Dynamic Behavior of Four-bar Mechanism with Three-dimensional Clearance and Wear

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***Abstract*—Because of machining tolerance as well as wear, joint clearances are inevitable in multibody systems. It can seriously degrade the dynamic performance of connected parts and significantly increase the operating noise. Most of previous studies about clearance joints were conducted on planar multibody systems, but actually the relative motion of journal and bearing includes radial and axial component. Therefore, the wear of joint is also three-dimensional. The influence of different spatial clearances on the dynamic response of multibody system is studied with a four-bar mechanism as the research object. In addition, in the ABAQUS/Standard environment, wear behavior of three-dimensional clearance joint is simulated and the spatial shape of contact surface after wear is obtained.**

Keywords-multibody system; three-dimensional clearance; wear; dynamic analysis

I. Introduction

It is well known that wear exists in almost every mechanical system and can seriously degrade the dynamic performance of machine. After running for a long period, the clearance between linkages will get larger and larger due to wear which could lead to severe accident. Therefore, research on the wear behavior of joints in multibody system, so as to study the wear pattern and its effect on the dynamic behavior, is of great significance to improve the safety and reliability of equipment, especially in aerospace field.

In recent several decades, many researchers are interested in investigating the dynamic performance of multibody system (considering the effect of imperfect revolute joints), theoretically and experimentally [1]. Many factors including multiple clearances, wear, flexibility and lubrication, are taken into consideration partially in the proposed contact models. Erkaya et al. [2] studied the dynamic and kinematic behavior of a typical four-bar device involving two imperfect joints with two-dimensional clearance. The effect of parameter uncertainty on the kinematic accuracy and dynamic behavior of a planar space deployable device with revolute joint clearances is discussed in detail in Li's work [3].

However, most of the mentioned studies are on the assumption that the multibody systems, including slider-crank mechanism as well as four-bar mechanism, perform in planar domain to make the contact problem simplified. In fact, the relative movement between journal and bearing in multibody system also have out-of-plane component. Therefore, Tian [4] proposed an analytical model for flexible mechanism with cylindrical joint clearance considering lubrication condition. Furthermore, Wang [5] studied the effect of uncertain parameters on the dynamic performance of rigid-flexible mechanical system considering three-dimensional revolute joints. Recently, Marques [6] developed an enhanced model for a three-dimensional multibody system including revolute clearance joints. However, wear phenomenon in spatial revolute joints is rarely studied and reported in the published literature.

The aim of the present work is trying to understand the dynamic behavior of multibody system involving spacial revolute joint and wear. Thus, a typical four-bar mechanism is utilized to study the influence of spatial clearance joint and what dynamic response the system has. An introduction of contact model used in this work is presented in section 2. Section 3 presents a dynamic model with spatial revolute clearance joint developed in ADAMS software to obtain the displacement of journal and bearing. Afterwards in section 4, finite element model is developed in ABAQUS/Standard environment to investigate the effect of wear on the multibody system. Finally, the conclusions are presented in section 5.

II. Contact Force Model and Wear Model for Revolute Clearance Joint

A. Contact Force Model

Revolute joints are often used to connect two linkages and transfer motion or force. In ideal multibody systems, it is assumed that two parts connected with a revolute joint are perfectly conformal. However, the existence of joint clearance results in separation and complex contact making journal motion constrained within bearing inner surface.

In the present work, a modified contact force model based on the Lankarani-Nikravesh model is utilized to obtain the contact force to predicting the wear amount . The force which is normal to the contact plane is calculated as

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$$F_n = K\delta^n\left[1+\frac{3\left(1-c_e^2\right)\dot{\delta}}{4\dot{\delta}^{(-)}}\right] \tag{1}$$

where δ denotes the relative penetration depth, $\dot{\delta}^{(-)}$ represents the initial penetration velocity, n is generally set to be 1.5 for most metal contacts, c_e denotes the restitution coefficient (here c_e is set to be 0.9). K denotes generalized stiffness and can be evaluated by

$$K=\frac{4}{3\pi\left(h_i+h_j\right)}\left(\frac{R_iR_j}{R_j-R_i}\right)^{\frac{1}{2}}, \qquad h_m=\frac{1-\nu_m^2}{\pi E_m}\left(m=i,j\right) \tag{2}$$

where ν_m represents the corresponding Poisson's ratio and E_m represents the corresponding Yang's modulus of body m.

The contact force in tangential direction can be calculated by

$$F_t=\mu F_n \tag{3}$$

where μ represents friction coefficient.

Tangential friction force model is utilized to obtain the tangential contact characteristic of revolute joint, in which the Coulomb's friction law is generally employed. Nevertheless, several variables such as mechanical properties and relative sliding velocity in tangential direction are not taken into consideration in this law. And it may lead to sudden change of the tangential friction force and calculation difficulties because of its strong nonlinear properties in the relative motion. Thus, the mathematical expression about these parameters can be expressed as

$$\mu=\begin{cases}\mu_d, & |V|>V_d\\ \mu_s\sin\left(\dfrac{\pi}{2}\dfrac{|V|}{V_s}\right), & |V|<V_s\\ \dfrac{\mu_s+\mu_d}{2}+\dfrac{1}{2}\left[\left(\mu_s-\mu_d\right)\cos\left(\pi\dfrac{|V|-V_s}{V_d-V_s}\right)\right], & V_s\le|V|\le V_d\end{cases} \tag{4}$$

where V denotes the relative velocity in the tangential direction, V_s denotes the switch velocity from stick to slip, and V_d denotes the switch velocity from static friction to sliding friction. μ_s and μ_d denote the static and sliding friction coefficients, respectively.

B. Wear Model

Archard's model is widely applied in wear volume prediction in multibody systems with revolute clearance joint. The wear model can be expressed as

$$\frac{V_w}{s}=\frac{kF_n}{H} \tag{5}$$

where V_w denotes the wear volume, s denotes the relative sliding distance, k denotes the wear coefficient , F_n denotes the normal contact force and H denotes the hardness of the softer material.

III. Dynamic Behavior of Four-bar Mechanism with Spatial Revolute Joint

A. Modeling of Four-bar Mechanism

A four-bar mechanism is applied as an example to study the dynamic performance of multibody system with spatial revolute joint. The effect of clearance size and rotating speed on the dynamic response is investigated in the following part.

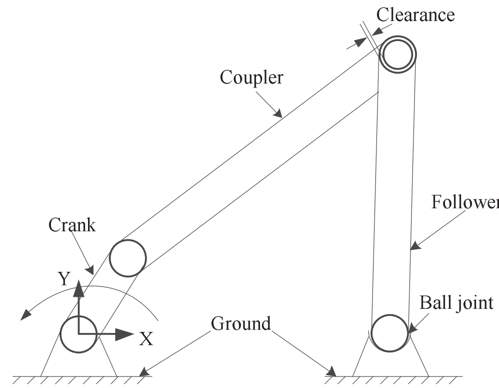

Figure 1. Schematic of the selected four-bar mechanism.

Fig. 1 presents the schematic of the selected four-bar mechanism, which is constituted by four parts: ground, crank, coupler, and follower. The ground part is completely fixed as a firm basement. The driving power is applied on crank with a constant angular velocity of 10 rad / s. The joints which connect ground and crank, crank and coupler, follower and ground respectively, are ideal joints without clearance and friction. Specially, the joint between follower and ground is a ball joint making the journal in follower able to perform three-dimensional motion. In contrast, the joint between connecting rod and follower is treated to be imperfect with clearance and dry friction condition. The geometric properties of the four-bar mechanism and the material and simulation parameters which are used in dynamic analysis are presented in the following tables.

TABLE I. Geometric Properties Of Four-bar Mechanism

No.	Body name	Length(mm)	Mass(kg)
1	Crank	100	0.46
2	Coupler	400	1.44
3	Follower	300	1.63
4	Ground	300	-

TABLE II. Parameters in dynamic simulation of Journal-bearing Structure

Parameter	Journal	Bearing
Young's modulus / GPa	206.8	206.8
Poisson ratio	0.29	0.29
Radius / mm	10;9.9; 9.8;9.7;9.6	10
Journal-bearing length / mm	32	30

The simulation analysis is conducted in ADAMS software, which is an excellent tool to study the dynamic behavior of multibody systems. The size of joint clearance is set using 0, 0.05 mm, 0.1 mm, 0.15 mm, and 0.2 mm. Thus, the corresponding radius values of journal are 10 mm, 9.9 mm, 9.8 mm, 9.7 mm, and 9.6 mm, respectively. In this model, all elements are set to be rigid body. The simulation step time is 5 seconds and the computer time is about 10 seconds using Intel CPU i7 8700 with 6 cores at 3.2 GHz. In the simulation procedure, the displacement, angular and force data of all components is recorded in every simulation step. The coordinates of bearing and journal end center will be used in the following wear analysis in ABAQUS/Standard environment.

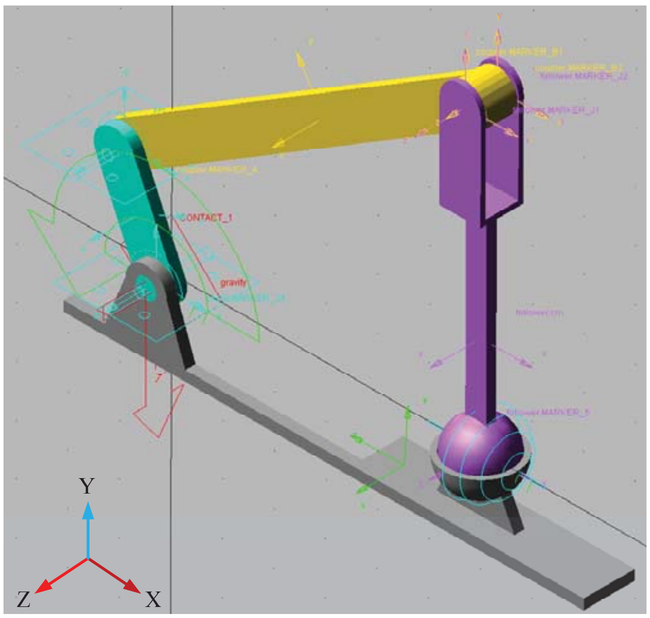

Figure 2. Four-bar mechanism with boundary constraints in ADAMS software.

B. Results and Analysis

Fig. 3 and Fig. 4 are the comparisons of displacement in both X and Y direction for the mass center of follower with different clearance sizes, respectively. We can see that the curve of large clearance size tends to have a large offset from the curve of ideal joint with no clearance. Results show clearly that the accuracy of displacement response will degrade sharply with the clearance between journal and bearing increasing. That is to say, when the clearance size of revolute joint gets large, the collision between journal and bearing will become more fiercely. As a result, the control accuracy decreases and working noise arises.

In Fig. 5, the angular velocity curves of the center of one journal end in X direction is represented. The dotted line is the corresponding curve of four-bar mechanism with ideal joint between coupler and follower, while the solid line is the corresponding curve of four-bar mechanism with 0.2 mm clearance.

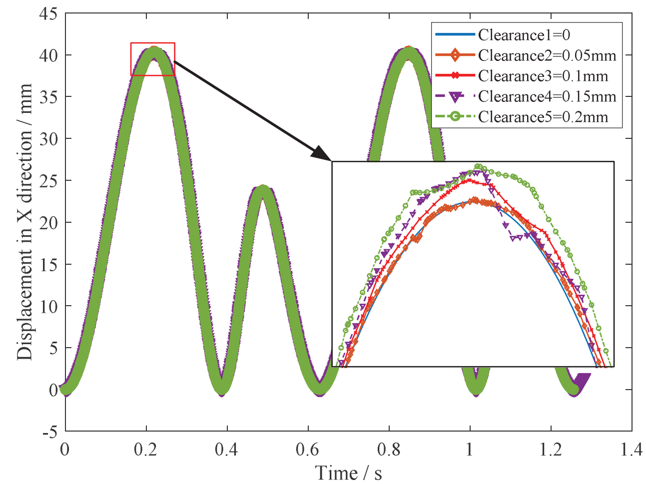

Figure 3. A comparison of displacement in X direction for the mass center of follower with different clearance sizes.

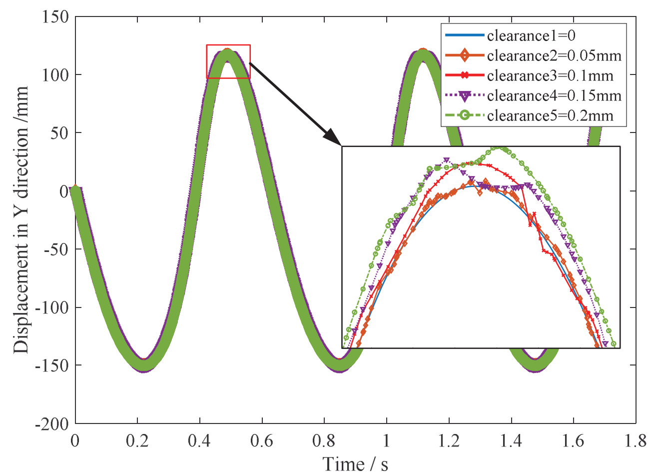

Figure 4. A comparison of displacement in Y direction for the mass center of follower with different clearance sizes.

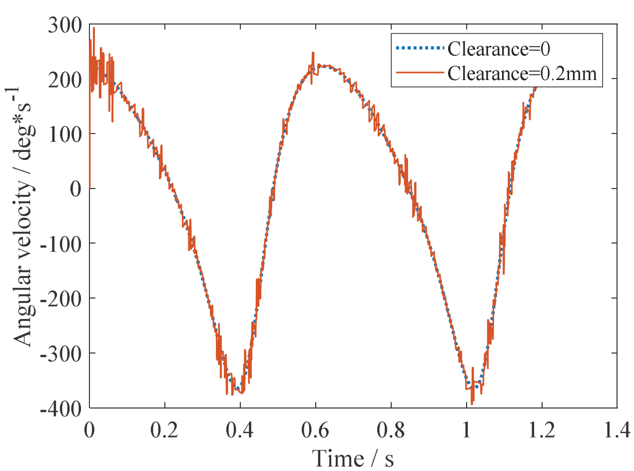

Figure 5. The angular velocity of the center of one journal end in X direction.

It can be observed that the angular velocity curve of model with 0.2 mm clearance fluctuates more fiercely compared to that of ideal joint. Due to the clearance between journal and bearing, contact between the two surfaces will arise with larger relative velocity which leads to frequent impact. Therefore, the dynamic response of multibody system shows obvious fluctuation and lower kinematic accuracy, which makes the force transfer inefficient and motion transfer inaccurate.

In order to investigate the trajectory of journal end center, a picture is plotted in Fig. 6 by comparing the coordinates of journal and bearing end center in the same side with 0.2 mm clearance. The dots are derived by calculating the difference between the coordinates of journal and bearing end center. In the middle of Fig. 6, the circle represents the clearance region with a radius of 0.2 mm. The two regions marked with red dotted line shows much denser distribution in X-Y plane, which means that it is more likely for contact and impact to take place in this area, eventually leading to wear in the two regions.

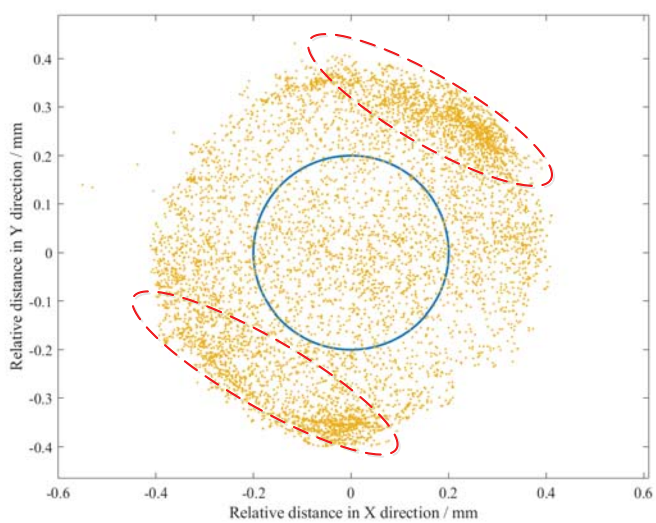

Figure 6. The center distribution of one journal end in X-Y plane (with 0.2 mm clearance).

IV. ANALYSIS OF WEAR CHARACTERISTICS IN THREE-DIMENSIONAL JOINT

In this section, a FEM model considering wear for journal-bearing structure with 0.2 mm clearance is developed in ABAQUS/Standard, seen in Fig. 7. From the above mentioned dynamic analysis model, the center coordinate values of two ends of journal are exported to a data file and set as boundary conditions in corresponding FEM model. The outer cylindrical surface is completely fixed and the two contact surfaces are applied hard contact which allows separation after contact. To make mesh size adapted to wear amount, ALE adaptive mesh control is used in "Step" module. The wear coefficient is set to be 2×10^{-2} to accelerate wear procedure. A user subroutine written by FORTRAN program language is developed to calculate the wear amount of nodes.

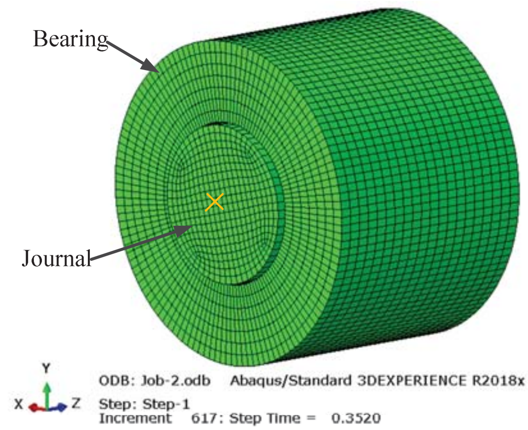

Figure 7. The FEM model of journal-bearing structure developed in ABAQUS/Standard.

Fig. 8 and Fig. 9 are the contour plots of node displacement in bearing from front and back view, respectively. It can be observed that wear tends to occur near the edges of bearing in spatial joint with clearance. And the wear situations of the two ends of bearing are also different. In addition, the shape and location of wear in bearing is quite similar to those of the dotted regions in Fig. 6 where the center distribution of one journal end in X-Y plane seems much denser. In other words, the contact in this region happens more frequently than other region. This can be explained by the three-dimensional movement of journal since 0.2 mm clearance is introduced in the model and ball joint used between follower and ground adds two revolute degree-of-freedoms.

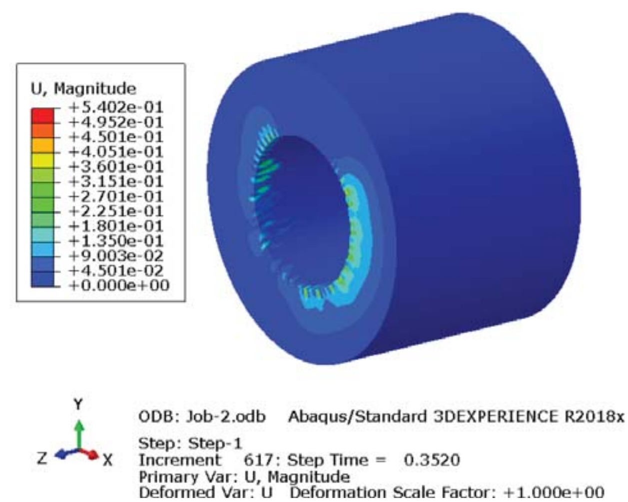

Figure 8. Contour plot of node displacement in bearing from front view.

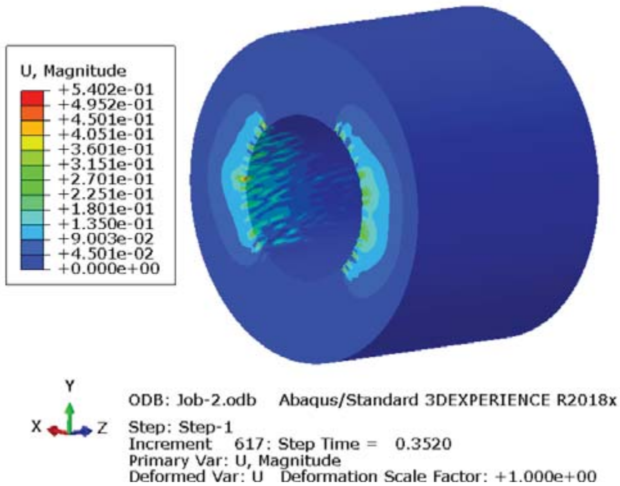

Figure 9. Contour plot of node displacement in bearing from back view.

V. CONCLUSIONS

Most of the previous studies on multibody system with clearance and wear are performed on planar models. However, those ideal links do not exist in reality and the movement of journal in a joint is three-dimensional. This work presents the dynamic performance of multibody system with spacial revolute joint and wear. A four-bar mechanism is utilized to illuminate the effect of spatial clearance and the dynamic response of mechanical system. Dynamic models having different spatial revolute clearance joints are developed in ADAMS software to obtain the displacement of journal and bearing. Results show that spatial joint with large clearance will result in low kinematic accuracy and impact in multibody system. The result of finite element model developed in ABAQUS/Standard environment shows that wear phenomenon tends to occur near the edges of bearing in spatial joint with clearance and the wear situations of the two ends of bearing are also different. It is necessary to take three-dimensional clearance joint instead of planar joint into consideration when performing wear analysis. Since wear phenomenon in reality is quite complex and the working condition is various, the work presented in this paper still needs to be further studied theoretically and experimentally.

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