Mechanism and Machine Theory 85 (2015) 106–115

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Model reduction of a flexible multibody system with clearance

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ARTICLE INFO

Article history:
Received 4 January 2014
Received in revised form 29 October 2014
Accepted 31 October 2014
Available online 26 November 2014

Keywords:
Component mode synthesis
Absolute nodal coordinate formulation
Clearance joint
Lubrication

ABSTRACT

A system reduction scheme related to a flexible multibody system with clearance is devised. In this work, the absolute nodal coordinate formulation is used to model the flexible multibody system, while imperfect joint is modeled as dry clearance joint or lubricated revolute joint. Meanwhile, the component mode synthesis is applied to reduce the size of the matrices. Finally, numerical examples are posted to analyze the proper selection of component modes and the convergence properties of the model reduction technique. It is obvious that the results of the reduced model are close to the results of the original model when the error of the maximum deformation energy between the reduced model and the original model is very small. The results of the reduced model with lubricated revolute joint can achieve high calculation accuracy with fewer modes than those with dry clearance joint.

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1. Introduction

Clearances always exist in mechanical systems due to abrasion, design tolerance or manufacture tolerance, which will cause high frequency vibration and reduce the lifetime. Therefore, it is necessary to investigate the effect of joint clearance on kinematic and dynamic behaviors of the systems.

The research on rigid multibody systems with clearance is very mature, and achieves volumes of study results. Flores et al. [1–3] performed a series of studies on the dynamics of rigid multibody systems with revolute clearance joints, spatial revolute joints, spherical clearance joints and translational clearance joints. They found that joint clearance seriously influences dynamic characteristic of mechanical systems and causes unwanted shake responses. Since the selection of a proper contact model is very important, Machado et al. [4] compared several contact force models to analyze advantages and limitations of those models. Qi et al. [5] investigated the effects of spatial prismatic joints on dynamics of a crank-slider mechanism. Bai et al. [6,7] used a new hybrid nonlinear contact force model to analyze the effects of revolute clearance joint on the dynamic behavior of planar mechanical systems. Flores et al. [8] and Erkaya and Uzmay [9] used experimental test to predict the performance of clearance joint models. Considering the effect of oil film, Flores et al. [10,11] also investigated dynamic behaviors of multibody systems with lubricated revolute joints and lubricated spherical joints. Then, selection of appropriate parameters, such as clearance size, lubricant viscosity and input crank speed, for planar mutibody systems with a lubricated revolute joint was investigated [12].

Compared to rigid mechanical systems, the dynamic features of the flexible mechanical systems with clearance are more complex. Based on the finite element method, Bauchau and Rodriguez [13] and Chunmei et al. [14] analyzed the effects of revolute clearance joint and spherical clearance joint on the dynamic behavior of flexible multibody systems. Tian et al. [15,16] studied the dynamics of flexible multibody systems with lubricated revolute joints and lubricated cylindrical joints based on the absolute nodal coordinate formulation (ANCF) [17].

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http://dx.doi.org/10.1016/j.mechmachtheory.2014.10.013
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However, a large amount of computation time is required for solving the motion equation of a flexible multibody system that contains a large number of degrees of freedom. Thus, a reduction technique is required to save computation time. Géradin and Cardona [18] used Craig–Bampton method to reduce the degrees of freedom of a flexible multibody system with respect to a co-rotational reference frame. Based on the ANCF, Kobayashi [19] extended the Craig–Bampton method to a flexible multibody system with large deformation. Sherif et al. [20] separated deformation modes of flexible bodies into low and high-frequency modes as well as with the neglecting of the latter-mentioned coupling effect of the second ones to reduce the size of the matrices of a suspended roller.

Furthermore, the existence of clearances in joints makes model reduction of such systems more difficult. The research on the model reduction of flexible multibody systems with clearance is still an open problem and there are few published results concerning the model reduction of multibody systems with clearance. Gerstmayr and Ambrósio [21] used component mode synthesis to reduce the size of flexible multibody systems with clearance based on absolute coordinates. However, important issues such as the proper selection of the component modes have not been addressed.

The Craig–Bampton method is an efficient way to reduce the degrees of freedom of a flexible multibody system with clearance. In this paper, flexible bodies are modeled by using the ANCF. Then, the Craig–Bampton method is used to reduce the degrees of freedom of the flexible bodies. Finally, numerical examples are posted to analyze the proper selection of modes and the convergence properties of the model reduction technique.

2. Model reduction of a flexible multibody system

The equations of motion for a flexible multibody system including kinematic constraints can be expressed as

$$\left\{ \mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{F} - \Phi_{\mathbf{q}}^{T}\boldsymbol{\lambda}\Phi = \mathbf{0} \right. \tag{1}$$

where $\mathbf{M}$ and $\mathbf{K}$ are generalized mass and stiffness matrices, respectively. Φ and $\Phi_{\mathbf{q}}$ are the constraint equation and its Jacobin matrix with respect to $\mathbf{q}$. $\mathbf{F}$ is the generalized force vector that contains gravity, contact and control forces. $\boldsymbol{\lambda}$ is the Lagrange multiplier vector.

In this paper, the ANCF is used to discretize flexible bodies in Eq. (1). Since this method leads to a high dimension of the equations of motion, model reduction techniques are required to reduce the degrees of freedom of the system. If a reduction via projection is used, $\mathbf{q}$ is approximated in a subspace $\mathcal{V}$ of lower dimension and the relation is represented by a projection matrix $\mathbf{V}$, the approximation can be expressed by

$$\mathbf{p} = \mathbf{V}\mathbf{q}. \tag{2}$$

In order to obtain matrix $\mathbf{V}$, various techniques have been developed through the last decade, such as component mode synthesis [22,23], improved reduction system method [24], Krylov subspace method [25]. Each of them has its corresponding advantages and disadvantages [26].

From Eqs. (1) and (2), the motion equation of the system with constraint force can be written as

$$\overline{\mathbf{M}}\ddot{\mathbf{p}} + \overline{\mathbf{K}}\mathbf{p} = \overline{\mathbf{F}} - \hat{\mathbf{Q}} \quad \Phi = \mathbf{0}\} \tag{3}$$

where $\overline{\mathbf{M}}$, $\overline{\mathbf{K}}$, $\overline{\mathbf{F}}$ and $\hat{\mathbf{Q}}$ are the mass matrix, stiffness matrix, generalized force vector and constraint force of the system under modal coordinate, respectively. All parameters in Eq. (3) are given as follows:

$$\overline{\mathbf{M}} = \mathbf{V}^{T}\mathbf{M}\mathbf{V}, \ \overline{\mathbf{K}} = \mathbf{V}^{T}\mathbf{K}\mathbf{V}, \ \overline{\mathbf{F}} = \mathbf{V}^{T}\mathbf{F}, \ \hat{\mathbf{Q}} = \mathbf{V}^{T}\Phi_{\mathbf{q}}^{T}\boldsymbol{\lambda}.$$

3. Revolute clearance joints: dry contact model

Clearances always exist in mechanical systems which lead to the failure of displacement constraints between bearing and journal. The journal can move freely inside the bearing until contact between the two bodies occurs. Force constraints of mechanical systems are introduced.

Fig. 1 shows a revolute clearance joint, connecting bearing (part of body i) and journal (part of body j). And their centers are points P_i and P_j, respectively. From Fig. 1, the eccentricity vector which connects points P_i and P_j can be given by

$$\mathbf{e}_{ij} = \mathbf{r}_{j} - \mathbf{r}_{i}. \tag{4}$$

Then the unit eccentricity vector can be expressed as

$$\mathbf{n} = \frac{\mathbf{e}_{ij}}{e_{ij}} \tag{5}$$

where e_{ij} is the magnitude of the eccentricity vector.

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