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Dynamics analysis of planar mechanical system considering revolute clearance joint wear

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ABSTRACT

In this work, the dynamics and wear phenomenon of clearance joint in planar mechanical system is presented using a computational methodology. The contact model in clearance joint is established using a hybrid nonlinear contact force model and the friction effect is considered by using a modified Coulomb friction model. The wear prediction of revolute clearance joint in mechanical systems is presented based on the Archard wear model. Finally, the integration of dynamics analysis and wear analysis is presented. An academic four-bar multibody mechanical system with revolute clearance joint is used as numerical example application to perform the investigation.

1. Introduction

Clearances in mechanism are unavoidable due to assemblage, manufacturing errors and wear. 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 clearances. The existence of clearance in joints also causes impact dynamic load, wear and unwanted vibration responses, 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 experimental measurements and eventually lead to important deviations between the projected performance of mechanisms and their real outcome [1–11].

Over the last few decades, effects of clearance on dynamic responses 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 behavior 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 was established for the contact 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. Rhee and Akay [16] 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. [17] also presented a methodology to assess the influence of the spherical joint clearances in spatial multibody systems. Bauchau and Ju [18] 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 were likely to occur. Bing and Ye [19] 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 condition. 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, optimization analysis and performance improvement of mechanism with joint clearance.

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Notation list

c	radial clearance
R_B	radius of bearing
R_J	radius of journal
$\boldsymbol{e}_{ij}$	eccentric vector of journal relative to bearing
e_{ij}	eccentricity of clearance vector
$\boldsymbol{n}$	unit normal vector of bearing and journal
$\boldsymbol{t}$	unit tangential vector of bearing and journal
$\boldsymbol{r}_i^Q$	positional vector of bearing
$\boldsymbol{r}_j^Q$	positional vector of journal
δ	deformation caused by collision
F_n	normal contact force
K_n	nonlinear stiffness coefficient
D_{mod}	modified damping coefficient
$\dot{\delta}$	relative deformation velocity
E^*	compound elastic modulus
ν	Poisson's ratio
E	Young's modulus
c_e	coefficient of restitution
$\dot{\delta}^{(-)}$	initial relative velocity of the impact point
F_t	tangential friction force
v_t	relative sliding velocity
μ_d	dynamic friction coefficient
μ_s	static friction coefficient
v_s	critical velocity of static friction
v_d	critical velocity of the maximum dynamic friction
$\boldsymbol{q}$	generalized coordinate column matrix
$\boldsymbol{M}$	generalized mass matrix
$\boldsymbol{C}$	generalized damp matrix
$\boldsymbol{K}$	generalized stiffness matrix
$\boldsymbol{\Phi}_q$	Jacobin matrix
$\boldsymbol{f}$	generalized force matrix
λ	Lagrange multiplier column matrix
$\boldsymbol{F}_c$	contact force relative to the $\boldsymbol{q}$
V	wear volume
s	sliding distance
k	dimensionless wear coefficient
H	hardness of material
A_a	actual contact area
h	wear depth
p	contact pressure

However, most researches are based on the assumption of regular clearance model, which assumes that joint clearance size is constant and the findings may be limited to the idealized case in which wear is assumed to be nonexistent. These studies assume that the clearance will remain the same throughout the service life of the system. This is contrary to a realistic situation in which wear is expected to increase the clearance size.

The existence of clearances in kinematic joint causes the surface wear and incessant material loss of surface during the motion of joint elements, which increases the clearance size and changes the dynamic characteristics of mechanical system. The large amount works and models have been presented to show how wear in multibody systems is important over the last decades [20–24]. In addition, in some mechanical systems, especially close-loop dynamic systems, wear in the joints significantly affects system dynamics, and the change in system dynamics greatly affects the wear progress.

In most wear tests and simulations, it is assumed that the operating condition is known and remains constant. However, wear of the contacting surfaces can change the kinematics of the system as well as the contact pressure distribution, resulting in changes in future wear patterns. In reality, the wear of joint clearance is non-uniform, so the clearance will change non-regularly throughout the service life of the system. In such a case, it is essential to investigate the dynamics characteristics of mechanical system considering the non-regular clearance due to joint wear.

The objective of this work is to study the dynamics characteristics of planar mechanical system considering revolute clearance joint wear. The first part of the paper presents a discussion on the dynamics analysis of a planar mechanical system with regular initial clearance, which is a constant. Then, the wear model is integrated to the dynamics model of mechanical system with clearance and the wear prediction of revolute clearance joint in mechanical systems based on the Archard wear model is presented. Finally, the dynamics of planar mechanical system with non-regular clearance caused by wear are investigated.

The main computational process for dynamics analysis of mechanical system considering clearance joint wear includes two processes, which are dynamics analysis and wear analysis. The contact force model of revolute joint with clearance in multibody systems is established using a new hybrid nonlinear continuous contact force model. And the friction effect is considered by using a modified Coulomb friction model. The joint wear is presented based on the Archard wear model. Finally, a four-bar multibody mechanical system is used as numerical example application to perform the simulation and show the dynamics responses of planar mechanical system with revolute clearance joint wear.

2. Dynamics modeling of multibody system with revolute clearance joint

2.1. Definition of 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. 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 responses of the system and eventually lead to important deviations between the projected performance of mechanisms and their real outcome as well as unwanted shake responses and wear.

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.

Fig. 1 depicts a revolute joint with clearance. The difference in radii between the bearing and journal defines the size of radial clearance. Although, a revolute joint with clearance does not constrain 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, two kinematic constraints are removed and two degrees of freedom are introduced instead. The dynamics of the joint are then controlled by forces working on the journal and bearing. Thus, whilst a perfect revolute joint in a mechanical