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**VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY**  
**DEPARTMENT OF ENGINEERING SCIENCE AND MECHANICS**

Final Technical Report on  
**CONTROL OF LARGE SPACE STRUCTURES**  
**WITH VARYING CONFIGURATION**

Covering the Period  
15 April 1989 - 31 August 1992  
on the  
Research Grant F49620-89-C-0045DEF

Submitted to  
Dr. Spencer T. Wu  
Air Force Office of Scientific Research  
12 February 1993

Principal Investigator: Leonard Meirovitch  
University Distinguished Professor

### Abstract

The research has produced significant advances in the state of the art on the following subjects:

- i a mathematical formulation for the maneuvering and control of flexible articulated multi-body systems,
- ii a theory for the modeling of flexible structures and
- iii a perturbation theory for the maneuvering and control of articulated flexible multibody systems.

Two Ph.D. degrees were awarded to graduate students working on the project and two more Ph.D. degrees are expected to be awarded by this fall.

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#### (a) Objectives of the Research

The main objective of the research was the development of a theory permitting design of maneuvers and control for large space structure with configuration varying with time, such as flexible space robots. The research involves several aspects as follows:

- (i) Development of methodology for the derivation of hybrid (ordinary and partial differential) equations for flexible articulated multibodies. A variety of engineering systems, such as aircraft, rotorcraft, robots and spacecraft, can be modeled as flexible multibody systems. The individual flexible bodies are in general characterized by distributed parameters, so that the mathematical formulation consists of hybrid differential equations. The equations for the rigid-body motions are conveniently expressed in terms of quasi-coordinates, which tend to be simpler than the equations in terms of inertial coordinates. It should be pointed out that quasi-coordinates correspond to motions in terms of body-axes components. In the case of rotational motions, these are the familiar pitch, roll and yaw. The partial differential equations correspond to Timoshenko beams bending in two orthogonal planes and including rotatory inertia and shear deformation effects. The partial differential equations are supplemented by appropriate boundary conditions. The hybrid set is conveniently expressed in state form, making it suitable for control design.
- (ii) Development of a modeling technique capable of approximating the elastic deformations of a flexible multibody system with a large degree of accuracy and with as few terms as possible. To this end, a new concept has been created, namely, the quasi-comparison functions, defined as linear combinations of admissible functions capable of satisfying the boundary conditions with only a finite number of terms. The quasi-comparison functions are particularly useful for approximating solutions for flexible multibodies, as closed-form solutions satisfying the differential eigenvalue problems for the individual bodies are not possible, because they are coupled by the boundary conditions. There are

two approaches in common use for modeling flexible multibodies. The most popular one is the finite element method, whereby the solution is approximated over small subdomains (finite elements) by means of interpolation functions, generally taken as low-degree polynomials. The finite element method is relatively easy to implement but has a significant disadvantage in that it requires a very large number of degrees of freedom to achieve reasonable accuracy. The other approach is component mode synthesis, which can be regarded as a Rayleigh-Ritz method. In component mode synthesis, the solution over each of the multibodies is approximated by a linear combination of "component modes" multiplied by generalized coordinates. The main drawback lies in the choice of component modes. The implication of the term "modes" is that they must satisfy a component eigenvalue problem. However, this is not strictly possible, as there is no eigenvalue problem for an individual body that has much significance for the fully assembled system. Indeed, there is no way boundary conditions reflecting the effect of the adjacent bodies can be defined, let alone satisfied. The approach developed in this project proposes to replace component modes by quasi-comparison functions. Quasi-comparison functions represent linear combinations chosen from several families of admissible functions in a way that all possible boundary conditions can be satisfied by merely adjusting the coefficients in the series. Still, the method does not suggest adjusting the coefficients a priori. Indeed, the coefficients are adjusted as a matter of course during a variational process, thus permitting better approximations not only of the boundary conditions but also of the differential equations. Numerical examples demonstrated that the method converges remarkably fast.

- (iii) Development of an approach to the control design for maneuvering articulated flexible multibodies. The difficulty in designing controls for multibody systems lies in the fact that the discretized equations of motion are nonlinear and of large order. The nonlinearity is due to the "rigid-body" maneuvers and the large order due to the elastic effects. Moreover, the maneuvering motions tend to be large and the elastic motions

tend to be small. Consistent with this, a perturbation technique is developed, whereby the equations are separated into a low-order set of nonlinear equations for the maneuvering motions and a high-order set of linear perturbation equations for the elastic motions and perturbations in the rigid-body motions. Design of controls for the maneuvering motions can be carried out independently of the perturbation equations. On the other hand, the maneuvering motions enter into the perturbation equations in the form of time-varying coefficients and persistent disturbances. Various approaches to designing vibration controls are proposed. One approach represents a substructure decentralized control implemented in discrete time. A second approach is suitable for the case in which the time-varying terms are relatively small. According to this approach the control design can be carried out by means of a perturbation technique requiring the solution of a matrix Riccati equation and a matrix Liapunov equation.

#### **(b) Status of the Research Effort**

The research has produced significant advances in the state of the art. In particular, the derivation of the hybrid differential equations of motion for the maneuvering and control of flexible articulated multibody systems described in (i) has been largely completed. The theory for the modeling of flexible multibody systems described in (ii) is also largely completed. The theory has been demonstrated to give extremely accurate results with relatively low computational effort. The perturbation theory described in (iii) has been developed. Due to the magnitude of the task, various aspects of practical implementation of the control design must be investigated yet.

#### **(c) Research Dissemination**

##### *Keynote Lectures*

1. "A Method for Improving the Convergence Characteristics of Substructure Synthesis," *International Symposium on Advanced Computers for Dynamics and Design*, Tsuchiura, Japan, Sept. 6-8, 1989. Second author: M.K. Kwak.

2. "On the Maneuvering and Control of Space Structures," *International Conference on Dynamics of Flexible Structures in Space*, Cranfield, Bedford, UK, May 15-18, 1990. Second author: M.K. Kwak.

#### *Invited Conference Presentations*

1. "A Substructure Synthesis Approach to the Control of Flexible Multi-Body Systems," *ASME 1989 Winter Annual Meeting*, San Francisco, CA, Dec. 11-15, 1989. Second author: M.K. Kwak.
2. "On the Maneuvering of Flexible Multi-Body Systems," *Southeastern Conference on Theoretical and Applied Mechanics*, Atlanta, GA, March 22-23, 1990. Second author: M.K. Kwak.
3. "A Rayleigh-Ritz Based Substructure Synthesis," *Elastic Multibody Systems Symposium*, German National Science Foundation, Oberpfaffenhofen, Germany, Oct. 24-25, 1991.

#### *Journal Publications*

1. "Hybrid State Equations of Motion for Flexible Bodies in Terms of Quasi-Coordinates," *Journal of Guidance, Control, and Dynamics*, Vol. 14, No. 5, 1991, pp. 1008-1013.
2. "Rayleigh-Ritz Based Substructure Synthesis for Flexible Multibody Systems," *AIAA Journal*, Vol. 29, No. 10, 1991, pp. 1709-1719. Second author: M.K. Kwak.
3. "Control of Flexible Spacecraft with Time-Varying Configuration," *Journal of Guidance, Control, and Dynamics*, Vol. 15, No. 2, 1992, pp. 314-324. Second author: M.K. Kwak.
4. "An Inclusion Principle for the Rayleigh-Ritz Based Substructure of Synthesis," *AIAA Journal*, Vol., 30, No. 5, 1992, pp. 1344-1351. Second author: M.K. Kwak.
5. "New Approach to the Maneuvering and Control of Flexible Multibody Systems," *Journal of Guidance, Control, and Dynamics*, Vol. 15, No. 6, 1992, pp. 1342-1353. First author: M.K. Kwak.
6. "State Equations for Maneuvering and Control of Flexible Bodies Using Quasi-Momenta," *Journal of Guidance, Control, and Dynamics* (to appear).

7. "An Algorithm for the Computation of Optimal Control Gains for Second-Order Matrix Equations," *Journal of Sound and Vibration* (to appear). First author: M.K. Kwak.

#### **Contributed Conference Presentations**

1. "Control of Flexible Spacecraft with Time-Varying Configuration," *AAS/AIAA Astrodynamics Conference*, Stowe, VT, Aug. 7-10, 1989. Second author: M.K. Kwak.
2. "On the Modeling of Flexible Multi-Body Systems by the Rayleigh-Ritz Method," *AIAA Dynamic Specialist Conference*, Long Beach, CA April 5-6, 1990. Second author: M.K. Kwak.
3. "Dynamics and Control of Flexible Space Robots," *Canadian Society of Mechanical Engineers Forum 1990*, Toronto, Ontario, Canada, June 3-9, 1990. Second and third authors: T. Stemple and M.K. Kwak.
4. "An Algorithm for the Computation of Optimal Control Gains for Second-Order Matrix Equations," *AIAA Guidance, Navigation and Control Conference*, Portland, OR, Aug. 20-22, 1990. First author: M.K. Kwak.
5. "An Inclusion Principle for the Rayleigh-Ritz Based Substructure Synthesis," *AIAA/ASME/ASCE/AHS/ASC 32nd Structures, Structural Dynamics, and Materials Conference*, Baltimore, MD, April 8-10, 1991. Second author: M.K. Kwak.
6. "A New Approach to the Equations of Motion for the Maneuvering and Control of Flexible Multi-Body Systems," *AIAA/ASME/ASCE/AHS/ASC 32nd Structures, Structural Dynamics, and Materials Conference*, Baltimore, MD, April 8-10, 1991. First author: M.K. Kwak.
7. "Maneuvering and Control of Flexible Space Robots," *Eighth VPI&SU Symposium on Dynamics and Control of Large Structures*, Blacksburg, VA, May 6-8, 1991, First author: M.K. Kwak.
8. "State Equations for Maneuvering and Control of Flexible Bodies in Terms of Quasi-Momenta," *AIAA Guidance, Navigation and Control Conference*, New Orleans, LA, Aug. 12-14, 1991.

9. "Trajectory and Control Optimization for Flexible Space Robots," *AIAA Guidance, Navigation and Control Conference*, Hilton Head, SC, August 10-12, 1992, Second author: Y. Chen.

**(d) Professional Personnel**

The professional personnel associated with the research consisted of the principal investigator, an assistant professor (formerly a graduate student) and several graduate students.

*Ph.D. in Engineering Mechanics*

1. 1989, M.E.B. France, Dissertation title: "Discrete-Time Control of a Spacecraft with Retargetable Flexible Antennas"
2. 1989, M.K. Kwak, Dissertation title: "Dynamics and Control of Spacecraft with Retargeting Flexible Antennas"

Dr. Kwak continued as an assistant professor and research associate until the spring of 1992.

3. Y. Chen expects her degree by summer.
4. T.J. Stemple expects his degree by fall.