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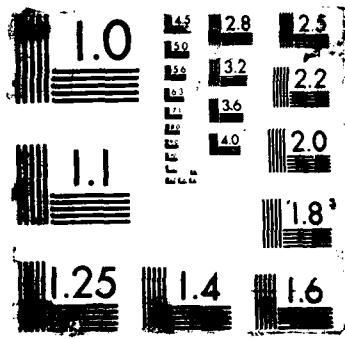
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A unified variational approach to dynamics of flexible multibody systems has been developed and demonstrated on several test problems, including a deployable space structure, flexible manipulators with feedback control, spinning blades, impacting elastic bodies, and a variety of mechanisms. A new recursive formulation was developed for dynamics of flexible multibody systems. This new formulation demonstrated in excess of an order of magnitude speed up in computation, compared to the Cartesian coordinate approach, with comparable accuracy and improved stability. A substructuring formulation that accounts for geometrically nonlinear deformation effects in spinning blades and large space structures was developed and demonstrated, using both the Cartesian coordinate and recursive relative coordinate formulations. The substructure technique was further extended to account for contact-impact effects between structural components. A new formulation of translational joints between flexible bodies was developed, to account for deformation due to sliding contacts.

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**SUMMARY**

A unified variational approach to dynamics of flexible multibody systems has been developed and demonstrated on several test problems, including a deployable space structure, flexible manipulators with feedback control, spinning blades, impacting elastic bodies, and a variety of mechanisms. Reliable results were demonstrated, using a conventional Cartesian coordinate approach. A new recursive formulation was developed for dynamics of flexible multibody systems. This new formulation demonstrated in excess of an order of magnitude speed up in computation, compared to the Cartesian coordinate approach, with comparable accuracy and improved stability. A substructuring formulation that accounts for geometrically nonlinear deformation effects in spinning blades and large space structures has been developed and demonstrated, using both the Cartesian coordinate and recursive relative coordinate formulations. The substructure technique was further extended to account for contact-impact effects between structural components. It demonstrated the capability to approximate wave propagation effects accurately and with reasonable computational cost. A new formulation of translational joints between flexible bodies was developed, to account for deformation due to sliding contacts. The substructuring method developed was shown to be essential in accounting for local deformations due to reaction forces on sliding contact points and surfaces.

## RESEARCH OBJECTIVES

Three principal research objectives were pursued, as follows:

A. A variational formulation of the equations of motion was sought, to provide a unified formulation of equations for multiflexible body systems, to create a general purpose simulation capability, and to support advancements in relative coordinate formulations and numerical integration.

B. An extended articulated structure kinematics formulation was to be developed, using finite element based static correction and vibration modes, an extended library of articulated joints that include translating booms, and a mixed Cartesian-relative coordinate formulation to enhance computational efficiency.

C. Numerical methods were to be developed to integrate differential-algebraic equations of motion. Numerical examples were to be studied to evaluate and guide further development of integration methods and system equation formulation.

## RESULTS OF RESEARCH

Progress on each of the three major project objectives is summarized as follows:

### A. Variational Formulation of Equations of Motion

An integrated variational formulation for the equations of motion of a single body has been derived, using only fundamental principles of virtual work and linear elasticity. This formulation is being used throughout this research and related efforts on flexible body dynamics. A paper presenting this work has been completed and accepted for publication [1]. This variational formulation has been used, under separate funding support by NASA-Langley Research Center, to carry out an analysis of deployment of the COFS articulated structure [6]. While successful results for this complicated

deformable, closed loop articulated structure were obtained with the Cartesian coordinate approach, computational complexity clearly indicates the potential that exists for extending the formulation to relative coordinates, which is discussed in Objective B.

As noted, Cartesian coordinate formulations, while very general, lead to substantial computation overhead. A recently developed rigid body relative coordinate, recursive formulation has been extended to flexible multibody systems [2]. It has demonstrated in excess of an order of magnitude gain in computational efficiency for dynamic analysis of complex articulated structures. This method is expected to be most significant in deployable space structures and in treating substructured models that account for geometric nonlinearity of large space structures. Implementation of the algorithm for a mixed open/closed loop flexible manipulator yielded an efficiency gain of a factor of 25 over a state-of-the-art Cartesian formulation.

Coupling of control elements with dynamics of articulated structures was demonstrated [5]. The recursive, relative coordinate approach demonstrated not only an order of magnitude speed-up, but greater numerical stability than the Cartesian formulation. Numerical experiments were carried out to study the interaction and coupling between control effects and geometrically nonlinear articulated structural dynamics of a manipulator. Extension of control implementation with the recursive relative coordinate formulation yielded excellent results and is ideally suited for high speed computing in a parallel processor environment [7].

## B. Extended Articulated Structure Kinematic Formulation

A method for selecting no more than a statically determinant subset of boundary conditions for each flexible body in an articulated structure was developed, exploiting research results from a related prior project [7]. Well conditioning of equilibrium equations was used as the criterion for selecting from among redundant boundary conditions. The resulting computational algorithm uses geometric data that define kinematic connections on each body to form the coefficient matrix of its equilibrium equations. LU factorization and singular value decomposition are then used to select the best conditioned subset of equilibrium equations, hence defining retained boundary conditions. The method was successfully demonstrated on a variety of examples in Ref. 7.

Deformation mode selection, using the subset of boundary conditions described above, was investigated in Ref. 1, to include use of static correction modes and normal vibration modes. Numerical studies have clearly shown the need for static correction modes, to compliment normal modes of vibration. Very recent numerical experimentation with Ritz modes indicates even greater potential for characterizing deformation modes that are excited due to motion of articulated structures.

A substructuring technique for representing geometrically nonlinear dynamic effects has been developed and demonstrated in Refs. 3 and 7. Accurate predictions are achieved, providing enough substructures and associated moving reference frames are selected. While the method demonstrates feasibility of accounting for geometric nonlinearity due to large component elastic deformation, computational cost associated with use of this technique in a Cartesian coordinate formulation is high. The technique is ideally suited for use with the relative coordinate formulations developed

under this project [2]. Results with this recursive formulation in Refs. 2 and 7 have demonstrated an order of magnitude speed up, over the Cartesian approach used in Refs. 1 and 3.

Impact and variable kinematic structure were investigated, through analysis of several examples in Refs. 4 and 7. Techniques for selection of deformation modes that are capable of capturing wave propagation effects associated with impact and variable structure were developed and demonstrated, with good results.

Formulations of kinematic translational constraints between flexible bodies were developed to include flexible surfaces in joints that move relative to one another in Ref. 8. Three types of translational articulated joints were presented. A new approach was employed to account for translational kinematic couplings between flexible bodies, due to deformation of contacting surfaces. Static correction modes and the substructure synthesis method of Ref. 4, which divides components into substructures and defines local deformation modes on each substructure, was shown to be essential in order to account for deformations induced by reactions in the moving contact points of the translational joints.

### **C. Numerical Methods and Experimentation**

Hybrid numerical integration, dual rate integration, and a variety of methods for selecting deformation modes of articulated structures were investigated. Numerical experience with the examples reported in Refs. 1-8 indicates that, due to inertial coupling in articulated structures and the essential nature of nonlinearities associated with kinematic constraints, the most reliable method of system integration remains use of variable timestep, variable order numerical integration algorithms that provide positive error control for solution reliability.

**PARTICIPATING PROFESSIONALS**

The following professionals participated in research sponsored by the project:

E. J. Haug (Principal Investigator)  
S. C. Wu  
R. S. Hwang  
S. S. Kim  
J. L. Chang

Research carried out under this project led to the award of Ph.D. degrees to S. C. Wu, R. S. Hwang, and S. S. Kim.

## PUBLICATIONS DUE TO PROJECT

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