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Computational prediction and experimental validation of revolute joint clearance wear in the low-velocity planar mechanism

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ABSTRACT

Within the multibody dynamics framework, the paper proposed an efficient procedure to calculate revolute joint wear of planar mechanism with low velocity. Firstly, based on the wear test data, a method to calculate the wear coefficient that corresponds to the actual working condition of the mechanism is proposed. Then, an efficient iterative prediction method for joint clearance wear evolving in the multibody dynamic system in is proposed based on the Archard's wear model. Meanwhile, the wear tests of the typical mechanism have verified the method proposed in this paper. The research shows that when the increments of the wear depth of revolute joints are not big, the method can provide high prediction accuracy; however, as the predicted wear depth increases, the prediction error increases as well.

1. Introduction

The linkage mechanism is widely used in mechanical equipments of various industries including construction machinery and aeronautics and astronautics, such as excavator, landing gears, satellite antenna systems, etc. However, problems like performance degradation and mechanical failures are inevitable in the linkage mechanism [1]. Given that the connecting links among bars are the weakest, hinge joints, as the most common pair for bars, are first and most vulnerable to wear failure when force transmission is happening in the mechanism. Therefore a research on the dynamic wear process of hinge joint clearance and its influence on mechanical equipments will guide the designer to come up with proper solutions at the design phase. It is thus of universal significance for improving the reliability of mechanical products.

In the past decades, many researchers have analytically and experimentally studied how hinge joint clearance influences the dynamic characteristics of mechanical systems. In the early researches, models, such as the spring-damper approach proposed by Dubowsky [2] and the massless link approach proposed by Earles and Wu [3], are simple. Among them, the concept of a mass less link gets much attention for it is easy-to-use and is further used in researches like the clearance contact loss in mechanisms [4], mechanism path generation and transmission quality, etc [5].

However, due to the fact that the models above are too simplistic to take many factors into account, they cannot describe the contact-impact phenomenon in joint clearance. Some scholars later proposed more complicated contact-impact models, which can be divided into the discontinuous method [6] and the continuous method [7]. The discontinuous method assumes that the period of

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the impact is very short and the configuration of the system doesn't change. Though adopted by many scholars [8–10], its application is limited for the duration of impact process is usually unknown. The continuous method [7] assumes that the impact forces and penetrations between the pin and the bushing vary continuously and adopts a continuous impact force model to calculate the interaction forces during the impact and sliding process happening in the joint clearance.

In recent years, the continuous contact-impact thought is widely adopted [11–13] and various continuous contact force models have been developed, such as the Kelvin-Voigt model [14] , the Hertz model [15] and the Lankarani-Nikravesh model [11], etc. The impact force in Lankarani-Nikravesh model takes into consideration both the influence of the impact deformation and the damping hysteresis effect; therefore the model well accounts for the energy dissipation in the course of contact. In recent years, as accepted by more and more scholars, the model has been applied in researching how revolute joint clearance influences the dynamic characteristics of mechanical systems.

Zhao and Bai [1] carried out a dynamics analysis of a space robot manipulator with one joint clearance. The nonlinear equivalent spring-damp model and the Coulomb friction model are used to study the contact effect and the friction effect in joint clearance, respectively. Zhang et al. [16] investigated the effects of joint clearance on the deployment of solar panel on spacecraft system. Considering the clearance in joints, the contact model is performed using a nonlinear continuous contact force model and the friction effect is considered using a modified Coulomb friction model. Ma et al. [17] studied the dynamics of mechanical systems with planar revolute joints with clearance. A hybrid contact force model is established based on the Lankarani-Nikravesh contact force model and the elastic foundation model. Meanwhile, the effectiveness of the hybrid model was validated by the theoretical and experimental ways. Zhang et al. [18] focused on the development of methodologies to analyze the dynamic performance of the 3-RRR parallel mechanism with multiple clearance joints. Rahmanian and Ghazavi [19] studied the nonlinear dynamic behavior in the planar slider-crank mechanism with revolute clearance joint. Bifurcation analysis with varying clearance sizes was performed.

All in all, great achievements have been made in researches on the dynamic characteristics of mechanical systems with the influence of revolute joint clearance considered. These achievements will play a positive role in dynamic design, optimization analysis and performance improvement in mechanical systems with joint clearance.

However, many researches assume the clearance size to be a constant value but leave out of consideration the fact that the clearance size is always changing due to the clearance wear. In fact, the clearance wear is inevitable as the mechanical system operates. It will gradually and slowly degrade the performance of the mechanical system. Therefore it is of more practical significance for engineering applications of mechanical systems to consider the clearance wear at the design phase. Currently, many researches [20–22] have established proper theoretical methods to predict clearance wear. But it must be admitted that these prediction method is lacking in experimental verification; it is thus unknown how these prediction methods match the reality. Besides, in the movement of the mechanical system, the clearance wear in one motion cycle is very tiny. Multiple motion cycles are required in order to get the observable clearance wear. Therefore in order to predict the change of the clearance wear during its service life, it is necessary to simulate the mechanical operation for quite a number of motion cycles, which incurs excessive computational burden and is infeasible for practical engineering applications.

This paper aims to establish an efficient method to predict the clearance wear of the planar low-velocity mechanisms and performs the experiment of the typical mechanism to test the effectiveness of the proposed method. It should be noted that the proposed method in this paper applies only to the low-velocity mechanism because this paper assumes that the pin and bushing contact each other all the time, which is almost the same as the movement of low-velocity mechanism in real situation. When the mechanism is a high-velocity mechanism, there are three configurations of the joint components (i.e. the pin and bushing) [23]: free-flight motion, the impact condition and the sliding condition. In other words, it doesn't accord with the assumption that the pin and the bushing contact each other all the time.

The paper organization is as follows: Section 2 gives a brief introduction of the modeling theory of revolute joint clearance; Section 3 proposes a high efficient method of predicting the wear depth in joint clearance; Section 4 verifies the method by experiment; finally, Section 5 concludes the method proposed in this paper.

2. The modeling of multibody dynamic system with clearance

The modeling of multibody dynamic system with clearance can be divided into two parts: The model of multi-body dynamic system and the clearance contact model.

2.1. Multibody dynamic system model

The multi-rigid-body system refers to the complicated mechanical system composed of multiple rigid bodies connected by kinematic pairs. The multi-rigid-body system dynamics, currently a mature theoretical method, focuses on the motion law of the multi-rigid-body system.

In Cartesian coordinate system, the generalized coordinate of Rigid-body $i$is defined as follows:

$$\mathbf{q}_i = [\mathbf{r}_i^T \quad \mathbf{p}_i^T]^T \tag{1}$$

Here, $\mathbf{r}_i = [x, y, z]^T$ and $\mathbf{p}_i = [e_0, e_1, e_2, e_3]^T$ refer to the displacement coordinate and the rotational coordinate corresponding to Euler parameter. Furthermore, the velocity and the acceleration of Rigid body i can be represented as follows: