Design, Simulation & Control of a Segmented Reflector Test-bed

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Abstract

Segmented reflectors are one of the best practical choices for future astrophysical missions. Because it lacks the dimensional stability provided by a monolithic primary mirror, a segmented reflector requires an active control system in order to make the reflecting surface have comparable optical performance. This paper describes a control oriented test-bed developed at the Control and Structures Research Laboratory (CSRL) at California State University, Los Angeles (CSULA). The CSRL test-bed is a 2.4 m focal length Cassegrain configuration telescope consisting of a 2.66 m actively controlled segmented primary and an active secondary. The primary consists of six hexagonal panels surrounding a fixed central panel and supported by a light-weight flexible truss structure. The project has been funded by NASA to study the complex dynamic behavior of large segmented optical systems.

1. Introduction

One of NASA's missions is the development of large aperture space telescopes. The Precision Segmented Reflector (PSR) and the Next Generation Space Telescope (NGST) programs were geared to develop the necessary technology for implementation of segmented reflectors in space applications. One of the main requirements established by the NGST program is that the future space observatory have a collecting area of at least 4-5 meters in diameter.

Although the dimensional stability provided by a single mirror telescope makes it an attractive choice for space applications, because of the volume and mass constraints during launch, large monolithic telescopes have become impractical. It has been estimated that a 10 meter diameter primary mirror of a monolithic telescope would have the equivalent weight of a fully loaded 747 (Carrier, 1990). This has led to another approach in the design of space telescopes. That is to build a deployable reflector composed of smaller individual mirrors that come together to simulate a single monolithic mirror.

To address issues involved in the control of a segmented reflector, NASA has funded a five-year research project, The Control & Structures Research Laboratory (CSRL) at California State University, Los Angeles (CSULA). The goal of this project has been to design and fabricate a test-bed for a segmented space telescope. This test-bed is capable of performing experiments that simulate the dynamics of a large segmented optical system. It is an experimental tool capable of addressing the technical challenges presented by a complex three-dimensional structure such as Control-Structures Interaction (CSI), distributed control of multi-input multi-output systems, electronics, actuator and sensor design, and digital implementation. It is specifically designed to demonstrate the advantages of decentralized control approach to large scale systems.

In order to enable validation of the control strategies and to achieve the performance of a realistic system, the top level requirements used in the design the test-bed are similar to an actual space-borne system including:

- Figure maintenance to within 1 micron (RMS distortion) with respect to a nominal shape of the primary mirror.
- Pointing accuracy of 2 arc seconds.
- A high level of disturbance rejection (100:1) and attenuation of vibration due to gravity, thermal, and seismic effects and Control-Structure Interaction (CSI). The bandwidth of these disturbances is 0 - 50 Hz.

2. System Description

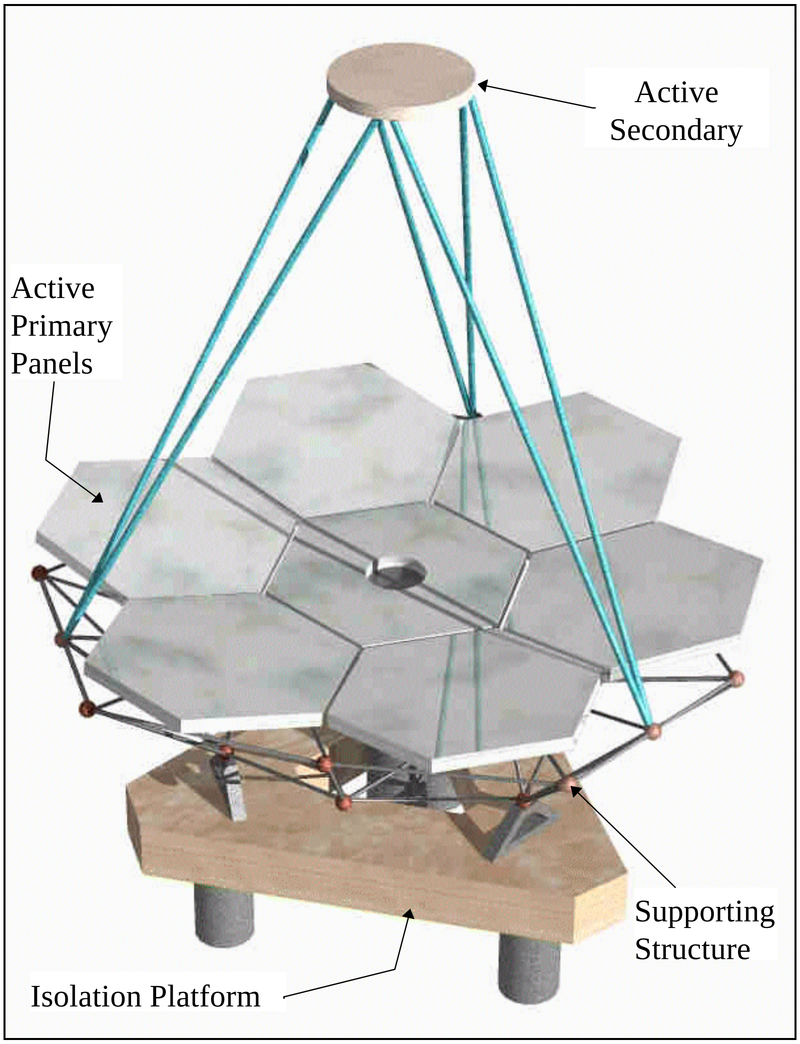

Figure 1: CSRL test-bed

Figure 1 shows the major features of the test-bed, including the primary and secondary mirrors, the supporting structure, and the isolation platform. The active optical elements are the primary mirror segments which interact dynamically with actuators, sensors, and supporting structure. The optical system emulates that of a f/2.4 meters Cassegrain telescope. The major components of the CSRL test-bed are discussed below:

2.1 Segmented Primary Mirror

The CSRL primary mirror is designed to emulate the critical properties of a segmented mirror. These properties include segmentation geometry, inter-segment spacing, segment mass, inertia, stiffness, and optical focal ratio. As shown in Figure 2, the primary mirror is composed of a ring of six actively controlled hexagonal panels arranged around a central panel. The central panel is fixed to serve as a point of reference to the moving panels. Because the test-bed is a control oriented experiment and because of the difficulty and added expense of fabrication of actual optical quality segments made from glass, the panels are fabricated from flat aluminum honeycomb plates. The required paraboloid surface is thus maintained by positioning the flat panels as tangents to that surface.

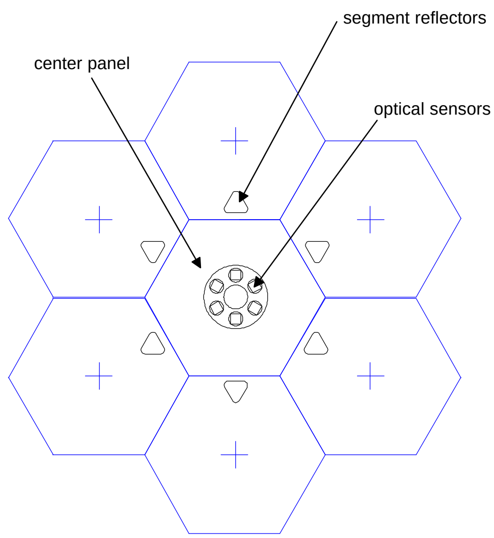

Figure 2: CSRL Primary Mirror

A design requirement for the primary mirror and it's support structure was to separate the controllable from the uncontrollable motions of the panels. This was achieved by mounting the panels on specially designed flexures in such a way as to separate the torsional and lateral motion of the panels i.e. modes that cannot be controlled, from those of the tilt and piston motion i.e. modes that can be controlled. The design parameters were evaluated by performing dynamic analysis on a finite element model. An eigenvalue analysis was performed on a finite element model containing one panel and its support structure. The first three modes of the system, representing the piston and two tilts of the panel occur at substantially lower frequencies than the next modes. They occur within the bandwidth of frequencies required for control of the CSRL test-bed. The design is essentially to create a three degree of freedom system for each panel. The flexures were designed to separate the frequencies of panel motion in the tilt and piston direction from those in the lateral and torsional directions. They are arranged on each panel on a circle an equal distant apart from each other. This arrangement coupled with the piston motion of each actuator allows each panel to behave as a three degree of freedom system.

The active panels are moved by high performance actuators designed for the precision control of the CSRL primary mirror. These actuators have extremely low noise level, are able to generate substantial force over a wide mechanical range, and have a bandwidth sufficient to accommodate the spectrum of the expected disturbances. To avoid friction, disk flexures have been used instead of conventional bearings. The actuators have been fitted with collocated position sensors.

The relative displacement between the edges of adjacent segments is measured by an ensemble of 24 edge sensors. The edge sensors provide information about the panels' displacement relative to the fixed central panel. This information is used in order to determine the position of each panel with respect to an inertial reference. Since each of the 6 panels is a three degree of freedom system, only 18 position values are necessary to determine the shape of the primary mirror. Because of this, the 24 edge sensors provide redundant information about the shape of the primary mirror and must be decomposed into 18 position measurements by the use of a least squares filtering.

2.2 Supporting Structure

One of the fundamental design goals has been a strong, light-weight structure whose structural-dynamic characteristics are representative of a large, flexible space borne system. These include low frequency modes, high modal density and global mode shapes that properly reflect the coupling of the sub-elements of the structure. A careful trade-off between the need for the structure to support itself in the 1-g laboratory environment versus the need to keep the frequency of the first mode as low as possible was achieved using multi-criteria optimization techniques and Pareto optimality concept.

The test-bed is supported on a triangular isolation platform. This platform is an optical bench designed to act as an inertial reference frame for the entire system. It is made of an aluminum honeycomb core with a stainless steel top and bottom skin. The isolation platform is mounted on three passive isolation pillars that provide an isolation system for the structure and the panels in order to remove any outside disturbances from the test-bed.

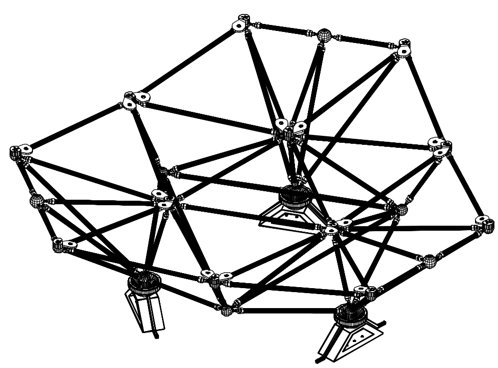

Figure 3: Primary Support Truss

Figure 3 shows the primary support structure. It is a truss made from stainless steel struts connected together with the use of aluminum node-balls and adjustable fittings. Platforms have been placed on the upper level nodes in order to support the actuators and the primary mirror segments. The entire system is mounted on the optical bench using three flexured bipods in such a way as to constraint the structure in only six degrees of freedom.

2.3 Active Secondary Mirror and Optical Scoring System

The CSRL test-bed secondary reflector consists of an actively controlled mirror whose housing is supported by a tripod that is attached to the primary truss at three points. The mirror is suspended from its housing by means of isolation springs as show in Figure 4. In a similar fashion to the primary mirror segments, the secondary mirror has three degrees of freedom consisting of one piston and two tilt motions. The two tilt motions provide beam steering control by removing any angular motion between the primary mirror and the secondary mirror. The piston motion aligns the mirror to the focal plane. The control system hardware consists of a number of reluctance actuators and position sensors.

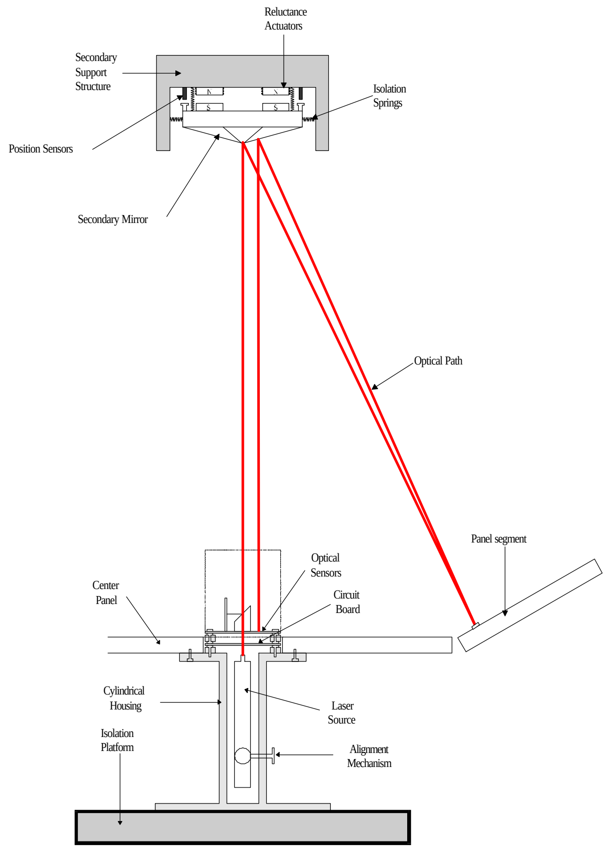

Figure 4: Secondary Mirror & Optical Scoring System

The test-bed has been fitted with an optical scoring system to provide an independent measure of performance. This has been accomplished by the use of a laser source and an optical sensor module. This module, in addition to the secondary mirror module compose the optical scoring system.

The optical scoring system is composed of a laser source which is placed in the center of the primary mirror and is aimed to the secondary mirror. The secondary mirror splits the laser beam and directs it toward each panel. Small mirrors mounted on the edge of the panels return each sub-beam back to the secondary mirror which in turn reflects the beam back to the center of the primary mirror. An array of optical sensors detect any deviation from a reference position (Figure 4).

3. Finite Element Modeling

A Finite Element Analysis (FEA) model including all of the structural components of the CSRL test-bed was constructed using MSC/NASTRAN. It is composed of a model of the following subsystems.

- Primary mirror assembly
- Primary truss
- Bi-pod assembly
- The secondary truss

From an independent study, the natural frequency of a single panel has been shown to be in the neighborhood of 190 - 200 Hz. Since the control bandwidth of the test-bed is only in the 0-50 Hz. Panels were idealized as a rigid body. This idealization has been implemented by modeling each hexagonal segment as an equilateral triangle with vertex at the panel support points. This triangle is made up of high stiffness - low density beams and a distribution of mass at the three vertices. Each panel is attached to the truss by three support assemblies. Each assembly is composed of an idealized three-point model for the flexure/actuator connection as shown in Figure 5.

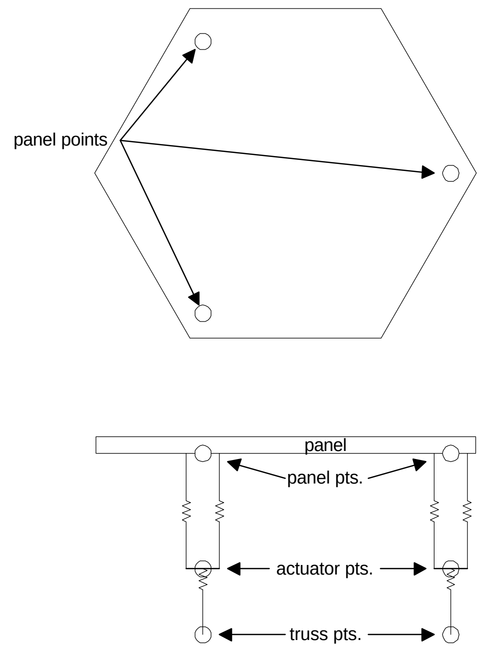

Figure 5: FEA model of the panel and the panel support

The CSRL truss was modeled as a geometric arrangement of the individual struts and node balls. The struts were modeled as a series of beams that include the steel tubes and connector assembly. The physical nodes of the structure are made of solid aluminum nodeballs and were modeled as rigid bodies. Rigid elements and concentrated mass elements were used to represent the stiffness and inertial properties of the nodeballs. The secondary truss elements were modeled in a similar fashion. The secondary mirror was modeled as a concentrated mass that accounts for the inertial characteristics of the mirror and its housing.

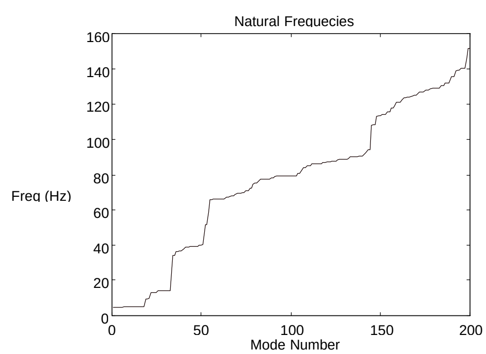

Figure 6: Frequency Histogram

Modal analysis was performed on the finite element model to obtain the global modes of the test-bed. The eigenvalue analysis of the system showed that the lowest natural frequency of the structure is 4.8 Hz. Figure 6 shows the frequency histogram for the first 100 modes of the structure.

In order to characterize the modes, an analysis of the mode shapes was performed. Post processing of the MSC/NASTRAN results was performed with MSC/PATRAN to animate the modes. The first 18 modes represent the piston and tilt motion of the individual segments of the primary mirror (Figure 7). These modes occur at frequencies between 4.8 and 5.2 Hz.

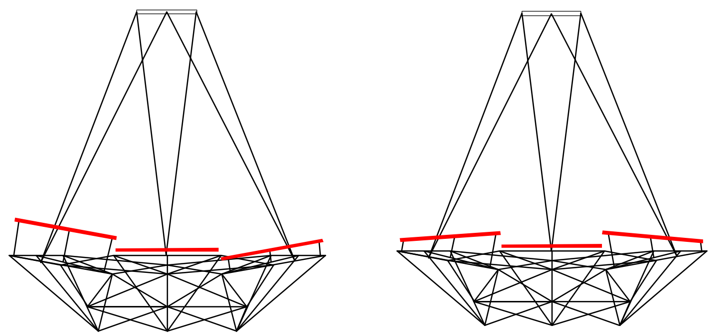

Figure 7: Piston and tilt motion of the primary mirror

Figure 8 shows a representation of the next three modes. These modes occur between 9.3 and 9.9 Hz. They represent a rocking motion of the primary dish and the supporting structure.

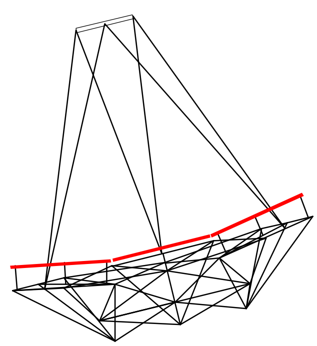

Figure 8: Rocking motion of the test-bed

4. Control System

The CSRL test-bed has an active control system consisting of sensors, actuators, and a computer operated data acquisition system.

4.1 Sensors

The CSRL edge-sensor system consists of 24 position sensors mounted on the peripheries of the six actively controlled panels. The sensors (KDM-8200) were provided by Kaman Instrument Corp. They are low noise, high resolution (1 μm) inductive transducers with a dynamic range of 50,000 Hz. The sensors measure the relative displacements of the edges of adjacent panels. The figure maintenance is achieved through the measurement and control of the relative positions of the panels with respect to the center panel, which acts as a reference.

4.2 Computer Architecture

The sensor signal is first conditioned through a pre-amplifier before being transmitted to an Analog-to-Digital converter (A/D). A Digital Signal Processor (DSP) identifies the current position of the mirror segments. The DSP is a Pentek 4285 board that contains four Texas Instruments TMS320C40 processors running in parallel at 40 MHz. each. It is able to support a variety of multi-input multi-output (MIMO) control algorithms including PID, H_2, H_∞, neural networks, and other adaptive control techniques. It is in charge of real-time processing, memory access, data acquisition and signal generation.

Position commands are issued to a Digital to Analog converter (D/A) which outputs a voltage signal. Both the A/D and D/A stages are executed by a series of Pentek 6102 16-bit converters that reduce the effects of quantization noise. This signal is then sent to a Glentek GA4555P linear amplifier in order to boost the signal power and convert the voltage input from the D/A into a proportional current output.

4.3 Actuators

Eighteen voice-coil linear actuators mounted on specially designed platforms are used for figure maintenance and shape control. The actuators are manufactured by Northern Magnetic Corp. and have a maximum force output of 15 lb., a resolution of 0.1 µm, a stroke of ±2.5 mm and a bandwidth higher than 100 Hz with a collocated position sensor. The position sensors used are the same as those fitted on panel edges and are used to provide an effective overall damping increase.

5. Control Simulations

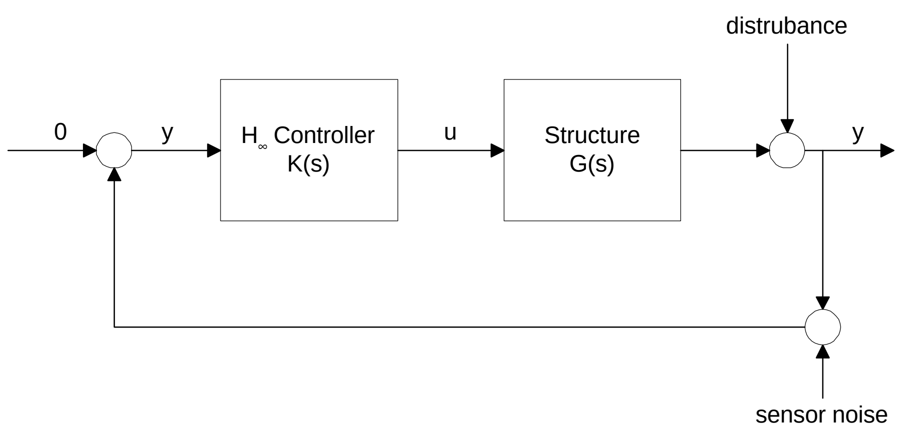

Figure 9: H¥ Control loop

Active control was achieved using an H_∞ control algorithm. The controller was designed to provide vibration suppression, figure maintenance, and shape control of the primary mirror. The controller is composed of six independent 20th order controllers that provide decentralized shape control. Two independent simulations were performed by allowing high frequency noise and low frequency disturbances into the system as shown in Figure 9.

5.1 Vibration attenuation

In order to show the level of vibration attenuation of the system, a high frequency sensor noise was assumed. This noise is shown in Figure 10 and can be described as a multi-channel high frequency sinusoidal excitation. Figure 10 also shows the closed loop response of the six panels. Each curve on the plot represents the position of each actuator in the system. Although the input noise has a high peak to peak amplitude, the output undergoes a 100:1 attenuation which conforms with the general requirements of the CSRL test-bed.

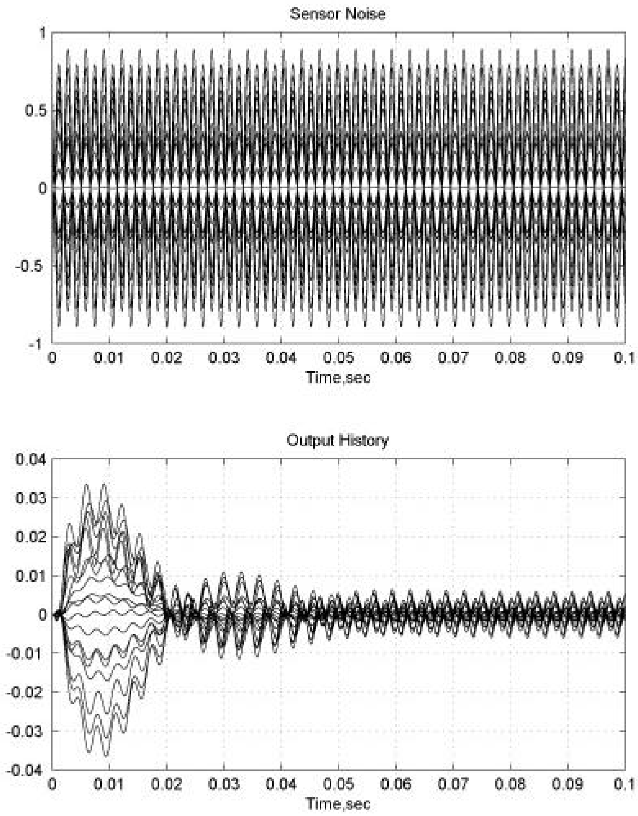

Figure 10: Sensor noise and closed loop response of six panels to H_∞ control

5.2 Figure Maintenance

High amplitude, low frequency disturbances were also applied. These disturbances were randomly selected in a low frequency bandwidth. Figure 11 shows applied disturbances as well as the closed loop time response of the six panels using the H_∞ controller. It is evident that very good figure maintenance is achieved with a very fast response time.

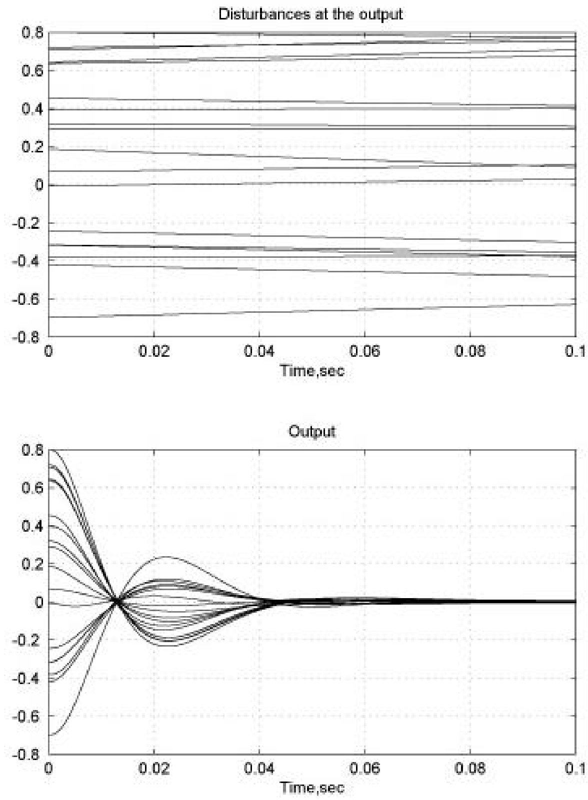

Figure 11: Disturbance input and closed loop response of the six panels to H_{∞} control

6. Summary

This paper described the segmented reflector telescope test-bed developed at the Control & Structures Research Laboratory at California State University, Los Angeles. The test-bed is an experimental facility used to study the effectiveness of space reflectors whose primary mirror is composed of individual segments.

The test-bed emulates a Cassegrain configuration segmented telescope. It is composed of several subsystems including a segmented primary mirror, a supporting truss, and a secondary mirror. Its segmented primary mirror is mounted on a flexible truss which was designed to exhibit the dynamic characteristics of a large flexible structure. A finite element model of the test-bed was developed for analysis. Several simulation studies were performed in order to identify the characteristics of the test-bed. These simulations led to a control model which was then used for control system design.

The test-bed has been fitted with an array of sensors and actuators that together with a digital signal processor and electronics constitute a control system that provides shape and pointing control of the telescope. Several control algorithms have been implemented for shape control of the primary mirror. These include PID, H_2, H_∞ and neural networks controllers.

7. References

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