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A new approach for dynamic analysis of flexible manipulator systems

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Abstract

In this paper, a new approach for dynamic analysis of the flexible multibody manipulator systems is described. The organization of the computer implementations which are used to automatically construct and numerically solve the system of loosely coupled dynamic equations expressed in terms of the absolute, joint and elastic coordinates is discussed. The main processor source code consists of three main modules: constraint module, mass module and force module. The constraint module is used to numerically evaluate the relationship between the absolute and joint accelerations. The mass module is used to numerically evaluate the system mass matrix as well as the non-linear Coriolis and centrifugal forces associated with the absolute, joint and elastic coordinates. At the same time, the force module is used to numerically evaluate the generalized external and elastic forces associated with the absolute, joint and elastic coordinates. Computational efficiency is achieved by taking advantage of the structure of the resulting system of loosely coupled equations. The absolute, joint and elastic accelerations are integrated forward in time using direct numerical integration methods. The absolute positions and velocities can then be determined using the kinematic relationships. The flexible 2-DOF double-pendulum and spatial manipulator systems are used as illustrated examples to demonstrate and verify the application of the computational procedures discussed in this paper.

Keywords: Flexible manipulators; Constraint module; Mass module; Force module

1. Introduction

One important potential application of multibody dynamics which connected with rigid and flexible body components in recent researches are the flexible manipulator systems. Yen et al. [1] proposed the extended bond graph (EBG) method to simulate a two-link flexible manipulator system. This EBG module is first derived to represent the dynamics of an elastic link undergoing large motions by applying the spatial discretization of the conjugate variable approximation method, the shadow-beam kinematic description and the principle of virtual work. Sutter et al. [2] described an articulated space crane concept and

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evaluated four articulating joint concepts. It was concluded that a space crane with three booms, three articulating joints, and one rotary joint provides an adequate reach envelope for an expected work area. The maximum allowable tip velocity was calculated as a function of the crane payload mass for an emergency stop scenario. Sutter et al. [3] also examined the structural performance of two truss configurations of the phase one space station. The finite element analysis program MSC/NASTRAN is used to determine and compare the frequencies, mode shapes, transient response, and truss-strutt compressive loads of the two space station models. Das et al. [4] developed a formulation for the flexibility induced motion of the space crane relative to its nominal motion. An algorithm is proposed for the computation of the relative motion driving forces. In this formulation, the distributed mass of the crane is lumped by two schemes based on the trapezoidal and Simpson's rules. A numerical study was also presented to examine the effect of increasing the truss mass on the tip deflection and its effect on the stepsize used in the simulation. Park et al. [5] presented a computationally oriented formulation and solution procedures for the analysis of rigid-flexible multibody dynamic systems. The solution of the resulting equations of motion including system constraints is obtained by a partitioned procedure, which solves first for the constraint force vector, then the generalized coordinates for the rigid and flexible components, and finally interaction quantities such as active control forces, maneuvering space ranges and corrections due to state measurements, with each solution stage being processed by the corresponding separate module.

Recently, Hwang et al. [6,7] presented a recursive method for the kinematic and dynamic analysis of flexible multibody systems. The kinematic position, velocity and acceleration equations of two interconnected flexible bodies are developed. In this paper, the computer implementations of the recursive method with Newton–Euler approach are discussed. The organization of the computer source code developed based on the recursive method with Newton–Euler approach is described. This code consists of three main modules: constraint module, mass module and force module. In the constraint module, the kinematic relationships between the absolute, joint, and elastic accelerations are developed. In the mass module, the mass matrix of each body in the system as well as the non-linear Coriolis and centrifugal forces associated with the absolute, joint and elastic coordinates are evaluated. In the force module, the externally applied forces and elastic forces associated with the absolute, joint and elastic coordinates are evaluated. Having defined the system mass matrix, generalized forces, and the kinematic relationships, the large system of loosely coupled equations expressed in terms of the absolute, joint and elastic coordinates can be constructed. Computational efficiency is achieved by taking advantage of the structure of the resulting system of loosely coupled equations. The absolute, joint and elastic accelerations are integrated forward in time using direct numerical integration methods that have variable order and variable step size [8,9].

2. System dynamic equations of motion

In the recent investigations [6,7], the dynamic equations of motion among bodies $i, i-1$ and corresponding joint can be expressed a recursive form as

$$\boldsymbol{a}_i = \boldsymbol{H}^a_{i,i-1}\boldsymbol{a}_{i-1} + \boldsymbol{H}^p_i\ddot{\boldsymbol{p}}_i + \boldsymbol{\beta}_i \tag{1}$$

For the multibody system interconnected with rigid and flexible bodies, Eq. (1) can be expressed explicitly from the base to the end as a set of equations of motion. Consequently, these equations of motion can be written in a compact matrix form as

$$\underline{\boldsymbol{a}} = \underline{\boldsymbol{H}}^p\underline{\ddot{\boldsymbol{p}}} + \underline{\boldsymbol{\beta}} \tag{2}$$

where the vectors $\underline{\boldsymbol{a}}$, $\underline{\ddot{\boldsymbol{p}}}$ and $\underline{\boldsymbol{\beta}}$, and the matrix $\underline{\boldsymbol{H}}^p$ are defined as follows:

$$\underline{\boldsymbol{a}} = [\boldsymbol{a}_1^{\mathrm{T}}\ \ \boldsymbol{a}_2^{\mathrm{T}}\ \ \cdots\ \ \boldsymbol{a}_{i-1}^{\mathrm{T}}\ \ \boldsymbol{a}_i^{\mathrm{T}}]^{\mathrm{T}} \tag{3}$$

$$\underline{\ddot{\boldsymbol{p}}} = [\ddot{\boldsymbol{p}}_1^{\mathrm{T}}\ \ \ddot{\boldsymbol{p}}_2^{\mathrm{T}}\ \ \cdots\ \ \ddot{\boldsymbol{p}}_{i-1}^{\mathrm{T}}\ \ \ddot{\boldsymbol{p}}_i^{\mathrm{T}}]^{\mathrm{T}} \tag{4}$$

$$\underline{\boldsymbol{\beta}} = [\hat{\boldsymbol{\beta}}_1^{\mathrm{T}}\ \ \hat{\boldsymbol{\beta}}_2^{\mathrm{T}}\ \ \cdots\ \ \hat{\boldsymbol{\beta}}_{i-1}^{\mathrm{T}}\ \ \hat{\boldsymbol{\beta}}_i^{\mathrm{T}}]^{\mathrm{T}} \quad \text{where}$$

$$\hat{\boldsymbol{\beta}}_i = \boldsymbol{\beta}_i + \boldsymbol{H}^a_{i,i-1}\hat{\boldsymbol{\beta}}_{i-1} (i = 1 \Rightarrow \hat{\boldsymbol{\beta}}_0 = \boldsymbol{a}_0) \tag{5}$$