Representation of Control Systems for Preliminary Space Station Design

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A method for integrating linear control systems into a structural dynamic software module is presented. The method is in contrast to integrating a separate control software package and represents a structural analogy to control systems. Examples of PID attitude control and control of a flexible manipulator arm on the space station are presented.

Introduction

THE field of control/structure interaction combines the two disciplines of structural dynamics and control engineering. This pairing can also imply combining two sets of software tools, one for each discipline. For applications where the control systems can be represented as linear dynamic components, however, it is often possible to analyze the control/structure interaction problem within a structural dynamics code. Proportional plus derivative controllers with collocated sensors and actuators provide a trivial case that can be represented by springs and dampers. This paper extends the representation to arbitrary multiple-input multiple-output linear control systems. When the approach is applicable, it offers some advantages over the more common approach of transferring modal data to a control system simulation code. Elimination of excess software accelerates turnaround time for simulations, while reducing training time. A more significant advantage is that the structural dynamics routine treats the problem in physical coordinates, which allows the plotting of the closed-loop mode shapes. This can greatly increase the engineer's physical insight into the problem.

Analyses that can be performed using this approach include the evaluation of closed-loop eigenvalues and eigenvectors (stability analysis). Transient response to physical forcing functions can be calculated along with open- or closed-loop transfer functions (Bode plots). Although most structural dynamics routines do not offer a root-locus capability, this can be performed by manually varying a parameter and recalculating closed-loop eigenvalues. In summary, most of the linear analyses available to the control engineer can be performed directly in a structural dynamics routine.

This paper is organized as follows: First, the method for incorporating control systems is described; next, examples of PID attitude control and manipulator control on a realistic space station model are presented, followed by some conclusions. The overall software approach is described in greater detail in Refs. 1–3.

Methods for Control System Simulation

The biggest difference between a structural engineer's and a control engineer's approach to dynamic systems was recognized by Young.[4] In a structural system, two connected components apply equal and opposite forces to each other at the point of connection. In a control system, however, the controller applies an input to the plant, but no reaction is applied by the plant to the controller. Similarly, the sensors measure an output while applying no reaction force to the structure. For the simplest case of collocated sensors and actuators and proportional plus derivative control, springs and dampers can be used to represent the control system. For situations where the sensors and actuators are not collocated, Young[4] introduces the concept of unilateral connectors. The unilateral connector is a structural connector represented by Eq. (1a) for displacement measurements and Eq. (1b) for velocity measurements.

$$\begin{bmatrix} 0 & 0 \\ -k_p & 0 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix} \tag{1a}$$

$$\begin{bmatrix} 0 & 0 \\ -k_d & 0 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} = \begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix} \tag{1b}$$

where

x_1 = degree of freedom connected to structural model
x_2 = degree of freedom connected to control system
f_1 = force applied at degree of freedom x_1
f_2 = force applied at degree of freedom x_2
k_p = proportional gain
k_d = derivative gain

The key idea of the unilateral connector is that it applies a force at degree of freedom x_2, based on the position or velocity of x_1, while applying no reaction force at degree of freedom 1. The reason for the sign reversal on k_p and k_d is that f_1 and f_2 are the forces applied to the connector, which are opposite in direction to the forces applied by the connector to the structural model.

Unilateral connectors can be used to simulate proportional and derivative control effectively, independent of the necessity to collocate sensors and actuators. In order to simulate more complex control laws, however, it is essential to represent control law dynamics. With this in mind, consider the following state-space representation of a general, multiple-input/multiple-output, linear continuous-time control law applied to displacement and velocity measurements on a flexible structure.

$$\dot{z} = Az + B_1 y_1 + B_2 \dot{y}_2 \tag{2a}$$

$$f_u = Cz + D_1 y_1 + D_2 \dot{y}_2 \tag{2b}$$

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where

z = control law dynamics states
y_1 = physical displacement measurements at grid points
y_2 = physical velocity measurements at grid points
f_u = force applied by the control system to the structural model.

Note that both displacement and velocity measurements (possibly at different locations) are included. The direct feedthrough terms D_1 and D_2 represent proportional and derivative control, respectively. The control law dynamics z can represent anything from a simple integrator to a complex optimal control law.

The control law in Eqs. (2) can in turn be represented by a dynamic component described by the following set of matrix differential equations:

$$\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -D_2 & 0 & 0 \\ 0 & -B_2 & 0 & I \end{bmatrix} \begin{Bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \dot{u} \\ \dot{z} \end{Bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -D_1 & 0 & 0 & -C \\ -B_1 & 0 & 0 & -A \end{bmatrix} \begin{Bmatrix} y_1 \\ y_2 \\ u \\ z \end{Bmatrix} = \begin{Bmatrix} f_1 \\ f_2 \\ -f_u \\ f_z \end{Bmatrix} \tag{3}$$

Note that, in keeping with the philosophy of unilateral connectors, no reaction forces are applied at the measurement locations y_1 and y_2; f_u is the force applied by the controller to the structure (again, the reason for the sign reversal is that this is opposite to the force applied by the structure to the controller); f_z is a force applied directly to the compensator dynamic degrees of freedom and is typically set to zero. The component is connected to the flexible structure by coupling the degrees of freedom in y_1, y_2, and u to the physical locations of displacement measurements, velocity measurements, and actuators, respectively, on the structure.

The structural dynamics routine used to represent control systems must have a few special capabilities. The most fundamental is that it must have the flexibility to define a general matrix component such as that described by Eq. (3) and to differentiate between first- and second-order components. A complex eigensolver must be available to calculate closed-loop frequencies and mode shapes. The capability to perform transient and frequency domain responses on a system with complex modes is also required. An interactive, graphically oriented interface is a positive feature that will allow the user to take full advantage of the approach described here.

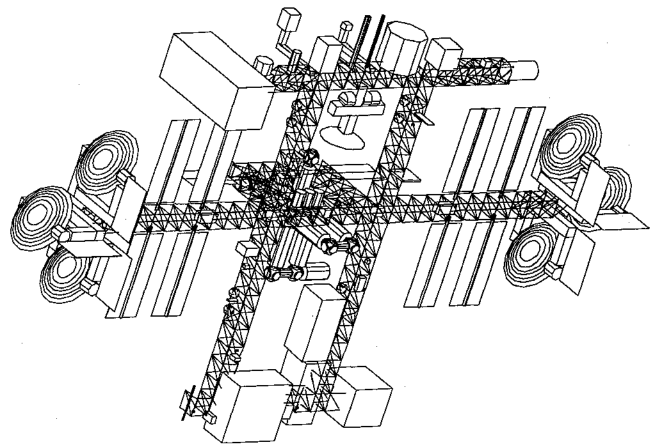

Fig. 1 Hybrid block 3 space station concept.

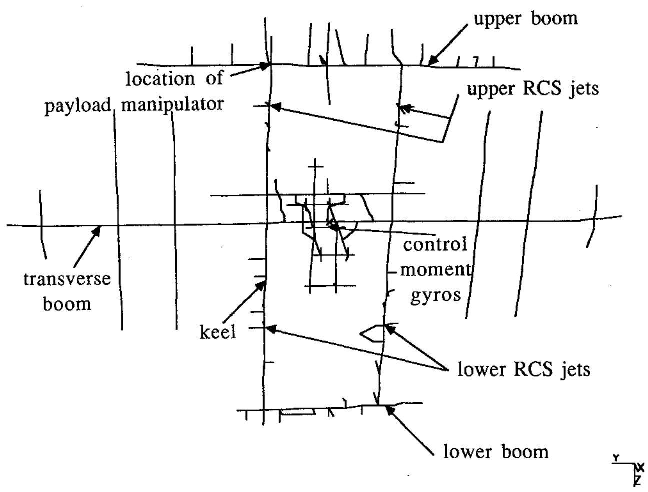

Fig. 2 Finite-element model of the space station.

Table 1 Space station mass properties

Mass = 6.17×10^5 kg
$I_{xx} = 2.10 \times 10^9$ kg · m²
$I_{xy} = 2.60 \times 10^6$ kg · m²
$I_{yy} = 3.46 \times 10^8$ kg · m²
$I_{xz} = 4.82 \times 10^6$ kg · m²
$I_{yz} = -3.25 \times 10^6$ kg · m²
$I_{zz} = 1.83 \times 10^9$ kg · m²

Examples

The particular configuration chosen as an example for this paper is a dual-keel, 300 kW growth configuration of the space station with a hybrid power system employing both solar voltaic arrays and solar dynamic collectors.[5] This is one of a number of space station concepts that have been considered in recent years. Figures 1 and 2 show the spacecraft concept and the resulting finite-element model. Table 1 shows the inertial properties for this configuration. Natural frequencies and mode shapes for the first six flexible modes obtained from this model are shown in Table 2. Note that these first six modes range in frequency from 0.0598 to 0.127 Hz. With major structural modes at these low frequencies, concern exists for unacceptable dynamic excitation of the space station during assembly and payload motion and, possibly, for control/structure interaction. Since the purpose of this paper is to demonstrate the method for incorporating control systems and since control frequencies are relatively low, the first six flexible modes were considered to be a sufficient structural dynamic representation. The issue of spillover is not considered here, and a more complete study would require appending higher frequency modes until a convergence of results is observed. Since structural dynamic codes are typically designed to handle a large number of modes, this approach would provide an excellent tool for the study of spillover effects resulting from linear control systems.

In order to better understand the effect of dynamic flexibilities and control/structure interaction, forcing functions are defined and response calculated for a reaction control system (RCS) jet firing during a reboost maneuver. Each RCS jet is assumed to deliver 330 N of thrust[5] at the locations shown in Fig. 2. The RCS thruster forces are shown in Fig. 3. The thrusters are assumed to fire in pairs in a staggered sequence, thus racking the station in the pitch plane.

For this example, a simple PID attitude control system is implemented. The measurements input into the control system

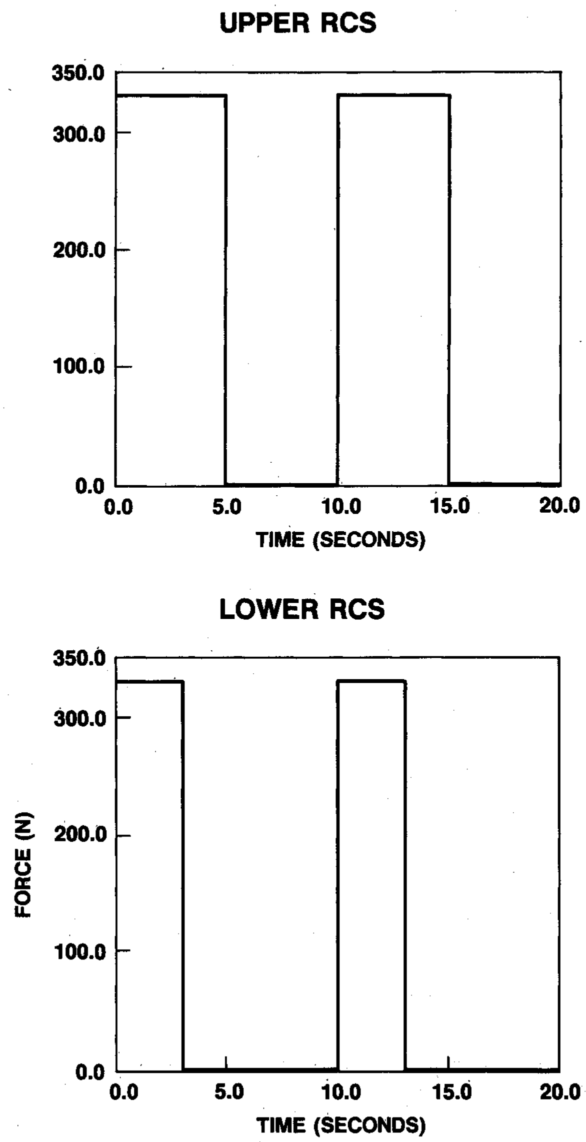

Fig. 3 RCS thruster forcing functions.

are the three orthogonal rotations and rotational velocities at a grid point corresponding to the control system location. These could be based on a combination of star sensors or integrating gyros. Although sensor dynamics could be modeled by appending further states to the control system, they are not modeled in this case. The output of the control system is a set of three orthogonal torques applied to the space station at the same grid. These torques would be applied by a set of control-moment gyros. Reference 6 suggests a control frequency of 0.01 Hz, a damping ratio of 0.707, and an integral frequency of 0.001 Hz. The control gains about each of the three axes can then be calculated on the basis of rigid body mass properties (Table 1). These gains are listed in Table 3.

Three control systems were modeled using the methods presented in this paper. The first was identical to that described above, except that no integral control gains were included [proportional plus derivative (PD) control]. The second includes the integral terms in order to eliminate steady-state errors for continuously acting disturbances such as gravity gradients, aerodynamic pressures, etc. The third is a purely hypothetical higher bandwidth PID controller. In this case, the control frequency is increased to 0.1 Hz and the integral frequency to 0.01 Hz. The first two controllers have frequencies well below the first flexible frequency of the space station (0.0598 Hz), and so the interaction with flexible dynamics should be limited. The third controller, instead, has frequencies directly in the range of the flexible frequencies and will show a significant interaction. These control systems were added to the space station structural model with 0.5% critical damping in the six flexible modes. Closed-loop frequencies for the structure with no control and with the three control systems are listed in Table 4.

As expected, controllers one and two do not affect the flexible frequencies, though they do increase damping in modes 3, 4, and 6. The control frequencies are very close to the design frequencies. Small errors are due to the nonzero cross products of inertia and some coupling with flexible motion. As anticipated, however, controller three has a very strong effect on the flexible frequencies. In this case, the controller frequencies combine with the flexible frequencies in such a way that they are no longer distinguishable.

To examine the effect of the control systems on the rotational response of the solar dynamic collectors, consider the case of the RCS rockets firing to reboost the space station. In the case of reboost, a control law would select the rocket firing sequence so as to maintain attitude and keep the control-moment gyros from saturating. In order to analyze the effect of the attitude control system, however, it is assumed that the rockets are fired in an open-loop fashion, and attitude is maintained entirely by the control-moment gyros. The rotational response of the right solar dynamic collector about the boom (y axis) for the uncontrolled system and the three controlled systems is illustrated in Fig. 4. Since the center of effort of the RCS jets is not exactly aligned with the

Table 2 First six flexible modes

Natural freq., Hz	Mode shape description
0.0598	Boom bending horizontal
0.0634	Boom bending vertical
0.110	Second boom bending vertical
0.115	Keel torsion and boom bending
0.121	Boom Torsion
0.127	Keel and boom torsion

Table 3 PID control gains

Axis	x	y	z
G_d	2.00×10^8	3.29×10^7	1.74×10^8
G_p	9.48×10^6	1.56×10^6	8.24×10^6
G_i	5.21×10^4	8.58×10^3	4.53×10^4

Table 4 Closed-loop frequencies

	Frequency, Hz/Damping ratio Controller		
Frequencies	1	2	3
Integral	—	0.0009/1.000	0.0090/1.000
	—	0.0010/1.000	0.0100/1.000
	—	0.0010/1.000	0.0100/1.000
Control	0.0107/0.706	0.0100/0.704	0.0484/0.036
	0.0107/0.707	0.0100/0.706	0.1014/0.709
	0.0109/0.696	0.0102/0.696	0.0903/1.000
	—	—	0.5960/1.000
Flexible	0.0598/0.006	0.0598/0.006	0.0593/0.006
	0.0634/0.005	0.0634/0.005	0.0634/0.005
	0.1104/0.251	0.1104/0.250	0.0700/0.015
	0.1206/0.006	0.1205/0.006	0.1200/0.010
	0.1261/0.072	0.1261/0.072	0.1911/0.085

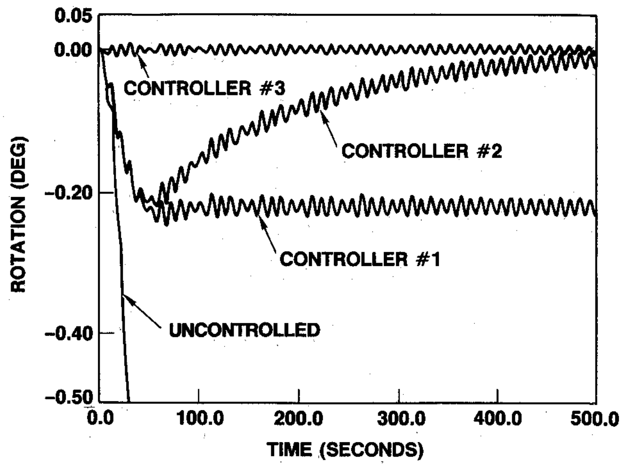

Fig. 4 Response of right solar dynamic collector to RCS firing.

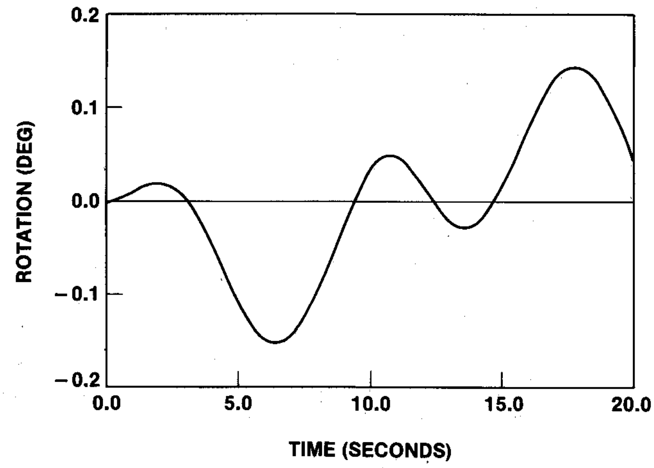

Fig. 7 Response of right solar dynamic collector to payload motion.

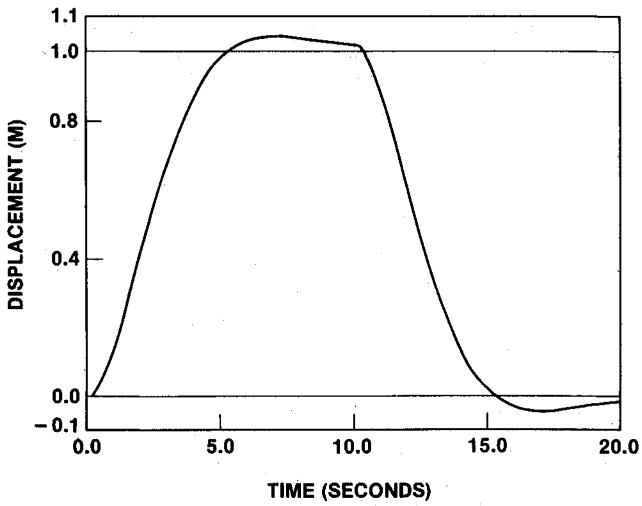

Fig. 5 Response of payload to command.

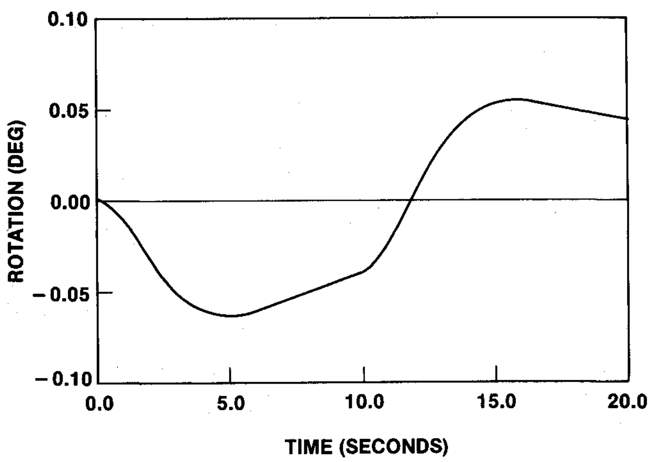

Fig. 6 Response of space station to payload motion.

space station center of gravity, there is a tendency for the whole station to rotate during reboost. This is evidenced by the response of the uncontrolled station, which rotates 0.5 deg after approximately 30 s. The eventual attitude error is 124 deg at the end of the 500-s reboost phase. The PD-controlled station maintains attitude, but indicates approximately a 0.2 deg steady-state error during reboost. Some flexible motion is also observed. The effect of integral control in eliminating steady-state error is indicated by the response with the second controller. Flexible motion is very similar, as is the maximum attitude error of about 0.2 deg, but steady-state error is eventually eliminated. The third controller has a high-enough bandwidth to maintain approximately zero-attitude error. Flexible motion is still present, though it is somewhat reduced.

It is hypothesized that the attitude control system is not effective in eliminating vibration of the solar dynamic collectors. This is because a dominant mode in this vibration is the first flexible mode at 0.0598 Hz. This mode, which is a symmetric bending of the boom, has an insignificant rotational component at the location of the control-moment gyros. This suggests that this mode is essentially uncontrollable with respect to the attitude-control system. In fact, the frequency and damping of this mode are affected very little by even the high-bandwidth controller.

Now consider vibrations induced by a moving payload. The payload is a 10,000-kg mass attached to a flexible 10-m-long manipulator arm. The manipulator is located at the position shown in Fig. 2 and rotates about the boom axis. Position of the payload is controlled by a PD compensator that measures payload displacement and applies a torque to the manipulator base (noncollocated sensors and actuators). The control gains are selected to provide a control frequency of 0.1 Hz and a damping ratio of 0.707 for a rigid manipulator connected to ground.

Commands are given to move the payload by 1 m and then back to zero after 10 s. The payload displacement is plotted in Fig. 5, indicating a 5% overshoot and a rise time of approximately 5 s. The payload positioning, therefore, follows the expected profile. The rotational response of the station about the boom axis at the attitude control system is plotted in Fig. 6. The attitude is disturbed by approximately 0.05 deg for this particular payload motion. The rotational response at the right solar dynamic collector is plotted in Fig. 7. Here the error peaks near 0.2 deg due to excitation of the boom torsional mode. This exceeds acceptable tolerances for the solar dynamic collectors and represents a situation that would require further study.

Conclusions

For a complex and flexible system such as the space station, it is imperative to examine the combined effects of a number of dynamic components acting simultaneously. Components of the form represented in Eq. (3) provide an effective way of modeling the effect of control systems on a flexible structure. They offer the advantage of working within a structural dynamics program and can be combined with a number of other linear effects, including any number or combination of linear control systems, spinning bodies, or passive damping. The approach also can be used to complement a control-system simulation code by physically representing closed-loop mode shapes.

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