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Modeling and analysis of planar multibody system with mixed lubricated revolute joint

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ABSTRACT

By coupling the mixed lubrication model of a lubricated revolute clearance joint with the dynamics model of multibody system, this study presents a new methodology for modeling and analysis of planar multibody system with mixed lubricated revolute joints. The lubrication model is solved by the Finite Element Method, while the multibody dynamics equations are established by Lagrange's method. The hydrodynamic forces built up by the lubricant fluid are evaluated from the knowledge of the system variables and then included into the equations of motion of the multibody system. In the end, the proposed approach is applied to the piston–connecting rod–crank system in a four-stoke gasoline engine with lubricated clearance joint at the small end of the connecting rod.

1. Introduction

Due to wear, manufacturing tolerances, and mainly to allowing for the assembly and correct functioning conditions of the pair elements, the clearance in the revolute joint is inevitable in the mechanical systems [1]. In most machines and mechanisms, the joints are designed to operate with some lubricant fluid, which is an effective way of ensuring better performance of the mechanical systems [2–4]. Internal combustion engine (ICE) is an important application, and the lubricated revolute joints in it play crucial roles in maintaining its stability of motion and reducing the friction power loss. Therefore, the proper description of lubricated revolute joints in multibody mechanical systems is required to achieve better models and an improved understanding of the dynamics and tribology performances of machines. Furthermore, an in-depth study of the effects of lubricated revolute joint on the engine performance is of primordial importance to optimize the mechanism design parameters.

Over the last decades, considerable studies on the dynamics effects of clearance joints have been carried out theoretically and experimentally in the framework of multibody systems. Dubowsky and Freudenstein [5,6] formulated an impact pair model to predict the dynamic response of mechanical systems with clearance joints. Haines [7] carried out an experimental investigation on the dynamic behavior of revolute joints with varying degrees of clearance. Khemili et al. [8] proposed a complete theoretical and experimental approach to dynamically analyze a flexible slider–crank mechanism with one clearance joint. Orden [9] presented a methodology for the study of typical smooth joint clearances in multibody systems. Alves [10] presented a comparative study on the most relevant existing viscoelastic contact force models. Flores et al. [11–13] have achieved a lot in relevant experiment and simulation in the field of multibody system with planar and spatial clearance joints. Muvengei et al. [14] numerically studied the parametric effects of clearance joints at different locations on the dynamic response of multibody systems. Varedi [15] optimized the mass distribution of the links of a mechanism to eliminate the impact forces in the clearance joint. Bai et al. [16] investigated the dynamic behavior of planar mechanical systems with clearance in revolute joints using a new hybrid contact force model. Zhao et al. [17–19] investigated the effects of clearance joint in slider–crank system on the dynamic performance of the system and the wear at the joint. Erkaya [20] investigated joint clearance effects on partly compliant and classic articulated mechanisms.

However, most of the above works are only devoted to dry contact clearance joints. More recently, a large number of studies have included the lubrication action at the clearance joints in the computational simulations of multibody systems. Considering the effect of clearance, surface compliance and lubrication, Roger et al. [21] simulated journal-bearing elements with a mathematical lubrication model which only includes the squeeze-film effect. Later on, Liu et al. [22] extended Roger's work to include both squeeze-film and wedge-film actions. Schwab et al. [23] compared

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Nomenclature

a_p	Piston pin offset
b	The width of the bearing
c	Radial clearance
$\boldsymbol{F}^n$	Total normal force
$\boldsymbol{F}^t$	Total friction force
$\boldsymbol{F}_G$	Combustion gas force
h	Oil film thickness
L_1, L_2	The length of crank and connecting rod, respectively
L_c, L_r	Determine the positions of the mass centers of the connecting rod and crank, respectively
$\mathbf{M}$	System mass matrix
M	Total moment about journal axis
$\boldsymbol{N}$	Shape function of discrete elements
p	Oil film pressure
p_c	Asperity contact pressure
$\boldsymbol{Q}$	Generalized force vector
$\boldsymbol{q}$	Generalized Cartesian coordinates of the system
r	Radius of the crankshaft
r_{pis}	Radius of piston
m_{pis}	Mass of the piston
m_{rod}	Mass of the connecting rod
J_{rod}	Rotational inertia of the connecting rod relative to its center of mass
x, y	Local coordinate axis along the circumferential direction and axial direction of the bearing
ω_c	The angular velocity of crank
μ	Dynamic viscosity of oil
ϕ_x, ϕ_y	Pressure flow factors
ϕ_s	Shear flow factor
Φ_{fs}, Φ_{fp}	Tilt angle of the piston
ϕ_c	Contact factor
Φ_f	Term to average the sliding velocity component of the shear stress
σ	Composite roughness of the surface
ε	Eccentricity ratio
θ	Angular coordinate in $\xi' P_j \eta'$
θ^*	Terminal points of the oil film
β_1, β_2	The location of the mass center of the crank and rod, respectively
Ω	The lubrication domain
Γ	Boundary of integral domain
μ_f	Friction coefficient of the asperity contact
$\boldsymbol{\Phi}$	Kinematic constraints
$\boldsymbol{\lambda}$	Lagrange multipliers
α, β	Feedback parameters in Baumgarte's approach

Coordinate systems

XOY	The global coordinate system of the multibody system
$\eta o \xi$	Body-fixed coordinate systems
$\xi' P_j \eta'$	Local coordinate system used to evaluate hydrodynamic forces
$x' P_j y'$	Local coordinate system fixed on the journal center and parallel to the global coordinate system

different revolute joint clearance models in the dynamic analysis of rigid and elastic mechanical systems. By combining the dry contact model and the pure squeeze-film effect, Flores et al. [2,24] proposed a hybrid model for revolute clearance joints. However, for high angular velocities, the simple squeeze approach is not valid. Based on the Pinkus and Sternlicht's fluid forces formulation [25] for dynamically loaded journal-bearing system, Flores et al. [26] continued the study and presented a general methodology for modeling lubricated revolute joints in constrained rigid planar multibody systems. Costa [27] investigated the influence of the hip joint on the kinematic response of the model of human gait, and found that the system's response tends to be smoother due to the damping effects of the synovial fluid. In these studies, hydrodynamic lubrication models were presented in the case where the infinitely long and short journal bearing conditions were considered. Spatial rigid-multibody systems with lubricated spherical clearance joints were also studied by Flores and Lankarani [28]. With the modifications to Flores's hydrodynamic force model [26,29] to consider possible cavitation effects, Tian et al. [30–32] investigated the behavior of planar and spatial flexible multibody systems with lubricated clearance revolute joints. Daniel et al. [33] analyzed the dynamic of a slider–crank mechanism with lubricated clearance joint. The hydrodynamic lubrication model used for their analysis considered the infinitely long journal bearing condition and wedge-film effect. Machado et al. [29] studied the effect of the lubricated revolute joint parameters and hydrodynamic force models on the dynamic response of planar multibody systems. In their study, the Pinkus and Sternlicht [25] model for infinitely long journal-bearings and the Frêne et al. [34] models for infinitely long and short journal-bearings were considered.

As is discussed above, many endeavors have been made to investigate the effects of the clearance, including the dry contact model and hydrodynamic force model, on the dynamic performance of the mechanical system. However, in order to achieve better models to reveal the dynamics performance of machines, as well as an in-depth study on the effects of lubricated revolute joint on the engine performance, there are still several other problems remaining to be addressed. Firstly, because Reynolds equation is a non-homogeneous partial differential of elliptical type, it is difficult to obtain its exact solution. In the above studies, the lubricant effects are studied under the assumptions of either an infinitely-short or an infinitely-long journal/bearing for the cylindrical joint, and the analytic equations for the lubrication forces can be obtained directly without the evaluation of the pressure distribution [35]. Although the above assumptions simplify the solution process, it will inherently influence the accuracy of the solution. With the increasing power of today's computers, the hydrodynamic analysis of lubricated joints in the multibody systems can be conducted in greater details

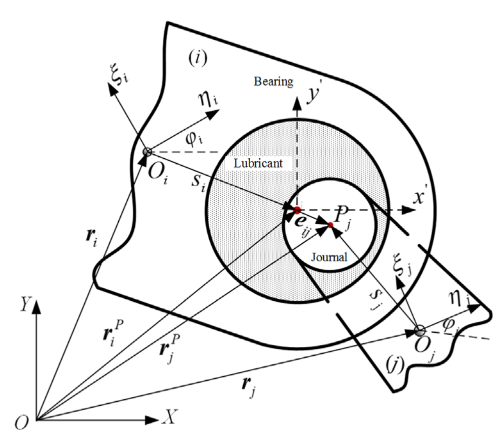

Fig. 1. Generic configuration of a lubricated dynamically loaded joint in a multibody system.