bearing aspect ratio and axial land width ratio [8,9]. Several studies have been carried out to geometrically optimize the design of hybrid journal bearings for specific configurations and for different external load conditions [10,11]. Depending on the load and speed working conditions, several types of configurations are possible for hybrid journal bearings. Particularly, it has been shown by Rowe [9], that for hybrid performance and easy manufacture, hole-entry type bearings with holes disposed circumferentially along two rows may offer advantages over other configurations.

The present work compares the tribological performance of the upper journal bearing of a compressor working with conventional

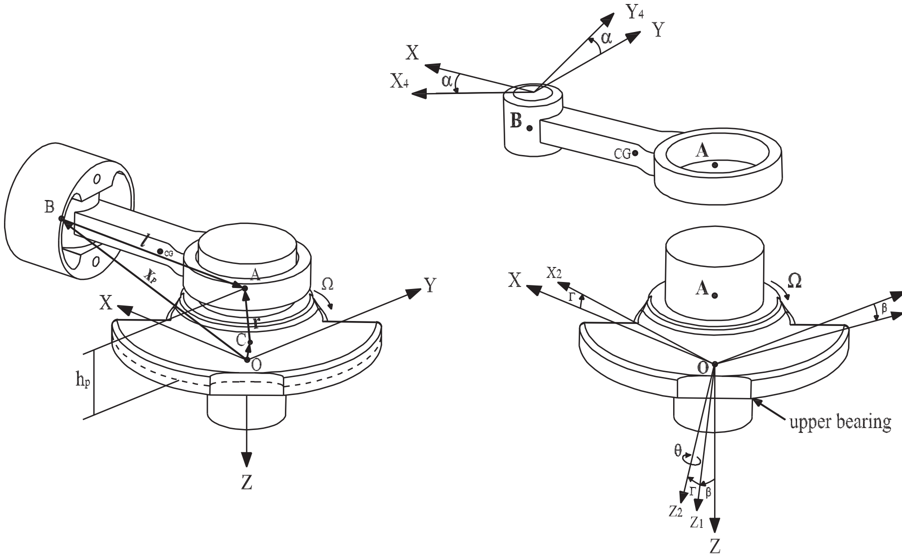

Fig. 2. Geometry and reference systems. Left: illustration of the main constraint equation; right: reference frames and rotation angles.