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Transfer matrix method for dynamics modeling and independent modal space vibration control design of linear hybrid multibody system

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ABSTRACT

In this paper, an efficient method of dynamics modeling and vibration control design of a linear hybrid multibody system (MS) is studied based on the transfer matrix method. The natural vibration characteristics of a linear hybrid MS are solved by using low-order transfer equations. Then, by constructing the brand-new body dynamics equation, augmented operator and augmented eigenvector, the orthogonality of augmented eigenvector of a linear hybrid MS is satisfied, and its state space model expressed in each independent model space is obtained easily. According to this dynamics model, a robust independent modal space-fuzzy controller is designed for vibration control of a general MS, and the genetic optimization of some critical control parameters of fuzzy tuners is also presented. Two illustrative examples are performed, which results show that this method is computationally efficient and with perfect control performance.

1. Introduction

Most modern engineering system can be regarded as a hybrid multibody system (MS) with a series of bodies, hinges and control subsystems. The structures of such systems are rather complex, and the computational cost of their dynamics analysis and control design is relatively high, so it is more and more important to explore an efficient method of dynamics modeling and control design for these systems [1,2]. Many scholars have done a lot of research in this field, which significantly promoted the development of dynamics modeling and control design of complex MS. Tang studied the active vibration control of an MS with quick startup and brake by optimizing the driving load [3]. Järvenpää proposed a multibody dynamics model to explore the rolling contact vibration control [4]. Yazici studied a robust delay-dependent H_∞ controller of seismic-excited systems, which could guarantee the stability at maximum actuator delay and parametric uncertainty [5]. Neto deduced a flexible MS model with composite piezoelectric sensors and actuators [6]. Park studied an adaptive reference-model-tracking fuzzy vibration control of earthquake-excited structures in the modal space, which has the robust and adaptive fault-tolerant performances [7]. Yazici studied an optimal state feedback controller for active vibration mitigation of an aircraft system by the linear matrix inequalities approach [8]. Lipiński studied dynamics modeling and control design of a redundantly actuated planar manipulator, and a model-based-proportional-derivative feedforward-feedback controller is suggested [9].

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When investigating the problems of dynamics and control design of a hybrid MS, one often needs to establish an appropriate dynamics model of the system firstly, and then designs the corresponding controller according to different control theories [10]. Many MS dynamics methods (for example, Wittenburg method [1,11], Kane method [12], and Lagrange method [6]) can develop the MS dynamics model. Taking the linear time-invariant MS as an example, by ordinary MS dynamics methods, one can obtain its global dynamics equation as the following form

$$\mathbf{M}_{\mathrm{all}}\ddot{\xi}_{\mathrm{all}}(t) + \mathbf{C}_{\mathrm{all}}\dot{\xi}_{\mathrm{all}}(t) + \mathbf{K}_{\mathrm{all}}\xi_{\mathrm{all}}(t) = \mathbf{Q}_f\mathbf{u}_f(t) + \mathbf{Q}_C\mathbf{u}_C(t) \tag{1}$$

Here, ξ_{all} is the generalized coordinates of the system. $\mathbf{M}_{\mathrm{all}}$, $\mathbf{K}_{\mathrm{all}}$ and $\mathbf{C}_{\mathrm{all}}$ are the mass, stiffness and damping matrices of the system, respectively. $\mathbf{u}_f$ and $\mathbf{u}_C$ are the external disturbance and the control force. $\mathbf{Q}_f$ and $\mathbf{Q}_C$ are the corresponding coefficient matrices. It is evident that the orders of involved matrices in Eq. (1) obtained by ordinary multibody dynamics methods is very high for a complex hybrid MS, which increase with the degrees of freedom (DOF) of the system. Especially when the finite element technique is used to describe the deformation of flexible components, the DOF of the system is more enormous. Hence the analysis of the vibration characteristics and dynamic response of a complex hybrid MS would have a high computational cost [10,13]. The cost and complexity of the controller are also associated with the order of Eq. (1). High matrix order would bring many difficulties in design and real-time implementation of the control system for a complex MS. Moreover, the dynamics model defined by Eq. (1) is often with inaccuracies and uncertainties inevitably due to the inaccuracy of parameters measurement, disturbance measurement, model simplification and so on, which would affect both the accuracy of dynamics analysis and the performance of control system [10,13].

The transfer matrix method (TMM) [14] which has been widely applied to structural mechanics, rotor dynamics, and MS dynamics, has such characteristics as easy programming, low matrix order, fast calculation and non-indispensable global dynamics equations. Thus, TMM could provide a powerful means for efficient dynamics modeling and control design of an MS. By utilizing TMM, Kim investigated the dynamics modeling and vibration analysis of a 3-dimensional planetary gear system [15]. Lee computed the in-plane bending vibration of a rotating beam with multiple edge cracks [16]. Rui et al. developed TMM of linear MS [11,17], and applied this method to vibration characteristics analysis, dynamic response solution and active vibration control of some engineering systems, such as multiple-launch rocket system [13], elastically coupled launch vehicle boosters [18], and so on.

In this paper, for solving the problems encountered in the dynamics analysis and control design, an efficient method of dynamics modeling and vibration control design of linear hybrid MS is studied based on the TMM, and a robust independent modal space-fuzzy vibration controller of a general MS is designed and optimized. Two illustrative examples are also carried out to validate the method and the control performance.

2. Dynamics model of linear hybrid MS based on TMM

In order to be convenient for description and easy for understanding, a hybrid MS with closed-loop control shown in Fig. 1 is used as an example to demonstrate the process of the dynamics modeling by TMM [11,13]. However, such analysis method can also be applicable to any linear hybrid MS. As shown in Fig. 1, the hybrid MS consists of various elements including bodies (rigid body, flexible body, etc.), hinges (spring, pin hinge, etc.), and control subsystem (actuator, measurement device, etc.). The control force (moment) $\mathbf{u}_{C,m}$ which is obtained according to a predesigned control algorithm and the measured output $\tilde{\mathbf{z}}_{f,l}$ of feedback object l, is applied to drive the controlled object m to realize an expectant motion.

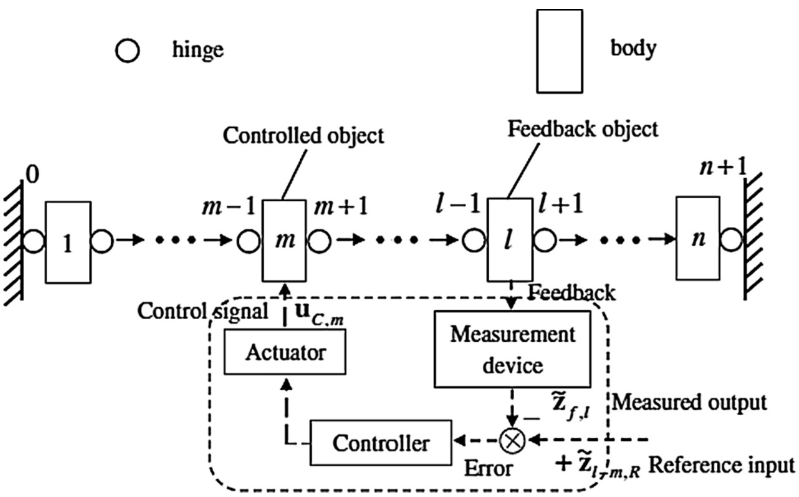

Fig. 1. Multibody system with closed-loop control [13].