AIAA JOURNAL
Vol. 41, No. 8, August 2003

Vibration Testing and Finite Element Analysis of an Inflatable Structure

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Vibration testing and finite element analysis of an inflated thin-film torus are presented. Inflatable structures show significant promises for future space applications. However, their extremely lightweight, flexible, and high damping properties pose difficult problems in vibration testing and analysis. Smart materials are used as sensors and actuators for performing vibration tests of an inflated torus. In addition, a predictive model has been developed, which can be compared with experimental results. A commercial finite element package, ANSYS, is used to model a prestressed inflatable structure. Both experimental and finite element results are in reasonable agreement with each other. The predictive model can be used for analyzing the dynamics of inflated structures and for designing control systems to attenuate vibration in an inflated torus.

Introduction

INFLATED space-based devices have become popular over the past three decades because of their minimal launch mass and launch volume.[1–3] The dynamic behavior is particularly important for satellite structures because they are subjected to a variety of dynamic loadings. However, they are extremely lightweight, flexible, and highly damped posing difficult problems in vibration testing and analysis. These vibration problems are difficult to observe by traditional shaker-based ground testing. The choice of applicable sensing and actuation systems suitable for use with inflated structure is somewhat limited because of their low stiffness and high flexibility. In addition, excitation methods have to be carefully chosen because the extremely flexible nature causes point excitation to result in only local deformation. Griffith and Main[4] used a modified impact hammer to excite the global modes of the structure while avoiding local excitation. Slade et al.[5] tested a torus attached to three struts with a lens in a thermal vacuum chamber. They found significant differences in the response between the structure in ambient and vacuum conditions. Park et al.[6] investigated the feasibility of using smart materials, such as PVDF films, to find modal parameters and to attenuate vibration in a flexible inflated structure.

Analytical solutions for free vibrations of toroidal structures without prestress have been studied by many researchers.[7–9] However, there have been relatively few studies on the toroidal shells with prestress conditions. Liepins[10] used a finite difference method to solve governing equations of a prestressed toroidal membrane. Plaut et al.[11] used shell analysis of an inflatable arch with fixed boundary conditions to find the deflections when subjected to snow and wind loadings. Jha et al.[12] used the Sanders linear shell theory to formulate the governing equations and to compute the natural frequencies and mode shapes using Galerkin's method. Recently, commercial finite element packages have been used to model inflatable structures in order to avoid the complexity introduced by conventional analytical solutions of a prestressed structure. Briand et al.[13] showed that finite element analysis must include an adequate size of meshing and adequate boundary conditions. Lewis and Inman's finite element study[14] found that the aspect ratio of a toroidal inflated structure has a significant impact on its natural frequencies and modes shapes. They also demonstrates that increasing the pressure results in increased natural frequencies.

In this study smart materials are used as sensors and actuators for performing vibration tests of an inflated torus. In addition, a predictive finite element model has been developed, which can be compared to experimental results in order to understand dynamic behavior of inflatable structures. A commercial finite element package, ANSYS, with a linear thin shell element is used to model the prestressed inflated structure. Finite element results are in reasonable agreement with those of experiments. This paper summarizes the experimental setup, procedures, considerations needed to obtain frequency response functions (FRFs) with high coherence, and some approximations and assumptions made in the finite element modeling.

Description of the Structure

The test structure is an inflatable torus made of Kapton with a 1.8-m ring diameter and a 0.15-m tube diameter as shown in Fig. 1. The torus was made of flat sheets of polyimide film Kapton and fabricated in the Emerging Technology Laboratory at University of Kentucky. Three 120-deg segments were joined to form the complete torus. The method of fabrication results in many variations in the thickness in the joining regions. In addition, epoxy adds significant mass and stiffness in the bonded joins.[4] The joining region width (flap around the inner and outer diameter) is measured at 5.1 cm, and the thickness is about 300 μm in this region. A list of the structure's physical properties is given in Table 1. A more detailed description on the fabrication process, including resin types, bonding temperature, exact geometrics of segments, and overlaps of the test structure, can be found in the Ref. 15.

Experimental Testing

The structure was tested in laboratory conditions in order to find resonant frequencies and mode shapes. The modes of interest are ring modes, which are in-plane and out-of-plane motions of the torus.

The torus was suspended using a rubber wire in order to minimize the effects of the boundary conditions. With the suspended wires the

Received 24 July 2001; revision received 11 May 2002; accepted for publication 10 January 2003.

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Table 1 Physical parameters of a test structure

Property	Value
Ring diameter	1.8 m
Tube diameter	0.15 m
Joining region width	0.051 m
Internal pressure	0.5 psi
Elastic modulus	$2.55e-9$ Pa
Mass density	1418 kg/m^3
Poisson's ratio	0.34
Thickness	$46e-9$ m
Joining region thickness	$300e-9$ m

Fig. 1 Inflated test object for dynamic analysis.

rigid-body modes appear to occur at 1–2 Hz, which would be negligible considering that the frequency range of interest is 10–200 Hz. The internal pressure of the torus was maintained at 0.5 psi using a small aquarium pump. No noticeable effect on the measurement of FRF was found from the pump noise and the flow of air into the structure.

Two difference methods were selected to excite a torus. One is use of a conventional electromagnetic shaker (manufactured by Ling Dynamic Systems) to provide the point force excitation to the structure. A single piece of metal was attached on the arm of the shaker and glued on the torus, as shown in Fig. 2. The other excitation was realized using the recently developed Macro Fiber Composite (MFC^{TM}) actuator.[16] The MFC offers high performance and flexibility suitable for use in the inflatable structure. The MFC was bonded to the surface of the torus using double-sided tape, as shown in Fig. 3. The identified resonant frequencies and mode shapes with the different excitation methods were then compared to each other.

To measure the response of the torus, an accelerometer (PCB Model 352C22) and a PVDF sensor were attached to the torus. To

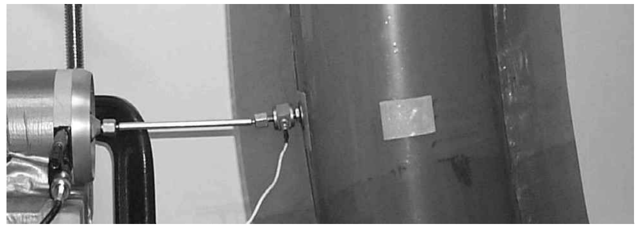

Fig. 2 Connection between the torus and the shaker.

Fig. 3 MFC actuator attached to the torus.

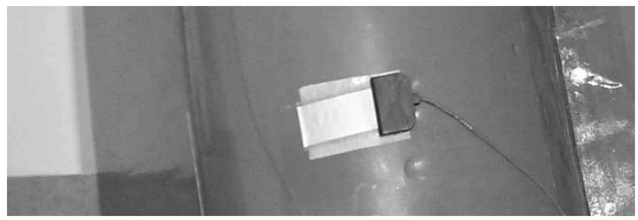

Fig. 4 PVDF sensor bonded to the torus.

reduce electromagnetic interference effects, a specially designed PVDF sensor (Measurement Specialties SDT1-028K) has been used, as shown in Fig. 4. This sensor is equipped with a protective coating and a shielded cable that is optimized against the 60-Hz electromagnetic field. These sensors are bonded to the surface of the structure with a doubled-sided tape at 16 evenly spaced locations.

Excitation was given in two directions. The first was in the out-of-plane direction and the second in the in-plane direction in order to measure the corresponding modes. Force, acceleration, and strain data were collected through the DSPT Siglab multichannel dynamic signal analyzer. The excitation signal was a chirp signal varying from 5 to 100 Hz. Ten runs were averaged to estimate frequency response functions.

As expected, the extremely flexible nature of the inflatable torus made collecting modal parameter information quite difficult. In particular, local excitation with a shaker as a point input only exaggerated the local properties of the structure. To ensure enough input energy at each frequency from excitation and to avoid the leakage for such a relatively high-damped structure, the chirp input frequency for each test was divided into three subranges (5–35, 35–65, and 65–100 Hz). Furthermore, the time period of excitation was held for as long as possible (51,200 samples at each subrange) so that the excitation ceased and that the corresponding response signal in a data frame was damped out.[17] By focusing the small bandwidth, sufficient input energy could be provided to the entire structure and thereby able to excite the global modes. The careful selection of excitation signal (specific length and bandwidth) was found to be critical for a flexible inflatable torus when trying to obtain reliable vibratory responses with reasonable accuracy.

Overview on Experimental Results

After completion of the data measurements, a modal analysis was performed by using the Unified Matrix Polynomial Approach

Table 2 Comparison between FEA and experimental results

Mode	Accelerometer	PVDF	FEA	Motion	Difference between finite element method and experiment, %
1	12.84	12.81	14.36	Out of plane	10.58
2	16.37	16.31	15.64	In plane	4.67
3	32.9	31.7	40.61	Out of plane	18.99
4	40.24	40.74	41.71	In plane	3.61
5	65.64	65.4	62.44	Out of plane	5.12
6	68.1	67.78	72.77	In plane	6.41
7	102.05	100.92	107.16	Out of plane	4.76
8	——	——	109.71	In plane	——

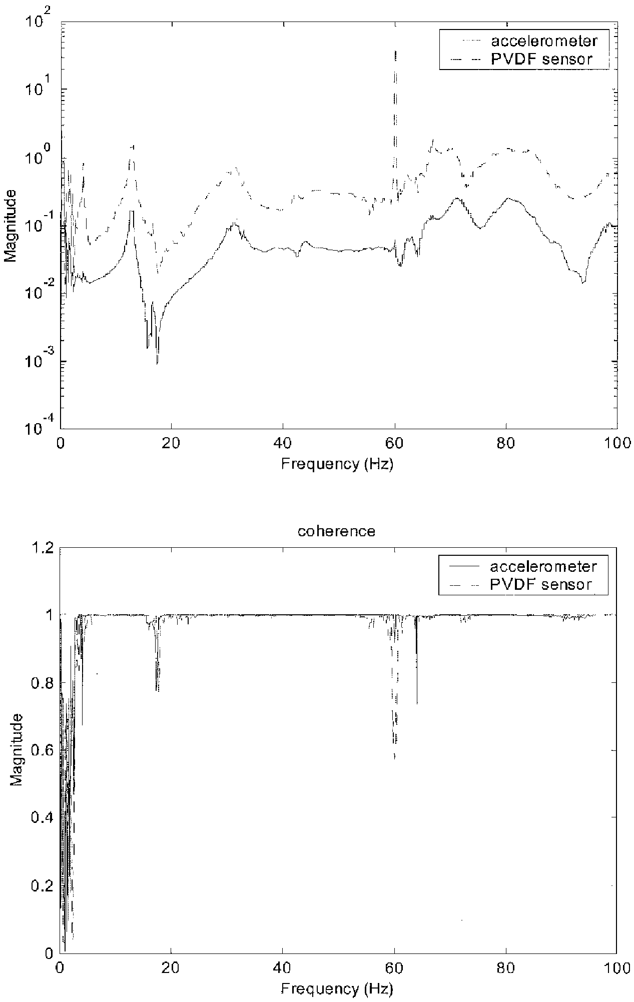

Fig. 5 Out-of-plane transfer function with a shaker input (measured 90 deg from the excitation point).

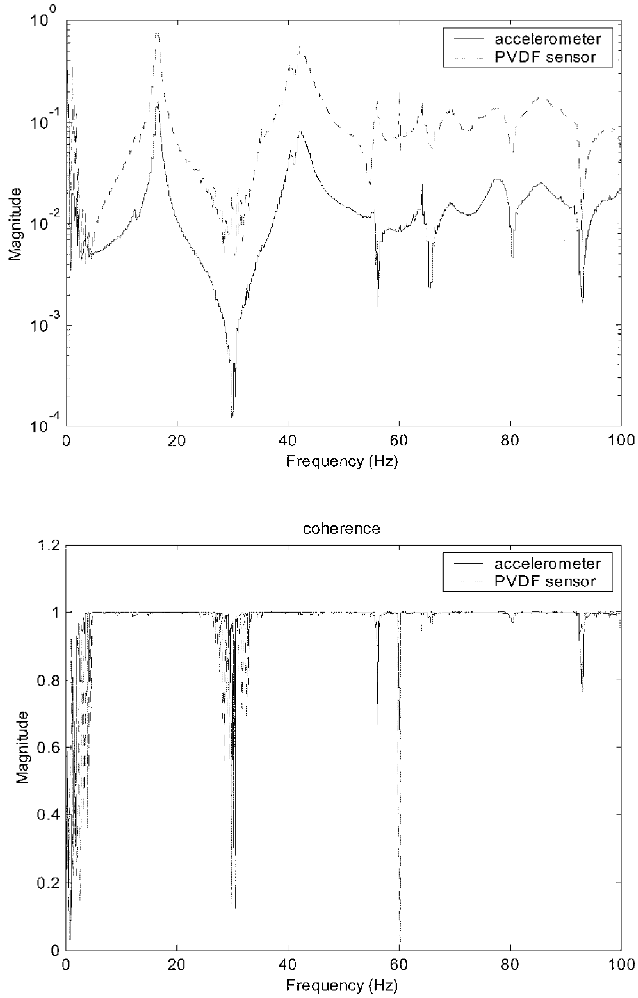

Fig. 6 In-plane transfer function with a shaker input (measured 90 deg from the excitation point).

pseudo-least-square method.[18] This method determines an orthogonal polynomial to curve fit the measured data and provides eigenvalues and eigenvectors of the system. Figures 5 and 6 show sample frequency response functions of out-of-plane and in-plane motions. The coherence plots, which indicate the correlation between a single-input and single-output measurement, are also shown to indicate the test results are reasonable. For the out-of-plane motion three resonant peaks are identifiable. Frequencies near 13 and 32 Hz are easily characterized as the two first apparent out-of-plane frequencies. The third resonant peak near 65 Hz is not so easy to define because of a shell mode present around the same frequency. For the in-plane motion the first two resonant peaks are around 16 and 42 Hz. However, as the frequency increases, it is not easy to identify resonant frequencies because of a number of shell modes present.

Experimentally identified mode shapes are expected to have a sequential number of nodal lines. Therefore, mode shapes of each resonant peak are generated in order to determine global in-plane and out-of-plane modes. The identified resonant frequencies are found in Table 2, and out-of-plane mode shapes are illustrated in Fig. 7.

The first conclusion that can be made is that the data measured with the PVDF sensors are consistent with those acquired with an accelerometer. The identified resonant frequencies using the PVDF sensors are almost identical to those measured with the accelerometer. The experimental results presented here validate the usefulness of PVDF sensors for measuring dynamics of inflatable space structures. Further, identified resonant frequencies are almost identical to those found with the shaker and with the MFC excitation. Indeed, the MFC is very lightweight, and mass-loading effect is

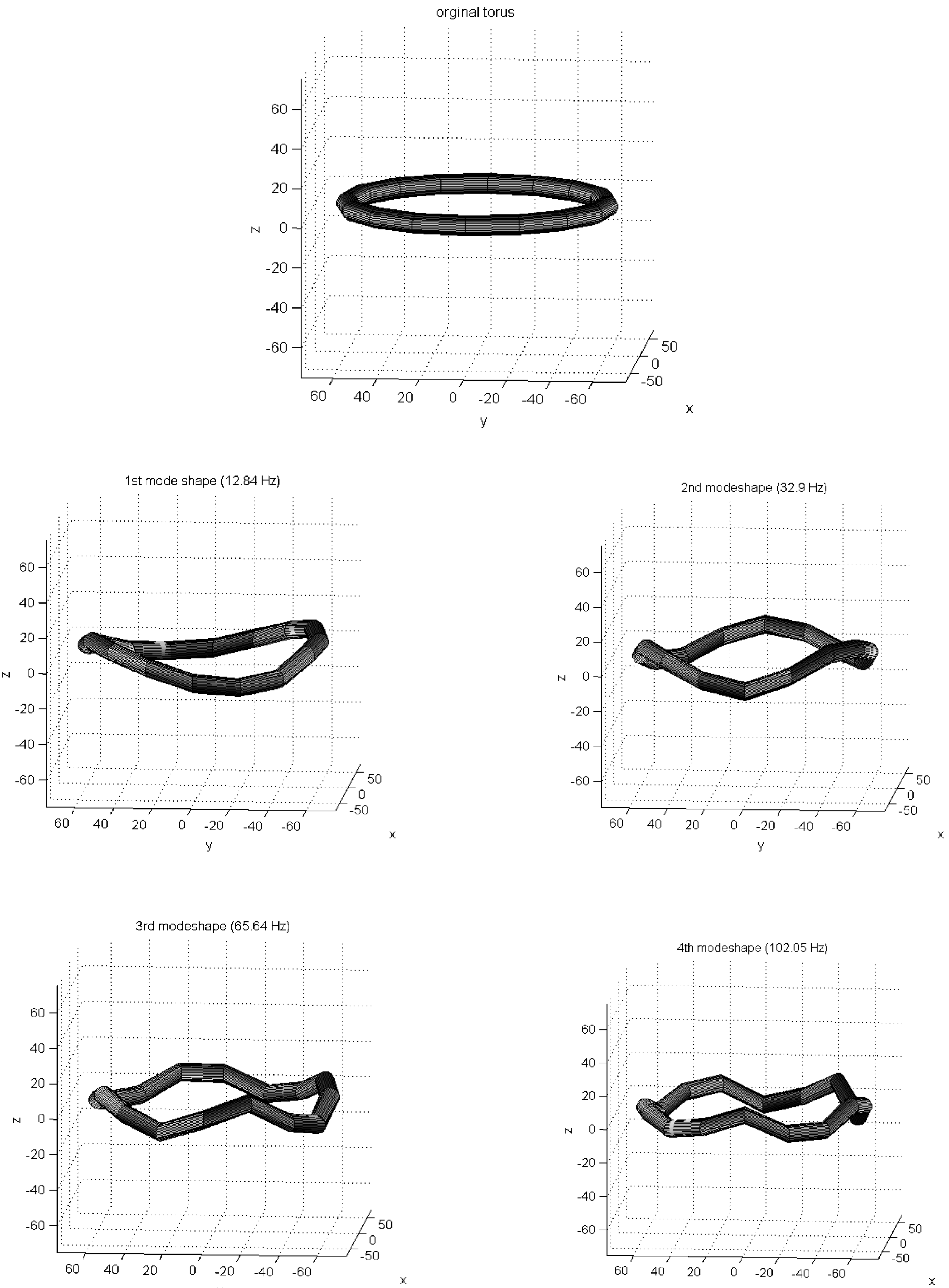

Fig. 7 Identified resonant frequencies and out-of-plane mode shapes of the torus with the MFC actuator excitation.

negligible. It is obvious during the tests that the MFC excitation produced less interference with suspension modes of the free-free torus than excitations from the shaker. Without connections to the ground (except for the electrical cable), these actuators and the PVDF sensor can be considered as an integral part of an inflated structure. These combinations could also be used on control devices of an inflatable structure for not only vibration suppression but also for static shape control. A more complete description of the experimental procedure and results can be found in Ref. 19.

Finite Element Analysis

Recently, commercial finite element packages have been readily available, and their utility has increased with the development of fast computers. The finite element method provides a relatively easy way to model the system. In this section our experimental results will be compared and validated with the use of commercial finite element analysis. The software package ANSYS was used for the current research effort.

Modeling

Linear thin shell elements that have eight nodes, four corners, and four midside nodes were used. These elements are well suited to model a curved shell. Each node has six degrees of freedom and translation and rotation in the x, y, and z directions. The model is defined by geometry, based on nodes and elements, the real constants, which define the elements thickness, and the material properties. The torus was meshed with 288 elements, 24 elements around the ring, 10 elements around the tube, and 1 for the joining regions. Figure 8 shows the mesh configuration of an inflated torus.

Because Lewis and Inman[14] showed that the PVDF patches have a very limited effect on the vibratory response of a low-aspect-ratio torus (aspect ratio of 0.083), they were not taken into account in this analysis. Generally the natural frequencies are decreased slightly because of the PVDF patches, as should be expected by adding mass to the system, but there is little influence on the mode shapes.[20]

An internal pressure of 0.5 psi was applied to simulate the pressure in the torus. For the static analysis one node has to be restrained to zero displacement to prevent rigid-body motion. In the modal analysis this constraint was removed to solve the problem for free-free response. A prestressed matrix was used to perform the modal analysis. Mass was added to the surrounding elements representing the flaps (resulting from the fabrication) to simulate the presence of epoxy.

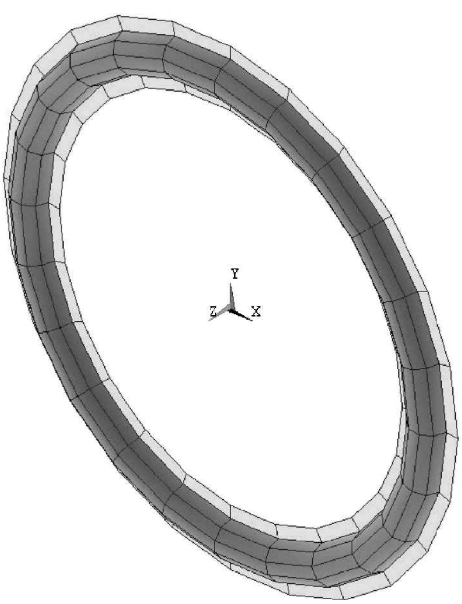

Fig. 8 Mesh configuration of the inflated torus.

Convergence is demonstrated on the model of the torus by solving for the modal frequencies with varying mesh densities. To confirm the convergence, the torus was meshed with 12, 24, and 48 elements around the ring (hence total 132, 288, and 528 elements, respectively). The models with only 12 elements around the ring do a poor job of predicting modes higher than the fourth mode. All of the models with 24 elements or greater around the ring produce very similar results. More detailed information on the procedure in finite element modeling and convergence studies can be found in Ref. 14.

In the present study the mass and sloshing effects from internal gas on the overall dynamics of the torus were not considered. This might be a somewhat important problem because the mass of the enclosed air would be on the same order as the mass of the Kapton. The exclusion of these effects might be one of the reasons to cause deviations in the results between the modeling and the experiment (which will be detailed in the following section). For future inflatable satellite structures the inflation pressure will be maintained by an onboard control system and bottle of pressurized nitrogen. As the satellite moves in and out of the sun, nitrogen can be vented and refilled to account for the change in pressure.[21]

Assumptions

The torus was assumed to have uniform thickness even in the joining region. This is not the actual case for our test torus. However, measuring and then modeling all of the variations in the thickness were beyond our scope. Furthermore, those parameters are found not to affect the analytical results a great deal. Another assumption was made that the pressure remains constant while the torus is vibrating. In addition, the material was considered to be linearly elastic.

Finite Element Model Verification

At present, there are no reliable published data on modal testing of inflated prestressed toroidal structures. For this reason, a previous analytical work was used for comparison and verification of the finite element model. Table 3 compares resonant frequencies with the analytical solutions[12] of free vibration analysis of an inflated torus with a circular cross section (aspect ratio 0.16). In the analytical study[12] the shell theory of Sanders, including the effect of pressure, was used in formulating the governing equations. These partial differential equations were reduced to ordinary differential equations with variable coefficients using complete waves in the form of trigonometric functions. The solutions (natural frequencies and mode shapes) were obtained using Galerkin's method. As in the finite element study, it was assumed that the thickness is uniform and the material is linearly elastic and isotropic in the analytical study.

The second and the third columns of Table 3 list the natural frequencies calculated using finite element analysis and shell theory, respectively. Comparison between the second and the third columns demonstrates that, although the two analyses give close results, the difference is as high as 17%. This anomaly can be explained by closely examining the procedure adapted in the two methods. In the finite element analysis (FEA) the initial stresses from the internal pressure were calculated first. Thereafter, only these initial stresses (not the internal pressure) are considered in the free vibration analysis. This is a typical procedure for the free vibration analysis of an inflated structure using a finite element method. On the other hand, in the analytical study effects of both the initial stresses and the direct pressure are considered. The direct pressure is important to include, as it acts perpendicular to the deformed area of the shell while the torus is vibrating in the presence of the initial stresses. This effect is difficult to consider in the finite element analysis using

Table 3 Comparison between FEA and analytical analysis

Mode	FEA, Hz	Analytic analysis, Hz
1	8.63	7.52
2	11.24	9.32
3	20.02	18.68

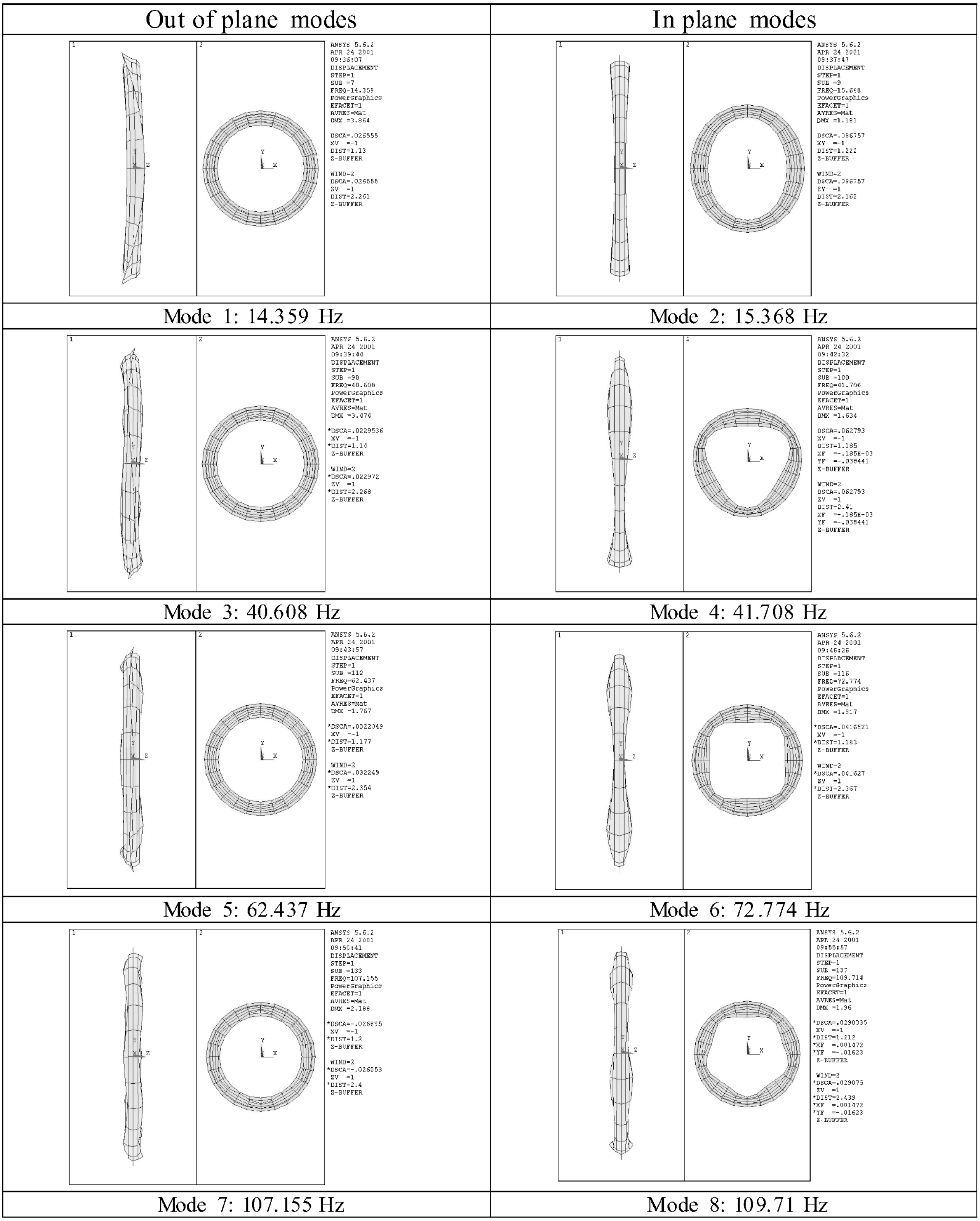

Fig. 9 In-plane and out-of-plane mode shapes.

commercial codes. Two procedures yield similar results when the internal pressure is small, as shown in Ref. 22.

Comparison of FEA and Experimental Results

The bending modes are orthogonal pairs of ring modes, alternating out of plane and in plane of the torus as represented in Fig. 9. Table 2 gives the resonant frequencies found with the FEA and with the experiments using accelerometer/PVDF sensors. The results match satisfactorily between FEA and experiments. It is observed that results for in-plane modes are closer than for out-of-plane modes. It is also observed that out-of-plane motion modes come before in-plane motion modes. Other than ring modes, different types of modes were found in the FEA. There are shell modes, that is, many different types of wrinkling motions, where the tube expands and contracts from side to side, or the torus expands and contracts uniformly. The first shell mode occurs at 55.533 Hz in the FEA, represented in Fig. 10, and experimentally identified at 55.6 Hz.

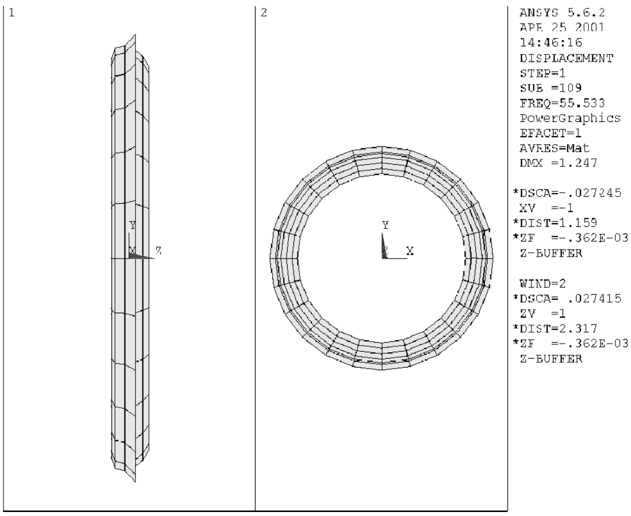

Fig. 10 First shell mode shape at 55.533 Hz.

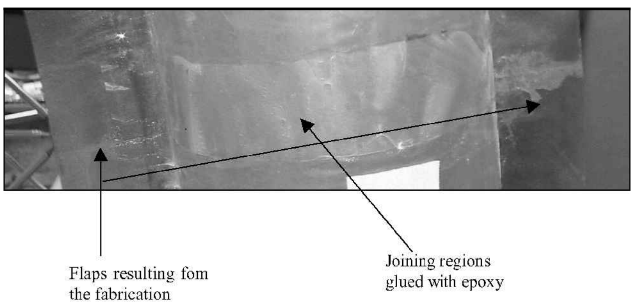

Fig. 11 Joining regions of the torus.

Table 4 Frequencies for a perfecttorus (without flaps)

Mode	In plane, Hz	Out of plane, Hz
1	31.761	38.747
2	81.192	84.173
3	138.59	139.43

Fig. 12 Tube that air is supplied through.

The test results compare favorably with the analytical model built with ANSYS, even though some variations appear as large as 19% in the third mode as shown in Table 2. Other than the third mode, the differences are in the range of 3–6% (except the first mode), and the sequence of the modes (in and out of plane) is well predicted by the finite element study. These differences can be explained by several factors such as the following:

1) Nonconstant thickness is caused by a method of fabrication and difficulty in modeling the joining regions.

2) The presence of flaps around the torus is another factor. Indeed a finite element analysis performed for a torus without the joining region resulting from the method of fabrication showed that the presence of the flaps was considerably lower than the resonant frequencies. This confirms the fact that the method of fabrication results in adding considerable mass to the structure (Fig. 11).

3) The presence of epoxy to glue the different parts also adds mass and stiffness to the structure.[4]

4) Even though the airflow in the structure does not significantly affect the measurements, the tube through which air is supplied to the structure affects the experimental results (Fig. 12).

5) Boundary conditions are not completely free–free because of the rubber wire used to suspend the structure affecting the response of the torus.

Impact of the Flaps on the Structure

A finite analysis was performed for the same torus but without the joining region (flaps) to see what impact was made on the model. The results show that the impact is considerable. Resonant frequencies are found much higher than those of the torus with the joining region and the in-plane modes appearing before the out-of-plane modes. Moreover the first shell mode occurs at a very high frequency that is at 216.9 Hz. Results are listed in Table 4.

Discussion

Smart sensors/actuators have been used to measure the dynamics of inflatable structures. A PVDF patch was used to measure the vibration response, and an MFC actuator was used as an excitation device in modal tests of an inflated torus. This presents a vast improvement over testing the dynamics of a large inflated torus using traditional shaker and accelerometer methods. The experimentally obtained modal parameters of two different test types, the shaker-accelerometer and MFC-PVDF sensor, are in good agreement with each other. The MFC actuators and the PVDF sensors hardly interfere with the suspension modes of a free-free boundary condition of the torus. The experimental results presented validate the usefulness and potential of flexible smart materials for measuring the dynamics of inflatable space structures. This implies that smart materials applied to a larger torus, such as the 6-m and larger versions of interest to NASA and the U.S. Air Force Research Laboratory, would allow for vibration testing currently not possible with traditional hardware.

A finite element analysis was performed using the commercial finite element software ANSYS to study the dynamics of an inflated torus. Results are in reasonable agreement with the experimental data, and so the conclusion can be made that these earlier results are validated. Still there are some variations between theoretical and experimental results, but these differences are not of an important scale and are attributed to the assumptions made on the model. The FEA also confirms that the presence of the flaps considerably affects the frequencies and mode shapes by adding mass and stiffness to the structure. Figure 13 shows a global overview on our experimental and simulation results. In conclusion, the predictive model can be used as a guideline for analyzing the dynamics of inflated structures and for designing control systems to attenuate vibration in an inflated torus. These tasks are currently under investigation.

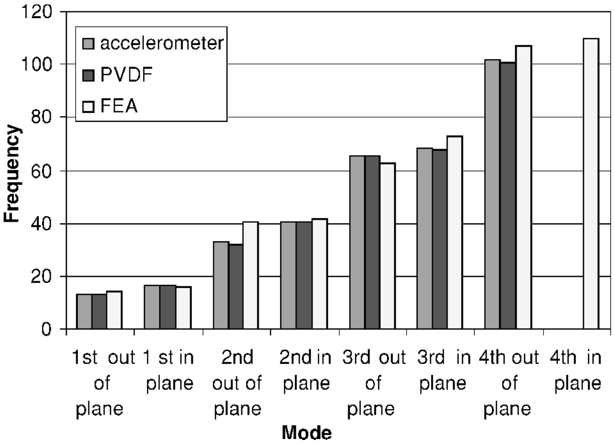

Fig. 13 Summary of the results.

Conclusions

Smart materials, such as PVDF sensors and MFC actuators, have been used in vibration testing of an inflated thin-film polyimide torus in order to identify resonant frequencies and associated mode shapes. The experimentally obtained results are in good agreement with the shaker–accelerometer combination. The use of smart materials offers several advantages for the analysis of inflatable structures. These sensors/actuators are flexible enough to conform to the doubly curved surface of the toroidal shell. Thus, they can be fully integrated in an unobtrusive way into the skin of an inflatable structure. The experimental results also compare favorably with the analytical model built with the finite element software ANSYS, even though some variations appear. The reason for the difference was explained. It has been shown that the method of fabrication considerably affects the modes particularly by adding mass and stiffness to the structure.

Acknowledgments

This work was sponsored by the U.S. Air Force Office of Scientific Research under Grant F49620-99-1-0231 and AFIT/EN 99-018. The authors gratefully acknowledge the support. In addition, Honeywell Corp. has supported part of this work, as did NASA Langley Research Center, Hampton, Virginia, for actuator characterization. Our most sincere thanks are extended to W. Keats Wilkie from NASA Langley Research Center for providing the MFC devices.

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