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VIBRATION ANALYSIS OF INFLATED TORUS STRUCTURE USING FREQUENCY RESPONSE TRANSMISSIBILITY

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Abstract

In the present work, transmissibility based vibration study of an inflated torus structure has been attempted to study the effect of internal pressure. Experiment has been performed using Macro fiber composites (MFC) as an actuator and Laser Doppler Vibrometer (LDV) as a sensor to study the transmissibility of torus.

Keywords: Inflated Torus Structure; MFC; LDV; Transmissibility

1. Introduction

With the advancement in satellite technology, there has been a parallel increase in the mass and size of satellite antenna. Thus, it seems an arduous task to launch the satellites with large and heavy antennas with current rocket technology. The inflated structures being light weight, possessing high strength-to-mass ratio as well as high packing efficiency is an emerging area in the field of light weight structures for space applications. The torus shaped inflated structure acts as a support for the antenna and hence the efficiency of communication system depends largely on the performance of torus. Anticipating the criticality of this problem NASA started exploring the pertinence of inflatable structures to satellite technology and launched first inflatable communication satellite ECHO-I in 1960 and ECHO-II 1964. Apart from communication satellites, NASA also launched the EXPLORER and PAGEOS series of climate research satellites (Cassapakis & Thomas, 1995) and explored the applicability inflatable flexible composites structures for space suits, habitats, transfer vehicles and depots for the Moon and Mars mission (Cassapakis, Love, & Palisoc, 1998).

Figure 1. Torus antenna

In a typical communication satellite, reflector lens is supported by an inflated torus structure which is connected to the main satellite body with inflatable struts as shown in Figure *1*. Torus because of its dual curvature is selected as the main supporting structure (E. J. Ruggiero, 2003), is susceptible to shock and harmonic vibrations and prone to damage due to its low structural stiffness. This makes its damage detection and system identification a vital issue.

Vibration behavior of the torus has been studied by several researchers. (Liepins, 1965) has performed free vibration study using Finite difference method and reported that the pre-stress due to internal pressure has an effect on lower fundamental frequencies only. (Jha, Inman, & Plaut, 2002) have analyzed free vibration behavior of a pre-stressed inflated torus membrane using Sander's theory. (Park, Ruggiero, & Inman, 2002) and (Sodano, Park, & Inman, 2004) carried out experimental investigations on torus structure and demonstrated the feasibility of smart materials such as Polyvinylidene fluoride (PVDF) and macro-fiber composites (MFC) as sensors and actuators for modal testing.

2. Experimental Configuration

The test structure is a synthetic rubber torus of ring diameter 0.84 m, tube diameter 0.26 m and thickness 3 mm suspended as shown in Figure *2*. Suspensions just give support to the structure and do not restrict any operational degree of freedom. Internal pressure of torus is varied between 5 to 9 kPa. Total weight of the torus system inflated at 9.5 kPa is 4 kg.

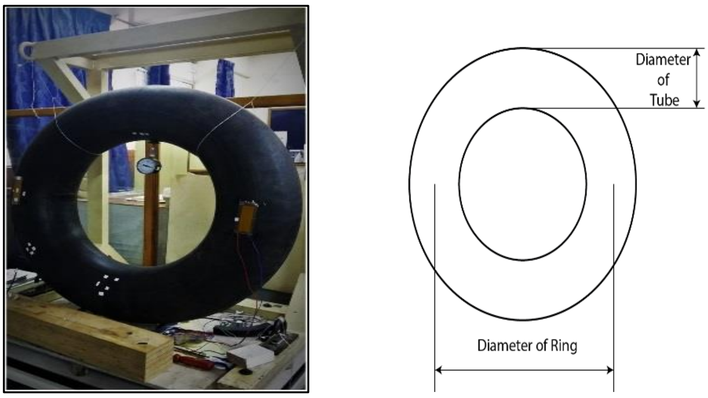

Figure 2. Torus

Excitation

The structure is excited with the help of Macro Fiber Composite (MFC) developed at NASA's Langley Research Center in 1996, commercially available through Smart Material Corp. It consists of rectangular piezo ceramic rods sandwiched between layers of adhesive, electrodes and polyimide film as shown in Figure *3*.

Figure 3. Macro Fiber Composite

Table 1. MFC Specifications

Actuator - MFC (Type M8557P1)	
Active area	85 x 57 mm^2
Volume density	5.44 g/cm^3
Piezo ceramic rod (Rectangular)	180 µm thickness 350 µm fiber width d_{33} effect
Blocking force	923 N
Free strain	1800 ppm
Operating Voltage	-500 V to 1500 V
Temperature	-40 ºC to +85 ºC

Sensing

Displacement at various points are measured with the Laser Doppler Vibrometer as shown in Figure *4*, which is a non-contact vibration measurement device and works on the principle of Doppler effect and interferometry for vibration measurement. It senses the frequency shift of light scattered back from a moving surface.

Figure 4. Laser Doppler Vibrometer

Table 2. LDV Specifications

3-D Laser Doppler Vibrometer
Make: Polytec GmbH
Type: He-Ne Laser (λ = 633 nm)
Minimum Detectable Vibration speed = 5 µm/s
Maximum Detectable Vibration speed = 50 m/s at 1 Hz resolution
Bandwidth = 30 MHz
Operating distance = 0.5 – 50 m

Experimental Procedure

The experimental set up is shown in Figure *5*. Excitation function (which is Pseudorandom signal in our experiment) is generated by Internal Function generator (PCI-6111). The signal generated from function generator is amplified by a high Voltage Amplifier (HVA 1500/50-2) having range between -500 V to 1500 V with a maximum output current of 50 mA DC.

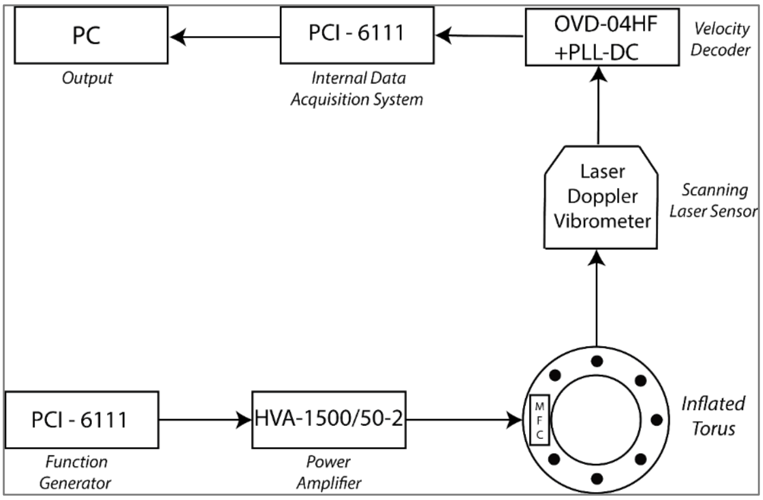

Figure 5. Experimental set up

From power amplifier, voltage is given to Macro-Fiber composite based actuator (Type M8557P1) attached to the torus. Vibrations transmitted at different points is measured by Laser Doppler Vibrometer. The interferometer signal is decoded in the controller (OFV-3001S) with the velocity decoder (OVD-04HF+PLL-DC). An analog voltage signal is thus generated which is proportional to the vibration velocity. Data acquisition board used is PCI-6111 with 2 simultaneous input channels, 1 MHz bandwidth and up to 6400 FFT lines. The data we receive is in the form of displacement amplitudes in frequency domain and thus transmissibility can be calculated by taking the ratio of output displacement to the input displacement. The resulting experimental transmissibility curve is de-noised using Savitzky-Golay filter.

3. Results and Discussion

The response to the actuation provided by the MFC is recorded at different positions on the torus front surface and found to have a general decrease in no. of frequency peaks with increase in pressure from 5 kPa to 9 kPa as shown in Figure *6*. It has been observed that the torus displays distance dependent transmissibility as shown in Figure *7*. However, many similar peak frequencies are observed at opposite angles such as at 45º and 315º, 90º and 270º, 135º and 225º. The damping ratio is of the order 0.1 or less i.e., the system largely behaves as an underdamped system as evident from Table *3*, which signifies that the system oscillates for some time until vibration gradually decays. The time for oscillations can be characterized from the settling time as shown in Figure *8* for 45-degree position.

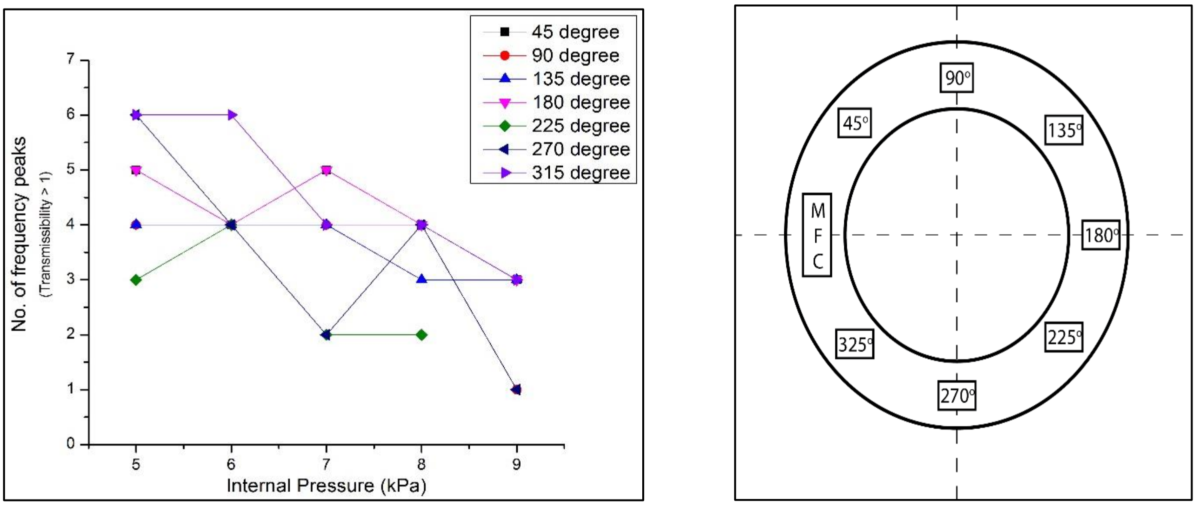

Figure 6. Variation of frequency peaks with pressure

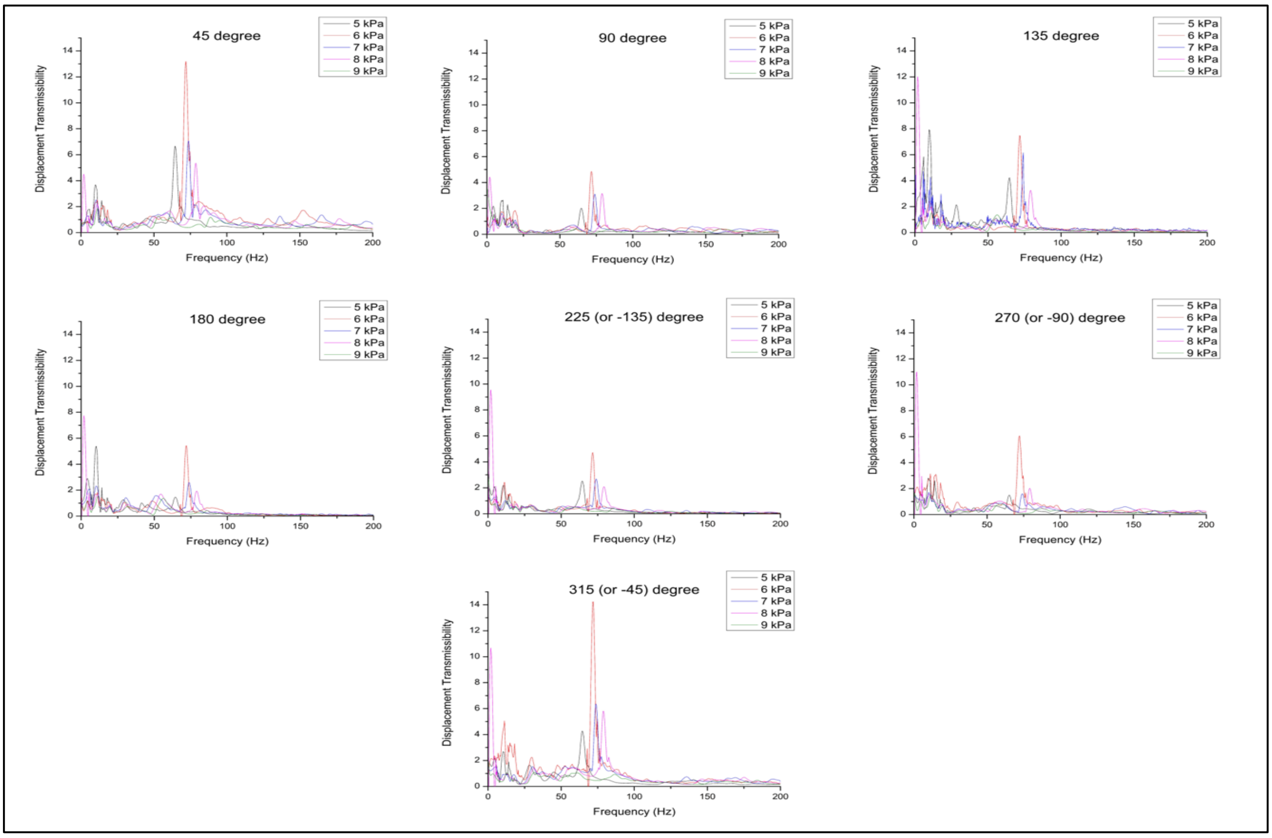

Figure 7. Effect of measuring position

Table 3. Peak frequencies and Damping ratio

Actuator position	Sensor location	Pressure									
		5 kPa		6 kPa		7 kPa		8 kPa		9 kPa	
		Peaks (Hz)	Damping ratio	Peaks (Hz)	Damping ratio	Peaks (Hz)	Damping ratio	Peaks (Hz)	Damping ratio	Peaks (Hz)	Damping ratio
0 degree	45 degree	5.2	0.27	10	0.18	4.4	0.37	1.87	0.48	11.5	0.13
		10	0.12	71.8	0.018	10.3	0.12	11	0.14	54	0.03
		14	0.05	128	0.025	73.7	0.015	78.7	0.015	88.7	0.025
		45.2	0.09	152	0.03	136.3	0.016	177	0.02	Nil	Nil
		64.4	0.02	Nil	Nil	164.8	0.018	Nil	Nil	Nil	Nil
	90 degree	4.4	0.22	5.3	0.35	5	0.34	1.9	0.47	11.5	0.14
		10.4	0.11	9.7	0.14	10	0.12	11	0.15	Nil	Nil
		14	0.06	19.4	0.07	19.4	0.07	16	0.07	Nil	Nil
		64.7	0.02	71.6	0.02	73.8	0.02	78.9	0.02	Nil	Nil
	135 degree	6	0.15	10	0.15	6	0.36	1.8	0.48	4.4	0.25
		9.7	0.11	15	0.09	11.2	0.15	11	0.15	11.6	0.11
		28.3	0.05	18	0.06	18	0.11	79	0.016	56.2	0.05
		64.7	0.02	71.7	0.016	74	0.02				
	180 degree	4	0.4	11.2	0.15	5.4	0.27	1.8	0.55	4.4	0.25
		10.3	0.11	13.7	0.09	10.3	0.15	11	0.15	11.6	0.11
		14	0.02	29.4	0.06	30.3	0.08	54.4	0.05	56	0.05
		29	0.09	71.8	0.02	51.5	0.07	74.8	0.02	Nil	Nil
		64.4	0.025	Nil	Nil	73.7	0.02	Nil	Nil	Nil	Nil
	225 degree	4.4	0.3	4.4	0.4	4.4	0.45	1.85	0.47	Nil	Nil
		10.3	0.12	11.2	0.08	74	0.017	79.2	0.016	Nil	Nil
		64.3	0.02	15	0.098	Nil	Nil	Nil	Nil	Nil	Nil
		Nil	Nil	71.5	0.015	Nil	Nil	Nil	Nil	Nil	Nil
	270 degree	4.4	0.32	2	0.89	10	0.14	2	0.42	11.7	0.15
		7	0.04	11.2	0.12	74	0.016	5.3	0.02	Nil	Nil
		9	0.12	18	0.05	Nil	Nil	10	0.24	Nil	Nil
		14	0.05	74	0.016	Nil	Nil	79	0.012	Nil	Nil
		17.8	0.04	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
		65.3	0.02	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	315 degree	4.4	0.36	11.2	0.09	5	0.55	2	0.44	13	0.12
		10.3	0.11	15	0.08	30	0.07	31.3	0.07	31.8	0.09
		14	0.04	18	0.03	52.6	0.15	59.3	0.09	60.6	0.08
		28.2	0.08	29.8	0.05	73.8	0.016	78.8	0.016	Nil	Nil
		44.7	0.07	57.5	0.06	Nil	Nil	Nil	Nil	Nil	Nil
		64.4	0.02	71.8	0.016	Nil	Nil	Nil	Nil	Nil	Nil

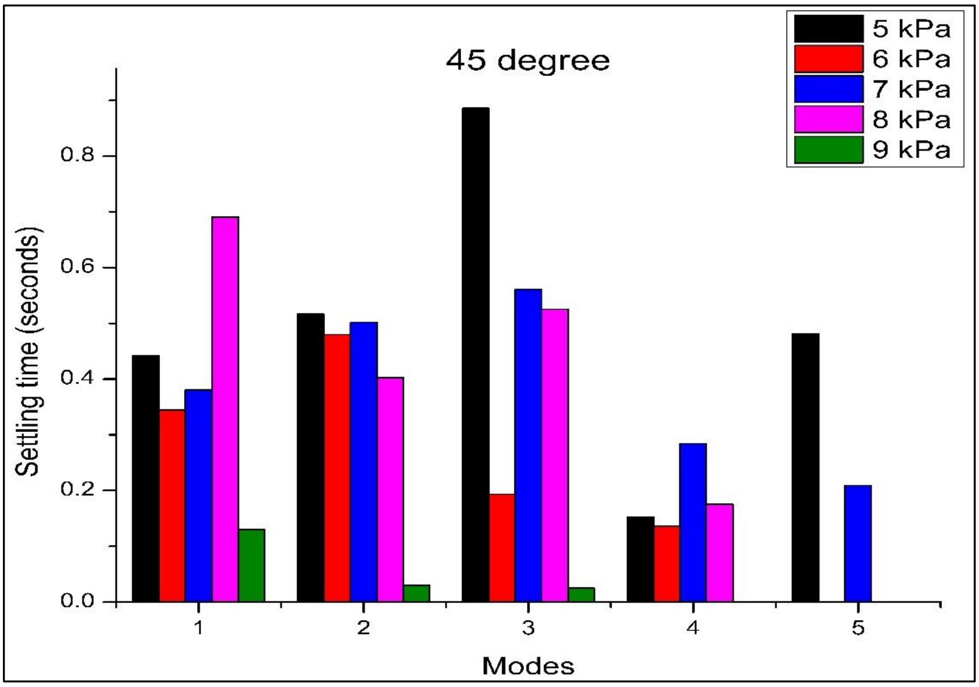

Figure 8. Settling time (45-degree position)

4. Future Work

The future work in this direction includes the measurement of in-planes modes at the corresponding pressures using MFC as a sensor also, thus replacing LDV which will be followed by simulating the same on a finite element software and eventually carrying out similar investigations on the torus of various materials such as Kapton, Kevlar, etc.

5. Acknowledgement

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