Development and Integration of Control System Models
Final Report

Submitted To:
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Contract Number:
NAS8-97095/H-28168D

Submitted by:
Young K. Kim
The University Of Alabama In Huntsville
Huntsville, Alabama

31 March 1998
# TABLE OF CONTENTS

1. Summary .................................................................................................................. 1

2. AXAF-I TREETOPS Dynamics and Control Modeling ................................................. 2
   2.1 Introduction ........................................................................................................ 2
   2.2 Description of AXAF-I TREETOPS Simulation .................................................... 2
      2.2.1 AXAF-I Structural Model ........................................................................... 5
      2.2.1.1 AXAF-I Body Models ....................................................................... 5
      2.2.1.2 AXAF-I Hinge Models .................................................................... 8
   2.2.2 STABLE Sensor and Actuator Models ............................................................ 10
   2.2.3 AXAF-I Control Law Model .......................................................................... 11
   2.3 AXAF-I TREETOPS Simulation Results ............................................................... 15
   2.4 Conclusion ........................................................................................................ 21
   2.5 References ....................................................................................................... 21

3. Optical Modeling and Analysis of SSE Optical System ............................................. 22
   3.1 Introduction ....................................................................................................... 22
   3.2 SSE MACOS Optical Modeling and Analysis ..................................................... 22
   3.3 SSE Optics MACOS Simulation Results ............................................................. 25
   3.4 Conclusion ....................................................................................................... 32
   3.5 References ....................................................................................................... 32

Appendix A  AXAF-I User Defined Controller Subroutine ............................................. 33
Appendix B  AXAF-I TREETOPS Input File AXAFI.INT ......................................... 37
Appendix C  AXAF-I TREETOPS Input File AXAFI.FLN ......................................... 55
Appendix D  AXAF-I TREETOPS Input File AXAFI.RET ......................................... 60
Appendix E  NASTRAN Model of AXAF-I Solar Array ............................................. 61
Appendix F  NASTRAN Normal Modal Analysis Output of AXAF-I Solar Array ....... 68
Appendix G  SSE MACOS Input File .......................................................................... 70

# LIST OF FIGURES

Figure 2.2-1:  Configuration of AXAF-I TREETOPS Model .......................................... 3
Figure 2.2.1.1-1: AXAF-I RW Positive Spin Vectors Relative to Body #1 Coordinates ...... 7
Figure 2.2.3-1:  AXAF-I TREETOPS Dynamics and NPM Control Model Layout ......... 12
Figure 2.2.3-2:  Block Diagram of AXAF-I NPM PID Control Law ............................... 13
Figure 2.3.1-1:  Attitude and Angular Velocity Errors of AXAF-I Spacecraft under NPM Control with Initial Errors ......................................................... 17
LIST OF TABLES

Table 2.2.1.1-1: Mass properties and locations of C.M. of AXAF-I Body #1, #2, #3 ... 6
Table 2.2.1.1-2: Nodes Definition of TREETOPS AXAF-I Body #1 ....................... 6
Table 2.2.1.1-3: Nodes Definition of TREETOPS AXAF-I Body #2 and #3 ............... 7
Table 2.2.1.1-4: Mass properties of reaction wheels and isolators ....................... 8
Table 2.2.1.1-5: Nodes Definition of TREETOPS AXAF-I Reaction Wheel Isolators and Non-Rotating and Rotating bodies of Reaction Wheels ....................... 8
Table 2.2.1.2-1: Hinges Definition of AXAF-I TREETOPS Model ....................... 9
Table 2.2.2-1: Definition of TREETOPS AXAF-I Sensors Model ......................... 11
Table 2.2.2-2: Definition of TREETOPS AXAF-I Actuators Model ....................... 11
Table 2.2.3-1: Requirements of the AXAF-I NPM control law ............................. 12
Table 2.2.3-2: AXAF-I NPM PID Control Law Parameters ................................. 15
Table 3.2-1: Optical Prescriptions of SSE MACOS Optical Elements .................... 25
Table 3.3-1: SSE Rigid Body Rotation vs. Movement of Sun Image at Detector ... 26
Table 3.3-2: Movement of Ring Lens vs. Movement of Sun Image at Detector ......... 28
Table 3.3-3: Rotation of Ring Lens vs. Movement of Image at Detector ................. 30
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 axis 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·sec²/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>$I_{xx}$, $I_{yy}$, $I_{zz}$, $I_{xy}$, $I_{xz}$, $I_{yz}$ (Slug - $ft^2$)</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 coordinate</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 $\cdot$ ft$^2$)</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</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>(0,0,-5E-6)</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>
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 - B11N1</td>
<td>3 RDOF, 3 TDOF</td>
<td>(0.5,0.75,0.4330127) - (0,0,1)</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>(0.5,0,0.8660254) - (0,0,1)</td>
<td>(0.8660254,0,-0.5) - (0,1,0)</td>
</tr>
<tr>
<td>22</td>
<td>B21N2 - B22N2</td>
<td>0 DOF</td>
<td>(0,0,1) - (0,0,1)</td>
<td>(0,1,0) - (0,1,0)</td>
</tr>
<tr>
<td>23</td>
<td>B22N1 - B23N1</td>
<td>1 RDOF</td>
<td>(0,0,1) - (0,0,1)</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>(0.5,-0.75,0.4330127) - (0,0,1)</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>(0.5,-0.75,-0.4330127) - (0,0,1)</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>43</td>
<td>B42N1 - B43N1</td>
<td>1 RDOF</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,-0.8660254) - (0,0,1)</td>
<td>(0.86602540,0.5) - (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) - (0,0,1)</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 2.2.3-1: Requirements of the AXAF-I NPM control law

<table>
<thead>
<tr>
<th>Description</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude Control Error (arcsec, 1σ, 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.

Figure 2.2.3-1: AXAF-I TREETOPS Dynamics and NPM Control Model Layout
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].

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

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

where \( T_{sc} = [T_x, T_y, T_z] \) is the torque about X, Y, Z axis on the C.M. of the spacecraft in the inertial coordinates and \( T_w = [T_1, T_2, \ldots, T_6] \) 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.

$$ T_w = D T $$

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.
### Table 2.2.3-2: AXAF-I NPM PID Control Law Parameters

<table>
<thead>
<tr>
<th>Control Parameters</th>
<th>Roll (X)</th>
<th>Pitch (Y)</th>
<th>Yaw (Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain, $K_p$ (ft·lb/rad)</td>
<td>6.506</td>
<td>68.382</td>
<td>72.908</td>
</tr>
<tr>
<td>Rate gain, $K_r$ (ft·lb/rad/sec)</td>
<td>325.3</td>
<td>3419.1</td>
<td>3645.4</td>
</tr>
<tr>
<td>Integral gain, $K_i$ (ft·lb/rad/sec)</td>
<td>6.506E-3</td>
<td>3.4191E-2</td>
<td>3.6454E-2</td>
</tr>
<tr>
<td>Bending filter, $\frac{a_0 + a_1 Z^{-1} + a_2 Z^{-2}}{1 + a_3 Z^{-1} + a_4 Z^{-2}}$</td>
<td>$a_0 = 7.94213E-5$</td>
<td>$a_0 = 9.79132E-4$</td>
<td>$a_0 = 9.79132E-4$</td>
</tr>
<tr>
<td></td>
<td>$a_1 = 1.588426E-4$</td>
<td>$a_1 = 1.958264E-3$</td>
<td>$a_1 = 1.958264E-3$</td>
</tr>
<tr>
<td></td>
<td>$a_2 = 7.94213E-5$</td>
<td>$a_2 = 9.79132E-4$</td>
<td>$a_2 = 9.79132E-4$</td>
</tr>
<tr>
<td></td>
<td>$a_3 = -1.978409$</td>
<td>$a_3 = -1.910409$</td>
<td>$a_3 = -1.910409$</td>
</tr>
<tr>
<td></td>
<td>$a_4 = 0.978726$</td>
<td>$a_4 = 0.914326$</td>
<td>$a_4 = 0.914326$</td>
</tr>
<tr>
<td>Position limit, $L_p$ (rad)</td>
<td>0.05695</td>
<td>6.98E-4</td>
<td>6.98E-4</td>
</tr>
<tr>
<td>Integral limit, $L_i$ (rad/sec)</td>
<td>0.06</td>
<td>0.011</td>
<td>0.01</td>
</tr>
<tr>
<td>Rate limit, $L_r$ (rad/sec)</td>
<td>1E6</td>
<td>1E6</td>
<td>1E6</td>
</tr>
<tr>
<td>Body torque command limit, $T_L$ (ft·lb)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

#### 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, 3-sigma) and yaw (Z-axis) attitude errors and initial 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.
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, $l$, 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>
<thead>
<tr>
<th>Optical Element No.</th>
<th>Element Type</th>
<th>Surface Type</th>
<th>Radius of Curvature / Aspheric 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,-0.1564,-0.9877)</td>
</tr>
<tr>
<td>4</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.512549</td>
<td>(0,-0.1564,-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,-0.1564,-0.9877)</td>
</tr>
<tr>
<td>6</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.</td>
<td>(0,-0.1564,-0.9877)</td>
</tr>
<tr>
<td>7</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.</td>
<td>(0,-0.1564,-0.9877)</td>
</tr>
<tr>
<td>8</td>
<td>Refractor</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.</td>
<td>(0,-0.1564,-0.9877)</td>
</tr>
<tr>
<td>9</td>
<td>FocalPlane</td>
<td>Flat</td>
<td>-1e22 / 0</td>
<td>1.</td>
<td>(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 CCS (Charge Coupled Device) 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

<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>
<td>20.9669</td>
</tr>
<tr>
<td>1.0</td>
<td>8.39</td>
<td>8.3892</td>
<td>21.0380</td>
<td>21.0335</td>
</tr>
<tr>
<td>1.2</td>
<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>
<td>1.6</td>
<td>8.99</td>
<td>8.9892</td>
<td>21.2362</td>
<td>21.2317</td>
</tr>
<tr>
<td>2.4</td>
<td>9.79</td>
<td>9.7892</td>
<td>21.4862</td>
<td>21.4817</td>
</tr>
<tr>
<td>2.8</td>
<td>10.19</td>
<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 3.3-3: Rotation of Ring Lens vs. Movement of Image at Detector**

(length unit = inch)

<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>
<td>20.6550</td>
</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>
<td>7.39</td>
<td>7.3724</td>
<td>20.6676</td>
<td>20.6652</td>
</tr>
<tr>
<td>-3.0</td>
<td>7.39</td>
<td>7.3762</td>
<td>20.6721</td>
<td>20.6694</td>
</tr>
<tr>
<td>-2.5</td>
<td>7.39</td>
<td>7.3787</td>
<td>20.6771</td>
<td>20.6742</td>
</tr>
<tr>
<td>-2.0</td>
<td>7.39</td>
<td>7.3811</td>
<td>20.6825</td>
<td>20.6795</td>
</tr>
<tr>
<td>-1.5</td>
<td>7.39</td>
<td>7.3833</td>
<td>20.6884</td>
<td>20.6850</td>
</tr>
<tr>
<td>-1.0</td>
<td>7.39</td>
<td>7.3849</td>
<td>20.6948</td>
<td>20.6911</td>
</tr>
<tr>
<td>-0.5</td>
<td>7.39</td>
<td>7.3856</td>
<td>20.7016</td>
<td>20.6977</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>0.5</td>
<td>7.39</td>
<td>7.3856</td>
<td>20.7167</td>
<td>20.7127</td>
</tr>
<tr>
<td>1.0</td>
<td>7.39</td>
<td>7.3849</td>
<td>20.7249</td>
<td>20.7211</td>
</tr>
<tr>
<td>1.5</td>
<td>7.39</td>
<td>7.3833</td>
<td>20.7335</td>
<td>20.7301</td>
</tr>
<tr>
<td>2.0</td>
<td>7.39</td>
<td>7.3811</td>
<td>20.7426</td>
<td>20.7396</td>
</tr>
<tr>
<td>2.5</td>
<td>7.39</td>
<td>7.3787</td>
<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>
<td>4.5</td>
<td>7.39</td>
<td>7.3633</td>
<td>20.7943</td>
<td>20.7951</td>
</tr>
<tr>
<td>5.0</td>
<td>7.39</td>
<td>7.3586</td>
<td>20.8058</td>
<td>20.8084</td>
</tr>
<tr>
<td>5.5</td>
<td>7.39</td>
<td>7.3533</td>
<td>20.8176</td>
<td>20.8217</td>
</tr>
<tr>
<td>6.0</td>
<td>7.39</td>
<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.

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
C CONTROL LAW SUBRoutines FOR AXAF.INT: JANUARY 1998
C Written by William Lightsey/ED12/NASA
C Modified by Young Kim/UAH
C
SUBROUTINE CONTAINING NORMAL POINT AND MANEUVER CONTROL LAW
C PROPORTIONAL GAIN
C
KP(1)=cntdta(1)=6.506D0
KP(2)=cntdta(2)=68.382D0
KP(3)=cntdta(3)=72.908D0
C INTEGRAL GAIN
C
KI(1)=cntdta(4)=6.506D-3
KI(2)=cntdta(5)=3.4191D-2
KI(3)=cntdta(6)=6.4654D-2
C RATE GAIN
C
KR(1)=cntdta(7)=325.30D0
KR(2)=cntdta(8)=3419.1D0
KR(3)=cntdta(9)=3645.4D0
C POSITION LIMITER, LP (rad)
C
THELIM(1)=cntdta(10)=0.05695D0
THELIM(2)=cntdta(11)=6.98D-4
THELIM(3)=cntdta(12)=6.98D-4
C INTEGRAL LIMITER, LI (rad-sec)
C
CILIM(1)=cntdta(13)=0.06D0
CILIM(2)=cntdta(14)=0.011D0
CILIM(3)=cntdta(15)=0.01D0
C RATE LIMITER, LR (rad/sec)
C
OMELIM(1)=0.0019D0
OMELIM(2)=0.0019D0
OMELIM(3)=0.0019D0
c according to DM05 dated on 2/28/97
C
OMELIM(1)=cntdta(16)=1.0D6
OMELIM(2)=cntdta(17)=1.0D6
OMELIM(3)=cntdta(18)=1.0D6
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),TFF(3),OMDC(3),TQG(3),TPC(3),TC(3),
&CILIM(3),OMELIM(3),THELIM(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
C INITIALIZE PARAMETERS
C
   DO 2 I=1,3
     CIP(I)=0.D0
   2 C
C DEFINE PID CONTROL PARAMETERS
C
C SAMPLING TIME
C
   DTFC=0.064D0
C
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
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
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

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

ENDIF  !end of initialization

C READ INTEGRATING AND RATE GYRO SENSORS OUTPUT

C DO 1 I=1,3
  THE(I)=U(I)
  OME(I)=U(I+3)
1

C BEGIN CONTROL LAW CALCULATIONS

C LIMIT POSITION ERROR SIGNAL

C DO 100 I=1,3
  THE(I)=DMAX1(-THELIM(I),DMIN1(THELIM(I),THE(I)))
100

C INTEGRAL AND PROPORTIONAL PATH SIGNALS

C DO 101 I=1,3
  OMP(I)=KP(I)*THE(I)
  CI(I)=DTFC*THE(I)+CIP(I)
101

C LIMIT THE INTEGRAL PATH SIGNAL

C DO 57 I=1,3
  CI(I)=DMAX1(-CILIM(I),DMIN1(CILIM(I),CI(I)))
  DO 102 I=1,3
    OMI(I)=KI(I)*CI(I)
 102  CIP(I)=CI(I)
57

C LIMIT THE RATE COMMAND SIGNALS

C DO 56 I=1,3
  OME(I)=DMAX1(-OMELIM(I),DMIN1(OMELIM(I),OME(I)))
  DO 103 I=1,3
    OMR(I)=KR(I)*OME(I)
103

C COMPUTE FEED FORWARD TORQUE FROM GG TORQUE AND MANEUVER TORQUE
C ** need to include the wXh term if you have a commanded rate
  TFF3(I)=OMDMC(I)*IV(I,I)-TGG(I)-TQUNLD(I)

C TOTAL COMMANDED TORQUE SIGNAL PRIOR TO ADDING FEED FORWARD TORQUE

C 103 TPC(I)=OMR(I)+OMI(I)+OMP(I)

C NEW CONTROL LAW MOD MOVING INTEGRAL PATH
  103 TPF(I)=OMR(I)+OMP(I)

C COMMAND TORQUE BENDING FILTER
  CALL PCBPF(T,KBF,TPC,TCF)
C PROPORTIONALLY LIMIT TOTAL TORQUE COMMAND
C
DO 104 I=1,3
104 TCF(I)=DMAX1(-TPCLIM,DMIN1(TPCLIM,TCF(I)))
C
C ADD THE FEED FORwort Torkue
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 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 CONTINUE
RETURN
END
C
C SUBROUTINE PCBF(T,KBF,TIN,TOUT)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C 2ND ORDER BENDING FILTER FOR PC COMMAND TORQUE
DOUBLE PRECISION KBF(5,3),TIN(3),TOUT(3),S1(3),S2(3)
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
TOUT(I)=KBF(1,I)*TIN(I)+S1(I)
S1(I)=KBF(2,I)*TIN(I)-KBF(4,I)*TOUT(I)+S2(I)
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(1/98)
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 Small angle speedup option (All,Bypass,First,Nth) A
12 SI 0 Mass matrix speedup option (All,Bypass,First,Nth) A
13 SI 0 Non-Linear speedup option (All,Bypass,First,Nth) A
14 SI 0 Constraint stabilization option (Y/N) N
15 SI 0 Stabilization epsilon N

BODY

17 BO 1 Body ID number 1
18 BO 1 Type (Rigid, Flexible, NASTRAN) R
19 BO 1 Number of modes N
20 BO 1 Modal calculation option (0, 1 or 2) 2
21 BO 1 Foreshortening option (Y/N) Y
22 BO 1 Model reduction method (NO, MS, MC, CC, QM, CV) MS
23 BO 1 NASTRAN data file FORTRAN unit number (40 - 60) 41
24 BO 1 Number of augmented nodes (0 if none) 0
25 BO 1 Damping matrix option (NS, CD, HL, SD) NS
26 BO 1 Constant damping ratio 0.0
27 BO 1 Low frequency, High frequency ratios 0.0
28 BO 1 Mode ID number, damping ratio 0.0
29 BO 1 Conversion factors: Length, Mass, Force
30 BO 1 Inertia reference node (0=Bdy Ref Frm; 1=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, 31.22, 2.63, 1.98
46 BO 1 Node ID, Node coord. (meters) x,y,z 12, 31.28, 3.28, 1.98
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) 0
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
Node ID, Node structural joint ID 2, 72
Node ID, Node structural joint ID 3, 50
Node ID, Node structural joint ID 4, 54
Node ID, Node structural joint ID 5, 30
Node ID, Node structural joint ID 6, 34
Node ID, Node structural joint ID 7, 10
Node ID, Node structural joint ID 8, 14
Node ID, Node structural joint ID 9, 1
Node ID, Node structural joint ID 10, 10.4

Body ID number
Type (Rigid, Flexible, NASTRAN) N
Number of modes
Modal calculation option (0, 1 or 2) 0
Foreshortening option (Y/N) Y
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
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
Node ID, Node structural joint ID 2, 72
Node ID, Node structural joint ID 3, 50
Node ID, Node structural joint ID 4, 54
Node ID, Node structural joint ID 5, 30
Node ID, Node structural joint ID 6, 34
Node ID, Node structural joint ID 7, 10
Node ID, Node structural joint ID 8, 14
Node ID, Node structural joint ID 9, 1
Node ID, Node structural joint ID 10, 10.4

Body ID number
Type (Rigid, Flexible, NASTRAN) R
Number of modes
Modal calculation option (0, 1 or 2) 0
Foreshortening option (Y/N) Y
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
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) 1
Moments of inertia (kg-m²) Ixx, Iyy, Izz
Products of inertia (kg-m²) Ixy, Ixz, Iyz
Mass (kg)
Number of Nodes
Node ID, Node coord. (meters) x, y, z
Node ID, Node structural joint ID 1, 0, 0, 0
Node ID, Node structural joint ID 2, 0, 0, 0
Node ID, Node coord. (meters) x, y, z
Node ID, Node structural joint ID 1, 0, 0, 0
Node ID, Node structural joint ID 2, 0, 0, 0

Body ID number
Type (Rigid, Flexible, NASTRAN) R
Number of modes
| BO  | 12 | Modal calculation option (0, 1 or 2)                  |
| BO  | 12 | Foreshortening option (Y/N)                          |
| BO  | 12 | Model reduction method (NO, MS, MC, CC, QM, CV)      |
| BO  | 12 | NASTRAN data file FORTRAN unit number (40 - 60)      |
| BO  | 12 | Number of augmented nodes (0 if none)                |
| BO  | 12 | Damping matrix option (NS, CD, HL, SD)               |
| BO  | 12 | Constant damping ratio                               |
| BO  | 12 | Low frequency, High frequency ratios                 |
| BO  | 12 | Mode ID number, damping ratio                        |
| BO  | 12 | Conversion factors: Length, Mass, Force              |
| BO  | 12 | Inertia reference node (0=Bdy Ref Frm; 1=mass cen)   |
| BO  | 12 | Moments of inertia (kg-m²) Ixx, Iyy, Izz             |
| BO  | 12 | Products of inertia (kg-m²) Ixy, Ixz, Iyz           |
| BO  | 12 | Mass (kg)                                            |
| BO  | 12 | Number of Nodes                                      |
| BO  | 12 | Node ID, Node coord. (meters) x, y, z                |
| BO  | 12 | Node ID, Node structural joint ID                    |

| BO  | 13 | Body ID number                                      |
| BO  | 13 | Type (Rigid, Flexible, NASTRAN)                     |
| BO  | 13 | Number of modes                                     |
| BO  | 13 | Modal calculation option (0, 1 or 2)                |
| BO  | 13 | Foreshortening option (Y/N)                         |
| BO  | 13 | Model reduction method (NO, MS, MC, CC, QM, CV)      |
| BO  | 13 | NASTRAN data file FORTRAN unit number (40 - 60)      |
| BO  | 13 | Number of augmented nodes (0 if none)               |
| BO  | 13 | Damping matrix option (NS, CD, HL, SD)               |
| BO  | 13 | Constant damping ratio                               |
| BO  | 13 | Low frequency, High frequency ratios                 |
| BO  | 13 | Mode ID number, damping ratio                        |
| BO  | 13 | Conversion factors: Length, Mass, Force              |
| BO  | 13 | Inertia reference node (0=Bdy Ref Frm; 1=mass cen)   |
| BO  | 13 | Moments of inertia (kg-m²) Ixx, Iyy, Izz             |
| BO  | 13 | Products of inertia (kg-m²) Ixy, Ixz, Iyz           |
| BO  | 13 | Mass (kg)                                            |
| BO  | 13 | Number of Nodes                                      |
| BO  | 13 | Node ID, Node coord. (meters) x, y, z                |
| BO  | 13 | Node ID, Node structural joint ID                    |

| BO  | 21 | Body ID number                                      |
| BO  | 21 | Type (Rigid, Flexible, NASTRAN)                     |
| BO  | 21 | Number of modes                                     |
| BO  | 21 | Modal calculation option (0, 1 or 2)                |
| BO  | 21 | Foreshortening option (Y/N)                         |
| BO  | 21 | Model reduction method (NO, MS, MC, CC, QM, CV)      |
| BO  | 21 | NASTRAN data file FORTRAN unit number (40 - 60)      |
| BO  | 21 | Number of augmented nodes (0 if none)               |
| BO  | 21 | Damping matrix option (NS, CD, HL, SD)               |
| BO  | 21 | Constant damping ratio                               |
| BO  | 21 | Low frequency, High frequency ratios                 |
| BO  | 21 | Mode ID number, damping ratio                        |
| BO  | 21 | Conversion factors: Length, Mass, Force              |
| BO  | 21 | Inertia reference node (0=Bdy Ref Frm; 1=mass cen)   |
| BO  | 21 | Moments of inertia (kg-m²) Ixx, Iyy, Izz             |
| BO  | 21 | Products of inertia (kg-m²) Ixy, Ixz, Iyz           |
| BO  | 21 | Mass (kg)                                            |
| BO  | 21 | Number of Nodes                                      |
| BO  | 21 | Node ID, Node coord. (meters) x, y, z                |
| BO  | 21 | Node ID, Node structural joint ID                    |

<p>| BO  | 22 | Body ID number                                      |
| BO  | 22 | Type (Rigid, Flexible, NASTRAN)                     |
| BO  | 22 | Number of modes                                     |
| BO  | 22 | Modal calculation option (0, 1 or 2)                |
| BO  | 22 | Foreshortening option (Y/N)                         |
| BO  | 22 | Model reduction method (NO, MS, MC, CC, QM, CV)      |
| BO  | 22 | NASTRAN data file FORTRAN unit number (40 - 60)      |
| BO  | 22 | Number of augmented nodes (0 if none)               |
| BO  | 22 | Damping matrix option (NS, CD, HL, SD)               |
| BO  | 22 | Constant damping ratio                               |
| BO  | 22 | Low frequency, High frequency ratios                 |
| BO  | 22 | Mode ID number, damping ratio                        |</p>
<table>
<thead>
<tr>
<th>Body ID number</th>
<th>Type (Rigid, Flexible, NASTRAN)</th>
<th>Number of Modes</th>
<th>Modal Calculation Option (0, 1 or 2)</th>
<th>Foreshortening Option (Y/N)</th>
<th>Model Reduction Method (NO, MS, MC, CC, QM, CV)</th>
<th>NASTRAN Data File FORTRAN Unit Number (40 - 60)</th>
<th>Number of Augmented Nodes (0 if none)</th>
<th>Damping Matrix Option (NS, CD, HL, SD)</th>
<th>Constant Damping Ratio</th>
<th>Low Frequency, High Frequency Ratios</th>
<th>Mode ID Number, Damping Ratio</th>
<th>Conversion Factors: Length, Mass, Force</th>
<th>Inertia Reference Node (0 = Bdy Ref Frm; 1 = Mass cen)</th>
<th>Moments of Inertia (kg-m²) Ixx, Iyy, Izz</th>
<th>Products of Inertia (kg-m²) Ixy, Ixz, Iyz</th>
<th>Mass (kg)</th>
<th>Number of Nodes</th>
<th>Number of Nodes, Node Coord. (meters) x, y, z</th>
<th>Node ID, Node Structural Joint ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>R</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Constant Damping Ratio</td>
<td>Low Frequency, High Frequency Ratios</td>
<td>Mode ID Number, Damping Ratio</td>
<td>Conversion Factors: Length, Mass, Force</td>
<td>Inertia Reference Node (0 = Bdy Ref Frm; 1 = Mass cen)</td>
<td>Moments of Inertia (kg-m²) Ixx, Iyy, Izz</td>
<td>Products of Inertia (kg-m²) Ixy, Ixz, Iyz</td>
<td>Mass (kg)</td>
<td>Number of Nodes</td>
<td>Number of Nodes, Node Coord. (meters) x, y, z</td>
<td>Node ID, Node Structural Joint ID</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03961, 0.03961, 0.07921</td>
<td>0.60, -1E-6</td>
<td>0.3659</td>
<td>2</td>
<td>1, 0, -5E-6, 0</td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.54E-2, 1.54E-2, 2.36E-2</td>
<td>0, 0, 0</td>
<td>0.23</td>
<td>2</td>
<td>2, 0, 0, 0</td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.475E-2, 1.475E-2, 2.2125E-2</td>
<td>0, 0, 0</td>
<td>0.1823</td>
<td>2</td>
<td>2, 0, 0, 0</td>
</tr>
<tr>
<td>32</td>
<td></td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.475E-2, 1.475E-2, 2.2125E-2</td>
<td>0, 0, 0</td>
<td>0.1823</td>
<td>2</td>
<td>2, 0, 0, 0</td>
</tr>
<tr>
<td>32</td>
<td></td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.475E-2, 1.475E-2, 2.2125E-2</td>
<td>0, 0, 0</td>
<td>0.1823</td>
<td>2</td>
<td>2, 0, 0, 0</td>
</tr>
</tbody>
</table>
Body ID number
Type (Rigid, Flexible, NASTRAN)
Number of modes
Modal calculation option (0, 1 or 2)
Foreshortening option (Y/N)
Model reduction method (NO, MS, MC, CC, QH, CV)
NASTRAN data file FORTRAN unit number (40 - 60)
Number of augmented nodes (0 if none)
Damping matrix option (NS, CD, HL, SD)
Constant damping ratio
Low frequency, High frequency ratios
Mode ID number, damping ratio
Conversion factors: Length, Mass, Force
Inertia reference node (0 = Bdy Ref Frm; 1 = mass cen)
Moments of inertia (kg-m2) Ixx, Iyy, Izz
Products of inertia (kg-m2) Ixy, Ixz, Iyz
Mass (kg)
Number of Nodes
Node ID, Node coord. (meters) x, y, z
Node ID, Node structural joint ID

Body ID number
Type (Rigid, Flexible, NASTRAN)
Number of modes
Modal calculation option (0, 1 or 2)
Foreshortening option (Y/N)
Model reduction method (NO, MS, MC, CC, QH, CV)
NASTRAN data file FORTRAN unit number (40 - 60)
Number of augmented nodes (0 if none)
Damping matrix option (NS, CD, HL, SD)
Constant damping ratio
Low frequency, High frequency ratios
Mode ID number, damping ratio
Conversion factors: Length, Mass, Force
Inertia reference node (0 = Bdy Ref Frm; 1 = mass cen)
Moments of inertia (kg-m2) Ixx, Iyy, Izz
Products of inertia (kg-m2) Ixy, Ixz, Iyz
Mass (kg)
Number of Nodes
Node ID, Node coord. (meters) x, y, z
Node ID, Node structural joint ID

Body ID number
Type (Rigid, Flexible, NASTRAN)
Number of modes
Modal calculation option (0, 1 or 2)
Foreshortening option (Y/N)
Model reduction method (NO, MS, MC, CC, QM, CV)
NASTRAN data file FORTRAN unit number (40 - 60)
Number of augmented nodes (0 if none)
Damping matrix option (NS, CD, HL, SD)
Constant damping ratio
Low frequency, High frequency ratios
Mode ID number, damping ratio
Conversion factors: Length, Mass, Force
Inertia reference node (0 = Bdy Ref Frm; 1 = mass cen)
Moments of inertia (kg-m2) Ixx, Iyy, Izz
Products of inertia (kg-m2) Ixy, Ixz, Iyz
Mass (kg)
Number of Nodes
Node ID, Node coord. (meters) x, y, z
Node ID, Node structural joint ID
| Body ID number | 51 | Type (Rigid, Flexible, NASTRAN) | R |
| Number of modes | 51 |
| Modal calculation option | (0, 1 or 2) |
| Foreshortening option (Y/N) | |
| Model reduction method (NC, MS, MC, CC, QM, CV) | |
| NASTRAN data file FORTRAN unit number (40 - 60) | |
| Number of augmented nodes (0 if none) | |
| Damping matrix option (NS, CD, HL, SD) | |
| Constant damping ratio | |
| Low frequency, High frequency ratios | |
| Conversion factors: Length, Mass, Force | |
| Inertia reference node (0=Bdy Ref Frm; 1=mass cen) | |
| Moments of inertia (kg-m\(^2\)) | I\(_{xx}\), I\(_{yy}\), I\(_{zz}\) |
| Products of inertia (kg-m\(^2\)) | I\(_{xy}\), I\(_{xz}\), I\(_{yz}\) |
| Mass (kg) | |
| Number of Nodes | 2 |
| Node ID, Node coord. (meters) | x, y, z |
| Node ID, Node structural joint ID | |

| Body ID number | 52 | Type (Rigid, Flexible, NASTRAN) | R |
| Number of modes | 52 |
| Modal calculation option | (0, 1 or 2) |
| Foreshortening option (Y/N) | |
| Model reduction method (NC, MS, MC, CC, QM, CV) | |
| NASTRAN data file FORTRAN unit number (40 - 60) | |
| Number of augmented nodes (0 if none) | |
| Damping matrix option (NS, CD, HL, SD) | |
| Constant damping ratio | |
| Low frequency, High frequency ratios | |
| Conversion factors: Length, Mass, Force | |
| Inertia reference node (0=Bdy Ref Frm; 1=mass cen) | |
| Moments of inertia (kg-m\(^2\)) | I\(_{xx}\), I\(_{yy}\), I\(_{zz}\) |
| Products of inertia (kg-m\(^2\)) | I\(_{xy}\), I\(_{xz}\), I\(_{yz}\) |
| Mass (kg) | |
| Number of Nodes | 2 |
| Node ID, Node coord. (meters) | x, y, z |
| Node ID, Node structural joint ID | |

| Body ID number | 53 | Type (Rigid, Flexible, NASTRAN) | R |
| Number of modes | 53 |
| Modal calculation option | (0, 1 or 2) |
| Foreshortening option (Y/N) | |
| Model reduction method (NC, MS, MC, CC, QM, CV) | |
| NASTRAN data file FORTRAN unit number (40 - 60) | |
| Number of augmented nodes (0 if none) | |
| Damping matrix option (NS, CD, HL, SD) | |
| Constant damping ratio | |
| Low frequency, High frequency ratios | |
| Conversion factors: Length, Mass, Force | |
| Inertia reference node (0=Bdy Ref Frm; 1=mass cen) | |
| Moments of inertia (kg-m\(^2\)) | I\(_{xx}\), I\(_{yy}\), I\(_{zz}\) |
| Products of inertia (kg-m\(^2\)) | I\(_{xy}\), I\(_{xz}\), I\(_{yz}\) |
| Mass (kg) | |

42
<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
<th>Column 5</th>
<th>Column 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>415 BO</td>
<td>53</td>
<td>Number of Nodes</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>416 BO</td>
<td>53</td>
<td>Node ID, Node coord. (meters) x,y,z</td>
<td>1,0,-5E-6,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>417 BO</td>
<td>53</td>
<td>Node ID, Node coord. (meters) x,y,z</td>
<td>2,0,0,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>418 BO</td>
<td>53</td>
<td>Node ID, Node structural joint ID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>419 BO</td>
<td>61</td>
<td>Body ID number</td>
<td>61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>420 BO</td>
<td>61</td>
<td>Type (Rigid, Flexible, NASTRAN)</td>
<td>R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>421 BO</td>
<td>61</td>
<td>Number of modes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>422 BO</td>
<td>61</td>
<td>Modal calculation option (0, 1 or 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>423 BO</td>
<td>61</td>
<td>Foreshortening option (Y/N)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>424 BO</td>
<td>61</td>
<td>Model reduction method (NO, MS, MC, CC, QM, CV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>425 BO</td>
<td>61</td>
<td>NASTRAN data file FORTRAN unit number (40 - 60)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>426 BO</td>
<td>61</td>
<td>Number of augmented nodes (0 if none)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>427 BO</td>
<td>61</td>
<td>Damping matrix option (NS, CD, HL, SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>428 BO</td>
<td>61</td>
<td>Constant damping ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>429 BO</td>
<td>61</td>
<td>Low frequency, High frequency ratios</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>430 BO</td>
<td>61</td>
<td>Node ID number, damping ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>431 BO</td>
<td>61</td>
<td>Conversion factors: Length, Mass, Force</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>432 BO</td>
<td>61</td>
<td>Inertia reference node (0=Bdy Ref Frm; 1=mass cen)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>433 BO</td>
<td>61</td>
<td>Moments of inertia (kg-m^2) Ixx, Iyy, Izz</td>
<td>1.54E-2, 1.54E-2, 2.36E-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>434 BO</td>
<td>61</td>
<td>Products of inertia (kg-m^2) Ixy, Ixz, Iyz</td>
<td>0, 0, 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>435 BO</td>
<td>61</td>
<td>Mass (kg)</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>436 BO</td>
<td>61</td>
<td>Number of Nodes</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>437 BO</td>
<td>61</td>
<td>Node ID, Node coord. (meters) x,y,z</td>
<td>1,0,0,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>438 BO</td>
<td>61</td>
<td>Node ID, Node coord. (meters) x,y,z</td>
<td>2,0,0,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>439 BO</td>
<td>61</td>
<td>Node ID, Node structural joint ID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>440 BO</td>
<td>62</td>
<td>Body ID number</td>
<td>62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>441 BO</td>
<td>62</td>
<td>Type (Rigid, Flexible, NASTRAN)</td>
<td>R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>442 BO</td>
<td>62</td>
<td>Number of modes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>443 BO</td>
<td>62</td>
<td>Modal calculation option (0, 1 or 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>444 BO</td>
<td>62</td>
<td>Foreshortening option (Y/N)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>445 BO</td>
<td>62</td>
<td>Model reduction method (NO, MS, MC, CC, QM, CV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>446 BO</td>
<td>62</td>
<td>NASTRAN data file FORTRAN unit number (40 - 60)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>447 BO</td>
<td>62</td>
<td>Number of augmented nodes (0 if none)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>448 BO</td>
<td>62</td>
<td>Damping matrix option (NS, CD, HL, SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>449 BO</td>
<td>62</td>
<td>Constant damping ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450 BO</td>
<td>62</td>
<td>Low frequency, High frequency ratios</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>451 BO</td>
<td>62</td>
<td>Node ID number, damping ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>452 BO</td>
<td>62</td>
<td>Conversion factors: Length, Mass, Force</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>453 BO</td>
<td>62</td>
<td>Inertia reference node (0=Bdy Ref Frm; 1=mass cen)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>454 BO</td>
<td>62</td>
<td>Moments of inertia (kg-m^2) Ixx, Iyy, Izz</td>
<td>1.475E-2, 1.475E-2, 2.2125E-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>455 BO</td>
<td>62</td>
<td>Products of inertia (kg-m^2) Ixy, Ixz, Iyz</td>
<td>0, 0, 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>456 BO</td>
<td>62</td>
<td>Mass (kg)</td>
<td>0.1823</td>
<td></td>
<td></td>
</tr>
<tr>
<td>457 BO</td>
<td>62</td>
<td>Number of Nodes</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>458 BO</td>
<td>62</td>
<td>Node ID, Node coord. (meters) x,y,z</td>
<td>1,0,0,0.1936</td>
<td></td>
<td></td>
</tr>
<tr>
<td>459 BO</td>
<td>62</td>
<td>Node ID, Node coord. (meters) x,y,z</td>
<td>2,0,0,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>460 BO</td>
<td>62</td>
<td>Node ID, Node structural joint ID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>461 BO</td>
<td>63</td>
<td>Body ID number</td>
<td>63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>462 BO</td>
<td>63</td>
<td>Type (Rigid, Flexible, NASTRAN)</td>
<td>R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>463 BO</td>
<td>63</td>
<td>Number of modes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>464 BO</td>
<td>63</td>
<td>Modal calculation option (0, 1 or 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>465 BO</td>
<td>63</td>
<td>Foreshortening option (Y/N)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>466 BO</td>
<td>63</td>
<td>Model reduction method (NO, MS, MC, CC, QM, CV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>467 BO</td>
<td>63</td>
<td>NASTRAN data file FORTRAN unit number (40 - 60)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>468 BO</td>
<td>63</td>
<td>Number of augmented nodes (0 if none)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>469 BO</td>
<td>63</td>
<td>Damping matrix option (NS, CD, HL, SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>470 BO</td>
<td>63</td>
<td>Constant damping ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>471 BO</td>
<td>63</td>
<td>Low frequency, High frequency ratios</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>472 BO</td>
<td>63</td>
<td>Node ID number, damping ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>473 BO</td>
<td>63</td>
<td>Conversion factors: Length, Mass, Force</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>474 BO</td>
<td>63</td>
<td>Inertia reference node (0=Bdy Ref Frm; 1=mass cen)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>475 BO</td>
<td>63</td>
<td>Moments of inertia (kg-m^2) Ixx, Iyy, Izz</td>
<td>0.03961, 0.03961, 0.07921</td>
<td></td>
<td></td>
</tr>
<tr>
<td>476 BO</td>
<td>63</td>
<td>Products of inertia (kg-m^2) Ixy, Ixz, Iyz</td>
<td>0, 0, -1E-6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>477 BO</td>
<td>63</td>
<td>Mass (kg)</td>
<td>0.3659</td>
<td></td>
<td></td>
</tr>
<tr>
<td>478 BO</td>
<td>63</td>
<td>Number of Nodes</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>479 BO</td>
<td>63</td>
<td>Node ID, Node coord. (meters) x,y,z</td>
<td>1,0,-5E-6,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>480 BO</td>
<td>63</td>
<td>Node ID, Node coord. (meters) x,y,z</td>
<td>2,0,0,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>481 BO</td>
<td>63</td>
<td>Node ID, Node structural joint ID</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HINGE

482 HI 1 Hinge ID number 1
| 483  | 1 Inboard body ID, Outboard body ID | 0,1 |
| 484  | 1 "p" node ID, "q" node ID | 0,1 |
| 485  | 1 Number of rotation DOFs, Rotation option (F or G) | 3,6 |
| 486  | 1 L1 unit vector in inboard body coord. x, y, z | 1,0,0 |
| 487  | 1 L1 unit vector in outboard body coord. x, y, z | 1,0,0 |
| 488  | 1 L2 unit vector in inboard body coord. x, y, z | 0,0,1 |
| 489  | 1 L2 unit vector in outboard body coord. x, y, z | 0,0,1 |
| 490  | 1 L3 unit vector in inboard body coord. x, y, z | 0,0,1 |
| 491  | 1 L3 unit vector in outboard body coord. x, y, z | 0,0,1 |
| 492  | 1 Initial rotation angles (deg) | 0.2,77778E-2,2.7777E-2 |
| 493  | 1 Initial rotation rates (deg/sec) | 0.8E-4, 0.6E-4 |
| 494  | 1 Rotation stiffness (newton-meters/rad) | 0 |
| 495  | 1 Rotation damping (newton-meters/rad/sec) | 0,0,0 |
| 496  | 1 Null torque angles (deg) | 0,0,0 |
| 497  | 1 Number of translation DOFs | 0 |
| 498  | 1 First translation unit vector g1 | 1,0,0 |
| 499  | 1 Second translation unit vector g2 | 0,1,0 |
| 500  | 1 Third translation unit vector g3 | 0,0,1 |
| 501  | 1 Initial translation (meters) | 0,0,0 |
| 502  | 1 Initial translation velocity (meters/sec) | 0,0,0 |
| 503  | 1 Translation stiffness (newtons/meters) | 0,0,0 |
| 504  | 1 Translation damping (newtons/meter/sec) | 0,0,0 |
| 505  | 1 Null force translations | 0,0,0 |

| 506  | 2 Hinge ID number | 2 |
| 507  | 2 Inboard body ID, Outboard body ID | 1,2 |
| 508  | 2 "p" node ID, "q" node ID | 9,2 |
| 509  | 2 No of rotation DOFs, Hinge 1 rotation option (F/G) | 0 |
| 510  | 2 L1 unit vector in inboard body coord. x, y, z | 0,1,0 |
| 511  | 2 L1 unit vector in outboard body coord. x, y, z | 0,1,0 |
| 512  | 2 L2 unit vector in inboard body coord. x, y, z | 1,0,0 |
| 513  | 2 L2 unit vector in outboard body coord. x, y, z | 1,0,0 |
| 514  | 2 L3 unit vector in inboard body coord. x, y, z | 1,0,0 |
| 515  | 2 L3 unit vector in outboard body coord. x, y, z | 1,0,0 |
| 516  | 2 Initial rotation angles (deg) | 0,0,0 |
| 517  | 2 Initial rotation rates (deg/sec) | 0,0,0 |
| 518  | 2 Rotation stiffness (newton-meters/rad) | 0,0,0 |
| 519  | 2 Rotation damping (newton-meters/rad/sec) | 0,0,0 |
| 520  | 2 Null torque angles (deg) | 0,0,0 |
| 521  | 2 Number of translation DOFs | 0 |
| 522  | 2 First translation unit vector g1 | 1,0,0 |
| 523  | 2 Second translation unit vector g2 | 0,1,0 |
| 524  | 2 Third translation unit vector g3 | 0,0,1 |
| 525  | 2 Initial translation (meters) | 0,0,0 |
| 526  | 2 Initial translation velocity (meters/sec) | 0,0,0 |
| 527  | 2 Translation stiffness (newtons/meters) | 0,0,0 |
| 528  | 2 Translation damping (newtons/meter/sec) | 0,0,0 |
| 529  | 2 Null force translations | 0,0,0 |

| 530  | 3 Hinge ID number | 3 |
| 531  | 3 Inboard body ID, Outboard body ID | 1,3 |
| 532  | 3 "p" node ID, "q" node ID | 10,2 |
| 533  | 3 Number of rotation DOFs, Rotation option (F or G) | 0 |
| 534  | 3 L1 unit vector in inboard body coord. x, y, z | 0,-1,0 |
| 535  | 3 L1 unit vector in outboard body coord. x, y, z | 0,1,0 |
| 536  | 3 L2 unit vector in inboard body coord. x, y, z | 1,0,0 |
| 537  | 3 L2 unit vector in outboard body coord. x, y, z | 1,0,0 |
| 538  | 3 L3 unit vector in inboard body coord. x, y, z | 1,0,0 |
| 539  | 3 L3 unit vector in outboard body coord. x, y, z | 1,0,0 |
| 540  | 3 Initial rotation angles (deg) | 0,0,0 |
| 541  | 3 Initial rotation rates (deg/sec) | 0,0,0 |
| 542  | 3 Rotation stiffness (newton-meters/rad) | 0,0,0 |
| 543  | 3 Rotation damping (newton-meters/rad/sec) | 0,0,0 |
| 544  | 3 Null torque angles (deg) | 0,0,0 |
| 545  | 3 Number of translation DOFs | 0 |
| 546  | 3 First translation unit vector g1 | 1,0,0 |
| 547  | 3 Second translation unit vector g2 | 0,1,0 |
| 548  | 3 Third translation unit vector g3 | 0,0,1 |
| 549  | 3 Initial translation (meters) | 0,0,0 |
| 550  | 3 Initial translation velocity (meters/sec) | 0,0,0 |
| 551  | 3 Translation stiffness (newtons/meters) | 0,0,0 |
| 552  | 3 Translation damping (newtons/meter/sec) | 0,0,0 |
| 553  | 3 Null force translations | 0,0,0 |

<p>| 554  | 11 Hinge ID number | 11 |</p>
<table>
<thead>
<tr>
<th>Hinge ID number</th>
<th>Inboard body ID, Outboard body ID</th>
<th>&quot;p&quot; node ID, &quot;q&quot; node ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1,11</td>
<td>1,1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of rotation DOFs, Rotation option {F or G}</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 unit vector in inboard body coord. x,y,z</td>
<td>0.5, 0.75, 0.4330127</td>
</tr>
<tr>
<td>L1 unit vector in outboard body coord. x,y,z</td>
<td>0, 0.1</td>
</tr>
<tr>
<td>L2 unit vector in inboard body coord. x,y,z</td>
<td>0, 0.1</td>
</tr>
<tr>
<td>L2 unit vector in outboard body coord. x,y,z</td>
<td>0.8660254, -0.4330127, -0.25</td>
</tr>
<tr>
<td>L3 unit vector in inboard body coord. x,y,z</td>
<td>0, 0.1</td>
</tr>
<tr>
<td>L3 unit vector in outboard body coord. x,y,z</td>
<td>0.362 0.362 0.362</td>
</tr>
<tr>
<td>Initial rotation angles (deg)</td>
<td>0 0 0</td>
</tr>
<tr>
<td>Initial rotation rates (deg/sec)</td>
<td>0 0 0</td>
</tr>
<tr>
<td>Rotation stiffness (newton-meters/rad)</td>
<td>204.7 204.7 204.7</td>
</tr>
<tr>
<td>Rotation damping (newton-meters/rad/sec)</td>
<td>3.75 3.75 3.75</td>
</tr>
<tr>
<td>Null torque angles (deg)</td>
<td>0 0 0</td>
</tr>
<tr>
<td>Number of translation DOFs</td>
<td>3</td>
</tr>
<tr>
<td>First translation unit vector g1</td>
<td>1 0 0</td>
</tr>
<tr>
<td>Second translation unit vector g2</td>
<td>0 0 0</td>
</tr>
<tr>
<td>Third translation unit vector g3</td>
<td>0 0 0</td>
</tr>
<tr>
<td>Initial translation (meters)</td>
<td>2121.3 2121.3 2121.3</td>
</tr>
<tr>
<td>Initial translation velocity (meters/sec)</td>
<td>2121.3 2121.3 2121.3</td>
</tr>
<tr>
<td>Translation stiffness (newtons/meters)</td>
<td>2121.3 2121.3 2121.3</td>
</tr>
<tr>
<td>Translation damping (newtons/meter/sec)</td>
<td>3.75 3.75 3.75</td>
</tr>
<tr>
<td>Null force translations</td>
<td>0 0 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hinge ID number</th>
<th>Inboard body ID, Outboard body ID</th>
<th>&quot;p&quot; node ID, &quot;q&quot; node ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

| Number of rotation DOFs                           | 2 |
| First translation unit vector g1                  | 1 0 0 |
| Second translation unit vector g2                 | 0 0 0 |
| Third translation unit vector g3                   | 0 0 0 |
| Initial rotation angles (deg)                      | 0 0 0 |
| Initial rotation rates (deg/sec)                   | 0 0 0 |
| Rotation stiffness (newton-meters/rad)             | 3.75 3.75 3.75 |
| Rotation damping (newton-meters/rad/sec)           | 3.75 3.75 3.75 |
| Null torque angles (deg)                           | 0 0 0 |
| Number of translation DOFs                         | 2 |
| First translation unit vector g1                   | 1 0 0 |
| Second translation unit vector g2                  | 0 0 0 |
| Third translation unit vector g3                    | 0 0 0 |
| Initial translation (meters)                       | 2121.3 2121.3 2121.3 |
| Initial translation velocity (meters/sec)          | 2121.3 2121.3 2121.3 |
| Translation stiffness (newtons/meters)             | 2121.3 2121.3 2121.3 |
| Translation damping (newtons/meter/sec)            | 3.75 3.75 3.75 |
| Null force translations                            | 0 0 0 |

<table>
<thead>
<tr>
<th>Hinge ID number</th>
<th>Inboard body ID, Outboard body ID</th>
<th>&quot;p&quot; node ID, &quot;q&quot; node ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>

| Number of rotation DOFs                           | 1 |
| L1 unit vector in inboard body coord. x,y,z       | 0, 0.1 |
| L1 unit vector in outboard body coord. x,y,z      | 0, 0.1 |
| L2 unit vector in inboard body coord. x,y,z       | 0, 0.1 |
| L2 unit vector in outboard body coord. x,y,z      | 0, 0.1 |
| L3 unit vector in inboard body coord. x,y,z       | 0.1, 0 |
| L3 unit vector in outboard body coord. x,y,z      | 0.1, 0 |
| Initial rotation angles (deg)                      | 0 0 0 |
| Initial rotation rates (deg/sec)                   | 0 0 0 |
| Rotation stiffness (newton-meters/rad)             | 13500 |
| Rotation damping (newton-meters/rad/sec)           | 0 0 0 |
| Null torque angles (deg)                           | 0 0 0 |
| Number of translation DOFs                         | 0 0 0 |
| First translation unit vector g1                   | 1 0 0 |
| Second translation unit vector g2                  | 0 0 0 |
| Third translation unit vector g3                    | 0 0 0 |
| Initial translation (meters)                       | 0 0 0 |
| Initial translation velocity (meters/sec)          | 0 0 0 |
| Translation stiffness (newtons/meters)             | 0 0 0 |
| Translation damping (newtons/meter/sec)            | 0 0 0 |
| Null force translations                            | 0 0 0 |

<table>
<thead>
<tr>
<th>Hinge ID number</th>
<th>Inboard body ID, Outboard body ID</th>
<th>&quot;p&quot; node ID, &quot;q&quot; node ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Hinge ID number</td>
<td>Inboard body ID, Outboard body ID</td>
<td>&quot;p&quot; node ID, &quot;q&quot; node ID</td>
</tr>
<tr>
<td>-----------------</td>
<td>----------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>21</td>
<td>21</td>
<td>1, 21</td>
</tr>
<tr>
<td>22</td>
<td>22</td>
<td>22, 22</td>
</tr>
<tr>
<td>23</td>
<td>23</td>
<td>22, 23</td>
</tr>
<tr>
<td>24</td>
<td>24</td>
<td>24, 24</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>25, 25</td>
</tr>
<tr>
<td>26</td>
<td>26</td>
<td>26, 26</td>
</tr>
<tr>
<td>27</td>
<td>27</td>
<td>27, 27</td>
</tr>
<tr>
<td>28</td>
<td>28</td>
<td>28, 28</td>
</tr>
<tr>
<td>29</td>
<td>29</td>
<td>29, 29</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>30, 30</td>
</tr>
<tr>
<td>31</td>
<td>31</td>
<td>31, 31</td>
</tr>
</tbody>
</table>
699 HI 31 Inboard body ID, Outboard body ID 1,31
700 HI 31 "p" node ID, "q" node ID 5,1
701 HI 31 Number of rotation DOFs, Rotation option (F or G) 3
702 HI 31 L1 unit vector in inboard body coord. x,y,z 0.5,-0.75,0.4330127
703 HI 31 L1 unit vector in outboard body coord. x,y,z 0,0,1
704 HI 31 L2 unit vector in inboard body coord. x,y,z 0,0,1
705 HI 31 L2 unit vector in outboard body coord. x,y,z 0,0,1
706 HI 31 L3 unit vector in inboard body coord. x,y,z 0.8660254,0.4330127,-0.25
707 HI 31 L3 unit vector in outboard body coord. x,y,z 0,1,1
708 HI 31 Initial rotation angles (deg) 0 0 0
709 HI 31 Initial rotation rates (deg/sec) 0 0 0
710 HI 31 Rotation stiffness (newton-meters/rad) 204.7 204.7 204.7
711 HI 31 Rotation damping (newton-meters/rad) 0.362 0.362 0.362
712 HI 31 Null torque angles (deg) 0 0 0
713 HI 31 Number of translation DOFs 3
714 HI 31 First translation unit vector gl 1 0 0
715 HI 31 Second translation unit vector g2 0 1 0
716 HI 31 Third translation unit vector g3 0 0 1
717 HI 31 Initial translation (meters) 0 0 0
718 HI 31 Initial translation velocity (meters/sec) 2121.3 2121.3 2121.3
719 HI 31 Translation stiffness (newtons/meters) 3.75 3.75 3.75
720 HI 31 Translation damping (newtons/meter/sec) 0 0 0
721 HI 31 Null force translations 0 0 0
722 HI 32 Hinge ID number 32
723 HI 32 Inboard body ID, Outboard body ID 31,32
724 HI 32 "p" node ID, "q" node ID 2,2
725 HI 32 Number of rotation DOFs 0
726 HI 32 L1 unit vector in inboard body coord. x,y,z 0,0,1
727 HI 32 L1 unit vector in outboard body coord. x,y,z 0,0,1
728 HI 32 L2 unit vector in inboard body coord. x,y,z 0,0,1
729 HI 32 L2 unit vector in outboard body coord. x,y,z 0,0,1
730 HI 32 L3 unit vector in inboard body coord. x,y,z 0,1,0
731 HI 32 L3 unit vector in outboard body coord. x,y,z 0,1,0
732 HI 32 Initial rotation angles (deg) 0 0 0
733 HI 32 Initial rotation rates (deg/sec) 0 0 0
734 HI 32 Rotation stiffness (newton-meters/rad) 0 0 0
735 HI 32 Rotation damping (newton-meters/rad) 0 0 0
736 HI 32 Null torque angles (deg) 0
737 HI 32 Number of translation DOFs 0
738 HI 32 First translation unit vector g1 1 0 0
739 HI 32 Second translation unit vector g2 0 1 0
740 HI 32 Third translation unit vector g3 0 0 1
741 HI 32 Initial translation (meters) 0 0 0
742 HI 32 Initial translation velocity (meters/sec) 2121.3 2121.3 2121.3
743 HI 32 Translation stiffness (newtons/meters) 3.75 3.75 3.75
744 HI 32 Translation damping (newtons/meter/sec) 0 0 0
745 HI 32 Null force translations 0 0 0
746 HI 33 Hinge ID number 33
747 HI 33 Inboard body ID, Outboard body ID 32,33
748 HI 33 "p" node ID, "q" node ID 1,1
749 HI 33 Number of rotation DOFs 1
750 HI 33 L1 unit vector in inboard body coord. x,y,z 0,0,1
751 HI 33 L1 unit vector in outboard body coord. x,y,z 0,0,1
752 HI 33 L2 unit vector in inboard body coord. x,y,z 0,0,1
753 HI 33 L2 unit vector in outboard body coord. x,y,z 0,0,1
754 HI 33 L3 unit vector in inboard body coord. x,y,z 0,1,0
755 HI 33 L3 unit vector in outboard body coord. x,y,z 0,1,0
756 HI 33 Initial rotation angles (deg) 0 0 0
757 HI 33 Initial rotation rates (deg/sec) 0 0 0
758 HI 33 Rotation stiffness (newton-meters/rad) 0 0 0
759 HI 33 Rotation damping (newton-meters/rad) 0 0 0
760 HI 33 Null torque angles (deg) 0
761 HI 33 Number of translation DOFs 0
762 HI 33 First translation unit vector g1 1 0 0
763 HI 33 Second translation unit vector g2 0 1 0
764 HI 33 Third translation unit vector g3 0 0 1
765 HI 33 Initial translation (meters) 0 0 0
766 HI 33 Initial translation velocity (meters/sec) 2121.3 2121.3 2121.3
767 HI 33 Translation stiffness (newtons/meters) 3.75 3.75 3.75
768 HI 33 Translation damping (newtons/meter/sec) 0 0 0
769 HI 33 Null force translations

770 HI 41 Hinge ID number 41

47
41 Inboard body ID, Outboard body ID 1, 41
41 "p" node ID, "q" node ID 6, 1
41 Number of rotation DOFs, Rotation option (F or G) 3
41 L1 unit vector in inboard body coord. x, y, z 0.5, -0.75, 0.4330127
41 L1 unit vector in outboard body coord. x, y, z 0, 0, 1
41 L2 unit vector in inboard body coord. x, y, z 0.8660254, 0.4330127, 0.25
41 L2 unit vector in outboard body coord. x, y, z
41 L3 unit vector in inboard body coord. x, y, z 0, 1, 0
41 L3 unit vector in outboard body coord. x, y, z
41 Initial translation velocity (meters/sec) 0
41 Initial translation (meters) 0
41 Third translation unit vector g3
41 Number of rotation DOFs, Rotation option (F or G)
41 Null torque angles (deg) 0
41 Rotation stiffness (newton-meters/rad) 204.7
41 Rotation damping (newton-meters/rad/sec) 0.362
41 Initial translation (meters) 0
41 Initial translation velocity (meters/sec) 0
41 Translation stiffness (newtons/meters) 2121.3
41 Translation damping (newtons/meter/sec) 3.75
41 Null force translations 0
42 Hinge ID number 42
42 Inboard body ID, Outboard body ID 41, 42
42 "p" node ID, "q" node ID 2, 2
42 Number of rotation DOFs 0
42 L1 unit vector in inboard body coord. x, y, z 0, 0, 1
42 L1 unit vector in outboard body coord. x, y, z 0, 0, 1
42 L2 unit vector in inboard body coord. x, y, z 
42 L2 unit vector in outboard body coord. x, y, z
42 L3 unit vector in inboard body coord. x, y, z 0, 1, 0
42 L3 unit vector in outboard body coord. x, y, z 0, 1, 0
42 Initial rotation angles (deg) 0
42 Initial rotation rates (deg/sec) 0
42 Initial rotation rates (deg/sec) 0
42 Rotation stiffness (newton-meters/rad) 0
42 Rotation damping (newton-meters/rad/sec) 0
42 Null torque angles (deg) 0
42 Number of translation DOFs 0
42 First translation unit vector g1 1
42 Second translation unit vector g2 0
42 Third translation unit vector g3 0
42 Initial translation (meters) 0
42 Initial translation (meters) 0
42 Initial translation velocity (meters/sec) 0
42 Translation stiffness (newtons/meters) 0
42 Translation damping (newtons/meter/sec) 0
42 Null force translations 0
43 Hinge ID number 43
43 Inboard body ID, Outboard body ID 42, 43
43 "p" node ID, "q" node ID 1, 1
43 Number of rotation DOFs 1
43 L1 unit vector in inboard body coord. x, y, z 0, 0, 1
43 L1 unit vector in outboard body coord. x, y, z 0, 0, 1
43 L2 unit vector in inboard body coord. x, y, z 
43 L2 unit vector in outboard body coord. x, y, z
43 L3 unit vector in inboard body coord. x, y, z 0, 1, 0
43 L3 unit vector in outboard body coord. x, y, z 0, 1, 0
43 Initial rotation angles (deg) 0
43 Initial rotation angles (deg) 0
43 Initial rotation rates (deg/sec) -13500
43 Rotation stiffness (newton-meters/rad) 0
43 Rotation damping (newton-meters/rad/sec) 0
43 Null torque angles (deg) 0
43 Number of translation DOFs 0
43 First translation unit vector g1 1
43 Second translation unit vector g2 0
43 Third translation unit vector g3 0
43 Initial translation (meters) 0
43 Initial translation velocity (meters/sec) 0
43 Translation stiffness (newtons/meters) 0
43 Translation damping (newtons/meter/sec) 0
43 Null force translations 0
51 Hinge ID number 51
<table>
<thead>
<tr>
<th>Column</th>
<th>Description</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>843</td>
<td>Hi 51 Inboard body ID, Outboard body ID</td>
<td>1.51</td>
</tr>
<tr>
<td>844</td>
<td>Hi 51 &quot;p&quot; node ID, &quot;g&quot; node ID</td>
<td>2.2</td>
</tr>
<tr>
<td>845</td>
<td>Hi 51 Number of rotation DOFs, Rotation option (F or G)</td>
<td>3</td>
</tr>
<tr>
<td>846</td>
<td>Hi 51 L1 unit vector in inboard body coord. x,y,z</td>
<td>0.5, 0.0, -0.8660254</td>
</tr>
<tr>
<td>847</td>
<td>Hi 51 L1 unit vector in outboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>848</td>
<td>Hi 51 L2 unit vector in inboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>849</td>
<td>Hi 51 L2 unit vector in outboard body coord. x,y,z</td>
<td>0.8660254, 0.0, 0.5</td>
</tr>
<tr>
<td>850</td>
<td>Hi 51 L3 unit vector in inboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>851</td>
<td>Hi 51 L3 unit vector in outboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>852</td>
<td>Hi 51 Initial rotation angles (deg)</td>
<td>0.0</td>
</tr>
<tr>
<td>853</td>
<td>Hi 51 Initial rotation rates (deg/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>854</td>
<td>Hi 51 Rotation stiffness (newton-meters/rad)</td>
<td>204.7, 204.7, 204.7</td>
</tr>
<tr>
<td>855</td>
<td>Hi 51 Rotation damping (newton-meters/rad/sec)</td>
<td>0.362, 0.362, 0.362</td>
</tr>
<tr>
<td>856</td>
<td>Hi 51 Null torque angles (deg)</td>
<td>0.0</td>
</tr>
<tr>
<td>857</td>
<td>Hi 51 Number of translation DOFs</td>
<td>3</td>
</tr>
<tr>
<td>858</td>
<td>Hi 51 First translation unit vector g1</td>
<td>1.0</td>
</tr>
<tr>
<td>859</td>
<td>Hi 51 Second translation unit vector g2</td>
<td>1.0</td>
</tr>
<tr>
<td>860</td>
<td>Hi 51 Third translation unit vector g3</td>
<td>0.0</td>
</tr>
<tr>
<td>861</td>
<td>Hi 51 Initial translation (meters)</td>
<td>0.0</td>
</tr>
<tr>
<td>862</td>
<td>Hi 51 Initial translation velocity (meters/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>863</td>
<td>Hi 51 Translation stiffness (newtons/meters)</td>
<td>2121.3, 2121.3, 2121.3</td>
</tr>
<tr>
<td>864</td>
<td>Hi 51 Translation damping (newtons/meters/sec)</td>
<td>3.75, 3.75, 3.75</td>
</tr>
<tr>
<td>865</td>
<td>Hi 51 Null force translations</td>
<td>0.0</td>
</tr>
<tr>
<td>866</td>
<td>Hi 52 Hinge ID number</td>
<td>52</td>
</tr>
<tr>
<td>867</td>
<td>Hi 52 Inboard body ID, Outboard body ID</td>
<td>52, 52</td>
</tr>
<tr>
<td>868</td>
<td>Hi 52 &quot;p&quot; node ID, &quot;g&quot; node ID</td>
<td>0.0</td>
</tr>
<tr>
<td>869</td>
<td>Hi 52 Number of rotation DOFs</td>
<td>1.0</td>
</tr>
<tr>
<td>870</td>
<td>Hi 52 L1 unit vector in inboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>871</td>
<td>Hi 52 L1 unit vector in outboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>872</td>
<td>Hi 52 L2 unit vector in inboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>873</td>
<td>Hi 52 L2 unit vector in outboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>874</td>
<td>Hi 52 L3 unit vector in inboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>875</td>
<td>Hi 52 L3 unit vector in outboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>876</td>
<td>Hi 52 Initial rotation angles (deg)</td>
<td>0.0</td>
</tr>
<tr>
<td>877</td>
<td>Hi 52 Initial rotation rates (deg/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>878</td>
<td>Hi 52 Rotation stiffness (newton-meters/rad)</td>
<td>0.0</td>
</tr>
<tr>
<td>879</td>
<td>Hi 52 Rotation damping (newton-meters/rad/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>880</td>
<td>Hi 52 Null torque angles (deg)</td>
<td>0.0</td>
</tr>
<tr>
<td>881</td>
<td>Hi 52 Number of translation DOFs</td>
<td>3</td>
</tr>
<tr>
<td>882</td>
<td>Hi 52 First translation unit vector g1</td>
<td>1.0</td>
</tr>
<tr>
<td>883</td>
<td>Hi 52 Second translation unit vector g2</td>
<td>0.0</td>
</tr>
<tr>
<td>884</td>
<td>Hi 52 Third translation unit vector g3</td>
<td>0.0</td>
</tr>
<tr>
<td>885</td>
<td>Hi 52 Initial translation (meters)</td>
<td>0.0</td>
</tr>
<tr>
<td>886</td>
<td>Hi 52 Initial translation velocity (meters/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>887</td>
<td>Hi 52 Translation stiffness (newtons/meters)</td>
<td>0.0</td>
</tr>
<tr>
<td>888</td>
<td>Hi 52 Translation damping (newtons/meters/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>889</td>
<td>Hi 52 Null force translations</td>
<td>0.0</td>
</tr>
<tr>
<td>890</td>
<td>Hi 53 Hinge ID number</td>
<td>53</td>
</tr>
<tr>
<td>891</td>
<td>Hi 53 Inboard body ID, Outboard body ID</td>
<td>52, 53</td>
</tr>
<tr>
<td>892</td>
<td>Hi 53 &quot;p&quot; node ID, &quot;g&quot; node ID</td>
<td>1.1</td>
</tr>
<tr>
<td>893</td>
<td>Hi 53 Number of rotation DOFs</td>
<td>1</td>
</tr>
<tr>
<td>894</td>
<td>Hi 53 L1 unit vector in inboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>895</td>
<td>Hi 53 L1 unit vector in outboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>896</td>
<td>Hi 53 L2 unit vector in inboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>897</td>
<td>Hi 53 L2 unit vector in outboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>898</td>
<td>Hi 53 L3 unit vector in inboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>899</td>
<td>Hi 53 L3 unit vector in outboard body coord. x,y,z</td>
<td>0.0, 1</td>
</tr>
<tr>
<td>900</td>
<td>Hi 53 Initial rotation angles (deg)</td>
<td>0.0</td>
</tr>
<tr>
<td>901</td>
<td>Hi 53 Initial rotation rates (deg/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>902</td>
<td>Hi 53 Rotation stiffness (newton-meters/rad)</td>
<td>0.0</td>
</tr>
<tr>
<td>903</td>
<td>Hi 53 Rotation damping (newton-meters/rad/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>904</td>
<td>Hi 53 Null torque angles (deg)</td>
<td>0.0</td>
</tr>
<tr>
<td>905</td>
<td>Hi 53 Number of translation DOFs</td>
<td>0.0</td>
</tr>
<tr>
<td>906</td>
<td>Hi 53 First translation unit vector g1</td>
<td>1.0</td>
</tr>
<tr>
<td>907</td>
<td>Hi 53 Second translation unit vector g2</td>
<td>0.0</td>
</tr>
<tr>
<td>908</td>
<td>Hi 53 Third translation unit vector g3</td>
<td>0.0</td>
</tr>
<tr>
<td>909</td>
<td>Hi 53 Initial translation (meters)</td>
<td>0.0</td>
</tr>
<tr>
<td>910</td>
<td>Hi 53 Initial translation velocity (meters/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>911</td>
<td>Hi 53 Translation stiffness (newtons/meters)</td>
<td>0.0</td>
</tr>
<tr>
<td>912</td>
<td>Hi 53 Translation damping (newtons/meters/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>913</td>
<td>Hi 53 Null force translations</td>
<td>0.0</td>
</tr>
<tr>
<td>914</td>
<td>Hi 61 Hinge ID number</td>
<td>61</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Inboard body ID, Outboard body ID</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td><em>p</em> node ID, <em>q</em> node ID</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Number of rotation DOFs, Rotation option (F or G)</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>L1 unit vector in inboard body coord. x, y, z</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>L1 unit vector in outboard body coord. x, y, z</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>L2 unit vector in inboard body coord. x, y, z</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>L2 unit vector in outboard body coord. x, y, z</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>L3 unit vector in inboard body coord. x, y, z</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>L3 unit vector in outboard body coord. x, y, z</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Initial rotation angles (deg)</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Initial rotation damping (newton-meters/rad/sec)</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Null torque angles (deg)</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Number of translation DOFs</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>First translation unit vector g1</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Second translation unit vector g2</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Third translation unit vector g3</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Initial translation (meters)</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Initial translation velocity (meters/sec)</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Translation stiffness (newtons/meters)</td>
</tr>
<tr>
<td>H1</td>
<td>61</td>
<td>Null force translations</td>
</tr>
</tbody>
</table>

| H1 | 62 | Hinge ID number | 61, 62 |
| H1 | 62 | Inboard body ID, Outboard body ID | 2, 2 |
| H1 | 62 | Number of rotation DOFs | 0 |
| H1 | 62 | L1 unit vector in inboard body coord. x, y, z | 0, 0, 1 |
| H1 | 62 | L1 unit vector in outboard body coord. x, y, z | 0, 0, 1 |
| H1 | 62 | L2 unit vector in inboard body coord. x, y, z | 0, 1, 0 |
| H1 | 62 | L2 unit vector in outboard body coord. x, y, z | 0, 1, 0 |
| H1 | 62 | L3 unit vector in inboard body coord. x, y, z | 0, 0, 1 |
| H1 | 62 | L3 unit vector in outboard body coord. x, y, z | 0, 0, 1 |
| H1 | 62 | Initial rotation angles (deg) | 0, 0, 0 |
| H1 | 62 | Initial rotation damping (newton-meters/rad/sec) | 0, 0, 0 |
| H1 | 62 | Null torque angles (deg) | 0, 0, 0 |
| H1 | 62 | Number of translation DOFs | 0, 0, 0 |
| H1 | 62 | First translation unit vector g1 | 1, 0, 0 |
| H1 | 62 | Second translation unit vector g2 | 0, 1, 0 |
| H1 | 62 | Third translation unit vector g3 | 0, 0, 1 |
| H1 | 62 | Initial translation (meters) | 0, 0, 0 |
| H1 | 62 | Initial translation velocity (meters/sec) | 2221.3, 2221.3, 2221.3 |
| H1 | 62 | Translation stiffness (newtons/meters) | 3.75, 3.75, 3.75 |
| H1 | 62 | Null force translations | 0, 0, 0 |

<p>| H1 | 63 | Hinge ID number | 61, 62 |
| H1 | 63 | Inboard body ID, Outboard body ID | 1, 1 |
| H1 | 63 | <em>p</em> node ID, <em>q</em> node ID | 1, 1 |
| H1 | 63 | Number of rotation DOFs | 1 |
| H1 | 63 | L1 unit vector in inboard body coord. x, y, z | 0, 0, 1 |
| H1 | 63 | L1 unit vector in outboard body coord. x, y, z | 0, 0, 1 |
| H1 | 63 | L2 unit vector in inboard body coord. x, y, z | 0, 1, 0 |
| H1 | 63 | L2 unit vector in outboard body coord. x, y, z | 0, 1, 0 |
| H1 | 63 | L3 unit vector in inboard body coord. x, y, z | 0, 0, 1 |
| H1 | 63 | L3 unit vector in outboard body coord. x, y, z | 0, 0, 1 |
| H1 | 63 | Initial rotation angles (deg) | 0, 0, 0 |
| H1 | 63 | Initial rotation damping (newton-meters/rad/sec) | 0, 0, 0 |
| H1 | 63 | Null torque angles (deg) | 0, 0, 0 |
| H1 | 63 | Number of translation DOFs | 0, 0, 0 |
| H1 | 63 | First translation unit vector g1 | 1, 0, 0 |
| H1 | 63 | Second translation unit vector g2 | 0, 1, 0 |
| H1 | 63 | Third translation unit vector g3 | 0, 0, 1 |
| H1 | 63 | Initial translation (meters) | 0, 0, 0 |
| H1 | 63 | Initial translation velocity (meters/sec) | 2221.3, 2221.3, 2221.3 |
| H1 | 63 | Translation stiffness (newtons/meters) | 3.75, 3.75, 3.75 |
| H1 | 63 | Null force translations | 0, 0, 0 |</p>
<table>
<thead>
<tr>
<th>Sensor ID number</th>
<th>Type (G, R, AN, V, P, AC, T, I, SU, ST, IM, P3, V3, CR, CT)</th>
<th>Mounting point body ID, Mounting point node ID</th>
<th>1, 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Second mounting point body ID, Second node ID</td>
<td>Input axis unit vector (IA) x, y, z</td>
<td>1, 0, 0</td>
</tr>
<tr>
<td></td>
<td>First focal plane unit vector (Fp1) x, y, z</td>
<td>Mounting point Hinge index, Axis index</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Second focal plane unit vector (Fp2) x, y, z</td>
<td>Sun/Star unit vector (Us) x, y, z</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Euler Angle Sequence (1-6)</td>
<td>CMG ID number and Gimbal number</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor ID number</th>
<th>Type (G, R, AN, V, P, AC, T, I, SU, ST, IM, P3, V3, CR, CT)</th>
<th>Mounting point body ID, Mounting point node ID</th>
<th>1, 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Second mounting point body ID, Second node ID</td>
<td>Input axis unit vector (IA) x, y, z</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td></td>
<td>First focal plane unit vector (Fp1) x, y, z</td>
<td>Mounting point Hinge index, Axis index</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Second focal plane unit vector (Fp2) x, y, z</td>
<td>Sun/Star unit vector (Us) x, y, z</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Euler Angle Sequence (1-6)</td>
<td>CMG ID number and Gimbal number</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor ID number</th>
<th>Type (G, R, AN, V, P, AC, T, I, SU, ST, IM, P3, V3, CR, CT)</th>
<th>Mounting point body ID, Mounting point node ID</th>
<th>1, 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Second mounting point body ID, Second node ID</td>
<td>Input axis unit vector (IA) x, y, z</td>
<td>1, 0, 0</td>
</tr>
<tr>
<td></td>
<td>First focal plane unit vector (Fp1) x, y, z</td>
<td>Mounting point Hinge index, Axis index</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Second focal plane unit vector (Fp2) x, y, z</td>
<td>Sun/Star unit vector (Us) x, y, z</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Euler Angle Sequence (1-6)</td>
<td>CMG ID number and Gimbal number</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor ID number</th>
<th>Type (G, R, AN, V, P, AC, T, I, SU, ST, IM, P3, V3, CR, CT)</th>
<th>Mounting point body ID, Mounting point node ID</th>
<th>1, 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Second mounting point body ID, Second node ID</td>
<td>Input axis unit vector (IA) x, y, z</td>
<td>1, 0, 0</td>
</tr>
<tr>
<td></td>
<td>First focal plane unit vector (Fp1) x, y, z</td>
<td>Mounting point Hinge index, Axis index</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Second focal plane unit vector (Fp2) x, y, z</td>
<td>Sun/Star unit vector (Us) x, y, z</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Euler Angle Sequence (1-6)</td>
<td>CMG ID number and Gimbal number</td>
<td></td>
</tr>
</tbody>
</table>
1053 SE 1 Type (G,R,AN,V,P,AC,T,I,SU,ST,IM,P3,V3,CR,CT) IM
1054 SE 1 Mounting point body ID, Mounting point node ID 1,1
1055 SE 1 Second mounting point body ID, Second node ID
1056 SE 1 Input axis unit vector (IA) x,y,z
1057 SE 1 Mounting point Hinge index, Axis index
1058 SE 1 First focal plane unit vector (Fp1) x,y,z
1059 SE 1 Second focal plane unit vector (Fp2) x,y,z
1060 SE 1 Sun/Star unit vector (Us) x,y,z
1061 SE 1 Euler Angle Sequence (1-6) 1
1062 SE 1 CMG ID number and Gimbal number

AC
1063 AC 13 Actuator ID number 13
1064 AC 13 Type(J,H,MO,T,B,MA,SG,DG,W,L,MI-M7) T
1065 AC 13 Actuator location; Node or Hinge (N or H)
1066 AC 13 Mounting point body ID number, node ID number
1067 AC 13 Second mounting point body ID, second node ID
1068 AC 13 Output axis unit vector x,y,z
1069 AC 13 Mounting point Hinge index, Axis index 13,1
1070 AC 13 Initial rotor spin axis unit vector x,y,z
1071 AC 13 Initial rotor momentum, H
1072 AC 13 Outer gimbal- angle(deg), inertia, friction(D,S,B,N)
1073 AC 13 Outer gimbal axis unit vector x,y,z
1074 AC 13 Out gim fric (Tfi,Tgfo,GAM)/(Tfi,M,D,Kf)/(m,M,B,k)
1075 AC 13 Inner gimbal- angle(deg), inertia, friction(D,S,B,N)
1076 AC 13 Inner gimbal axis unit vector x,y,z
1077 AC 13 In gim fric (Tfi,Tgfo,GAM)/(Tfi,M,D,Kf)/(m,M,B,k)
1078 AC 13 Initial length and rate, y(to) and ydot(to)
1079 AC 13 Constants; K1 or wo, n or zeta, Kg, Jm
1080 AC 13 Non-linearities; TLim, Tco, Dz

23
1081 AC 23 Actuator ID number 23
1082 AC 23 Type(J,H,MO,T,B,MA,SG,DG,W,L,MI-M7) T
1083 AC 23 Actuator location; Node or Hinge (N or H)
1084 AC 23 Mounting point body ID number, node ID number
1085 AC 23 Second mounting point body ID, second node ID
1086 AC 23 Output axis unit vector x,y,z
1087 AC 23 Mounting point Hinge index, Axis index 23,1
1088 AC 23 Rotor spin axis unit vector x,y,z
1089 AC 23 Initial rotor momentum, H
1090 AC 23 Outer gimbal- angle(deg), inertia, friction(D,S,B,N)
1091 AC 23 Outer gimbal axis unit vector x,y,z
1092 AC 23 Out gim fric (Tfi,Tgfo,GAM)/(Tfi,M,D,Kf)/(m,M,B,k)
1093 AC 23 Inner gimbal- angle(deg), inertia, friction(D,S,B,N)
1094 AC 23 Inner gimbal axis unit vector x,y,z
1095 AC 23 In gim fric (Tfi,Tgfo,GAM)/(Tfi,M,D,Kf)/(m,M,B,k)
1096 AC 23 Initial length and rate, y(to) and ydot(to)
1097 AC 23 Constants; K1 or wo, n or zeta, Kg, Jm
1098 AC 23 Non-linearities; TLim, Tco, Dz

33
1099 AC 33 Actuator ID number 33
1100 AC 33 Type(J,H,MO,T,B,MA,SG,DG,W,L,MI-M7) T
1101 AC 33 Actuator location; Node or Hinge (N or H)
1102 AC 33 Mounting point body ID number, node ID number
1103 AC 33 Second mounting point body ID, second node ID
1104 AC 33 Output axis unit vector x,y,z
1105 AC 33 Mounting point Hinge index, Axis index 33,1
1106 AC 33 Rotor spin axis unit vector x,y,z
1107 AC 33 Initial rotor momentum, H
1108 AC 33 Outer gimbal- angle(deg), inertia, friction(D,S,B,N)
1109 AC 33 Outer gimbal axis unit vector x,y,z
1110 AC 33 Out gim fric (Tfi,Tgfo,GAM)/(Tfi,M,D,Kf)/(m,M,B,k)
1111 AC 33 Inner gimbal- angle(deg), inertia, friction(D,S,B,N)
1112 AC 33 Inner gimbal axis unit vector x,y,z
1113 AC 33 In gim fric (Tfi,Tgfo,GAM)/(Tfi,M,D,Kf)/(m,M,B,k)
1114 AC 33 Initial length and rate, y(to) and ydot(to)
1115 AC 33 Constants; K1 or wo, n or zeta, Kg, Jm
1116 AC 33 Non-linearities; TLim, Tco, Dz

43
1117 AC 43 Actuator ID number 43
1118 AC 43 Type(J,H,MO,T,B,MA,SG,DG,W,L,MI-M7) T
1119 AC 43 Actuator location; Node or Hinge (N or H)
1120 AC 43 Mounting point body ID number, node ID number
Second mounting point body ID, second node ID
Output axis unit vector x,y,z
Mounting point Hinge index, Axis index
Initial rotor momentum, H
Outer gimbal- angle(deg), inertia, friction(D,S,B,N)
Outer gimbal axis unit vector x,y,z
Inner gimbal- angle(deg), inertia, friction(D,S,B,N)
Inner gimbal axis unit vector x,y,z
Initial length and rate, y(to) and ydot(to)
Constants; K1 or wo, n or zeta, Kg, Jm
Non-linearities; TLim, Tco, Dz
Actuator ID number
Type(J,H,MO,T,B,MA,SG,DG,W,L,MI-M7)
Actuator location; Node or Hinge (N or H)
Mounting point body ID number, node ID number
Mounting point body ID, second node ID
Output axis unit vector x,y,z
Mounting point Hinge index, Axis index
Rotor spin axis unit vector x,y,z
Initial rotor momentum, H
Outer gimbal- angle(deg), inertia, friction(D,S,B,N)
Outer gimbal axis unit vector x,y,z
Inner gimbal- angle(deg), inertia, friction(D,S,B,N)
Inner gimbal axis unit vector x,y,z
Initial length and rate, y(to) and ydot(to)
Constants; K1 or wo, n or zeta, Kg, Jm
Non-linearities; TLim, Tco, Dz
Controller ID number
Controller type (CB,CM,DB,DM,UC,UD)
Sample time (sec)
Number of inputs, Number of outputs
Number of states
Output No., Input type (I,S,T), Input ID, Gain
Interconnect ID number
Source type(S,C,or F), Source ID, Source row #
Destination type(A or C), Dest ID, Dest row #
Gain
Controller
1
Controller type (CB,CM,DB,DM,UC,UD)
Sample time (sec)
Number of inputs, Number of outputs
Number of states
Output No., Input type (I,S,T), Input ID, Gain
Interconnect
<table>
<thead>
<tr>
<th>Interconnect ID number</th>
<th>Source type (S, C, or F), Source ID, Source row #</th>
<th>Destination type (A or C), Dest ID, Dest row #</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, 3</td>
<td>C, 1, 3</td>
<td>A, 33, 1</td>
<td>1</td>
</tr>
<tr>
<td>S, 1</td>
<td>S, 1, 1</td>
<td>C, 1, 1</td>
<td>-1</td>
</tr>
<tr>
<td>S, 1</td>
<td>S, 1, 2</td>
<td>C, 1, 2</td>
<td>-1</td>
</tr>
<tr>
<td>S, 1</td>
<td>S, 1, 1</td>
<td>C, 1, 1</td>
<td>-1</td>
</tr>
<tr>
<td>S, 1</td>
<td>S, 1, 4</td>
<td>C, 1, 2</td>
<td>-1</td>
</tr>
<tr>
<td>S, 1</td>
<td>S, 1, 5</td>
<td>C, 1, 2</td>
<td>-1</td>
</tr>
<tr>
<td>S, 1</td>
<td>S, 1, 6</td>
<td>C, 1, 2</td>
<td>-1</td>
</tr>
<tr>
<td>S, 1</td>
<td>S, 1, 6</td>
<td>C, 1, 6</td>
<td>-1</td>
</tr>
</tbody>
</table>

**CNTDTA**

<table>
<thead>
<tr>
<th>Number of data values (max = 150)</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array value</td>
<td>6.506</td>
</tr>
<tr>
<td>Array value</td>
<td>68.382</td>
</tr>
<tr>
<td>Array value</td>
<td>72.008</td>
</tr>
<tr>
<td>Array value</td>
<td>6.506E-3</td>
</tr>
<tr>
<td>Array value</td>
<td>3.419E-2</td>
</tr>
<tr>
<td>Array value</td>
<td>3.6454E-2</td>
</tr>
<tr>
<td>Array value</td>
<td>325.30</td>
</tr>
<tr>
<td>Array value</td>
<td>3419.10</td>
</tr>
<tr>
<td>Array value</td>
<td>3645.40</td>
</tr>
<tr>
<td>Array value</td>
<td>0.05695</td>
</tr>
<tr>
<td>Array value</td>
<td>3.98E-4</td>
</tr>
<tr>
<td>Array value</td>
<td>6.98E-4</td>
</tr>
<tr>
<td>Array value</td>
<td>0.06</td>
</tr>
<tr>
<td>Array value</td>
<td>0.011</td>
</tr>
<tr>
<td>Array value</td>
<td>0.01</td>
</tr>
<tr>
<td>Array value</td>
<td>1.6E</td>
</tr>
<tr>
<td>Array value</td>
<td>1.6E</td>
</tr>
<tr>
<td>Array value</td>
<td>1.6E</td>
</tr>
<tr>
<td>Array value</td>
<td>0.25</td>
</tr>
</tbody>
</table>
## Appendix C

**AXAF-I TREETOPS Input File AXAFI.FLN**

**FLAG, REVISION NUMBER**

XXXXXX 1

**BODY ID**

2

**MODES, NODES, MODAL OPTIONS**

| 6 | 10 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |

**NODAL LOCATION VECTORS**

| -0.25659736E-16 | 0.14245523E+02 | 0.00000000E+00 | 0.33627405E+01 |
| 0.00000000E+00 | 0.33627405E+01 | 0.55389451E-01 |
| 0.46979787E+01 | 0.55389451E-01 |
| 0.26258866E+02 | 0.55389451E-01 |

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

| 0.25688829E+01 | 0.66230670E+03 |
| -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 |

**PHI PRIME for node # 2**

| 50299722E-01 | 46979787E+01 |
| 33627405E+01 | 55389451E-01 |
| 19303728E+02 | 33627405E+01 |

**PHI for node # 3**

| 0.34267600E-05 | 0.25275900E-02 |
| -0.13720400E-01 | 0.73277400E-04 |
| -0.13447378E+00 | 0.12957398E+00 |
| 0.11949118E-01 | 0.12530541E+00 |

**PHI PRIME for node # 3**

| -0.98232809E-01 | 0.14805712E+00 |
| 0.10336061E-01 | 0.34299412E+00 |

**PHI for node # 4**

| 0.31104200E-03 | 0.80964200E-02 |
| 0.57645100E-02 | 0.56919800E-02 |
| -0.30644700E-01 | 0.63790800E-02 |
| 0.67396022E+03 |

**PHI PRIME for node # 4**

| -0.98232809E-01 | 0.34850594E-02 |
| 0.14805712E+00 |
| 0.10336061E-01 |

**PHI for node # 5**

| 0.31104200E-03 | 0.80964200E-02 |
| 0.57645100E-02 | 0.56919800E-02 |
| -0.30644700E-01 | 0.63790800E-02 |
| 0.67396022E+03 |

**PHI PRIME for node # 5**

| -0.18535821E+00 | 0.60430577E-03 |
| 0.00000000E+00 | 0.12438258E+00 |
| 0.00000000E+00 | 0.86916597E+00 |

55
**PHI for node # 6**

<table>
<thead>
<tr>
<th>PHI for node # 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8739800E-02</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
</tbody>
</table>

**PHI PRIME for node # 6**

<table>
<thead>
<tr>
<th>PHI PRIME for node # 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.16690028E+00</td>
</tr>
<tr>
<td>0.14613825E+00</td>
</tr>
<tr>
<td>0.14191768E+00</td>
</tr>
<tr>
<td>0.12347534E+00</td>
</tr>
</tbody>
</table>

**PHI for node # 7**

<table>
<thead>
<tr>
<th>PHI for node # 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.57220400E-07</td>
</tr>
<tr>
<td>0.30484500E-02</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
</tbody>
</table>

**PHI PRIME for node # 7**

<table>
<thead>
<tr>
<th>PHI PRIME for node # 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13160566E+00</td>
</tr>
<tr>
<td>0.18981800E-01</td>
</tr>
<tr>
<td>0.30484500E-02</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
</tbody>
</table>

**PHI for node # 8**

<table>
<thead>
<tr>
<th>PHI for node # 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.30484500E-02</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
</tbody>
</table>

**PHI PRIME for node # 8**

<table>
<thead>
<tr>
<th>PHI PRIME for node # 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13160566E+00</td>
</tr>
<tr>
<td>0.18981800E-01</td>
</tr>
<tr>
<td>0.30484500E-02</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
</tbody>
</table>

**PHI for node # 9**

<table>
<thead>
<tr>
<th>PHI for node # 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.30484500E-02</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
</tbody>
</table>

**PHI PRIME for node # 9**

<table>
<thead>
<tr>
<th>PHI PRIME for node # 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13160566E+00</td>
</tr>
<tr>
<td>0.18981800E-01</td>
</tr>
<tr>
<td>0.30484500E-02</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
</tbody>
</table>

**MASS MATRIX**

<table>
<thead>
<tr>
<th>MASS MATRIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12000000E+02</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
</tbody>
</table>

**DAMPING MATRIX**

<table>
<thead>
<tr>
<th>DAMPING MATRIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
<tr>
<td>0.00000000E+00</td>
</tr>
</tbody>
</table>
STIFFNESS MATRIX

\[
\begin{pmatrix}
0.22020840E+02 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1044012E+04 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0.77901960E+04 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

*** MODAL COUPLING TERMS ***

INTEGRAL PHI DM

\[
\begin{pmatrix}
-0.25688829E+01 & 0.14245523E+02 & 0.50299722E-01 & 0.00000000E+00 & -0.98421063E-02 \\
0 & 0.12000853E+02 & 0.55389451E-01 & 0.33627405E+01 & 0.55389451E-01 \\
0.53627405E+01 & 0.55389451E-01 & 0.2625866E+02 & 0.55389451E-01 & 0.19303728E+02 \\
0.53627405E+01 & 0.55389451E-01 & 0.2625866E+02 & 0.55389451E-01 & 0.33627405E+01 \\
0.53627405E+01 & 0.55389451E-01 & 0.2625866E+02 & 0.55389451E-01 & 0.33627405E+01 \\
0.53627405E+01 & 0.55389451E-01 & 0.2625866E+02 & 0.55389451E-01 & 0.33627405E+01 \\
\end{pmatrix}
\]

PHI for node #

\[
\begin{pmatrix}
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
\end{pmatrix}
\]

PHI PRIME for node #

\[
\begin{pmatrix}
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
\end{pmatrix}
\]

PHI for node #

\[
\begin{pmatrix}
0.34267600E-05 & 0.25257900E-02 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
0.00000000E+00 & 0.00000000E+00 \\
\end{pmatrix}
\]

57
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Matrix</td>
<td>Phi for node # 10</td>
</tr>
<tr>
<td>0.110851678+01 0.43101644E-02 0.11149274E-05</td>
<td></td>
</tr>
<tr>
<td>Phi Prime for node # 10</td>
<td></td>
</tr>
<tr>
<td>-0.18157300E-08 0.30487400E-02-0.39931300E+01-0.35094500E+01-0.45004300E+00</td>
<td></td>
</tr>
<tr>
<td>0.34790800E-01 0.17810200E-01-0.56774400E-03 0.48784100E+01-0.69819200E-07</td>
<td></td>
</tr>
<tr>
<td>-0.11027400E-01 0.38676400E+01 0.57003100E-02 0.28693600E-02 0.54549700E+01</td>
<td></td>
</tr>
<tr>
<td>0.16186900E-06 0.14442800E-02 0.36909800E+01</td>
<td></td>
</tr>
<tr>
<td>Mass Matrix</td>
<td></td>
</tr>
<tr>
<td>0.12000000E+02 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>Damping Matrix</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>Stiffness Matrix</td>
<td></td>
</tr>
<tr>
<td>0.22020840E+02 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.20798280E+03 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.01040012E+04 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.00000000E+00 0.34207440E+04 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
<tr>
<td>0.00000000E+00 0.77901960E+04 0.00000000E+00 0.00000000E+00 0.00000000E+00</td>
<td></td>
</tr>
</tbody>
</table>

** Modal Coupling Terms **
Appendix D
AXAF-I TREE TOPS 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
$$$$$$$ by YK
$ALTER 105 $ FOR '91 CSA NASTRAN
$ALTER 106 $ FOR '93 CSA NASTRAN
RFINSERT READ $ FOR '94 CSA NASTRAN
TABPT EQEXIN/ $
GKAM ,,PHIA,MI,LAMA,DIT,,,CASECC/MMASS,MDAMP,MSTIFF,PHIDH/-1/
0/0.0/1.E+30/-1/-1/-1/V,N,NONCUP/V,N,FMODE/ $ 
VECPLOT ,,BGPDT,EQEXIN,CSTM,,,/RMAT1///4 $ 
TRNSP RMAT1/RMAT $ 
MATGEN ,/ZEROG/7/LUSET/1 $ 
VECPLOT ZEROG,BGPDT,EQEXIN,CSTM,CASECC,/COORD///3 $ 
MATGEN ,/PVECX/4/1/LUSET/0/1/6/1 $ 
MATGEN ,/PVECY/4/1/LUSET/0/1/6/2 $ 
MATGEN ,/PVECZ/4/1/LUSET/0/1/6/3 $ 
MATGEN ,/PVECX/6/2/1/1 $ 
MATGEN ,/PVECY/6/2/1/1 $ 
MATGEN ,/PVECY/6/3/2/1 $ 
PARTN COORD,,PVECX/,XGEOM,,/I $ 
PARTN COORD,,PVECY/,YGEOM,,/I $ 
PARTN COORD,,PVECZ/,ZGEOM,,/I $ 
MERGE XGEOM,,YGEOM,,PVECXY,/XYGEOM/1 $ 
MERGE XYGEOM,,ZGEO,,PCEXY/XYGEOM/1 $ 
UMERGE USET,PHIA,,PHIAB/C,Y,MAJOR=N/C,Y,SUB0=A/C,Y,SUB1=SB $ 
OUTPUT5 MGG,PHIAJB/MMASS,MSTIFF,XYZGEO,/C,N,-1/C,N,11/C,N,DYNACSJB/1 $ $ 
ENDALTER $ 
$$$$$$$$$$$$$$$$$$$
CEND $ $ $ RECEIVED FROM TRW/ZIGGY JAB 3/2/93 $ 
$ $---------------------------------------------------------------
$ $ necessary alter for Lanczos with sol 3 $ 
$COMPILE SOL3 SOUIN=MSCSOU $ 
$RFALTER RF3D83 $ $---------------------------------------------------------------
LINE=48
TITLE = 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 $
$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 i00.
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--------
$EIGR 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 tippee CBARS. OSAS. (Uncomment only if the wing
$ is to be run alone.)
$
$PBAR 872 809 100. 1000. 1000. 2000.
$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.
+9424020
$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 1.

***************************************************************************

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.

SADA STIFFNESS (TDRS VALUES)

CELLAS2 89235 50.00E3 84501 1 84502 1
CELLAS2 89236 50.00E3 84501 2 84502 2
CELLAS2 89237 50.00E3 84501 3 84502 3
CELLAS2 89238 8.00E5 84501 4 84502 4
CELLAS2 89239 8.00E4 84501 5 84502 5
CELLAS2 89240 8.00E5 84501 6 84502 6

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)

RBE2 80000 87064 123456 87060 87036 87040 87037 87039
84504

Bottom grids of tepee

GRID 84023 810 450.113 60.25 -4.53
GRID 84024 810 450.113 60.25 -4.53
GRID 84027 810 450.113 60.25 -9.53
GRID 84028 810 450.113 60.25 -9.53
GRID 84031 810 450.113 60.25 -14.53
GRID 84032 810 450.113 60.25 -14.53

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)

RBE2 63051 63001 123456 63001 123456
60001 84502 63001 123456 123456
spc1, 100, 12346, 63001

Modify Location of I/F per IOC M533.2.94-073
RH 5/94
GRID 63001 600 0. -.11811 0.0 600
GRID 63001 810 445.88 68.025 -9.53

RBE2 63051 63001 123456 63002
GRID 63002 600 0. .94488 0.0 600
GRID 63003 600 0. .94488 0.0 600

BAPTA & SADM Hinge

RBE2 63052 63002 123 63003
CELLAS2 63061 2.3454+563002 4 63003 4
CELLAS2 63062 5.8414+463002 5 63003 5
CELLAS2 63063 1.6374+663002 6 63003 6
CONM2 60265 60501 602 0.1411
CONM2 60266 60502 602 0.1411
CONM2 60267 60601 602 0.1411
CONM2 60268 60602 602 0.1411

$ 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 0.0 602
GRID 60401 602 22.6379 0.0 0.0 602
GRID 60402 602 -22.6379 0.0 0.0 602
GRID 60403 602 -40.3545 0.0 0.0 602
GRID 60500 602 40.3545 17.6379 0.0 602
GRID 60501 602 22.6379 17.6379 0.0 602
GRID 60502 602 -22.6379 17.6379 0.0 602
GRID 60503 602 -40.3545 17.6379 0.0 602
GRID 60600 602 40.3545 62.6184 0.0 602
GRID 60601 602 22.6379 62.6184 0.0 602
GRID 60602 602 -22.637962.6184 0.0 602
GRID 60603 602 -40.354562.6184 0.0 602
GRID 60700 602 40.3545 83.465 0.0 602
GRID 60701 602 22.6379 83.465 0.0 602
GRID 60702 602 -22.637983.465 0.0 602
GRID 60703 602 -40.354583.465 0.0 602

$ Outboard Panel

$ Edge Beams
CBAR 60351 611 60800 60801 0.0 0.0 603
CBAR 60352 611 60801 60802 0.0 0.0 603
CBAR 60353 611 60802 60803 0.0 0.0 603
CBAR 60354 611 61100 61101 0.0 0.0 603
CBAR 60355 611 61101 61102 0.0 0.0 603
CBAR 60356 611 61102 61103 0.0 0.0 603

$ Panel Wt
CONM2 60361 60801 603 0.12346
CONM2 60362 60802 603 0.12346
CONM2 60363 61101 603 0.12346
CONM2 60364 61102 603 0.12346
CONM2 60365 60901 603 0.54586
CONM2 60366 60902 603 0.54586
CONM2 60367 61001 603 0.54586
CONM2 60368 61002 603 0.54586

$ Tip Masses for Outboard Panel
CONM2 60369 61100 603 0.26
CONM2 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
GRID 60801 603 22.6379 0.0 0.0 603
GRID 60802 603 -22.63790.0 0.0 603
GRID 60803 603 -40.35450.0 0.0 603
GRID 60900 603 40.3545 20.8466 0.0 603
GRID 60901 603 22.6379 20.8466 0.0 603
GRID 60902 603 -22.637920.8466 0.0 603
GRID 60903 603 -40.354520.8466 0.0 603
GRID 61000 603 40.3545 65.8271 0.0 603
GRID 61001 603 22.6379 65.8271 0.0 603
GRID 61002 603 -22.637965.8271 0.0 603
GRID 61003 603 -40.354565.8271 0.0 603
GRID 61100 603 40.3545 83.465 0.0 603
GRID 61101 603 22.6379 83.465 0.0 603
GRID 61102 603 -22.637983.465 0.0 603
GRID 61103 603 -40.354583.465 0.0 603
$ $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$ Yoke
$ $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$ GRID 63004 600 -6.715 16.1516 0.0 600
GRID 63005 600 -13.430731.3582 70.0 600
GRID 63006 600 -18.0335 1.7815 0.0 600
GRID 63007 600 -22.637852.2047 0.0 600
GRID 63008 600 6.715 16.1516 0.0 600
GRID 63009 600 13.4307 31.3582 70.0 600
GRID 63010 600 18.0335 41.7815 0.0 600
GRID 63011 600 22.6378 52.2047 0.0 600
$ Yoke Cross Bar
GRID 63012 600 -11.3189 52.2047 0.0 600
GRID 63013 600 0. 52.2047 0.0 600
GRID 63014 600 11.3189 52.2047 0.0 600
$ CBAR 63001 612 63003 63004 0. 0. 1.
CBAR 63002 612 63004 63005 0. 0. 1.
CBAR 63003 612 63005 63006 0. 0. 1.
CBAR 63004 612 63006 63007 0. 0. 1.
CBAR 63005 612 63007 63008 0. 0. 1.
CBAR 63006 612 63008 63009 0. 0. 1.
CBAR 63007 612 63009 63010 0. 0. 1.
CBAR 63008 612 63010 63011 0. 0. 1.
$ Yoke Cross Bar
CBAR 63009 613 63007 63012 0. 0. 1.
CBAR 63010 613 63012 63013 0. 0. 1.
CBAR 63011 613 63013 63014 0. 0. 1.
CBAR 63012 613 63014 63011 0. 0. 1.
$ $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$ Hinge Lines
$ $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$ Yoke to Wing I/F
$ CBAR 63101 614 63007 63101 1. 0. 0.
CBAR 63102 614 63102 60002 1. 0. 0.
CBAR 63103 614 63011 63103 1. 0. 0.
CBAR 63104 614 63104 60001 1. 0. 0.
GRID 63101 601 -22.6378-2.0866 0.5953 601
GRID 63102 601 -22.6378-2.0866 0.5953 601
GRID 63103 601 22.6378 -2.0866 0.5953 601
GRID 63104 601 22.6378 -2.0866 0.5953 601
RBE2 63105 63101 123456 63102
RBE2 63106 63103 123456 63104
$ Inbd to Mid
CBAR 63111 615 60302 63111 1. 0. 0.
CBAR 63112 615 63112 60402 1. 0. 0.
CBAR 63113 615 60301 63113 1. 0. 0.
CBAR 63114 615 63114 60401 1. 0. 0.
| GRID | 63111 | 602  | -22.6378-2.0866-0.5953 602 |
| GRID | 63112 | 602  | -22.6378-2.0866-0.5953 602 |
| GRID | 63113 | 602  | 22.6378-2.0866-0.5953 602 |
| GRID | 63114 | 602  | 22.6378-2.0866-0.5953 602 |
| RBE2 | 63115 | 63111 | 123456 63112 |
| RBE2 | 63116 | 63113 | 123456 63114 |
| $ | Outbd to Mid |
| CBAR | 63121 | 615  | 60702 63121 1. 0. 0. |
| CBAR | 63122 | 615  | 63122 60802 1. 0. 0. |
| CBAR | 63123 | 615  | 60701 63123 1. 0. 0. |
| CBAR | 63124 | 615  | 63124 60801 1. 0. 0. |
| GRID | 63121 | 603  | -22.6378-2.0866 0.5953 603 |
| GRID | 63122 | 603  | -22.6378-2.0866 0.5953 603 |
| GRID | 63123 | 603  | 22.6378-2.0866 0.5953 603 |
| GRID | 63124 | 603  | 22.6378-2.0866 0.5953 603 |
| RBE2 | 63125 | 63121 | 123456 63122 |
| RBE2 | 63126 | 63123 | 123456 63124 |

$ Coordinate Systems

| CORD2R | 600  | 0. 0. 0. 0. 0. 1. +C600 |
| +C600   | 1. 0. |
| $CORD2R | 600  | 445.88 68.025 -9.53 445.88 68.025 -9.53 |
| +C600   | 446.88 68.025 -9.53 |

$ Materials and Properties

| MAT1 | 614  | 8.238+6 3.133+6 |
| MAT1 | 615  | 8.238+6 3.133+6 |
| MAT1 | 623  | 1.218+4 |
| MAT1 | 631  | 2.2336+77.542+6 |
| MAT1 | 632  | 1.3779+74.6412+6 |
| MAT1 | 633  | 2.64+7 1.0153+6 |
| MAT2 | 621  | 2.226+7 3.168+5 0. 2.226+7 0. 5.802+5 0. +MT2A |
| +MT2A | .324-6 .324-6 0. 68. |
| MAT2 | 622  | 1.8710+74.6593+50. 2.5824+70. 5.802+5 0. +MT2B |
| +MT2B | .324-6 .324-6 0. 68. |
| PBAR  | 611  | 631  | 7.44-3 1.2013-21.3935-34.5648-3 |
| PBAR  | 614  | 614  | .15655 1.946-3 5.237-3 7.616-3 .11759 |
| PBAR  | 615  | 615  | .15655 1.946-3 5.979-3 7.616-3 .13236 |
| PSHELL | 601  | 621  | 9.449-3 621 25484. 623 91.67 2.8702-3+PS601 |
| +PS601 | .4378 -.4378 |
| PSHELL | 602  | 622  | 1.1811-2622 16354.1 623 73.33 3.587-3 +PS602 |
| +PS602 | .438976 -.438976 |

$ 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 5.107020E+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 6.036208E-01
Y 8.271776E+01 8.297881E-15 0.000000E+00 6.036208E-01
Z 8.271776E+01 3.319152E-14 1.709532E+02 0.000000E+00

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 *
***

68
### Real Eigenvalues

<table>
<thead>
<tr>
<th>Mode Extraction</th>
<th>Eigenvalue</th>
<th>Radian Frequency</th>
<th>Cyclic Frequency</th>
<th>Generalized Mass</th>
<th>Generalized Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Order</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1.835065E+00</td>
<td>1.354646E+00</td>
<td>2.155986E-01</td>
<td>1.000000E+00</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1.733193E+01</td>
<td>4.163164E+00</td>
<td>6.625881E+01</td>
<td>1.000000E+00</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2.648359E+01</td>
<td>5.146221E+00</td>
<td>8.190466E-01</td>
<td>1.000000E+00</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>8.700010E+01</td>
<td>9.327385E+00</td>
<td>1.484499E+00</td>
<td>1.000000E+00</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>2.850619E+02</td>
<td>1.688378E+01</td>
<td>2.687136E+00</td>
<td>1.000000E+00</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>6.491830E+02</td>
<td>2.547907E+01</td>
<td>4.055120E+00</td>
<td>1.000000E+00</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>1.019662E+03</td>
<td>3.193215E+01</td>
<td>5.082160E+00</td>
<td>1.000000E+00</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>2.025334E+03</td>
<td>4.500371E+01</td>
<td>7.162563E+00</td>
<td>1.000000E+00</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>2.203281E+03</td>
<td>4.693912E+01</td>
<td>7.470593E+00</td>
<td>1.000000E+00</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.468234E+04</td>
<td>1.211707E+02</td>
<td>1.928492E+01</td>
<td>1.000000E+00</td>
</tr>
</tbody>
</table>
## Appendix G
### SSE MACOS Input File

<table>
<thead>
<tr>
<th>Field</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChfRayDir</td>
<td>0.0000000000D+00 0.0000000000D+00 1.0000000000D+00</td>
<td>Channel Ray Direction</td>
</tr>
<tr>
<td>ChfRayPos</td>
<td>0.0000000000D+00 0.0000000000D+00 -1.0000000000D+01</td>
<td>Channel Ray Position</td>
</tr>
<tr>
<td>zSource</td>
<td>1.0000000000D+22</td>
<td>Source Position</td>
</tr>
<tr>
<td>IndRef</td>
<td>1.0000000000D+00</td>
<td>Indirect Reference</td>
</tr>
<tr>
<td>Extinc</td>
<td>0.0000000000D+00</td>
<td>Extinction</td>
</tr>
<tr>
<td>Wavelen</td>
<td>2.8347000000D-05</td>
<td>Wavelength</td>
</tr>
<tr>
<td>Flux</td>
<td>1.0000000000D+00</td>
<td>Flux</td>
</tr>
<tr>
<td>GridType</td>
<td>Circular</td>
<td>Grid Type</td>
</tr>
<tr>
<td>Aperture</td>
<td>17.2</td>
<td>Aperture</td>
</tr>
<tr>
<td>Obscuratn</td>
<td>0.0000000000D+00</td>
<td>Obscuration</td>
</tr>
<tr>
<td>nGridpts</td>
<td>100</td>
<td>Number of Grid Points</td>
</tr>
<tr>
<td>xGrid</td>
<td>0.0000000000D+00 0.0000000000D+00 1.0000000000D+00</td>
<td>X Grid</td>
</tr>
<tr>
<td>yGrid</td>
<td>0.0000000000D+00 0.0000000000D+00 1.0000000000D+00</td>
<td>Y Grid</td>
</tr>
<tr>
<td>nElt</td>
<td>9</td>
<td>Number of Elements</td>
</tr>
<tr>
<td>iElt</td>
<td>1</td>
<td>Element Index</td>
</tr>
<tr>
<td>EltName</td>
<td>ring_front</td>
<td>Element Name</td>
</tr>
<tr>
<td>Element</td>
<td>Refractor</td>
<td>Element Type</td>
</tr>
<tr>
<td>Surface</td>
<td>Flat</td>
<td>Surface Type</td>
</tr>
<tr>
<td>KrElt</td>
<td>-1.0000000000D+22</td>
<td>Refractive Index</td>
</tr>
<tr>
<td>KeElt</td>
<td>0.0000000000D+00</td>
<td>Extinction Index</td>
</tr>
<tr>
<td>psiElt</td>
<td>0.0000000000D+00 0.0000000000D+00 -1.0000000000D+00</td>
<td>Psi Index</td>
</tr>
<tr>
<td>VptElt</td>
<td>0.0000000000D+00 0.0000000000D+00 -1.3777300000D+00</td>
<td>Vertex Index</td>
</tr>
<tr>
<td>RptElt</td>
<td>0.0000000000D+00 0.0000000000D+00 -1.3777300000D+00</td>
<td>R Point Index</td>
</tr>
<tr>
<td>Extinc</td>
<td>1.5950590000D+00</td>
<td>Extinction</td>
</tr>
<tr>
<td>nObs</td>
<td>1</td>
<td>Number of Observations</td>
</tr>
<tr>
<td>nECoord</td>
<td>-6</td>
<td>Number of Cordinate Points</td>
</tr>
<tr>
<td>iElt</td>
<td>2</td>
<td>Element Index</td>
</tr>
<tr>
<td>EltName</td>
<td>ring_back</td>
<td>Element Name</td>
</tr>
<tr>
<td>Element</td>
<td>Refractor</td>
<td>Element Type</td>
</tr>
<tr>
<td>Surface</td>
<td>Aspheric</td>
<td>Surface Type</td>
</tr>
<tr>
<td>KrElt</td>
<td>1.3374230000D+01</td>
<td>Refractive Index</td>
</tr>
<tr>
<td>KeElt</td>
<td>0.0000000000D+00</td>
<td>Extinction Index</td>
</tr>
<tr>
<td>psiElt</td>
<td>0.0000000000D+00 0.0000000000D+00 -1.0000000000D+00</td>
<td>Psi Index</td>
</tr>
<tr>
<td>VptElt</td>
<td>0.0000000000D+00 0.0000000000D+00 -1.3747300000D+00</td>
<td>Vertex Index</td>
</tr>
<tr>
<td>RptElt</td>
<td>0.0000000000D+00 0.0000000000D+00 -1.3747300000D+00</td>
<td>R Point Index</td>
</tr>
<tr>
<td>Extinc</td>
<td>1.0000000000D+00</td>
<td>Extinction</td>
</tr>
<tr>
<td>AsphCoef</td>
<td>4.1455200000D-04 -3.4447600000D-06 1.9907500000D-08 0.0000000000D+00</td>
<td>Aspheric Coefficient</td>
</tr>
<tr>
<td>nObs</td>
<td>1</td>
<td>Number of Observations</td>
</tr>
<tr>
<td>iElt</td>
<td>3</td>
<td>Element Index</td>
</tr>
</tbody>
</table>

70
<table>
<thead>
<tr>
<th>EltName</th>
<th>NDfilter_front</th>
<th>Element</th>
<th>Refractor</th>
<th>Surface</th>
<th>Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>KrElt</td>
<td>-1.0000000000D+22</td>
<td>KgElt</td>
<td>0.0000000000+00</td>
<td>psiElt</td>
<td>-1.564298529D-01 -9.876890711D-01</td>
</tr>
<tr>
<td>VptElt</td>
<td>0.0000000000D+00</td>
<td>RptElt</td>
<td>1.901096200D+01</td>
<td>VptElt</td>
<td>7.3367853000D+01</td>
</tr>
<tr>
<td>IndRef</td>
<td>1.454853000D+00</td>
<td>Extinc</td>
<td>0.0000000000D+00</td>
<td>nObs</td>
<td>0</td>
</tr>
<tr>
<td>ApType</td>
<td>Circular</td>
<td>ApVec</td>
<td>3.000000000D+00</td>
<td>zElt</td>
<td>1.000000000D+22</td>
</tr>
<tr>
<td>PropType</td>
<td>Geometric</td>
<td>nECoord</td>
<td>-6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EltName</th>
<th>NDfilter_back</th>
<th>Element</th>
<th>Refractor</th>
<th>Surface</th>
<th>Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>KrElt</td>
<td>-1.0000000000D+22</td>
<td>KgElt</td>
<td>0.0000000000+00</td>
<td>psiElt</td>
<td>-1.564298529D-01 -9.876890711D-01</td>
</tr>
<tr>
<td>VptElt</td>
<td>0.0000000000D+00</td>
<td>RptElt</td>
<td>1.901096200D+01</td>
<td>VptElt</td>
<td>7.3367853000D+01</td>
</tr>
<tr>
<td>IndRef</td>
<td>1.0000000000D+00</td>
<td>Extinc</td>
<td>0.0000000000D+00</td>
<td>nObs</td>
<td>0</td>
</tr>
<tr>
<td>ApType</td>
<td>Circular</td>
<td>ApVec</td>
<td>3.000000000D+00</td>
<td>zElt</td>
<td>1.000000000D+22</td>
</tr>
<tr>
<td>PropType</td>
<td>Geometric</td>
<td>nECoord</td>
<td>-6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EltName</th>
<th>Cylinder_front</th>
<th>Element</th>
<th>Refractor</th>
<th>Surface</th>
<th>Conic</th>
</tr>
</thead>
<tbody>
<tr>
<td>fElt</td>
<td>4.803140000D+00</td>
<td>eElt</td>
<td>0.0000000000+00</td>
<td>KrElt</td>
<td>4.803140000D+00</td>
</tr>
<tr>
<td>KgElt</td>
<td>0.0000000000+00</td>
<td>KgElt</td>
<td>0.0000000000+00</td>
<td>psiElt</td>
<td>-1.564298529D-01 -9.876890711D-01</td>
</tr>
<tr>
<td>VptElt</td>
<td>0.0000000000D+00</td>
<td>RptElt</td>
<td>1.996007600D+01</td>
<td>VptElt</td>
<td>7.357189100D+01</td>
</tr>
<tr>
<td>IndRef</td>
<td>1.996007600D+00</td>
<td>Extinc</td>
<td>0.0000000000D+00</td>
<td>nObs</td>
<td>0</td>
</tr>
<tr>
<td>ApType</td>
<td>Rectangular</td>
<td>ApVec</td>
<td>-1.250000000D+00</td>
<td>zElt</td>
<td>4.803140000D+00</td>
</tr>
<tr>
<td>PropType</td>
<td>Geometric</td>
<td>nECoord</td>
<td>-6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EltName</th>
<th>Cylinder_back</th>
<th>Element</th>
<th>Refractor</th>
<th>Surface</th>
<th>Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>KrElt</td>
<td>-1.0000000000D+22</td>
<td>KgElt</td>
<td>0.0000000000+00</td>
<td>psiElt</td>
<td>-1.564298529D-01 -9.876890711D-01</td>
</tr>
<tr>
<td>VptElt</td>
<td>0.0000000000D+00</td>
<td>RptElt</td>
<td>2.018179300D+01</td>
<td>VptElt</td>
<td>7.497176100D+01</td>
</tr>
<tr>
<td>IndRef</td>
<td>2.018179300D+01</td>
<td>Extinc</td>
<td>1.0000000000D+00</td>
<td>nObs</td>
<td>0</td>
</tr>
<tr>
<td>ApType</td>
<td></td>
<td>ApVec</td>
<td></td>
<td>zElt</td>
<td></td>
</tr>
<tr>
<td>PropType</td>
<td></td>
<td>nECoord</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Extinc= 0.0000000000D+00
nObs= 0
ApType= Rectangular
ApVec= -1.2500000000D+00 1.2500000000D+00 -3.2500000000D+00 3.2500000000D+00
zElt= 1.0000000000D+22
PropType= Geometric
nECoord= -6

iElt= 7
EltName= NBPfilter_front
Element= Refractor
Surface= Flat
KrElh= -1.0000000000D+22
KcElt= 0.0000000000D+00
psiel= 0.0000000000D+00 -1.564298529D-01 -9.876890711D-01
VptElt= 0.0000000000D+00 2.065109600D+01 7.793482000D+01
RptElt= 0.0000000000D+00 2.065109600D+01 7.793482000D+01
IndRef= 1.454853000D+00
Extinc= 0.0000000000D+00
nObs= 0
ApType= Circular
ApVec= 2.0000000000D+00 0.0000000000D+00 0.0000000000D+00
zElt= 1.0000000000D+22
PropType= Geometric
nECoord= -6

iElt= 8
EltName= NBPfilter_back
Element= Refractor
Surface= Flat
KrElh= -1.0000000000D+22
KcElt= 0.0000000000D+00
psiel= 0.0000000000D+00 -1.564298529D-01 -9.876890711D-01
VptElt= 0.0000000000D+00 2.068238300D+01 7.813235800D+01
RptElt= 0.0000000000D+00 2.068238300D+01 7.813235800D+01
IndRef= 1.0000000000D+00
Extinc= 0.0000000000D+00
nObs= 0
ApType= Circular
ApVec= 2.0000000000D+00 0.0000000000D+00 0.0000000000D+00
zElt= 1.0000000000D+22
PropType= Geometric
nECoord= -6

iElt= 9
EltName= Focal_plane
Element= FocalPlane
Surface= Flat
KrElh= -1.0000000000D+22
KcElt= 0.0000000000D+00
psiel= 0.0000000000D+00 -1.564298529D-01 -9.876890711D-01
VptElt= 0.0000000000D+00 2.101021800D+01 8.020223000D+01
RptElt= 0.0000000000D+00 2.101021800D+01 8.020223000D+01
IndRef= 1.0000000000D+00
Extinc= 0.0000000000D+00
nObs= 0
ApType= Rectangular
zElt= 1.0000000000D+22
PropType= Geometric
nECoord= -6

nOutCord= 5
Tout= 1.0000000000D+00 0.0000000000D+00 0.0000000000D+00 0.0000000000D+00
0.0000000000D+00 0.0000000000D+00 0.0000000000D+00 0.0000000000D+00
0.0000000000D+00 1.0000000000D+00 0.0000000000D+00 0.0000000000D+00
0.0000000000D+00 0.0000000000D+00 0.0000000000D+00

72
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td>1.000000000D+00</td>
<td></td>
</tr>
<tr>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td></td>
</tr>
<tr>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.000000000D+00</td>
<td>0.000000000D+00</td>
<td>1.000000000D+00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

73
Development and Integration of Control System Models

Young K. Kim, Ph.D.

The University of Alabama in Huntsville
Huntsville, Alabama 35899

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

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.

Dynamics, Control, Optics, AXAF-I
SSE, TREETOPS, MACOS

UNCLASSIFIED

UNCLASSIFIED

76