Integrated Controls/Structures Study of Advanced Space Systems

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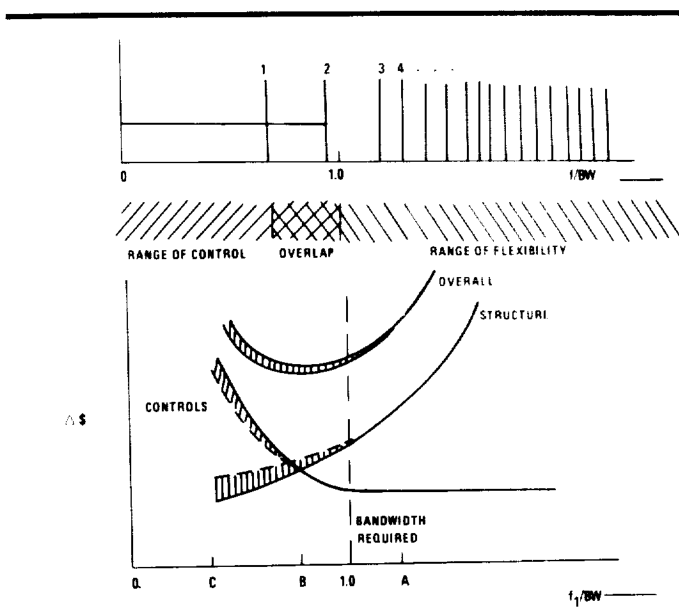
PURPOSE OF STUDY

The integrated control/structures study was a task preformed jointly by the Martin Marietta Corporation and the Honeywell Systems and Research Center under a contract to the NASA Langley Research Center entitled "Advanced Space Systems Analysis" (Reference 1).

Figure 1 depicts the purpose of the study. For a given antenna mission one can postulate a cost tradeoff between a stiff structure utilizing minimal controls (and control expense) to point and stabilize the vehicle. Extra costs for a stiff structure would be caused by weight, packaging size, etc. Likewise, a more flexible vehicle should result in reduced structural costs but increased costs associated with additional control hardware and data processing required for vibration control of the structure. Figure 1 denotes that this tradeoff occurs as the ratio of the control bandwidth required for the mission to the lowest (significant) bending mode of the vehicle. The Honeywell portion consisted of establishing the cost of controlling a spacecraft for a specific mission and the same basic configuration but varying the flexibility.



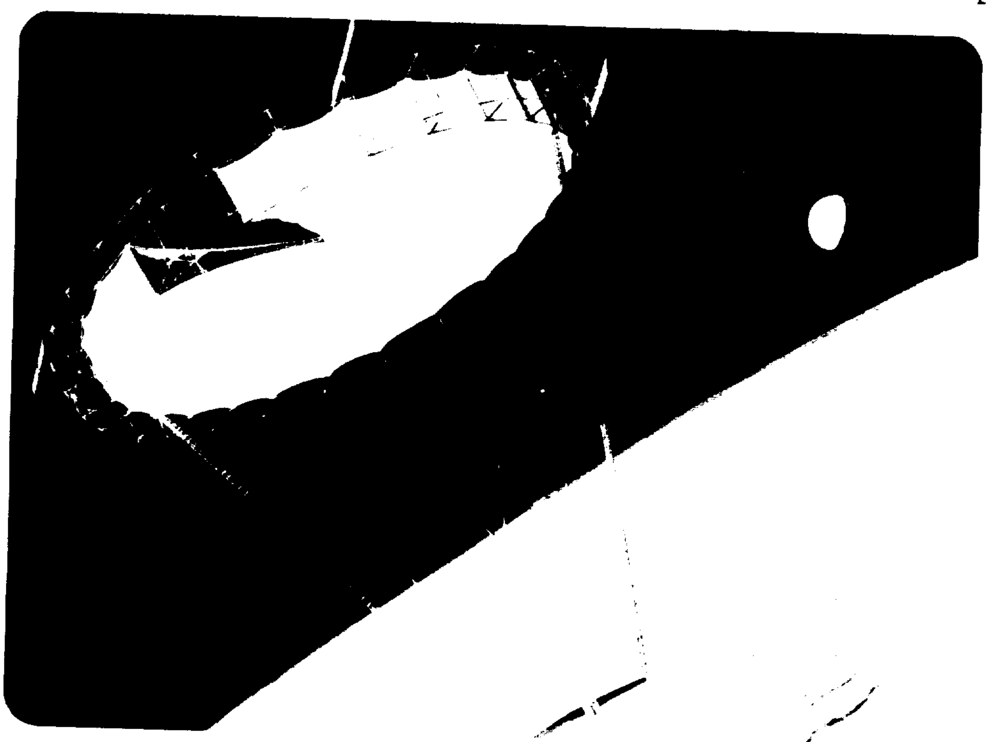
* EXAMINE TRADE-OFF OF CONTROL COST AND STRUCTURAL COST FOR LARGE ANTENNAS

APPROACH: DESIGN, "PRICE" AND COMPARE 4 SPACECRAFT FOR A TYPICAL ANTENNA MISSION

Figure 1

RADIOMETER CONCEPTUAL DESIGN

The study vehicle is shown in Figure 2. This is a conceptual design of a symmetric feed radiometer. The reflector is an electrostatically suspended membrane supported by a 170 meter (inside diameter) box truss ring. The feed is supported by two astromasts with two pairs of tension cables. The size used was determined to be the largest which could be packaged into one shuttle orbiter bay. The control design includes the effects of the astromast and hoop flexible modes, but does not include the electrostatic shape control.



170 METER RADIOMETER

- **BOX TRUSS RING**
- **170 METER DIAMETER REFLECTOR (INNER DIAMETER)**
- **RADIOMETER CHARACTERISTICS**
  - FREQUENCIES; 1.08, 2.03, 4.95 GHz
  - SPHERICAL SURFACE; F/D = 2
  - LINE FEED
- **ELECTROSTATIC MEMBRANE**
  - 0.3 TO 0.5 mil POLYMER FILM SURFACE
  - 50 m EFFECTIVE APERITURE

Figure 2

STRUCTURAL OPTIONS

The Four structures were supplied by Martin Marietta to conduct the control design cost tradeoff analysis. Major characteristics are described in Figure 3. Early in the structural design phase it was discovered that aluminum elements could meet all the constraints of a single orbiter launch. Two of the designs, including the most flexible spacecraft, were developed assuming an aluminum structure. It should be noted, however, that none of the designs achieved the low first bending modes characteristic of other antenna concepts such as an offset feed wrap rib concept. Three factors contributed to this in varying degrees:

1). The box truss based concept is inherently stiff
2). Centerline feed concepts allow utilization of symmetry to achieve stiffness
3). Tension cables served to stiffen astromast feed supports

SPACECRAFT DESIGNATION	BOX CHARACTERISTIC DIMENSION	MATERIAL	1ST BENDING MODE
1. "RIGID"	14.00 m	GRAPHITE/EPOXY	3.9 v/s
2. "INTERMEDIATE #1"	8.65 m	GRAPHITE/EPOXY	.52 v/s
3. "INTERMEDIATE #2"	11.00 m	ALUMINUM	.53 v/s
4. "FLEXIBLE"	8.65 m	ALUMINUM	.291 v/s

Figure 3

STRAWMAN REQUIREMENTS

The mission requirements chosen for the study are shown in Figure 4. These are representative of an earth observation Radiometer; however, the slew requirement was set stringent to force the consideration of the effects of flexibility in the vehicle. In doing so, results were generated which provide guidelines for the design of many future large space structures and which indicate the value and future direction of LSS control.

MISSION: EARTH ORIENTED

ORBIT: 1000 km CIRCULAR INCLINED 60°

SLEW: 45° IN 5 MINUTES

POINTING ACCURACY: .005°

SURFACE ACCURACY: 1.5 mm (RIM AND FEED)

Figure 4

GENERAL CONTROL CONFIGURATION

Many aspects of a mission drive a control design. Since the purpose of this task was to examine the effects of flexibility, the bandwidth of a controller was of major concern. The slew command provides the most stringent of the control requirements and thus received the most attention in this study. In addition, the low amount of coupling between control axes permits one to consider each axis individually although the techniques extend to the highly coupled case. Figure 5 is a block diagram showing the structure of the controller used for analyzing the control requirements.

As in any physical system there are errors in disturbances which must be accomodated. The principal error source for the slew loop is the uncertainty between commanded and actual torque delivered by either jets or momentum exchange devices. For this study, we assumed that there was a 10% uncertainty in the control torque applied to the spacecraft. This uncertainty is modeled as an unknown disturbance torque, T_D. Note that this also accounts for center of gravity (CG) and inertia uncertainties.

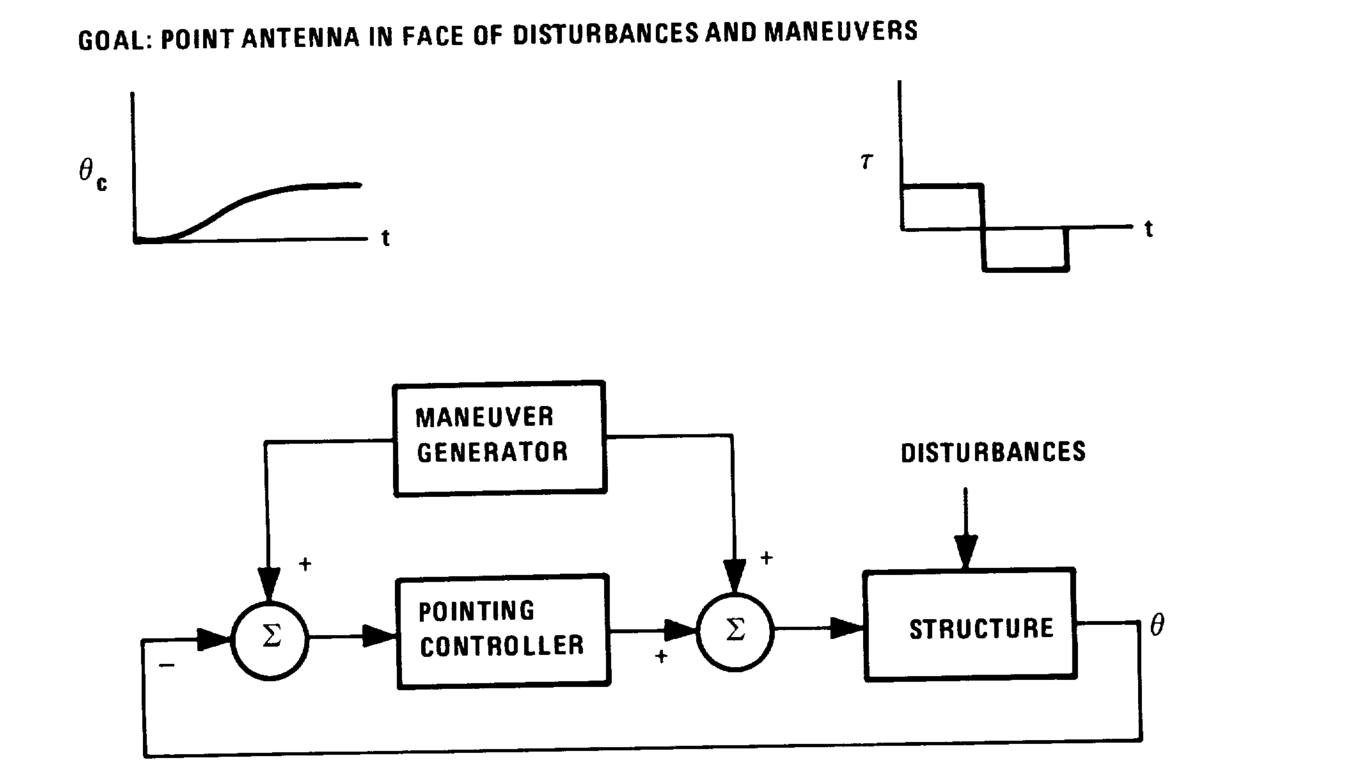


Figure 5

SLEW OPTION COMPARISON

There are many approaches available in the design of the nominal slew profile. For example, it is possible to design a slew which requires the bandwidth of the regulator to be minimized. An alternative is to minimize the energy (e.g. fuel) required to perform the maneuvers. The major characteristics of the minimal fuel and minimal bandwidth controls as applied to spacecraft are given in Figure 6. As can be seen the minimum bandwidth maneuver consists of performing the basic maneuver rapidly and then allow the structure to settle out. The minimum fuel maneuver is one in which the entire maneuver time is utilized. The minimum bandwidth maneuver requires roughly 17 times the torque and 4 times angular impulse (fuel) as the minimum fuel control but requires 1/5 the bandwidth. The decision as to which approach to use was based exclusively on fuel usage. A factor of 5 on bandwidth is very significant in terms of actuator and sensor capabilities but the cost associated with bandwidth must only be paid once. The fuel costs must be paid for on every slew maneuver and thus the minimum fuel approach was selected.

	MINIMUM BANDWIDTH CONTROL	MINIMUM FUEL CONTROL
TIME TO SLEW (T_3)	300 sec	300 sec
MANEUVER TIME (T_2)	74 sec	300 sec.
TORQUE REQUIRED	24,438 nt-m	1,468 nt-m
CONTROL BANDWIDTH (ω_b)	.04	.2 r/sec
IMPULSE REQUIRED	1.8×10^6 nt m-sec	$.44 \times 10^6$ nt-m-sec

Figure 6

OTHER BANDWIDTH REQUIREMENTS

Other disturbance sources for which we require feedback are summarized in Figure 7. These are aerodynamic torque, solar torque, and gravity gradient. Aerodynamic drag consists of a force exerted on a projected area of the spacecraft. Discussed in more detail in Reference 2, for a nominally local vertical orientation this results in a constant torque, a term at orbit rate, and a term at twice orbit rate. Solar torque has an effect on this spacecraft analogous to aero torque. At any point of interest in the orbit the angle of incidence of sunlight on each section of the spacecraft must be determined. Reference 3 contains the appropriate expressions for computing the total force resulting from solar torque. Because of the local vertical orientation of the spacecraft, however, solar torque does not contribute any net angular momentum to the spacecraft. However, large forces and torques do occur. A simple approximation to the torques includes both constant and orbit rate terms. In addition, shadowing of the spacecraft by the earth results in a nearly step change in the disturbance torque. Gravity gradient torques can cause a spacecraft to deviate from the desired attitude. Following a standard development of gravity gradient such as in Reference 4, conditions for the bandwidth of a controller can be determined.

- AERO TORQUE (TWO HARMONIC DIURNAL AIR DENSITY MODEL)
  - CONSTANT TORQUE
  - ORBIT RATE
  - 2x ORBIT RATE
- SOLAR TORQUE
  - CONSTANT
  - ORBIT RATE
  - STEP (SHADOWING) ← DOMINATES
- GRAVITY GRADIENT
  - MINIMUM B.W. FOR STABILITY
  - WIDER BANDWIDTH OFTEN PREFERRED
  - USUALLY SMALL

Figure 7

COMBINED AERO and SOLAR FORCING FUNCTIONS

The combined examination of aerodynamic and solar torques can be computed for various orbit and attitude parameters of the vehicle. As shown in Figure 8 for a given orbit these forces can be plotted. The altitude (ALT), orbit period (T), velocity (VEL), orbit inclination (INCL), and ascending node (PSIN) are all indicated in the graph. The attitude of the spacecraft (TH, PSI, PHI) of the earth pointing is also shown. The solid line refers to the x axis of the vehicle, the dash line to the y axis and the dot dash line to the z axis.

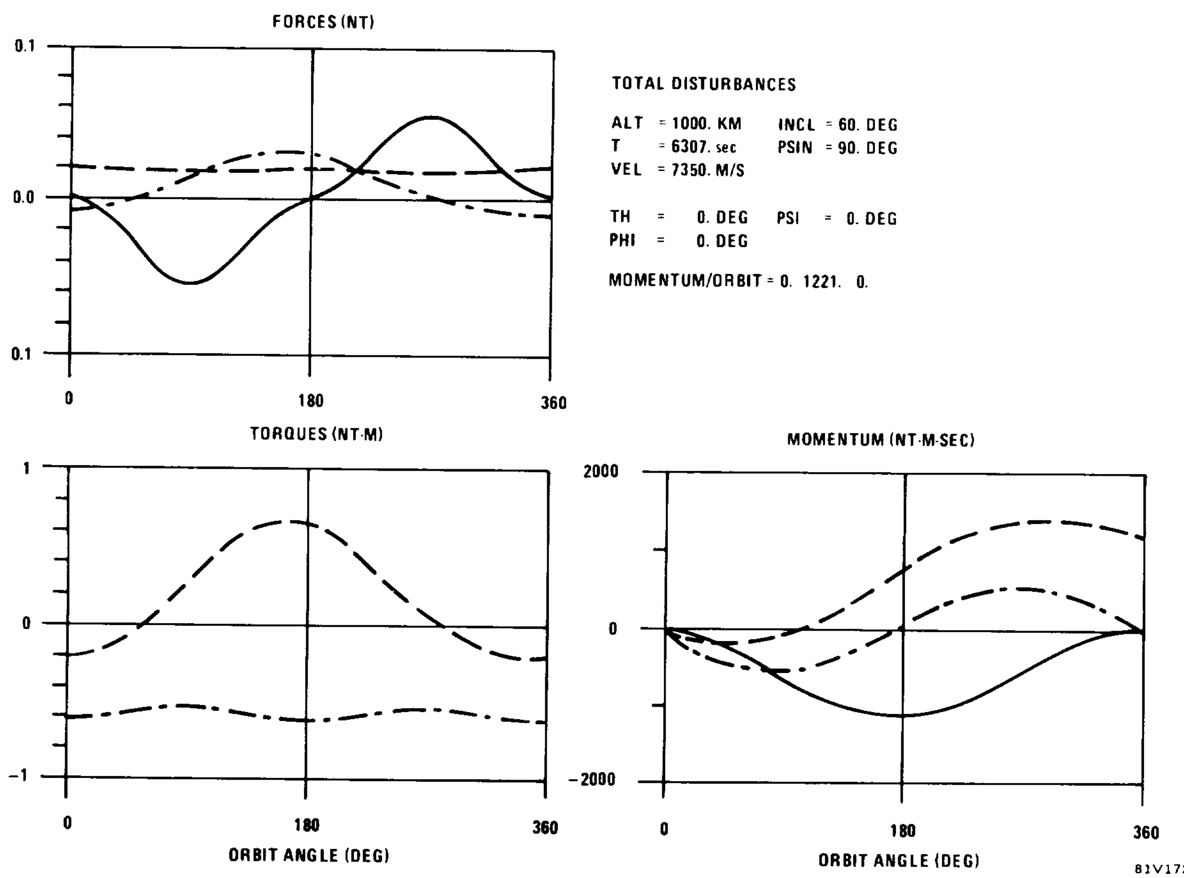


Figure 8

SUMMARY OF BANDWIDTH DRIVERS

A detailed analysis of all the disturbance sources (slew uncertainty, aerodynamic torque, solar torque, gravity gradient, and orbit maintenance) is provided in the final report of the ASSA contract (Reference 1). The bandwidth requirements to meet the mission goals stated earlier are summarized in Figure 9. Not shown are the gravity gradient and orbit maintenance bandwidth requirements which were negligible. Note that the significant bandwidth driver for this mission and spacecraft is the minimum energy slew bandwidth of .2 rad./sec. For comparison purposes the first bending modes of the four spacecraft are also shown. Only the flexible spacecraft with a first bending mode of .291 rad./sec. significantly interacts with the slew bandwidth. As will be discussed later the first bending mode, indeed the first few bending modes, of the spacecrafts are not significant and therefore the dynamic interaction we had searched for to provide the most challenging control problem did not occur for this type of structure.

• **SLEW BANDWIDTH (z)**	**.2 r/s**	
• **SOLAR STEP (y)**	**≈ .01 r/s**	
• **SOLAR STEP (z)**	**≈ .01 r/s**	
• **1ST BENDING MODE**	**RIGID**	**3.9 r/s**
	FLEXIBLE	**.291**
	INTER. 1	**.52**
	INTER. 2	**.53**

Figure 9

CONTROL LAW DESIGN

As shown in Figure 10 two types of control laws or algorithms were designed for connecting the sensor outputs to the actuators. The first is for the low bandwidth control loops for which flexibility of the spacecraft is not an issue. These loops can be handled with standard lead compensators which involve achieving the appropriate phase margin during the cross-over region of the control loop through the use of lead compensators on the basic $1/s^2$ rigid body model of a spacecraft. This implies that all the bending modes of the vehicle are significantly higher than the desired cross-over point of the control loop. For the integrated control/structures study this included the required bandwidth for all disturbances sited earlier except the slew uncertainty bandwidth requirement.

The higher bandwidth control was required to meet the mission specifications in the face of the 10% uncertainty in the minimum energy slew maneuver. The effects of the flexibility of the vehicle must be considered. The most critical case in terms of driving the costs of control harware concerns the effects of the energy contained in the flexible modes violating the pointing and stabilization spec. Assuming that all passive damping and isolation techniques have been exhausted the use of dedicated vibration control to damp the structural modes to achieve a lower energy level for the structural modes. The implementation of this type of control would require the placement of actuators and sensors on various points along the flexible structure to implement dedicated damping of a particular structure. None of the four spacecraft studied exhibited enough bending mode energy to violate the pointing specifications and therefore none warranted this type of dedicated vibration control.

The other important effect of structural flexibility in control loop design concerns the stability of the control loop in the face of rapid changes of gain and phase caused by the bending modes of the vehicle. Control stability can be achieved by the proper placement of sensors and actuators (co-location is an important issue as discussed in Reference 5) and the proper attention to significant bending modes in the control law design. As we will see three of the four spacecraft examined in study required special attention to bending modes.

- **LOW BANDWIDTH CONTROL**
  - NO OVERLAP WITH BENDING MODES
  - INCLUDES ALL DISTURBANCES EXCEPT SLEW UNCERTAINTY
  - LEAD COMPENSATION AT CROSSOVER AND CMG'S ARE SUFFICIENT

- **HIGH BANDWIDTH CONTROL**
  - CASE 1: FLEXIBILITY EFFECTS VIOLATE POINTING SPEC.
    - REQUIRES DEDICATED VIBRATION CONTROL
    - NONE OF FOUR SPACECRAFT STUDIED EXHIBITED THIS PROBLEM
  - CASE 2: FLEXIBILITY AFFECTS ONLY STABILITY
    - CAN BE SOLVED BY PROPER SENSOR/ACTUATOR LOCATIONS AND CONTROL LAW DESIGN
    - 3 OF 4 SPACECRAFT AFFECTED

Figure 10

RIGID BODY CONTROL DESIGN

The generic form of the rigid body controller for spacecraft without attention to flexibility effects is shown in Figure 11. The $1/s^2$ term is essentially the rigid body motion of a torque input to an attitude output for a given spacecraft. The use of a lead compensator control law as shown in the figure provides lead at crossover with appropriate phase margin (approximately 45°) and $1/s^3$ rolloff at high frequency to accommodate uncertainties.

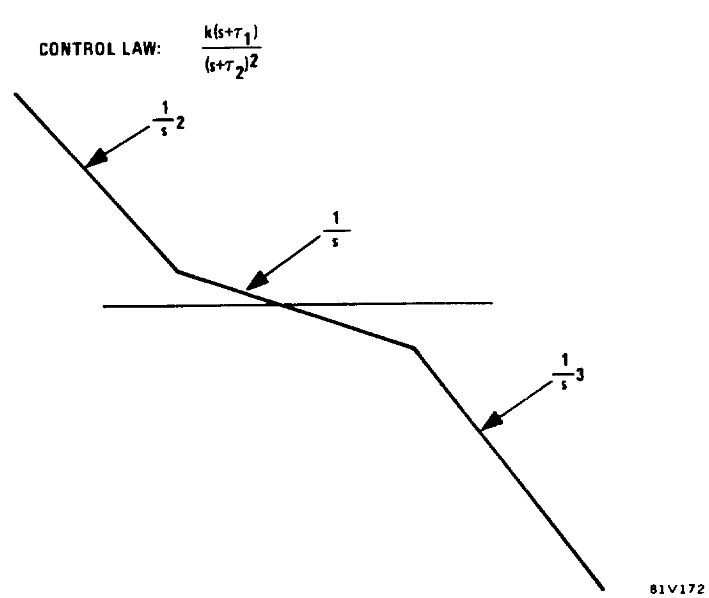


Figure 11

FLEXIBILITY EFFECTS OF RIGID BODY CONTROLLERS

Figures 12 through 15 show the effects of applying the rigid body control law designed to crossover at .2 rad/sec. to meet the slew uncertainty disturbance. Figure 12 shows the rigid body controller applied to the rigid body spacecraft. Note that none of the flexure modes (1/2 percent damping assumed for all bending modes) exceed the 0 db line in the gain plot. This means that the controller is gain stable and no specific attention to the additional compensation is necessary for this spacecraft design. Figures 13 and 14 show the rigid body control laws applied to the two intermediate spacecraft designs. In both cases one bending mode exceeds the 0 db line and other bending modes are close to the 0 db line. This means that the closed loop system would be unstable. Finally, in Figure 15 the rigid body controller is applied to the most flexible spacecraft examined in the study. Here we have a significant number of bending modes exceeding or near the 0 db line.

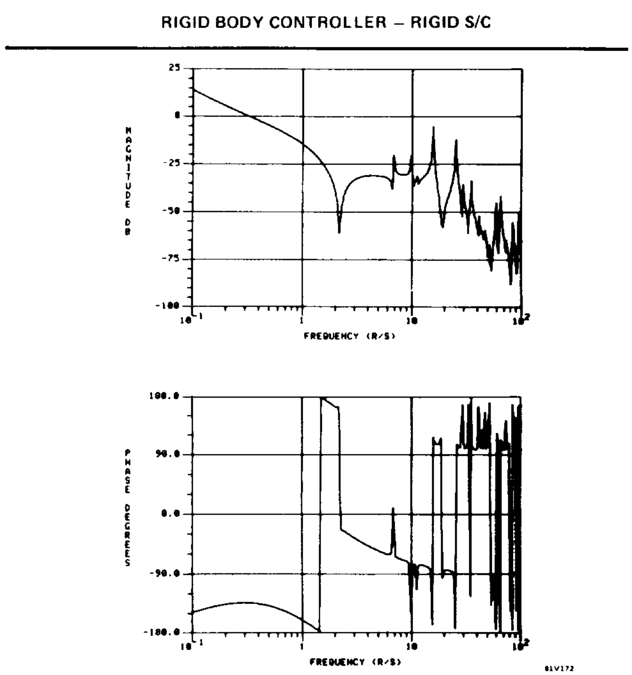


Figure 12

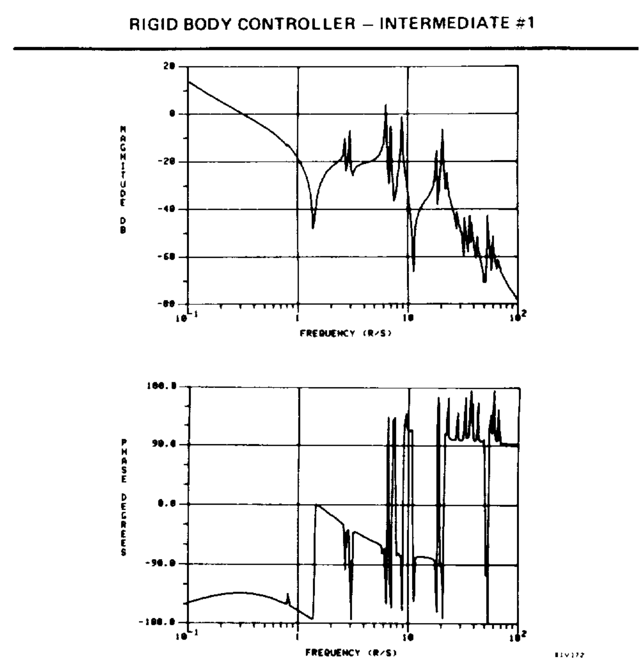


Figure 13

RIGID BODY CONTROLLER – INTERMEDIATE 2

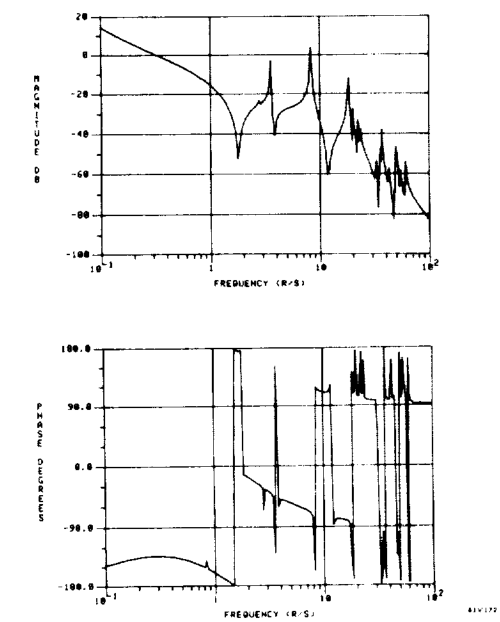


Figure 14

RIGID BODY CONTROLLER – FLEXIBLE S/C

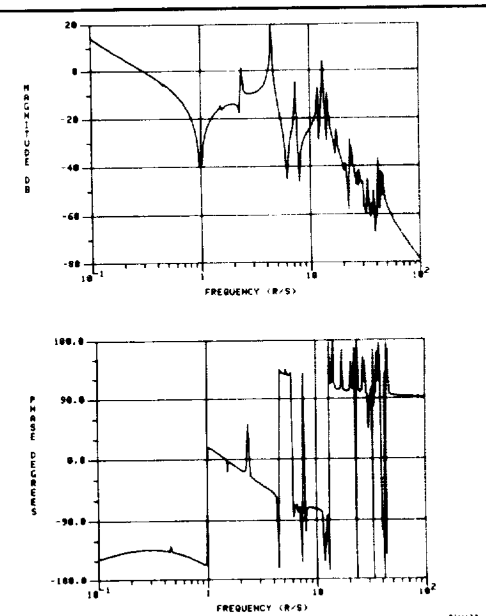


Figure 15

DEALING WITH FLEXIBILITY

It is obvious that the rigid body control law will not be appropriate for three of the four spacecraft designs. Figure 16 shows the numerous options one has at his disposal to attack the problems for all but the rigid spacecraft. One would be to modify the mission. This would result in a lower bandwidth requirement and essentially eliminate the overlap of bandwidth required to the flexure modes. This would be a last resort if other options were not available. The second option is to stiffen the structure to increase the bending modes and increase the damping. This of course is the objective of the rigid spacecraft. Option 3 is to utilize notch filters in the compensation path along with the rigid body control law. This indeed was the approach taken with the two intermediate spacecraft because both exhibited difficulties and only a few critical modes. Options 4 and 5 involve a change in the actuator type or to utilize distributed control. Both options were explored during the course of the study. Details of these options are discussed in Reference 1. The last option is to utilize a technique called slow roll-off. This is the solution chosen for the flexible spacecraft problem.

- **MODIFYING THE MISSION**
  - **CHANGE SLEW TIME TO 50 MINUTES**
- **STIFFEN STRUCTURE**
- **NOTCH FILTERS**
- **CHANGE ACTUATOR TYPE**
- **DISTRIBUTED CONTROL**
- **SLOW ROLL-OFF**

Figure 16

NOTCH FILTERS

The use of appropriately designed notch filters is a viable solution for the two intermediate spacecraft control law designs. Figure 17 shows a notch filter which can be utilized for both the intermediate spacecraft. Note that the 0 db exceedence of the flexure modes of the two spacecraft does not dictate a very deep notch in the filter, i.e., less than 10 db. This represents a very modest requirement in terms of assuring robustness. Also shown in Figure 17 is an attempt to design a notch filter which would be appropriate for the significant bending mode above the 0 db line for the flexible spacecraft. Note here that a very deep notch is required. A notch of such depth and the additional requirement for notch filters for the other unstable modes presents a critical robustness problem if the location of the frequency of the bending modes change. Another approach utilizing the slow roll-off technique was applied to the flexible spacecraft.

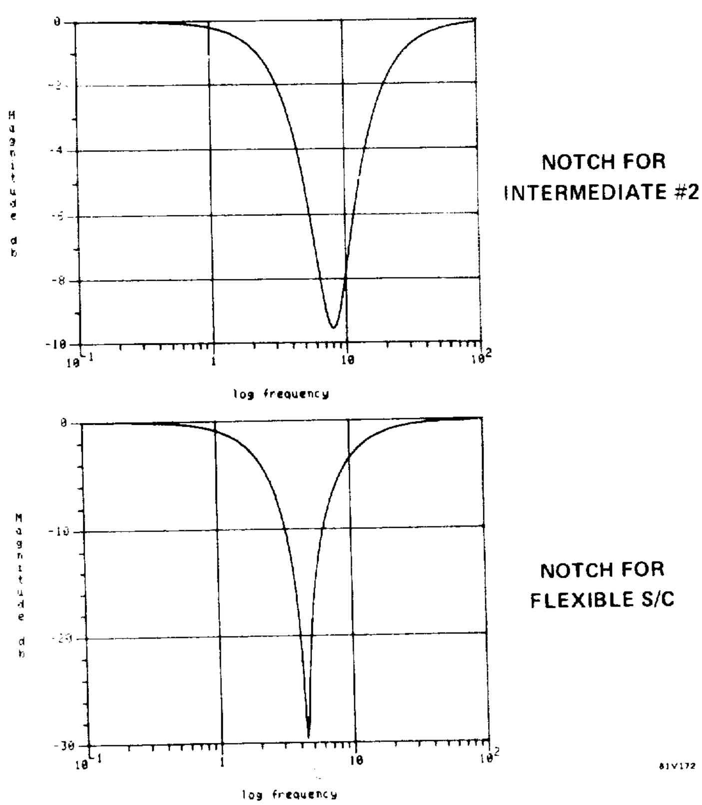


Figure 17

INTERMEDIATE SPACECRAFT CONTROL RESULTS

Using the notch filter shown in Figure 17a on the intermediate spacecraft number 1, the effect of the attenuation of the bending modes is shown in Figure 18. The notch filter has the effect of achieving gain stabilization and thereby solving the control problem.

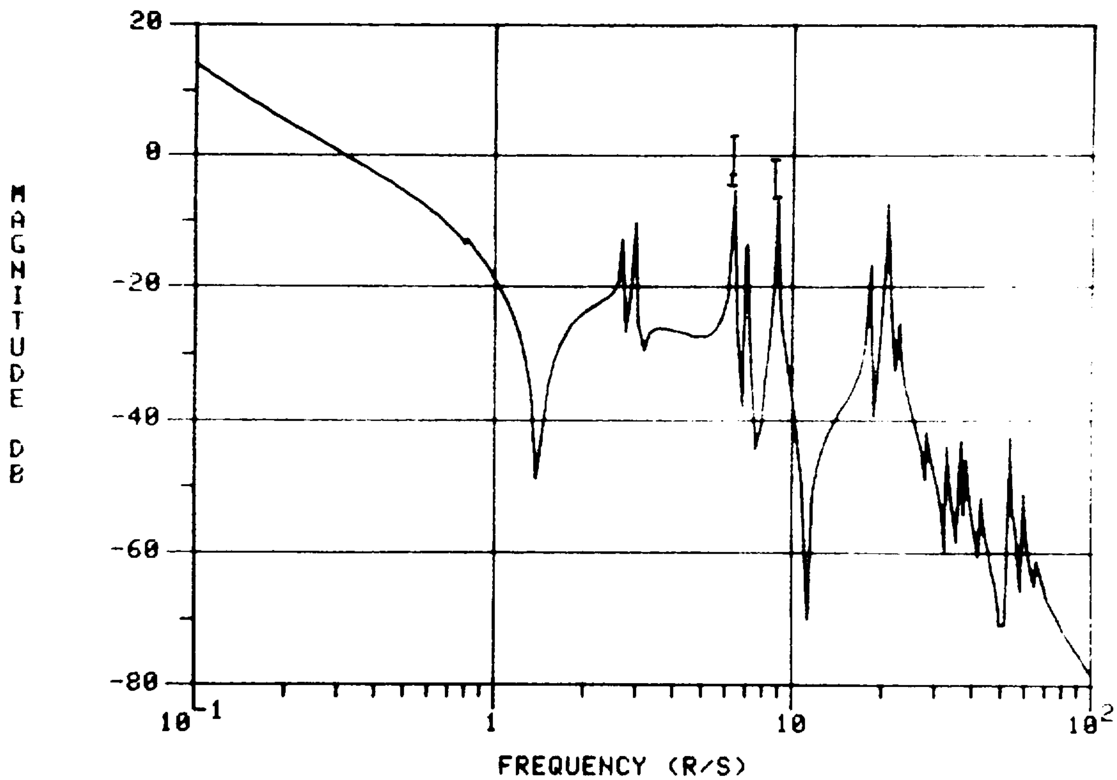


Figure 18

SLOW ROLL-OFF

The option to achieve robust control for the flexible spacecraft involves achieving phase stabilization, i.e., assuring that for every gain above 0 db we have adequate phase margin. Figure 19 describes the properties of a compensator used to achieve slow roll-off. As shown, the rigid body control law must be modified with the appropriate compensator, which consists of a cascaded set of lead-lags. Bending modes contain phase variations that basically oscillate between +90 degress and -90 degress (this assumes co-located sensors and actuators as discussed in Reference 5). In order to achieve a 45^{o} phase margin the compensator must achieve a roll-off less than first order. The appropriate gain roll-off to achieve this through the use of the modified compensator would be approximately 13 db per decade for the region of the critical flexure modes. This is achieved by the cascading shown in the Figure 19. This type of compensation achieves a robust control for the envelope of transfer functions associated with these flexure modes. Slow roll-off requires much higher bandwidth (perhaps two orders of magnitude in frequency) than to implement either the rigid body controller or the rigid body with notch filtering. This requires higher bandwidth sensors and actuators plus an additional throughput requirement on digital processing.

It should be noted that this technique is not restricted to scalar or lightly coupled system. Reference 6 contains a version of these results for the multi-input spacecraft. The approach is similar in that one puts identical compensators of the form shown in Figure 19 into each input channel. In this case, additional design freedom provided by the multi-input problem can be used to increase damping on specified modes of the spacecraft.

- **MODIFY COMPENSATOR**

$$\frac{K(s+a)(s+10a)\cdots(s+10^{b}a)}{(s+3.6a)(s+3.6a)\cdots(s+3.6\times 10^{b}a)(S+C)}$$

- **GIVES $\approx 45^{\circ}$ MARGIN**
- **CONTROLS ENVELOPE OF TRANSFER FUNCTION $\Rightarrow$ ROBUST**
- **REQUIRES PHASE PROPERTY OF COLOCATION**
- **EXTENDS TO MIMO**

Figure 19

SLOW ROLL-OFF FOR THE FLEXIBLE SPACECRAFT

Results of utilizing the slow roll-off technique on the flexible spacecraft are shown in Figure 20. Note that by achieving a phase margin of 45° up to a frequency of 11 rad./sec. there is no need to attenuate the bending modes below the 0 db line in the feedback control loop.

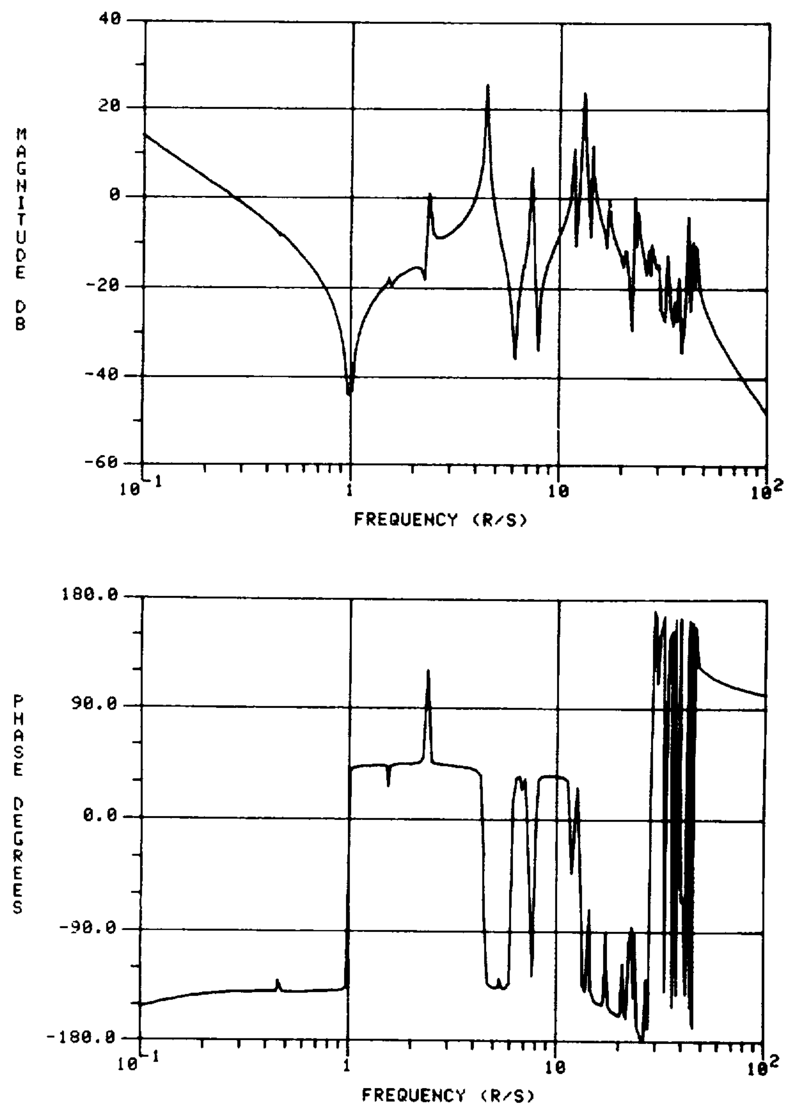


Figure 20

SENSORS AND ACTUATORS

The sensors and actuators required to implement the four control laws discussed are summarized in Figure 21.

Sensors - The primary sensors are gyros (co-located with CMG's and slew jets) on the rim of the spacecraft. For the y, z axis, two gyros are located to sense each axis and the outputs are then averaged to form the effective attitude measurement. This is done to take advantage of the co-location in the wide bandwidth cases. In order to provide an absolute reference one star sensor is required for each gyro.

Actuators - A combination of CMG's and jets are used to control all spacecraft versions. As indicated earlier the distinction between the various versions is in the bandwidth required of the components. The jets have the combined roles of the solar/aero drag makeup i.e., orbit maintenance, large slew maneuvering and CMG unloading. The CMG's are included for attitude maintenance during "normal" operation when the jets are not used.

- **GYROS (6)** } **4 ON RIM (±y, ±z)**
- **STAR SENSORS (6)** } **2 ON FEED**
- **CMGS (RIGID REQUIRES 2x)**
- **SLEW JETS-HYDRAZINE (8) - ON RIM (± y)**
- **ORBIT MAINTENANCE JETS - ELECTRIC (24)**

Figure 21

SENSOR/ACTUATOR PLACEMENT

Figure 22 shows the summary of the placement of the various sensors and actuators. Two gyros are located at (3) on the feed to provide the x axis reference. Note that due to low bandwidth requirement the position of these gyros is not critical. Also shown in Figure 22 is the placement of the jets and CMG's. Single axis devices have been selected and used in pairs, one pair to each axis. A total of six devices are required for redundancy. CMG's are placed as in Figure 22 at locations (1) to provide minimal momentum in the $\pm$ z and the $\pm$ x directions and at locations marked (2) with a nominal $\pm$ x orientation. These provide control torques about x, z, and y, respectively. A maximum torque capability of 2 nt-m is required.

In order to accomplish the 45° slew in 300 seconds jets must be located to thrust is located in the $\pm$ x directions at points marked 1. Chemical (Hydrazine) engines are mounted in pairs. The jets, each with four to six Newtons (NT) of thrust, are located at the top and bottom edges of the rim (4 locations).

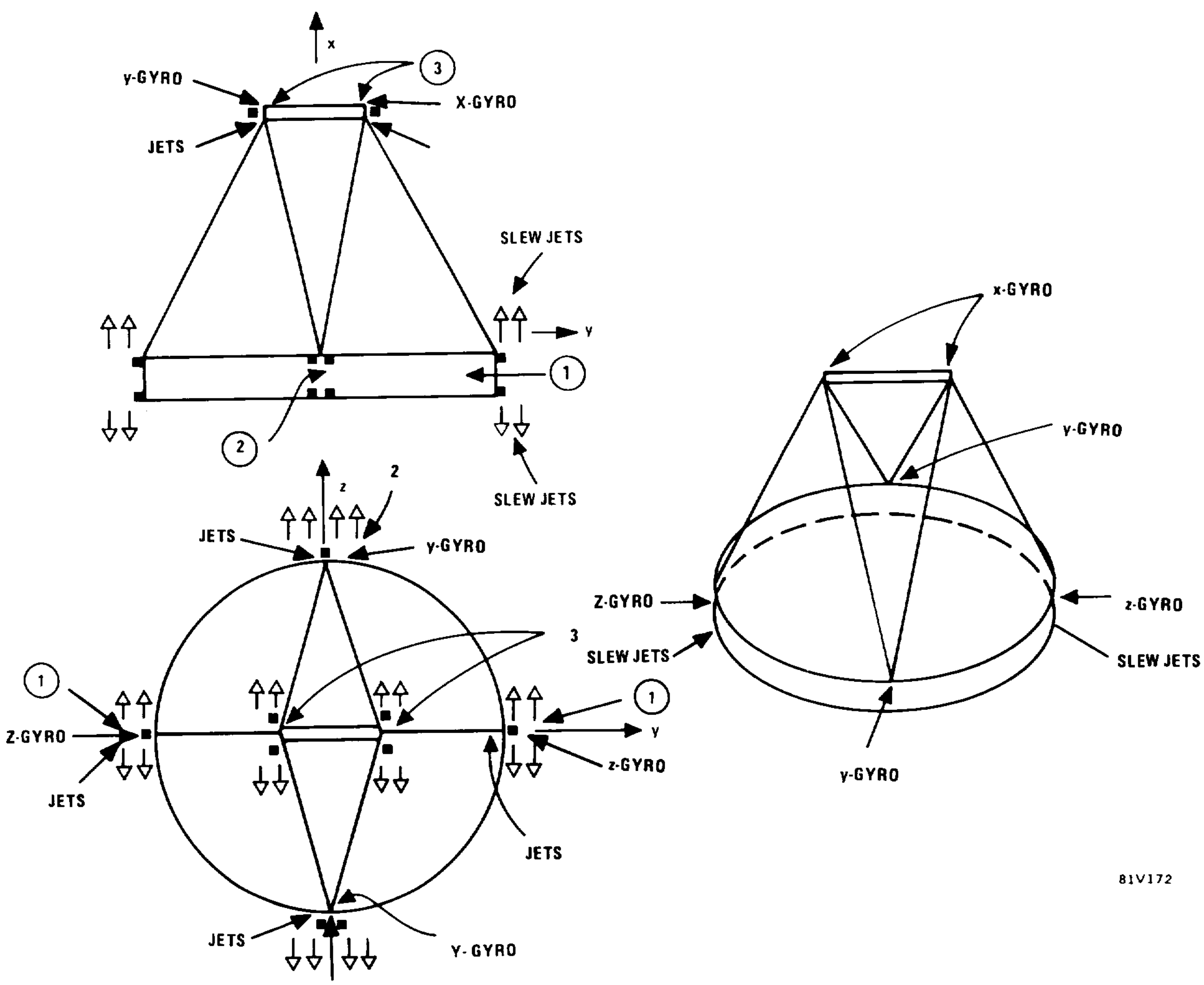


Figure 22

COST OF CONTROL

The purpose of costing each of the versions of the spacecraft is to determine the cost differential of each design. As such the relative prices and the reasons for the differences are far more important than the absolute cost estimates. In order to determine an overall control system cost the differences between each version are first highlighted. Following this, component costs were determined based on past history and taking into account the identified differences. Figure 23 briefly describes the results of the cost exercise. One should note that the rigid spacecraft had the highest control cost. This was because the stiffer heavier structure required larger CMG's than was required on the two intermediate spacecraft and the flexible spacecraft. The flexible spacecraft has a slightly larger increase in cost over the intermediate designs ($10,000). This is due to a requirement for higher throughput in the computations which dictates a more powerful digital computer. The higher throughtput is required because of the higher bandwidth dictated by the slow roll-off compensation design for the flexible spacecraft. It is estimated that the computations need to run at a 160 Hz for this design as opposed to approximately 10 Hz for the two intermediate spacecraft designs, and 3 Hz for the rigid body spacecraft design. One further note is that the impact of development costs for the respective systems and the cost of required testings (i.e., the flexible spacecraft design would require higher developmental costs) were not considered in this cost analysis.

- **EMPHASIS ON RELATIVE COST**
  - **LARGER CMG**
  - **WIDER B.W./COMPUTATION**

RIGID	**$12.98 M**
INTER.	**$12.38 M**
FLEXIBLE	**$12.39 M**

Figure 23

SUMMARY AND CONCLUSIONS

The major conclusions of this study were:

- o For the type of spacecraft and missions studied the cost of the control system is a relatively weak function of the degree of frequency overlap. In fact, the control system for the rigid version was most expensive due to the larger CMG's required. It is important to note that the spacecraft studied in this development were stiff by nature due to the box truss design techniques used. A more flexible spacecraft, such as an off-set wrap rib, exhibits much lower frequencies for critical bending modes and therefore would require dedicated vibration control. This should be examined in terms of the cost impact of the control systems.

- o There is a need for a control design methodology for spacecraft with overlaps between structural resonances and control system bandwidth. The solution of automatically stiffening the spacecraft, i.e., a "structural solution", does not result in a minimum cost design. Thus, there is validity for large space structures control.

- o Structural uncertainties are a major driver in LSS control design. At least as important as initial uncertainties are ageing effects. Controllers must be either robust to this uncertainty or adapt to it. Robust controllers were used in this study; however, adaptive control should be explored where bandwidth requirements dictate.

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