

The Process of Control Design for the NASA Langley Minimast Structure *

Gary J. Balas
Dept. of Aerospace Engineering and Mechanics
University of Minnesota
Minneapolis, MN 55455

Peter Young
Dept. of Electrical Engineering
Caltech
Pasadena, CA 91125

John C. Doyle
Dept. of Electrical Engineering
Caltech
Pasadena, CA 91125

Abstract

The NASA Langley Minimast Facility is an experimental flexible structure designed to emulate future large space structures. The Minimast system consists of a 18 bay, 20 meter-long truss beam structure which is cantilevered at its base from a rigid foundation. It is desired to use active control to attenuate the response of the structure at bay 10 and 18 due to impulse disturbances at bay 9 while minimizing actuator torque commanded from the torque wheel actuators. This paper details the design process used to select sensors for feedback and performance weights on the Minimast facility. Initially, a series of controllers are synthesized using H_2 optimal control techniques for the given structural model, a variety of sensor locations and performance criteria to determine the "best" displacement sensor and/or accelerometers to be used for feedback. Upon selection of the sensors, controllers are formulated to determine the affect of using a reduced order model of the Minimast structure instead of the higher order structural analysis model for control design and the relationship between the actuator torque level and the closed-loop performance. Based on this information, controllers are designed using μ -synthesis techniques and implemented on the Minimast structure. Results of the implementation of these controllers on the Minimast experimental facility are presented.

1 Introduction

The objective of active control on the NASA Langley Minimast Facility is to attenuate the response of the structure due to input disturbance excitations entering the structure. The disturbances enter at the midpoint of the structure via three shakers and three torque wheel actuators (TWAs) located on the tip of the structure are used for control. It is necessary to select from a number of displacement and acceleration sensors available which to employ for control feedback.

This paper describes a systematic approach to the selection of sensors to be used for feedback to achieve the performance specifications in the presences of model errors and physical constraints. Upon selection of the sensors, a group of controllers are formulated to determine the affect on performance of using a reduced order model of the Minimast structure as opposed to the higher order structural analysis model for control design. The structural model, actuators, selected sensors, uncertainty descriptions and physical constraints are included in the control design problem formulation and controllers are formulated via μ -synthesis techniques for the Minimast structure. Experimental results of these controllers are presented.

2 The Minimast Facility

The Minimast facility is a deployable and retractable beam truss designed to represent future deployable space trusses [1]. Figure 1, obtained from the paper by Hsieh et. al., shows the Minimast facility located at NASA Langley Research Center [2]. The Minimast facility consists of a 18 bay, 20.16 meter

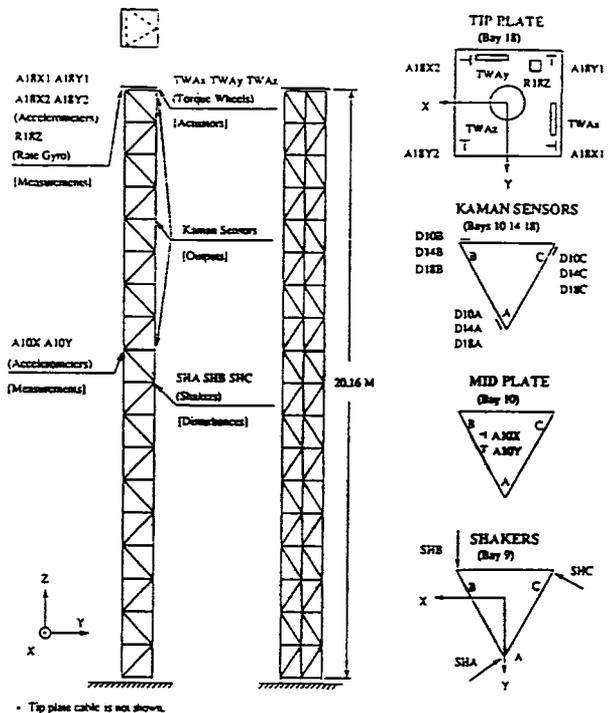


Figure 1: Minimast Facility with Actuator and Sensor Locations

long truss beam structure which is cantilever at its base from a rigid foundation. The structural members of the truss are made of a graphite/epoxy composite material with joints composed of titanium and stainless steel. A cable is attached to the tip of the Minimast structure to off load the 350lb tip mass.

2.1 Actuators and Sensors

The actuators and sensors to be used for control purposes are located on bays 10 and 18. The three torque wheel actuators used for control are located at the tip platform (bay 18) in the x, y and z directions. They are denoted TWAX, TWAY and TWAZ, respectively. The TWAs are represented accurately by second order transfer functions.

$$\begin{aligned} \text{TWX (Input Voltage to Torque (Nm))} &= \frac{34861.3s}{(s+23.50)(s+336.90)} \\ \text{TWY (Input Voltage to Torque (Nm))} &= \frac{38508.9s}{(s+23.56)(s+401.31)} \\ \text{TWZ (Input Voltage to Torque (Nm))} &= \frac{36433.0s}{(s+23.44)(s+372.34)} \end{aligned}$$

The torque wheel actuators can saturate since the input voltage is restricted to between ± 50 volts. This effectively limits the current to the motor with

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the back EMF limiting the speed to 62 RPM. The disturbance excitations enter the structure via three 50lb shakers attached at bay 9 of the structure. The shakers are represented as having no dynamics since their bandwidth is far above the bandwidth of the system. Placement of the actuators and shakers on the structure is shown in Figure 1.

There are two types of sensors located on bay 10 and 18 which are available for feedback: accelerometers and displacement sensors. The accelerometers, Sunstrand QA-1400, have a bandwidth of 0-200 Hz and very low noise characteristics. There are a total of six accelerometers, four of them are located on the tip platform (bay 18) and two of them are located at the mid-platform (bay 10). The accelerometers are located along the x and y axes and are denoted A18X1, A18Y1, A18X2, A18Y2, A10X and A10Y, respectively. Only the accelerometers on bay 18 will be considered for feedback. There are three Kaman displacement sensors located at bay 10 and 18. These are mounted on a support structure parallel to the Minimast platform faces and measure displacement normal to the probe. The Kaman sensors have a range of ± 1 inch at bay 10 and ± 2 inches at bay 18. They are scaled to $\pm 1mv/mil$ and $\pm 0.5mv/mil$ at bay 10 and 18 respectively. The sensor locations can be seen in Figure 1.

All the sensors are filtered through a third order, 10 Hz Bessel filter prior to digitization. The transfer function for the third order Bessel filter is:

$$\frac{7.0653 \times 10^5}{s^3 + 215.734s^2 + 1.9514 \times 10^4s + 7.0653 \times 10^5}$$

There are limitations on the excitation force, control torques and structural displacements to avoid potential damage of the Minimast facility [1,2]. These limitations are accounted for in the control design process.

2.2 Structural Model

A NASTRAN finite element model of the Minimast structure was developed and refined by NASA Langley engineers [2]. The structure is modeled as a six input, 12 output, 28 mode system. The natural frequencies, damping values and mode descriptions for the Minimast model is given in Table 1. A reduced order model of the Minimast structure is formulated based on the first five modes of the structure.

Mode Number	Predicted Frequency (Hz)	Predicted Damping	Mode Description
1	0.83	.018	1st Y Bending
2	0.83	.018	1st X Bending
3	4.37	.012	1st Torsional
4	6.38	.010	2nd Y Bending
5	6.44	.010	2nd X Bending
6	14.72	.005	Tip Plate
7	14.83	.005	Diagonal
8	15.42	.005	1st Axial
9	15.57	.005	Tip Plate
10	15.60	.005	Tip Plate
33	17.17	.005	Diagonal
117	20.29	.005	Tip Plate
118	21.80	.005	Second Torsion
119	23.75	.005	Both Plates
120	25.83	.005	Both Plates
121	31.62	.005	3rd Y Bending
122	33.10	.005	3rd X Bending
123	39.14	.005	3rd Torsion
126	42.46	.005	4th Y Bending
127	45.95	.005	4th X Bending
128	54.14	.005	Tip Plate
129	57.25	.005	4th Torsion
132	60.85	.005	Mid Plate
133	62.68	.005	Tip Plate
134	66.04	.005	Tip Plate
135	72.18	.005	5th Y Bending
136	72.37	.005	5th X Bending
137	73.34	.005	5th Torsion

Table 1: Natural Frequencies, Damping Levels and Modes of the Minimast Structure

3 Control Objective

The objective of active control is to attenuate the structural response of the Minimast structure due to external disturbances entering through the exciters at bay 9. The control actuators are torque wheels which are located on the tip platform of the Minimast structure. A number of sensors are available to the engineer and their selection for use in feedback is left to the discretion of the individual investigator. It is desired to use only accelerometers if they are able to provide sufficient information to the controller. Accelerometers are preferred for space applications due to their long history of space flight, their ease of placement on the structure and stand alone capabilities. It is desired to avoid the use of displacement sensors since they require a reference point or support structure for measurement.

4 Problem Formulation

A series of controllers are designed for three different performance objectives and five different feedback sensor configurations in an effort to select the sensors pairs to be used for feedback. The three performance objectives are to attenuate the structural response of Minimast at:

- Bay 10 and 18 displacement sensors
- Bay 18 displacement sensors
- Bay 10 displacement sensors

subject to external disturbances entering at bay 9.

The five feedback sensor configurations to be evaluated are:

- Bay 18 accelerometers only
- Bay 18 accelerometers and Bay 18 displacement sensors
- Bay 18 accelerometers, Bay 10 and 18 displacement sensors
- Bay 10 and 18 displacement sensors
- Bay 18 displacement sensors

The following questions are to be determined:

1. Can accelerometers alone be used as feedback sensors to achieve the performance objective?
2. Is enough information measured such that the problem approaches a state feedback control design problem?
3. Are the same characteristics evident on the full order and reduced order control design models?

The interconnection structure describing the control problem formulation is shown in figure 2. The input disturbances are modeled as 0.1 second, 50N impulses into the exciters. This set of disturbances is represented in the problem formulation by the filter, *Dist.wt*, whose transfer function is $\frac{155}{s+31}$. The sensor noise for the Sunstrand accelerometers and Kaman displacement sensors are very small and taken to be 2×10^{-5} for *nois18*, *nois10*, and *noisac*. The controllers will be implemented via a digital computer at a sample rate of 80 Hz. The sample time delay is accounted for via a Pade delay, *Pade.Delay*, whose transfer function representation is $\frac{1-0.125s}{1+0.125s}$. The filter block in the figure represents the third order, 10Hz Bessel filters inline with all the sensors prior to being input to the controller K. The torque actuators are included in the problem formulation via the block *Torg.act*. Transfer function representations of the filters and torque actuators are provided in the *Actuators and Sensors* section. The Minimast structure model, *Minimast*, is the six input, ten output, 28 mode model. Comparisons of results between employing the five mode and 28 mode model will be discussed.

The torque level restrictions on the torque wheel actuators are included into the problem formulation via the *Act.mag* block. The actuator magnitude weight is selected to correspond with the size of the input disturbances. For impulse disturbances of size 50N entering the shakers, the torque wheel actuators will be restricted to a maximum input of ± 1 volt with the *Act.mag*

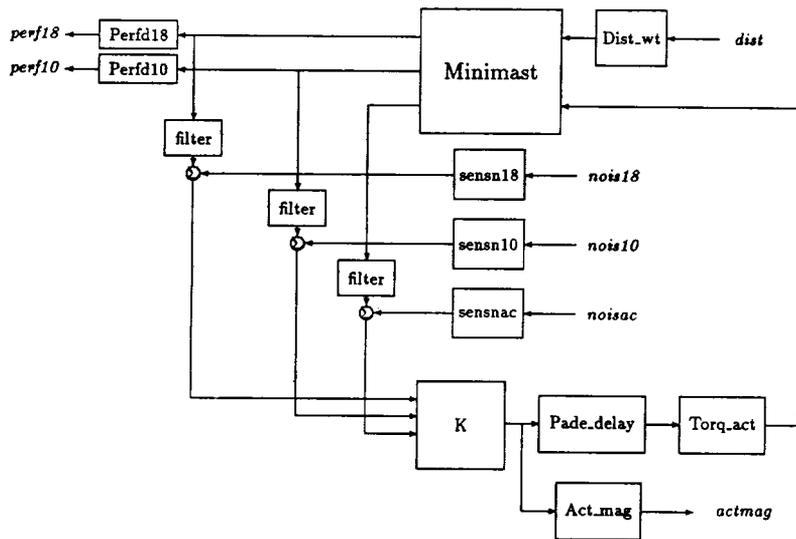


Figure 2: Interconnection Structure for Sensor Selection

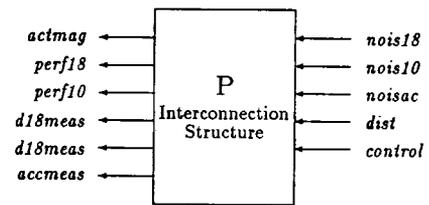


Figure 3: Control Design Plant

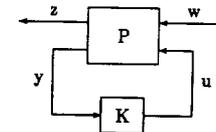


Figure 4: Linear Fractional Interconnection

scaling set to 1. This corresponds to $\pm 80Nm$ of torque. The performance objective of attenuating the vibration of the structure is included via weights on the displacement sensors at bay 10 and 18. The scalings are chosen to have the H_∞ norm of the closed-loop transfer functions between the disturbance inputs *dist* and the displacement outputs be smaller than 1. This leads to selection of *Perfd18* to be 1500 and *Perfd10* to be 3000. Measuring performance in terms of damping levels, the performance weights would require the closed-loop system to have approximately 50% damping of the first three modes. The block diagram of the sensor selection problem is shown in Figure 2 and the interconnection structure used for control design is shown in Figure 3.

5 Control Designs

5.1 Sensor Selection

Controllers are designed for the problem formulation using H_2 optimal control design techniques [3,4,5]. The optimal H_2 controller will minimize the two-norm ($\|\cdot\|_2$) of the closed-loop transfer function in Figure 4 from *w* to *z* which is denoted T_{zw} .

The optimal H_2 controller has the well known separation structure such that the squared two-norm of the closed-loop transfer function T_{zw} is equal to the squared two-norm of the full information problem (FI) plus the squared two-norm of the output estimation problem (OE). This is also equal to the squared two-norm of the disturbance feedforward problem (DF) plus the squared two-norm of the full control problem (FC). That is

$$\|T_{zw}\|_2^2 = FI^2 + DF^2 = OE^2 + FC^2$$

The full information problem is better known as the state feedback problem. The selection of feedback sensors problem is dominated by the state feedback problem.

For each performance objective and set of feedback sensors the corresponding outputs of the interconnection structure are selected and a control design is synthesized. The selection criteria is based on the corresponding H_2 norm of the full information, output estimation, disturbance feedforward, and full control cases. In addition to these criteria, the weighted infinity norm $\|\cdot\|_\infty$ from disturbance to performance and from disturbance to control signal magnitude is evaluated. No uncertainty models are included in problem description for the selection of the sensors. The nomenclature used in table is:

- FI - Full Information H_2 norm
- OE - Output Estimation H_2 norm
- DF - Disturbance Feedforward H_2 norm

- FC - Full Control H_2 norm
- CM - $\|\cdot\|_\infty$ of disturbance to control magnitude
- DP - $\|\cdot\|_\infty$ of disturbance to displacements

The results in Table 2 indicate that use of accelerometers only for feedback with performance specifications on bay 10 and 18 incorporates all the characteristics of interest in this control design problem. Bay 18 accelerometers lead to almost a full information (state feedback) control design problem with the full information part of the control design problem dominates the output estimation problem. This implies that one is able to easily observe all the information required for control design and the difficult part is controlling the system via the torque wheel actuators.

Measuring accelerations at bay 18 is better for performance than measuring displacements at bay 18 or 10 and is as good as measuring bay 10 and 18 displacements. These results also indicate that little is gained from feeding back the displacement sensors and bay 10 and 18 in addition to the bay 18 accelerometers. All results in Table 2 are all based on the full order Minimast model. Results from using the reduced order model, shown in Table 3, correspond directly with the results obtained with the full order model. Hence only bay 18 accelerometers will be feedback for control purposes and the reduced order model will be used in the control problem formulation. The truncated structural modes of the full order model are accounted for in the final control design via an additive uncertainty description.

5.2 Actuator Magnitude Level Weight

In an effort to determine the affect of the actuator torque level on the system performance, the actuator magnitude weight *Act.mag* is varied in the control designs. The actuator magnitude weight is scaled from 8 to 0.1 which corresponds to actuator signal levels varying from $\pm 10N/m$ to $\pm 800N/m$. It is of interested to determine the importance of the actuator magnitude scaling on the performance of the control designs and the appropriate level of magnitude weight for the system. The control design problem is the same as shown in Figure 2 but the actuator magnitude weight *Act.mag* is varied. The Minimast model is the full order system, performance is associated with attenuating the disturbances at bay 10 and 18 and the accelerometers at bay 18 are used for feedback.

Time history are generated with an input 0.1 second, 50N unit step into shaker A. The open-loop tip displacement response at bay 18 is attenuated to 2% of its initial excitation within 50 seconds and bay 10 the response is attenuated within 40 seconds. Two control designs are presented. The controller designed with *Act.mag* set to 1 attenuates the response at bay 18 within 1.5 seconds and at bay 10 within 1.7 seconds. The time simulations of the open-loop system and the two closed-loop systems are shown in Figure 5. The controller design with *Act.mag* set to 1 generates 57Nm, 102Nm and 28Nm of torque from torque actuators X, Y and Z respectively. Changing the

Act_mag to 8 leads to the displacement at bay 18 being attenuated within 26 seconds and at bay 10 within 20 seconds. The maximum torque requirements are $7Nm$, $12Nm$ and $8Nm$ from torque actuators X, Y, and Z respectively. The commands to the TWAY for each controller are shown in Figure 6. The trend is the same for other Act_mag weightings. Hence severely limiting the torque command signals will drastically reduce the closed-loop vibration attenuation properties of the controller. This same trend is noted when implementing controllers on the Minimast experimental facility.

5.3 Actuator Frequency Shaped Magnitude Weights

It is of interest to determine the effect of limiting high frequency actuator command signals has on the performance of the control designs. To investigate this issue, the magnitude weight of the actuator signal is scaled with a frequency dependent filter. This acts as a high pass filter to limit high frequency control signals. The interconnection structure in Figure 2 is used but now the Act_mag weight has dynamics. Three different actuator weights are used:

$$\begin{aligned} Act_mag1 &= 100 \frac{s+20}{s+2000} \\ Act_mag2 &= 100 \frac{s+5}{s+500} \\ Act_mag3 &= \left(90 \frac{s+20}{s+2000} \right)^2 \end{aligned}$$

The addition of a high frequency filter to the actuator magnitude weights leads to the same level of low frequency performance as before but the high frequency structural modes are not as highly damped as in previous control designs. In the control design using Act_mag1 , there was little change in the performance and torque levels in the simulation. The second actuator magnitude weight, Act_mag2 , more severely limited the low frequency actuator response. This lead to a slower time response of the system with little or no additional damping of the second bending modes and high natural frequencies. The damping level of the second structural mode differs slightly from the open-loop model.

To reflect the desire for good low frequency response while restricting the amount of high frequency attenuation, the third frequency shaped actuator magnitude weight Act_mag3 is formulated. The closed-loop response of the controller synthesized with this weight had similar properties to the controller synthesized with Act_mag1 although the second bending mode was not attenuated as much. These same trends are also found using the reduced order model. Therefore the results indicate that in order to achieve low frequency performance of the structure, significant actuator signal levels are required and that the large actuator commands are not due to the high frequency modes of the Minimast facility.

6 Experimental Control Design

Results from the feedback sensor selection and actuator magnitude weight control problems along with uncertainty models of the Minimast facility are incorporated into the experimental control problem formulation. Figure 2 forms the basis of the control problem interconnection structure with additional uncertainty weights included to account for modeling errors. Controllers are designed for the modified interconnection structure using μ -synthesis techniques and implemented on the Minimast facility [5,6,7,8].

Input multiplicative uncertainty is included in the block diagram between the torque wheel actuators model and the input to the Minimast model. The input uncertainty weight is selected to be a constant 2% across frequency reflecting a significant amount of confidence in the TWAs models. Unmodeled high frequency modes of the Minimast structure are accounted for in the problem formulation via an additive uncertainty weight wrapping around the plant. The transfer function of the additive weight is

$$22.222 \left(\frac{s^2 + 25.46s + 324}{s^2 + 1414s + 10^6} \right) \left(\frac{s^2 + 42.43s + 900}{s^2 + 282.84s + 40000} \right)$$

This weight includes sufficient low frequency uncertainty, in addition to its high frequency components, to prevent the controller from trying to attenuate rigid body modes of the support structure. The bay 18 performance weight $Perf18$ is selected as 4000 and the bay 10 performance weight $Perf10$ is taken as $20000 \frac{s+5}{s+50}$. The actuator magnitude weight Act_mag is 0.4. The control design achieved *robust performance* for the given uncertainty models and performance specifications. A more detailed description of the controllers

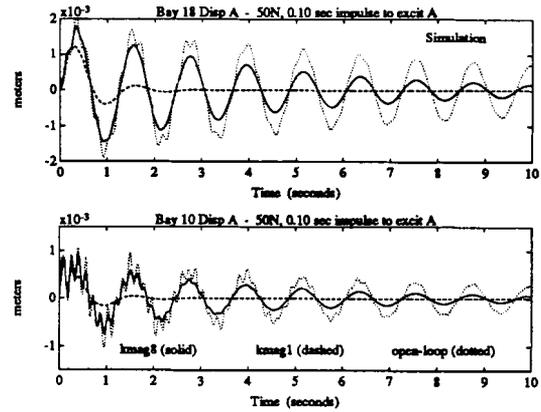


Figure 5: Time History Simulations (Displacements)

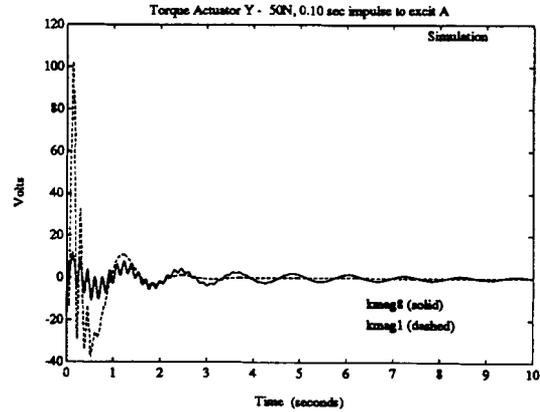


Figure 6: Time History Simulations (Torque Commands)

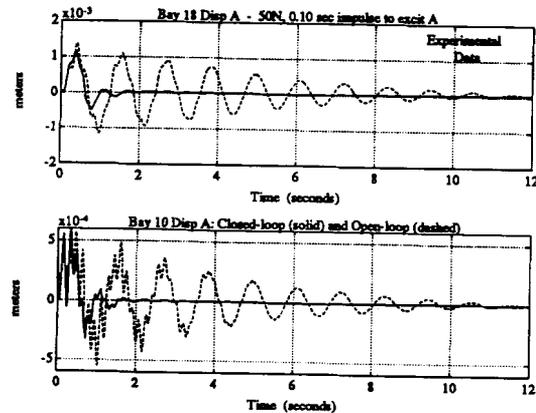


Figure 7: Experimental Displacement Time Response

designed via μ -synthesis for the Minimast facility is presented in the Caltech CSI/GI final report [9].

For implementation, the controller is discretized at 80 Hz. The experimental open-loop response of the Minimast structure at Bay 10 and 18 to a 0.1 second, 50N impulse disturbance to exciter A is shown in Figure 7. Only the X displacement sensor is shown for bay 10 and 18 since the other sensor responses are similar. One notices that there is approximately three times higher damping in the first modes of the physical structure than in the structural model. Figure 7 also shows the closed-loop displacements at bay 10 and 18 to the input disturbance with the μ -synthesis controller implemented. Figure 8 is the time response of input voltage commands to the TWAs during the excitation. The torques generated by the TWAs can be determined via the TWA models which are shown in Figure 8.

7 Summary

H_2 optimal control techniques are used to select a set of feedback sensors for control design. The results indicate that using only bay 18 accelerometers on the Minimast structure for feedback with performance specifications on bay 10 and 18, all the characteristics of interest are incorporated in the control design problem. It is found that measuring accelerations at bay 18 is better for performance than measuring displacements at bay 10 or 18 and is as good as measuring bay 10 and 18 displacements. These same results are observed on the full and reduced order design models. The control design problem on the Minimast facility is a direct tradeoff between the actuator magnitude and the amount of closed-loop vibration attenuation achieved.

These results are combined with descriptions of modeling errors to synthesize controllers via μ -synthesis techniques. Experimental results of the μ -synthesis controller indicate that excellent vibration attenuation levels are achieved with bay 18 accelerometers alone used for feedback.

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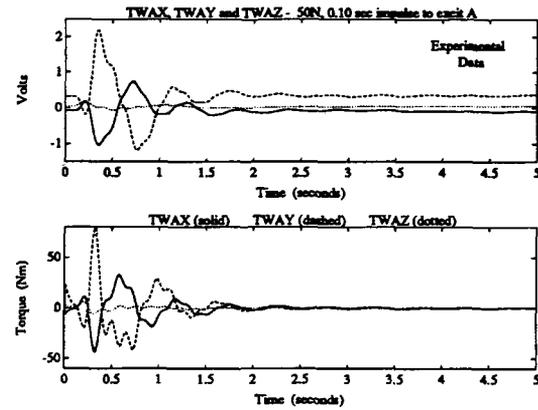


Figure 8: Experimental Torque Wheel Actuator Commands

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Perf. Specs	Feedback Sensors				
	Accelerometers	Accelerometers Bay 18	Accelerometers Bay 18	Displacement Sensors Bay 10 and 18	Displacement Sensors Bay 18
	Bay 18	Bay 10 and 18	Bay 18	Bay 10 and 18	Bay 18
Bay 18 and Bay 10	FI = 3.641	FI = 3.641	FI = 3.641	FI = 3.641	FI = 3.641
	OE = 0.678	OE = 0.300	OE = 0.337	OE = 0.476	OE = 2.152
	DF = 3.626	DF = 3.648	DF = 3.648	DF = 3.655	DF = 3.813
	FC = 0.754	FC = 0.189	FC = 0.254	FC = 0.351	FC = 1.830
	CM = 1.340	CM = 1.333	CM = 1.336	CM = 1.337	CM = 1.277
DP = 1.524	DP = 1.487	DP = 1.485	DP = 1.485	DP = 1.646	
Bay 10	FI = 2.942	FI = 2.942	FI = 2.942	FI = 2.942	FI = 2.942
	OE = 0.560	OE = 0.380	OE = 0.430	OE = 0.525	OE = 1.887
	DF = 2.943	DF = 2.961	DF = 2.963	DF = 2.929	DF = 3.009
	FC = 0.554	FC = 0.189	FC = 0.247	FC = 0.341	FC = 1.779
	CM = 1.264	CM = 1.260	CM = 1.263	CM = 1.263	CM = 1.215
DP = 1.447	DP = 1.429	DP = 1.425	DP = 1.424	DP = 1.908	
Bay 18	FI = 2.966	FI = 2.966	FI = 2.966	FI = 2.966	FI = 2.966
	OE = 0.498	OE = 0.170	OE = 0.200	OE = 0.265	OE = 0.827
	DF = 2.963	DF = 2.970	DF = 2.972	DF = 2.976	DF = 3.049
	FC = 0.512	FC = 0.016	FC = 0.059	FC = 0.085	FC = 0.428
	CM = 1.340	CM = 1.279	CM = 1.278	CM = 1.278	CM = 1.251
DP = 1.157	DP = 1.381	DP = 1.383	DP = 1.383	DP = 1.455	

Table 2: Full Order Model Sensor Selection

		Feedback Sensors			
Perf. Specs	Accelerometers	Accelerometers Bay 18 Displacement Sensors Bay 10 and 18	Accelerometers Bay 18 Displacement Sensors Bay 18	Displacement Sensors Bay 10 and 18	Displacement Sensors Bay 18
	Bay 18 and Bay 10	FI = 3.621 OE = 0.654 DF = 3.607 FC = 0.728 CM = 1.336 DP = 1.526	FI = 3.621 OE = 0.275 DF = 3.629 FC = 0.130 CM = 1.330 DP = 1.487	FI = 3.621 OE = 0.298 DF = 3.630 FC = 0.165 CM = 1.332 DP = 1.486	FI = 3.621 OE = 0.560 DF = 3.653 FC = 0.292 CM = 1.335 DP = 1.484

Table 3: Reduced Order Model Sensor Selection