Mechanism and Machine Theory 46 (2011) 1434–1452

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Analysis of the dynamics of a slider–crank mechanism with hydrodynamic lubrication in the connecting rod–slider joint clearance

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ARTICLE INFO

Article history:
Received 5 March 2010
Received in revised form 4 May 2011
Accepted 18 May 2011
Available online 16 June 2011

Keywords:
Joint clearance
Hydrodynamic lubrication
Pressure distribution
Eksergian equation of motion
Lagrange equation of motion

ABSTRACT

The conventional slider-connecting rod–crank mechanism is widely applied in mechanical systems. The use of hydrodynamic bearings in the mechanism joints is of particular interest in reducing friction, mainly in special conditions of lubrication such as the connecting rod–slider joint. This bearing belongs to a class of bearings with alternating rotational motion. This paper proposes a mathematical model for this particular problem, considering the dynamics of the slider-connecting rod–crank system interacting with the lubrication phenomenon in bearings with alternating motion. Two models were used to analyze the dynamics of the system. The first model (by Eksergian Equation of Motion) represents the system when the connecting rod end is in contact with the bearing surface, assuming, in this condition, the same behavior as that of rigid bearings (without clearance). The second model (by Lagrange Method) represents the system when the connecting rod end is in the hydrodynamic lubrication mode in the slider bore clearance. In this condition, the slider moves in relation to the connecting rod, presenting a problem of multi-degrees-of-freedom. The mathematic model of hydrodynamic lubrication was introduced to obtain more realistic results of the system's dynamic behavior.

1. Introduction

The lubrication system is a crucial element in the optimal performance of machines in general in view of its numerous functions, e.g., lubricating and protecting components, reducing friction, and cleaning and cooling internal mechanisms. The operation of this system requires proper calibration. Therefore, excessive or insufficient lubrication influences the dynamic behavior of the machine and can seriously damage the mechanisms involved. The mechanisms of many machines contain numerous hydrodynamic bearings, but the hydrodynamic bearing of the connecting rod–slider joint is particularly important because it is part of a new class of hydrodynamic bearing called a Hydrodynamic Bearing with Alternating Motion. Unlike traditional hydrodynamic bearings, this type of hydrodynamic bearing does not make a complete rotation. Therefore, recent years have seen a growing need to study the behavior of this specific type of hydrodynamic bearing and its influence on the dynamic behavior of the machine.

Most of the research into the hydrodynamic bearing of the connecting rod–slider joint has so far been conducted by the Musashi Institute of Technology. In fact, this institute has developed and constructed devices to investigate lubrication and friction in the hydrodynamic bearing of slider pins for more than 15 years. Takiguchi et al. [1], for example, studied the rotating motion of a floating piston pin applied in gasoline-powered automotive engines. Three years later, Takiguchi et al. [2] developed a measuring device that determines the status of lubrication in the hydrodynamic bearing of the connecting rod–slider joint based on measured friction force. In another study conducted at the Musashi Institute of Technology, Suhara et al. [3] examined lubrication conditions in the hydrodynamic bearing of the slider pin of gasoline-powered automotive engines, considering as parameters of analysis the length, internal diameter and material of the piston pin. More recently, Zhang et al. [4,5] developed tools to investigate wear in

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doi:10.1016/j.mechmachtheory.2011.05.007

hydrodynamic bearings of the piston pin. In 2005, Ligier and Ragot [6] analyzed the behavior of the hydrodynamic bearing of the piston pin. The following year, these authors [7] presented a general view of the operation of the hydrodynamic bearing of the connecting rod–piston joint in four-stroke engines, emphasizing the oil feed in the bearing.

As mentioned earlier, hydrodynamic bearings with alternating motion are part of slider–crank mechanisms. Hence, a reliable mathematical model of this mechanism must take into account the behavior of the bearing in the connecting rod–slider joint. Owing to the wide application of the slider–crank mechanism, many studies have focused on devising a mathematical model and analyzing the dynamic behavior of this mechanical system. Schwab, Meijaard and Meijers [8] compared the dynamic behavior of the slider–crank mechanism, considering different connecting rod–slider joint models such as a Hertz contact model with dissipation, an impact model and a hydrodynamic bearing model. In the aforementioned work, the authors also compared the dynamic behavior of the mechanism considering the connecting rod as an elastic and rigid component. The results obtained by those authors show that the assumption of a connecting rod as an elastic component, as well as the lubrication condition in the joint, tends to significantly decrease the vibrations in the dynamic response of the mechanism. Flores et al. [9] analyzed the dynamic behavior of the slider–crank mechanism, modeling the connecting rod–slider joint as a dry contact without friction, a dry contact with friction and as a hybrid model which considers hydrodynamic lubrication for small eccentricity and dry contact with friction for high eccentricity. Their results show that the dry contact model with friction is more realistic than the dry contact model without friction, due to the magnitude of the oscillations in the dynamic response. As for the hybrid model, the results they obtained showed the smallest oscillation in the dynamic response, but there are no results in the literature that can support this observation. Soon thereafter, Flores et al. [10] analyzed the dynamics of the slider–crank mechanism considering the effects of dry contact, friction and hydrodynamic lubrication on the connecting rod–slider joint. The results obtained with the dry contact model without friction showed high oscillations in the dynamic response of the mechanism, making this model less realistic than the dry contact model with friction. When the model with hydrodynamic bearing was considered, the results were very similar to those obtained in the slider–crank mechanism with ideal joints. Erkaya, Su and Uzmay [11] analyzed the kinematics and dynamics of a modified slider–crank mechanism with an additional eccentric link between the connecting rod and crank pin. The results they obtained with the slider–crank mechanism they developed were evaluated and compared to that of a conventional slider–crank mechanism. This comparison indicated that although the conventional and modified slider–crank mechanisms have the same stroke and the same gas pressure in the cylinder, the modified mechanism has a higher torque output than the conventional mechanism. Khemili and Romdhane [12] analyzed the dynamic behavior of a planar flexible slider–crank mechanism with clearance, performing simulated and experimental tests and comparing the experimental results with the numerical results of the simulations using ADAMS software. They found that the presence of clearance affects the dynamic response of the system, and that the coupler's flexibility acts as a suspension system in the mechanism. Estupiñan and Santos [13] developed a mathematical model for a linear reciprocating compressor. They checked the dynamic behavior of the mechanical system, considering the dynamics of the mechanical components based on multibody dynamics (rigid components) and the finite element method (flexible components). They also evaluated the influence of the hydrodynamic bearing, describing the hydrodynamic forces in the joints using the Reynolds equation. Their results showed that maximum forces and minimum film thickness are obtained when the piston is close to the top dead center and that the nonlinear behavior of the orbits increases due to the tilting oscillations of the crank, which are influenced by the length of the crank pin.

This work involves an analysis of the dynamic behavior of the slider–crank mechanism and the hydrodynamic lubrication condition of the bearing in the connecting rod–slider joint. For this reason, the analysis is based on two different models, whose application depends on the lubrication conditions (eccentricity value) of the bearing. The first model (1dof) considers the connecting rod–slider joint as an ideal joint and is applied when the connecting rod end is in contact with the bearing surface [14]. The second model (3dof) is applied when the connecting rod end is in hydrodynamic lubrication in the slider bore clearance. In this condition, the slider moves in relation to the connecting rod, characterizing a problem of multiple degrees of freedom in which the interaction between the connecting rod and the slider occurs through the hydrodynamic forces of the lubricant fluid. Therefore, the solution is obtained from a hybrid model composed of a model of the slider–crank mechanism with ideal joints and a model of the slider–crank mechanism with hydrodynamic bearing in the connecting rod–slider joint.

Thus, an important parameter in this analysis is the minimum oil film thickness considered in the hydrodynamic lubrication. According to Flores [9], for high eccentricity (low minimum oil film thickness), the pressure causes elastic deformation of the surfaces, which can be of the same order as the lubricant film thickness. These circumstances differ from those obtained in hydrodynamic lubrication and a more realistic analysis can be made based on the theory of elastohydrodynamic lubrication. For this reason, this work considered the hydrodynamic lubrication condition for a minimum oil film thickness exceeding 10% of the radial clearance, which represents an eccentricity ratio of 0.9.

The dynamic responses of the slider–crank mechanism obtained from the hybrid model are compared with those obtained from the conventional model (slider–crank mechanism with ideal joints). Moreover, the pressure distribution in the bearing is obtained during one period of lubrication condition. It is important to emphasize that the hydrodynamic model used in the present work was developed previously by the authors in cooperation with Bannwart [15].

2. Methodology

In this work, a planar slider–crank mechanism was modeled in order to determine its dynamic behavior. However, instead of the conventional slider–crank mechanism, a hydrodynamic bearing was considered in the connecting rod–slider joint. This assumption considers that the pin is not restricted to only one direction of motion, which is the case when the bearing is considered without clearance.