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Optimal dynamic design of a planar slider-crank mechanism with a joint clearance

S.M. Varedi, H.M. Daniali *, M. Dardel, A. Fathi

Department of Mechanical Engineering, Babol University of Technology, Babol, Iran

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ABSTRACT

In general, in dynamic analysis of mechanisms, joints are assumed to be ideal without clearance. However, in reality, clearances in the joints are inevitable due to tolerances, and defects arising from design and manufacturing. When a joint clearance is introduced, the mechanism gains two uncontrollable degrees of freedom. Therefore, poor dynamic performance, reduction in components life and generation of undesirable vibrations result in the impacts of mating parts in the clearance joint. In this paper, an optimization method is proposed to alleviate the undesirable effects of joint clearance. The main consideration here is to optimize the mass distribution of the links of a mechanism to reduce or eliminate the impact forces in the clearance joint. An algorithm based on PSO solves this highly nonlinear optimization problem for a slider–crank mechanism with a revolute clearance joint between the slider and the connecting rod. Finally, an example is included to demonstrate the efficiency of the algorithm.

1. Introduction

Geometrical perfection is usually assumed in the synthesis of mechanisms; i.e. they are treated without clearance at the joints. But in practice, clearances in the joints are inevitable due to tolerances, and defects arising from design, manufacturing and wearing. Clearance can lead to poor precision, kinematic uncertainty, impulsive forces and undesirable vibrations in mechanisms [1]. Therefore, clearance has to be considered in a successful design and analysis of mechanisms, when accuracy is the primary goal. This issue has attracted the attention of researchers and they have introduced various methods to study clearances and contact forces in the joints of mechanisms [1–8]. Dubowsky and Freudenstein [9,10] formulated an impact pair model to predict the dynamic response of an elastic mechanical joint with clearance. Earles and Wu [11] introduced a model based on permanent contact condition. In their model, clearance is replaced by a mass-less virtual link that connects the journal center to the bearing center. Bengisu et al. [12] developed a separation parameter for a four-bar mechanism based on a zero-clearance analysis. They also predicted contact-loss in a mechanism with multiple joint clearances. Using the general trend of the Hertz contact law, Lankarani and Nikravesh developed a contact force model in which a hysteresis damping function was incorporated with the intent to represent the energy dissipated during the impact [13]. This model has been used extensively in the literatures [1–5,13–19]. Flores and Ambro'sio [14] used contact force approach to model and simulate the performance of a slider–crank mechanism with one clearance joint. Also, Flores et al. [15] studied the effect of friction between the journal and the bearing, using a modified Coulomb's friction law. Moreover, Flores and Lankarani [16] modeled joint clearance in the spatial mechanism. Flores analyzed the effects of lubrication of clearance joint on the dynamic of mechanisms, as well [15–17]. Schwab et al. [20] compared several models of contact forces. They analyzed and simulated a slider–crank mechanism with one clearance joint of rigid or flexible connecting rod, for both dry and lubricated contact conditions. Tian et al. [21] studied

* Corresponding author at: Department of Mechanical Engineering, Babol University of Technology, P.O. Box 47148-71167, Babol, Iran. Tel./fax: +98 1132312268.
E-mail address: mohammadi@nit.ac.ir (H.M. Daniali).

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dynamics of spatial flexible multi-body systems with clearance spherical joints, considering both dry and lubricated contact conditions. For dry contact, the contact forces were measured through a Hertzian-based contact law which includes a damping term representing the energy dissipation. The frictional forces were evaluated using a modified law of Coulomb's friction. While, in the case of lubricated joints, the resulting lubricant forces were derived from the corresponding Reynolds' equation. Ting et al. [22] studied the effects of the joint clearance on the position and the orientation deviations of mechanisms and robotic manipulators, using mass-less virtual link approach to model the clearances. Zhu and Ting [23] made the uncertainty analysis of planar and spatial robots with clearance joints.

Almost all the reported works have been devoted to the effects of joint clearance on analysis of mechanisms, while the reported works on the synthesis are more limited [24–27]. Feng et al. [24] developed an optimization method to control the inertia forces by re-distribution of masses of the moving links in planar mechanisms, in the presence of clearances at joints. They supposed a permanent contact between the journal and the bearing. Therefore clearance was modeled with a virtual mass-less link (VML) that connects the journal center to the bearing center. Erkaya and Uzmay [25] used a Genetic Algorithm Method to find the optimized link parameters for the path generation problem in the presences of clearance. Moreover, Zhang and Huang [26] made a robust tolerance design for function generation mechanisms.

The primary purpose of the present work is to study the dynamic behavior of planar slider–crank mechanism with rigid links, in the presence of clearance in the revolute joint between the slider and the connecting rod. In this joint, if there is no lubricant, the journal moves freely within the bearing boundaries until it contacts with the bearing. When the journal and the bearing are in contact, deformation takes place in the contact zone resulting in a contact force normal to the plane of collision. This force can be formulated by a nonlinear continuous model proposed by Lankarani and Nikravesh [13]. Moreover, the friction effects due to the relative tangential velocity on the contact zone are also modeled according to the modified Coulomb friction law [28]. Therefore, the normal and tangential forces are introduced into the equations of motion of the system for the contact mode.

It is noteworthy that in order to improve the dynamic performance of a mechanism, one has to maintain the contact between the journal and the bearing in the joints. Here we present an optimization technique to fulfill this requirement by mass re-distribution of the moving links. The mass, the mass center and the moment of inertia of the moving links are taken as the design variables, while the journal center locus is the objective function. A planar slider–crank mechanism, in the presence of clearance in the revolute joint between the slider and the connecting rod, is used as numerical example to demonstrate and validate the optimal design technique.

2. Modeling of revolute joints with clearance

Here, we model revolute joint in the presence of clearance, as depicted in Fig. 1(a). The journal and bearing radii are R_J and R_B, respectively. Moreover, the radial clearance, c, is the difference between their radii. It is noteworthy that the existence of the clearance in the revolute joints introduces two extra degrees of freedom, that is, the horizontal and vertical displacements of the center of the journal and; consequently, the journal and bearing can freely move relative to each other.

The journal and the bearing experience three different modes of relative motion; namely, contact mode, free flight mode, and impact mode, as illustrated in Fig. 1(b). In the contact mode, the journal and the bearing are in permanent contact and only a sliding or rolling relative motion is assumed. Clearly, this mode is terminated when the journal loses the contact with the bearing. Then the free flight mode is started, in which the journal can move freely inside the bearing boundaries. Therefore, no reaction force develops in the joint. Finally, in the impact mode, which occurs at the termination of the free-flight mode, there is an impact force between the journal and the bearing. This causes a discontinuity in the kinematic and dynamic characteristics of the system. At the termination of the impact mode, the journal can enter either in free flight or in contact modes. It is noted that, during the contact mode, there are a normal

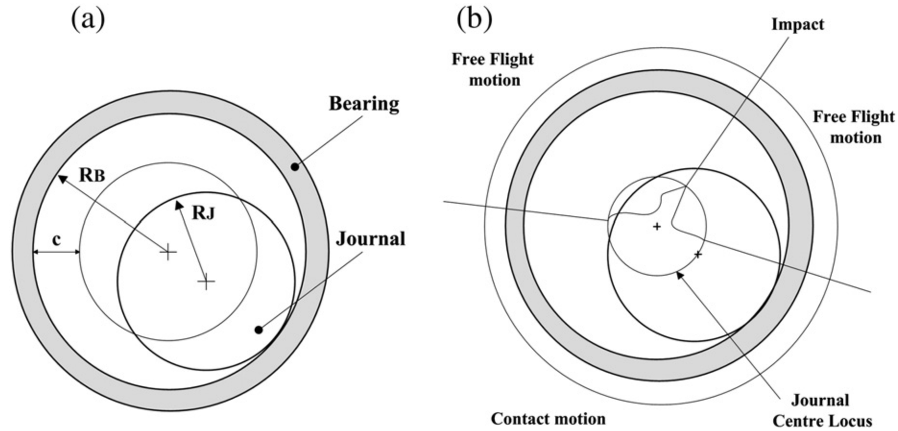

Fig. 1. (a) Revolute joint with clearance, in which clearance is exaggerated for clarity and (b) modes of the journal motion inside the bearing.