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Research on the rigid-flexible multibody dynamics of concrete placing boom

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ABSTRACT

A method is proposed for rigid-flexible multibody dynamic modeling of concrete placing booms, to improve the calculation efficiency and ensure the accuracy. Concrete placing booms consist of four types of substructures, according to the slender rods and the mechanism features. The transfer matrixes of substructures are derived based on the discrete time transfer matrix method. Then, the manipulator's overall transfer matrix is assembled and used for the numerical calculation. An experiment based on a test rig is performed to validate the proposed method, and a model based on ADAMS (short of MSC.ADAMS) is also established to compare the calculating efficiency of the proposed method.

1. Introduction

A Concrete placing boom is a large flexible manipulator used for placing liquid concrete in construction sites. In order to satisfy the civil engineering requirements, concrete placing booms become longer and longer, and the longest had reached 101 m in 2013. The manipulator, consisting of a series of slender rods and complex mechanisms, could be of high flexibility and low damping. Thus, considerable structural stress, hydraulic pressure fluctuation and vibration at the tip will be produced during operation. Therefore, a numerical method to efficiently simulate the dynamic performance of the manipulator is desirable, for the application of predictive control [1], real-time simulation [2], intelligence [3,4] and fault diagnosis [5].

Dynamic modeling methods for concrete placing booms or the similar flexible manipulators have been proposed to deal with different problems. Cazzulani G. et al. proposed a virtual prototype model and analyzed the dynamic performance of a concrete placing boom test rig. With the proposed model, they studied a negative derivative feedback control strategy to suppress the vibration at the boom tip [6–8], and researched on problems of the manipulator's health monitoring [9]. Oliver Lenord et al. studied the dynamic performance of a controlled hydraulically driven elastic manipulator based on an interdisciplinary model [10]. Heinze established an experimentally verified model for hydraulic crane boom and studied the trajectory tracking control strategy based on PID control theory [11]. Liu et al. established a model of truck mounted concrete pump boom based on Lagrange formula for tip trajectory synthesis [12], and proposed a flexible dynamic modeling method using the kineto-elastic-dynamics technique [13]. Sun X. et al. compared the efficiency of open-loop and closed-loop control methods on the vibration reduction of the booms [14]. Ren W. et al. studied the tip vibration of different working conditions basing on transfer matrix method, where the stiffness of hydraulic cylinder and clearance gap is especially taken into account [15].

Based on traditional kinetic theory, explicit functions of a multibody dynamic model of the manipulator could be derived. Such an explicit model is efficient and it is especially useful in the manipulator's optimal design and automation control. However, the equation derivation of the model is cumbersome, while an over-simplified model can hardly describe the complexity of a real mechanism. Therefore, a new method is desired, not only to keep the features of slender rods and complex mechanisms but also to establish a rigid-flexible model conveniently.

In 1998, Rui proposed a discrete time transfer matrix method for dynamics analysis of multibody system. The method, which combined the transfer matrix method with the numerical integration procedure, retained the high computing efficiency of the transfer matrix for chained systems [16]. Then the method was gradually developed for rigid-flexible multibody dynamics [17–18]. Due to the advantage of computational efficiency, this method was applied to many mechanical engineering fields, such as shipboard gun system [19] and self-propelled

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artillery system [20]. Li developed a computing method to improve the accuracy [21]. Rong performed the real-time simulation based on this method [22] and applied it to the study of spatial structures [23].

The aim of this paper is to propose an accurate and efficient dynamic modeling method, which can adapt to any types of concrete placing boom. For this reason, at first, the manipulator is divided into several substructures based on its structural feature [24,25]. The substructures, where the stiffness and damping of hydraulic cylinders [26] are taken into account and the features of slender rods and complex mechanisms are retained, are regarded as units, which are the foundation for the manipulator's modular modeling. Then, the transfer matrixes and transfer equations of each substructure are obtained according to the discrete time transfer matrix method. Since a substructure is treated as a unit, the manipulator can then be regarded as a chain system. Thus, the overall transfer matrix can be directly assembled based on the transfer matrixes, and used for calculating the movements and tip vibration of the booms.

2. Physical model

A concrete placing boom consists of a variety of link mechanisms, which are made up of booms, links and hydraulic cylinders. Generally, there are two types of mechanisms in the manipulator: slider crank mechanism and six-bar mechanism, as shown in Fig. 1.

The slider crank mechanism is defined as substructure A, and the six-bar mechanism is defined as substructure B. According to the difference of the connection points in each link, substructure B is further defined into three subcategories — both links of substructure B_1 are two-force members, while the left link of substructure B_2 is a three-force member, and the right link of substructure B_3 is a three-force member.

Therefore, each type of concrete placing boom can be treated as a chain of substructures and transformed into $A + B_i + B_j + \ldots$ ($i, j\ldots = 1, 2, 3$).

3. Dynamic modeling

3.1. State vector

The state vectors at the connection points between rigid elements and hinges moving in plane are defined as:

$$\mathbf{Z} = \begin{bmatrix} x & y & \theta & M & q_x & q_y & 1 \end{bmatrix}^{\mathrm{T}} \tag{1}$$

where x and y are the position coordinates at the connection point with respect to the inertial reference frame, θ is the orientation angle rotating in the frame; M, q_x and q_y are the corresponding internal torque and internal forces in the same reference frame, respectively. The "1" is a constant term, which is used to transfer the time invariant part in numerical computation. The positive direction of input end is along the coordinate while the positive direction of output end is against the coordinate.

The state vectors of flexible bodies are defined as:

$$\mathbf{Z} = \begin{bmatrix} x & y & \theta & M & q_x & q_y & q^1 & q^2 & q^3 & 1 \end{bmatrix}^{\mathrm{T}} \tag{2}$$

where the q^1, q^2, and q^3 are the generalized modal coordinates which are used to describe the deformation of a flexible body. The superscript is the order of the modal, and the highest order is set at three in this article.

In addition, the denotation of each state vector $\mathbf{Z}$ is represented by its subscript. For example, the $\mathbf{Z}_{i,j}$ means the state vector from element i to element j. When narrating the state vector in element i, $\mathbf{Z}_{I,i}$ denotes the input state vector while $\mathbf{Z}_{O,i}$ means the output state vector.

3.2. Transfer equations and transfer matrixes of substructures

3.2.1. Transfer equation and transfer matrix of substructure A

As shown in Fig. 2, the substructure A contains eight elements, SA_0 is the input end and SA_9 is the output end. SA_1–2 and SA_5 are rigid bodies while SA_3 is a drive element, SA_4 is a elastic hinge, SA_7 is the element of Euler–Bernoulli beam, SA_6 is a rigid to flexible hinge, whose outboard body is flexible body and inboard body is rigid body, SA_8 is a flexible to rigid hinge, while the outboard body is rigid body and the inboard body is flexible body. P_1 is the connection point and the arrow shows the transfer direction. All transfer matrix $\mathbf{U}_\alpha$ (α is element's ID) in this article can be found in Refs. [16–23]. The transfer equations of each branch in substructure A are

$$\begin{cases} \mathbf{Z}_{O,\mathrm{SA\_1}} = \mathbf{U}_{\mathrm{SA\_1}}\mathbf{Z}_{I,\mathrm{SA\_1}} \\ \mathbf{Z}_{O,\mathrm{SA\_5}} = \mathbf{U}_{\mathrm{SA\_5}}\mathbf{U}_{\mathrm{SA\_4}}\mathbf{U}_{\mathrm{SA\_3}}\mathbf{U}_{\mathrm{SA\_2}}\mathbf{Z}_{I,\mathrm{SA\_2}} \\ \mathbf{Z}_{O,\mathrm{SA\_8}} = \mathbf{U}_{\mathrm{SA\_8}}\mathbf{U}_{\mathrm{SA\_7}}\mathbf{U}_{\mathrm{SA\_6}}\mathbf{Z}_{I,\mathrm{SA\_6}} \end{cases} \tag{3}$$

The relationship between displacements and forces at point P_1 can be written as follows:

$$\begin{cases} x_{I,\mathrm{SA\_6}} = x_{O,\mathrm{SA\_1}} = x_{O,\mathrm{SA\_5}} \\ y_{I,\mathrm{SA\_6}} = y_{O,\mathrm{SA\_1}} = y_{O,\mathrm{SA\_5}} \\ \theta_{I,\mathrm{SA\_6}} = \theta_{O,\mathrm{SA\_1}} \\ M_{I,\mathrm{SA\_6}} = M_{O,\mathrm{SA\_1}}; M_{O,\mathrm{SA\_5}} = 0 \\ q_{x,I,\mathrm{SA\_6}} = q_{x,O,\mathrm{SA\_1}} + q_{x,O,\mathrm{SA\_5}} \\ q_{y,I,\mathrm{SA\_6}} = q_{y,O,\mathrm{SA\_1}} + q_{y,O,\mathrm{SA\_5}} \end{cases} \tag{4}$$

Combining Eq. (3) with (4) yields Eq. (5).

$$\begin{cases} \mathbf{U}_{\mathrm{SA\_8}}\mathbf{U}_{\mathrm{SA\_7}}\mathbf{U}_{\mathrm{SA\_6}}\mathbf{U}_{\mathrm{SA\_1}}\mathbf{Z}_{I,\mathrm{SA\_1}} + \mathbf{U}_{\mathrm{SA\_8}}\mathbf{U}_{\mathrm{SA\_7}}\mathbf{U}_{\mathrm{SA\_6}}\mathbf{E}_1\mathbf{U}_{\mathrm{SA\_5}}\mathbf{U}_{\mathrm{SA\_4}}\mathbf{U}_{\mathrm{SA\_3}}\mathbf{U}_{\mathrm{SA\_2}}\mathbf{Z}_{I,\mathrm{SA\_2}} = \mathbf{Z}_{O,\mathrm{SA\_8}} \\ \mathbf{E}_2\mathbf{U}_{\mathrm{SA\_1}}\mathbf{Z}_{O,\mathrm{SA\_1}} = \mathbf{E}_2\mathbf{U}_{\mathrm{SA\_5}}\mathbf{U}_{\mathrm{SA\_4}}\mathbf{U}_{\mathrm{SA\_3}}\mathbf{U}_{\mathrm{SA\_2}}\mathbf{Z}_{O,\mathrm{SA\_2}} \\ \mathbf{E}_3\mathbf{U}_{\mathrm{SA\_5}}\mathbf{U}_{\mathrm{SA\_4}}\mathbf{U}_{\mathrm{SA\_3}}\mathbf{U}_{\mathrm{SA\_2}}\mathbf{Z}_{O,\mathrm{SA\_2}} = 0 \end{cases} \tag{5}$$

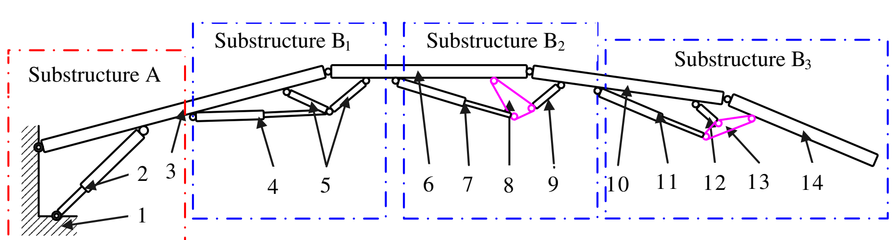

Fig. 1. Conventional diagram of mechanisms in concrete placing boom. 1—base; 2—hydraulic cylinder I; 3—boom I; 4—hydraulic cylinder II; 5—link II; 6—boom II; 7—hydraulic cylinder III; 8—link(L) III; 9—link(R) IIII; 10—boom III; 11—hydraulic cylinder IV; 12—link(L) IV; 13—link(R) IV; 14—boom IV.