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Dynamic behaviour analysis of planar mechanical systems with clearance in revolute joints using a new hybrid contact force model

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A B S T R A C T

In this study, the dynamic behaviour of planar mechanical systems including revolute joints with clearance is investigated using a computational methodology. The contact model in revolute joint clearance is established using a new nonlinear continuous contact force model, which is a hybrid contact force model, and the friction effect is considered using modified Coulomb friction model. And then, the dynamic characteristics of planar mechanical system with revolute joint clearance are analysed based on the new contact model. Numerical results for two simple planar mechanisms with revolute clearance joints are presented and discussed. The correctness and validity of the new contact force model of revolute joint clearance is verified through the demonstrative application examples. Clearance size and friction effect are analysed separately. The numerical simulation results show that the proposed contact force model is a new method to predict the dynamic behaviour of planar mechanical system with clearance in revolute joints.

1. Introduction

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

Over the last few decades, effects of clearance on dynamic behaviour of planar and spatial mechanisms using theoretical and experimental approaches have been studied by many researchers. Stoenescu 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] investigated the dynamic behaviour of a planar flexible slider-crank mechanism having joint with clearance. And simulation and experimental tests were carried out for this goal. Zhao and Bai [14] studied the dynamics of a space robot manipulator with one joint clearance. The nonlinear equivalent spring-damper model is established for the contact model in joint clearance. Also, the friction effect is 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] focus 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 characterisation 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 condition. In conclusion, a great deal of researches on dynamic

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characteristics of mechanism with clearance are progressing and lots of productions are obtained, which have played a positive role in dynamic design, optimisation analysis and performance improvement of mechanism with joint clearance.

Contact and impact are the typical phenomena of mechanism with joint clearance. Contact force model of revolute joints with clearance is one of the important contents in dynamics analysis of mechanism with clearance. Moreover, reasonable contact force model is crucial to 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 [15,20,21]. 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, as well as 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 in line tallies with real contact-impact behaviour of objects. The continuous contact force model is widely used for contact-impact analysis of mechanism with clearance. The elastic contact force is widely represented by Hertz contact law. The representative contact force model is Lankarani–Nikravesh model [18,20,22,23] established by Lankarani and Nikravesh [22]. A common Hertz contact force expression is used in this model and the damping effect is considered, which can describe the energy loss during the impact process.

Hertz theory is available only in solving the contact problem that the geometric shape of contact bodies is non-conformal. The properties of conformal contact at the contact surfaces of revolute joints consequentially result in the limitation of Hertz model in solving the contact problem of revolute joints with clearances. And Hertz model is available only in the case that there is a large clearance with a small normal load. However, clearance in actual revolute joint is very small and the contact process of journal and bearing does not always satisfy the non-conformal contact condition. Usually, the achieved results are not precise, especially in small clearance for bearing and journal contact. Besides, in most of the past literatures, contact stiffness and damping coefficient were calculated simply according to the impact situation of two sphere bodies or taken as a constant according to experience, which does not meet the actual situation [16,24–27].

Liu et al. [16] developed a class of non-conformal contact model caused by joint clearance, which was based on the improved Winkler elastic foundation model and Hertz quadratic pressure distribution assumption. The model was applied to static contact analysis of cylindrical joints with clearance and verified by finite element method. The application of the above model was not only in the contact problem of revolute joint with big clearance but also the contact analysis of revolute joint with small clearance, which developed the clearance contact analysis. Based on the research mentioned above, nonlinear stiffness coefficient is proposed for contact and a new nonlinear continuous contact model in the joint clearance is proposed in this paper, which is a hybrid model of Lankarani–Nikravesh model and improved elastic foundation model.

The objective of this paper is to study the dynamic behaviour of planar mechanical systems with revolute joint clearance base on the new nonlinear continuous contact force model using a computational methodology. The slider-crank mechanism with revolute joint clearances is used as numerical example to demonstrate and validate the hybrid contact force model presented in this work. The dynamic response obtained with numerical models is compared with that of experimental slider-crank setup [28]. Furthermore, numerical results for planar four-bar mechanism with revolute clearance joints are presented and discussed. The clearance size and friction effects are analysed separately.

This paper is organised as follows. Section 2 defines the clearance and presents the mathematic model of revolute joint with clearance. Section 3 establishes the new hybrid contact model of revolute joint with clearance. Section 4 establishes the modified friction force model of revolute joint with clearance. In Section 5 the slider-crank mechanism [28] with revolute joint clearance is used as numerical example to demonstrate and validate the new hybrid contact force model. In Section 6 the planar four-bar mechanism with revolute joint clearance is used as numerical example to investigate the dynamic behaviour of mechanical system with revolute clearance joints. Finally, Section 7 ends the paper with the concluding remarks.

2. Model of revolute joint with clearance

2.1. Vector model in joint clearance

The existence of clearance in joints of mechanical system is inevitable. Joint clearance of 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 [3,28–31]. 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 projected behaviour of 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 of two bodies linked by a revolute joint are coincident. The introduction of clearance in a joint separates these two points.

The study performs of dynamics analysis of planar mechanical system with clearance joint based on the clearance vector model [20], which is developed by introducing a clearance vector, 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 centre of bearing and ends at the centre of journal, as shown in Fig. 1. It shows that clearance vector must be within the clearance circle, whose radius is determined by the tolerances of the journal

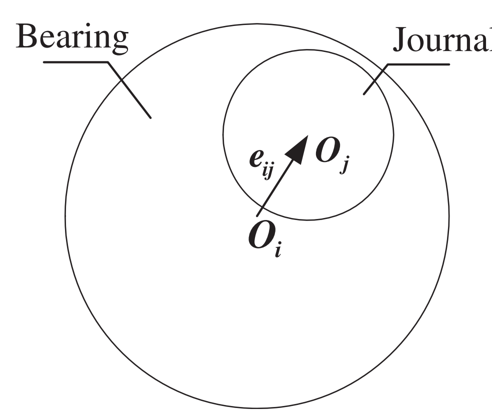

Fig. 1. Sketch map of clearance vector model in clearance joint.