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Dynamics modeling and quantitative analysis of multibody systems including revolute clearance joint

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ABSTRACT

The dynamics characteristics of multibody mechanical systems including revolute joints with clearance are investigated using a computational methodology and a quantitative analysis method is proposed in this work. The contact force model in revolute joint clearance is performed using a nonlinear continuous contact force model and the friction effect is considered using a modified Coulomb friction model. The planar four-bar mechanism is used as demonstrative application example to validate the quantitative analysis method. Numerical results for four-bar mechanism with revolute clearance joint are presented and discussed. Further, two kinds of dimensionless indicator are defined for quantitative analysis of mechanical system with joint clearance. And the clearance size, friction effects and crank driving speed are analyzed separately.

1. Introduction

Clearances in mechanism are unavoidable due to assemblage, manufacturing errors and wear. Moreover, the clearance occurs in each joint with the movement of mechanism. The movement of the real mechanisms is deflected from the ideal mechanism and motion accuracy is decreased due to the joint clearances. The existence of clearance in joints also causes impact dynamic load, affects the transfer of system load, and may lead to destruction of the mechanism and failure of the mechanism's kinematic and dynamic outputs. These clearances modify the dynamic response of the system, justify the deviations between the numerical predictions and the experimental measurements and eventually lead to important deviations between the projected behavior of the mechanisms and their real outcome [1–11].

Over the last few decades, the effects of clearance on dynamic response of planar and spatial mechanisms using theoretical and experimental approaches have been studied by many researchers. Stoenecu and Marghitu [12] investigated the dynamic response of a planar, rigid-link mechanism with a sliding joint clearance and the response of the system with clearance was chaotic at relatively high crank speeds and low values of the coefficient of restitution. Khemili and Romdhane [13] have investigated the dynamic behavior of a planar flexible slider–crank mechanism having joint with clearance. Simulation and experimental tests were carried out for this goal. Zhao and Bai [14] have investigated the dynamics of a space robot manipulator with one joint clearance. The nonlinear equivalent spring-damper model was established for the contact force model in joint clearance. Also, the friction effect was considered using the Coulomb friction model. Flores et al. [15] presented dynamic analysis of planar multi-body systems with revolute joint clearances, including dry contact and lubricant effect. Liu et al. [16] developed a class of non-conformal contact model caused by joint clearance, which is based on the improved Winkler elastic foundation model and Hertz quadratic pressure distribution assumption. Rhee and Akay [17] investigated dynamic response of a revolute joint with clearance. A four-bar mechanism was implemented as an example used to model the motion of a rocker arm pin at the ground connection. Flores et al. [18] also presented a methodology to assess the influence of the spherical joint clearances in spatial multibody systems. Bauchau and Ju [19] focused on the development of methodologies for the analysis of unilateral contact conditions in joints with clearance and of the resulting normal and friction forces. Two joint configurations were developed, the planar and spatial clearance joints that can deal with typical configurations where contact and clearance are likely to occur. Shi and Jin [20] presented a general methodology for dynamic characterization of the reheat-stop-valve mechanism with revolute clearance joints, in which the leading ingredients of the model proposed were the contact force model in consideration of the manufacturing tolerance and the thermal effects of the high temperature steam in working

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condition. Erkaya and Uzmay [2,6,21–23] have studied kinematics and dynamics of planar mechanisms having revolute joints with clearance. A neural network-genetic algorithm procedure has been proposed to decrease the deviations arising from joint clearance on kinematic and dynamic characteristics of mechanisms. Also, an experimental investigation has been implemented to analyze the bearing vibrations of mechanism with joint clearances. In conclusion, a great deal of researches on dynamic characteristics of mechanism with clearance are progressing and lots of productions are obtained, which have played a positive role in dynamic design, precision analysis and performance improvement of mechanism with joint clearance. However, these studies are qualitative analysis of multibody systems with clearance joint and less focus on quantitative analysis.

Contact and impact are the typical phenomena of multibody systems with joint clearance. The contact force model of revolute joints with clearance is one of the important contents in dynamics analysis of multibody systems with clearance. Moreover, reasonable contact and impact force model is crucial to the design and analysis of mechanism with clearance. The contact-impact models of mechanism with clearance are mainly focus on the discrete analysis method and continuous contact analysis method [15,20,24]. The former assumes that the contact-impact is very short and does not change the overall configuration of the object. Then, the contact-impact process is divided into two stages, before and after impact, and relative sliding, viscous stagnation and reverse movement will occur between two objects after the impact. The latter assumes that interaction forces between the impact objects are continuous in the entire contact-impact process. This approach tallies with real contact-impact behavior of objects. The continuous contact force model is widely used for contact-impact analysis of mechanism with clearance and the elastic contact force is widely represented by Hertz contact law. The continuous contact force model should include the energy dissipation of impact between the journal and bearing. There are so many contact force models besides Hertz model, such as Kelvin–Voigt viscoelastic model [25], the nonlinear damping model of Hunt and Crossley [26], the nonlinear model of Dubowsky and Freudenstein [27], the nonlinear model of Lankarani and Nikravesh [28], which includes energy loss due to the internal damping. In addition, Bai and Zhao [29] proposed a new nonlinear contact force model in revolute clearance joint, which is a hybrid model of the Lankarani–Nikravesh model and the improved Winkler elastic foundation model. This model also considers the effect of damping and describes the energy losing in the contact process. This work analyzes the dynamics characteristics of multibody systems with revolute clearance joint using this new nonlinear continuous contact force model.

So, the objective of this paper is to study the dynamics characteristics of planar multibody mechanical systems with revolute clearance joint base on the new nonlinear continuous contact force model using a computational methodology. The planar four-bar mechanism is used as demonstrative application example. Numerical results for four-bar mechanisms with revolute clearance joints are presented and discussed. Further, two kinds of dimensionless indicator are defined for quantitative analysis of mechanism with joint clearance. In the present work, the clearance size and friction effects are analyzed separately. Meanwhile, the effects of clearance on dynamics characteristics of mechanism with different crank driving speeds are analyzed.

This paper is organized as follows. Section 2 defines the clearance and presents the model of revolute joint with clearance. Section 3 presents the contact force model of revolute joint with clearance. Section 4 establishes the friction force model of revolute joint with clearance. In Section 5 the planar four-bar mechanism with revolute joint clearance is used as numerical example to investigate the dynamics characteristics of multibody mechanical system with revolute clearance joint. In Section 6 two kinds of dimensionless indicator are defined for quantitative analysis of mechanism with joint clearance. Finally, Section 7 ends the paper with the concluding remarks.

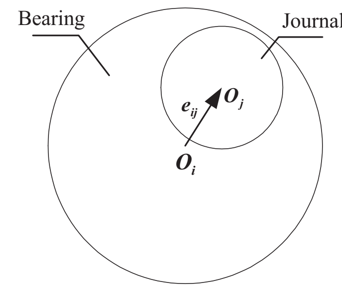

Fig. 1. Sketch map of clearance vector model in clearance joint.

2. Model of revolute joint with clearance

2.1. Vector model in joint clearance

The joint clearance of multibody mechanical system is necessary to allow the relative motion of connected bodies, as well as to permit the assemblage of the mechanical system. Clearance exists also due to manufacturing tolerances, imperfections, wear and material deformation [3,30–33]. It is known that the performance of mechanisms is degraded by the presence of clearance due to the contact-impact force. These clearances modify the dynamic response of the system and eventually lead to important deviations between the expected behavior of the mechanisms and their real outcome as well as energy dissipation and unwanted shake responses.

In general, a clearance joint can be included in mechanism much like a revolute joint. The classical approach, known as zero-clearance approach, considers that the connecting points, i.e. the centers of journal and bearing, of two bodies linked by a revolute joint are coincident. The connecting points are the centers of journal and bearing. The introduction of the clearance in a joint separates these two points.

The study performs of the dynamics analysis of multibody mechanical system with clearance joint based on the clearance vector model [20], which is developed by introducing a clearance vector, $\boldsymbol{e}_{ij}$, in a revolute joint as shown in Fig. 1. Clearance vector represents the potential real movement and the relative position between journal and bearing.

Clearance vector is defined in a local floating Cartesian coordinate frame. The origin of clearance vector fixes at the center of bearing and ends at the center of journal as shown in Fig. 1. It shows that the clearance vector must be within the clearance circle whose radius is determined by the tolerances of journal and bearing diameters. And the clearance vector can identify whether the journal and bearing of joint contact or not. Furthermore, it should be noted that the proposed clearance vector does not depend on the local configuration of the revolute joint because clearance is unavoidable existent in revolute joint.

2.2. Definition of clearance

Fig. 2 depicts a revolute joint with clearance. The difference in radii between the bearing and journal defines the size of the radial clearance. Although, a revolute joint with clearance does not constraint any degree of freedom from the mechanical system like the ideal joint, it imposes some kinematic restrictions, limiting the journal to move within the bearing. Thus, when clearance is present in a revolute joint, the two kinematic constraints are removed and