Development and Integration of Control System Models
Final Report

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1. Summary

The design of a pointing control system requires an iterative procedure that includes mathematical modeling of the multi-body mechanical system, dynamics and control simulation, and performance analysis and evaluation. Since the performance of a pointing control system is determined from the interaction of the control system and the dynamics of the mechanical system, the design of a control system that meets performance requirements depends on how well the dynamics of the mechanical system is understood and can be modeled. Most mechanical systems are comprised of rigid and flexible multibodies dynamic systems that could yield undesirable vibration due to any disturbance and could deteriorate the performances of pointing control systems. Therefore, in order to meet the performance requirements, the control system and mechanical system must interact favorably to suppress these disturbances.

The computer simulation tool, TREETOPS, has been developed and used at MSFC to model these complicated mechanical systems and to perform their dynamics and control analysis with pointing control systems. It has been shown that TREETOPS, in conjunction with various tools of MATLAB, provides an effective approach for the control engineer to model and analyze of pointing control systems through various projects at MSFC. This TREETOPS tool has been used to develop dynamics and control models of the Suppression of Transient Accelerations By Levitation Evaluation (STABLE) and the Active Rack Isolation System (ARIS) projects.

Under this NASA contract, the TREETOPS simulation is being maintained on workstations of ED11, NASA/MSFC and continuously upgraded to account for increasing sophistication of control system missions. A TREEOPS model of Advanced X-ray Astrophysics Facility - Imaging (AXAF-I) dynamics and control system was developed to evaluate the AXAF-I pointing performance for Normal Pointing Mode (NPM). An optical model of the Shooting Star Experiment (SSE) was also developed using the Modeling and Analysis for Controller Optical Systems (MACOS) software developed by JPL. These mathematical models and performance analyses were completed with cooperation of Mr. Mark West and Mr. William Lightsey of NASA/MSFC. The description of the TREETOPS dynamics and control model of AXAF-I and the numerical results of the AXAF-I NPM pointing accuracy and stability analysis are documented in Section 2. The description of MACOS model of the SSE optical system and its optical performance analysis results are documented in Section 3.
2. AXAF-I TREETOPS Dynamics and Control Modeling

2.1 Introduction

Advanced X-ray Astrophysics Facility - Imaging (AXAF-I) is being designed and manufactured by TRW under the program management of NASA Marshall Space Flight Center (MSFC) with the flight scheduled in December 1998. This study was done to assist the pointing control analysis team of NASA/MSFC to evaluate the AXAF-I pointing performance.

The objective of this study is to develop a multi-body dynamics and control model of the AXAF-I for TREETOPS simulation to evaluate the AXAF-I pointing performance for the Normal Pointing Mode (NPM). The unfavorable effects on the AXAF-I pointing performance, due to the static and dynamic unbalance of reaction wheels, and possible interaction between the flexible modes of solar arrays and the dynamics of reaction wheels with isolators are also investigated. The TREETOPS model of AXAF-I dynamic system consists of one rigid body spacecraft, the non-rotating masses and the rotating masses of six reaction wheels with their isolators, and two flexible solar arrays.

The modal data of the flexible solar array was generated off-line using NASTRAN simulation with a NASTRAN data of solar array provided by TRW Space and Electronics Group. This modal data is incorporated with the AXAF-I TREETOPS model using TREEFLX simulation. This section describes the details of TREETOPS model of AXAF-I dynamics and pointing control system for Normal Pointing Mode. This section also presents the results of the NPM pointing control analysis obtained from the TREETOPS simulation. The parameters of the NPM pointing control law and the mass properties of AXAF-I observatory including solar arrays, reaction wheels, and isolators are provided by TRW [1]. The AXAF-I NPM PID control law was coded in FORTRAN with the cooperation of Mr. William Lightsey of NASA/MSFC and combined with the AXAF-I TREETOPS dynamics model. For detailed information on the analytical formulation and modeling aspects of TREETOPS and TREEFLX, the reader is referred to the user’s guide [2].

2.2 Description of AXAF-I TREETOPS Simulation

A TREETOPS model of AXAF-I dynamics and control system that includes one rigid body spacecraft, six reaction wheels with isolators, two flexible solar arrays, and Normal Pointing Mode (NPM) control is described in this section.

The AXAF-I spacecraft including the telescope, aspect camera and science instruments is modeled as one rigid body with three rotational degrees of freedom (DOF). Two solar
arrays are modeled as flexible bodies using modal data obtained from NASTRAN simulation and fixed to the AXAF-I spacecraft. The AXAF-I has six reaction wheels mounted on the telescope with six isolators to reduce the vibration transferred to the spacecraft. Each reaction wheel isolator (RWI) is modeled as one rigid body connected to the spacecraft using a six DOF hinge with corresponding torsional and linear stiffness. Each reaction wheel (RW) is modeled as two rigid bodies (one non-rotating base rigid body and one rotating rigid body). The non-rotating base body of reaction wheel is assumed to be fixed on the isolator. The rotating bodies of the reaction wheels have one rotational DOF about their spin axes. Therefore, the AXAF-I TREETOPS model consists of total twenty-one bodies with fifty-seven DOFs. The configuration of the AXAF-I TREETOPS model is shown in Figure 2.2-1.
Total mass and moments of inertia of the AXAF-I observatory are available from Reference [1]. Mass properties of the solar arrays were determined from NASTRAN simulation with the NASTRAN model of a solar array provided by TRW. Mass properties of the reaction wheel isolators were also given by TRW. Mass properties of AXAF-I spacecraft were estimated by subtracting mass properties of two solar arrays from total mass properties of the AXAF-I observatory. Mass properties of non-rotating and rotating bodies of the reaction wheels are estimated from the technical data provided by the vendor, TELDIX.

In this study, in order to measure the angular velocity and the attitude angular errors about X, Y, and Z axes of the AXAF-I spacecraft, three ideal TREETOPS Rate Gyro Sensors and one IMU Sensor were used instead of the detailed models and control logic of rate gyros and aspect camera hardware. Also, the detailed control logic of the reaction wheels was not used, but the dynamics of each reaction wheel is determined through TREETOPS simulation with the torques distributed to six reaction wheels by the control torque distribution law. Six reaction wheels are spinning at nominal speeds pointing to the corresponding directions to contribute zero angular momentum to the AXAF-I spacecraft for orbiting equilibrium condition. Each reaction wheel is mounted on its isolator and the direction of the spin axis of reaction wheel is set by connecting the reaction wheel isolator to the AXAF-I spacecraft with the appropriate rotational angle using the TREETOPS Hinge notation.

It should be noted that even though the default printout units are mks units in the AXAF-I TREETOPS input file (AXAFI.INT file), Appendix B, the actual units of length, mass, and force used in the AXAF-I TREETOPS model are ft, slug and lbf, respectively. Since the NASTRAN modal output of solar array has units of inch, lbf-sec^2/in, lbf for length, mass, and force, respectively, the conversion factors (0.08333, 12, 1) are used for length, mass, and force units used in the AXAF-I TREETOPS model. All rigid bodies excluding the two solar arrays are defined by specifying mass properties (mass and moments of inertia) and nodal points for the center of mass and body connecting points in the local body coordinate system. The two solar arrays are defined in a flexible body modal data file (AXAFI.FLN file) that is created by importing the mass properties, nodal points, and modal data for selected modes (specified in AXAFI.RET file) from the NASTRAN output using TREEFLX. The AXAFI.FLN and AXAFI.RET are in Appendix C and D, respectively. Although all bodies and connecting hinges are defined in their local body coordinate systems, TREETOPS determines the kinematics and dynamics of the AXAF-I observatory in inertia coordinate system using the proper coordinate transformations.

AXAF-I Pointing Control and Aspect Determination (PCAD) flight software has various control modes, however, this study considers only the Normal Pointing Mode (NPM) control. The NPM pointing control logic was coded in FORTRAN in the User Supplied Discrete Controller (USDC) subroutine. The USDC subroutine is in APPENDIX A.
2.2.1 AXAF-I Structural Model

The AXAX-I observatory was modeled as a twenty-one multi-body dynamics system (one rigid body for the spacecraft, two flexible bodies for two solar arrays, six rigid bodies for six reaction wheel isolators, and twelve rigid bodies for six reaction wheels) and all bodies are connected with the same number of hinges according to the tree topology of TREETOPS simulation.

2.2.1.1 AXAF-I Body Models

The AXAF-I TREETOPS rigid body models are defined by providing the input data for the mass properties (total mass and moments of inertia) and the nodal points that correspond to the center of mass, the origin of local body coordinate systems, and hinge connecting points). Two AXAF-I solar arrays are modeled for TREETOPS simulation by converting the NASTRAN modal output to the appropriate format using TREEFLX.

The AXAF-I spacecraft is defined by Body #1 according to the TREETOPS tree topology and assumed to be linked by Hinge #1 with three rotational DOFs to the origin of the inertial coordinate system. For Body #1, twelve nodal points are defined to represent the center of mass (C.M.), the origin of local body coordinate system, two connecting points to two solar arrays, and six connecting points to six reaction wheel isolators. The mass properties of Body #1 were estimated by subtracting mass properties of two solar arrays from total mass properties of AXAF-I observatory.

The positive y-axis flexible solar array of AXAF-I is defined as Body #2 and the negative y-axis flexible solar array is defined as Body #3. A normal modes analysis was done off-line using NASTRAN model of the AXAF-I solar array. The NASTRAN data of the AXAF-I solar array was provided by TRW, Appendix E. The mass properties (mass and moments of inertia) and the output of normal modes analysis of AXAF-I solar array were obtained from NASTRAN and are in Appendix F. In order to define Body #2 and #3 of the AXAF-I TREETOPS model, the NASTRAN output file was assigned to each Body #2 and #3, and then TREEFLX was used to create a AXAFI.FLN file. The AXAFI.FLN file contains the mass properties, selected mode shapes, mode slopes and the coordinates of the selected nodes. For this study ten nodes and first six modes were selected.

The mass properties (Mass, Moment of Inertia about C.M.) and the locations of C.M. of Body #1, #2, #3 used for this study are described in Table 2.2.1.1-1.
Table 2.2.1.1-1: Mass properties and locations of C.M. of AXAF-I Body #1, #2, #3

<table>
<thead>
<tr>
<th>Body ID</th>
<th>Mass (Slug)</th>
<th>$I_{xx}, I_{yy}, I_{zz}, I_{xy}, I_{xz}, I_{yx}$ (Slug - ft²)</th>
<th>Location of C.M. in inertial coordinates (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>310.57</td>
<td>5903, 35830, 37314, -94, 737,-89</td>
<td>(31.32, -0.02, 0.09)</td>
</tr>
<tr>
<td>2</td>
<td>2.57</td>
<td>141, 11.66, 166.24, 0, 0, 0.17</td>
<td>(37.65,19.19,0.05)</td>
</tr>
<tr>
<td>3</td>
<td>2.57</td>
<td>141, 11.66, 166.24, 0, 0, 0.17</td>
<td>(37.65,-19.19,0.05)</td>
</tr>
</tbody>
</table>

The nodes of AXAF-I spacecraft (Body #1) are described in Table 2.2.1.1-2 (B1N2 denotes node #2 of Body #1).

Table 2.2.1.1-2: Nodes Definition of TREETOPS AXAF-I Body #1

<table>
<thead>
<tr>
<th>Node</th>
<th>Description</th>
<th>Location in body coordinates (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1N1</td>
<td>C.M. of Body #1</td>
<td>(31.32, -0.02, 0.09)</td>
</tr>
<tr>
<td>B1N2</td>
<td>Origin of Body #1</td>
<td>(0,0)</td>
</tr>
<tr>
<td>B1N3</td>
<td>Attaching point of #1 reaction wheel isolator</td>
<td>(40.08, 2.70,-2.70)</td>
</tr>
<tr>
<td>B1N4</td>
<td>Attaching point of #2 reaction wheel isolator</td>
<td>(38.79, 2.70,-2.70)</td>
</tr>
<tr>
<td>B1N5</td>
<td>Attaching point of #3 reaction wheel isolator</td>
<td>(37.51, 2.70,-2.70)</td>
</tr>
<tr>
<td>B1N6</td>
<td>Attaching point of #4 reaction wheel isolator</td>
<td>(40.08, -2.70,-2.70)</td>
</tr>
<tr>
<td>B1N7</td>
<td>Attaching point of #5 reaction wheel isolator</td>
<td>(38.79, -2.70,-2.70)</td>
</tr>
<tr>
<td>B1N8</td>
<td>Attaching point of #6 reaction wheel isolator</td>
<td>(37.51, -2.70,-2.70)</td>
</tr>
<tr>
<td>B1N9</td>
<td>Attaching point of +Y-axis solar array</td>
<td>(37.65,4.94,0)</td>
</tr>
<tr>
<td>B1N10</td>
<td>Attaching point of -Y-axis solar array</td>
<td>(37.65,4.94,0)</td>
</tr>
<tr>
<td>B1N11</td>
<td>Attaching point of IRU A</td>
<td>(31, 2.12, 2.63)</td>
</tr>
<tr>
<td>B1N12</td>
<td>Attaching point of IRU B</td>
<td>(31.28, 3.28, 1.98)</td>
</tr>
</tbody>
</table>

Since AXAF-I +Y-axis solar array (Body #2) and -Y-axis solar array (Body #3) have same mass properties and configuration, the NASTRAN modal output of either one of solar arrays can be used for both Body #2 and #3. The nodes of Body #2 and #3 are asymmetric about X-axis and described with the external and internal NASTRAN Grid ID numbers in Table 2.2.1.1-3.
Table 2.2.1.1-3: Nodes Definition of TREETOPS AXAF-I Body #2 and #3

<table>
<thead>
<tr>
<th>TREETOPS Node #</th>
<th>NASTRAN internal Grid ID #</th>
<th>NASTRAN external Grid ID #</th>
<th>Location in body coordinates (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2N2, B3N2</td>
<td>72</td>
<td>63001</td>
<td>(0, 0, 0)</td>
</tr>
<tr>
<td>B2N3, B3N3</td>
<td>50</td>
<td>60000</td>
<td>(3.36, 4.70, 0.06)</td>
</tr>
<tr>
<td>B2N4, B3N4</td>
<td>54</td>
<td>60003</td>
<td>(-3.36, 4.70, 0.06)</td>
</tr>
<tr>
<td>B2N5, B3N5</td>
<td>30</td>
<td>60400</td>
<td>(3.36, 12.00, 0.06)</td>
</tr>
<tr>
<td>B2N6, B3N6</td>
<td>34</td>
<td>60403</td>
<td>(-3.36, 12.00, 0.06)</td>
</tr>
<tr>
<td>B2N7, B3N7</td>
<td>10</td>
<td>60800</td>
<td>(3.36, 19.30, 0.06)</td>
</tr>
<tr>
<td>B2N8, B3N8</td>
<td>14</td>
<td>60803</td>
<td>(-3.36, 19.30, 0.06)</td>
</tr>
<tr>
<td>B2N9, B3N9</td>
<td>1</td>
<td>61100</td>
<td>(3.36, 26.26, 0.06)</td>
</tr>
<tr>
<td>B2N10, B3N10</td>
<td>4</td>
<td>61103</td>
<td>(-3.36, 26.26, 0.06)</td>
</tr>
</tbody>
</table>

Six reaction wheels are mounted on their isolators that are fixed to Body #1 with their spin directions shown in Figure 2.2.1.1-1 [1]. Each isolator of reaction wheels #1, #2, #3, #4, #5, and #6 was respectively defined by Body #11, #21, #31, #41, #51, #61. These RW isolators are linked to the corresponding attaching nodes of Body #1 by Hinge #11, #21, #31, #41, #51, #61. Each hinge has three rotational and three translational DOFs with appropriate stiffness.

Figure 2.2.1.1-1: AXAF-I RW Positive Spin Vectors Relative to Body #1 Coordinates
Each reaction wheel was modeled as two rigid body dynamics systems (one non-rotating base rigid body and one rotating rigid body). Each non-rotating rigid body of reaction wheels #1, #2, #3, #4, #5, and #6 was respectively defined by Body #12, #22, #32, #42, #52, #62 and assumed to be fixed to the its isolator by defining Hinges #12, #22, #32, #42, #52, #62 with zero DOF. Also, each rotating rigid body of reaction wheels #1, #2, #3, #4, #5, and #6 was respectively defined by Body #13, #23, #33, #43, #53, #63 and linked to its corresponding non-rotating rigid body by Hinge #13, #23, #33, #43, #53, #63. The mass properties (Mass, Moment of Inertia about C.M.) of the reaction wheel isolators and the reaction wheels used for this study are described in Table 2.2.1.1-4.

Table 2.2.1.1-4: Mass properties of reaction wheels and isolators

<table>
<thead>
<tr>
<th>Body</th>
<th>Mass (Slug)</th>
<th>$I_{xx}, I_{yy}, I_{zz}, I_{xy}, I_{xz}, I_{yx}$ (Slug – ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction wheel isolator (Body #11, #21, #31, #41, #51, #61)</td>
<td>0.23</td>
<td>1.54E-2, 1.54E-2, 2.36E-2, 0, 0, 0</td>
</tr>
<tr>
<td>Non-rotating body of reaction wheel (Body #12, #22, #32, #42, #52, #62)</td>
<td>0.1823</td>
<td>1.475E-2, 1.475E-2, 2.2125E-2, 0, 0, 0</td>
</tr>
<tr>
<td>Rotating body of reaction wheel (Body #13, #23, #33, #43, #53, #63)</td>
<td>0.3659</td>
<td>0.03961, 0.03961, 0.07921, 0, 0, 1E-6</td>
</tr>
</tbody>
</table>

For each reaction wheel isolator and reaction wheel, two nodal points are defined with respect to each body’s coordinate system to represent the center of mass, the origin of local coordinate system. Table 2.2.1.1-5 summarized the nodes of the reaction wheel isolators (Body #11, #21, #31, #41, #51, #61), the non-rotating bodies of reaction wheels (Body #12, #22, #32, #42, #52, #62), and the rotating bodies of reaction wheels (Body #13, #23, #33, #43, #53, #63). The unbalance of reaction wheels was defined by specifying non-zero products of inertia and the C.M. offset of the rotating bodies of the reaction wheels as shown in Table 2.2.1.1-4 and Table 2.2.1.1-5.

Table 2.2.1.1-5: Nodes Definition of TREETOPS AXAF-I Reaction Wheel Isolators and Non-Rotating and Rotating bodies of Reaction Wheels

<table>
<thead>
<tr>
<th>Body</th>
<th>Node</th>
<th>Description</th>
<th>Location in body coordinates (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B11,21,31,41,51,61</td>
<td>N1</td>
<td>Center of Mass</td>
<td>(0,0,0)</td>
</tr>
<tr>
<td>B11,21,31,41,51,61</td>
<td>N2</td>
<td>Origin of each body coordinate</td>
<td>(0,0,0)</td>
</tr>
<tr>
<td>B12,22,32,42,52,62</td>
<td>N1</td>
<td>Center of Mass</td>
<td>(0,0,0.1936)</td>
</tr>
<tr>
<td>B12,22,32,42,52,62</td>
<td>N2</td>
<td>Origin of each body coordinate</td>
<td>(0,0,0)</td>
</tr>
<tr>
<td>B13,23,33,43,53,63</td>
<td>N1</td>
<td>Center of Mass</td>
<td>(0,-5E-6,0)</td>
</tr>
<tr>
<td>B13,23,33,43,53,63</td>
<td>N2</td>
<td>Origin of each body coordinate</td>
<td>(0,0,0)</td>
</tr>
</tbody>
</table>

8
2.2.1.2 AXAF-I Hinge Models

According to the tree topology of TREETOPS modeling, the number of hinges that connects neighboring bodies must be equal to total number of bodies. Therefore, AXAF-I TREETOPS model has twenty-one hinges and each hinge defines nodal points of two connecting bodies, the relationship of each body's coordinate system and DOFs of relative motion between two bodies. The definitions of all hinges of AXAF-I TREETOPS model are summarized in Table 2.2.1.2-1.

### Table 2.2.1.2-1: Hinges Definition of AXAF-I TREETOPS Model

<table>
<thead>
<tr>
<th>Hinge</th>
<th>Connecting nodes</th>
<th>No. of DOF</th>
<th>L1_in - L1_out</th>
<th>L3_in - L3_out</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B0N0 - B1N1</td>
<td>3 RDOF</td>
<td>(1,0,0) - (1,0,0)</td>
<td>(0,0,1) - (0,0,1)</td>
</tr>
<tr>
<td>2</td>
<td>B1N9 - B2N2</td>
<td>0 DOF</td>
<td>(0,1,0) - (0,1,0)</td>
<td>(1,0,0) - (1,0,0)</td>
</tr>
<tr>
<td>3</td>
<td>B1N10 - B3N2</td>
<td>0 DOF</td>
<td>(0,-1,0) - (0,1,0)</td>
<td>(1,0,0) - (1,0,0)</td>
</tr>
<tr>
<td>11</td>
<td>B1N3 - B1N1</td>
<td>3 RDOF, 3 TDOF</td>
<td>(0.5,0.75,0.4330127)</td>
<td>(0.8660254,-0.4330127, -0.25) - (0,1,0)</td>
</tr>
<tr>
<td>12</td>
<td>B1N2 - B12N2</td>
<td>0 DOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>13</td>
<td>B12N1 - B13N1</td>
<td>1 RDOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>21</td>
<td>B1N4 - B21N1</td>
<td>3 RDOF, 3 TDOF</td>
<td>(0.5,0.75,0.4330127)</td>
<td>(0.8660254,0,-0.5)</td>
</tr>
<tr>
<td>22</td>
<td>B21N2 - B22N2</td>
<td>0 DOF</td>
<td>(0,1,0) - (0,1,0)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>31</td>
<td>B1N5 - B31N1</td>
<td>3 RDOF, 3 TDOF</td>
<td>(0.25,0.4330127)</td>
<td>(0.8660254,0.4330127, -0.25) - (0,1,0)</td>
</tr>
<tr>
<td>32</td>
<td>B31N2 - B32N2</td>
<td>0 DOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>33</td>
<td>B32N1 - B33N1</td>
<td>1 RDOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>41</td>
<td>B1N6 - B41N1</td>
<td>3 RDOF, 3 TDOF</td>
<td>(0.25,0.4330127)</td>
<td>(0.8660254,0.4330127, 0.25) - (0,1,0)</td>
</tr>
<tr>
<td>42</td>
<td>B41N2 - B42N2</td>
<td>0 DOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>51</td>
<td>B1N7 - B51N1</td>
<td>3 RDOF, 3 TDOF</td>
<td>(0.5,-0.75,0.4330127)</td>
<td>(0.8660254,0.4330127, -0.25) - (0,1,0)</td>
</tr>
<tr>
<td>52</td>
<td>B51N2 - B52N2</td>
<td>0 DOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>53</td>
<td>B52N1 - B53N1</td>
<td>1 RDOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>61</td>
<td>B1N8 - B61N1</td>
<td>3 RDOF, 3 TDOF</td>
<td>(0.5,0.75,0.4330127)</td>
<td>(0.8660254,-0.4330127, 0.25) - (0,1,0)</td>
</tr>
<tr>
<td>62</td>
<td>B61N2 - B62N2</td>
<td>0 DOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>63</td>
<td>B62N1 - B63N1</td>
<td>1 RDOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
</tbody>
</table>
The Hinges between Body #1 and six reaction wheel isolators (HI #11, #21, #31, #41, #51, #61) have 204.5 lb-ft/rad of rotational stiffness and 0.362 lb-ft/rad/sec of rotational damping and also, 2121.3 lb/ft of translational stiffness and 3.75 lb/ft/sec of translational damping. For nominal equilibrium condition, reaction wheels #1, #3, #5 have positive 2250 rpm of rotational speed and reaction wheels #2, #4, #6 have negative 2250 rpm of rotational speed resulting in zero sum of angular momentum to Body #1. The Hinges for spin axes of six reaction wheels (HI #13, #23, #33, #43, #53, #63) have zero rotational stiffness with initial 2250 rpm of angular velocities.

2.2.2 AXAF-I TREETOPS Sensor and Actuator Models

For the NPM pointing control of AXAF-I spacecraft, the angular attitude and angular velocity errors of AXAF-I spacecraft are measured and fed back to a PID controller to determine the control torque to obtain the desired pointing accuracy. AXAF-I has two Inertial Reference Unit (IRU) boxes and each IRU has two rate gyros. Since one gyro measures the angular velocities about two axis, total eight angular velocity measurements are available from two IRU boxes. Therefore, the angular velocity at the C.M. of AXAF-I spacecraft can be determined by transferring the eight angular velocity measurements of the two IRUs to the C.M. of AXAF-I spacecraft. AXAF-I has an Aspect Camera that measures the position of the selected Stars to determine the angular attitude error of the AXAF-I spacecraft. The AXAF-I flight software estimates the attitude errors and gyro drift errors of the AXAF-I spacecraft by processing the outputs of the rate gyros and the aspect camera with an attitude and aspect determination algorithm.

In this study, the detailed models of the IRUs, the aspect camera, and the attitude and aspect determination algorithm are not included. Instead, only functional outputs of these hardware sensors are obtained from the ideal TREETOPS sensor models. For the AXAF-I TREETOPS simulation, three ideal TREETOPS Rate Gyros are used to measure three angular velocities of the AXAF-I spacecraft about X, Y, Z axes and one TREETOPS IMU sensor is used to measure three rotational angles of the AXAF-I spacecraft with respect to the inertial coordinates. Three TREETOPS Integrating Gyros are attached on the C.M. of AXAF-I spacecraft to measure the integrals of the angular rate outputs of Rate Gyros. The descriptions of AXAF-I TREETOPS sensors are summarized in Table 2.2.2-1.
Table 2.2.2-1: Definition of TREETOPS AXAF-I Sensors Model

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Type</th>
<th>Attached node</th>
<th>Direction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IMU Sensor</td>
<td>B1N1</td>
<td>(1,0,0),(0,1,0),(0,0,1)</td>
<td>Euler angles w.r.t. inertial frame</td>
</tr>
<tr>
<td>11</td>
<td>Integrating Gyro</td>
<td>B1N1</td>
<td>(1,0,0)</td>
<td>[ \dot{\omega}_x ]</td>
</tr>
<tr>
<td>12</td>
<td>Integrating Gyro</td>
<td>B1N1</td>
<td>(0,1,0)</td>
<td>[ \dot{\omega}_y ]</td>
</tr>
<tr>
<td>13</td>
<td>Integrating Gyro</td>
<td>B1N1</td>
<td>(0,0,1)</td>
<td>[ \dot{\omega}_z ]</td>
</tr>
<tr>
<td>14</td>
<td>Rate Gyro</td>
<td>B1N1</td>
<td>(1,0,0)</td>
<td>[ \omega_x ]</td>
</tr>
<tr>
<td>15</td>
<td>Rate Gyro</td>
<td>B1N1</td>
<td>(0,1,0)</td>
<td>[ \omega_y ]</td>
</tr>
<tr>
<td>16</td>
<td>Rate Gyro</td>
<td>B1N1</td>
<td>(0,0,1)</td>
<td>[ \omega_z ]</td>
</tr>
</tbody>
</table>

The AXAF-I has six reaction wheels to generate the control torque to compensate the attitude and angular velocity errors of the spacecraft under NPM control. The control torque at the C.M. of the spacecraft is determined from the AXAF-I NPM control law and distributed to six reaction wheels according to the RW steering law. For the AXAF-I TREETOPS simulation, six TREETOPS Torque actuators are mounted along the spin axes of the six hinges between the non-rotating and rotating bodies of the six reaction wheels. The inputs to these actuators are to be determined by the AXAF-I NPM control law defined in the USDC subroutine in Appendix A. The TREETOPS actuators for AXAF-I are described in Table 2.2.2-2.

Table 2.2.2-2: Definition of TREETOPS AXAF-I Actuators Model

<table>
<thead>
<tr>
<th>Actuator ID</th>
<th>Type</th>
<th>Acting Node</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Torque Motor</td>
<td>Hinge 13</td>
<td>Torque about the spin axis of RW #1</td>
</tr>
<tr>
<td>23</td>
<td>Torque Motor</td>
<td>Hinge 23</td>
<td>Torque about the spin axis of RW #2</td>
</tr>
<tr>
<td>33</td>
<td>Torque Motor</td>
<td>Hinge 33</td>
<td>Torque about the spin axis of RW #3</td>
</tr>
<tr>
<td>43</td>
<td>Torque Motor</td>
<td>Hinge 43</td>
<td>Torque about the spin axis of RW #4</td>
</tr>
<tr>
<td>53</td>
<td>Torque Motor</td>
<td>Hinge 53</td>
<td>Torque about the spin axis of RW #5</td>
</tr>
<tr>
<td>63</td>
<td>Torque Motor</td>
<td>Hinge 63</td>
<td>Torque about the spin axis of RW #6</td>
</tr>
</tbody>
</table>
2.2.3 AXAF-I NPM Control Law Model

The AXAF-I Normal Point Mode (NPM) control is designed to point the telescope at the science target with the required pointing accuracy and stability after the Normal Maneuver Mode (NMM) control acquires the acquisition stars within the allowable error. The AXAF-I flight software uses a Proportional-Integral-Derivative (PID) control law for the NPM pointing control of the spacecraft. The requirements of the NPM control law are given in Table 2.2.3-1 [1].

<table>
<thead>
<tr>
<th>Description</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude Control Error (arcsec, $1 \sigma$, per axis)</td>
<td>4.0</td>
</tr>
<tr>
<td>Attitude Control Stability (arcsec, rms per axis, 95% of all 10-second intervals)</td>
<td>0.120</td>
</tr>
<tr>
<td>Period of not requiring pointing and stability after completion of momentum unloading</td>
<td>15 minutes</td>
</tr>
</tbody>
</table>

For the AXAF-I TREETOPS simulation, the NPM control law and control parameters that were developed by TRW are combined with the AXAF-I TREETOPS dynamics model. The hierarchy of AXAF-I TREETOPS dynamics and NPM control model is shown in Figure 2.2.3-1.

![AXAF-I TREETOPS Dynamics and NPM Control Model Layout](image-url)
The NPM PID control law has about 0.01 Hz of control bandwidth for roll motion and about 0.03 Hz of control bandwidth for pitch and yaw motions. The block diagram of AXAF-I NPM PID control law is shown in Figure 2.2.3-2 [1].

![Block Diagram of AXAF-I NPM PID Control Law](image)

Figure 2.2.3-2: Block Diagram of AXAF-I NPM PID Control Law

The AXAF-I has six reaction wheels in a pyramidal configuration shown in Figure 2.2.1.1-1. The total torque acting on the C.M. of the spacecraft by the six reaction wheels are given by the following equation

\[ T_{sc} = B \cdot T_w \]

where \( T_{sc} = [T_x, T_y, T_z]^T \) is the torque about X, Y, Z axis on the C.M. of the spacecraft in the inertial coordinates and \( T_w = [T_1, T_2, \cdots, T_6]^T \) is the torque on the six reaction wheels.
The transfer matrix, $B$ consists of six columns that are the unit vectors of the spin axes of the six reaction wheels and is given by

$$B = \begin{bmatrix}
0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \\
0.75 & 0.0 & -0.75 & -0.75 & 0.0 & 0.75 \\
0.433 & 0.866 & 0.433 & -0.433 & -0.866 & -0.433 \\
\end{bmatrix}$$

For the AXAF-I TREETOPS NPM control simulation, the attitude errors and angular velocity errors of the AXAF-I spacecraft are obtained from the outputs of one TREETOPS IRU sensor and three TREETOPS Rate Gyro sensors. The AXAF-I NPM control law determines the control torque, $T$ on the C.M. of the spacecraft to compensate for attitude errors and angular velocity errors. This control torque, $T$ is opposite to the total torque acting on the spacecraft due to the six reaction wheels, $T_{sc}$. Once the required control torque, $T$ is calculated by the AXAF-I NPM PID control law, the control torque on each reaction wheel is determined using the following pseudo-inverse steering law which provides the inputs to the AXAF-I TREETOPS Torque actuators.

$$T_w = DT$$

The steering matrix, $D$ is the negative pseudo-inverse matrix of $B$ and is given by

$$D = \begin{bmatrix}
0.3333 & 0.3333 & 0.1925 \\
0.3333 & 0 & 0.3849 \\
0.3333 & -0.3333 & 0.1925 \\
0.3333 & -0.3333 & -0.1925 \\
0.3333 & 0 & -0.3849 \\
0.3333 & 0.3333 & -0.1925 \\
\end{bmatrix}$$

The AXAF-I NPM PID control law and the reaction wheel steering law were coded in the FOTRAN subroutine USDC, Appendix A. The parameters of AXAF-I NPM PID control law are summarized in Table 2.2.3-2.
2.3 AXAF-I TREETOPS Simulation Results

The NPM control mode is activated to achieve the required pointing accuracy and stability after the Normal Maneuver Mode (NMM) controller slews the AXAF-I to acquire acquisition stars with the allowable error (less than 100 arcsec per axis, 3-sigma). This subsection describes numerical results of AXAF-I NPM pointing control analysis from the TREETOPS simulation. The input files of AXAF-I TREETOPS simulation are in Appendix B, C and D. For the evaluation of the NPM pointing accuracy and stability of AXAF-I, a transient response analysis is performed with initial 100 arcsec per axis and 2.88 arcsec/sec of pitch and yaw angular velocity errors using TREETOPS simulation. These initial errors are defined in the input data of Hinge #1 of the AXAF-I TREETOPS model. The numerical results of the transient response analysis with initial attitude and angular velocity errors are shown in Figure 2.3.1-1 through Figure 2.3.1-4.
Figure 2.3.1-1 shows the attitude and angular velocity errors of AXAF-I spacecraft under NPM control when the initial attitude and angular velocity errors of the spacecraft are given. It is noticed that the initial 100 arcsec of pitch and yaw attitude errors are reduced to about 0.75 arcsec in 500 seconds under NPM control thus satisfying the AXAF-I pointing accuracy requirement. It is also noticed that the changes of the pitch and yaw attitude are less than 0.01 arcsec for 10 seconds in 500 seconds thus satisfying the AXAF-I pointing stability requirement.

In Figure 2.3.1-2 the control torque on six reaction wheels required to correct the 100 arcsec of pitch and yaw attitude errors and 2.88 arcsec/sec of pitch and yaw angular velocity errors of AXAF-I spacecraft are plotted. Maximum torque of 0.043 ft-lb is loaded on reaction wheel #1. It is noted that the actual torque limit of reaction wheel hardware is about 0.1 ft-lb.

Figure 2.3.1-3 shows the spin speed changes of six reaction wheels from the nominal wheel speeds (± 2250 rpm) under NPM control when the initial attitude and angular velocity errors of the spacecraft are given. The spin speeds of reaction wheels #1, #2, #3, #4, #5, #6 are changed by 34, 24, -7, -34, -24, 7 rpm, respectively to compensate for the angular momentum due to the initial angular velocity errors.

Figure 2.3.1-4 shows the rotational angle about x-axis and the nutational angles (about y- and z-axis) of the reaction wheel isolator #1 due to the static and dynamic unbalance of the reaction wheel #1. From Figure 2.3.1-4 the amplitude of nutational angles is about 45 arcsec and these angles contribute to the misalignment error of the spin axis direction of reaction wheel.
Figure 2.3.1-1: Attitude and Angular Velocity Errors of AXAF-I Spacecraft under NPM Control with Initial Errors
Figure 2.3.1-2: Control Torque on Six Reaction Wheels under NPM Control with Initial Errors
Figure 2.3.1-3: Spin Speeds of Six Reaction Wheels under NPM Control with Initial Errors
Rotational Movement of Reaction Wheel Isolator #1

Figure 2.3.1-4 Angular movement of Reaction Wheel #1 under NPM Control with Initial Errors
2.4 Conclusion

A TREETOPS multi-body dynamics and control model of AXAF-I observatory was developed for NPM pointing control and documented in Section 1. The NPM pointing accuracy and stability of AXAF-I was evaluated from the numerical results of transient response analysis with initial attitude and angular velocity errors.

The simulation results indicated that the pointing accuracy and stability requirements of AXAF-I could be met for the NPM operation. Possibly unfavorable effects on the pointing performance of AXAF-I due to the interaction between the dynamics of reaction wheels and the flexible solar arrays are negligible. It is noticed that there are two nutational modes (one increasing frequency and another decreasing frequency) for each reaction wheel isolator due to the gyroscopic effects of the spinning unbalanced reaction wheel. The effect of unbalanced reaction wheels, specified in Subsection 2.2.1.1, on the pointing performance of AXAF-I was insignificant for the NPM operation.

This study incorporated the simplified NPM pointing control logic with the ideal sensors of attitude and angular velocity errors in AXAF-I multi-body dynamics model for TREETOPS simulation. Additional studies, which include the detailed flight software control logic of AXAF-I pointing control and aspect determination with various control modes, are needed to evaluate in greater depth the pointing performance of AXAF-I on orbit.

2.5 References


3. Optical Modeling and Analysis of SSE Optical System

3.1 Introduction

This section documents the configuration and optical prescription of the optical system of the Shooting Star Experiment (SSE) provided by Mr. Gary W. Wilkerson, Micro Craft, Inc. in October 1997 and the performance analysis results of this optical system. This optical performance analysis was done using the Modeling and Analysis for Controller Optical Systems (MACOS) developed by JPL [1]. In order to determine the Sun pointing error, the SSE uses one Fresnel lens and four Sun image detecting optical assemblies that are located symmetrically on the spacecraft. Since the optical functions of four Sun image detecting optical systems are identical, only one Sun image detecting optical system that includes one Fresnel lens, two filters, one cylindrical lens, and one Charge Coupled Device (CCD) detector was modeled in this study. The ray tray analyses were performed to determine the Sun image movements on the CCD detector due to the rigid body motions of the SSE optical system and the motions of the Fresnel lens due to flexibility of inflatable supporting structure. These results may be easily translated to the other three Sun image detecting systems by adjusting coordinate systems.

3.2 SSE MACOS Optical Modeling and Analysis

In this section one Sun image detecting optical system that includes one Fresnel lens, two filters, one cylindrical lens, and one CCD detector was modeled via MACOS simulation. The hardware Fresnel ring lens that is made of multi-segments with various slopes was modeled mathematically as one aspheric surface lens whose curvature was derived by interpolating the various slopes of the multi-segments with center obscured. The difference of thickness between the hardware Fresnel lens and the MACOS model of Fresnel lens was corrected by moving back the vertex point of MACOS Fresnel lens by the thickness difference.

The pointing errors of the Fresnel lens to the center of Sun due to the rigid body motions of SSE optical system and the motions of Fresnel lens due to flexibility of inflatable supporting may be determined by measuring the movements of the center of the spot diagram on the CCD detector. This spot diagram was obtained for a bundle of collimated Sun rays from the ray tray analysis using MACOS. The nominal configuration of the SSE MACOS optical model and the coordinate system used for the ray tray analysis are shown in Figure 3.2-1.
Ring Lens:
- \( r_1 = 7.59, r_2 = 7.19, r_0 = 7.39 \)
- Thickness = 0.003
- Radius of Curvature = 13.37423

Cylindrical Lens:
- Thickness = 1.41732, Radius of Curvature = 4.80314
- Length = 6.5, Width = 2.5
- Offset from center of N.D. filter = 0.905510

Detector:
- Thickness = 0.1, Width = 0.25, Length = 1.18

Natural Density Filter:
- \( l_1 = 73.367853, l_2 = 19.010962 \)
- Diameter = 6, Thickness = 0.25
- Gap to cylindrical lens = 0.1

Narrow Band Pass Filter:
- \( l_2 = 2.999994, l_3 = 2.095673 \)
- Diameter = 4, Thickness = 0.2

Points:
- \( p_1 = (0, 0, -1.37773) \), \( p_2 = (0, 0, -1.37473) \)
- \( p_3 = (0, 19.010962, 73.367853) \), \( p_4 = (0, 19.050071, 73.614775) \)
- \( p_5 = (0, 19.960076, 73.571891) \), \( p_6 = (0, 20.181793, 74.971761) \)
- \( p_7 = (0, 20.651096, 77.934820) \), \( p_8 = (0, 20.682383, 78.132358) \)
- \( p_9 = (0, 21.010218, 80.202230) \)  (Note: length unit = inch)

Figure 3.2-1: Configuration of SSE MACOS Optical Model
The Sun has an apparent diameter of about 0.54 degrees with respect to the Line of Sight (LOS) of the SSE Fresnel lens. Assuming that the apparent diameter of the Sun may have little effect on the movement of the center of spot diagram of the Sun rays on the CCD detector through 0.4 inch width of ring lens, 1 inch square area of collimated Sun rays coming into the center of the ring lens aligned to the cylindrical lens and the CCD detector are used for the ray tray analyses. The indices of refraction of lens and filter are chosen based on the wavelength of 720 nano-meter for the ray tray analyses.

The rigid body translational motions and rotational motion about the LOS axis (z-axis) of the SSE optical system barely contribute to the movement of the center of spot diagram on the CCD detector. However, the rigid body rotational motions about x and y axis change the movement of the center of spot diagram on the CCD detector. Therefore, the relationship between the rigid body rotational angle about x-axis and the movement of the center of spot diagram on the CCD detector is to be investigated in this study. The inflatable supporting structure of the SSE vehicle can cause relative motion of the Fresnel lens with respect to the rest of SSE optical system. The relative torsional motion about the SSE optical axis may not affect the movement of the center of spot diagram on the CCD detector. The relative z-axis motion is believed to be considerably small and its effect on the movement of the center of spot diagram on the CCD detector is not considered in this study. The relationships of the relative translational y-axis motion and rotational motion about x-axis with the movement of the center of spot diagram on the CCD detector are also to be investigated in this study.

The MACOS model of the SSE Sun image detecting optical system consists of nine optical elements according to the definition of MACOS software. Each lens or filter is defined using two Refractor type of elements. A Fresnel ring lens is defined using element #1 (Circular Flat Refractor) and element #2 (Circular Aspheric Refractor) with center obscured. A neutral density filter is defined using element #3 (Circular Flat Refractor) and element #4 (Circular Flat Refractor). The neutral density filter is tilted by 9 degrees with respect to optical axis of Fresnel lens as shown in Figure 3.2-1. A cylindrical lens that consists of a x-axis directional conic surface and a y-axis directional flat surface could be modeled using MACOS Anamorphic Refractor and Flat Refractor elements. However, since the MACOS Anamorphic Refractor element with 9 degrees tilt yields numerical instability problem, a cylindrical lens was defined using element #5 (Rectangular Conic Refractor) and element #6 (Rectangular Flat Refractor). This approximation may introduce spot diagram errors only in the x-axis direction and has insignificant effect on the movement (y-axis directional) of the center of spot diagram on the CCD detector. A narrow band pass filter is defined using element #7 (Circular Flat Refractor) and element #8 (Circular Flat Refractor). A CCD detector is defined using element #9 (Rectangular Flat FocalPlane). The central optical line of cylindrical lens, narrow band pass filter and CCD detector is offset by 0.905510 inch with respect to the central optical line of neutral density filter as shown in Figure 3.2-1.

The dimensions of the SSE MACOS optical elements are defined in Figure 3.2-1. Each vertex point of nine elements is denoted as \( p_i, (i = 1, \ldots, 9) \) and shown in Figure 3.2-1 with
respect to the global coordinate system. Since the focal distance, \( f \), was determined by the SSE optics design team for the Fresnel lens of 0.003 inch thickness, the vertex points of elements \#2 and \#3 (\( p_1 \) and \( p_2 \)) are moved back by the height of the aspheric surface at the center of the ring lens from the origin of the global coordinate that located at the center of the ring lens on the SSE optical axis. The prescriptions of the SSE MACOS optical elements are summarized in Table 3.2-1.

Table 3.2-1: Optical Prescriptions of SSE MACOS Optical Elements
(length unit = inch)

<table>
<thead>
<tr>
<th>Optical Element No.</th>
<th>Element Type</th>
<th>Surface Type</th>
<th>Radius of Curvature / Asperic Coeff.</th>
<th>Index of Refraction</th>
<th>Principal Axis Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.595059</td>
<td>(0,0,-1)</td>
</tr>
<tr>
<td>2</td>
<td>Refractor</td>
<td>Aspheric</td>
<td>13.37423 / A=0.414552e-3, B=-0.344476e-5, C=0.199075e-7</td>
<td>1.</td>
<td>(0,0,-1)</td>
</tr>
<tr>
<td>3</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.454853</td>
<td>(0.0,0.1564,-0.9877)</td>
</tr>
<tr>
<td>4</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.512549</td>
<td>(0.0,0.1564,-0.9877)</td>
</tr>
<tr>
<td>5</td>
<td>Refractor</td>
<td>Conic</td>
<td>4.80314 / 0</td>
<td>1.454853</td>
<td>(0.0,0.1564,-0.9877)</td>
</tr>
<tr>
<td>6</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.512549</td>
<td>(0.0,0.1564,-0.9877)</td>
</tr>
<tr>
<td>7</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.454853</td>
<td>(0.0,0.1564,-0.9877)</td>
</tr>
<tr>
<td>8</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.512549</td>
<td>(0.0,0.1564,-0.9877)</td>
</tr>
<tr>
<td>9</td>
<td>FocalPlane</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.512549</td>
<td>(0.0,0.1564,-0.9877)</td>
</tr>
</tbody>
</table>

3.3 SSE Optics MACOS Simulation Results

A MACOS model of the SSE Sun image detecting system was first developed for the nominal configuration shown in Figure 3.2-1. The optical prescriptions and configuration of the SSE optical model provided by the SSE Optical Design Team were confirmed through the ray tray analysis using MACOS. The input file of the SSE MACOS simulation for the nominal configuration is attached in Appendix G. In order to determine the Sun image movement on the CCD detector due to the rigid body motion of the SSE optical system and the motion of the Fresnel lens that may result from the flexibility of inflatable supporting structure, the ray tray analyses were performed using MACOS for following three cases; case 1: y-axis translational movement of Sun image on the CCD detector due to the rigid body rotational motion about the x-axis of total SSE optical system, case 2: y-axis translational movement of Sun image on the CCD detector due to the y-axis directional movement of the Fresnel lens only, case 3: y-axis translational movement of Sun image on the CCD detector due to rotation about the x-axis of the Fresnel lens only.
Case 1:

In order to determine the y-axis translational Sun image movement on the CDD detector due to the rigid body rotational motion of about the x-axis of total SSE optical system, all nine elements of the nominal SSE MACOS optical model were rotated about x-axis at node $p_i$ by various angles and the ray tray analyses were performed with a bundle of collimated rays fully covering the width of ring lens. The y-axis locations of chief ray and center of spot diagram of the collimated Sun rays at the ring lens and the CCD detector were calculated using MACOS for the various rotational angles of the SSE optical system and summarized in Table 3.3-1 with respect to the global coordinate system defined in Figure 3.2-1.

Table 3.3-1: SSE Rigid Body Rotation vs. Movement of Sun Image at Detector
(length unit = inch)

<table>
<thead>
<tr>
<th>Rigid body rotation about x-axis (degree)</th>
<th>Chief ray location at ring lens (y-axis)</th>
<th>Center of spot diagram location at ring lens (y-axis)</th>
<th>Chief ray location at detector (y-axis)</th>
<th>Center of spot diagram location at detector (y-axis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>7.39</td>
<td>7.3844</td>
<td>21.1542</td>
<td>21.1508</td>
</tr>
<tr>
<td>-0.4</td>
<td>7.39</td>
<td>7.3845</td>
<td>21.0628</td>
<td>21.0593</td>
</tr>
<tr>
<td>-0.2</td>
<td>7.39</td>
<td>7.3845</td>
<td>20.8841</td>
<td>20.8801</td>
</tr>
<tr>
<td>0.0</td>
<td>7.39</td>
<td>7.3892</td>
<td>20.7089</td>
<td>20.7048</td>
</tr>
<tr>
<td>0.2</td>
<td>7.39</td>
<td>7.3845</td>
<td>20.5364</td>
<td>20.5322</td>
</tr>
<tr>
<td>0.4</td>
<td>7.39</td>
<td>7.3845</td>
<td>20.3655</td>
<td>20.3612</td>
</tr>
<tr>
<td>0.6</td>
<td>7.39</td>
<td>7.3843</td>
<td>20.1954</td>
<td>20.1910</td>
</tr>
<tr>
<td>0.8</td>
<td>7.39</td>
<td>7.3839</td>
<td>20.0255</td>
<td>20.0134</td>
</tr>
<tr>
<td>1.0</td>
<td>7.39</td>
<td>7.3836</td>
<td>19.8549</td>
<td>19.8507</td>
</tr>
<tr>
<td>1.2</td>
<td>7.39</td>
<td>7.3829</td>
<td>19.6828</td>
<td>19.6786</td>
</tr>
<tr>
<td>1.4</td>
<td>7.39</td>
<td>7.3822</td>
<td>19.5084</td>
<td>19.5045</td>
</tr>
<tr>
<td>1.5</td>
<td>7.39</td>
<td>7.3818</td>
<td>19.4197</td>
<td>19.4159</td>
</tr>
</tbody>
</table>

w.r.t. global coordinate system

The actual Sun image movement on the CDD detector due to the rigid body rotation about the x-axis of the SSE optical system is determined by subtracting the movement of the CCD detector center from the movement of the spot diagram center of the collimated Sun rays at the CCD detector and plotted in Figure 3.3-1. The movements of the CCD detector center and of the spot diagram center of the collimated Sun rays at the CCD detector are obtained by calculating relative displacements with respect to nominal
positions from Table 3.3-1. As shown in Figure 3.3-1, the 1.18 inch length of the CCD detector can allow rigid body rotation of the SSE vehicle about the x-axis from -0.5 degrees to 1.5 degrees. Since two Sun image detecting systems are located symmetrically about the center line of the SSE vehicle, total Field of View (FOV) allowed for the rigid body rotation of the SSE optical system about the x-axis is ±1.5 degrees.

Figure 3.3-1: Movement of Centroid of Spot Diagram at Detector due to SSE Rigid Body Rotational Motion about X-Axis
Case 2:

In order to determine the y-axis translational movement of the Sun image on the CCD detector due to the y-axis translational movement of the Fresnel lens that may result from the flexibility of inflatable supporting structure, the incoming bundle of Sun rays and the Fresnel lens were moved by various distances in the y-axis direction and the ray tray analyses were performed. The y-axis locations of chief ray and center of spot diagram of the collimated Sun rays at the ring lens and the CCD detector were calculated using MACOS for the various movement of the Fresnel lens and are summarized in Table 3.3-2 with respect to the global coordinate system.

Table 3.3-2: Movement of Ring Lens vs. Movement of Sun Image at Detector
(length unit = inch)

<table>
<thead>
<tr>
<th>Movement of ring lens (y-axis)</th>
<th>Chief ray location at ring lens (y-axis)</th>
<th>Center of spot diagram location at ring lens (y-axis)</th>
<th>Chief ray location at detector (y-axis)</th>
<th>Center of spot diagram location at detector (y-axis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.9</td>
<td>6.49</td>
<td>6.4892</td>
<td>20.4400</td>
<td>20.4400</td>
</tr>
<tr>
<td>-0.8</td>
<td>6.59</td>
<td>6.5892</td>
<td>20.4675</td>
<td>20.4640</td>
</tr>
<tr>
<td>-0.6</td>
<td>6.79</td>
<td>6.7892</td>
<td>20.5246</td>
<td>20.5209</td>
</tr>
<tr>
<td>-0.4</td>
<td>6.99</td>
<td>6.9892</td>
<td>20.5841</td>
<td>20.5803</td>
</tr>
<tr>
<td>-0.2</td>
<td>7.19</td>
<td>7.1892</td>
<td>20.6457</td>
<td>20.6417</td>
</tr>
<tr>
<td>0</td>
<td>7.39</td>
<td>7.3892</td>
<td>20.7089</td>
<td>20.7048</td>
</tr>
<tr>
<td>0.2</td>
<td>7.59</td>
<td>7.5892</td>
<td>20.7734</td>
<td>20.7692</td>
</tr>
<tr>
<td>0.4</td>
<td>7.79</td>
<td>7.7892</td>
<td>20.8388</td>
<td>20.8345</td>
</tr>
<tr>
<td>0.6</td>
<td>7.99</td>
<td>7.9892</td>
<td>20.9049</td>
<td>20.9005</td>
</tr>
<tr>
<td>0.8</td>
<td>8.19</td>
<td>8.1892</td>
<td>20.9714</td>
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</tr>
<tr>
<td>1.0</td>
<td>8.39</td>
<td>8.3892</td>
<td>21.0380</td>
<td>21.0335</td>
</tr>
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<td>8.59</td>
<td>8.5892</td>
<td>21.1046</td>
<td>21.1000</td>
</tr>
<tr>
<td>1.4</td>
<td>8.79</td>
<td>8.7892</td>
<td>21.1707</td>
<td>21.1663</td>
</tr>
<tr>
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<td>9.79</td>
<td>9.7892</td>
<td>21.4862</td>
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</tr>
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<td>10.1893</td>
<td>21.5983</td>
<td>21.5902</td>
</tr>
</tbody>
</table>

w.r.t. global coordinate system

The actual Sun image movement on the CDD detector due to the y-axis translational movement of the Fresnel lens is determined by calculating the relative displacements of the
spot diagram center of the collimated Sun rays at the CCD detector with respect to the nominal positions from Table 3.3-2 and plotted in Figure 3.3-2. It is shown that the 1.18 inch length of CCD detector can allow relative y-axis translational movement of the Fresnel lens with respect to the rest of optical system from -0.9 inch to 2.8 inch. Since two Sun image detecting systems are located symmetrically about the center line of the SSE vehicle, total relative y-axis translational movement of the Fresnel lens with respect to the rest elements of the optical system due to the flexibility of the inflatable supporting structure is ±2.8 inch.

Figure 3.3-2: Movement of Centroid of Spot Diagram at Detector due to Y-Axis Directional Movement of Fresnel Ring Lens
Case 3:

In order to determine the y-axis translational movement of the Sun image on the CCD detector due to the rotation of the Fresnel lens about the x-axis that may result from the flexibility of the inflatable supporting structure, the Fresnel lens were rotated by various angles about the x-axis and the ray tray analyses were performed with a bundle of collimated rays fully covering the width of the ring lens. The y-axis locations of the chief ray and the center of the spot diagram of the collimated Sun rays at the ring lens and the CCD detector were calculated using MACOS for the various rotations of the Fresnel lens. The results are summarized in Table 3.3-3 with respect to the global coordinate system.

<table>
<thead>
<tr>
<th>Rotation of ring lens about x-axis (degree)</th>
<th>Chief ray location at ring lens (y-axis)</th>
<th>Center of spot diagram location at ring lens (y-axis)</th>
<th>Chief ray location at detector (y-axis)</th>
<th>Center of spot diagram location at detector (y-axis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6.0</td>
<td>7.39</td>
<td>7.3473</td>
<td>20.6521</td>
<td>20.6502</td>
</tr>
<tr>
<td>-5.5</td>
<td>7.39</td>
<td>7.3533</td>
<td>20.6542</td>
<td>20.6524</td>
</tr>
<tr>
<td>-5.0</td>
<td>7.39</td>
<td>7.3586</td>
<td>20.6569</td>
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</tr>
<tr>
<td>-4.5</td>
<td>7.39</td>
<td>7.3633</td>
<td>20.6600</td>
<td>20.6577</td>
</tr>
<tr>
<td>-4.0</td>
<td>7.39</td>
<td>7.3682</td>
<td>20.6636</td>
<td>20.6613</td>
</tr>
<tr>
<td>-3.5</td>
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<tr>
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<tr>
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<td>20.6884</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>20.7089</td>
<td>20.7048</td>
</tr>
<tr>
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<td>7.3856</td>
<td>20.7167</td>
<td>20.7127</td>
</tr>
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<td>20.7211</td>
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<td>20.7335</td>
<td>20.7301</td>
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<tr>
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<td>20.7396</td>
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<td>20.7521</td>
<td>20.7495</td>
</tr>
<tr>
<td>3.0</td>
<td>7.39</td>
<td>7.3762</td>
<td>20.7621</td>
<td>20.7601</td>
</tr>
<tr>
<td>3.5</td>
<td>7.39</td>
<td>7.3724</td>
<td>20.7724</td>
<td>20.7712</td>
</tr>
<tr>
<td>4.0</td>
<td>7.39</td>
<td>7.3682</td>
<td>20.7832</td>
<td>20.7829</td>
</tr>
<tr>
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<td>20.7943</td>
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</tr>
<tr>
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<td>7.3586</td>
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<td>20.8084</td>
</tr>
<tr>
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<td>7.3473</td>
<td>20.8298</td>
<td>20.8364</td>
</tr>
</tbody>
</table>

w.r.t. global coordinate system
The actual Sun image movements on the CDD detector due to the rotations of the Fresnel lens about the x-axis were determined by calculating relative displacements of the spot diagram center of the collimated Sun rays at the CCD detector with respect to the nominal positions from Table 3.3-3 and are plotted in Figure 3.3-3. It is shown that the relative rotation of the Fresnel lens about the x-axis with respect to the rest of the optical system due to the flexibility of the inflatable supporting structure is insignificant comparing to those of Case 1 and Case 2.

![Graph showing movement of centroid of spot diagram at detector due to rotational motion of Fresnel ring lens about X-Axis.](image)

**Figure 3.3-3: Movement of Centroid of Spot Diagram at Detector due to Rotational Motion of Fresnel Ring Lens about X-Axis**
3.4 Conclusion

A mathematical optical model was developed for the up-to-date configuration and optical prescriptions of SSE Sun image detector system using MACOS software. In order to determine the Sun pointing error of the SSE optical system, the ray tray analyses were performed using the collimated Sun rays without the effects of apparent diameter of Sun and blur. Even though the 0.54 degrees of apparent diameter and blur of Sun may seem to have little effect on the movement of the center of spot diagram of the Sun rays on the CCD detector through 0.4 inch width of the ring lens, further study will be needed to confirm this assumption.

The rigid body rotations of the SSE vehicle about the x-axis and y-axis and the relative x-axis and y-axis translational movements of the Fresnel lens with respect to the rest elements of the SSE optical system result in dominant effects on the movement of the center of spot diagram of the Sun rays on the CCD detector. With the given 1.18 inch length of the CCD detector total field of view allowed for the rigid body rotation of the SSE system about the x-axis is ±1.5 degrees and the allowable relative x-axis and y-axis translational movements of the Fresnel lens with respect to the rest elements of the SSE optical system are ±2.8 inch without rigid body motion. The coupling effects of rigid body motion and flexible motion are not included in this study and further study is required to investigate these effects.

Since there are no distinctions between the movements of the center of spot diagram of the Sun rays on the CCD detector due to the rigid body rotations of the SSE vehicle about the x-axis and the relative y-axis translational movements of the Fresnel lens with respect to the rest of the SSE optical elements, these must be considered to design the attitude controller of the SSE vehicle.

3.5 References

Appendix A
AXAF-I User Defined Controller Subroutine

SUBROUTINE USCC(T,U,X,R,XDOT)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DIMENSION U(1),X(1),R(1),XDOT(1)
C
RETURN
END

SUBROUTINE USDC(T,U,R)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
INCLUDE 'DBP.F'
INCLUDE 'DBC.F'
DIMENSION U(1),R(1)
C
SUBROUTINE CONTAINING NORMAL POINT AND MANEUVER CONTROL LAW
C PROPORTIONAL GAIN
C KP(1)=cntdta(1)=6.506D0
C KP(2)=cntdta(2)=68.382D0
C KP(3)=cntdta(3)=72.908D0
C INTEGRAL GAIN
C KI(1)=cntdta(4)=6.506D-3
C KI(2)=cntdta(5)=3.4191D-2
C KI(3)=cntdta(6)=3.6454D-2
C RATE GAIN
C KR(1)=cntdta(7)=325.30D0
C KR(2)=cntdta(8)=3419.10D0
C KR(3)=cntdta(9)=3645.40D0
C POSITION LIMITER, LP (rad)
C THELIM(1)=cntdta(10)=0.05695D0
C THELIM(2)=cntdta(11)=6.98D-4
C THELIM(3)=cntdta(12)=6.98D-4
C INTEGRAL LIMITER, LI (rad-sec)
C CILIM(1)=cntdta(13)=0.06D0
C CILIM(2)=cntdta(14)=0.011D0
C CILIM(3)=cntdta(15)=0.01D0
C RATE LIMITER, LR (rad/sec)
cyk OMELIM(1)=0.0019D0
cyk OMELIM(2)=0.0019D0
cyk OMELIM(3)=0.0019D0
c according to DM05 dated on 2/28/97
C OMELIM(1)=cntdta(16)=1.D06
C OMELIM(2)=cntdta(17)=1.D06
C OMELIM(3)=cntdta(18)=1.D06
C BODY TORQUE COMMAND LIMITER (ft-lb)
C TPCLIM=cntdta(19)=0.25D0
C
DIMENSION OME(3),THE(3),OMP(3),CI(3),CIP(3),OMI(3),
&OMR(3),TFP3(3),OMDMC(3),TG2(3),TPC(3),TC(3),
&TQUNLD(3),D(6,3),TCRW(6)
C
DOUBLE PRECISION IV(3,3),KP(3),KI(3),KR(3),KBF(5,3)
C
IF (T .EQ. 0.D0) THEN
!beginning of initialization
C INITIALIZE PARAMETERS
C
    DO 2 I=1,3
    CIP(I)=0.D0
C DEFINE PID CONTROL PARAMETERS
C SAMPLING TIME
C
    DTFC=0.064D0
C PROPORTIONAL GAIN
    KP(1)=cntdta(1)
    KP(2)=cntdta(2)
    KP(3)=cntdta(3)
C INTEGRAL GAIN
    KI(1)=cntdta(4)
    KI(2)=cntdta(5)
    KI(3)=cntdta(6)
C RATE GAIN
    KR(1)=cntdta(7)
    KR(2)=cntdta(8)
    KR(3)=cntdta(9)
C POSITION LIMITER, LP (rad)
    THELIM(1)=cntdta(10)
    THELIM(2)=cntdta(11)
    THELIM(3)=cntdta(12)
C INTEGRAL LIMITER, LI (rad-sec)
    CILIM(1)=cntdta(13)
    CILIM(2)=cntdta(14)
    CILIM(3)=cntdta(15)
C RATE LIMITER, LR (rad/sec)
c according to DM05 dated on 2/28/97
    OMELIM(1)=cntdta(16)
    OMELIM(2)=cntdta(17)
    OMELIM(3)=cntdta(18)
C BODY TORQUE COMMAND LIMITER (ft-lb)
    TPCLIM=cntdta(19)
C PSEUDO-INVERSE MATRIX FOR RW STEERING LAW
C
    D(1,1)=-0.333333D0
    D(1,2)=-0.333333D0
    D(1,3)=-0.192450D0
    D(2,1)=-0.333333D0
    D(2,2)= 0.D0
    D(2,3)=-0.384900D0
    D(3,1)=-0.333333D0
    D(3,2)= 0.333333D0
    D(3,3)=-0.192450D0
    D(4,1)=-0.333333D0
    D(4,2)= 0.333333D0
    D(4,3)= 0.192450D0
    D(5,1)=-0.333333D0
    D(5,2)= 0.D0
    D(5,3)= 0.384900D0
    D(6,1)=-0.333333D0
    D(6,2)= 0.333333D0
    D(6,3)= 0.192450D0
C BENDING FILTER (2ND ORDER DIGITAL FILTER)
C
    KBF(1,1)=7.94213D-5
    KBF(2,1)=1.588426D-4
    KBF(3,1)=7.94213D-5
KBF(4,1)=-1.978409D0
KBF(5,1)=0.978726D0

KBF(1,2)=9.79132D-4
KBF(2,2)=1.958264D-3
KBF(3,2)=9.79132D-4
KBF(4,2)=-1.910409D0
KBF(5,2)=0.914326D0

ENDIF !end of initialization

C READ INTEGRATING AND RATE GYRO SENSORS OUTPUT
C
DO 1 I=1,3
THE(I)=U(I)
1 OME(I)=U(I+3)
C BEGIN CONTROL LAW CALCULATIONS
C
C LIMIT POSITION ERROR SIGNAL
C
DO 100 I=1,3
100 THE(I)=DMAXI(-THELIM(I),DMINI(THELIM(I),THE(I)))
C INTEGRAL AND PROPORTIONAL PATH SIGNALS
C
DO 101 I=1,3
101 OMP(I)=KP(I)*THE(I)
101 CI(I)=DTFC*THE(I)+CIP(I)
C LIMIT THE INTEGRAL PATH SIGNAL
C
DO 57 I=1,3
57 CI(I)=DMAXI(-CILIM(I),DMINI(CILIM(I),CI(I)))
DO 102 I=1,3
102 OMI(I)=KI(I)*CI(I)
102 CIP(I)=CI(I)
C LIMIT THE RATE COMMAND SIGNALS
C
DO 56 I=1,3
56 OME(I)=DMAXI(-OMELIM(I),DMINI(OMELIM(I),OME(I)))
DO 103 I=1,3
103 OMR(I)=KR(I)*OME(I)
C COMPUTE FEED FORWARD TORQUE FROM GG TORQUE AND MANEUVER TORQUE
C ** need to include the wXh term if you have a commanded rate
CYK TFF3(I)=OMDMC(I)*IV(I,I)-TGG(I)-TQUNLD(I)
C TOTAL COMMANDED TORQUE SIGNAL PRIOR TO ADDING FEED FORWARD TORQUE
C
C 103 TPC(I)=OMR(I)+OMI(I)+OMP(I)
C NEW CONTROL LAW MOD MOVING INTEGRAL PATH
103 TPC(I)=OMR(I)+OMP(I)
CYK
DO 565 I=1,3
565 TFF3(I)=0.D0
C COMMAND TORQUE BENDING FILTER
C
CALL PCB(F,T,KBF,TPC,TCF)
C PROPORTIONALLY LIMIT TOTAL TORQUE COMMAND
C
DO 104 I=1,3
 104 TCF(I)=DMAXI(-TPCLIM,DMINI(TPCLIM,TCF(I)))
C
C ADD THE FEED FORWARD TORQUE
C
DO 131 I=1,3
 131 TCF(I)=TCF(I)+TFF3(I)
C
C TOTAL CONTROL TORQUE AT THE C.M. OF SPACECRAFT
C THIS INCLUDES MODIFICATION TO THE CONTROLLER THAT MOVES THE INTEGRAL PATH
C
DO 59 I=1,3
 59 TC(I)= TCF(I)+OMI(I)
CONTINUE
C
C DISTRIBUTE TOTAL CONTROL TORQUE TO SIX REACTION USING RW STEERING LAW
C THE SIGN OF RW TORQUE IS OPPOSITE TO ONE OF CONTROL TORQUE OF S/C.
C
CALL MDM(D,TC,TCRW,6,6,3,1)
C
DO 595 I=1,6
 595 R(I)= TCRW(I)
CONTINUE
RETURN
END

C SUBROUTINE PCBF(T,KBF,TIN,TOUT)
C IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C 2ND ORDER BENDING FILTER FOR PC COMMAND TORQUE
C DOUBLE PRECISION KBF(5,3),TIN(3),TOUT(3),S1(3),S2(3)
C IF(T.EQ.0°) THEN
DO 1 I=1,3
 1 S1(I)=0.D0
ENDIF
DO 2 I=1,3
 2 S2(I)=0.D0
ENDIF
DO 3 I=1,3
 3 TOUT(I)=KBF(1,I)*TIN(I)+S1(I)
 4 S1(I)=KBF(2,I)*TIN(I)-KBF(4,I)*TOUT(I)+S2(I)
 5 S2(I)=KBF(3,I)*TIN(I)-KBF(5,I)*TOUT(I)
RETURN
END
Appendix B
AXAF-I TREETOPS Input File AXAFI.INT

TREETOPS REV 10 06/05/95

SIM CONTROL

1 SI 0 Title AXAF-I(T/98)
2 SI 0 Simulation stop time 1000
3 SI 0 Plot data interval 0.064
4 SI 0 Integration type (R,S or U) R
5 SI 0 Step size (sec) 0.0064
6 SI 0 Sandia integration absolute and relative error L
7 SI 0 Linearization option (L,Z or N) L
8 SI 0 Restart option (Y/N) N
9 SI 0 Contact force computation option (Y/N) N
10 SI 0 Constraint force computation option (Y/N) N
11 SI 0 Mass matrix speedup option (All,Bypass,First,Nth) A
12 SI 0 Non-Linear speedup option (All,Bypass,First,Nth) A
13 SI 0 Constraint stabilization option (Y/N) N
14 SI 0 Stabilization epsilon

BODY

17 BO 1 Body ID number 1
18 BO 1 Type (Rigid, Flexible, NASTRAN) R
19 BO 1 Number of modes
20 BO 1 Modal calculation option (0, 1 or 2)
21 BO 1 Foreshortening option (Y/N)
22 BO 1 Model reduction method (NO, MS, MC, CC, QM, CV)
23 BO 1 NASTRAN data file FORTRAN unit number (40 - 60)
24 BO 1 Number of augmented nodes (0 if none)
25 BO 1 Damping matrix option (NS, CD, HL, SD)
26 BO 1 Constant damping ratio
27 BO 1 Low frequency, High frequency ratios
28 BO 1 Mode ID number, damping ratio
29 BO 1 Conversion factors: Length, Mass, Force
30 BO 1 Inertia reference node (=Bdy Ref Frm; i=mass cen) 1
31 BO 1 Moments of inertia (kg-m2) Ixx, Iyy, Izz 4551, 35830, 35961
32 BO 1 Products of inertia (kg-m2) Ixy, Ixz, Iyz 94, -737, 89
33 BO 1 Mass (kg) 310.57
34 BO 1 Number of Nodes 12
35 BO 1 Node ID, Node coord. (meters) x, y, z 1, 31.32, -0.02, 0.09
36 BO 1 Node ID, Node coord. (meters) x, y, z 2, 0, 0, 0
37 BO 1 Node ID, Node coord. (meters) x, y, z 3, 40.08, 2.70, -2.70
38 BO 1 Node ID, Node coord. (meters) x, y, z 4, 38.79, 2.70, -2.70
39 BO 1 Node ID, Node coord. (meters) x, y, z 5, 37.51, 2.70, -2.70
40 BO 1 Node ID, Node coord. (meters) x, y, z 6, 40.08, -2.70, -2.70
41 BO 1 Node ID, Node coord. (meters) x, y, z 7, 38.79, -2.70, -2.70
42 BO 1 Node ID, Node coord. (meters) x, y, z 8, 37.51, -2.70, -2.70
43 BO 1 Node ID, Node coord. (meters) x, y, z 9, 37.65, 4.94, 0
44 BO 1 Node ID, Node coord. (meters) x, y, z 10, 37.65, -4.94, 0
45 BO 1 Node ID, Node coord. (meters) x, y, z 11, 31.28, 3.28, 1.98
46 BO 1 Node ID, Node coord. (meters) x, y, z
47 BO 1 Node ID, Node structural joint ID

48 BO 2 Body ID number 2
49 BO 2 Type (Rigid, Flexible, NASTRAN) N
50 BO 2 Number of modes 6
51 BO 2 Modal calculation option (0, 1 or 2)
52 BO 2 Foreshortening option (Y/N) N
53 BO 2 Model reduction method (NO, MS, MC, CC, QM, CV) MS
54 BO 2 NASTRAN data file FORTRAN unit number (40 - 60) 41
55 BO 2 Number of augmented nodes (0 if none) 0
Damping matrix option (NS,CD,HL,SD) CD
Constant damping ratio 0.
Low frequency, High frequency ratios
Mode ID number, damping ratio

Conversion factors: Length, Mass, Force 0.08333, 12, 1

Inertia reference node (0=Bdy Ref Frm; 1=mass cen) 0
Moments of inertia (kg-m²) Ixx, Iyy, Izz
Products of inertia (kg-m²) Ixy, Ixz, Iyz
Mass (kg)

Number of Nodes 10

Node ID, Node coord. (meters) x, y, z
Node ID, Node structural joint ID

Body ID number 3
Type (Rigid, Flexible, NASTRAN) N
Number of modes 6

Modal calculation option (0, 1 or 2) 0
Foreshortening option (Y/N) N
Model reduction method (NO, MS, MC, CC, QM, CV) MS

NASTRAN data file FORTRAN unit number (40 - 60) 42
Number of augmented nodes (0 if none) 0
Damping matrix option (NS, CD, HL, SD) CD
Constant damping ratio 0

Low frequency, High frequency ratios
Mode ID number, damping ratio
Conversion factors: Length, Mass, Force 0.08333, 12, 1
Inertia reference node (0=Bdy Ref Frm; 1=mass cen) 0
Moments of inertia (kg-m²) Ixx, Iyy, Izz
Products of inertia (kg-m²) Ixy, Ixz, Iyz
Mass (kg)

Number of Nodes 10
Node ID, Node coord. (meters) x, y, z
Node ID, Node structural joint ID

Body ID number 11
Type (Rigid, Flexible, NASTRAN) R
Number of modes 11

Modal calculation option (0, 1 or 2) 11
Foreshortening option (Y/N) 11
Model reduction method (NO, MS, MC, CC, QM, CV) 11
Number of augmented nodes (0 if none) 11
Damping matrix option (NS, CD, HL, SD) 11
Constant damping ratio 11
Low frequency, High frequency ratios 11
Mode ID number, damping ratio 11
Conversion factors: Length, Mass, Force 11
Inertia reference node (0=Bdy Ref Frm; 1=mass cen) 1
Moments of inertia (kg-m²) Ixx, Iyy, Izz 1.54E-2, 1.54E-2, 2.36E-2
Products of inertia (kg-m²) Ixy, Ixz, Iyz 0, 0, 0
Mass (kg) 0.23
Number of Nodes 2
Node ID, Node coord. (meters) x, y, z 1, 0, 0, 0
Node ID, Node structural joint ID 2

Body ID number 12
Type (Rigid, Flexible, NASTRAN) R
Number of modes 12
128 BO 12 Modal calculation option (0, 1 or 2)
130 BO 12 Foreshortening option (Y/N)
131 BO 12 Model reduction method (NO, MS, MC, CC, QM, CV)
131 BO 12 NASTRAN data file FORTRAN unit number (40 - 60)
132 BO 12 Number of augmented nodes (0 if none)
133 BO 12 Damping matrix option (NS, CD, HL, SD)
134 BO 12 Constant damping ratio
135 BO 12 Low frequency, High frequency ratios
136 BO 12 Mode ID number, damping ratio
137 BO 12 Conversion factors: Length, Mass, Force
138 BO 12 Inertia reference node (0=Bdy Ref Frm; 1=mass cen)
139 BO 12 Moments of inertia (kg-m²) Ixx, Iyy, Izz
140 BO 12 Products of inertia (kg-m²) Ixy, Ixz, Iyz
141 BO 12 Mass (kg)
142 BO 12 Number of Nodes
143 BO 12 Node ID, Node coord. (meters) x, y, z
144 BO 12 Node ID, Node coord. (meters) x, y, z
145 BO 12 Node ID, Node structural joint ID
146 BO 13 Body ID number
147 BO 13 Type (Rigid, Flexible, NASTRAN)
148 BO 13 Number of modes
149 BO 13 Modal calculation option (0, 1 or 2)
150 BO 13 Foreshortening option (Y/N)
151 BO 13 Model reduction method (NO, MS, MC, CC, QM, CV)
152 BO 13 NASTRAN data file FORTRAN unit number (40 - 60)
153 BO 13 Number of augmented nodes (0 if none)
154 BO 13 Damping matrix option (NS, CD, HL, SD)
155 BO 13 Constant damping ratio
156 BO 13 Low frequency, High frequency ratios
157 BO 13 Mode ID number, damping ratio
158 BO 13 Conversion factors: Length, Mass, Force
159 BO 13 Inertia reference node (0=Bdy Ref Frm; 1=mass cen)
160 BO 13 Moments of inertia (kg-m²) Ixx, Iyy, Izz
161 BO 13 Products of inertia (kg-m²) Ixy, Ixz, Iyz
162 BO 13 Mass (kg)
163 BO 13 Number of Nodes
164 BO 13 Node ID, Node coord. (meters) x, y, z
165 BO 13 Node ID, Node coord. (meters) x, y, z
166 BO 13 Node ID, Node structural joint ID
167 BO 21 Body ID number
168 BO 21 Type (Rigid, Flexible, NASTRAN)
169 BO 21 Number of modes
170 BO 21 Modal calculation option (0, 1 or 2)
171 BO 21 Foreshortening option (Y/N)
172 BO 21 Model reduction method (NO, MS, MC, CC, QM, CV)
173 BO 21 NASTRAN data file FORTRAN unit number (40 - 60)
174 BO 21 Number of augmented nodes (0 if none)
175 BO 21 Damping matrix option (NS, CD, HL, SD)
176 BO 21 Constant damping ratio
177 BO 21 Low frequency, High frequency ratios
178 BO 21 Mode ID number, damping ratio
179 BO 21 Conversion factors: Length, Mass, Force
180 BO 21 Inertia reference node (0=Bdy Ref Frm; 1=mass cen)
181 BO 21 Moments of inertia (kg-m²) Ixx, Iyy, Izz
182 BO 21 Products of inertia (kg-m²) Ixy, Ixz, Iyz
183 BO 21 Mass (kg)
184 BO 21 Number of Nodes
185 BO 21 Node ID, Node coord. (meters) x, y, z
186 BO 21 Node ID, Node coord. (meters) x, y, z
187 BO 21 Node ID, Node structural joint ID
188 BO 22 Body ID number
189 BO 22 Type (Rigid, Flexible, NASTRAN)
190 BO 22 Number of modes
191 BO 22 Modal calculation option (0, 1 or 2)
192 BO 22 Foreshortening option (Y/N)
193 BO 22 Model reduction method (NO, MS, MC, CC, QM, CV)
194 BO 22 NASTRAN data file FORTRAN unit number (40 - 60)
195 BO 22 Number of augmented nodes (0 if none)
196 BO 22 Damping matrix option (NS, CD, HL, SD)
197 BO 22 Constant damping ratio
198 BO 22 Low frequency, High frequency ratios
199 BO 22 Mode ID number, damping ratio
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<th>Type</th>
<th>Number of modes</th>
<th>Modal calculation option</th>
<th>Foreshortening option</th>
<th>Model reduction method</th>
<th>NASTRAN data file FORTRAN unit number</th>
<th>Number of augmented nodes</th>
<th>Damping matrix option</th>
<th>Constant damping ratio</th>
<th>Low frequency, High frequency ratios</th>
<th>Modal calculation option</th>
<th>Foreshortening option</th>
<th>Model reduction method</th>
<th>NASTRAN data file FORTRAN unit number</th>
<th>Number of augmented nodes</th>
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<td>0 if none</td>
<td>NS, CD, HL, SD</td>
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<td></td>
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<td>NS, CD, HL, SD</td>
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<td></td>
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<td>NS, CD, HL, SD</td>
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<td>NS, CD, HL, SD</td>
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33 Body ID number
33 Type (Rigid, Flexible, NASTRAN)
33 Number of modes
33 Modal calculation option (0, 1 or 2)
33 Foreshortening option (Y/N)
33 Model reduction method (NO, MS, MC, CC, QM, CV)
33 NASTRAN data file FORTRAN unit number (40 - 60)
33 Number of augmented nodes (0 if none)
33 Damping matrix option (NS, CD, HL, SD)
33 Constant damping ratio
33 Low frequency, High frequency ratios
33 Mode ID number, damping ratio
33 Conversion factors: Length, Mass, Force
33 Inertia reference node (0=bdy ref frm; 1=mass cen)
33 Moments of inertia (kg-m²) Ixx, Iyy, Izz
33 Mass (kg)
33 Number of Nodes
33 Node ID, Node coord. (meters) x, y, z
33 Node ID, Node structural joint ID

41 Body ID number
41 Type (Rigid, Flexible, NASTRAN)
41 Number of modes
41 Modal calculation option (0, 1 or 2)
41 Foreshortening option (Y/N)
41 Model reduction method (NO, MS, MC, CC, QM, CV)
41 NASTRAN data file FORTRAN unit number (40 - 60)
41 Number of augmented nodes (0 if none)
41 Damping matrix option (NS, CD, HL, SD)
41 Conversion factors: Length, Mass, Force
41 Moments of inertia (kg-m²) Ixx, Iyy, Izz
41 Mass (kg)
41 Number of Nodes
41 Node ID, Node coord. (meters) x, y, z
41 Node ID, Node structural joint ID

42 Body ID number
42 Type (Rigid, Flexible, NASTRAN)
42 Number of modes
42 Modal calculation option (0, 1 or 2)
42 Foreshortening option (Y/N)
42 Model reduction method (NO, MS, MC, CC, QM, CV)
42 NASTRAN data file FORTRAN unit number (40 - 60)
42 Number of augmented nodes (0 if none)
42 Damping matrix option (NS, CD, HL, SD)
42 Conversion factors: Length, Mass, Force
42 Moments of inertia (kg-m²) Ixx, Iyy, Izz
42 Mass (kg)
42 Number of Nodes
42 Node ID, Node coord. (meters) x, y, z
42 Node ID, Node structural joint ID

43 Body ID number
43 Type (Rigid, Flexible, NASTRAN)
43 Number of modes
43 Modal calculation option (0, 1 or 2)
43 Foreshortening option (Y/N)
43 Model reduction method (NO, MS, MC, CC, QM, CV)
43 NASTRAN data file FORTRAN unit number (40 - 60)
43 Number of augmented nodes (0 if none)
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<tr>
<th>Body ID Number</th>
<th>Type</th>
<th>Number of Modes</th>
<th>Modal Calculation Option</th>
<th>Foreshortening Option</th>
<th>Number of Augmented Nodes</th>
<th>Damping Matrix Option</th>
<th>Mass (kg)</th>
<th>Moments of Inertia (kg-m²)</th>
<th>Products of Inertia (kg-m²)</th>
<th>Node ID, Node Coord. (meters)</th>
<th>Node ID, Node Structural Joint ID</th>
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<td>2</td>
<td>0, 1 or 2</td>
<td>Y/N</td>
<td>0</td>
<td>NS, CD, HL, SD</td>
<td>0.3659</td>
<td>0.03961, 0.03961, 0.07921</td>
<td>0.0, -1E-6</td>
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<tr>
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<td>53</td>
<td>R</td>
<td>2</td>
<td>0, 1 or 2</td>
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<td>NS, CD, HL, SD</td>
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</tr>
</tbody>
</table>

### Example Data

- **Body ID Number**: 51, 52, 53
- **Type**: R (Rigid), F (Flexible), N (NASTRAN)
- **Number of Modes**: 2
- **Modal Calculation Option**: 0, 1 or 2
- **Foreshortening Option**: Y (Yes), N (No)
- **Damping Matrix Option**: NS (Natural), CD (Critical), HL (Half), SD (Stiffness)
- **Mass (kg)**: 0.3659, 0.23, 0.1823
- **Moments of Inertia (kg-m²)**: 0.03961, 0.03961, 0.07921
- **Products of Inertia (kg-m²)**: 0.0, -1E-6
- **Node ID, Node Coord. (meters)**: 1, 0, -5E-6; 1, 0, 0.1936
- **Node ID, Node Structural Joint ID**: none
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<th>415</th>
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<td>Type (Rigid, Flexible, NASTRAN)</td>
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<tr>
<td>421</td>
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<td>Mass (kg)</td>
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<td>439</td>
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<td>Node ID, Node structural joint ID</td>
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<table>
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<td>NASTRAN data file FORTRAN unit number (40 - 60)</td>
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HINGE

482 HI 1 Hinge ID number 1
| Hinge ID | Inboard body ID, Outboard body ID | "p" node ID, "q" node ID | Number of rotation DOFs, Rotation option (F or G) | L1 unit vector in inboard body coord. x,y,z | L1 unit vector in outboard body coord. x,y,z | L2 unit vector in inboard body coord. x,y,z | L2 unit vector in outboard body coord. x,y,z | L3 unit vector in inboard body coord. x,y,z | L3 unit vector in outboard body coord. x,y,z | Initial rotation angles (deg) | Initial rotation rates (deg/sec) | Rotation stiffness (newton-meters/rad) | Rotation damping (newton-meters/rad/sec) | Null torque angles (deg) | Number of translation DOFs | First translation unit vector g1 | Second translation unit vector g2 | Third translation unit vector g3 | Initial translation (meters) | Initial translation velocity (meters/sec) | Translation stiffness (newton-meters) | Translation damping (newton-meters/sec) | Null force translations |
|----------|----------------------------------|--------------------------|--------------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|----------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|----------------------------------|----------------------------------|
| 1        | 1 Inboard body ID, Outboard body ID | 0,1                      | 3,6                                               | 1,0,0                                          | 1,0,0                                          | 0,0,1                                          | 0,0,1                                          | 0,0,1                                          | 0,0,1                                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           |
| 2        | 2 Hinge ID number                  | 2                        |                                                  |                                                |                                               |                                                |                                                |                                                |                                                | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           |
| 3        | 3 Hinge ID number                  | 3                        |                                                  |                                                |                                               |                                                |                                                |                                                |                                                | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           |
| 4        | 4 Hinge ID number                  | 4                        |                                                  |                                                |                                               |                                                |                                                |                                                |                                                | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           |
| 5        | 5 Hinge ID number                  | 5                        |                                                  |                                                |                                               |                                                |                                                |                                                |                                                | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           |
| 6        | 6 Hinge ID number                  | 6                        |                                                  |                                                |                                               |                                                |                                                |                                                |                                                | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           |
| 7        | 7 Hinge ID number                  | 7                        |                                                  |                                                |                                               |                                                |                                                |                                                |                                                | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           |
| 8        | 8 Hinge ID number                  | 8                        |                                                  |                                                |                                               |                                                |                                                |                                                |                                                | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           |
| 9        | 9 Hinge ID number                  | 9                        |                                                  |                                                |                                               |                                                |                                                |                                                |                                                | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                          | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           | 0,0,1                           |

Note: The table continues with similar entries for each hinge ID number from 10 to 11.
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<th>L1 unit vector in outboard body coord. x,y,z</th>
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<th>Initial rotation rates (deg/sec)</th>
<th>Rotation stiffness (newton-meters/tad)</th>
<th>Rotation damping (newton-meters/rad/sec)</th>
<th>Null torque angles (deg)</th>
<th>Number of translation DOFs</th>
<th>First translation unit vector g1</th>
<th>Second translation unit vector g2</th>
<th>Third translation unit vector g3</th>
<th>Initial translation (meters)</th>
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| Hinge ID number | Inboard body ID, Outboard body ID | "p" node ID, "q" node ID | Number of rotation DOFs, Rotation option (F or G) | L1 unit vector in inboard body coord. x,y,z | L1 unit vector in outboard body coord. x,y,z | L2 unit vector in inboard body coord. x,y,z | L2 unit vector in outboard body coord. x,y,z | L3 unit vector in inboard body coord. x,y,z | L3 unit vector in outboard body coord. x,y,z | Initial rotation angles (deg) | Initial rotation rates (deg/sec) | Rotation stiffness (newton-meters/tad) | Rotation damping (newton-meters/rad/sec) | Null torque angles (deg) | Number of translation DOFs | First translation unit vector g1 | Second translation unit vector g2 | Third translation unit vector g3 | Initial translation (meters) | Initial translation velocity (meters/sec) | Translation damping (newtons/meter/sec) | Null force translations |
| Hinge ID number | Inboard body ID, Outboard body ID | L1 unit vector in inboard body coord. x,y,z | L1 unit vector in outboard body coord. x,y,z | L2 unit vector in inboard body coord. x,y,z | L2 unit vector in outboard body coord. x,y,z | L3 unit vector in inboard body coord. x,y,z | L3 unit vector in outboard body coord. x,y,z | Number of rotation DOFs | Rotation stiffness (newton-meters/rad) | Rotation damping (newton-meters/rad/sec) | Initial translation (meters) | Initial translation velocity (meters/sec) | Translation stiffness (newtons/meters) | Translation damping (newtons/meters/sec) | Null force translations |
|----------------|----------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|----------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| 1,31           | 1,31                             | 0.5, -0.75, 0.4330127                       | 0, 0, 1                                    | 0.8660254, 0.4330127, -0.25                 | 204.7, 204.7, 204.7                         | 3.75, 3.75, 3.75                             | 3.75, 3.75, 3.75                             | 3                                       | 0.362, 0.362, 0.362                     | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
| 1,32           | 2,2                              | 1, 0                                        | 0, 1                                       | 0.8660254, 0.4330127, -0.25                 | 204.7, 204.7, 204.7                         | 3.75, 3.75, 3.75                             | 3.75, 3.75, 3.75                             | 3                                       | 0.362, 0.362, 0.362                     | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
| 3              | 3                                | 0, 0, i                                      | 0, 0, i                                    | 0, 0, i                                     | 0, 0, i                                     | 0, 0, i                                      | 0, 0, i                                     | 0                                       | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
| 1,31           | 1,32                             | 0, 1                                        | 0, 1                                       | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0                                       | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
| 1,32           | 2,2                              | 1, 0                                        | 0, 1                                       | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0                                       | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
| 1              | 1,31                             | 0, 0, i                                      | 0, 0, i                                    | 0, 0, i                                     | 0, 0, i                                     | 0, 0, i                                      | 0, 0, i                                     | 0                                       | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
| 1,32           | 2,2                              | 1, 0                                        | 0, 1                                       | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0                                       | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
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| 1              | 1,31                             | 0, 0, i                                      | 0, 0, i                                    | 0, 0, i                                     | 0, 0, i                                     | 0, 0, i                                      | 0, 0, i                                     | 0                                       | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
| 1,32           | 2,2                              | 1, 0                                        | 0, 1                                       | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0                                       | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
| 1              | 1,31                             | 0, 0, i                                      | 0, 0, i                                    | 0, 0, i                                     | 0, 0, i                                     | 0, 0, i                                      | 0, 0, i                                     | 0                                       | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |
| 1,32           | 2,2                              | 1, 0                                        | 0, 1                                       | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0, 1                                        | 0                                       | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        | 0                                        |

41 Hinge ID number
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42 "p" node ID, "q" node ID
43 Number of rotation DOFs, Rotation option (F or G)
44 L1 unit vector in inboard body coord. x,y,z
45 L2 unit vector in inboard body coord. x,y,z
46 L3 unit vector in inboard body coord. x,y,z
47 Initial rotation angles (deg)
48 Initial rotation rates (deg/sec)
49 Rotation stiffness (newton-meters/rad)
50 Rotation damping (newton-meters/rad/sec)
51 Null force translations
52 Hinge ID number
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54 "p" node ID, "q" node ID
55 Number of rotation DOFs
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57 L2 unit vector in inboard body coord. x,y,z
58 L3 unit vector in inboard body coord. x,y,z
59 Initial rotation angles (deg)
60 Initial rotation rates (deg/sec)
61 Rotation stiffness (newton-meters/rad)
62 Rotation damping (newton-meters/rad/sec)
63 Null force translations
64 Hinge ID number
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71 Initial rotation angles (deg)
72 Initial rotation rates (deg/sec)
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74 Rotation damping (newton-meters/rad/sec)
75 Null force translations
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99 Null force translations
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120 Initial rotation rates (deg/sec)
121 Rotation stiffness (newton-meters/rad)
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ACTR

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2 Mounting point body ID, Mounting point node ID
3 Second mounting point body ID, Second node ID
4 Input axis unit vector (IA) x, y, z
5 Mounting point Hinge index, Axis index
6 First focal plane unit vector (Fp1) x, y, z
7 Second focal plane unit vector (Fp2) x, y, z
8 Sun/Star unit vector (Us) x, y, z
9 Euler Angle Sequence (1-6)
10 IM number and Gimbal number

11 Actuator ID number
12 Type (J, H, MO, T, B, MA, SG, DG, W, L, M1-M7)
13 Actuator location; Node or Hinge (N or H)
14 Mounting point body ID number, node ID number
15 Second mounting point body ID, second node ID
16 Output axis unit vector x, y, z
17 Mounting point Hinge index, Axis index
18 Rotor spin axis unit vector x, y, z
19 Initial rotor momentum, H
20 Outer gimbal- angle (deg), inertia, friction (D, S, B, N)
21 Outer gimbal axis unit vector x, y, z
22 Inner gimbal- angle (deg), inertia, friction (D, S, B, N)
23 Inner gimbal axis unit vector x, y, z
24 Initial length and rate, y(to) and ydot(to)
25 Constants; K1 or wo, n or zeta, Kg, Jm
26 Non-linearities; TLim, Tco, Dz
27 Actuator location; Node or Hinge (N or H)
28 Mounting point body ID number, node ID number
29 Second mounting point body ID, second node ID
30 Output axis unit vector x, y, z
31 Mounting point Hinge index, Axis index
32 Rotor spin axis unit vector x, y, z
33 Initial rotor momentum, H
34 Outer gimbal- angle (deg), inertia, friction (D, S, B, N)
35 Outer gimbal axis unit vector x, y, z
36 Inner gimbal- angle (deg), inertia, friction (D, S, B, N)
37 Inner gimbal axis unit vector x, y, z
38 Initial length and rate, y(to) and ydot(to)
39 Constants; K1 or wo, n or zeta, Kg, Jm
40 Non-linearities; TLim, Tco, Dz
41 Actuator location; Node or Hinge (N or H)
42 Mounting point body ID number, node ID number

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1121 AC 43 Second mounting point body ID, second node ID 43,1
1122 AC 43 Output axis unit vector x,y,z 53
1123 AC 43 Mounting point Hinge index, Axis index
1124 AC 43 Rotor spin axis unit vector x,y,z
1125 AC 43 Initial rotor momentum, H
1126 AC 43 Outer gimbal angle, inertia, friction(D,S,B,N)
1127 AC 43 Outer gimbal axis unit vector x,y,z
1128 AC 43 Inner gimbal angle, inertia, friction(D,S,B,N)
1129 AC 43 Inner gimbal axis unit vector x,y,z
1130 AC 43 Final length and rate, y(to) and ydot(to)
1131 AC 43 Constants; K1 or w, n or zeta, Kg, Jm
1132 AC 43 Non-linearities; TLim, Tco, Dz

1803 AC 63 Actuator ID number 63
1804 AC 63 Type(J,H,MO,T,B,MA-SA,DG,DL,LM-M7)
1805 AC 63 Actuator location; Node or Hinge (N or H)
1806 AC 63 Mounting point body ID number, node ID number
1807 AC 63 Second mounting point body ID, second node ID
1808 AC 63 Output axis unit vector x,y,z
1809 AC 63 Mounting point Hinge index, Axis index 63,1
1810 AC 63 Rotor spin axis unit vector x,y,z
1811 AC 63 Initial rotor momentum, H
1812 AC 63 Outer gimbal angle, inertia, friction(D,S,B,N)
1813 AC 63 Outer gimbal axis unit vector x,y,z
1814 AC 63 Inner gimbal angle, inertia, friction(D,S,B,N)
1815 AC 63 Inner gimbal axis unit vector x,y,z
1816 AC 63 Final length and rate, y(to) and ydot(to)
1817 AC 63 Constants; K1 or w, n or zeta, Kg, Jm
1818 AC 63 Non-linearities; TLim, Tco, Dz

CONTROLLER

1171 CO 1 Controller ID number 1
1172 CO 1 Controller type (CB,CM,DM,UD) UD
1173 CO 1 Sample time (sec) 0.064
1174 CO 1 Number of inputs, Number of outputs 6,6
1175 CO 1 Number of states
1176 CO 1 Output No., Input type (I,S,T), Input ID, Gain

INTERCONNECT

1177 IN 13 Interconnect ID number 13
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1180 IN 13 Gain 1

1181 IN 23 Interconnect ID number 23
1182 IN 23 Source type(S,C, or F),Source ID,Source row # C,1,2
1183 IN 23 Destination type(A or CI),Dest ID,Dest row # A,23,1
1184 IN 23 Gain 1

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Appendix C

AXAF-I TREETOPS Input File AXAFI.FLN

FLAG, REVISION NUMBER
XXXXXX 1

BODY ID
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0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0

MODAL LOCATION VECTORS
-0.25629736E-16 0.14245523E+02 0.00000000E+00 0.33627405E+01
0.46979787E+01 0.55389451E-01 0.12008538E+02 0.55389451E-01
0.12008538E+02 0.55389451E-01 0.13903728E+02 0.55389451E-01
0.33627405E+01 0.12000853E+02 0.55389451E-01 0.33627405E+01
0.55389451E-01 0.33627405E+01 0.19303728E+02 0.55389451E-01
0.26258866E+02 0.55389451E-01 0.67396022E+02 0.55389451E-01
0.25688829E+01 0.66230670E+03 0.11668189E+02 0.67396022E+02
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00

MASS, Ixx, Iyy, Izz, Ixy, Ixz, Iyz
0.25688829E+01 0.66230670E+03 0.11668189E+02 0.67396022E+02
-0.13009385E-17-0.20111547E+01 -0.13009385E-17-0.20111547E+01

PHI for node # 2
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00

PHI PRIME for node # 2
1.50299722E-01 4.6979787E+01 3.3627405E+01 5.5389451E-01
-0.19303728E+02 0.55389451E-01 0.67396022E+02 0.55389451E-01
0.26258866E+02 0.55389451E-01 0.67396022E+02 0.55389451E-01
0.25688829E+01 0.66230670E+03 0.11668189E+02 0.67396022E+02
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00

PHI for node # 3
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00

PHI PRIME for node # 3
-0.13447378E+00 0.39621025E-02-0.32939518E-03 0.12951566E-15
0.12957398E+00 0.23957638E+00 0.21752910E+00 0.12530541E+00
0.11949118E-01-0.96766111E-03-0.42796952E+00-0.34267600E-05
0.73277400E-04-0.31646000E-01 0.21297000E+01 0.80964200E-02

PHI for node # 4
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00

PHI PRIME for node # 4
-0.98232809E-01 0.34850594E-02 0.89734909E-03 0.45555262E-02
0.14805712E+00 0.19197648E+00 0.48632905E+00 0.32308772E+00
0.10336061E-01 0.26260770E-02-0.22925957E+00-0.34299412E+00
0.34299412E+00 0.69890076E-01 0.71339854E-01-0.70710548E-02

PHI for node # 5
0.10511700E-07 0.32662700E-02-0.14734100E+01-0.17949400E+01-0.25219900E+00
0.11283000E-01 0.17730500E-01 0.49816100E-03 0.16398500E+01-0.16279500E-06
-0.39222100E-02 0.28983700E-02-0.97617700E-03 0.58804400E+03-0.22196500E+01
0.63382000E-06-0.16895500E-01 0.71811900E+00 0.17949400E+01-0.25219900E+00

PHI PRIME for node # 5
-0.18535821E+00-0.60430578E-03 0.00000000E+00 0.13411016E-02 0.59774271E-02
0.00000000E+00 0.12438258E+00 0.86916597E+00 0.00000000E+00-0.20764791E+00

55
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<td>0.28507200E+01</td>
<td>0.13605566E+00</td>
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<td>0.12347534E+01</td>
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STIFFNESS MATRIX

```
0.22020840E+02 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
```

*** MODAL COUPLING TERMS ***

INTEGRAL PHI DM

```
-0.16740209E-04 0.29528532E-02 0.16005450E+01 0.17375877E+01
0.10254551E+00 0.94073675E-06
```

H PARAMETER

```
-0.83054904E+02 0.35595343E+00 0.16330605E-02 0.17008809E-01 0.22477178E+00
0.84318187E+02 0.43996190E+01 0.28534870E+01 0.69978860E+00 0.10266543E+02
0.48335086E+00 0.23821416E+00 0.12820144E-01 0.14205193E+02
```

MASS, Ixx, Iyy, Izz, Ixy, Ixz, Iyz

```
0.25688829E+01 0.66230670E+03 0.11668189E+02 0.67396022E+00 0.12951566E-15
```

FLAG, REVISION NUMBER

```
XXXXX 1
```

MODES, NODES, MODAL OPTIONS

```
6 10 2 0 0 0 0 0 0 0 0 0
```

MODAL LOCATION VECTORS

```
-0.25659736E-16 0.14245523E+02 0.50297722E-01 0.00000000E+00 0.98421063E-02
0.00000000E+00 0.33627405E+00 0.46979787E+00 0.55389451E-01 0.33627405E+00
0.46979787E+00 0.55389451E-01 0.12000853E+02 0.55389451E-01 0.33627405E+00
0.33627405E+00 0.12000853E+02 0.55389451E-01 0.33627405E+00 0.19303728E+02
0.55389451E-01 0.33627405E+00 0.19303728E+02 0.55389451E-01 0.33627405E+00
0.26258866E+02 0.55389451E-01 0.33627405E+00 0.55389451E-01 0.33627405E+00
```

MASS, Ixx, Izy, Iyy, Izz

```
0.25688829E+01 0.66230670E+03 0.11668189E+02 0.67396022E+00 0.12951566E-15
```

PHI for node # 2

```
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
```

PHI PRIME for node # 2

```
0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
```

PHI for node # 3

```
0.34267600E-05 0.25275900E-02 0.16523000E+00 0.61755000E+00 0.44938300E+00
```

57
<table>
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<tr>
<th>PHI for node # 10</th>
<th>PHI PRIME for node # 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11085167E+01</td>
<td>0.43101644E-02</td>
</tr>
<tr>
<td>0.11149274E-05</td>
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</table>

### MASS MATRIX

-0.18157300E-08  0.30484700E-02  -0.39931300E+01  0.35094500E+01  -0.45004300E+00

### DAMPING MATRIX

-0.34790800E-01  0.17810200E-01  -0.56774400E-03  0.48784100E+01  -0.69819200E-07

### STIFFNESS MATRIX

-0.11027400E-01  0.38676400E+01  0.57003100E-02  0.28693600E-02  0.54549700E+01

### INTEGRAL

-0.16186900E-06  0.14442800E-01  0.34909800E+01

### *** MODAL COUPLING TERMS ***

### INTEGRAL PHI DM

-0.20356174E+00  0.55588984E-04  0.31263051E-07  0.31879515E-03  0.10342194E-01

### H PARAMETER

-0.83350860E+00  0.23832211E-02  0.40227323E+01  0.46717960E+01  0.12234931E+00

### S1

-0.00000000E+00  0.00000000E+00  0.00000000E+00  0.00000000E+00  0.00000000E+00

### 59
Appendix D
AXAF-I TREETOPS Input File AXAFI.RET

26
1 2 3 4 5 6
36
1 2 3 4 5 6
Appendix E

NASTRAN Model of AXAF-I Solar Array

NASTRAN TITLEOPT=-1
ID AXAF,DEPLOYED ED12
$SOL 103
SOL 3
TIME 200
$SYK DIAG 8,9,13,14
diag 8,9
readfile ALTERS
$$$$$$$$$ by YK
$ALTER 105 $ FOR '91 CSA NASTRAN
$ALTER 106 $ FOR '93 CSA NASTRAN
RFINSERT READ $ FOR '94 CSA NASTRAN
TABPT EQEXIN/ $
GKAM,,PHIA,MI,LAMA,DIT,,/CASECC/MMASS,MDAMP,MSTIFF,PHIDH/-1/
CEND $ $ $ RECEIVED FROM TRW/ZIGGY JAB 3/2/93 $ $ $----------------------------- $ $ necessary alter for Lanczos with sol 3 $ $COMPILE SOL3 SOIN=MSCSOU $RFALTER RF3D83 $----------------------------- $LINE=48 $ $TILE = AXAF-I Solar Array Modes $SUBTITLE = Normal Modal Analysis $LABEL = FREE-FREE $SYK DISPLACEMENT = ALL
disp (plot) = all $ YK $ SYK ECHO = SORT
echo = none $ YK $ SPC=100 $ $MPC=10 $METHOD = 1000 $SET 1 = ALL

61
$SET 1 = 63001, 60000, 60003, 60400, 60403, 60800, 60803, 61100, 61103
$DISP = 1
$
$
$PLOTID = SEND PLOTS TO J. A. BRUNTY BIN 196
OUTPUT(PLOT)
$PLOTTER NAST
$SET 1 = 1 THRU 1000000
SET 1 = ALL
$SET 1 = 63001, 60000, 60003, 60400, 60403, 60800, 60803, 61100, 61103
$MAXIMUM DEFORMATION 100.
CSCALE=2
AXES X,Y,Z
VIEW 5., 35., 10.
FIND SCALE, ORIGIN 1, SET 1
PLOT SET 1, ORIGIN 1
PLOT SET 1, ORIGIN 1, LABEL GRID POINTS
$PLOT SET 1, ORIGIN 1, LABEL ELEMENTS
PLOT MODAL DEFORMATION, SET 1, ORIGIN 1
$-------------------------------
BEGIN BULK
param autospc yes
PARAM GRDPNT 0
PARAM WTMASS .002588
PARAM TINY 1.0
$PARAM K6ROT 0.25
$ FOR OUTPUT USED IN MSC/NASTRAN EXCEL
$PARAM POST 0
$ FOR OUTPUT USED IN PATRAN
PARAM, POST, -1
$ PARAM DEFAULT IS 1
$PARAM, POST, 1
$---------2--------3--------4--------5--------6--------7--------8--------9--------
$EIGRL 1000 -1.0 100.
$##EIGR 1000 BLAN -1. 100.
EIGR 1000 BLAN -1. 20.
$-------------------------------
$INCLUDE sa+yscif.osas
$
SADA REPRESENTED WITH A RIGID TEPEE TO PROVIDE INTERFACE
AT THE PROPER LOCATION AND CELAS TO PROVIDE FOR SADA
FLEXIBILITIES. HRG 3/30/94
$
$ Material properties of tepee CBARS. OSAS. (Uncomment only if the wing
is to be run alone.)
$
$$MAT1 809 10.0E06 .33
$
$$CBAR 87201 872 84023 84501 0. 0. 1.
+942219
$$CBAR 87202 872 84024 84501 0. 0. 1.
+942220
$$CBAR 87203 872 84027 84501 0. 0. 1.
+942419
$$CBAR 87204 872 84028 84501 0. 0. 1.
+942420
$$CBAR 87205 872 84031 84501 0. 0. 1.
+942619
$$CBAR 87206 872 84032 84501 0. 0. 1.
+942620
$
$ COINCIDENT GRIDS TO MODEL SADA FLEXIBILITY FOR +Y SA
$
$*******************************
***
Uncomment coordinate system 810 if this panel is to be run alone. OSAS.

CORD2R 810 0 0.0 0.0 0.0 0.0 0.0 l.

=================================================================

GRID 84501 810 445.88 68.025 -9.53
GRID 84502 810 445.88 68.025 -9.53
GRID 84503 810 445.88 68.025 -9.53 COMMENTED OUT PER R.H.
OSAS. 5/24/94.
GRID 84504 810 445.88 68.025 -9.53

SADA STIFFNESS (TDRS VALUES)

CELAS2 89235 50.00E3 84501 1 84502 1
CELAS2 89236 50.00E3 84501 2 84502 2
CELAS2 89237 50.00E3 84501 3 84502 3
CELAS2 89238 8.00E5 84501 4 84502 4
CELAS2 89239 8.00E4 84501 5 84502 5
CELAS2 89240 8.00E5 84501 6 84502 6

![Include rigid elements for free-free run only](include+9).osas

GRID 80000 87064 123456 87060 87036 87040 87037 87039
GRID 84504

INCLUDE sa+y.osas

### BASIC COORDINATE SYSTEM of S/A (600) FOR MODEL

Attachment of +y wing to tepee (corner grid of yoke to outboard grid of SADA)

RBAR 60001 84502 63001 123456 spc1,100,12346,63001

Modify Location of I/F per IOC M533.2.94-073

GRID 63001 600 0. -.11811 0.0 600
GRID 63002 600 0. .94488 0.0 600
GRID 63003 600 0. .94488 0.0 600

BAPTA & SADM Hinge

CELAS2 63061 2.3454+563002 4 63003 4
CELAS2 63062 5.8414+463002 5 63003 5
CELAS2 63063 1.6374+663002 6 63003 6
Inboard Panel

Edge Beams

CBAR 60151 611 60000 60001 0. 0. 1.
CBAR 60152 611 60001 60002 0. 0. 1.
CBAR 60153 611 60002 60003 0. 0. 1.
CBAR 60154 611 60300 60301 0. 0. 1.
CBAR 60155 611 60301 60302 0. 0. 1.
CBAR 60156 611 60302 60303 0. 0. 1.

Panel Wt

CONM2 60161 60001 601 0.12346
CONM2 60162 60002 601 0.12346
CONM2 60163 60301 601 0.12346
CONM2 60164 60302 601 0.12346
CONM2 60165 60101 601 0.1411
CONM2 60166 60102 601 0.1411
CONM2 60167 60201 601 0.1411
CONM2 60168 60202 601 0.1411

Quad's

CQUAD4 60101 601 60000 60001 60101 60100
CQUAD4 60102 602 60001 60002 60102 60101
CQUAD4 60103 601 60002 60003 60103 60102
CQUAD4 60104 601 60100 60101 60201 60200
CQUAD4 60105 602 60101 60102 60202 60201
CQUAD4 60106 601 60102 60103 60203 60202
CQUAD4 60107 601 60200 60201 60301 60300
CQUAD4 60108 602 60201 60202 60302 60301
CQUAD4 60109 601 60202 60203 60303 60302

Grids

GRID 60000 601 40.3545 0.0 0.0 601
GRID 60001 601 22.6379 0.0 0.0 601
GRID 60002 601 -22.6379 0.0 0.0 601
GRID 60003 601 -40.3545 0.0 0.0 601
GRID 60100 601 40.3545 20.8466 0.0 601
GRID 60101 601 22.6379 20.8466 0.0 601
GRID 60102 601 -22.637920.8466 0.0 601
GRID 60103 601 -40.354520.8466 0.0 601
GRID 60104 601 40.3545 65.8271 0.0 601
GRID 60105 601 22.6379 65.8271 0.0 601
GRID 60106 601 -22.637965.8271 0.0 601
GRID 60107 601 -40.354565.8271 0.0 601
GRID 60108 601 40.354583.465 0.0 601
GRID 60109 601 22.637983.465 0.0 601
GRID 60110 601 -22.637983.465 0.0 601
GRID 60111 601 -40.354583.465 0.0 601

Mid Panel

Edge Beams

CBAR 60251 611 60400 60401 0. 0. 1.
CBAR 60252 611 60401 60402 0. 0. 1.
CBAR 60253 611 60402 60403 0. 0. 1.
CBAR 60254 611 60700 60701 0. 0. 1.
CBAR 60255 611 60701 60702 0. 0. 1.
CBAR 60256 611 60702 60703 0. 0. 1.

Panel Wt

CONN2 60261 60401 602 0.12346
CONN2 60262 60402 602 0.12346
CONN2 60263 60701 602 0.12346
CONN2 60264 60702 602 0.12346
$ Quads
CQUAD4 60201 601 60400 60401
CQUAD4 60202 602 60401 60402
CQUAD4 60203 601 60402 60403
CQUAD4 60204 601 60500 60501
CQUAD4 60205 602 60501 60502
CQUAD4 60206 601 60502 60503
CQUAD4 60207 601 60600 60601
CQUAD4 60208 602 60601 60602
CQUAD4 60209 601 60602 60603
$ Grids
GRID 60400 602 40.3545 0.0
GRID 60401 602 22.6379 0.0
GRID 60402 602 -22.6379 0.0
GRID 60403 602 -40.3545 0.0
GRID 60500 602 40.3545 17.6379
GRID 60501 602 22.6379 17.6379
GRID 60502 602 -22.6379 17.6379
GRID 60503 602 -40.3545 17.6379
GRID 60600 602 40.3545 62.6184
GRID 60601 602 22.6379 62.6184
GRID 60602 602 -22.6379 62.6184
GRID 60603 602 -40.3545 62.6184
GRID 60700 602 40.3545 83.465
GRID 60701 602 22.6379 83.465
GRID 60702 602 -22.6379 83.465
GRID 60703 602 -40.3545 83.465

$ Outboard Panel
$ Edge Beams
CBAR 60351 611 60800 60801 0.0 0.603
CBAR 60352 611 60801 60802 0.0 0.603
CBAR 60353 611 60802 60803 0.0 0.603
CBAR 60354 611 61100 61101 0.0 0.603
CBAR 60355 611 61101 61102 0.0 0.603
CBAR 60356 611 61102 61103 0.0 0.603
$ Panel Wt
CONN2 60361 60801 603 0.12346
CONN2 60362 60802 603 0.12346
CONN2 60363 61101 603 0.12346
CONN2 60364 61102 603 0.12346
CONN2 60365 60901 603 0.54586
CONN2 60366 60902 603 0.54586
CONN2 60367 61001 603 0.54586
CONN2 60368 61002 603 0.54586
$ Tip Masses for Outboard Panel
CONN2 60369 61100 603 0.26
CONN2 60370 61103 603 0.26
$ Quads
CQUAD4 60301 601 60800 60801 60901 60900
CQUAD4 60302 602 60801 60802 60902 60901
CQUAD4 60303 601 60802 60803 60903 60902
CQUAD4 60304 601 60900 60901 61001 61000
CQUAD4 60305 602 60901 60902 61002 61001
CQUAD4 60306 601 60902 60903 61003 61002
CQUAD4 60307 601 61000 61001 61101 61100
CQUAD4 60308 602 61001 61002 61102 61101
CQUAD4 60309 601 61002 61003 61103 61102
$ Grids
GRID 60800 603 40.3545 0.0 0.0 603
### Coordinate Systems

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### Materials and Properties

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<td>2.226+7 3.168+5 5.802+5 5.802+5</td>
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### ENDDATA
Appendix F
NASTRAN Normal Modal Analysis Output
of AXAF-I Solar Array

NORMAL MODAL ANALYSIS
OUTPUT FROM GRID POINT WEIGHT GENERATOR
REFERENCE POINT = 0

MO - RIGID BODY MASS MATRIX IN BASIC COORDINATE SYSTEM
***
* 8.271776E+01 0.000000E+00 0.000000E+00 0.000000E+00 4.993016E+01 -1.414086E+04 *
* 0.000000E+00 8.271776E+01 0.000000E+00 -4.993016E+01 0.000000E+00 6.863821E-13 *
* 0.000000E+00 0.000000E+00 8.271776E+01 1.414086E+04 -2.745528E-12 0.000000E+00 *
* 0.000000E+00 -4.993016E+01 1.414086E+04 3.071223E+06 -7.028553E-10 -1.029573E-12 *
* 4.993016E+01 0.000000E+00 -6.863821E-13 -3.514276E+06 5.410720E+04 -9.326042E+03 *
* -1.414086E+04 6.863821E-13 0.000000E+00 -2.745528E-12 -9.326042E+03 3.125262E+06 *
***

S - TRANSFORMATION MATRIX FOR SCALAR MASS PARTITION
***
* 1.000000E+00 0.000000E+00 0.000000E+00 *
* 0.000000E+00 1.000000E+00 0.000000E+00 *
* 0.000000E+00 0.000000E+00 1.000000E+00 *
***

DIRECTION
MASS AXIS SYSTEM (S) MASS X-C.G. Y-C.G. Z-C.G.
X 8.271776E+01 0.000000E+00 1.709532E+02 0.000000E+00 6.036208E-01
Y 8.271776E+01 8.297881E-15 1.709532E+02 0.000000E+00 6.036208E-01
Z 8.271776E+01 3.319152E-14 1.709532E+02 0.000000E+00 6.036208E-01

I(S) - INERTIAS RELATIVE TO C.G.
***
* 6.537670E+05 2.334984E-10 6.152586E+13 *
* 2.334984E-10 5.407706E+04 7.903221E+02 *
* 6.152586E+13 7.903221E+02 7.078363E+05 *
***

I(Q) - PRINCIPAL INERTIAS
***
* 6.537670E+05 *
* 7.078372E+05 *
* 5.407610E+04 *
***

Q - TRANSFORMATION MATRIX
I(Q) = QT*IBAR(S)*Q
***
* 1.000000E+00 0.000000E+00 0.000000E+00 *
* 0.000000E+00 1.208886E+03 9.999993E-01 *
* 0.000000E+00 -9.999993E-01 1.208886E+03 *
***
### Real Eigenvalues

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<th>Cyclic Frequency</th>
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<th>Generalized Stiffness</th>
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Appendix G
SSE MACOS Input File

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ChfRayPos = 0.0000000000D+00 0.0000000000D+00 -1.0000000000D+01
zSource = 1.0000000000D+22
IndRef = 1.0000000000D+00
Extinc = 0.0000000000D+00
Wavelen = 2.8347000000D-05
Flux = 1.0000000000D+00
GridType = Circular
Aperture = 17.2
Obscratn = 0.0000000000D+00
nGridpts = 100
xGrid = 0.0000000000D+00 0.0000000000D+00 1.0000000000D+00
yGrid = 0.0000000000D+00 0.0000000000D+00 1.0000000000D+00
nElt = 9

iElt = 1
EltName = ring_front
Element = Refractor
Surface = Flat
KrElt = -1.0000000000D+22
KcElt = 0.0000000000D+00
psiElt = 0.0000000000D+00 0.0000000000D+00 -1.0000000000D+00
VptElt = 0.0000000000D+00 0.0000000000D+00 -1.3777300000D+00
RptElt = 0.0000000000D+00 0.0000000000D+00 -1.3777300000D+00
IndRef = 1.5950590000D+00
Extinc = 0.0000000000D+00
nObs = 1
ObsType = Circle
ObsVec = 7.1900000000D+00 0.0000000000D+00 0.0000000000D+00
xObs = 1.0000000000D+00 0.0000000000D+00 0.0000000000D+00
ApType = Circular
ApVec = 7.1900000000D+00 0.0000000000D+00 0.0000000000D+00
zElt = 1.0000000000D+22
PropType = Geometric
cnECoord = -6

iElt = 2
EltName = ring_back
Element = Refractor
Surface = Aspheric
KrElt = 1.3374230000D+01
KcElt = 0.0000000000D+00
psiElt = 0.0000000000D+00 0.0000000000D+00 -1.0000000000D+00
VptElt = 0.0000000000D+00 0.0000000000D+00 -1.3747300000D+00
RptElt = 0.0000000000D+00 0.0000000000D+00 -1.3747300000D+00
IndRef = 1.0000000000D+00
Extinc = 0.0000000000D+00
AsphCoef = 4.1455200000D-04 -3.4476000000D-06 1.9907500000D-08 0.0000000000D+00
nObs = 1
ObsType = Circle
ObsVec = 7.1900000000D+00 0.0000000000D+00 0.0000000000D+00
xObs = 1.0000000000D+00 0.0000000000D+00 0.0000000000D+00
ApType = Circular
ApVec = 7.1900000000D+00 0.0000000000D+00 0.0000000000D+00
zElt = 1.3374230000D+01
PropType = Geometric
cnECoord = -6

iElt = 3
EltName= NDfilter_front  
Element= Refractor  
Surface= Flat  
KreEl = -1.000000000D+22  
KcEl = 0.000000000D+00  
psiEl = 0.000000000D+00 -1.564298529D-01 -9.876890711D-01  
VptEl = 0.000000000D+00 1.901096200D+01 7.336785300D+01  
RptEl = 0.000000000D+00 1.901096200D+01 7.336785300D+01  
IndRef = 1.454853000D+00  
Extinc = 0.000000000D+00  
nObs = 0  
ApType = Circular  
ApVec = 3.000000000D+00 0.000000000D+00 0.000000000D+00  
zEl = 1.000000000D+22  
PropType = Geometric  
nECoord = -6  
iElt = 4  
EltName= NDfilter_back  
Element= Refractor  
Surface= Flat  
KreEl = -1.000000000D+22  
KcEl = 0.000000000D+00  
psiEl = 0.000000000D+00 -1.564298529D-01 -9.876890711D-01  
VptEl = 0.000000000D+00 1.905007100D+01 7.361477500D+01  
RptEl = 0.000000000D+00 1.905007100D+01 7.361477500D+01  
IndRef = 1.000000000D+00  
Extinc = 0.000000000D+00  
nObs = 0  
ApType = Circular  
ApVec = 3.000000000D+00 0.000000000D+00 0.000000000D+00  
zEl = 1.000000000D+22  
PropType = Geometric  
nECoord = -6  
iElt = 5  
EltName= Cylinder_front  
Element= Refractor  
EltName= Cylinder  
Element= Refractor  
Surface= Conic  
fEl = 4.803140000D+00  
eEl = 0.000000000D+00  
KrEl = 4.803140000D+00  
KrEl = 0.000000000D+00  
psiEl = 0.000000000D+00 -1.564298529D-01 -9.876890711D-01  
VptEl = 0.000000000D+00 1.996007600D+01 7.357189100D+01  
RptEl = 0.000000000D+00 1.996007600D+01 7.357189100D+01  
IndRef = 1.512549000D+00  
Extinc = 0.000000000D+00  
nObs = 0  
ApType = Rectangular  
ApVec = -1.250000000D+00 1.250000000D+00 -3.250000000D+00 3.250000000D+00  
zEl = 4.803140000D+00  
PropType = Geometric  
nECoord = -6  
iElt = 6  
EltName= Cylinder_back  
Element= Refractor  
Surface= Flat  
KreEl = -1.000000000D+22  
KcEl = 0.000000000D+00  
psiEl = 0.000000000D+00 -1.564298529D-01 -9.876890711D-01  
VptEl = 0.000000000D+00 2.018179300D+01 7.497176100D+01  
RptEl = 0.000000000D+00 2.018179300D+01 7.497176100D+01  
IndRef = 1.000000000D+00

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Extinc= 0.000000000D+00
nObs= 0
ApType= Rectangular
ApVec= -1.250000000D+00 1.250000000D+00 -3.250000000D+00 3.250000000D+00
zElt= 1.000000000D+22
PropType= Geometric
nECoord= -6

iElt= 7
EltName= NBPfilter_front
Element= Refractor
Surface= Flat
KrElt= -1.000000000D+22
KcElt= 0.000000000D+00
psiElt= 0.000000000D+00 -1.564298529D-01 -9.876890711D-01
VptElt= 0.000000000D+00 2.065109600D+01 7.793482000D+01
RptElt= 0.000000000D+00 2.065109600D+01 7.793482000D+01
IndRef= 1.454853000D+00
Extinc= 0.000000000D+00
nObs= 0
ApType= Circular
ApVec= 2.000000000D+00 0.000000000D+00 0.000000000D+00
zElt= 1.000000000D+22
PropType= Geometric
nECoord= -6

iElt= 8
EltName= NBPfilter_back
Element= Refractor
Surface= Flat
KrElt= -1.000000000D+22
KcElt= 0.000000000D+00
psiElt= 0.000000000D+00 -1.564298529D-01 -9.876890711D-01
VptElt= 0.000000000D+00 2.068238300D+01 7.813235800D+01
RptElt= 0.000000000D+00 2.068238300D+01 7.813235800D+01
IndRef= 1.000000000D+00
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ApType= Circular
ApVec= 2.000000000D+00 0.000000000D+00 0.000000000D+00
zElt= 1.000000000D+22
PropType= Geometric
nECoord= -6

iElt= 9
EltName= Focal_plane
Element= FocalPlane
Surface= Flat
KrElt= -1.000000000D+22
KcElt= 0.000000000D+00
psiElt= 0.000000000D+00 -1.564298529D-01 -9.876890711D-01
VptElt= 0.000000000D+00 2.101021800D+01 8.020223000D+01
RptElt= 0.000000000D+00 2.101021800D+01 8.020223000D+01
IndRef= 1.000000000D+00
Extinc= 0.000000000D+00
nObs= 0
ApType= Rectangular
zElt= 1.000000000D+22
PropType= Geometric
nECoord= -6

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The computer simulation tool, TREETOPS, has been upgraded and used at NASA/MSFC to model various complicated mechanical systems and to perform their dynamics and control analysis with pointing control systems. A TREETOPS model of Advanced X-ray Astrophysics Facility - Imaging (AXAF-I) dynamics and control system was developed to evaluate the AXAF-I pointing performance for Normal Pointing Mode. An optical model of Shooting Star Experiment (SSE) was also developed and its optical performance analysis was done using the MACOS software.