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Engineering Notes

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Multiple Sensors and Actuators for Vibration Suppression of an Inflated Torus

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Introduction

INFLATABLE structures have gained significant attention over the past few decades for future space applications because of their potential low mass and ability to become extremely large once deployed. One particularly important task is to understand the dynamic behavior of satellite structures because they are subjected to a variety of dynamic loadings. However, in the case of an inflatable satellite their extremely low mass, flexibility, and high damping properties pose complex problems for dynamic testing and analysis. The choice of applicable sensing and actuation systems suitable for use with inflated structures are somewhat limited because of their low stiffness, curved surfaces, and high flexibility. For instance excitation methods have to be carefully chosen because the exceptionally flexible nature causes point excitation to result in only local deformation. Griffith and Main[1] used a modified impact hammer to excite the global modes of the structure while avoiding local excitation. Slade et al.[2] tested an inflated torus attached to three struts with a lens in both ambient and vacuum chamber. Significant differences were found in the structures response in ambient and vacuum conditions. Although these early studies made significant grounds in the dynamic testing of inflated structures, both encountered problems associated with their measured data. Slade et al.[2] were unable to obtain consistency between tests when using a laser vibrometer because of their choice of excitation and suspension methods. Additionally, Griffith and Main[1] were unable to achieve high coherence when measuring a frequency response of the inflated torus.

However, recent progress in the development of new piezoelectric actuators has changed the way that inflatable structures are tested. Park et al.[3,4] were the first to investigate the feasibility of using smart materials, such as polyvinylidene fluoride (PVDF) films, to find modal parameters and to attenuate vibration in a flexible inflated structure. Their study found that one piezoelectric actuator can sufficiently excite the global modes of a scaled inflated structure, allowing a full modal analysis to be performed. Furthermore, it was found that excitation methods using smart material did not interfere with the suspension modes of the free-free torus as other methods do. Since the work of Park et al.,[3–5] piezoelectric materials have been shown to be a logical choice for sensing and actuation of inflatable structures.

In previous studies it was shown that one macrofiber composite (MFC) can globally excite the modes of a scaled inflatable torus, but it is unlikely that a single actuator could excite the enormous structures intended for space. Therefore, in this study we will investigate the use of multiple sensors and actuators to measure and suppress the vibration of an inflated torus. Additionally, it will be shown that the recently developed MFC actuator[6] can be used as either a sensor or actuator for global control of a flexible inflatable structure; the sensing capabilities of the MFC have not been previously demonstrated. Our experimental results show that multiple sensors and actuators allow for global control of the inflated torus. While adding multiple sensors and actuators increases the authority over the structure, when using positive position feedback control techniques the effectiveness of the controller is limited by the location of sensors/actuators and the mode intended to be controlled. The variability in performance of the controller can be attributed to phase differences in the mode being measured incurred by the relative location of the sensors and actuators to one another.

Multiple MFC Sensors and Actuators for Vibration Control of an Inflatable Torus

In the following sections, it will be shown that multiple MFC actuators can be used as either a sensor or an actuator for global vibration suppression of an inflatable structure. The MFC is constructed using piezoceramic fibers, which allow the actuator to be extremely flexible. The flexibility of the MFC allows it be integrated in an unobtrusive way into or onto the curved surface of an inflated structure. In addition to being flexible, the MFC can produce significantly more strain energy than that of a typical piezoceramic actuator as a result of the use of interdigitated electrodes that capitalize on the higher d_{33} piezoelectric coefficient. The MFC actuator is also far more robust to damage than monolithic materials because of the piezofibers being embedded in an epoxy matrix, allowing the actuator withstand substantial damage, including cracks and impacts. The robustness is one of the foremost important characteristics for the use in space applications where the actuator cannot be easily replaced. Because of these reasons and previous studies, it has been concluded that MFC are the ideal choice for use with in inflatable structures.[3–5]

Previous studies[3,4] have shown that one MFC patch can sufficiently excite the global modes of a scaled inflated torus for a modal analysis to be performed. However, the actual inflatable satellites intended for use in space would have a diameter as large as 30 m,

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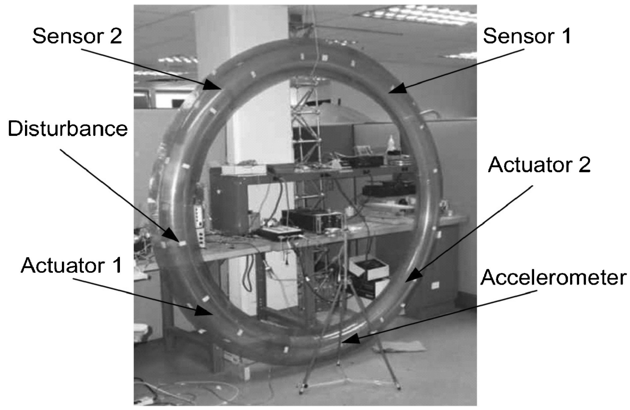

Fig. 1 Inflated torus suspended in free–free boundary conditions.

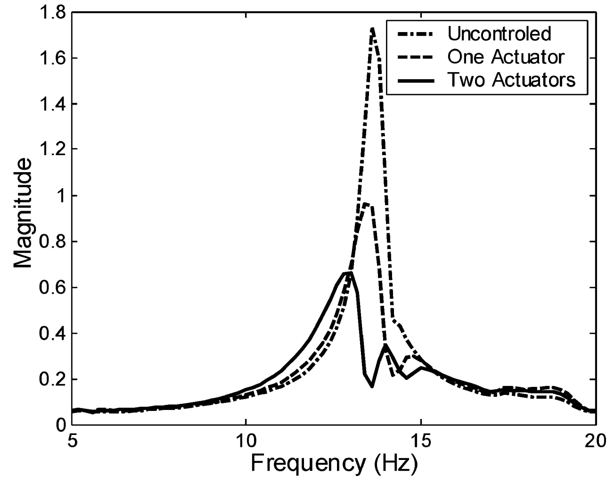

Fig. 2 Frequency response of the first mode with no control, one actuator, and two actuators.

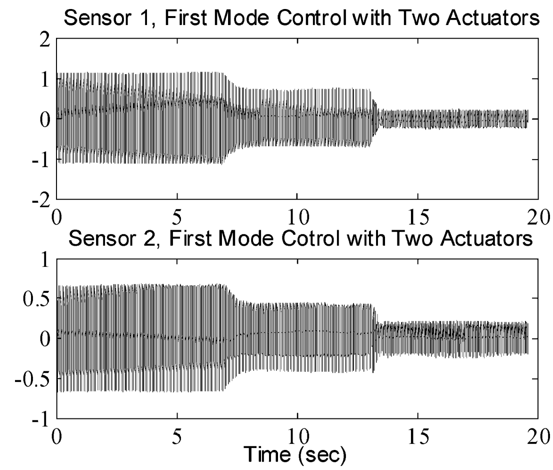

Fig. 3 Time response of the torus before and after control was applied.

and it is unlikely that one actuator could excite a structure of this size. Therefore, to develop control systems that are applicable to the actual inflatable satellites it is necessary that multiple sensors and actuators are used to suppress the vibration of the inflated structure. In addition, the inflated torus is a symmetric structure that contains repeated resonant frequencies, making it necessary that multiple actuators be used to globally suppress the vibration. The problems associated with the control of an inflatable torus with repeated modes are discussed by Jha and Inman.[7] However, experimental implementation of multiple sensor/actuator for vibration control of inflatable structures has never been investigated.

The work presented in this research develops a positive position feedback controller (PPF)[8] using two pairs of sensors and actuators. It will be shown that when using PPF techniques on a symmetric structure the relative location of the sensors and actuators influences the ability of the control system to attenuate certain modes of the structure. This causes the position of the sensors and actuators to work for one mode but not for another.

Experimental Setup

The test structure is an inflatable torus made of flat sheets of 46-μm polyimide film Kapton with a 1.8-m ring diameter and a 0.15-m tube diameter suspended in free–free boundary conditions as shown in Fig. 1. The internal pressure of the torus was maintained at 0.5 psi using a small aquarium pump. The sensing and actuation was realized using the MFC actuator, while the disturbance excitation was introduced using an electromagnetic shaker input with a coin-sized plate attached at the tip of the shaker to better distribute the energy and avoid local deformation. To ensure the response of the torus found using a MFC was accurate, an accelerometer (PCB Model 352C22) sensor was attached to the torus for comparison during the tests. The accelerometer had a mass of only 0.5 g, and therefore mass loading was not an issue. The accelerometer also played the role of measuring the vibration of the system before and after control was applied.

Results of Control Experiments

Two pairs of sensors and actuators were applied to the torus in the configuration shown in Fig. 1. The PPF controller was implemented and adjusted in real time using the dSPACE control board (model DS1102). It was found that control systems developed using MFC as both actuators and sensors were capable of significantly reducing vibration levels of the first mode in the torus. In one experiment, a control system was designed to attenuate vibration in the first out-of-plane mode (12.8 Hz) of the torus. Figure 2 shows the frequency response of the system before and after PPF control was applied. The time response of the vibration before and after the control system was applied is shown in Fig. 3. In Fig. 3, the uncontrolled vibration is shown until the first sensor/actuator pair is turned on at 7 s, and the second pair of sensor actuator is turned on at 13 s. The top plot is the response of sensor one, and the bottom plot is the response measured by sensor two. It can be seen from Fig. 3 that when one set of sensors and actuators is turned on there is a reduction in vibration level of approximately 50%. When both pairs of sensors and actuators are turned on, a more significant vibration was observed on the order of 80% reduction. An important point shown in this figure is that there is a global reduction in vibration. This can be presumed because the vibration is reduced at two locations that are not in close proximity to each other. In two previous studies, control of the first out-of-plane mode of an inflatable torus has been performed using smart materials. In Park et al.[3] a PVDF patch was used and only achieved 50% vibration reduction, later; Ruggiero et al.[9] used a signal MFC to achieve 70% vibration reduction; however, the controller had a poor settling time and appeared to be approaching instability because of a beat in the time response. Additionally, neither of these studies demonstrated global control of the structure. Therefore, the controller utilizing multiple sensors and actuators provides more significant vibration reduction than those previously implemented and provides a more stable response. As the bonding condition improves, it is expected that the control authority over the whole structure would increase.

After demonstrating that the control system was capable of supplying significant vibration reduction to the first mode, our next experiment was to apply vibration control to the second mode. To do so, a similar PPF controller was designed, and the same orientation of the sensors and actuators, shown in Fig. 1 was used. However, when the control scheme was applied to the second mode, significantly different results were observed. The time response of the second mode before and after control was applied as shown in Fig. 4. In Fig. 4, the uncontrolled vibration is present until the first sensor/actuator pair is turned on at about 6 s, followed by the second

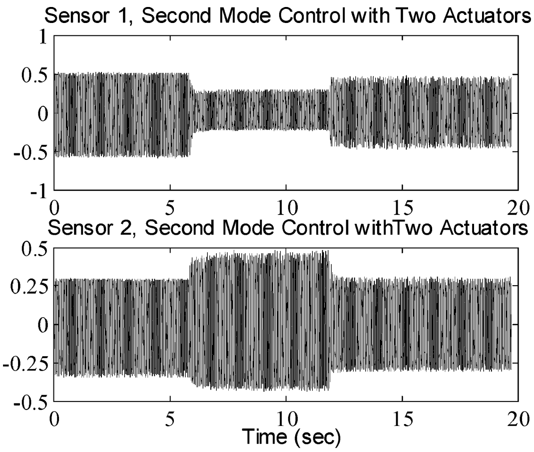

Fig. 4 Time response of the second mode before and after control was applied.

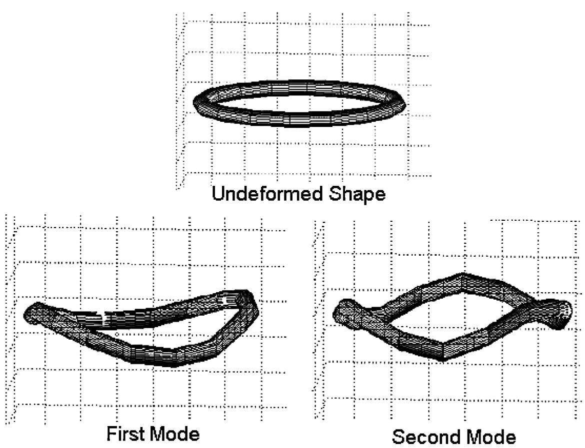

Fig. 5 First two out-of-plane mode shapes of the torus.

sensor/actuator pair turned on at about 12 s. When the first actuator is turned on, the vibration is reduced at sensor one's location but increased at sensor two's location and likewise when actuator two is turned on. This effect shows that the control system is ineffective at globally reducing the torus's second mode of vibration.

The results of the second mode experiment can be explained for two reasons, the relative phase of the sensor and actuator, and the existence of repeated frequencies and modes. The first reason can be seen by looking at Fig. 5, which shows the first two out of plane mode shapes of the torus.[5] Recalling the setup of our control experiment from Fig. 1, each sensor is located 180 deg from its corresponding actuator. Now looking at Fig. 5, the first mode has the same displacement at any two points 180 deg apart, but in the second mode the displacement is the same at any two points 120 deg apart. Because the sensors and actuators are located 180 deg from one another, when controlling the first mode they are experiencing the same vibration and can be considered in phase, but at any mode higher than the first mode, the sensor and actuator are experiencing significantly different vibrations and are out of phase. Because positive position feedback techniques rely only on a filter and not an analytic model, it is very important that the sensor and actuator be in phase and experience the same dynamics. In this case they are not in phase resulting is an ineffective controller. Therefore, this orientation of sensor and actuator with a PPF control scheme will only achieve global vibration reduction during the torus's first mode of vibration. The current setup could be made effective if an accurate model of the system was known and a different control method was used. However, the formulations of the model for a prestressed toriodal shell are nonlinear and very difficult determine (for more information on the modeling of a toroidal shell see Ref. 10). Because of the difficulties in modeling such a complex structure, control techniques that do not rely on an accurate model are all that can be performed on inflatable structure at this point.

The second issue that arises in performing control on the toroidal structure is the presences of repeated natural frequencies and mode shapes in the symmetric structure.[7] Because of the presence of repeated frequencies, the controller is required to have at least the same number of actuators as the number of times the resonant frequency is repeated. In this case, the control system that was designed might have worked because there were two repeated frequencies and two actuators present. However, because of the problems associated with the layout mentioned earlier and the complication requiring two actuators, the structure was unable to be controlled. The combined effect of these two issues is that the control system allows the mode shapes to rotate around the symmetric structure instead of globally suppressing them. This effect explains why an increase in vibration occurs at one sensor and a decrease at the other. For the control experiment to work on the second mode of the inflatable structure, the layout of the sensors and actuator needs to be reconfigured keeping in mind the presence of repeated frequencies that might cause spillover or perhaps additional actuators might be needed.

However, a solution simpler than determining the ideal locations of the sensors and actuators for each mode and one that would also allow the sensors and actuators to always be in phase exists. This solution is to use the self-sensing control techniques developed by Dosch et al.[11] In this configuration the sensor and actuator would always be in phase for every mode shape because they would be perfectly collocated. In addition, if a model were used to find the ideal location of the sensors and actuators, in-orbit changes in pressure as the satellite travels from orbital night to orbital day along with other possible changes would cause these locations to become ineffective at times. Therefore, the ideal location of both sensor and actuator that would allow for control of all modes regardless of parameter changes of the torus would be collocated, which can only be truly achieved using self-sensing actuators. Further, the use of self-sensing techniques would allow the number of actuator patches applied to the torus to be cut in half, in turn, reducing the amount of areas containing localized stiffness effects, number of patches that could be damaged, and the amount of hardware attached to the structure.

Conclusions

Inflated space structures have become popular over the last few decades because of their potential low mass and flexible nature allows them to be compactly packaged while in the cargo bay of the launch vehicle. Although this type of structure holds many advantages for use as a satellite, it poses certain difficulties for vibration testing and control. In this paper the use of multiple sensors and actuators for vibration suppression has been investigated. A positive position feedback control system that consisted of two pairs of sensors and actuators was implemented. It was found that both pairs functioning together could effectively reduce the vibration of the first mode by approximately 70%. Following the successful control of the first mode, a similar controller was implemented on the second mode of vibration. However, the controller was found to be ineffective. Reasons for the controller's poor performance were detailed, and it was suggested that the use of self-sensing actuators would alleviate many of the controller's short comings.

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