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On the Caltech Experimental Large Space Structure

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Abstract

This paper focuses on a large space structure experiment developed at the California Institute of Technology. The main thrust of the experiment is to address the identification and robust control issues associated with large space structures by capturing their characteristics in the laboratory. The design, modeling, identification and control objectives are discussed within the paper.

1 Introduction

Advances in technology associated with the control of large space structures are necessary due to the stringent requirements envisioned on the pointing and shape accuracy of future space missions. These structures will be extremely flexible and lightly damped due to their size and the materials used in their construction. Ideally, the use of noncollocated sensors and actuators should be allowed. The sensors should be placed where the performance requirements are defined and the actuators positioned to apply the desired control action.

This paper focuses on a large flexible space structure experiment developed at the California Institute of Technology. The main thrust of this experiment is to capture the characteristics of large flexible structures in the lab and investigate the identification and robust control issues associated with them. The design, modeling, identification and control objectives will be discussed.

2 Objectives

It is desired to develop a systematic approach to identification and control design of large flexible space structures using the Caltech experimental structure as a prototype. This approach should combine information from modeling and identification to develop nominal models and uncertainty descriptions for the structure, actuators and sensors. Formulation of the control problem in this framework allows the application of a robust control design methodology, specifically, μ-based analysis and synthesis techniques. An iterative process would use information gained from the implementation of control designs to refine further the nominal models and uncertainty descriptions, thereby generating updated control designs. The ability to approach the design, analysis and synthesis of control designs systematically for large space structures would greatly enhance their feasibility in the future.

3 Experimental Design

An experimental flexible structure was designed to include a number of attributes associated with large flexible space structures. These include closely spaced and lightly damped modes, noncollocated sensors and actuators, and numerous modes in the controller crossover region. In addition to these considerations, expandability of the structure was a desired feature. Expandability provides a means for increasing the modal density in a frequency range of interest. Another objective was to design the structure to have poor performance with the implementation of a collocated velocity feedback law. Although there has been a large quantity of research devoted to this control problem, other control design approaches may yield more benefit by taking advantage of the multiple sensors and actuators which will be available to the control designer.

The initial experimental structure consists of two stories, three longerons (columns) and three noncollocated sensors and actuators. The first story columns are 33 in. long with the second story columns measuring 29.9 in. Including the platforms, the structure has a height of 65 in. The two platforms are triangular in shape with a 16 in. base and a height of 13.9 in. The longerons are connected between the stories by a triangular mating fixture and three bolts. This allows for the easy addition of stories to the structure. Currently, the affect of the joint nonlinearities will be disregarded. Therefore, all the longerons were shrink fitted and welded to the mating brackets. Issues associated with joint nonlinearities are an area of future research. It is envisioned that the structure will be expanded up to 5 stories in the future.

The first story platform is a 3/8 in. thick plate of aluminum, weighing 5.2 lbs., with diagonal mounting brackets for attachment of the actuator diagonals. The second story platform is a 1/4 in. thick plate of aluminum with mounting holes for three accelerometers, weighing 3.4 lbs. A small offset mass is located on the second story platform to separate the symmetric natural frequencies. The entire structure hangs from a mounting structure fixed to the ceiling. The three actuators are attached to the mounting structure and act along the diagonals of the first story. Hanging the structure from the ceiling alleviates the problem of buckling of the longerons.

The two stories were designed to have the same natural frequency, with the second story columns having a fourth the stiffness of the first. This allows the interaction of the two stories to decrease the first natural frequency of the combined structure without significantly spreading out the remaining modes. Since the two stories have the same natural frequencies, which is close to the first combined structural frequency, fixing the first story to be rigid would provide little reduction in the second floor motion for similar second story excitation. This is similar to implementation of a collocated velocity feedback law at the actuators.

The actuators are a voice coil type design, built by Northern Magnetics Inc., which output a force proportional to an input voltage. The actuators are rated at ± 6 lbs. of force at ±

10 volts and have a bandwidth of approximately 60 Hz. Currently, tests are being performed to model more accurately the input/output relationship of the actuators.

The sensors are Sunstrand QA-1400 accelerometers. These are mounted on the second story platform, located along the x-axis, y-axis and at 45 degrees to both axes. The accelerometers are extremely sensitive and have a flat frequency response between 0 and 200 Hz. The noise associated with them is rated at 0.05 % of the output at 0-10 Hz and 2 % at 10-100 Hz. The sensors are scaled for accelerations of .016 g per volt. This provides a maximum $\pm$ 5 volt output at peak accelerations of the input disturbance. The accelerometer output is conditioned by a 40 Hz, *4th* order Butterworth filter prior to input into the A/D; this provides attenuation of the high frequency response and noise.

The closed loop design is implemented via a 5400 Masscomp computer. The computer control program is designed to sample at 200 Hz and implement a 3 input, 3 output control law. The computer speed is such that a 90*th* order control law, in modal coordinates, can be implemented. The 12 bit A/D has a range of $\pm$ 5 volts, .00244 volts per bit, along with a 12 bit D/A with a range of $\pm$ 5 volts. The noise associated with the computer is $\pm$ 1 lsb (least significant bit). The Masscomp computer is entirely dedicated to the closed loop experiment during realtime implementation.

4 Modeling

A finite element model of the experimental structure was formulated to provide a first approximation to the natural frequencies and mode shapes. The longerons were modeled as having fixed-fixed ends due to the welding of their end connections. The accelerometers, mounting brackets and additional masses were all modeled as concentrated masses. An HP modal test analyzer was used to determine the damping ratios and natural frequencies of the six global modes. This data is tabulated in Table 1. The mode shapes obtained from the finite element model were combined with the experimentally derived damping and natural frequencies to provide an initial plant model. The first group of local modes, which involve bending of the longerons, are in the frequency range of 37 to 42 Hz.

Damping Ratios and Natural Frequencies of the Caltech Experiment

Mode	NASTRAN Natural Frequency (Hz)	Experimental Natural Frequency (Hz)	Damping Ratio	Mode Type
1	.991	1.17	1.8 %	*1st* bending
2	.992	1.19	1.8 %	*1st* bending
3	2.004	2.26	1.0 %	*1st* torsional
4	2.069	2.66	1.6 %	*2nd* bending
5	2.100	2.75	1.8 %	*2nd* bending
6	3.832	4.43	0.9 %	*2nd* torsional

The actuator model was derived from a theoretical model and bench tests. A static test was run for input voltages from $\pm$ 5 volts and the output force was measured. A linear relationship between the input voltage and the output force was formulated. Frequency response data was measured from which the actuator appears to have a 60 Hz bandwidth. Improved actuator models using expanded experimental testing are being formulated.

The accelerometer model was provided by the manufacturer. The sensors are a force balance design with noise values of less than 10 nA rms between 0 and 10 Hz and 100 nA rms between 10 and 500 Hz. Tests were performed to verify the noise characteristics of the accelerometer. Due to the sensitivity of these devices, the accelerometers had to be isolated from the building by hanging them from a 3 ft. rubber band during the tests. It was determined that the building vibration is two orders of magnitude higher than the sensor noise in the low frequency range, with the accelerometer noise on the order of the manufacturer specifications.

The principle of operation for these sensors is that an applied acceleration produces a torque on the pendulous mass located inside the accelerometer. Displacement is sensed by a detector which produces a proportional output voltage. This output is amplified and conditioned, then fed to the torquer coil fixed to the mass. The current through the coil develops a restoring torque equal and opposite to the applied acceleration. The same current is also passed through an external load resistor generating the output voltage which is proportional to applied acceleration.

5 Control Objectives

The control objective associated with this experiment is to provide vibration suppression to the structure at the location of the accelerometers. Minimization of the closed-loop response of the system versus the open-loop response accelerations in the RMS sense along with minimizing the maximum magnitude of the accelerations are two of the performance requirements. A design variable will be the placement of the sensors. The designer is allowed to vary the location of the sensors in an effort to determine its affect on the achievable performance of the structure and vibration suppression at points of interest. The controllers will be designed for a certain robustness and performance level based on the nominal model and uncertainty descriptions. Validation of these levels will be studied on the experimental structure.

Robust control design for closely spaced and lightly damped modes in the region of crossover will also be addressed. Presently, it is unknown how well a system needs to be characterized in a crossover region of high modal density to assure stability in the presence of uncertainties. It is hoped that quantification of the uncertainty level for stability will be defined.

6 Conclusion

A number of goals have been outlined in this paper in regards to the identification and robust control issues in large space structures. The design, modeling, identification and control objectives of the Caltech experimental space structure have been discussed along with the present state of research. To date, a plant model has been synthesized and a single input/single output control design has been tested.

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