REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE 20 JULY 2004

3. REPORT TYPE AND DATES COVERED
Annual Progress Report 9/1/03-7/31/04

4. TITLE AND SUBTITLE
Vibration Analysis and Control of an Inflatable Structure Using Smart Materials

5. FUNDING NUMBERS
F49620-03-1-0163

6. AUTHOR(S)
Daniel J. Inman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Center for Intelligent Material Systems and Structures
310 Durham Hall, Virginia Tech
Blacksburg, VA 24061-0261

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research
DTIC-OCP, 8725 John J. Kingman Road, Suite 0944
Fort Belvoir, VA 22060-6218

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Air Force Office of Scientific Research position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Lightweight inflatable structures, or Gossamer spacecraft, are very attractive in aerospace applications for several reasons. These structures pose difficult problems, however, in modeling and in control due to their special geometry and material properties. Initially, the proposed work was to examine the nonlinear structural dynamics of an inflated torus with a membrane attached to it for the purpose of providing suitable models for the application of nonlinear control. This work/award commenced in April 2003. In March 2004, after a site visit by the AFOSR Program Manager, the focus of this effort was changed to correspond more closely with AFRL interests. In particular, after conversations with AFRL/DEBS and AFRL/VSSV, both of Kirtland AFB, the focus of the proposed effort was changed to examine the structural dynamics of a pressurized membrane with the goal of providing a sound modeling and theoretical understanding of the coupled structure, fluid, optical and control hardware of AFRL/DEBS's proposed system. The following is a brief report of our activities over 11 months of funding. The section numbers correspond to the categories requested on the AFOSR website for progress reports.

14. SUBJECT TERMS
inflatables, smart structures, ultraflexible spacecraft, nonlinear vibrations and control, structural dynamics

15. NUMBER OF PAGES
7

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

BEST AVAILABLE COPY

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

20040809 040

Annual Progress Report
August 1, 2004
on

VIBRATION ANALYSIS AND CONTROL OF AN INFLATABLE STRUCTURE USING SMART MATERIALS

(AFOSR Grant No. F49620-03-1-0163)

Daniel J. Inman
G. R. Goodson Professor and Director
Center for Intelligent Material Systems and Structures
Department of Mechanical Engineering
310 Durham Hall, Mail Code 0261
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0261
Phone: 540-231-4709 Fax: 540-231-2903
http://www.cimss.vt.edu, email: dinman@vt.edu

Abstract
Lightweight inflatable structures, or Gossamer spacecraft, are very attractive in aerospace applications for several reasons. These structures pose difficult problems, however, in modeling and in control due to their special geometry and material properties. Initially, the proposed work was to examine the nonlinear structural dynamics of an inflated torus with a membrane attached to it for the purpose of providing suitable models for the application of nonlinear control. This work/award commenced in April 2003. In March 2004, after a site visit by the AFOSR Program Manager, the focus of this effort was changed to correspond more closely with AFRL interests. In particular, after conversations with AFRL/DEBS and AFRL/VSSV, both of Kirtland AFB, the focus of the proposed effort was changed to examine the structural dynamics of a pressurized membrane with the goal of providing a sound modeling and theoretical understanding of the coupled structure, fluid, optical and control hardware of AFRL/DEBS's proposed system. The following is a brief report of our activities over 11 months of funding. The section numbers correspond to the categories requested on the AFOSR website for progress reports.

2. Objectives
Initially, our objectives were to further investigate the dynamics and control of ultra-flexible satellite components, building upon our previous AFOSR grant, and focusing on an inflated torus with a reflective surface mounted in it. Currently, our objectives are: a) to derive the equations of motion for a pressurized membrane, with boundary controllers and distributed controllers coupled to Zernicke Polynomials; and b) to formulate a spline-based approximation of the governing equations suitable for use with a modern control algorithm. In addition, we hope to design and implement an experimental apparatus for the verification and validation of the model.

3. Status of Effort

For our initial objective, we had constructed an experimental model of a generic torus system with reflective surface as a base line for researching the smart materials applicability to vibration suppression of flexible satellites and providing an experimental test bed for our nonlinear analysis. We integrated patches of Macro Fiber Composite (MFC) actuators and sensors into the torus and started some initial modeling. We have performed initial experiments using this system to identify key nonlinearities.

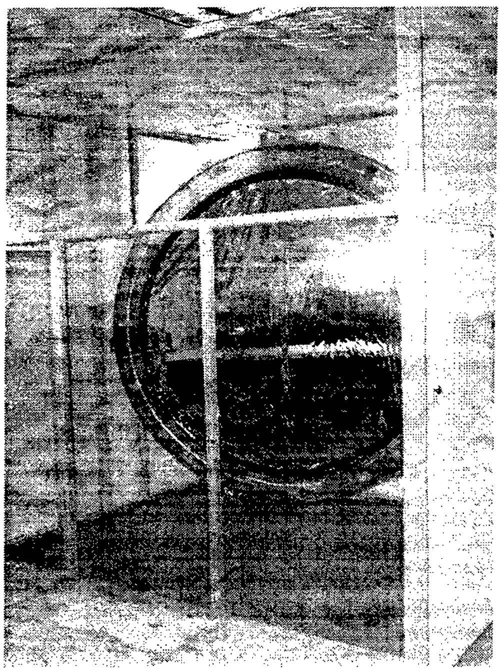

Figure 1 The inflated Torus test facility with smart sensors and actuators and reflective surface. The glass enclosure is to limit air currents from vibrating the torus-membrane system, which is freely suspended from the ceiling.

We also have obtained some preliminary experimental results indicating nonlinear behavior. If the mode is non-linear, then the frequency and width of the modal peak may vary tremendously depending on the level of excitation. Significant nonlinear behavior is observed for high levels of actuator excitation, as reported last year.

We also developed a new method of model updating taking into consideration the physical connectivity of the finite element model. With this analysis complete, we are attempting now to use this approach to improve the analytical model of the torus system using experimental data to derive corrections to the model.

Regarding the new focus, we have began to formulate the initial models of a membrane loaded with a controllable pressure and boundary controls. We are currently focusing on coupling the Zernicke Polynomials with the pressure distribution through the membrane layer.

4. Accomplishments

The accomplishments are delineated in the articles referenced below. The following summarizes these (numbers refer to papers listed below). In order to gain an appreciation for the dynamics of an inflated structure, many tests were made to determine as much of the dynamics as possible. A MIMO test was reported in J1 and extended to a torus with a reflector in J2. The results in J3 point out how the integrated smart materials used for the dynamic ground testing can also be used to perform successful vibration suppression once launched. The results of J4 expand those of our previous work to take into consideration the fact that if an ultra flexible spacecraft is controlled with too few actuators, only local vibration suppression is achieved. With too few actuators, the effect is to reduce the vibration by pushing the motion from one location to the next, rather than globally suppressing vibrations.

In J5, the nonlinear nature of the preload on the torus skin is recognized and a sliding mode controller is designed to illustrate that vibration suppression using smart materials, operating in largely a linear range can be used to keep the inflated torus from vibrating due to external disturbances.

In J6, several of the details of using a specific actuation device, the Macro Fiber Composite (MFC) actuator, for both sensing and actuation is investigated and its suitability for use with inflated structures is presented. In J7, optimal size and location of piezoelectric-based actuation and sensing is presented.

In J8, the importance of the geometric nonlinearity in the pressurized torus system is defined and analyzed.

In C4, a new method of model updating is defined. This method was invented to help us correct our finite element modeling by deriving correction factors based on the experimentally-measured modal information (undamped). We have not yet applied this to our torus data, however.

5. Personnel Supported

Faculty: Daniel J. Inman
Post Docs: none
Graduate Students: Pablo Tarazaga, Eric Ruggerio
Visitors: None
Undergraduates: Eddie Simmers, Justin Greene

6. Publications:

This section list publications to date resulting from this funding (just this year).

Journal Articles:

1. Ruggiero, Eric J., Gyuhae Park, and Daniel J. Inman, 2004, "Multi-Input Multi-Output Vibration Testing of an Inflatable Torus," *Mechanical Systems & Signal Processing*, Vol. 18, Issue 5, September, pp. 1187-1201.

2. Ruggiero, Eric J. and Daniel J. Inman. "A Comparison Between SISO and MIMO Modal Analysis Techniques on a Membrane Mirror Satellite," *Journal of Smart Material Systems and Structures (Special Edition)*, accepted May 2004.

3. Ruggiero, Eric J. and Daniel J. Inman. "Gossamer Spacecraft: Recent Trends in Design, Analysis, Experimentation, and Control," *Journal of Spacecraft and Rockets*, submitted February 2004.

4. Sodano, H. A., Park, G., and Inman, D. J. 2004. "Vibration Testing and Control of an Inflatable Torus Using Multiple Sensors/Actuators," *AIAA Journal of Spacecraft and Rockets*; in press.

5. Jha, A. and Inman, D.J., 2004. "Sliding Mode Control of an Ultralight Inflatable Structure Using Smart Materials," *Journal of Vibration and Control*; in press.

6. Sodano, H. A., G. Park, and D. J. Inman, 2004. "An Investigation into the Performance of Macro-Fiber Composites for Sensing and Structural Vibration Applications," *Mechanical Systems and Signal Processing*; Vol. 18, pp. 683-697.

7. Jha, A. and Inman, D.J., "'Optimal Size and Placement of Piezoelectric Actuators and Sensors for an Inflated Torus," *Journal of Intelligent Material Systems and Structures*; in press.

8. Jha. A. and D. J. Inman, "Importance of Geometric Nonlinearity and Follower Pressure Load in the Dynamic Analysis of a Gossamer Structure," *Journal of Sound and Vibration*; in press.

Conference Papers:

1. Ruggiero, Eric J., Garret Bonnema, and D. J. Inman. "Application of SISO and MIMO Modal Analysis Techniques on a Membrane Mirror Satellite." *Proceedings of 2003 ASME International Mechanical Engineering Congress and Exposition*, November 15-21, 2003, Washington, D.C.

2. Inman, D. J., 2003. "Smart Structures in Vibration, Control and Structural Health Monitoring," CANSMART International Workshop on Smart Materials and Structures, Montreal, Canada, October 16-17, 2003, Keynote Address.

3. Sodano, H. A., Lloyd, J. M. and Inman, D. J., 2004. "Experimental Comparison Between Several Active Composite Actuators for Power Generation,"

Proceedings, SPIE's 11th Annual International Symposium on Smart Structures and Materials, 14-18 March 2004, San Diego, CA, on CD, paper number 5390-43.

4. Tarazaga, P.A., Halevi, Y., and Inman, D.J., 2004. "Model Updating with the Use of Principal Submàtrices," *Proceedings*, International Modal Analysis Conference (IMAC XXII), January 26-29, 2004, Dearborn, MI.

Book Chapters:

Inman, D. J., 2004. "Vibration Computations and Nomographs," Chapter 18 in *The Engineering Handbook*, Second Edition, Ed. by Richard Dorf, CRC Press, LLC, Boca Raton, FL; in press.

Inman, D. J., 2004. "Passive Damping," in *Handbook of Noise and Vibration Control*, Ed. by Malcolm Crocker, John Wiley & sons, Inc., Hoboken, NJ; in press.

Lopes, V., Steffen, Jr., V., and Inman, D. J., 2004. "Optimal Placement of Piezoelectric Sensor/Actuators for Smart Structures Vibration Control." in *Dynamical Systems and Control (Stability and Control Vol. 22)*, Ed. by F. Udwadia, H. Weber, G. Leitmann, Chapman & Hall/CRC, Boca Raton, FL, Part II, pp. 221-236.

Ruggiero, E., Sodano, H., Park, G., and Inman, D. J., 2003. "Active Vibration Suppression of a Gossamer Spacecraft," in *Mechanics of Electromagnetic Material Systems and Structures*, Ed. by Y. Shinido, WIT Press, Boston, MA, pp. 287-293.

Inman, D. J. and Carneiro, S. H. S., 2003. "Smart Structures, Structural Health Monitoring and Crack Detection," in *Research Directions in Distributed Parameter Systems*, Ed. by R. C. Smith and M. A. Demetriou, Society for Industrial and Applied Mathematics (SIAM), Philadelphia, Chapter 7, pp. 169-186.

Theses

Pablo Tarzaga, "Model Updating using Sparse Matrices", MS July 2004.

Luke Martin, "Damage Detection using Microcomputing" MS May 2004

Williams, Brett, "Nonlinear Mechanical and Actuation Characterization of Piezoceramic Fiber Composites," March 2004.

Tanner, Troy, "Combined Shock and Vibration Isolation Through the Self-Powered, Semi-Active Control of a Magnetorheological Damper in Parallel with an Air Spring," November 2003.

Kikuta, Michael T., Mechanical Properties of Candidate Materials for Morphing Wings, December 2003.

Sodano, Henry, The Use of Macro-Fiber Composites (MFC) for Structural Applications, August 2003.

7. Interactions and Transitions:

a. Presentations: Made by D. J. Inman (* indicates and invited lecture)

*Inman, D. J., "Morphing Nano Air Vehicle Delivery Systems", DARPA Workshop on Nano Air Vehicles, Washington, DC, March 2-3, 2004.

*Inman, D. J., "Smart Materials for Impedance-Based Monitoring," NSF Pan American Advanced Study Institute on Damage Prognosis, Florianopolis, Brazil, October 19-30, 2003.

*Inman, D. J., "Power Harvesting for Sensing," NSF Pan American Advanced Study Institute on Damage Prognosis, Florianopolis, Brazil, October 19-30, 2003.

*Inman, D. J., "Smart Structures in Vibration, Control and Structural Health Monitoring," CANSMART International Workshop on Smart Materials and Structures, Montreal, Canada, October 16-17, 2003. *(Keynote address)*

*Inman, D. J., "Morphing UCAV's: Theory and Experiments," 14th International Conference on Adaptive Structures and Technologies, Seoul, Korea, October 7-9, 2003. *(Keynote address*

b. Consultation and Advisory: Prof. Inman served on the Division Review Committee for the Engineering Science and Analysis Division at Los Alamos National Labs. Prof. Inman also served on the Weapons Systems Review Board for Los Alamos National Laboratories.

Transitions: We transitioned results and exchanged ideas with AFRL by meeting with Brett J. deBlonk, PhD, Spacecraft Component Technology Branch, at US Air Force Research Lab AFRL/VSSV (August 03). We have also visited with Dan Marker of AFRL/DEBS to discuss ideas examined in our research. Prof. Inman gave two lectures at General Electric Corporate Research and one at NASA Glenn. all of which involved aspects of the proposed research. We taught a short course to industry:

Short Course: "Smart Structures and Nanotechnologies," Donaldson Brown Center, Virginia Tech, Blacksburg, VA, May 17-18, 2004; 9 students.

8. Patents

None

9. Honors and Awards

D. J. Inman was awarded the SPIE Smart Structures and Materials Lifetime Achievement Award in March, 2003. D. J. Inman was also invited to give 2 keynote addresses during the summer of 2004. One at the ASME Engineering Design Conference in Manchester, UK (July 20, 2004) and one at MOVIC an international conference on motion and control in St Louis MO, USA (August 14, 2004).

November 2003 – Received Henry C. Pusey Award for Best Technical Paper presented at the 73rd Shock and Vibration Symposium

May 2004 - Awarded the 'Benjamin Meaker Visiting Professorship' from the University of Bristol, UK, for visiting during the next academic year and giving a lecture on smart structures.