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DETECTION OF POTENTIAL SPACE STATION*CONTROL/STRUCTURE INTERACTION WITH CO-ST-IN

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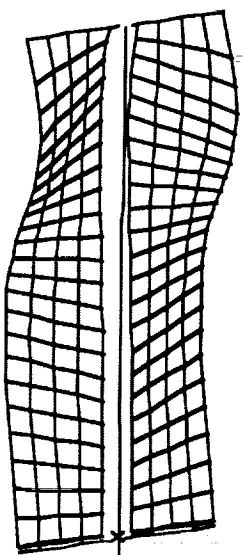
*Space Station Freedom

SOLAR POWER PROVIDED BY EIGHT PV ARRAYS

The electrical power for Space Station Freedom is generated by eight large photovoltaic (PV) arrays. Lockheed Missiles and Space Company's proposal defines an array which is 113.7 feet long and 33.8 feet wide, and weighs about 1,200 lbs. The eight solar arrays represent a significant portion of the structural weight and inertia of the Space Station outboard of the central modules. A detailed finite element model of the array was generated using 2,000 degrees of freedom (DOF). The array's stiffness is partially created by stretching the photovoltaic cell substrate using a differential stiffness method. The verification of the method to analyze the differential stiffness effect will be presented at the AIAA SDM conference in April. The predicted array first bending and first torsion mode frequencies are both at approximately 0.08 Hz. Each solar array has 39 modes of vibration under 1 Hz and 273 modes of vibration under 20 Hz.

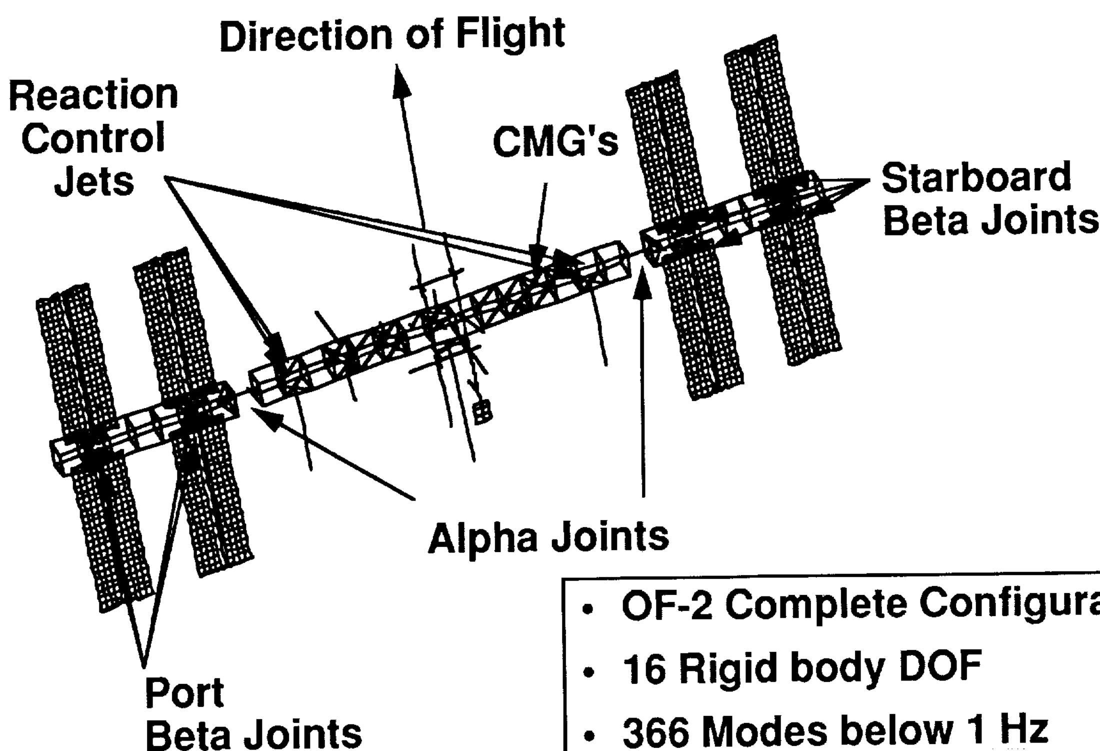


- **Differential Stiffness in Blanket**
- **2000 DOF**
- **First modes ~ 0.08 Hz**
- **39 Modes below 1 Hz**
- **273 Modes below 20 Hz**

Beta Joint

OVERALL SPACE STATION MODEL IS VERY LARGE

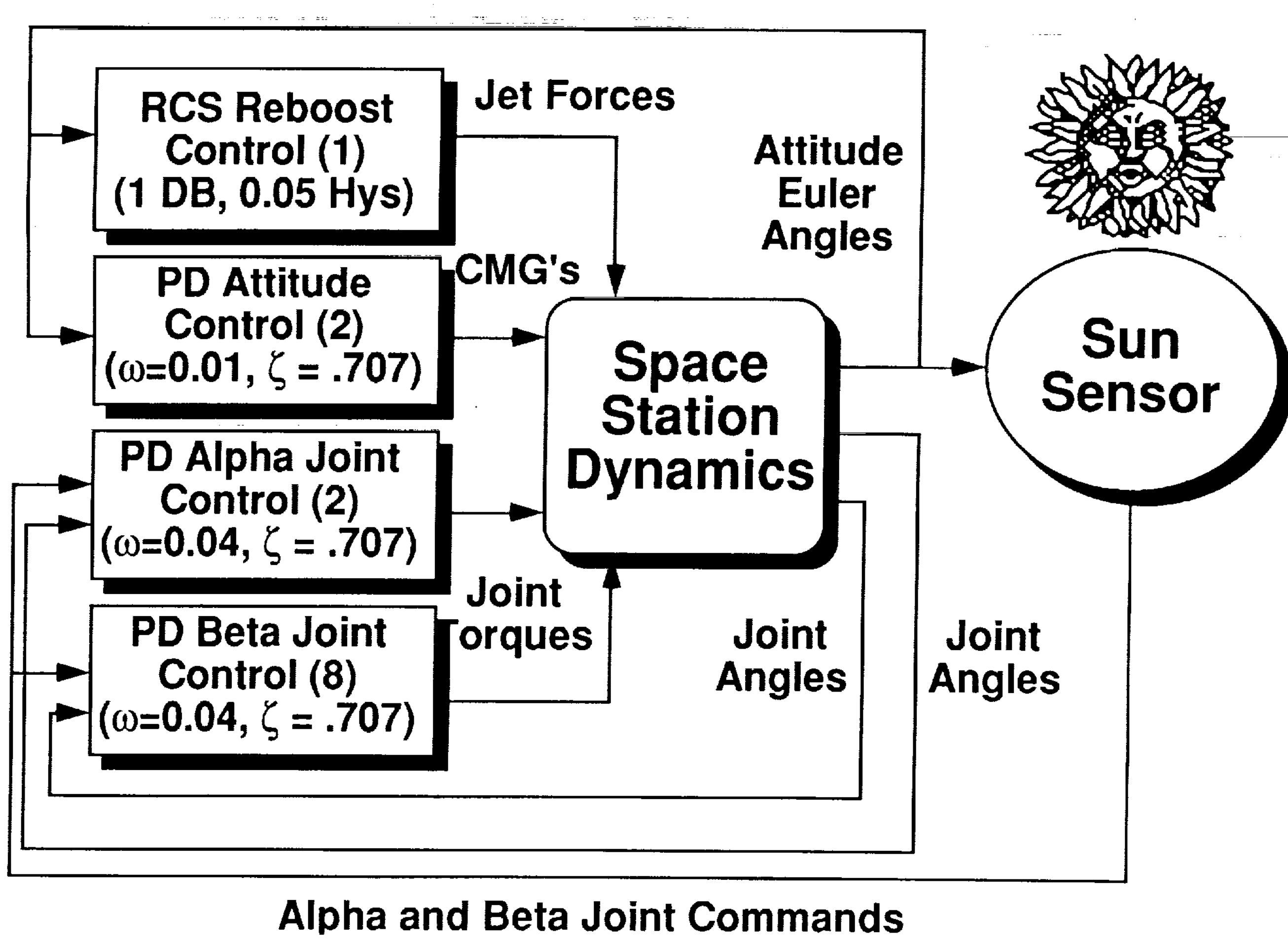
A Craig-Bampton dynamic component model of the photovoltaic array was formed as described in the previous slide, duplicated eight times and coupled to the overall Space Station model. The Space Station model used was the Microgravity Study, OF-2, assembly complete configuration. A finite element model of the beta joint was also created and included in the synthesized station model. Both the alpha joint and the beta joint were freed to rotate when system modes were generated, resulting in sixteen rigid body modes. There are a total of 366 normal modes under 1 Hz. Without any further model reduction at the component level, we would expect to find between 3,000 and 4,000 modes below 20 Hz. A modal ordering algorithm, described later, was used to select 99 modes of the 366 below 1 Hz for the controls analysis.



- OF-2 Complete Configuration
- 16 Rigid body DOF
- 366 Modes below 1 Hz
- 99 Modes selected for analysis
- 3000-4000 Modes below 20 Hz

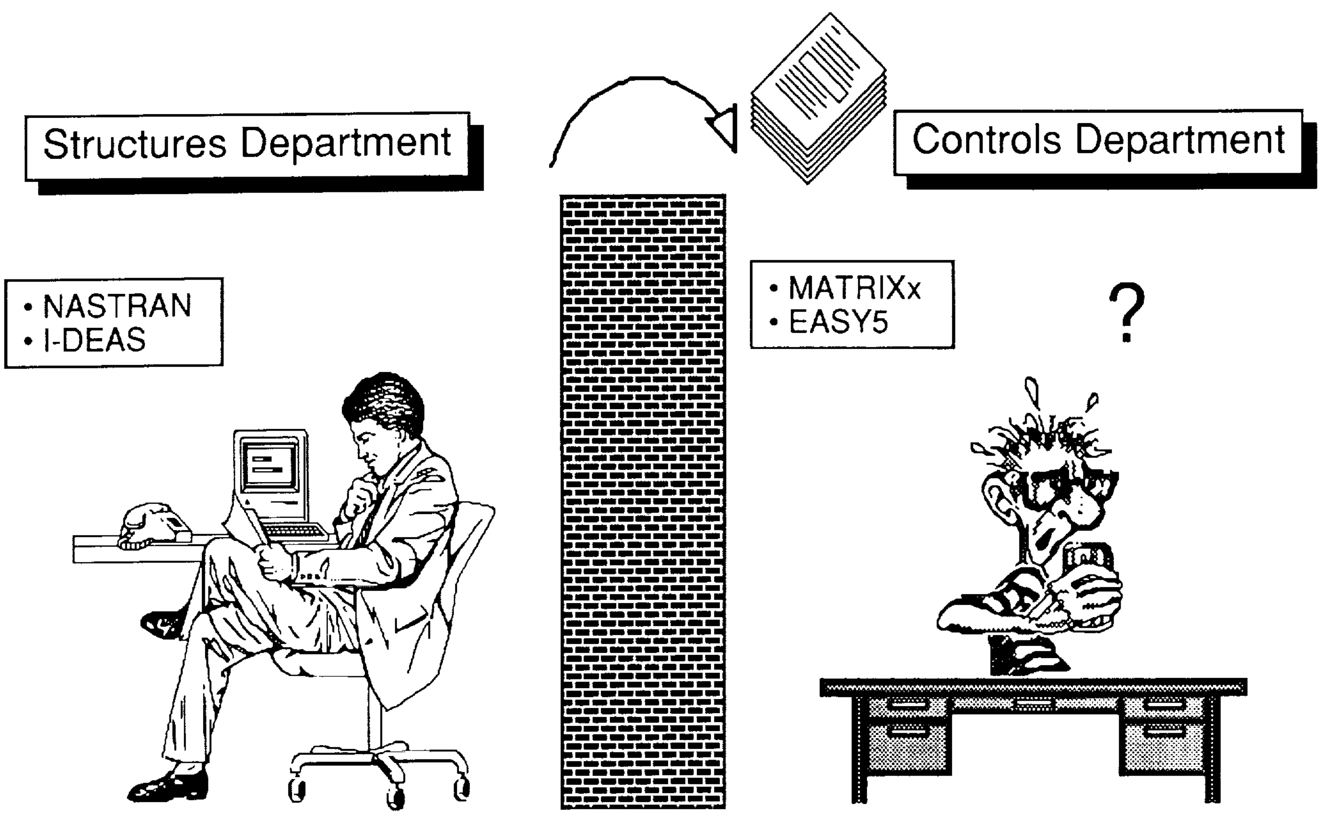
FOUR CONTROL SYSTEMS SIMULATED

Four control systems were simulated for this initial study. The first is three axis Proportional-plus-Derivative (PD) attitude control. Variations from commanded attitude are sensed at an avionics platform co-located with the Control-Moment-Gyros (CMG's) which apply a restoring torque to the Station. Control gains are chosen to result in control frequencies of 0.01 Hz and damping ratios of 0.707 about each axis. The second control system is a simplified model of the Reaction Control System (RCS) during reboost. In this model the RCS accelerates the station in the direction of flight (x) and controls attitude in pitch (θ_y) only. The pitch axis PD controller is deactivated during reboost, though roll and yaw controllers reamin active. The jet firing logic is based on a deadband of 1.0° and a hysteresis of 0.05°, where the error signal is the sum of the pitch rotation and rotational velocity. The final two control systems control the two alpha joints and the eight beta joints. These are PD controllers with control frequencies of 0.04 Hz and damping ratios of 0.707. The rotation of both the alpha and beta joints is commanded by a sun-sensor mounted on the avionics platform, resulting in a co-located inner loop, but a non co-located outer loop.



CONVENTIONAL APPROACH: MANUAL TRANSFER OF DATA

The conventional approach for control/structure interaction studies is undertaken by two separate departments. A finite element model is typically developed by a structures department and solved for some number of normal modes. Some subsets of these modes are then transferred (often manually) to a controls department where they are used to develop a structural dynamic model which is coupled to control systems for analysis. If structural loads are required, input forces are usually extracted from the coupled analysis and returned to the structures department which runs through a load cycle. Even if we side step the issue of developing truly coupled software to perform both the structural and control system analyses, a number of issues remain in the transfer of data between structural dynamic and control system analysis software. The emphasis of our development efforts at the NASA Lewis Research Center have been to retain current software tools in each of the two disciplines (MSC/NASTRAN for structural dynamics and BCS/EASY5 for control system analysis), while carefully examining the issue of data transfer.

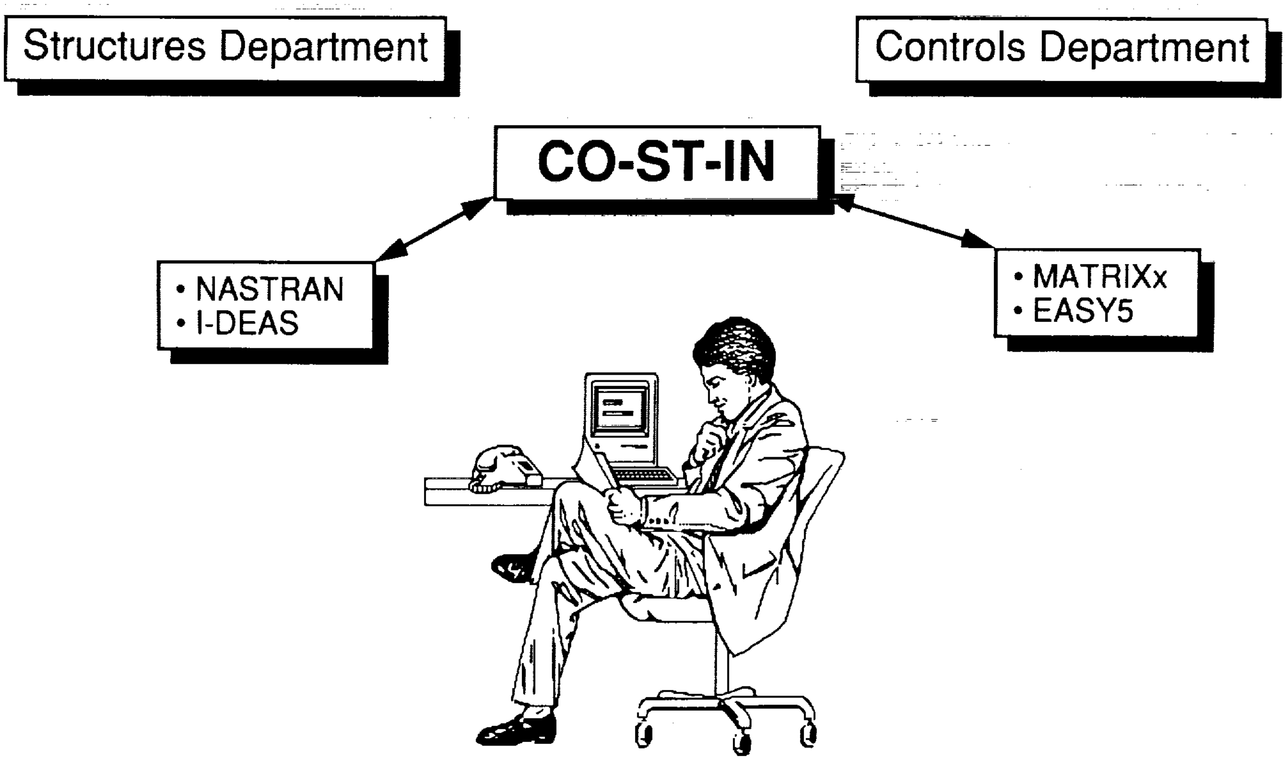


AUTOMATED APPROACH UNIFIES PROBLEM

The outcome of this development has been a software program called CO-ST-IN (COntrol-STructure-INteraction). The structural model is still developed and solved in MSC/NASTRAN, while control system analyses are performed in BCS/EASY5. CO-ST-IN simply acts to transfer data between the two programs, provided an efficient platform for coupled analyses. The emphasis in developing CO-ST-IN has been on the type of data to be transferred and how best to do this transfer. Some of the issues which we have considered are listed below:

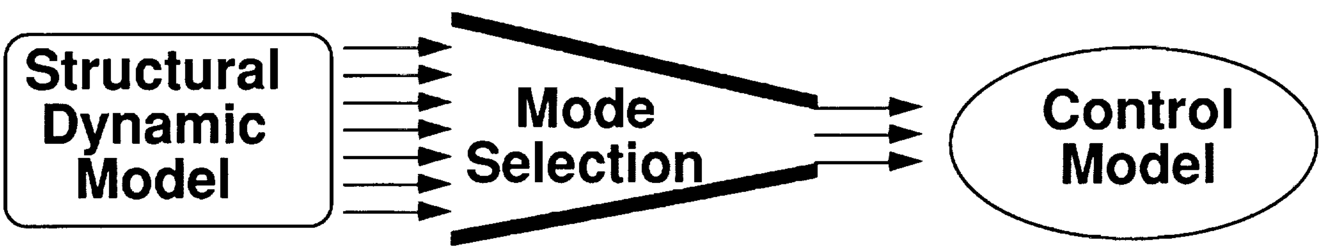
- Modal selection as a method of model reduction.
- Most efficient methods for recovering accurate internal loads and stresses.
- Alternate modal representations resulting in more accurate closed-loop models using fewer modes.

Each of these is discussed in greater detail in following slides.



MODAL ORDERING REDUCES MODEL SIZE

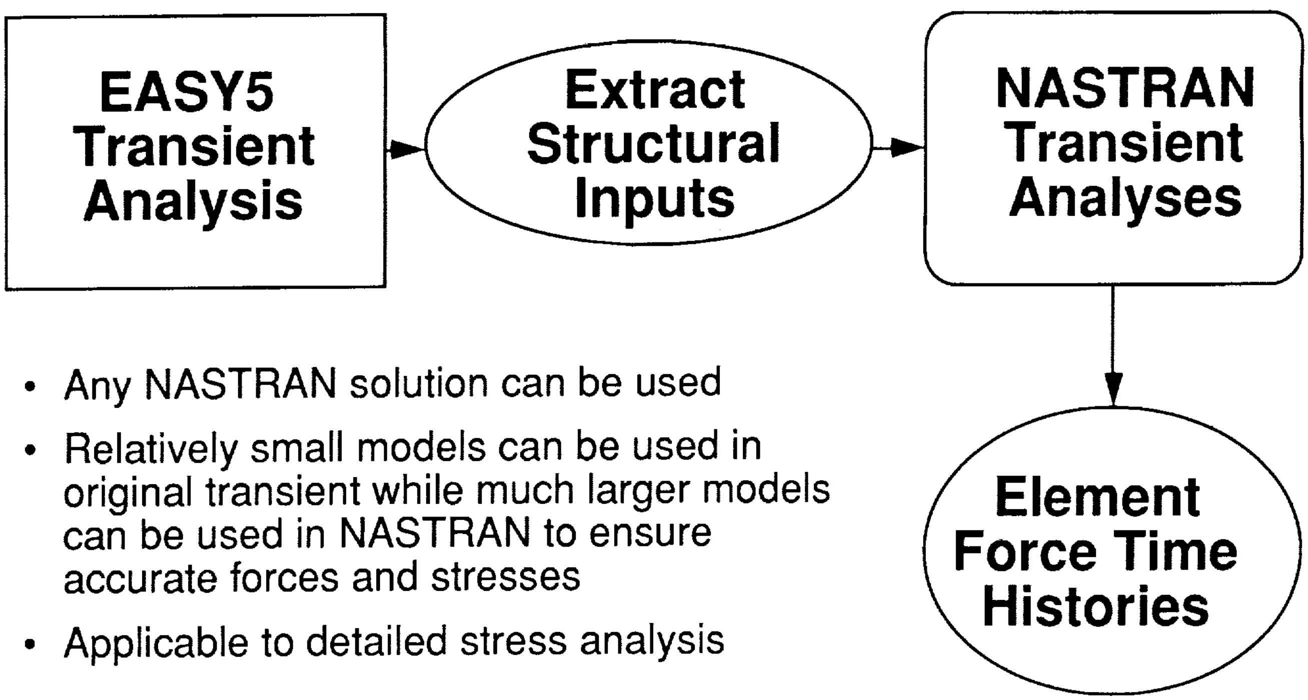
One of the largest discrepancies between typical structural dynamic and control system models is model size. The Phase I Space Station model presented here, for instance, has 366 modes below Hz. While this model can be handled effectively using structural dynamic software such as MSC/NASTRAN, it is too large for effective control system analysis using currently available software. While many methods of model reduction can be found in the literature, most methods based on state-space representations (such as internal balancing, component cost analysis and optimal Hankel-norm approximations) reduce to modal selection under the assumptions of light damping and sufficiently separated frequencies. This suggests that modal selection provides an especially powerful method of model reduction for lightly damped flexible structures. CO-ST-IN implements three algorithms in order to select modes. The first is approximate balanced singular value based on Moore's internal balancing, the second is the modal cost based on Skelton's component cost analysis and the final algorithm measures each mode's contribution to the static deflection of the structure. In order to implement meaningful modal selection algorithms we have found it essential to be able to group modes with equal or nearly equal frequencies and also to scale inputs and outputs so as to reflect their relative importance.



- Three algorithms used:
  (1) Approximate Balanced Singular Values
  (2) Modal Cost
  (3) Contribution to Static Deflection
- Modes grouped by frequency
- Inputs and outputs scaled to reflect relative importance

CONVENTIONAL INTERNAL LOADS AND STRESSES CALCULATION

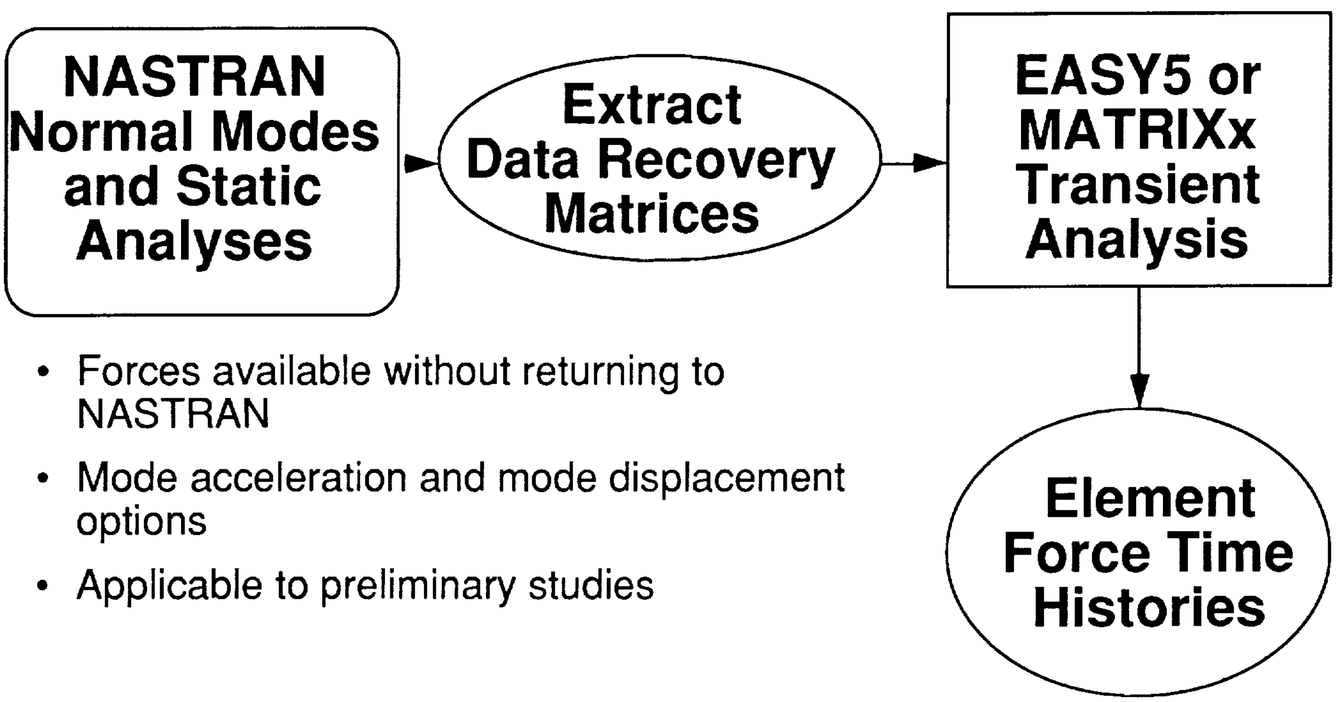
The conventional method for recovering internal loads and stresses is to extract structural input loads from the coupled control system simulation and apply these to the structural dynamic model. This approach offers a number of advantages when compared to methods which depend on the number of modes represented in the coupled simulation. The first is that structural dynamic software such as MSC/NASTRAN can effectively handle very large amounts of data, and structural engineers have the tools and expertise to reduce this data. A more fundamental advantage is that the number of modes used in the coupled simulation must only be large enough to calculate accurate input loads, but this is typically much smaller than the number of modes required to calculate accurate internal loads and stresses. This approach then allows the analyst to choose the model size which is most appropriate for each analysis, thereby greatly reducing the number of modes required in the control analysis. CO-ST-IN facilitates the implementation of this conventional approach by searching EASY5 output data for structural inputs and writing these as dynamic input data for NASTRAN.



- Any NASTRAN solution can be used
- Relatively small models can be used in original transient while much larger models can be used in NASTRAN to ensure accurate forces and stresses
- Applicable to detailed stress analysis

INTERNAL FORCES AND STRESSES CALCULATED IN CONTROL SIMULATION

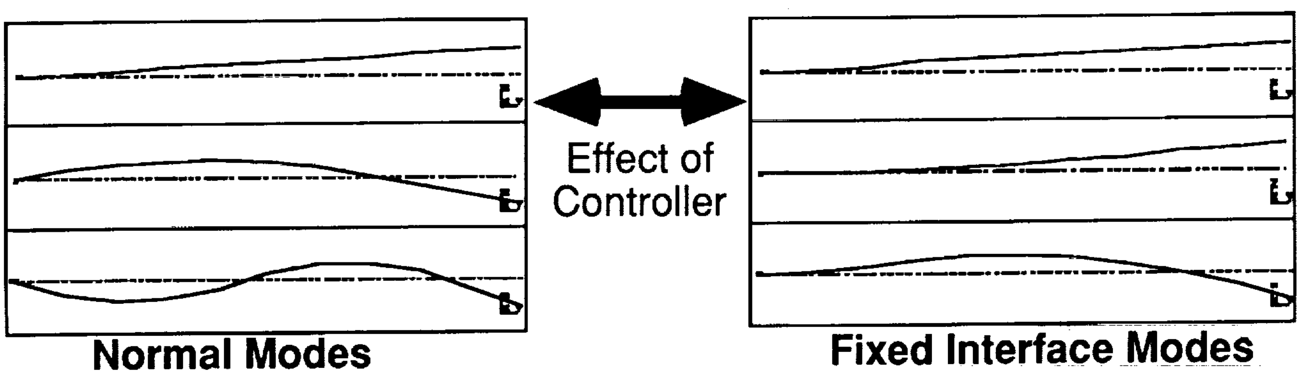
While the conventional approach described in the previous slide can be very powerful, it can also be somewhat cumbersome in situations where a quick turnaround of results is desired. This is because it is necessary to transfer loads back to the structural dynamic model after each dynamic simulation. Turnaround time for the analyses can be greatly reduced by extracting "data recovery matrices" from the structural dynamic routine and using these to calculate internal loads and stresses directly during the coupled simulations. Data recovery matrices are used by the structural dynamic routine to calculate internal loads and stresses given information on the modal displacements and additionally the input loads if a mode acceleration method is used. CO-ST-IN allows the user to extract these matrices from MSC/NASTRAN and transfer them to EASY5. Either the mode displacement or the mode acceleration methods can be used. The mode acceleration method adds a static correction (direct feedthrough) term to modal data, resulting in improved accuracy with a given number of modes. The mode acceleration method is particularly recommended in this case since the number of modes in the coupled analysis is typically limited.



- Forces available without returning to NASTRAN
- Mode acceleration and mode displacement options
- Applicable to preliminary studies

FIXED INTERFACE REPRESENTATIONS CAN BE MORE ACCURATE

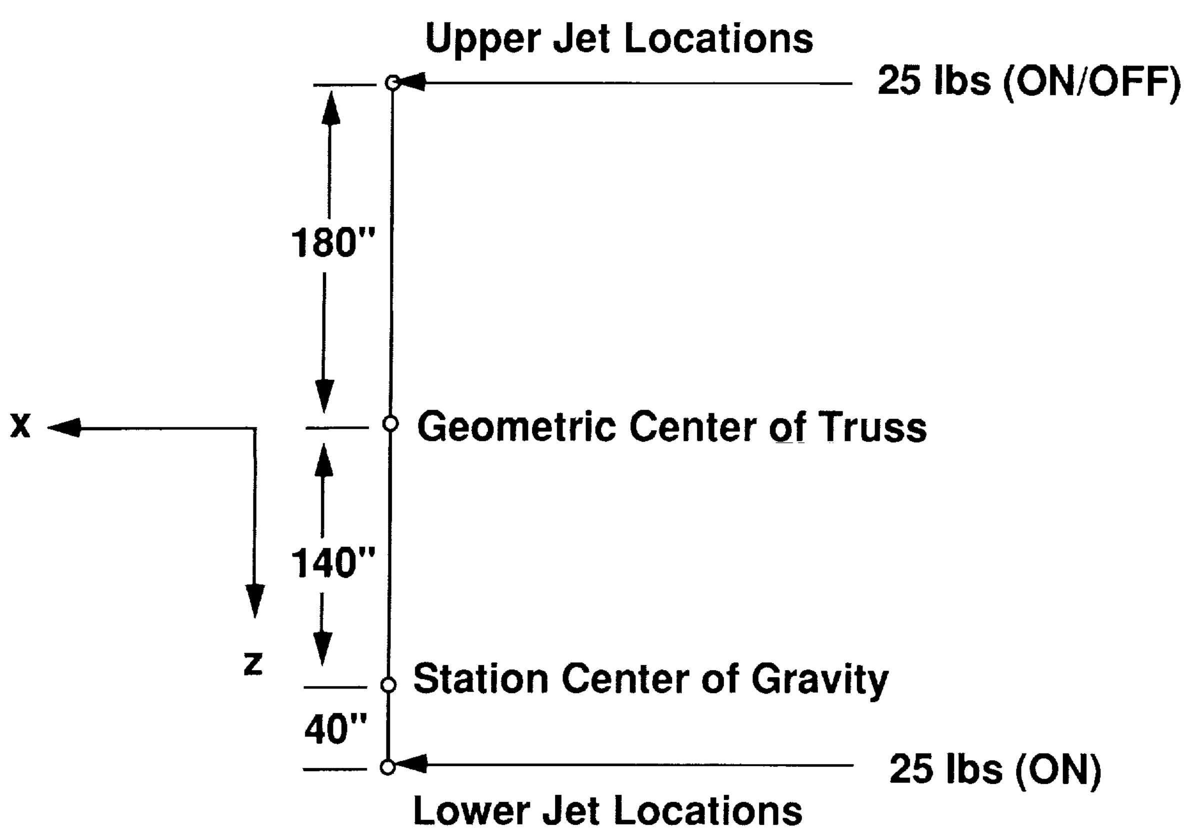
While the use of normal modes as a structural representation offers a number of advantages, these modes are calculated with all controlled DOF (i.e., DOF at which control actuators apply forces and moments) left free. This implies, in some cases, that a large number of modal DOF may be required in order to calculate an accurate closed-loop model. One method for circumventing this problem is to use a Craig-Bampton representation, based on the calculation of modes with controlled DOF held fixed. The actual effect of the controller lies somewhere between these two extremes, but we have found that even with relatively soft controllers, the Craig-Bampton representation results in more accurate closed-loop models. We have developed a simple procedure for calculating and extracting Craig-Bampton models using MSC/NASTRAN's superelement capability. Since we only transfer modal data, many of the advantages of the normal modes representation are retained.



- Fixed Interface Modes result in more accurate closed-loop poles and closed-loop frequency response when sensors and actuators are collocated.
- The improvement is large for "stiff" controllers, but still exists for "soft" controllers
- Fixed Interface Modes Result in Off-Diagonal Mass Terms
- Fixed Interface Representations are simple to calculate in MSC/NASTRAN and only normal mode data need to be transfered

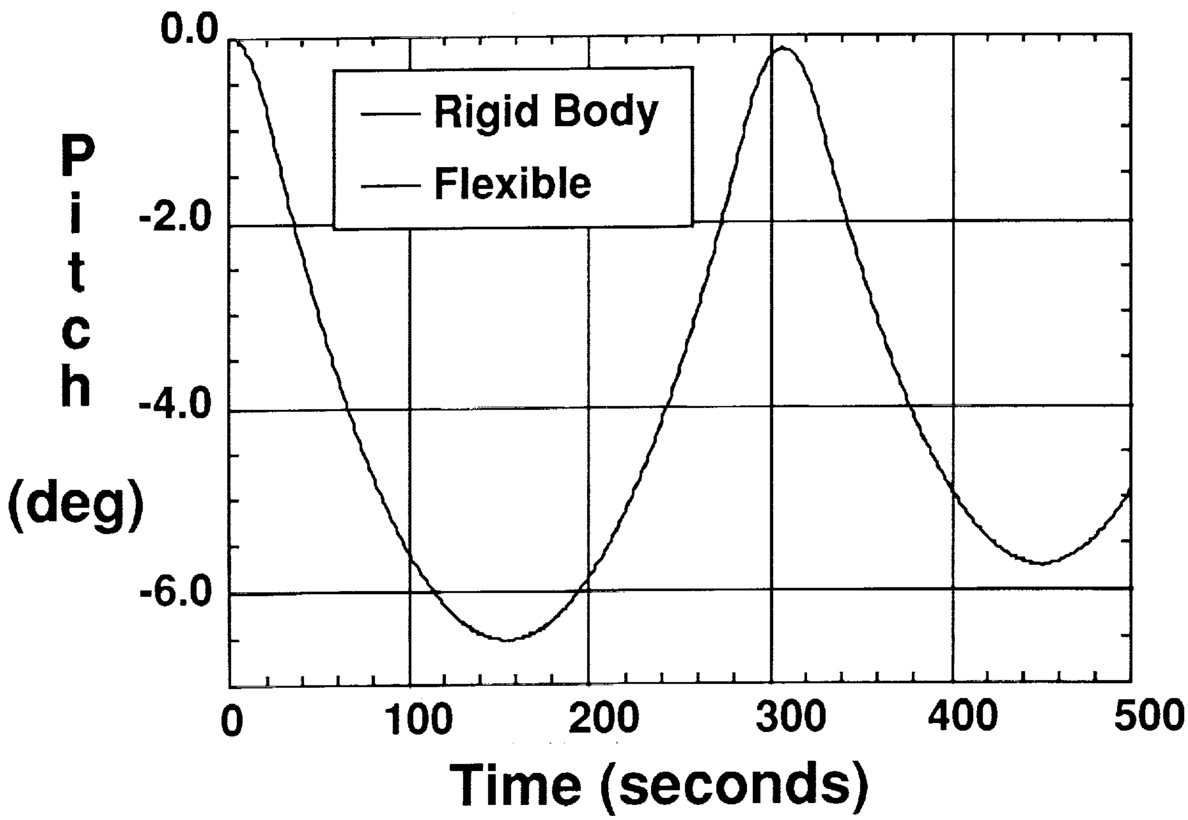
REBOOST JETS USED FOR PITCH CONTROL

We examined the response of the Space Station during a reboost maneuver where the Station is accelerated in the direction of flight (x-axis). In this case roll and yaw attitude are controlled by CMG's, while pitch is controlled by the four reboost jets, each firing with a force of 25 lbs. Because the module cluster lies below the boom, the Station center of mass is approximately 140" below the center of boom, so with all four jets firing the top of the station pitches forward. The pitch angle plus a rate gain times the pitch rate is fed back to the Reaction Control System (RCS). Once this error signal exceeds the deadband plus hysteresis the upper jets turn off and the Station rotates back until the error drops below the deadband at which time the upper jets switch back on and the procedure is repeated. Since the moment arm with all four jets firing is much larger than with only the lower jets firing, the station will initially exhibit a large overshoot as the lower jets turn it back around. This overshoot can be reduced by increasing the rate gain which adds an effective lead compensation to the control system.



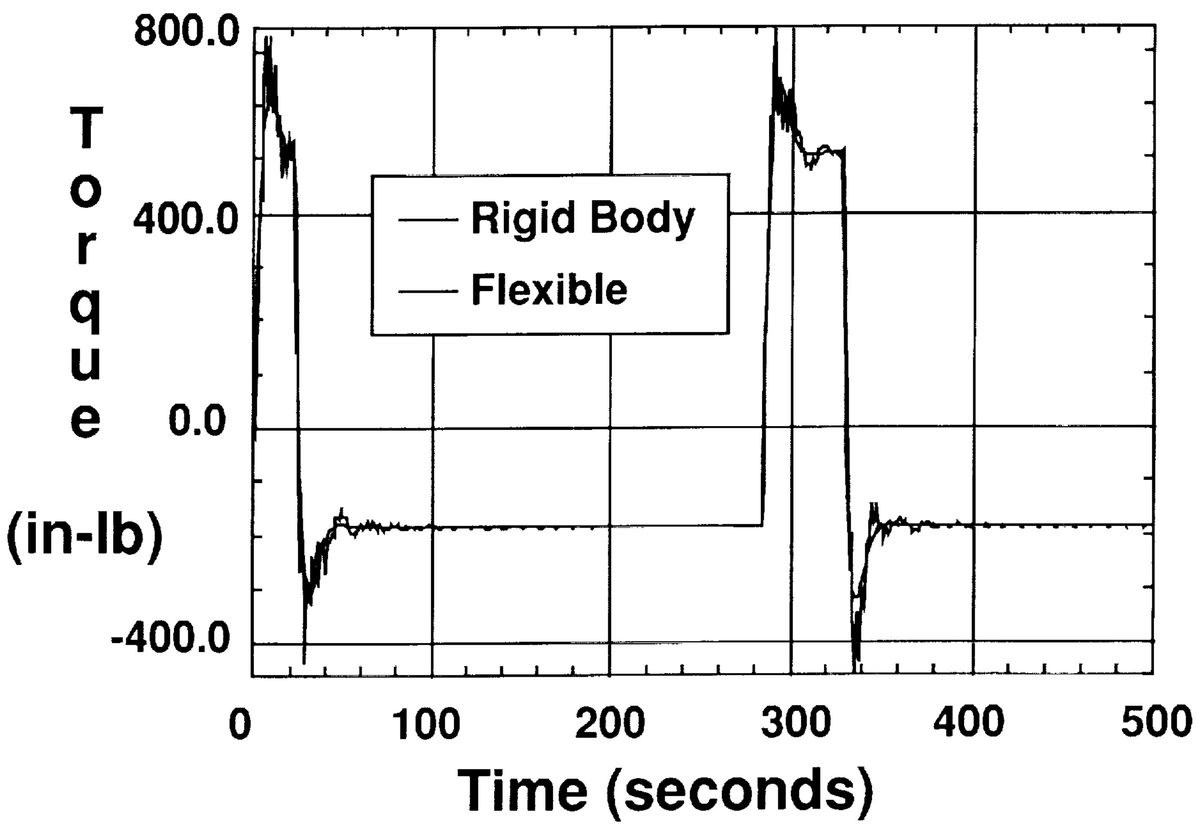
STATION PITCH RESPONSE TO REBOOST
(Rate Gain = 1.0, Hysteresis = 0.05°)

With a rate gain of 1.0, a deadband of 1° and hysteresis of 0.05°, the pitch response exhibits an initial transient with an 500% overshoot and it does not settle into a steady state limit cycle within the 500 second simulation. This is a relatively benign excitation from a structural point of view and the effect of flexible modes on the pitch response is very small.



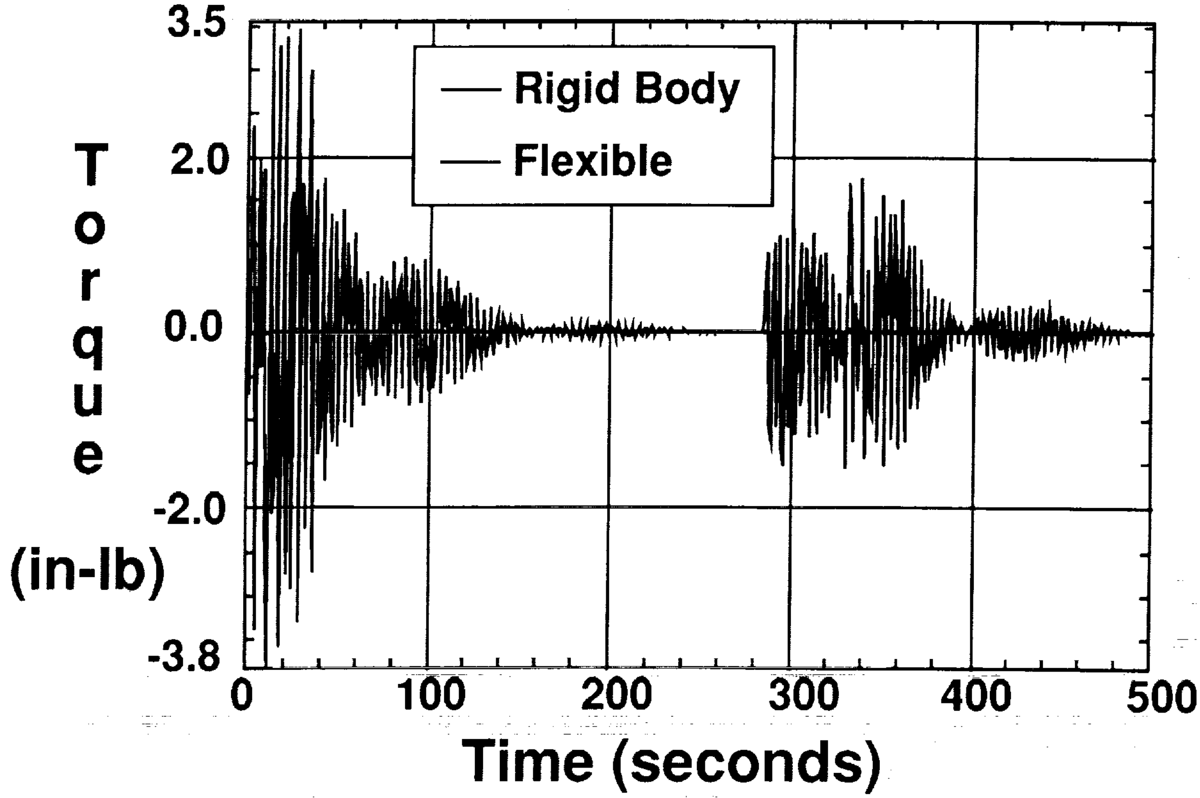
ALPHA JOINT TORQUE RESPONSE TO REBOOST
(Rate Gain = 1.0, Hysteresis = 0.05°)

One way to examine the model for potential control/structure interaction is to compare the response of control systems with and without the presence of flexible modes. In this case we examine the response of the alpha joint controllers which are acting to maintain the relative rotation at the alpha joints. The response with and without flexible modes is very similar, though the effect of flexible motion is clearly visible. Even with this relatively benign excitation, the structural dynamic response of the station outboard of the alpha joints will vary depending on whether it is excited by the forces calculated with flexible modes or those calculated with rigid body modes only.



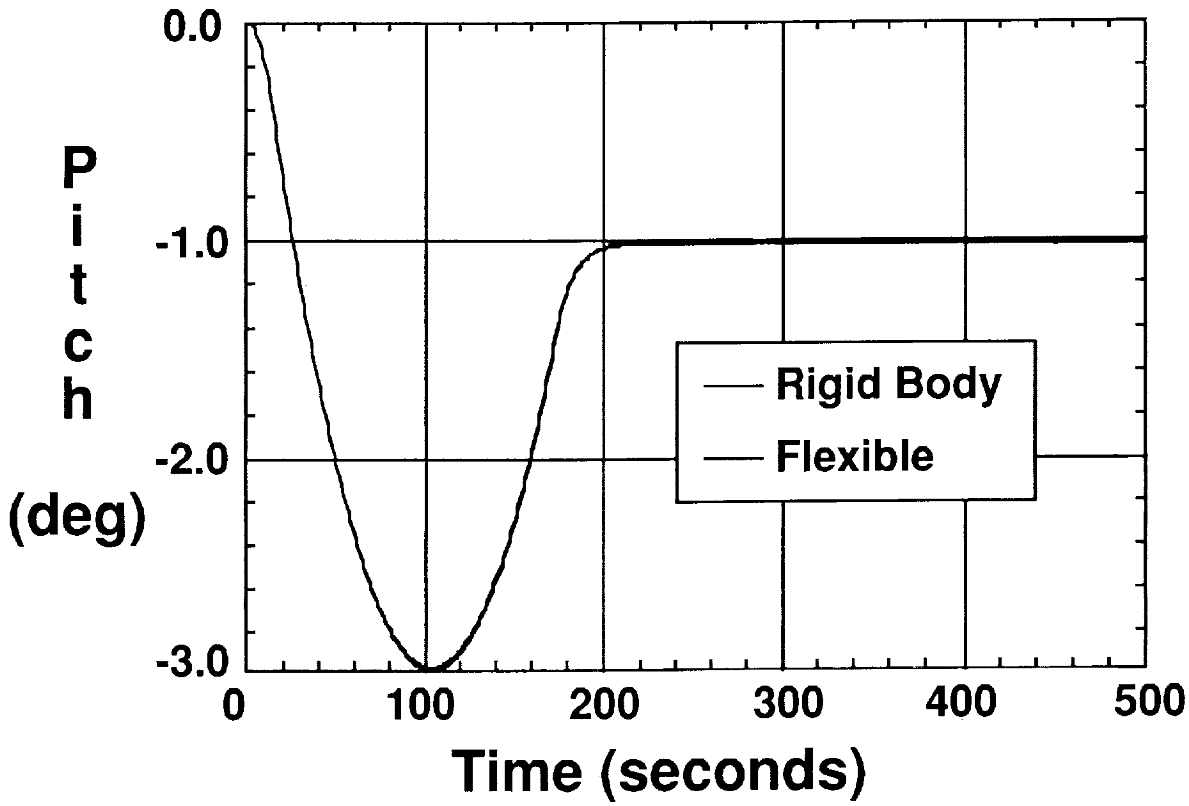
BETA JOINT TORQUE RESPONSE TO REBOOST
(Rate Gain = 1.0, Hysteresis = 0.05°)

While the alpha joints are strongly excited by the rigid body pitching of the Space Station, the beta joints are not. The response of the beta joint controllers to RCS jet firing is essentially zero with rigid body modes only, but increases to peak of near 4 in-lbs with the addition of flexible modes. While this is still a small response it does illustrate the effect of flexible modes.



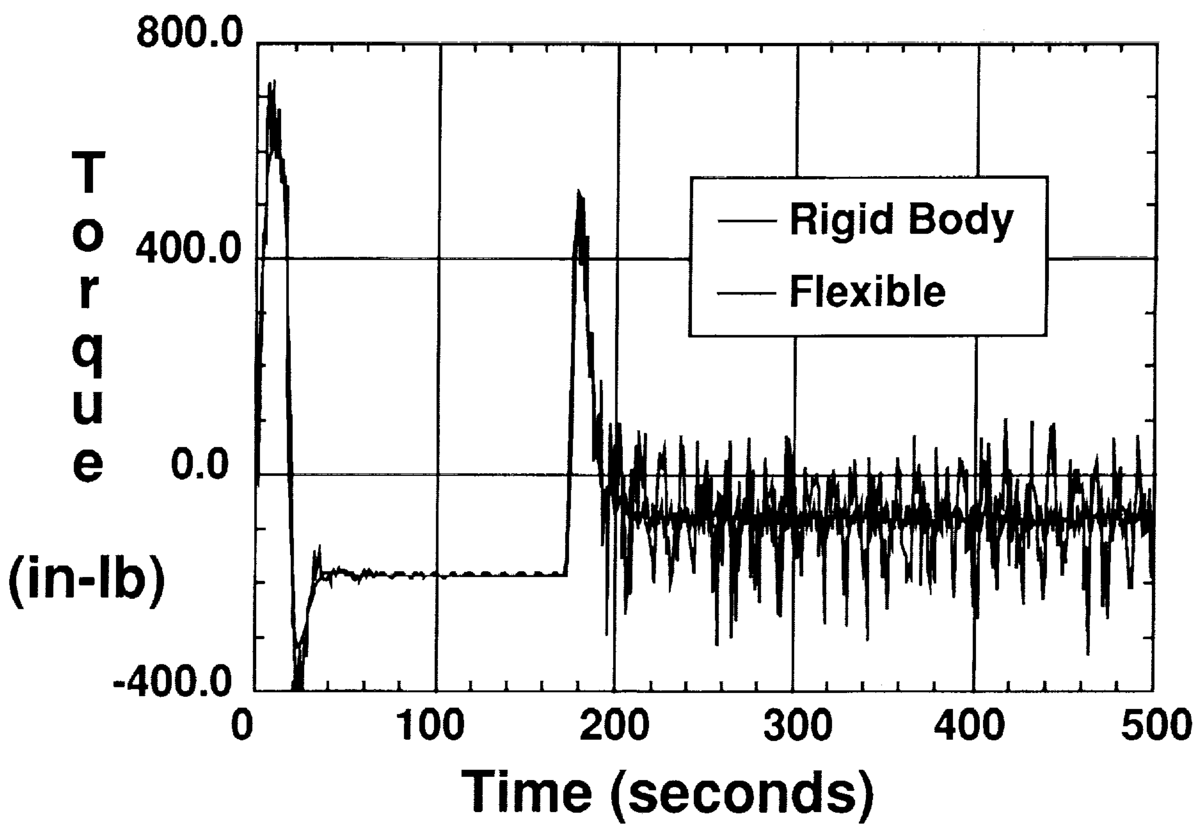
STATION PITCH RESPONSE TO REBOOST
(Rate Gain = 10.0, Hysteresis = 0.01°)

Now consider a variation in the control parameters to improve rigid body response. Increasing the rate gain reduces overshoot, while decreasing the hysteresis reduces the effect of limit cycling. As expected the response does improve. The overshoot is reduced to 200% and the pitch angle attains a constant steady state value after the initial 200 second transient. The response with flexible modes is offset slightly, though it is still very similar. The cost paid for the improved performance is that the upper RCS jets are now switching on and off at a much higher rate, possibly reducing efficiency and increasing the potential for excitation of structural modes.



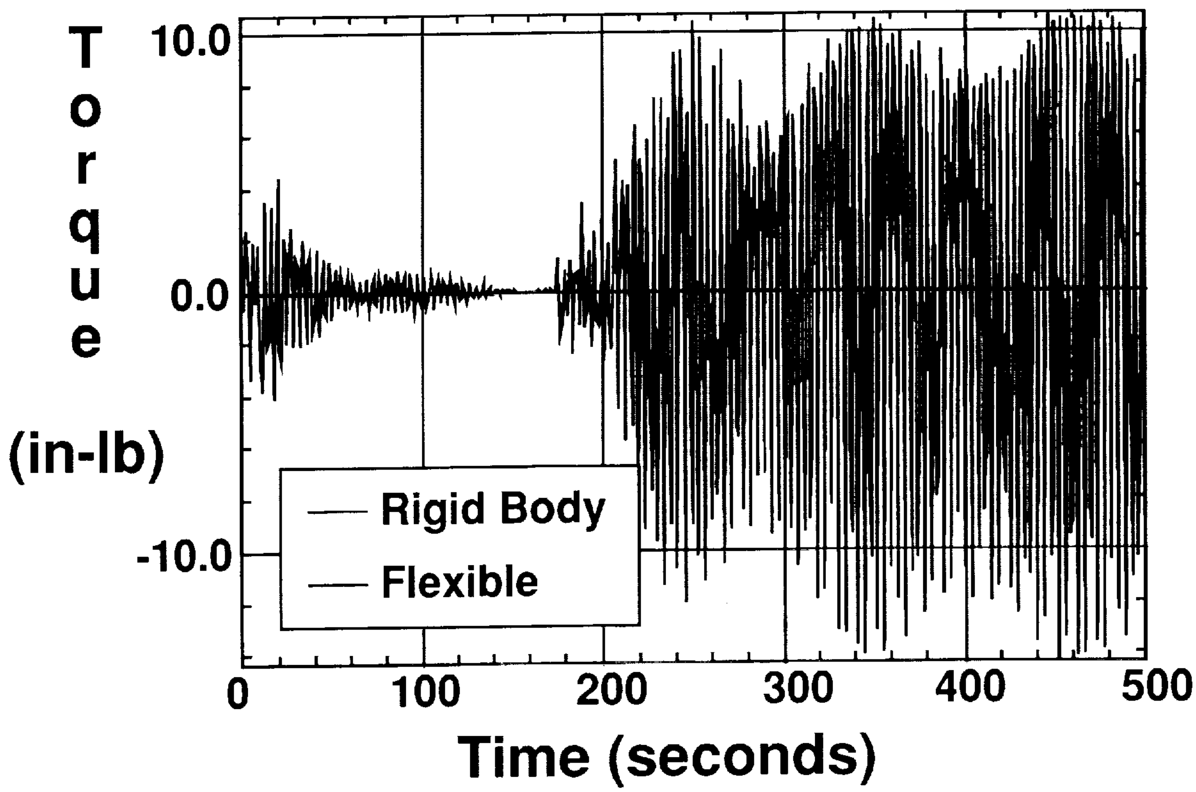
ALPHA JOINT TORQUE RESPONSE TO REBOOST
(Rate Gain = 10.0, Hysteresis = 0.01°)

Once again examine the torque response of the alpha joint controllers in order to identify any potential for control/structure interaction. In this case the rigid body response of the alpha joints undergoes two initial transients and then settles close to a steady state value. The flexible response follows a similar pattern, but the peak moments generated during the initial transient are significantly higher and the amplitude of the steady state response is close to an order of magnitude higher than with rigid body modes only. It is clear that with this choice of control parameters, there is a significant control/structure interaction. It is also clear that variation of control parameters and possibly filtering of the alpha joint control signals can reduce this effect, though careful analysis of the results will be necessary.



BETA JOINT TORQUE RESPONSE TO REBOOST
(Rate Gain = 10.0, Hysteresis = 0.01°)

With the increase in rate gain and decrease in hysteresis, the response of the beta joint controllers with a rigid body model is still near zero, but with a flexible modes peak torques of more than 10 in-lbs are observed. The response of the beta joint controllers, in this case is almost entirely due to the coupling effect of the flexible modes of vibration.



SUMMARY

The NASA Lewis Research Center is concerned with the potential of interaction between space station controllers and the solar PV array structures. The models required to handle this problem are very large, and we have developed automated methods for the transfer of data between structural dynamic and control system analysis software. These methods emphasize the need to achieve accurate coupled analysis results while using as small a model as possible. Specific tools which help the analyst in this regard include modal order techniques, the use of mode acceleration to calculate internal loads and stresses and the transfer of Craig-Bampton components to reduce problems associated with modal sufficiency. These techniques were applied to a space station model with 366 modes below 1 Hz. Attitude control, and alpha and beta joint control were simulated. The inclusion of alpha and beta joint controllers is important when examining overall space station dynamics. An initial choice of control parameters does indicate a potential for control/structure interaction during reboost. As expected this is exacerbated by increasing the rate gain and decreasing the hysteresis of the Reaction Control System (RCS) in order to improve rigid body performance.

- **CSI analysis of Space Station involves large models**
- **PV arrays are very flexible and can have a significant effect on station dynamics**
- **Selected Data Transfer Facilitates Analysis**
- **Alpha/Beta joint controllers are important**
- **Potential for CSI exists depending on control parameters**