Mechanism and Machine Theory 126 (2018) 429–456

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Research paper

Frequency analysis of a typical planar flexible multibody system with joint clearances

Esmaeil Salahshoor[a], Saeed Ebrahimi[a,*], Yunqing Zhang[b]

[a] Department of Mechanical Engineering, Yazd University, Yazd, Iran
[b] School of Mechanical Science and Engineering, Huazhong University of Science & Technology, Wuhan, China

ARTICLE INFO

Article history:
Received 18 March 2018
Revised 19 April 2018
Accepted 28 April 2018

Keywords:
Assumed modes method
Fast Fourier Transform
Floating frame of reference
Joint stiffness
Natural frequency

ABSTRACT

A comprehensive study of the effect of joint stiffness on the vibration behavior of a typical slider-crank mechanism with a flexible component and joint clearances is presented in this paper. Firstly, the dynamic response of the ideal mechanism is obtained using both the floating frame of reference (FFR) and assumed modes methods. Based on the results, it is concluded that in mechanisms with high crank speeds, the fundamental natural frequency could be reachable by lower external excitation frequencies. Then, considering the joint stiffness between the slider and the ground as well as the coupler and the slider, the responses of both mechanisms with the ideal and imperfect joints are compared with each other. Having found the exact number of equations of motion equal to the number of degrees of freedom, a deeper insight into the vibration behavior of this typical mechanism considering the joint stiffness is obtained. Finally, Fast Fourier Transform (FFT) algorithm is implemented to find the frequency components of the transverse deflection of the coupler midpoint and the vertical displacement of the slider. It is, however, observed that variation of the joint stiffness in a reasonable range does not considerably change the frequency components of the response.

1. Introduction

Clearances are unavoidable in real applications of multibody systems. This clearance permits the joined bodies to move relative to each other. Consequently, it degrades the performance, makes vibration and produces noise. Assuming the joints to be ideal does not usually lead to the exact modeling of multibody systems, especially when precision and non-vibrating conditions are required. The problem of dynamic modeling of multibody systems with clearance joint has attracted recently a great attention by many researchers [1]. Among all, Dubowsky and Freudenstein [2,3] formulated the mathematical model of a so-called impact pair for dynamic modeling of an elastic mechanical joint with clearances. A nonlinear dependency of the response of a four-bar mechanism with a clearance joint on both the clearance size and the contact friction was reported by Rhee and Akay [4]. For analyzing the dynamic behavior of a slider-crank mechanism with a clearance joint between its coupler and slider, a continuous analysis method is presented in [5].

Several continuous contact force models for revolute joints in the dynamic analysis of rigid and elastic mechanical systems were compared by Schwab et al. [6]. According to their results, the effect of compliance of the links or lubrication of the joints on the smooth behavior of the contact force is approved. Flores and Ambrósio [7] dealt with a computational

* Corresponding author.
E-mail addresses: esalahshoor@stu.yazd.ac.ir (E. Salahshoor), ebrahimi@yazd.ac.ir (S. Ebrahimi), zhangyq@hust.edu.cn (Y. Zhang).

https://doi.org/10.1016/j.mechmachtheory.2018.04.027
0094-114X/

methodology for dynamic analysis of multibody mechanical systems with joint clearance. The contact forces obtained from their approach were well correlated with the joint reaction forces of an ideal revolute joint without clearance. Afterwards, for the assessment of the influence of the friction coefficient and the clearance size on the dynamic behavior of multibody systems including revolute joints with clearance, a general methodology is presented in [8]. More information on the friction and different friction models could be found in [9–11]. Khemili and Romdhane [12] studied the dynamic behavior of a planar flexible slider-crank mechanism with a single clearance joint. They used software ADAMS for motion simulation and characterized the motion by the occurrence of three phases including a free motion, a continuous contact motion, and an impact motion. In addition to the above studies, wear phenomenon is addressed in the literature [13–16] and some authors considered the lubricated joints [17–21]. Some papers dealt with optimizing the behavior of multibody systems with clearance joint [22–25]. Due to the high nonlinearity involved in mechanical systems with joint clearance, chaos and bifurcation are considered by some researchers [26–28]. Recently, the practical issues of clearance modeling in some special mechanical systems have found great attention (see e.g. [29–31]). Three-dimensional clearance joints were also addressed in [32–35]. Marques et al. [32] presented a formulation for modeling spatial revolute joints with radial and axial clearances. Cavalieri and Cardona [35] proposed a new element to model the 3D revolute clearance joints.

In addition to the dynamic modeling of multibody systems with clearance joint, some efforts have been devoted to their frequency analysis, as well as the effects of clearance joints and the link/joint flexibilities on the vibration responses of multibody systems [36–52]. For modeling the clearance joints in nonlinear flexible multibody systems, a comprehensive approach was studied by Bauchau [36]. Flores et al. [37] constructed a slider-crank mechanism with an adjustable radial clearance. The numerical results and experimental data were in good agreement. Then, the FFT analysis showed that increasing the crank speed and the clearance size led to the increase in the number and magnitude of the contribution of the dominant frequencies. Erkaya and Uzmay [38] showed experimentally that how link flexibility and balancing could decrease the undesired effects of joint clearances. A planar and a spatial multi-rigid body hip joint model with spherical clearance were considered in [39,42]. Through an FFT analysis of the audible sounds from ceramic on ceramic hip acceleration, it was shown that hip squeaking frequencies increased with the decrease in hip implant size. In addition, squeaking frequencies were not considerably influenced by the initial conditions. The dynamic response of a planar four-bar mechanism with two revolute clearance joints and flexible coupler was studied in [40]. It was concluded that the flexibility had a considerable effect on the vibration response of the system. Zheng and Zhou [41] considered a slider-crank mechanism for a closed high speed press system in which the crankshaft, unlike its traditional model, was assumed to be flexible. One, two, three, and four clearance joints were taken into account. It was concluded that the clearance significantly affected the dynamic response of the mechanism. Erkaya and Doğan [43] considered a planar compliant slider-crank mechanism with clearance joints. The pseudo-rigid-body model of the compliant mechanism was employed. It was found that the small-length flexural pivot in compliant mechanism showed a good suspension characteristic to reduce the undesired effects of the clearance at lower running speeds and higher clearance sizes. Erkaya et al. carried out an experiment to find the effects of joint clearance on partly compliant slider-crank mechanism with a small flexural pivot [44]. A partly compliant mechanism with spherical clearance joint was also studied in [45]. The effects of harmonic drive and link flexibility on dynamic response of a 2D slide-crank mechanism with two clearance joints were presented in [46]. It was shown that the harmonic drive mechanism made a better effect on the body motion stability and reduction in vibration, noise and wear between mechanical parts. A dynamic model of flexible multilink mechanism with clearance and lubrication for ultra-precision presses was presented by Zheng et al. [47] to study its dynamic behavior more accurately. Effects of spherical clearance joint and flexible joint connection on the mechanism vibration were presented in [48]. It was experimentally shown that the vibration arising from clearance deteriorated the dynamics of system. To minimize the undesired effects of clearance joint, considering the flexible connection between the adjacent members presented an important idea. Vaidya and Padole [49] tried to determine the natural frequencies of a four-bar mechanism with two clearance joints. The contact in the clearance joints was represented by linear and torsional springs and incorporated in the assembled stiffness matrix. Furthermore, the vibration characteristics of a planar mechanism having imperfect joints were predicted by using the neural network approach [50]. For this purpose, the experimental data from three accelerometers was obtained to find out the vibration of the system. The vibration modes of a cantilever beam with a block placed on it with a clearance were investigated in [51]. Ebrahimi et al. tried to find the effect of joint stiffness on the variation of instantaneous natural frequencies and mode shapes of a flexible four-bar mechanism with a single clearance joint [52].

As the major contribution of the present study, it aims at investigating the effect of clearance joints with linear and nonlinear variable stiffness on the linear natural frequencies of a typical flexible multibody system. For this purpose, the exact number of the equations of motion equal to the number of degrees of freedom for a slider-crank mechanism with clearance joints is derived using assumed modes method to see the effect of the contact stiffness on some vibration characteristics of the system. Considering this mechanism, the joint stiffness between the slider and the ground as well as the coupler and the slider is taken into account. The responses of both mechanisms with the ideal and imperfect joints are compared with each other. Finally, the FFT algorithm is implemented to find the frequency components. A detailed discussion on the linear natural frequencies of the mechanism is presented to provide an extensive characterization of the vibration response due to the effect of clearances.