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14. 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, unique material properties and ultra flexible nature. The main objective for this past year has been focused on understanding the mechanics of a pressurized membrane. Such configurations are being considered by AFRL as part of their adaptive optics program. The objective then was to provide fundamental research having the potential to help AFRL in their adaptive optics pursuits. The following is a brief report of our activities over duration of this grant.

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Final Performance Report 31 July 2005

VIBRATION ANALYSIS AND CONTROL OF AN INFLATABLE STRUCTURE USING SMART MATERIALS

(F49620-03-1-0163)

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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, unique material properties and ultra flexible nature. The initial focus of this proposal was the study of the structural dynamics of an inflated torus. About midway through this contract, interaction with the AFOSR program manager and AFRL/DE changed the focus of the research effort from understanding the structural dynamics of an inflated torus to that of an inflated membrane. The main objective of last year of research was then focused on understanding the mechanics of a pressurized membrane. Such configurations are being considered by AFRL as part of their adaptive optics program. The objective then was to provide fundamental research having the potential to help AFRL in their pursuit of adaptive optical membranes. The following is a brief report of our results over the entire three-year funding. The headings refer to the categories requested in previous guidelines.

1. Objectives

Initially the proposed work was to examine the nonlinear structural dynamics of an inflated torus with a membrane attached to if for the purpose of providing suitable models for the application of nonlinear control. This award commenced in April 2003. In March 2004, after a visit from the AFOSR program manager (T. Kim) the focus of this effort was changed to correspond more closely with AFRL interests. In particular, after conversations with AFRL/DESE and AFRL/VSSV both of Kirltland AFB and with AFOSR, the focus of the proposed effort was changed to examine the structural dynamics of a pressurized membrane system. The ultimate goal is to provide a sound modeling and theoretical understanding of the coupled structure, fluid, optical and control hardware of AFRL/DESE's proposed pressure augmented, boundary-controlled, spatially actuated adaptive mirror system.

Our initial objectives were to construct a detailed model, including nonlinear effects of an inflated torus with integrated macro fiber composite actuators and sensors. The goal was to capture all relevant structural mechanics and go perform dynamic testing and control of a laboratory torus.

Our objectives the last half year and a half where to (a) derive the equations of motion for a pressurized membrane, with distributed controllers coupled to Zernicke Polynomials, (b) Formulate a spline-based approximation of the governing equations suitable for use with a modern control algorithm, and (c) design and implement an experimental apparatus for the verification and validation of pressurized membrane models.

2. Accomplishments

Year 1 Results: During the first year, we constructed a detailed 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. In addition, we selected specific smart materials for use in a suppression system and in ground testing. We have obtained a 1.5 m inflated test structure (of torus geometry: see Fig. 1) with reflective surface (Mylar film coated with a reflective surface). The mechanics modeling to date has focused on dynamic models of an inflated torus with patch Macro Fiber Composite (MFC) actuators and PVDF sensors. We performed initial experiments using this system and started 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 roof.

Wrinkling, while not identified as a goal in our original proposal, has emerged as a serious concern (see Figure 1) so we adjusted our goals somewhat to examine wrinkling. Controlling and eliminating the wrinkles may form a significant part of our future efforts.

We also 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. Therefore, the amount of damping estimated by the MIMO analysis technique presented in this work is valid only at the level of excitation used throughout the testing. Figure 2 shows the FRFs generated by three different levels of excitation—250 V, 375 V, and 500 V, clearly illustrating the existence of nonlinearity.

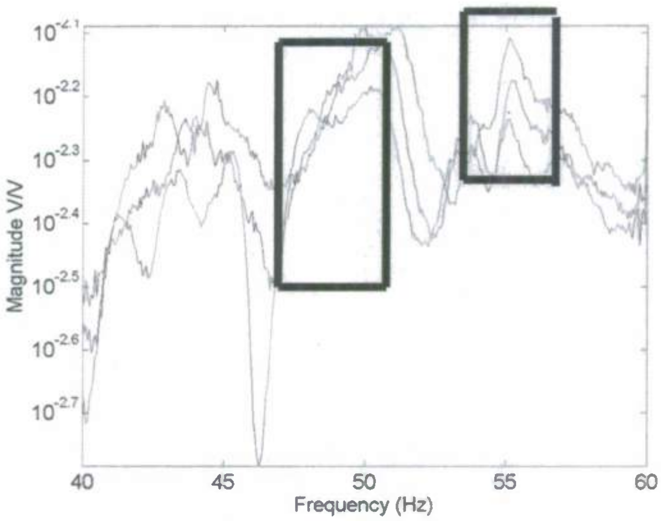

Figure 2. The non-linearity of the test structure is highlighted using three levels of excitation.

Year 2 Results We successfully modeled and tested a strip membrane (in one dimension) with an attached piezoelectric actuator in weak variational form. We used this model to develop an active control law (LQR) and successfully controlled the first three bending modes of vibration. We constructed and experiment and verified our modeling within 6%. These results were repeated for a rectangular membrane (in two dimensions). An experimental apparatus was constructed to investigate the effects of backpressure on a membrane system and an initial model of a pressurized membrane with back cavity was developed. Initial experimental results where obtained to show that the backpressure effectively damps vibration in the membrane. Last, an initial mapping was constructed between the structural modes of a clamped membrane and the Zernike polynomial description of optical aberrations for reflection.

Year 3 Results In year three our focus was to extend the one dimensional results of year two to 3 dimensions. We illustrated experimentally that the appropriate mechanics model to use for membrane mirrors with appended piezoelectric actuation is a thin plate subjected to an axial load rather then membrane theory. In short membrane theory alone cannot account for the added mass, added stiffness or actuation effects of the piezoelectric material. Experimental verification of this is given in Table 1. This result relates directly to our objective (a) of understanding mirror membrane dynamics. This and will support AFRL in its desire to design membrane optical systems.

Our second result was to design and construct a pressurized membrane system that can be used as a test apparatus for model development and verification. The test bed fits inside our altitude chamber, so that experiments can be performed over a range of temperatures and ambient pressures. Figure 1 shows a photograph of the pressurized membrane apparatus. The system consists of a Kapton membrane fitted with a piezoelectric actuator. The membrane is fitted over a pressurized chamber. The gap between the membrane surface and the backplane can be adjusted to allow experimental analysis of gap geometry and the membrane surface is fitted with a piezoelectric actuator. A laser vibrometer is used to measure surface deflection and velocity without contacting the surface of the membrane. In addition, an electromagnetic device is used for excitation.

This membrane test apparatus satisfies objective (c). In addition, this test apparatus will provide proof of concept experimental results in support of the AFRL/DE mission in adaptive optics. This device could also support civilian adaptive optics applications such as the NASA telescope program and the optics industry.

Thin plate theory with axial load frequencies compared to experiment:

Mode #	Experiment Frequency (Hz)	Analytic Frequency (Hz)	% Error
1	123	123	0.0
2	167	183	-9.6
3	194	204	-5.2
4	254	245	3.5
5	267	254	4.9

Membrane theory frequencies compared with experiment:

Mode #	Analytic Frequency (Hz)	FEM Frequency (Hz)	% Error
1	123	122.1	0.7
2	183	182.6	0.2
3	204	203.8	0.1
4	245	244.9	0.0
5	254	253.8	0.1

Table 1 Comparison of thin plate theory and membrane theory with experimental values in the frequency domain.

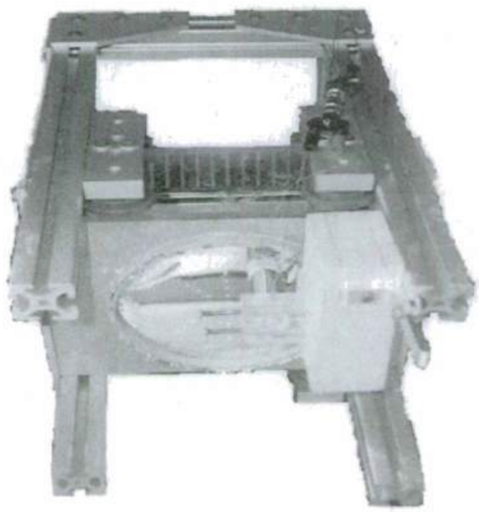

Figure 3 The pressurized membrane test apparatus

The third result obtained under this research was the development of a transformation between structural mode shapes and optical descriptions. This result was a joint effort with AFRL/DESE researchers (Dan Marker and Mike Wilkes). This bridge between the optical description of aberrations (i.e. Zernike polynomials) and structural properties (mode shapes) provides a mechanism for building high fidelity control laws for adaptive optics schemes useful to both the Air Force and the civilian optical communities.

Figure 4 shows a comparison between a purely optical description of an optical mode in terms of Zernike polynomials, and the approximation of the optical mode in terms of the structural modes of a membrane.

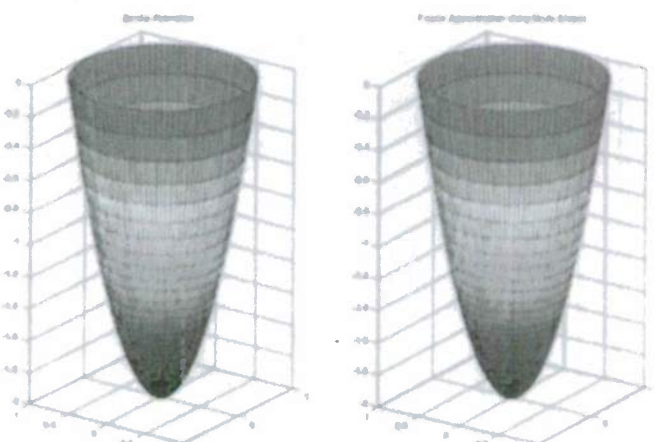

Figure 4 Optical mode on the left and its approximation in terms of plate modes on the right.

The clamped Zernike polynomials are proportional to the dynamical mode shapes of a circular membrane. In essence, they bridge the gap between the optical and mechanical worlds. The clamped Zernike polynomials enforce the zero boundary condition around the edge of the membrane optic. Consequently, the novel basis provides a means of describing three methods of control for achieving a nearly 100% effective adaptive optic: uniform pressure, boundary manipulation, and a mapping for distributed actuation within the domain of the membrane to eliminate the residual error. Further, the residual aberrations within the novel clamped Zernike polynomial basis were then expressed as a Fourier series using the mode shapes of a circular membrane. The resulting Fourier series expansion could be used in a modal space-based control algorithm for distributed actuation of the membrane mirror.

The work developed here helped lay the groundwork for a more intensive investigation into the actual design and construction of a prototype membrane adaptive optic. In addition some preliminary results of using structural control (LQR) to prevent vibration of the membrane (modeled as a plate) using piezoceramic based actuators and sensors has been simulated.

The details of these results have been presented in the conferences and journal papers listed below.

3. Personnel Supported

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

4. Publications:

This section list peer reviewed publications for this reporting year resulting from this funding separated into archival journal and conference papers.

Journal Articles:

1. 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*, November 2003, in press.
2. Park, G., Sausse, M., Inman, D.J., Main, J., "Vibration Testing and Finite Element Analysis of an Inflatable Structure," *AIAA Journal*, Vol. 41, No. 8, August 2003, pp. 1556 –1564.
3. Ruggiero, Eric J., Jha, Akhilesh, Park, Gyuhae, and Inman, Daniel J., 2003. "A Literature Review of Ultra-Light and Inflated Toroidal Satellite Components," *Shock and Vibration Digest*, Vol. 35, No. 3, May, 2003, pp. 173-183.

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

5. Jha, A. and Inman, D. J., "Importance of geometric non-linearity and follower pressure load in the dynamic analysis of a gossamer structure", *Journal of Sound and Vibration* Vol. 278(1-2), 22 November 2004, pages 207-231.

6. Williams, R. B., Inman, D., J., Schultz, M. R. and Hyer, M. W., "Nonlinear Tensile and Shear Behavior of Macro Fiber Composite Actuators", *Journal of Composite Materials*, Vol. 38, No. 10, 2004, pp 855-870.

7. Jha, A. and Inman, D.J., 2004. "Sliding Mode Control of a Gossamer Structure Using Smart Materials," *Journal of Vibration and Control*, Vol. 10, pp. 1199-1220.

8. Ruggiero, Eric J. and Daniel J. Inman. "A Comparison Between SISO and MIMO Modal Analysis Techniques on a Membrane Mirror Satellite," *Journal of Intelligent Material Systems and Structures (Special Edition)*, Vol. 16, No. 3, March 2005.

9. Sodano, H.A., Park, G. and Inman, D.J., 2004, "Multiple Sensors and Actuators for Vibration Suppression of an Inflated Torus, *AIAA Journal of Spacecraft and Rockets*, Vol. 42, No. 2, March-April, 2005.

10. Ruggiero, Eric J. and Daniel J. Inman. 2006. "Gossamer Spacecraft: Recent Trends in Design, Analysis, Experimentation, and Control," *Journal of Spacecraft and Rockets*, Vol. 43, No. 1, pp. 10-24.

CONFERENCE PROCEEDINGS

1. Jha, A. and Inman, D. J., 2003. "Vibration Analysis of a Gossamer Toroidal Structure," *Proceedings*, 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 7-10, 2003, Norfolk, VA, Paper No. AIAA 2003-1833.

2. Sodano, H., Park, G. and Inman, D.J., 2003, "Vibration Testing and Control of an Inflatable Torus Using Multiple Sensors/Actuators," *Proceedings*, 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 7-10, 2003, Norfolk, VA, Paper No. AIAA 2003-1644.

3. Ruggiero, Eric J., Pablo A. Tarazaga, and Daniel J. Inman. "Modal Analysis of an Ultra-flexible, Self-rigidizing Toroidal Satellite Component," *Proceedings of the 2004 ASME International Mechanical Engineering Conference and Exhibition*, IMECE2004-60113, November 13 – 19, 2004,Anaheim, CA.

4. Ruggiero, Eric J., John Singler, John Burns, and Daniel J. Inman. "Finite Element Formulation for Static Shape Control of a Thin Euler-Bernoulli Beam using Piezoelectric Actuators," *Proceedings of the 2004 ASME International Mechanical Engineering Conference and Exhibition*, IMECE2004-60117, November 13 – 19, 2004, Anaheim, CA.

5. Inman, D. J,, Ruggiero, E. J. and Lalli, J. H., "Composite Materials with Embedded Sensing", AIAA /CANEUS Conference on Micro-NanoTechnologies: From Concepts to Systems, Monterey, California , Nov 1-5, 2004, on CD.

6. Marques, R. F. A., Inman, D. J., and Rade, D. A., ""Assessment of Adaptive Techniques for the Control of Structures Subject to Temperature Variations", Twelfth International Congress on Sound and Vibration, Lisbon, Portugal, 11-16 July, 2005.

7. Ruggiero, E. J., and Inman, D. J., "Modeling and Control of a 1-D Member Membrane Strip with an Integrated PZT Bimoprh", 2005 ASME INTERNATIONAL MECHANICAL ENGINEERING CONGRESS & EXPOSITION, Orlando, Florida , November 5-11, 2005. Paper Number **ASME2005-80974.**

8. Ruggiero, E and Inman, D. J. , "Enhancing the Effective Bandwidth of a Membrane Optic Using a Shallow, Fluid-Filled Cavity", AIAA Structures Dynamics and Materials Conference, May 1-4, 2006, Newport, Rhode Island, Paper number AIAA-2006-1975, on CD.

9. Marker, D. K., Wilkes, M. M., Ruggiero, E. J., and Inman, D. J., 2006. "Membrane Adaptive Optics," *Proceedings*, SPIE's 13th Annual Symposium on Smart Structures and Materials, 26 Feb. – 2 March, San Diego, CA, Paper No. 5894-44, in *Advanced Wavefront Devices: Methods, Devices, and Applications III*, Mark T. Gruneisen, John D. Gonglewski, and Michael K. Giles, eds., pp. 360 - 367.

5. Interactions and Transitions:

a. *Presentations*: Made by D. J. Inman (* indicates and invited lecture) not including the conference papers listed above:

1. "Smart Materials in Damage Detection and Prognosis" 4th DAMAS Conference, Southampton UK, July 1-3, 2003 (Keynote)

2. "Introduction to Smart Structures and Control" Short course, Virginia Tech, May 12-14, 2003.

3. Ruggiero, Eric J. and Daniel J. Inman. "Active Dynamic Analysis and Vibration Control of Spider Satellites Using Smart Materials," *Xinetics, Inc. Presentation*, July 1, 2003, Devens, Massachusetts

4. *Inman, D. J, "Slewing Issues in LLS/ISAT", AFRL/NASA/NIA, Large Space Systems Workshop" Hampton, VA, August, 24-25, 2004.

5. *Inman, D. J., "The Role of Smart Materials in Structural Health Monitoring", Air Force Research Laboratory, Wright Paterson Air Force Base, 42 attended, September 9, 2004.

6. *Inman, D. J, and Hill, A. J. "Composite Materials with Embedded Sensing and Potential Applications" NASA Langley Research Center, 17 attended, February 23, 2005.

7. Inman, D.J. "Autonomous Structures: Adding Some Intelligence to Smart Structures", II ECCOMAS THEMATIC CONFERENCE ON SMART STRUCTURES AND MATERIALS, Lisbon, Portugal, 18-21 July 2005. Keynote Address

8. *"Mechanical Vibration: Where Do We Stand?" CISM - International Centre for Mechanical Sciences June 13- 17, 2005, Udine, Italy. 5 lectures given by D. J. Inman "Vibration and Smart Structures": Lecture 1: "Smart Materials and Structures", Lecture 2: "Basics of Control for Vibration Suppression", Lecture 3: "Application of Smart Materials for Vibration Suppression Pt 1", Lecture 4: Application of Smart Materials for Vibration Suppression Pt 2", Lecture 5: Smart Structures for Structural Health Monitoring".

9. *Inman, D. J. "Vibration and Control of Flexible Spacecraft" ASME 20th Biennial Conference on Mechanical Vibration and Noise, September 24-28, 2005, Long Beach, CA, 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. Prof. Inman also served on the NASA Advanced Telescope Roadmap Committee.

Transitions: During the first year, 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 also visited with Xinetics, Inc to exchange technology.

During the third year we transitioned results and exchanged ideas with the Air Force by meeting with Dan Marker and Mike Wilkes of AFRL/DEBS to discuss ideas examined in our research. The graduate student, E. Ruggiero, associated with this research spent considerable time working with AFRL through email on the transformations mentioned above. In addition, I have visited with NASA Langley Research Center and DARPA to share my AFOSR results with their flexible satellite programs. Dan Marker has visited CIMSS at VT on two occasions and the PI and/or students have visited AFRL and Dan Marker on 2 occasions.

7. New Discoveries (Patents and Inventions)

None

8. 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 10 keynote addresses at various conferences.

D. J. Inman was awarded the Benjamin Meaker Visiting Professorship by the University of Bristol, Aerospace Engineering Department in the UK. He is also a Fellow of AIAA, ASME, AAM and IIAV.