GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-20-621 R-5903-0A0 GTRC/~~GIT~~ DATE 3 / 13/ 85

Project Director: Dr. S. N. Atluri School/~~Lab~~ Civil Engineering

Sponsor: AFOSR Bolling AFB, DC

Type Agreement: Grant 84-0020 Amendment A

Award Period: From 12/1/84 To 11/30/86 (Performance) 1/30/86 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$
Funded:	$ 94,241	$ 182,260

Cost Sharing Amount: $ 15,056 Cost Sharing No: E-20-385 (F-5903-0A0)

Title: Studies of Control Dynamics and Modeling Problems in Large Space Structures.

ADMINISTRATIVE DATA

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Defense Priority Rating: N/A

Military Security Classification: N/A

(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT - See Page 2 of Grant Award

COMMENTS:

Equipment acquisition authorization on page 2 of Grant.

Additional Reporting Requirements on Page 3 of Grant.

COPIES TO:

SPONSOR'S I. D. NO. 02.104.001.85.001

Project Director	Procurement/EES Supply Services	GTRC
Research Administrative Network	~~Research~~ Security Services	Library
Research Property Management	Reports Coordinator (OCA)	Project File
Accounting	Research Communications (2)	Other A. Jones

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 04/30/90

Project No. E-20-621 Center No. R5903-0A0

Project Director ATLURI S N School/Lab CE

Sponsor AIR FORCE/BOLLING AFB, DC

Contract/Grant No. AFOSR-84-0020 Contract Entity GTRC

Prime Contract No.

Title STUDIES OF CONTROL DYNAMICS & MODELING PROBLEMS IN LARGE SPACE STRUCTURES

Effective Completion Date 861130 (Performance) 870130 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	870921
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

CommentsCONTINUED BY E-20-642.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

Final Technical Report

Dynamics and Control of Large Space Structures

Submitted to

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January 30, 1987

I. INTRODUCTION

In the following pages, a brief summary of research progress on the current AFOSR grant 84-0020B is given. The specific areas of accomplished research are: (i) Reduced-order nonlinear models for space-trusses and frames; (ii) Singular-solution approaches for control of continuum models of LSS; (iii) algorithms for feed-back control of nonlinear dynamic response; (iv) phenomenological constitutive models for rate-dependent hysteritic damping in space-structure joints.

A significant achievement has been the design of a balsa-wood bridge by undergraduate students at Georgia Tech, based on the methodology for simplified nonlinear analysis of space-frames as developed under the present AFOSR grant. This design has won the first-prize in a recent ASCE national competition.

A summary of each item of accomplished research is provided, followed by a list of archival publications documenting the technical details of the accomplished research.

II. SUMMARY OF ACCOMPLISH RESEARCH

(i) Reduced Order Nonlinear Models for Space-Trusses and Space-Frames:

- Present methodology results in discrete models that have about 30 times fewer degress of freedom than from using standard assumed displacement finite element methods.

- Exact (closed-form) expression for the tangent stiffness matrix of a finitely-deformed space-truss and of each of its members

- Each truss-member carries axial force, and undergoes large deformation (rotation).

- Effect of local-buckling of each truss-member is accounted for. Significant alteration of the global behavior of truss is noted when active-control is used to prevent local-buckling.

- Exact (closed-form) expression for the tangent stiffness matrix of a finitely-deformed space-frame and each of its members.

- Each frame-member resists axial force, bending and torsion; and undergoes large stretch and rotation.

- Effect of Material Nonlinearity, through the formatin of plastic-hinges is accounted for, exactly.

- Effects of active-control to prevent local buckling are studied in detail.

(ii) Singular-Solution Approach for Control of Continuum Models of LSS:

- Equivalent Plate and Shell-type continuum models of LSS are considered.

•Reduced-order discrete models for large deformation (and rotations) of plate and shell type continuua are studied.

•Fundamental solutions in infinite space for the highest-order linear differential operator of the nonlinear problem are derived.

•Unsymmetric Variational Statements and Petro-Galerkin Methods are used to derive integral-representations for nonlinear plate and shell behavior.

•New methodology - "field-boundary-element method", is used to derive tangent stiffness matrices for plates and shells.

•Present methodology leads to discrete models having about <u>30 times fewer degrees of freedom than standard finite element methods</u>.

•Present method yields 1 % accuracy of 3 times more eigenvalues of vibration for the same number of degrees-of-freedom than standard finite element method.

•Present reduced-order models are found to be very efficient in nonlinear transient dynamic analysis as compared to standard finite element methods.

(iii) <u>Algorithms for Feed-back Control of Nonlinear Dynamic Response</u>:

- Simple algorithms for active feed-back control of nonlinear transient dynamic response of LSS are successfully developed.

- Reduced-order models are used to develop semi-discrete ordinary differential equations for the problem of control of nonlinear dynamic motion.

- Optional control laws are developed for the <u>nominally</u> linear system.

- New and efficient algorithms are developed for solving the Riccati equation for the feed-back gain matrix.

- The same feed-back gain matrix is used for designing controllers, with feed-back based on the <u>sensed nonlinear state</u>.

- Present algorithms for controlling nonlinear motion are found to be asymptotically stable.

- Present methodology was successfully applied to <u>study of active control, through using piezo-ceramic liners, of nonlinear dynamic response of structures</u>.

- Present algorithms are successfully verified in the control of <u>nonlinear dynamic motion of plate and shells</u>.

(iv) Phenomenological Constitutive Models for Rate-Dependent Hysteritic Damping in Space-Sturctuve Joints:

- Models for $F(\ast, \dot{\ast})$, where F is the force, and $\ast$ and $\dot{\ast}$ are joint relative displacement and velocity repectively, are developed.

- Phenomenological constitutive model for joint hysterisis is analogous to rate-sensitive viscoplastic behavior of solids.

- Unlike continuum viscoplastic relations, present models for hysterisis have no loading/unloading criteria. One function $F(\ast, \dot{\ast})$ applies throughout, with only a sign of $\dot{\ast}$ being considered.

- Possibility of Chaotic motion due to presence of nonlinear hysterisis being studied.

- Extension of one-dimensional joint-friction model for $F(\ast, \dot{\ast})$, is being extended to 3-dimensional, multi-degree-of-freedom LSS joints.

- Efficient algorithms for solving Semi-discrete equations in the presence of hysteritic passive-control forces are being developed.

(v) First-Prize Award in ASCE Bridge-Design Contest, Using Mehtodology Developed for LSS Nonlinear Analysis:

- The details of Georgia Tech's winning design, based on the Methodology for LSS Nonlinear Analysis developed under AFOSR support, are published in the September 1986 issue of CIVIL ENGINEERING (magazine of ASCE). This article is enclosed herewith.

•ASCE contest specified a Balsa-wood bridge (3-dimensional) design, with a maximum load-carrying capacity versus self-weight ratio.

•Program developed for LSS nonlinear analysis, with exact tangent stiffness for space-frames and space-trusses was used in the bridge design.

•The LSS nonlinear analysis program was interfaced with an IBM-CAD system, to carry out interactive analysis/design. Present Reduced Order Model Strategy resulted in dramatic efficiency.

•Nonlinear behavior of bridges was analyzed in the post-buckling range, interactively. Design optimization was then achieved iteratively.

•Continuous-tension-arch concept was successfully employed.

•Large deformations and rotations are treated very simply.

•The winning design of Balsa-wood bridge from Georgia Tech carried 886 pounds at global buckling, with a self-weight of 81.7 grams. The second place design from elsewhere carried 388 pounds with a self-weight of 76.7 grams.

III. LIST OF ARCHIVAL PUBLICATIONS

The research completed under the current grant is documented in the following references, copies of which have been made available to AFOSR.

1. P. E. O'Donoghue, and S. N. Atluri, "Control of Transient Dynamic Response of Structures", Invited Paper, Proc. International Conf. on Numerical Methods in Engineering: Theory and Application, Swansea (G. N. Pande and J. Middleton, Eds.) Jan. 1985, pp.13-27.

2. P. E. O'Donoghue, and S. N. Atluri, "Servo-Elastic Oscillations: Control of Transient Dynamic Motion of a Plate", in Advances in Aerospace Sciences and Engineering (U. Yuceoglue and R. Hesser, Eds.) ASME AD-08, NY, pp.139-149.

3. S. N. Atluri, "Computational Solid Mechanics: Present Status and Future Trends" Proc. 4th International Conf. on Applied Numerical Modeling. (H. M. Hsia, et al., Eds.) 1984, pp.19-37.

4. P. E. O'Donoghue, and S. N. Atluri, "Control of Dynamic Response of a Continuum model of a Large Space Structure" AIAA 26th SDM Conf. Orlando, FL.

5. P. E. O'Donoghue, and S. N. Atluri, "Control of Dynamic Response of a Continuum model of a Large Space Structure" Computers and Structures Vol.

6. K. Kondoh, K. Tanaka, and S. N. Atluri, "An Explicit Expression for the Tangent-Stiffness of a Finitely Deformed 3-D Beam and Its Use in the Analysis of Space Frames" Computers and Structures (In Press).

7. K. Tanaka, K. Kondoh, and S. N. Atluri, "Instability Analysis of Space Trusses Using Exact Tangent-Stiffness Matrices" Finite Elements in Analysis & Design Vol. 1, No. 4, 1985, pp. 291-311.

8. K. Kondoh, S. N. Atluri, "Large-Deformation, Elasto-Plastic Analysis of Frames Under Nonconservative Loading, Using Explicitly Derived Tangent Stiffnesses Based on Assumed Stresses" Computational Mechanics (In Press).

9. S. N. Atluri, J.-D. Zhang, and P. E. O'Donoghue, "Analysis and Control of Finite Deformations of Plates and Shells: Formulations and Interior/Boundary Element Algorithms" Finite Element Analysis of Shell: Formulations & Algorithms. (T. J. R. Hughes & E. Hinton, Eds.) Pineridge Press, U.K. (In Print).

10. K. Kondoh, and S. N. Atluri, "Influence of Local Buckling on Global Instability: Simplified Large Deformation, Post-Buckling Analysis of Plane Trusses" Computers & Structures Vol. 24, No.4, 1985, pp.613-626.

11. K. Kondoh, and S. N. Atluri, "A Simplified Finite Element Method for Large Deformation, Post-Buckling Analysis of Large Frame Structures, Using Explicitly derived Tangent Stiffness Matrices" Int. Jrl. of Num. Meth. in Engg. Vol. 23, No. 1, pp.69-90, 1985.

12. J.-D. Zhang, and S. N. Atluri, "A Boundary/Interior Element Method for Quasi-static and Transient Response Analyses of Shallow Shells" Computers and Structures (In Print).

13. P. E. O'Donoghue, "A Singular Solution Approach for the Control of Dynamic Response of a Large Space Structure" Ph. D. Thesis, Georgia Tech, Dec. 1985.

14. S. N. Atluri, "Computational Mechanics & Control of Finite Deformations" Keynote Lecture, Proc. 4th International Conf. on Numerical Methods in Engineering. (R. P. Shaw, et al., Eds.) March 1986, Atlanta, GA.

15. S. N. Atluri, "Control Of Finite Deformations of Inelastic Solids" Invited General Lecture, "Finite Element Theory and Application Workshop", July 28-30, 1986, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center.

16. J.-D. Zhang and S. N. Atluri, "Analysis and Control of Nonlinear Response of Shells: An Interior/Boundary Element Approach" Proc. Int. Conf. on Boundary Element Methods in Engineering, New Orleans, Sept. 1986.

17. S. N. Atluri, "Field/Boundary Element Methods for Control of Nonlinear Dynamic Response of Plates & Shells" Proc. IUTAM Symp. on Boundary Integral Methods (T. A. Cruse, Ed.) Southwest Research Institute, San Antonio, TX, March 1987.

18. S. N. Atluri, "Nonlinear Response & Control of Space Structures", Lectutes delivered at: (i) M.I.T., March 31, 1986, (ii) University of Rhode Island, April 2, 1986, (iii) Boston University, April 3, 1986, (iv) University of Florida, April 9, 1986.

19. S. N. Atluri, "Control of Space Structures", Lectures at a five day intense seminar, "Finite and Boundary Element Methods", Advances in Computational Methods for Structural Mechanics, Aug. 18-22, 1986.

20. S. N. Atluri, "Reduced-order Modeling Techniques for Control of Large Space Structures", Proc. Third Forum on Space Structures, Texas A&M, July 8-10, 1985.

21. P. E. O'Donoghue, and S. N. Atluri, "Large Deformation & Control Analysis of Plates", Computational Mechanics (In Press).

22. P. E. O'Donoghue, and S. N. Atluri, "A Singular Solution Approach for Controlling the Nonlinear Response of a Continuum Model of a Large Space Structure", paper 86-0841, 27th Structures, Structural Dynamics & Material Conf., May 19-21, 1986, San Antonio, TX.

23. G. Y. Shi, and S. N. Atluri, "Distributed Control of Nonlinear Motion of a Space Frame" Computers and Structures (In Press).

Ph. D. Disserations

1. P. E. O'Donoghue, "Control of Large-Deformation Dynamic Motion", Ph.D. Thesis, November, 1985.

2. J.-D. Chang, "Control of Nonlinear Motion of Shells; and Combined Structural Optimization/Control" Ph.D. Thesis, June 1987 (Expected).

3. G. Y. Shi, "Joint Design, Nonlinear Damping, and Control of Travelling Waves in Space-Frames", Ph.D. Thesis, In Progress.