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Active vibration control of a three-stage tensegrity structure

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ABSTRACT

This experimental study demonstrates the efficiency of simple control strategies to damp a 3-stage tensegrity tower structure. The tower is mounted on a moving support which is excited with a limited bandwidth random signal (filtered white noise) by a shaker. Our goal is to minimize the transmissibility between base acceleration and top plate acceleration using piezoelectric displacement actuators and force sensors collocated at the bottom stage of vertical strings. Two types of controllers have been designed, namely, *local integral force feedback control* and *acceleration feedback control*. It can be shown that both controllers can effectively damp the first 2 bending modes by about 20 dB, and the acceleration feedback controller performs even better as it can also reduce the amplitude of the next 2 bending modes by about 5-10 dB.

Keywords: Tensegrity Structures, Vibration Control, Active Damping, Integral Force Feedback Control, Acceleration Feedback Control

1. INTRODUCTION

Vibration control of structures can be achieved by passive and active damping methods. The passive approach requires the detailed understanding of structural dynamics and materials properties. The performance may be limited by the environment and choices of material. On the other hand, the active approach requires sensors and actuators connected through a feedback control. In some cases, the active approach may allow for a low budget construction cost and simply designed structures since a stringent material constraint is not imposed. It may offer better performance and adapt to different environments compared to passively damped structures.

The tension-truss concept has been employed in some space antennas and space structures. It is the solution for sending large structures into space due to the limited capacity of launch vehicles. The use of tension members (strings/tendons/cables) in trusses enables the structures to be lightweight and deployable. By adjusting the tension of the members, the structure can be strong and stiff; the geometrical uncertainty can be eliminated and the resonance frequency of the structure can be shifted in some circumstances. The tension members can serve as actuators if a proper actuation system is implemented. With a control system, the tension structure can be a “smart” structure.

Tensegrity structures are very special cases of tension-trusses. They are built of bars and strings which are attached to the ends of the bars.[1] Members are assigned for special functions: the bars are always axially loaded and resist compressive force while the strings are in tension but can be slack. The ends of a bar can be

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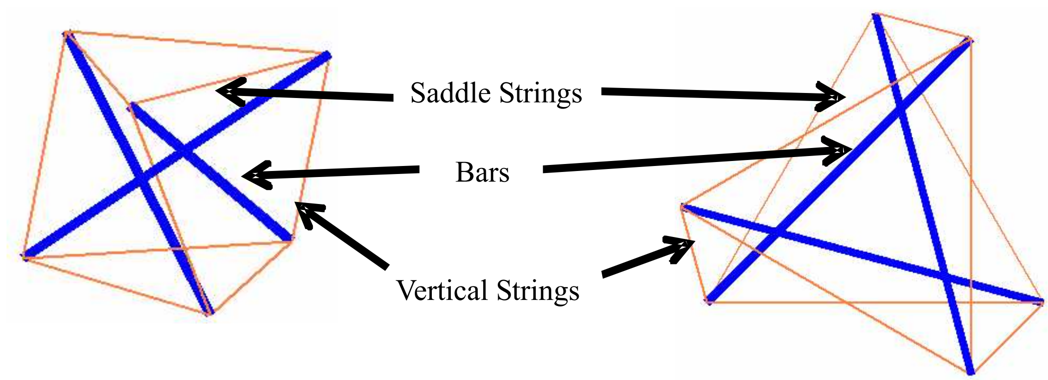

Figure 1. A 3 Dimensional Stable 3-Bar Unit: Perspective View (Left) and Top View (Right)

attached to strings or ball jointed to other ends of bars, but cannot be attached to each other through joints that impart torques. Most bar-string configurations which one might conceive are not in equilibrium, and if actually constructed, will collapse to a different shape. Only bar-string configurations in a stable equilibrium will be called tensegrity structures.[2] One of the important properties of tensegrity structures is the prestressability, which means the structures are in a stable equilibrium for a variety of tension values.[3] If well designed, the application of forces to a tensegrity structure will deform it into a slightly different shape in a way which supports the applied forces.

A given tensile or compressive member of a tensegrity structure can serve multiple functions. It can simultaneously be a load-carrying member of the structure, a sensor (measuring tension or length), an actuator (such as nickel-titanium wire), thermal insulator, or electrical conductor. In other words, by proper choice of materials and geometry, a grand challenge awaits the tensegrity designer: How to control the electrical, thermal, and mechanical energy in a material or structure? Tensegrity structures provide a promising paradigm for integrating structure and control design.

Some applications currently being investigated include shape controllable wings which are light, stiff, and deployable. Other applications include large tensegrity towers used for a variety of optical pointing experiments such as a large based telescope. These structures will demonstrate the integration of control and structure design for high performance applications, they will also include active vibration control to meet the performance requirements of accuracy in pointing.

In this paper, we focus on the vibration control in tensegrity structures. A 3-stage 3-bar class-1 tensegrity tower was manufactured, with piezoelectric force sensors and displacement actuators collocated at the bottom stage of the vertical strings. The structure is mounted on a shaker table which provides vibration to the bottom of the structure. The objective of the experiment is to reduce the vibration of the top of structure using active damping methods. Two types of controllers have been designed, namely, *local integral force feedback control* and *acceleration feedback control*. The integral force feedback control utilizes the information from the force sensors for the feedback control and so it is local control since the objective information (the top plate acceleration) is not feedback directly to the controller. In the acceleration feedback control, the top plate acceleration is used directly for feedback. The experimental results show that both controllers can effectively damp the first 2 resonant modes by about 20 dB, and the acceleration feedback performs better as it can also reduce the amplitude of the next 2 resonant modes by about 5-10 dB.

2. EXPERIMENTAL SETUP

2.1. Tensegrity Structure

Tensegrity structures are natural candidates to be smart or actively controlled structures since the control system can be embedded in the structure directly; for example string can act as actuators and/or sensors. Shape control

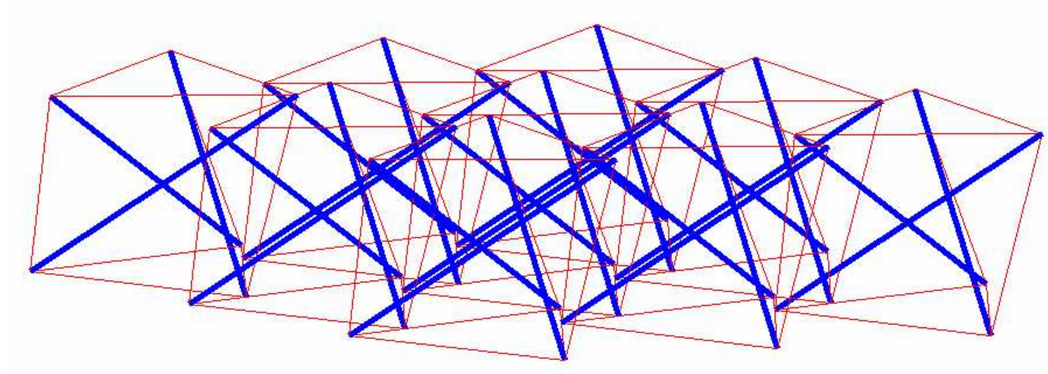

Figure 2. A 9 Stable 3-Bar Units Tensegrity Plate

of the tensegrity structures can be accomplished by moving along the equilibrium manifold.[1,4] The current design of future large space telescopes relies heavily on the use of lightweight deployable structures (example: NASA-TPF ESA-DARWIN). Large truss structures would support various optical instruments. This concept will certainly require the supporting structure to be actively controlled, to achieve stringent stability and pointing capabilities. Tensegrity is a good candidate for such structures (light, versatile). Figure 1 shows a simplest 3-dimensional tensegrity unit. It is a 3-bar 9-string prestensioned structure. The 3 bars can be twisted either in clockwise or in counterclockwise direction. The twist angle between the top and bottom triangles is always 30°. The strings in the top and bottom triangles are referred to as "Saddle" and the remaining 3 strings as "Vertical". A plate topology, as shown in figure 2, can be formed by a collection of this unit. It can be shown that the flat plate can be deployed into a curved plate if the lengths of all strings are controlled properly.[5]

The experimental hardware is shown in figure 3. A tensegrity tower is mounted on a shaker table which generates vibration in a single direction. Sensors and actuators are collocated at the bottom stage of the structure. Accelerometers are attached to the top and bottom of the structure in order to measure the vibration and the acceleration of the top of tower. A computer will perform data acquisition and control processes.

2.2. Tensegrity Tower

The tower in the experiment is the type of structure utilized in the Snelson's Needle Tower.[6] It is constructed by three 3-bar units stacking up in the vertical direction. The units are overlap to each other and additional "Diagonal" strings, which connected adjacent units, were added to stabilize the tower.[7] The bars in each stage are arranged to have different twisting compared to the adjacent stage. Both the top and bottom of the tower are mounted to rigid plates. The structure is referred to as class-1[1] since every nodal point is connected to 1 bar only. The following are the details and design information of the structure.

- The structure consists of 9 stainless steel tubes. Each tube is 18 inches long with a 5/16 inch diameter and a 0.030 inch wall thickness.
- There are 12 Saddle, 9 Vertical and 12 Diagonal strings. Spectra fiber 65Lb test line is used for these tendons.
- The height of the structure is 36 inches.
- The structure is cylindrical and the theoretical position for all nodal points should lie on a vertical cylinder with a 7.6 inch diameter.
- The structure is mounted on a supporting aluminum plate which is attached to a shaker table as shown in figure 3. A 0.5 inch thick Plexiglas plate is mounted on the top to allow the installation of accelerometers.

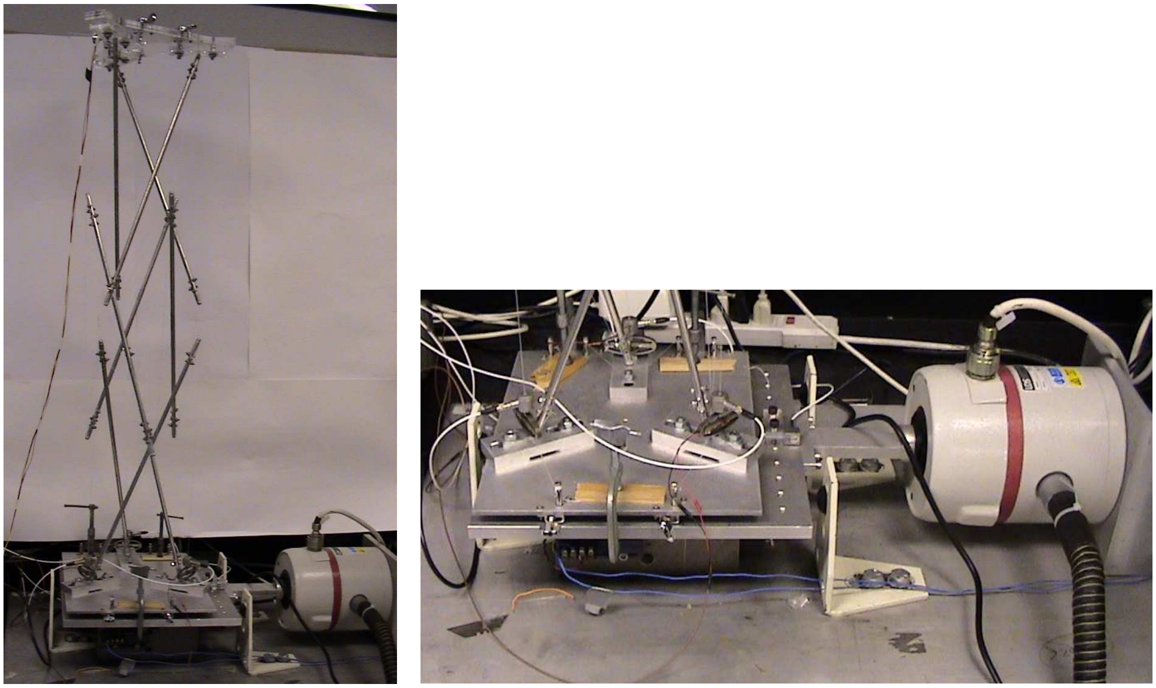

Figure 3. Experimental Setup

- The ends of each bar are aluminum spherical joints with holes for strings attachment. Every string is passed through the holes and connected to the adjustable screws on the bars. The screws can adjust the length and tension of strings.

2.3. Sensors and Actuators

It is natural to choose strings as the candidate for installation of actuators in the tensegrity structure since strings are easily replaceable. By changing the length (and hence the tension) of strings, the static and dynamic behavior of the structure will be altered[8] for various applications. Piezoelectric force sensors(ICP 208C01) and displacement actuators(APA 100M) are chosen for this experiment for several reasons. Firstly, they are lightweight, which will not affect the dynamics and weight of structure significantly. Secondly, they have a fast response, which is an essential consideration in vibration control. Thirdly, they are easily installed which will not create any redesign problem. In this experiment, the collocated[9] pair of sensors and actuators are installed in each vertical string of the bottom stage as shown in figure 4. Only 2 actuators were used for the active control implemented in this experiment.

2.4. Accelerometer

Accelerometers are mounted to the top plate and the shaker table. They measure the acceleration in the same direction as the shaker excitation. Therefore, the bottom accelerometer will measure the acceleration of the shaker vibration and the top accelerometer will measure the top plate acceleration in the direction parallel to the shaker excitation.

3. ACTIVE DAMPING CONTROL

The active damping methods are more versatile than passive damping in vibration control. The concept of active damping is to use actuators to remove energy from structures during vibration. It requires sensors to detect the vibration and a controller to determine the required damping. In the space station and aerospace

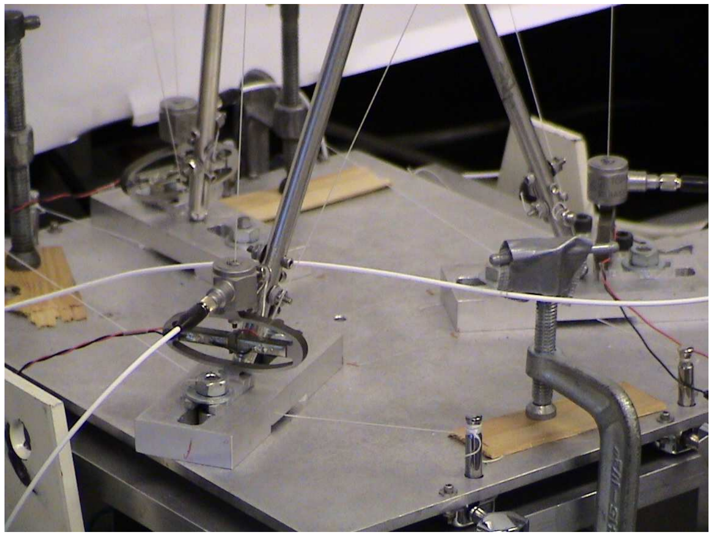

Figure 4. Collocated Sensor and Actuator in the Vertical String

structures, vibration can be caused by thermal expansion, solar radiation and atmospherical fluctuation. Sometimes, deployable space structures are subject to stringent geometrical constraints, therefore small vibrations can be problematic and may lead to malfunctions or even disasters. Hence, vibration control is a major issue in deployable structure design and, active damping is a solution to these environmental changes and geometrical constraints. Two types of active damping controllers have been designed in this experiment; namely, *local integral force feedback control* and *acceleration feedback control*.

3.1. Local Integral Force Feedback Control

Integral force feedback control is one of the simplest active damping strategies if sensors and actuators are collocated, since there always exists a control law which removes energy from the structure and no model is required.[9] Here, we assume that the sensors and actuators have no effect on the dynamics of the structure. For the force sensors and displacement actuators used in this experiment, the integral force feedback control law is

$$u = g \int_0^t T(\tau)\, d\tau, \tag{1}$$

where u is the displacement of the actuators, g is some positive constant and T is the force measurement of sensor. This control law is even applicable to nonlinear systems if all the controllable and observable states are asymptotically stable. From this law, the energy flow from the controller is

$$W = T\dot{u} = -gT^2 < 0, \tag{2}$$

which is always negative. Therefore, the controller always absorbs energy from the structure and hence adds damping. Note that this control is decentralized since every sensor signal is feedback to the corresponding collocated actuator.

Figure 5(left) shows the block diagram for the local integral force feedback control in this experiment. We call this control "local", since the local information (bottom vertical strings tension) is used for feedback but not the objective information (top plate acceleration). A high pass filter with cut-off frequency (1 rad/s) is used to remove the static component of the force sensors signal. This static component is due to the prestress characteristic of the tensegrity.

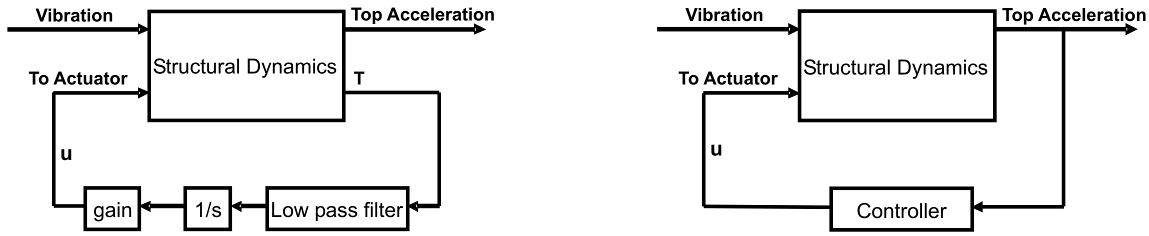

Figure 5. Block Diagram for Tensegrity Vibration Control: Local Integral Force Feedback (left), Acceleration Feedback (right)

3.2. Acceleration Feedback Control

Instead of performing local feedback, we can also design a closed loop feedback control by feeding back the top plate acceleration. Unlike the local integral force feedback control, this control is not decentralized and the action between the 2 actuators are always opposite to each other. The block diagram for the acceleration feedback control is shown in figure 5(right). The acceleration feedback control is an output feedback control problem. Two acceleration controllers have been design. The first controller borrows the same concept from the integral force feedback control, where acceleration is integrated for feedback, so

$$u = \frac{g}{s} y, \tag{3}$$

where y is the acceleration of the top plate and g is the gain. We call this as *integral acceleration control*. Again, this control requires no modelling. The second controller is designed with the aid of modelling and classical control techniques. It is called *compensated acceleration control* and expressed as

$$u = g \frac{s^2 + 80s + (22\pi)^2}{s\,(s + 26\pi)} y. \tag{4}$$

The detail of modelling can be found in F.Bossen's work.[10]

4. EXPERIMENTAL RESULT

The computer generates a band-limited white noise signal to the shaker which in turn vibrates the structure's bottom. Accelerometers record the acceleration amplitude of the top and bottom of the structure during the vibration. Figure 6 shows the relative acceleration (dB) between the top and bottom of the tower. It can be seen that all controllers can achieve significant damping of about 20dB for the first two bending modes (the two very close peaks around 3 Hz), but the integral force feedback is superior to the acceleration controls as it can effectively dampen these 2 resonant modes of the structure over a larger window in the frequency domain. For the next 2 bending resonant modes (2 peaks around 24 Hz), both integral force and acceleration feedback controllers can achieve some damping (less than 5 dB) but are clearly not as effective as for the first 2 bending modes. With the use of compensated acceleration controller in (4), 5-10 dB of damping can be obtained for these modes.

5. CONCLUSION

Local integral force feedback and acceleration feedback control give significant damping for the first 2 resonant bending modes. The acceleration feedback control is even better as it can also achieve effective damping for the next 2 resonant bending modes. But the simplicity of the integral force feedback control gives a promising strategy for future tensegrity vibration control. The experiment in this paper is a one dimensional vibration problem since the excitation and acceleration measurement are in the same direction. Further experiments can be conducted and they will be interesting and challenge problems in the tensegrity design for vibration isolation.

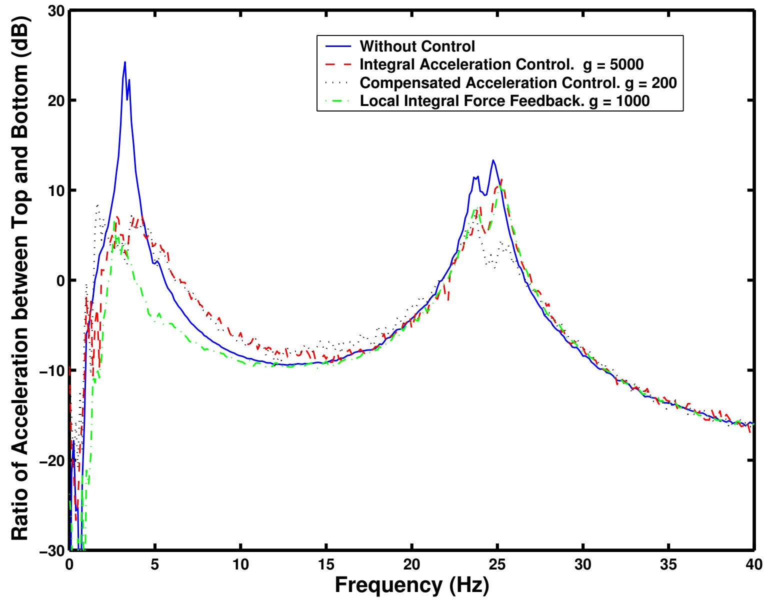

Figure 6. Acceleration Ratio between Top and Bottom Plate (dB) vs Frequency (Hz)

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