SSF Flexible Multi-Body Control/Structure Interaction Simulation

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ABSTRACT

For a large structure with the size of Space Station Freedom, it is important to consider the structural flexibity in the dynamics and control simulation. Conventionally, structural flexibility is obtained from the MSC/NASTRAN structural models. The interface between MSC/NASTRAN structural models and multi-body simulation programs is achieved by a flex-preprocessor. This approach becomes formidable as the size of finite element models grows with the evolution of SSF structures. The use of superelement and Craig-Bampton reduction in MSC/NASTRAN introduces difficulty in interfacing MSC/NASTRAN structural models with the Station/Orbiter Multi-Flex-Body Berthing Analysis Tool (SOMBAT), a program developed at JSC to perform flex-multibody dynamics and control simulation. To handle the dynamic reduction approach in MSC/NASTRAN, the flex-preprocessor in SOMBAT has been modified, and appropriate DMAP sequences have been developed. This paper presents the enhanced capability of SOMBAT for the space station freedom dynamics and control simulation. The procedure is validated through control structure interaction simulation for space station stage two scenarios.

INTRODUCTION

In the Station/Orbiter Multi-Flex-Body Analysis Tool (SOMBAT), the kinematics and dynamics are derived for multi-body systems in an open tree topology. An open tree topology is defined as a configuration in which bodies are interconnected in a singular sense, i.e., one joint for each body with no closures. Figure 1 describes a general open tree topology system. Body one is a special body in which there is no "body" inboard of it. "Leaf bodies" are defined as bodies with no body outboard of them, and the basic equations are derived from the "Leaf Body" level. "Branch" bodies are bodies with one and only one body outboard. "Base" bodies are bodies with two or more bodies directly outboard. The equations of motion of a multi-body system is first derived for the leaf body, and progressively defined inboard through the base bodies. In the attempt to bring in the structural flexibility for the multi-body systems, the method of assumed mode (equation 1) is used to approximate the displacement field within the bodies.

$$\{u\} = [\Psi]\{\eta\} \tag{1}$$

where u is the displacement, Ψ is the mode shape function, and η is the modal amplitude.

The equations of motion of a flex-multi-body dynamic system are highly nonlinear and very complicated, especially when the modal assumption is introduced for the flexible structural characteristics. For convenience, several different types of information pertaining to the structural flexibility are distinguished from the equations of motion. A flex pre-processor was designed to compute these intermediate terms for modeling multi-flex body dynamics. Based on the multi-body dynamics, SOMBAT also provides control system and orbital environment for complicated space station berthing and docking simulations. The organization of SOMBAT environment is outlined in Figure 2, and its SSF attitude control system is shown in Figure 3.

With the size (more than 300 ft long when completed) of Space Station Freedom(SSF), the consideration of structural flexibility in the control/structure interaction simulation is inevitable. Conventionally, the structural flexibility is extracted from the MSC/NASTRAN structural models. The interface between MSC/NASTRAN structural models and multi-body simulation program is achieved by a flex-preprocessor. Full size mass matrix and mode shape matrix extracted from MSC/NASTRAN are required for the flex-proprecessor to compute the rigid/flex coupling terms α (equation 2) and h (equation 3, reference [3]). With the first phase of structural data computed from MSC/NASTRAN, the process is rather straight forward, with little complexity involved in interpolating the mathematical representation of the flexible body terms. It becomes more difficult for large size MSC/NASTRAN structural model where dynamic reduction is used to generate body flexibility. The use of superelement and Craig-Bampton reduction in MSC/NASTRAN largely reduces the effort in structural analysis. However, it introduces difficulty in interfacing MSC/NASTRAN structural models with SOMBAT.

To avoid the ambiguity in mixing the physical and modal coordinates, some of the computation, which is currently achieved within the flex-preprocessor, is shifted to MSC/NASTRAN. Two DMAP sequences are developed to handle this new approach. In the first sequence, the corresponding structural-flex data and dynamic coupling terms for each body are computed. In the second sequence, the appropriate flex-body characteristics corresponding to physical joints within the body are extracted. This paper presents this enhanced capability of SOMBAT for the space station freedom simulation. The procedure is validated through control structure interaction simulation for space station scenarios. The assembly of space station is divided into 17 stages. Only the simulation of the stage complete two (SC-2) configuration is presented.

BACKGROUND

The rigid translation/flex coupling terms α and the rigid rotation/flex coupling terms h are defined as [reference 3]:

$$[\alpha] = [I][m][\Phi] - [\Phi]^T[m_o\tilde{r}][\Phi'] \tag{2}$$

$$[h] = [\tilde{r}][m][\Phi] + [I][m_o\tilde{r}][\Phi] + [I][i][\Phi'] \tag{3}$$

Where $[\Phi]$ is the mode shape matrix which contains only translational degrees of freedom, and $[\Phi']$ is the mode shape function which contains only rotational degrees of freedom.

$$[\Psi] = \begin{bmatrix} \Phi \\ \Phi' \end{bmatrix} \tag{4}$$

Where $[m]$, $[m_o\tilde{r}]$ and $[i]$ are sub-matrices of the rigid body mass matrix $[M]$ corresponding to each physical node.

$$[M] = \begin{bmatrix} m & -m_o\tilde{r} \\ m_o\tilde{r} & i \end{bmatrix} \tag{5}$$

$[m]$ is the consistant mass matrix corresponding to translational degrees of freedom at each node,

$$[m] = \begin{bmatrix} m_{xx} & m_{xy} & m_{xz} \\ m_{yx} & m_{yy} & m_{yz} \\ m_{zx} & m_{zy} & m_{zz} \end{bmatrix} \tag{6}$$

$[i]$ is the mass moment of inertia corresponging to each physical node,

$$[i] = \begin{bmatrix} i_{xx} & i_{xy} & i_{xz} \\ i_{yx} & i_{yy} & i_{yz} \\ i_{zx} & i_{zy} & i_{zz} \end{bmatrix} \tag{7}$$

m_o is the mass, and $[\tilde{r}]$ is defined from nodal vector.

$$[\tilde{r}_i] = \begin{bmatrix} 0 & -z_i & y_i \\ z_i & 0 & -x_i \\ -y_i & x_i & 0 \end{bmatrix} \tag{8}$$

Equation (2) and (3) can be rearranged in the compact form as:

$$\begin{bmatrix} \alpha \\ h \end{bmatrix} = [RBE][MGG][\Psi] \tag{9}$$

Where $[RBE]$ is the rigid body transformation matrix defined as follow:

$$[RBE] = \begin{bmatrix} I & \phi & I & \phi & ... & I & \phi \\ \tilde{r}_1 & I & \tilde{r}_2 & I & ... & \tilde{r}_n & I \end{bmatrix} \tag{10}$$

Where $[I]$ is 3X3 unit matrix, $[\phi]$ is a 3X3 matrix in which all the elements are zero, and subscript n is the total number of physical nodes retained in the analysis set.

The matrices $[RBE]$, $[MGG]$ and mode shape function $[\Psi]$ are readily available in MSC/NASTRAN. With appropriate DMAP sequence developed for SOL 103, the output of the first stage of MSC/NASTRAN run will provide the mode shape functions (PHG), modal mass matrix (MMASS), modal stiffness matrix (MSTIFF), nodal coordinate array (COORD), and the rigid/flex coupling terms α and h. These data set, however, can not directly interface with the SOMBAT. Since the use of mixed physical and modal coordinate in the MSC/NASTRAN superelement has complicated the solution sequence. A user DMAP was developed to resort these data sets. The final form of the complete flexible body data file contains: the mode shape functions (PHIA) and the geometric matrix (XYZGEO) corresponding to each physical node defined in SOMBAT, the modal mass (MMASS), modal stiffness (MSTIFF) and coupling terms α and h corresponding to the desired modes, and the rigid body mass matrix (MSPT). The flexible body data file is then used as input to the flex-preprocessor to further compute the appropriate information for SOMBAT.

ANALYSIS

The space station assembly sequence consists of different configurations such as SC-1, SC-2, SC-3, etc., until the complete station is assembled (SC-17). Through the entire process, the CMG (Control Moment Gyro) and RCS (Reaction Control System) controllers are the primary control hardwares that ensure the stability and maneuverability of the space station. In this paper, the SC-2 detailed finite element model from preliminary design review is used with the reaction jet controllers (RCS) to demonstrate the enhanced capability of SOMBAT simulation.

Figure 4 shows the space station SC-2 base line (α gimbal = 0°, β gimbal = 0°) configuration. The SC-2 configuration is made up of the following component bodies. (1) Space station core body (Inboard of α gimbal). Contains CMG controller and RCS module. (2) Starboard power boom (Outboard of α gimbal). Contains radiator, and the β gimbals. (3) Starboard inboard upper solar array. (4) Starboard inboard lower solar array.

In this stage, the space station is modeled as four bodies in this presentation (see Figure 5). The joint between core body and power boom is α gimbal, and the joints between solar arrays and the power boom are the β

gimbals. The flight mode in the control structural simulation is the feathered mode (α=90°, β=90°), with the space station coordinate rotate (-90,0,0) Euler angle from LVLH (Local Vertical Local Horizontal, which is a coordinate system defined with Z-axis pointing toward the earth and X-axis pointing toward the flight direction). The core body has a six degree of freedom joint attached to the fixed inertial reference frame. This multi-body setup is convenient, since throughout the operation, articulation of α and β joints is necessary for the solar pannels to track the sun. For the cases shown in this paper, these joints are both fixed.

As a checkup of the modal accuracy, the linearization process is used to recover the system frequencies from the multi-body dynamic equations. They are listed in Table 1 to compare with the result from MSC/NASTRAN solution 103 for the one body model. In the Table, ATH indicates attitude hold simulation in which the reaction jet controllers are used to control the space station structure at certain attitude, TEA indicates TEA SEEKER simulation in which the reaction jet controllers are used to manuever the space station to torque equibrium attitude. The mark X indicates those modes which are excited during the simulation. Figure 6 shows the attitude variation of SC2 feathered configuration under free drift, for 5000 seconds. No controller was activated in this case. It is presented to demonstrate the accuracy of SOMBAT simulation for SC2 four body model, and validate the enhanced capability of SOMBAT to handle super element and Craig-Bampton reduction in the MSC/NASTRAN structural model.

Two test cases are presented to further show the performance of SOMBAT in control structural simulations. In the first case, the space station was maneuvered to seek torque equilibrium attitude (TEA). In the second case, the space station was held at zero attitude. For both cases, the aerodynamic and plume load from the orbiter were not considered, and the reaction jet controllers were used.

RESULTS AND DISCUSSION

Figures 7 through 9 show the results of SC-2 TEA SEEKER simulation (without aerodynamic load, the TEA of SC-2 is approximately along the principal axes, ATT_X=-78°, ATT_Y=-0.227°, ATT_Z=-3.706°). Figures 10 through 12 show the results of attitude hold simulation. In the figures, the attitude ATT_X, ATT_Y and ATT_Z indicate the orientation of space station with respect to LVLH coordinate. And the body rate RATE_X, RATE_Y and RATE_Z indicate the space station angular rate with respect to LVLH coordinate. The results show that for the SC-2 feathered configuration, both maneuvers are stable and satisfy the 1 degree pointing stability requirement. The comparison between one body model and four body model show similar dynamic behavior.

The system frequencies listed in Table 1 show good agreement between one body and four body models except for the 8th mode. This is due to the assumption of boundary condition of each body in the model synthesis process. Also, since the selected modes from each component body are limited, modes higher than 32nd mode start showing inaccuracy. This error, however, is tolerable from the control and stability point of view. The use of flex filter enables the controller to respond only to lower frequency modes. Further study shows that, for the controller with flex filter, the system modes are important only to 0.25 Hz. The inaccuracy incurred through the modal synthesis process thus can be eliminated in the control structure simulation. The current results demonstrate similar dynamic behavior between one body and four body systems. This provides one confidence on the enhanced capability of SOMBAT to interface with the MSC/NASTRAN structural models in which the superelement and Craig-Bampton reduction were applied.

SUMMARY AND CONCLUSION

In order to handle the large size finite element models, a dynamic reduction modeling technique (Craig-Bampton Reduction) is applied, with the superelement modeling featured in MSC/NASTRAN, for space station structural components. To accommondate this new technique, the SOMBAT flex-preprocessor has been modified, and two DMAP sequences have been developed to compute and extract the corresponding body-flex data. The results shown in this paper provide validation of the flexible multi-body dynamic simulation of this enhanced capability. This approach has made the control structure interaction simulation for a large space multi-body system feasible and accurate.

ACKNOWLEDGMENT

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[2]. TREETOPS Theoretical Manual, DYNACS Engineering Co., Palm Harbor, FL, May, 1991.

[3]. ANTEFLX Theoretical Manual, DYNACS Engineering Co., Palm Harbor, FL, July, 1991.

[4]. Station/Orbiter Multi-Flex-Body Berthing Simulation Tool (SOM-BAT), DYNACS Engineering Co., Palm Harbor, FL, 1991.

TABLE 1 SYSTEM FREQUENCIES

Mode (Hz)	ONE-BODY	ATH	TEA	FOUR-BODY
1	0.11428	X	X	0.11427
2	0.11462		X	0.11439
3	0.11837	X	X	0.11939
4	0.12358		X	0.12357
5	0.12368		X	0.12370
6	0.14153	X	X	0.14325
7	0.15282		X	0.15639
8	0.18598	X	X	*******
9	0.19549	X	X	0.19440
10	0.19636	X	X	0.19850
11	0.21945			0.21948
12	0.21979		X	0.21990
13	0.24468			0.24468
14	0.24470		X	0.24470
15	0.25791	X	X	0.25141
16	0.28309		X	0.28447
17	0.31063		X	0.31064
18	0.31073		X	0.31079
19	0.33722	X	X	0.32601
20	0.36360			0.36360
21	0.36360			0.36360
22	0.39549		X	0.39560
23	0.39688	X		0.39670
24	0.41214			0.41215
25	0.41215			0.41216
26	0.45502			0.45498
27	0.45593			0.45522
28	0.52082			0.52083
29	0.52084			0.52085
30	0.66644			0.66808
31	0.66657		X	0.66871
32	0.73030			0.73109
33	0.73112		X	0.74668
34	0.75151	X	X	0.87700
35	0.89326	X	X	1.00600
36	0.92053	X	X	1.00800
37	0.99850		X	1.04765
38	1.00637		X	1.49641
39	1.02803		X	1.50377
40	1.21450		X	1.50838

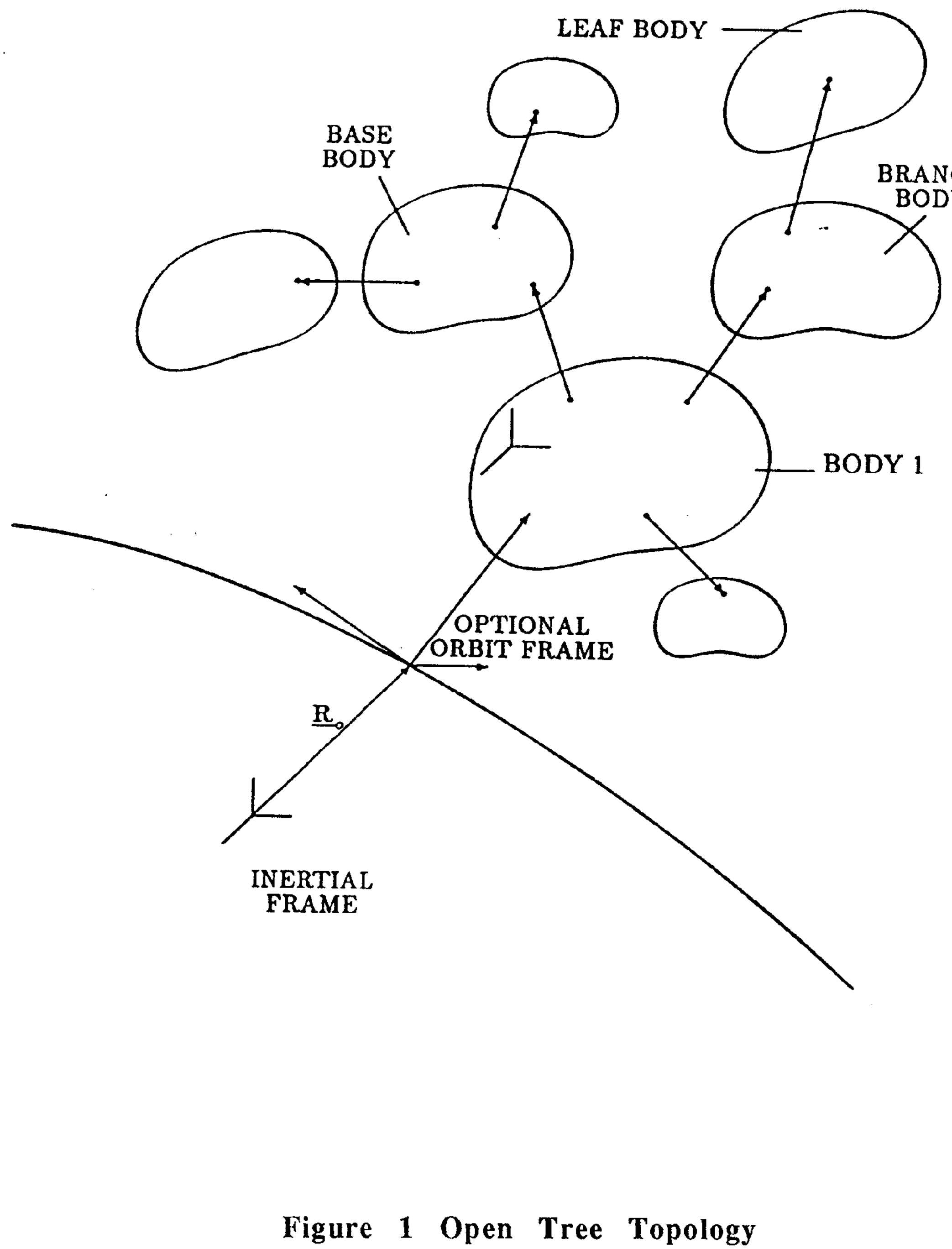

Figure 1 Open Tree Topology

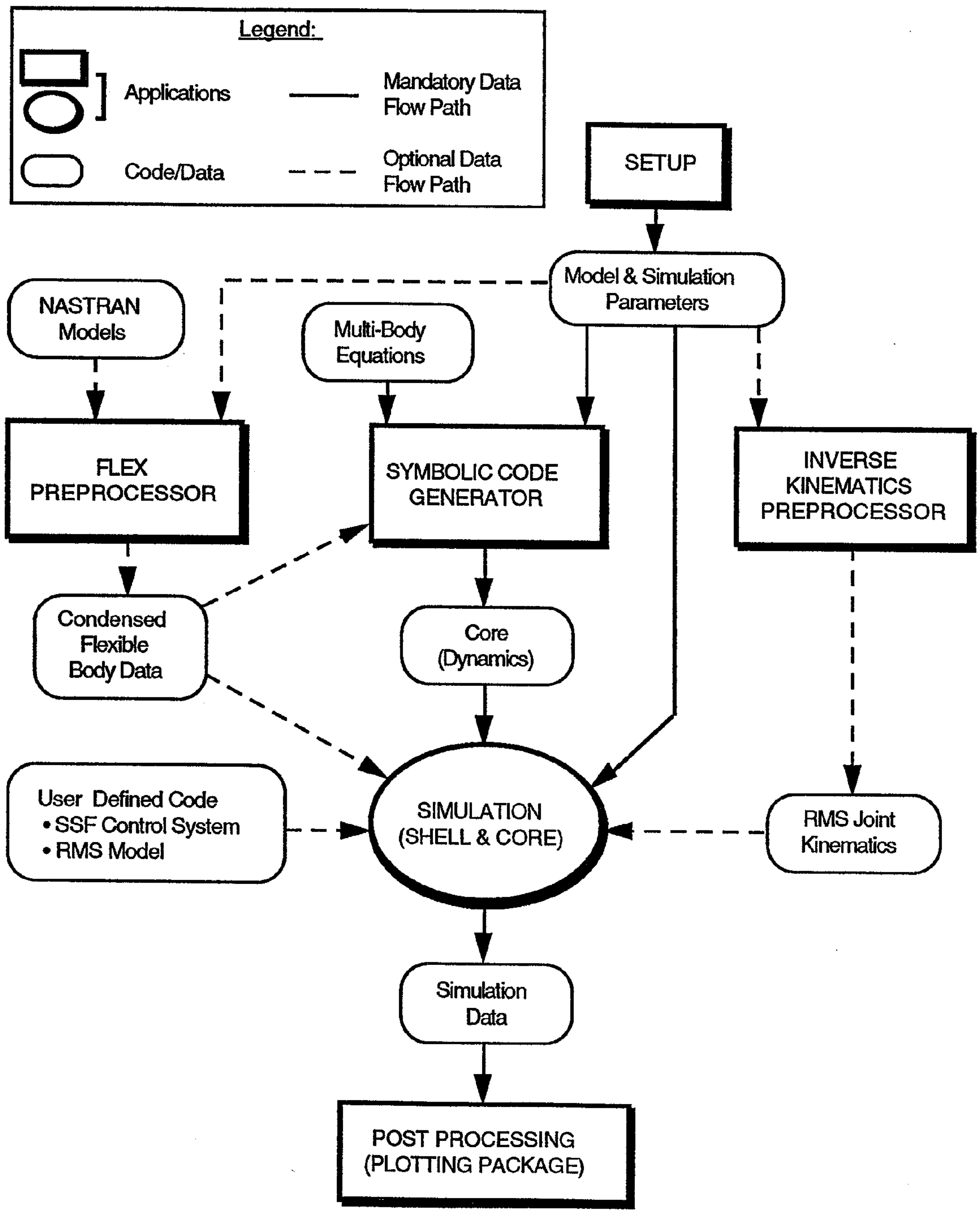

Figure 2 Organization of SOMBAT Simulation Environment

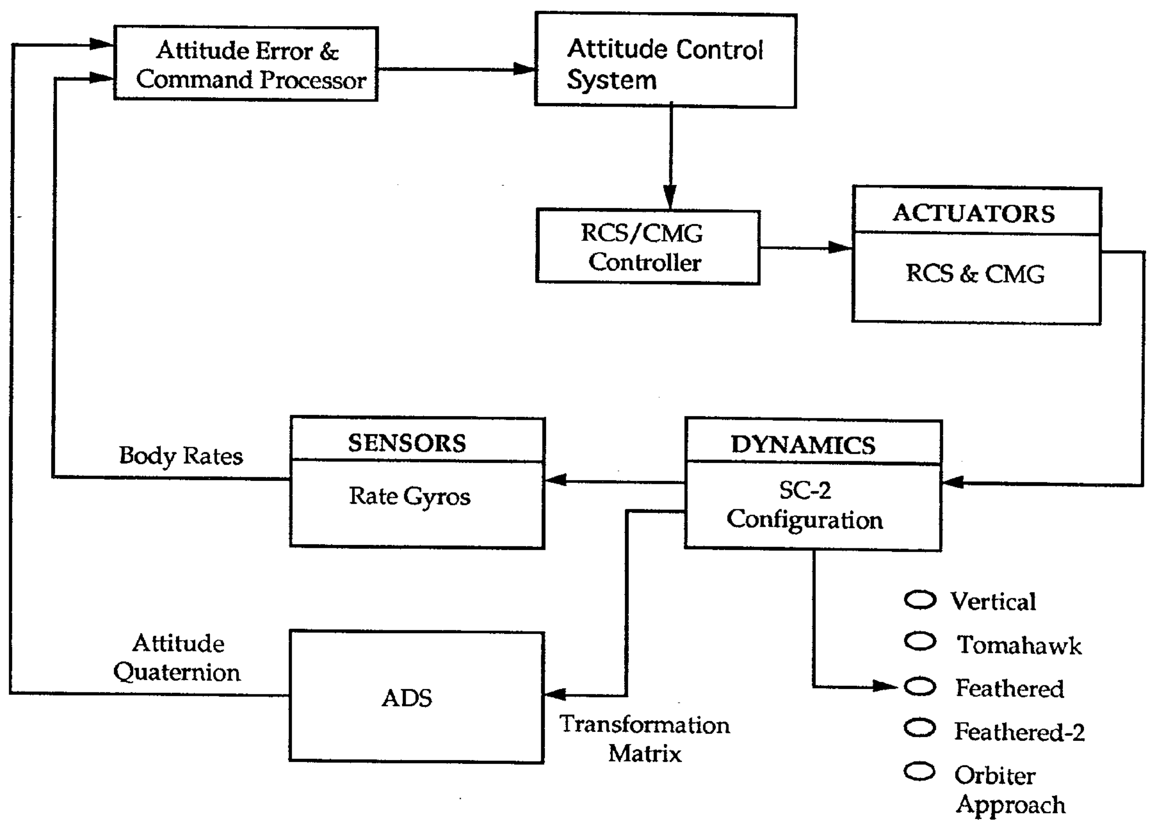

Figure 3 Attitude Control System Block Diagram

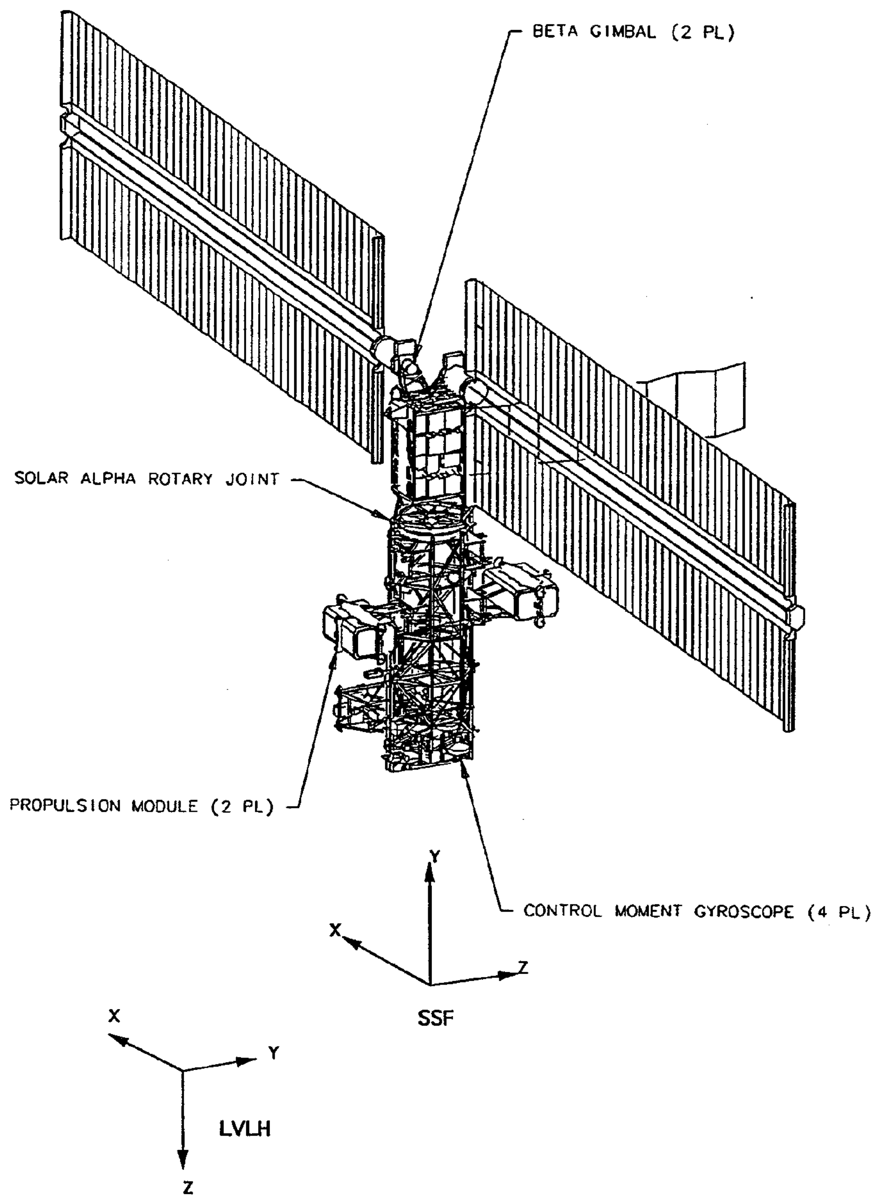

Figure 4 SSF SC-2 Configuration

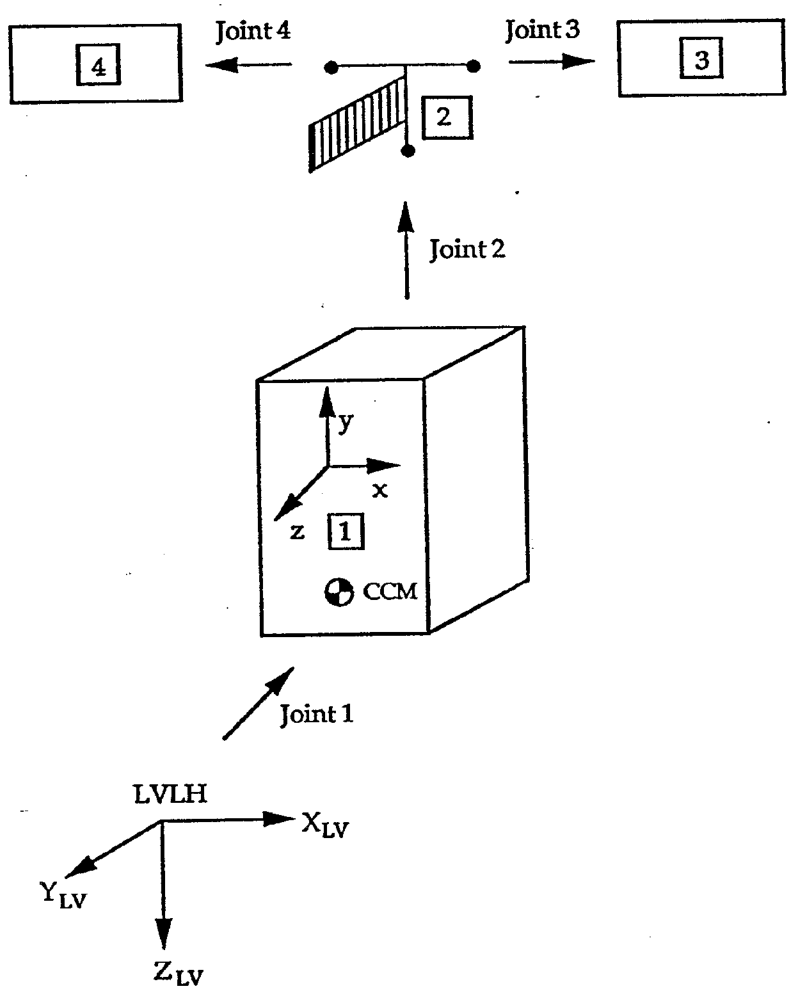

Figure 5 SC-2 Four Body Configration

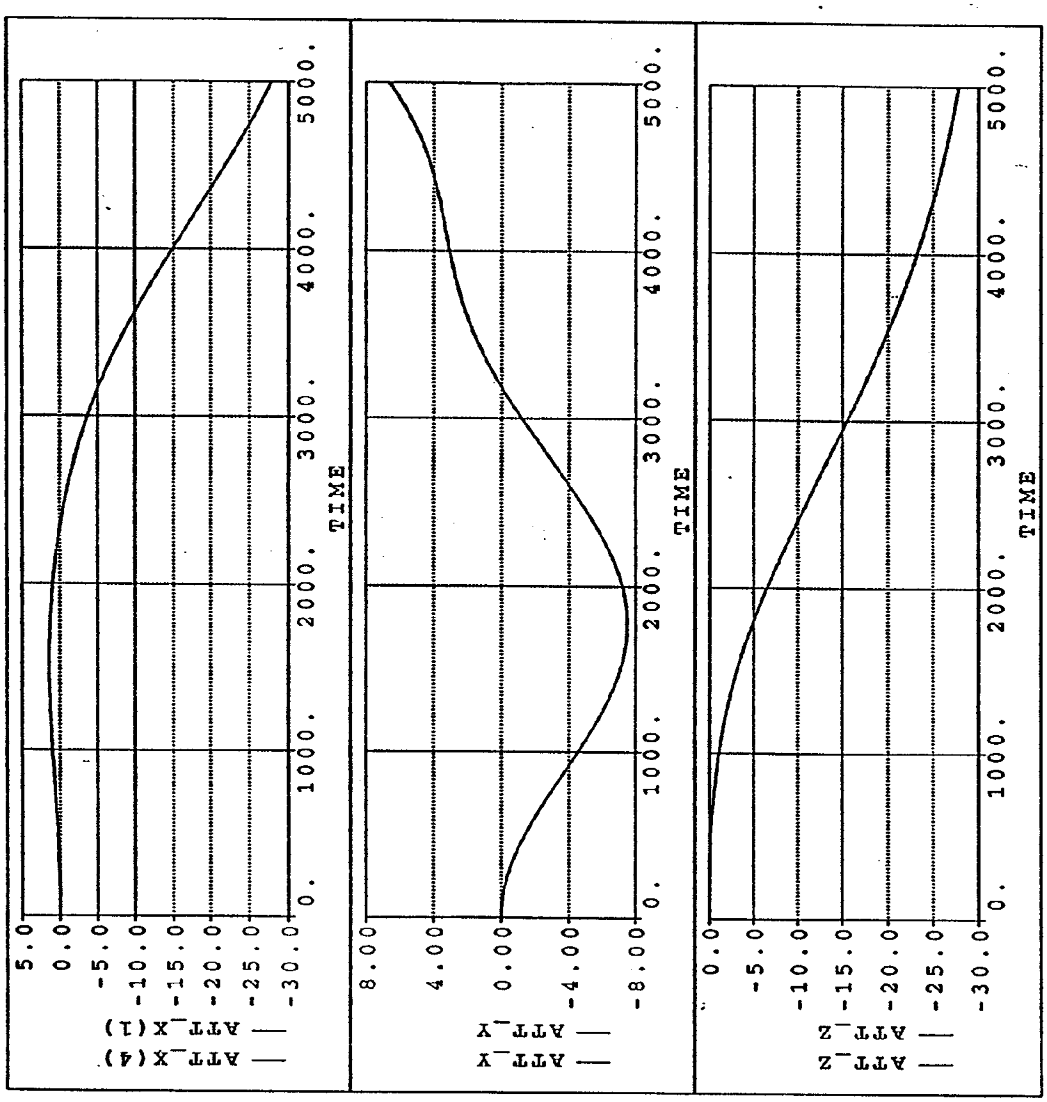

Figure 6 SC2 Attitude - Free Drift

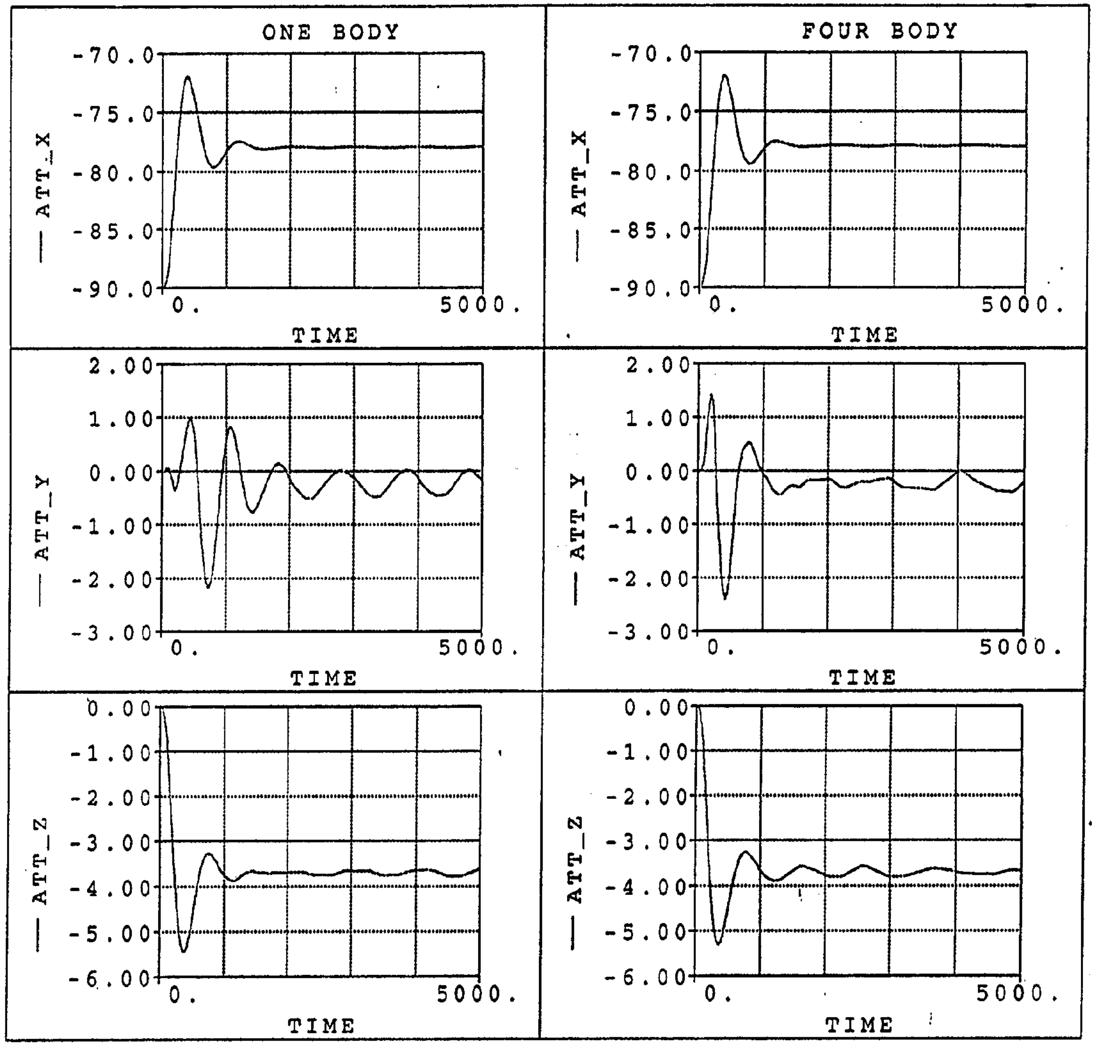

Figure 7 SC2 Attitude - TEA Seeker

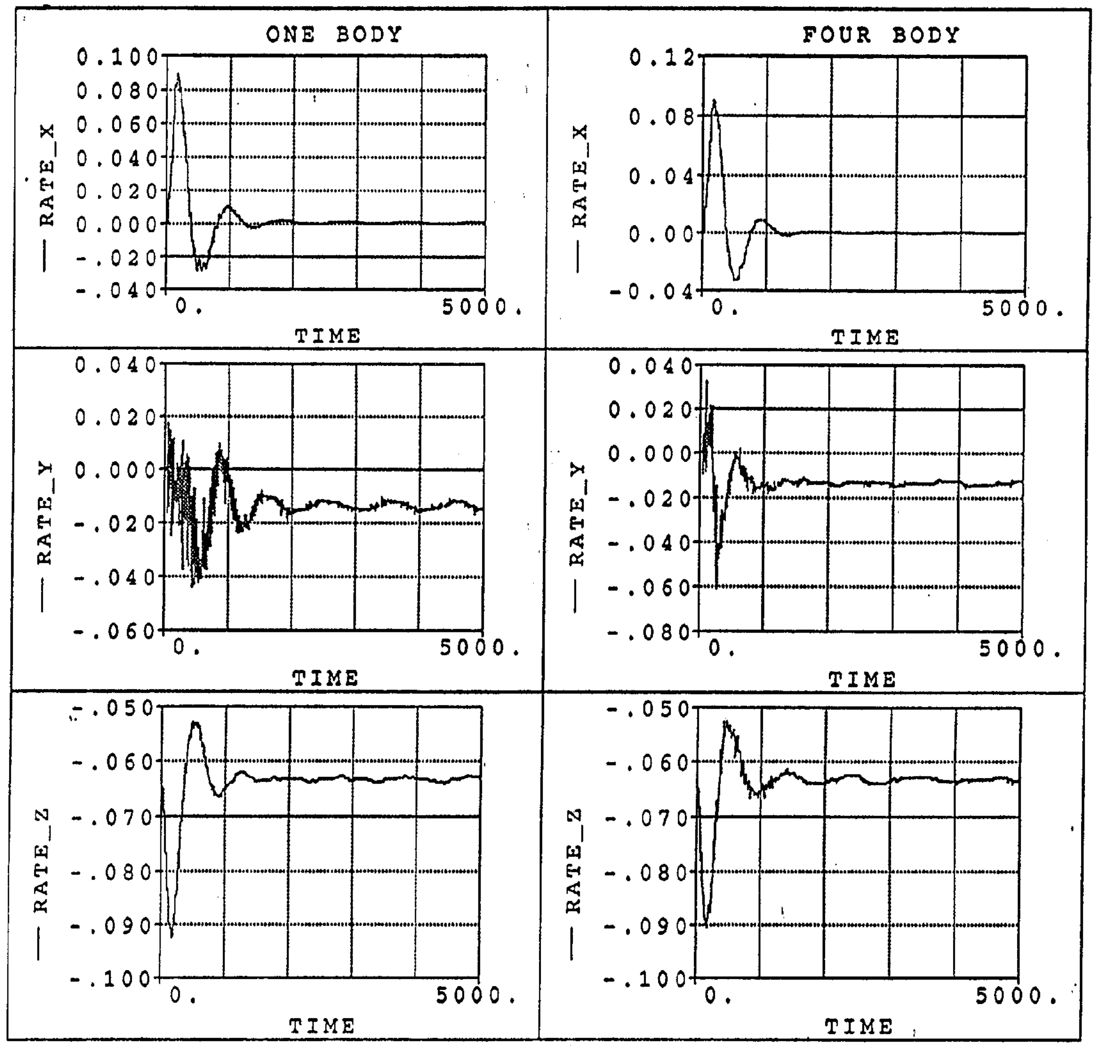

Figure 8 SC2 Body Rate - TEA Seeker

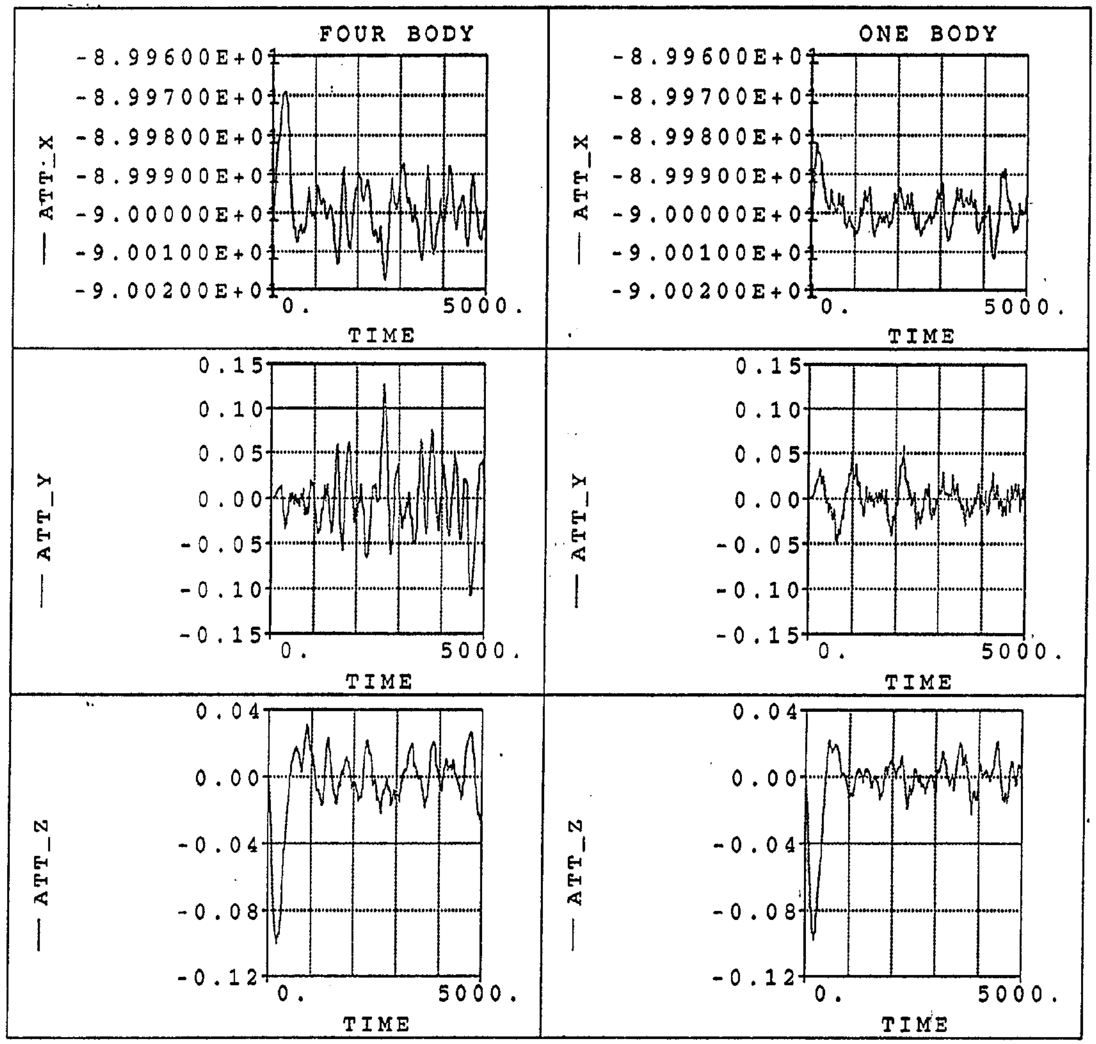

Figure 9 SC2 Attitude - Attitude Hold

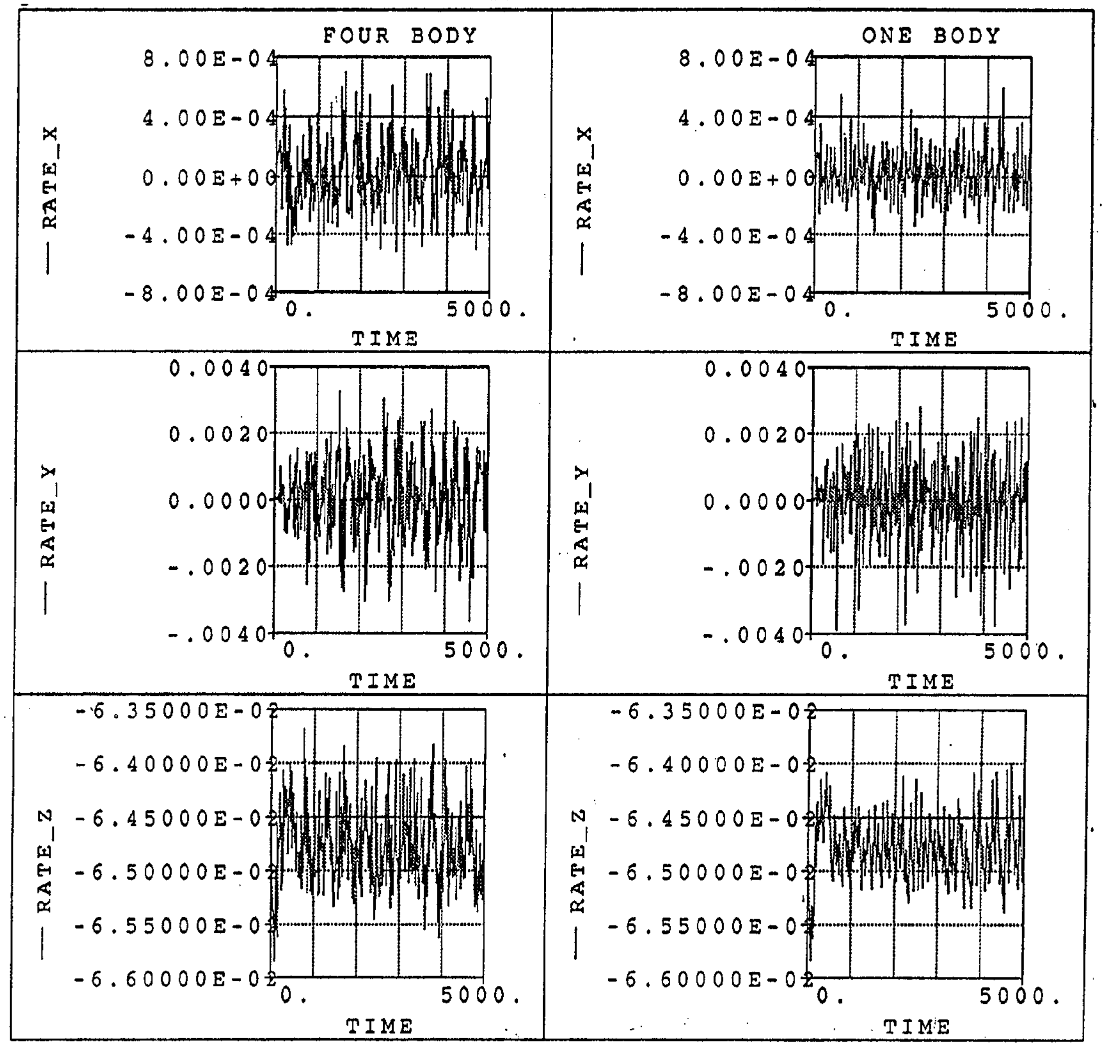

Figure 10 SC2 Body Rate - Attitude Hold