A MODERN CONTROL APPROACH TO THE DESIGN OF THE SPS CONTROL SYSTEM

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The Problem

The structural dynamics of the solar power satellite are complex. There are many low frequency vibration modes with frequencies that are closely clustered. In addition, the requirements on the vibraton of the microwave antenna are very severe. Lastly, the possibility of thermal induced vibration is such that severe structural-thermal interactions are possible. One way of eliminating these problems is to design the structure stiff enough and with low coefficient of thermal expansion material so that the vibrations do not create a problem, and the thermal interactions can not occur. A second possibility is to use the active control system to mitigate the structural problems.

A cautionary note must be sounded. The first approach might actually exacerbate the structural problem if the control system were designed without consideration of the structural dynamics. This comes from the interaction of the control actuators and the sensors with the vibration of the structure. The so called "control and observation spill-over" problem is so important that it must be kept in view as one goes about developing the control system. Since the detailed structural, thermal and control models are required to guarantee that spill-over does not occur, it makes sense to evaluate other advantages that a complex control system may provide. One possibility is that the control system will permit lighter structural material with lower stiffness, the loss of structural stiffness being overcome by the active control system. Figure 1 shows the spill-over problem and the potential solutions to the problem.

The Approach

There are several distinct avenues that one may follow if the control system is designed using modern control methods. These are:

- Design of an optimal controller with an estimator (Kalman Filter) to reconstruct the missing measurements of the structural motion.
- Design of a control system that uses only measurements, that is with no estimation of the missing dynamic states. This is sometimes called direct output feedback.
- Design of a control system on a very limited set of models and then adaptively modify the control system during its operation.

Fig. 1 illustrates the first two of these techniques. The emphasis in this presentation is on the second of the approaches, since this seems the most robust method. In the context of modern control, the term robust has a very specific meaning. A control system is robust if the variations in the parameters of the system being controlled do not alter the stability, and if the expected parameter variations do not dramaticly alter the response.

The robustness results that are available from the modern optimal control techniques are the following:

- A control system that uses "full state feedback" (i.e. for each state in the system their is a feedback gain to each control), has infinite gain margin when used in the system whose model was used for the design.
- A control system that is optimal has at least 60° of phase margin.
- A control system that is optimal and that is designed with an integral compensation in each control channel, is more robust than one without

integral compensation.

The procedure for accomplishing the design of the optimal robust control is as follows:

- Step 1- Develop a model that includes the rigid body dynamics, the gravity gradient dynamics, the rotational dynamics of any controllers that are included, the flexible dynamics through a large finite element model of the structure, and any significant thermal/structural interactions.
- Step 2- Reduce the dimension of the model. This is a key step since the validity of the robustness results depends on the minimization of spill-over which takes place at this step. Order reduction techniques include methods based on singular perturbation, variable time scale, or modal truncation based on cost of control.
- Step 3- Design the control system using the model of step 2 and a performance measure for the quality of control that penalizes motions in regions of the structure where loads nust be reduced, and also gives the overall rigid body control performance that is required (pointing of the microwave antenna to some specified angle, for example).
- Step 4- Verify the design of step 2 on a larger dimension version of the dynamic model than was used to develop the design. This is necessary because the only way one can evaluate the spill-over effect is with a dynamic model that is of larger dimension than the design model.
- Step 5- Repeat steps 2,3, and 4 until the design has the desired level of robustness for typical parameter uncertainties in the structural and control actuator dynamics.

The effectiveness of this approach as a design technique relies on the fact that any infinite dimensional system may be evaluated on a sufficiently large finite dimensional approximation, as long as the control system has a specified high frequency characteristic. In the case of optimal designs, this characteristic is the roll off of the control,at the higher frequencies, that is at least 20 db/ decade.

An Example

Figure 2 shows a structure that was used to evaluate the design proceedure described above. This structure was an earlier version of a space construction base that was developed by Grumman for JSC. The controller was asked to reduce the motion of the solar array, while stabilizing an unstable gravity gradient orientation. In addition the pointing of the overall system was to be insured. The actuators consisted of only the rigid body actuators which were three orthogonal control moment gyroscopes mounted close to the shuttle attachment point at the bottom of the mast that carries the solar array and construction boom. The control sensors were a set of 52 strain sensors (26 strain gages configured in such a way that both strain and strain rate were sensed), plus the normal complement of rigid body sensors (attitude and rate in each axis). The resulting design is extremely robust, and the verification on the higher dimension model has been formulated as a 16 mm movie that shows precisely how the control operation helps damp the solar array vibration while maintaining rigid body control despite the unstable gravity gradient torques.

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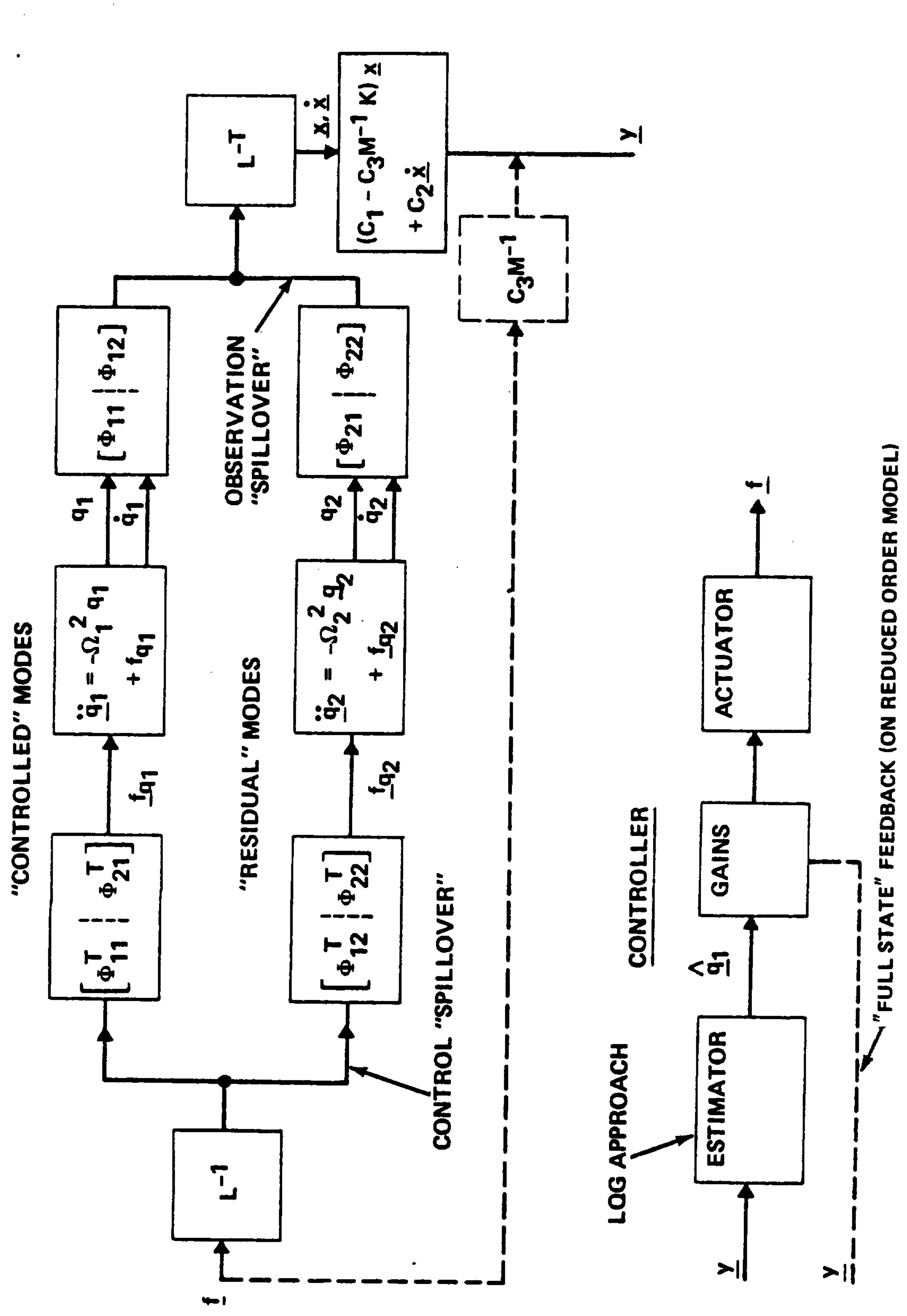

Fig. 1 Control Approaches to Spillover Elimination

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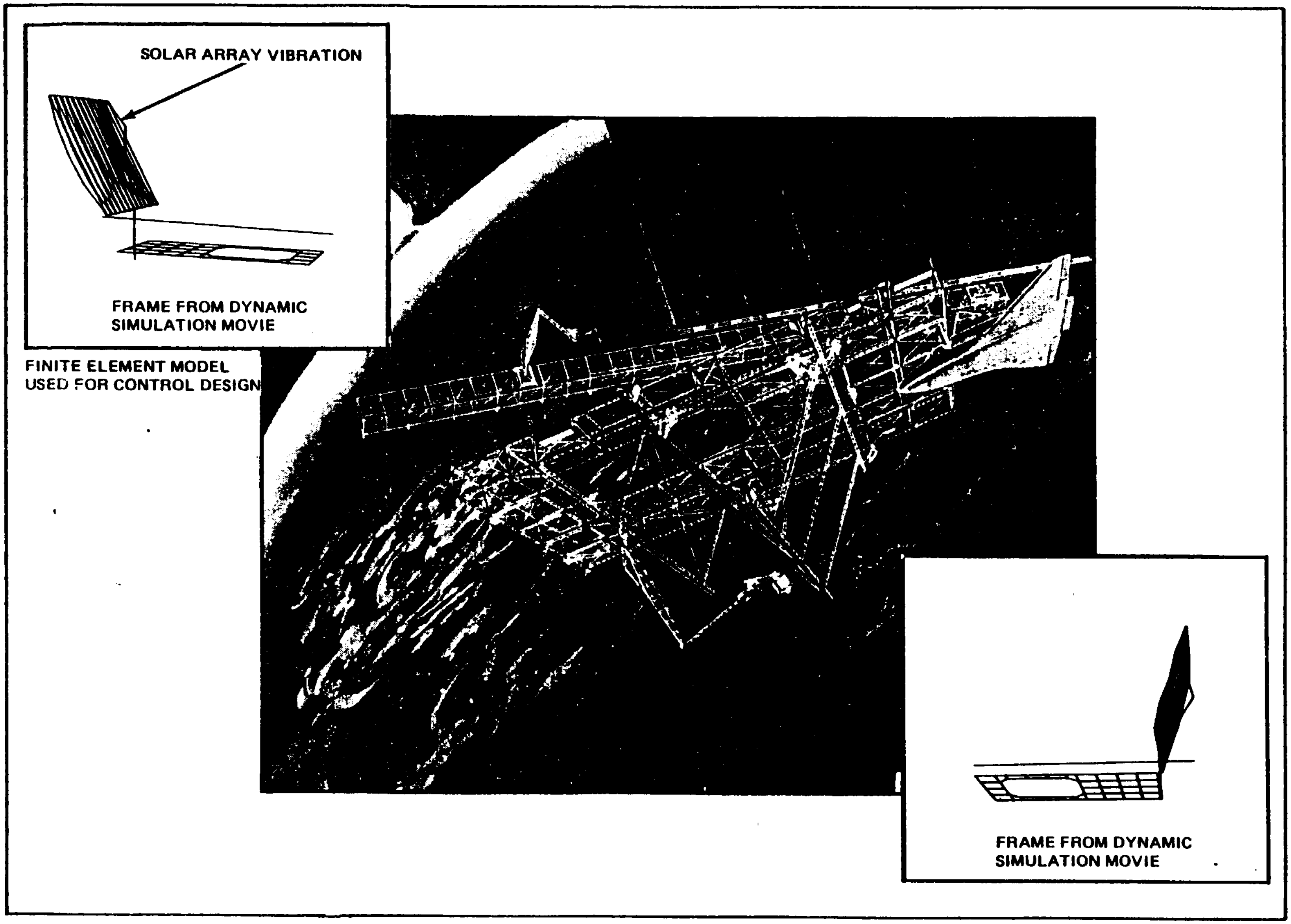

Fig. 2 Orbital Construction Demonstration Article