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In this investigation a method for the spatial kinematic and dynamic analysis of deformable multibody systems that are subject to topology changes and impacts is presented. A pieced interval analysis scheme that accounts for the change in the spatial system topology due to the changes in the connectivity between bodies is developed. Deformable bodies in the system are discretized using the finite element method and accordingly a finite set of deformation modes is employed to characterize the system vibration. Even though there are infinitely many arrangements for

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deformable body axes, computational difficulties may be encountered due to the use of a limited number of deformation modes. Therefore, the deformable body references have to be carefully selected, and accordingly as the system topology changes, new bases for the configuration space have to be identified. In order to guarantee a smooth transition from one configuration space to another, a set of spatial interface conditions or compatibility conditions that are formulated using a set of nonlinear algebraic equations are developed. The solution of these equations uniquely define the spatial configuration of the deformable multibody system after the change in the system kinematic structure. The techniques proposed in this research are applied to several technological systems such as robotic manipulators and weapon systems.

SPATIAL DYNAMICS OF DEFORMABLE MULTIBODY
SYSTEMS WITH VARIABLE KINEMATIC STRUCTURE

Final Report

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ABSTRACT

In this investigation a method for the spatial kinematic and dynamic analysis of deformable multibody systems that are subject to topology changes and impacts is presented. A pieced interval analysis scheme that accounts for the change in the spatial system topology due to the changes in the connectivity between bodies is developed. Deformable bodies in the system are discretized using the finite element method and accordingly a finite set of deformation modes is employed to characterize the system vibration. Even though there are infinitely many arrangements for deformable body axes, computational difficulties may be encountered due to the use of a limited number of deformation modes. Therefore, the deformable body references have to be carefully selected, and accordingly as the system topology changes, new bases for the configuration space have to be identified. In order to guarantee a smooth transition from one configuration space to another, a set of spatial interface conditions or compatibility conditions that are formulated using a set of nonlinear algebraic equations are developed. The solution of these equations uniquely define the spatial configuration of the deformable multibody system after the change in the system kinematic structure. The techniques proposed in this research are applied to several technological systems such as robotic manipulators and weapon systems.

1. INTRODUCTION

The objective of the proposed research is development of methods for the spatial kinematic and dynamic analysis of deformable multibody systems with intermittent motion. Intermittent motion may be defined as motion in which sudden or violent events occur which are traditionally characterized by discontinuities in force, velocity, mass or sudden imposition or release of kinematic constraints. Many industrial and technological systems such as robotic manipulators, walking machines, and space structures are subjected to a change in their kinematic structure during the functional operations. Mass captures, mass releases, and sudden additions or deletions of mechanical joints are possible sources of these mechanical structure changes. Current methodology for the dynamic analysis of multibody systems with variable kinematic structure calls for the division of the time domain into a connected set of subintervals. Over each subinterval, a new set of kinematic constraints are defined and accordingly the system configuration is identified using different sets of generalized coordinates. As time progresses, different sets of constraint equations are imposed, thus the dimension and rank of the system constraint Jacobian matrix depend on time, and accordingly a sequence of configuration spaces which have different dimension and basis has to be defined. The trajectories prescribed by different bodies in the multibody system, then, depend on a set of degrees of freedom that has variable dimension. Moreover, at points in time at which kinematic constraints are added or deleted, these trajectories have corners, which may be divided into two categories; rest point and true corner [1]. A "rest point" is defined to be a corner which occurs only when the system is fully at rest, i.e., when the total generalized velocity vector of the system vanishes. This may characterize one type of change in the kinematic structure when a smooth transition from one configuration space to another occurs. Another typical change in the kinematic structure, however, results in "true corner" because of impacts between system components and accordingly jump discontinuities in the system velocity vector occurs. In the

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problem under investigation. as time advances, a set of constraints may be added or deleted on the boundary of the flexible bodies in the system. This, in turn, may require the use of a new set of vibrational modes and accordingly the imposition of a new set of reference conditions [2]. In order to preserve the continuity of the motion of the system components, a set of interface conditions which allow a smooth transition from one configuration space to another have to be defined. These interface conditions which are formulated using a set of nonlinear algebraic equations that depend on the system reference and elastic coordinates are also used to select and define the location and orientation of new references for the deformable bodies. Therefore the number of these interface conditions must be equal to the number of the body reference coordinates.

2.   STATEMENT OF THE PROBLEM

Several basic problems of multibody system design have been solved during the last few years. Most of the investigations were concerned with the dynamic behavior of multibody systems containing rigid links and accordingly the effect of elastic deformation on the dynamic behavior of multibody systems has not been fully investigated. Quite often, it is desirable to build light weight mechanical and structural systems which operate at very high speed. The choice of the kinematic and dynamic parameters for the mechanical systems is greatly influenced by the flexibility of the system components. It is the objective of this research to develop techniques for the spatial kinematics and dynamic analysis of multibody systems that are subject to change in the kinematic structure during their functional use. The multibody systems are assumed to consist of a set of interconnected rigid and deformable bodies that undergo large translational and rotational displacements. Deformations in the system joints as well as the coupling between the rigid body motion and the elastic deformation is considered in the computer-based analysis techniques developed in this research. Points in time at which corners occur are monitored using a logical function that depends on the system generalized coordinates, velocities, and possibly on time [3-5]. If at these points the system experiences a change in its kinematic structure, a new set of

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kinematic constraints and accordingly a new set of system degrees of freedom are defined. In order to preserve the continuity of the curves describing the system configuration, a set of spatial interface conditions that define the location and orientation of the newly selected body reference are developed and imposed. These interface conditions which are formulated using a set of nonlinear algebraic equations guarantee a smooth transition from one configuration space to another. If the system at this corner is subjected to impacts (true corner), a set of generalized impulse-momentum equations [3-5] are formulated and solved in order to define the jump discontinuities in the system velocity vector as well as the generalized impulse of the system reaction forces.

3. BRIEF OUTLINE OF RESEARCH FINDINGS

In this research project several problems related to the dynamics of spatial deformable multibody systems with variable kinematic structure were examined. The research effort was focused on the analysis of impact and intermittent motion as well as flexible body modeling.

Intermittent Motion: Several basic problems in the spatial dynamics of deformable multibody systems with variable kinematic structure are examined and solved in this research project. A detailed analysis for the formulations, applications and numerical results are presented in the papers listed in Section 4. The tasks accomplished in the area of intermittent motion can be briefly summarized as follows:

(1) A pieced interval analysis scheme that accounts for the change in the spatial system topology due to the change in the connectivity between bodies is developed [4.3]. In order to guarantee a smooth transition from one configuration space to another, a set of spatial interface conditions or compatibility conditions are developed.

(2) A velocity transformation method that can be used to predict the jump discontinuities in the joint reaction forces as the result of the change in system topology is developed [4.4]. The analysis presented in Refs. 4.3 and 4.4 are used to study the spatial dynamics of the Cincinnati Milacron T3 robot.

(3)   The validity of using the generalized impulse momentum equations that involve the coefficient of restitutions and the constraint Jacobian matrix has been examined [4.13]. It was shown in Ref. 4.13 that the generalized impulse momentum equations can be used with confidence to study the propagation of elastic waves in constrained multibody systems.

(4)   A method for the impact analysis of nonholonomic spatial deformable multibody system is developed [4.1, 4.2]. A set of generalized impulse momentum equations that involve the coefficient of restitution and the Jacobian matrices of the holonomic and nonholonomic constraint equations are developed. The techniques developed in Refs. 4.1 and 4.2 are applied to study the dynamics of robotic manipulators and multibody helicopter systems which are subject to impact loading.

(5)   The relationships between the generalized and actual forces in deformable body dynamics are defined [4.6]. These relationships are used to study the effect of impact on the connection forces in high cyclic rate flexible mechanism such as the MK 19 machine gun.

(6)   A comparison between different numerical techniques for solving the equations of motion of holonomic and nonholonomic multibody systems is presented   [4.9]

Flexible Body Modeling. In multibody systems with variable kinematic structure, the flexibility can have a significant effect on the dynamic response of the system. Several studies have been made in this research project in order to better understand the coupling between the rigid body motion and the elastic deformation. These studies can be briefly described as follows:

(1)   A set of generalized Newton Euler equations that account for the coupling between the rigid body motion and the elastic deformation are developed and presented in a closed form [4.11].

(2) A recursive Lagrangian formulation is developed for the dynamic analysis of open loop deformable multibody systems[4.5].

(3) A comparison between the use ot the finite element method and classical approximation techniques in the nonlinear dynamics of multibody systems is presented [4.10].

(4) The invariants of motion that define the coupling between the rigid body motion and the elastic deformation are developed for the constant strain triangular elements [4.7] and for rectangular plates [4.14].

(5) The effect of the small initial curvature on the dynamic response of curved beams that undergo finite rotations is examined [4.8, 4.12, 4.15]. It was shown in these investigations that the coupling between the axial and bending displacements as the results of the initial curvature can be significant.

4. LIST OF PUBLICATIONS

1. Rismantab-Sany, J. and Shabana, A.A., "Impulsive Motion of Nonholonomic Multi-Body Systems, Part I: Kinematic and Dynamic Equations," Journal of Sound and Vibration, Vol. 127, No. 2, 1988, pp. 193-204.

2. Shabana, A A and Rismantab-Sany, J., "Impulsive Motion of Nonholonomic Multi-Body Systems, Part II: Impact Analysis," Journal of Sound and Vibration,, Vol. 127, No. 2, 1988, pp. 205-219.

3. Chang, C.W. and Shabana, A.A., "Spatial Dynamics of Deformable Multi-Body Systems with Variable Kinematic Structure, Part I: Dynamic Model," ASME Journal of Mechanisms Transmissions and Automation in Design, to appear.

4. Chang, C.W. and Shabana, A.A., "Spatial Dynamics of Deformable Multi-Body Systems with Variable Kinematic Structure, Part II: Velocity Transformation," ASME Journal of Mechanisms, Transmissions, and Automation in Design, to appear.

5. Changizi, K. and Shabana, A.A., "A Recursive Formulation for the Dynamic Analysis of Open Loop Deformable Multi-Body Systems," ASME Journal of Applied Mechanics, Vol. 55, Sept. 1988, pp. 687-693, presented also at the 109th ASME Winter Annual Meeting, Nov. 28-Dec. 2, 1988, Chicago, Illinois.

6. Shabana, A. and Chang, C.W., "Connection Forces in Deformable Multibody Dynamics," International Journal of Computers and Structures, to appear.

7. Shabana, A. and Niamathullah, S.K., "Total Lagrangian Formulation for Large Displacements Analysis of the Triangular Finite Elements," Computer Methods in Applied Mechanics and Engineering, Vol. 72, 1989, pp. 195-199.

8. Bartolone, D.F. and Shabana, A., "Effect of Beam Initial Curvature on the Dynamics of Deformable Multibody Systems," Mechanism and Machine Theory, to appear.

9. Rismantab-Sany, J. and Shabana, A., "On the Numerical Solution of Differential and Algebraic Equations of Deformable Mechanical Systems Subject to Nonholonomic Constraints," International Journal of Computers and Structures, to appear.

10. Shabana, A., "On the Use of the Finite Element Method and Classical Approximation Techniques in the Nonlinear Dynamics of Multibody Systems," The International Journal of Nonlinear Mechanics, to appear, also presented at the second conference on Nonlinear Vibrations, Stability, and Dynamics of Structures and Mechanisms, Blacksburg, VA, June 1-3, 1988.

11. Shabana, A., "Dynamics of Flexible Bodies Using Generalized Newton-Euler Equations," ASME Journal of Dynamic Systems, Measurement and Control, to appear.

12. Chen, Da Chih and Shabana, A.A., "Effect of the Coupling Between the Longitudinal and Transverse Displacements on the Dynamics of Rotating Curved Beams," ASME Journal of Applied Mechanics, to appear.

13. Rismantab-Sany, J. and Shabana, A., "On the Use of the Momentum Balance in the Impact Analysis of Constrained Elastic Systems," ASME Journal of Vibration and Acoustics, to appear.

14. Chang, B. and Shabana, A.A., "Total Lagrangian Formulation for the Large Displacement of Rectangular Plates," International Journal for Numerical Methods in Engineering, to appear.

15. Gau, W.H. and Shabana, A.A., "Effects of Shear Deformation and Rotary Inertia on the Nonlinear Dynamics of Rotating Curved Beams," ASME Journal of Vibration and Acoustics, to appear.

5. **LIST OF PARTICIPATING SCIENTIFIC PERSONNEL**

    Several graduate research assistants have contributed to the completion of this project. Their names and the advanced degrees earned by them while employed on this project are:

1. J. Rismantat-Sany, Ph.D., Fall 1989
2. K. Changizi, Ph.D., Fall 1989
3. Y.L. Hwang, Ph.D., expected to finish in Fall 1991
4. D.F. Bartolone, M.S. degree, Winter 1988
5. W.H. Gau, M.S. degree, Fall 1988, currently working on his Ph.D. degree
6. D.C. Chen, M.S. degree, Winter 1989, currently working on his Ph.D. degree
7. W.C. Hsu, M.S. degree, Winter 1989, currently working on his Ph.D. degree

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2. Agarwal, O.P. and Shabana, A.A., "Dynamic Analysis of Multi-Body Systems Using Component Modes," Computers and Structures, Vol. 21, No. 6, 1985, pp. 303-312.

3. Khulief, Y.A. and Shabana, A.A., "A continuous Force Model for the Impact Analysis of Flexible Multibody Systems," Mechanism and Machine Theory, to appear.

4. Khulief, Y.A. and Shabana, A.A., "Dynamic Analysis of Constrained System of Rigid and Flexible Bodies with Intermittent Motion," Journal of Mechanisms, Transmissions, and Automation in Design, paper No. 84-DET-116.

5. Khulief, Y.A. and Shabana, A.A., "Dynamics of Multibody Systems with Variable Kinematic Structure," ASME Journal of Mechanisms, Transmissions, and Automation in Design, Vol. 108, No. 2, June 1986, pp. 167-175.