Enhanced Modeling Features Within TREETOPS

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MOTIVATION

The original motivation for TREETOPS was to build a generic multi-body simulation and remove the burden of writing multi-body equations from the engineers. The motivation of the enhancement was twofold: 1)to extend the menu of built in features (sensors, actuators, constraints, etc) that did not require user code and 2)to extend the control system design capabilities by linking with other government funded software (NASTRAN and MATLAB).

These enhancements also serve to bridge the gap between structures and controls groups. It is common on large space programs for the structures groups to build hi-fidelity models of the structure using NASTRAN and for the controls group to build lower order models because they lack the tools to incorporate the former into their analysis. Now the controls engineers can accept the hi-fidelity NASTRAN models into TREETOPS, add sensors and actuators, perform model reduction and couple the result directly into MATLAB to perform their design. The controller can then be imported directly into TREETOPS for non-linear, time-history simulation.

SUMMARY OF ENHANCEMENTS

TREETOPS is more than a time-history simulation. It is a suite of programs oriented toward design and analysis of embedded control systems for flexible spacecraft. The enhancements to TREETOPS can be divided into two categories. *Internal* enhancements add to the menu of time history simulation features and *External* enhancements provide links to other software and provide stand alone utility features.

Internal Enhancements

- Orbital Environment–Standard NASA models of the earth's magnetic field and atmosphere have been added to TREETOPS. You can specify the "shape" of each body and appendage, the orbit and certain atmospheric paramenters and TREETOPS will in turn compute the aerodynamic drag forces. You can also include gravity gradient moments on each body in your model through a simple menu option. The magnetic field operates through magnetic actuators to produce controllable moments at any point on the structure.

- Actuators–The new actuators include reaction wheels, single gimbal control moment gyros (SGCMG), double gimbal CMG's (DGCMG) and seven variations of motor drive actuators.

  The previous actuators were simply input devices that applied a force or moment. The reaction wheels, SGCMG's and DGCMG's have their own dynamics that are closely coupled to the structure dynamics. Furthermore, you can select friction models for the gimbals, such as the Dahl friction model, that are described by non-linear differential equations. When you select one of the actuators from the menu TREE-TOPS will form the associated differential equations augment them to the structure equations and simultaneously solve the complete set.

  The motor drive actuators simulate a wide variety of electric motors driving through gear trains. These models include gear train compliance, backlash, coulomb friction and no-back-drive options. Seven varieties of motor drive actuators have been added to TREETOPS representing different degrees of complexity.

- Devices–the new devices include cables, brakes and locks.

    A cable is connected between any two nodes on the structure and constrains the distance between the two nodes to be less than or equal to the cable length. An alternate way of looking at a cable is that node 2 is constrainted to be within or on a sphere centered at node 1. The sphere radius is equal to the cable length.

    A brake is a device that mounts on a hinge degree of freedom and produces a force that can inhibit motion but not cause motion. The braking force is an input command, just like other actuators, and when the velocity goes to zero a constraint is instituted just like a coulomb damper.

    Locks are like brakes except that they mount between two nodes rather than on a hinge axis.

- Manipulators–Two enchancements have been made to facilitate the simulation of manipulators. The first is a grapple option where the manipulator tip can attach to another point on the structure and create a closed tree topology. The second option is a contact option where the manipulator tip makes contact with a surface producing equal and opposite forces but does not form a closed loop constraint.

- Cut joints–A cut joint facilitates the modeling of closed tree topologies. It lets you constrain any combination of the relative degrees of freedom between two nodes and is specified just like a TREETOPS hinge. A "closed loop constraint" can be thought of as a subset of cut joints because it constrains all 3 relative translations between two nodes but allows all 3 relative rotations.

- Flexibility–Previous versions of TREETOPS had a restriction that the deformation of any flexible body must be zero at the attach point node. This restriction has been removed.

External Enhancements

As stated previously, TREETOPS is a suite of programs for performing analysis, design and simulation of spacecraft control systems. By linking TREE-TOPS with NASTRAN and MATLAB, the job is now much easier. All three programs were developed under government funding and are available free or at low cost. Furthermore, all 3 programs run on UNIX workstations which brings the cost of performing complex design tasks down to an acceptable level.

- TREEFLEX–A new program that links NASTRAN and TREETOPS. Each flexible body in a TREETOPS simulation has certain volume integrals that are required and others that are optional. TREEFLEX will read data from a NASTRAN output file, compute all required volume integrals and write them in the proper format. All data files are in an ASCII format to facilitate transfer of data from one computer to another or from one subcontractor to another. Options are available in TREEFLEX to specify the NASTRAN modes that will be retained, the number of optional terms that will be retained and the damping for each mode. In addition, the computation of augmented modal data has been further automated making it easier to "augment" the modes of inboard bodies to account for the mass and inertia of outboard bodies.

- TREESEL– A model reduction program. A common problem in multibody systems is that the number of system modes which is equal to the sum of individual component modes becomes very large. TREESEL uses a modified Component Cost Analysis (CCA) method to rank individual component modes based on their contribution to overall system costs. The modes having the least impact on system response are then deleted using TREEFLX. In other words, the substructure modes are selected based on system level cost criteria. All model reduction is done in physical coordinates.

- Link to MATLAB–MATLAB is a public domain program, developed under government funding. It provided the basis for several well-known commercial controls analysis programs. We have incorporated the public domain version into the TREETOPS suite because the user interface is well-known and widely accepted. Portability and low cost were emphasized in this link. An ASCII file format was adopted to store linear

system data (ABCD matrix quadruples). TREETOPS writes linear plant models in this format and reads controller models in the same format from the same file. The link to MATLAB was completed by simply adding two functions, one for reading quadruples and the other for writing them.

- TREEFREQ–Frequency domain analysis. This is a post-processor that reads linear system data and performs frequency domain analysis. Poles and zeros are computed, frequency response in computed and plotted in Bode, Nichols or Nyquist format.

- Utility Function–Each of these utilities operates on linear system data.

    – EIGEN computes and prints system Eigen values.

    – LINC will combine several linear systems into one.

    – BL2M converts a block diagram controller into matrix form.

    – SPRT produces a pretty printout of ABCD System quadruples.

EXAMPLE PROBLEM NO. 1 - AXAF

The Advanced X-ray Astrophysics Facility (AXAF) is a proposed NASA spacecraft for the 1990's. It *is* a multi-body spacecraft.

Two different models of the spacecraft were used for two different controller design Tasks. The first task was basic attitude or pointing control in the presence of external disturbances. A three body model was chosen with a rigid core body and two flexible solar panel appendages as sketched in figure 1. A simple proportional-derivative controller, defined in block diagram form, used reaction wheels for actuators and attitude and rate sensors for feedback. Disturbances included aerodynamic drag, gravity gradient and rotating machinery vibrations. Note that no user supplied code is required and the problem is completely defined by the .INT and .FLN files. A typical line-of-sight disturbance response is shown in figure 2.

The second task was to design a closed loop controller for calibrating the optical system. A two body model was used with the optical bench and solar panels combined to form the first rigid body and the High Resolution Mirror Assembly (HRMA) formed the second body as shown in figure 3. Six motor drive actuators in a tripod configuration gave control of all 6 relative degrees of freedom. Relative attitude and rate sensors simulated the optical sensors which are not yet defined. A user controller was incorporated to illustrate the technique of incorporating user supplied code. The pointing system was operating in parallel with the optical calibration system. The .INT file and user controller listing completely defines this problem. The same system model was used to design the actuator servo loop and then to design the controller loops. Figure 4 shows the relative velocity frequency response between two motor drive actuator end points in response to a force input. As you would expect the transfer function is approximately 1/ks and the effect of the other 5 actuators constraining the 6 relative degrees of freedom is negligible for this particular example.

EXAMPLE PROBLEM NO. 2 - SPACE STATION

This example demonstrates the NASTRAN/TREETOPS interface and model reduction procedures as they apply to large dimension, real-world problems.

The NASTRAN model known as the MB-1 configuration was developed by the structures group at NASA Langley Research Center and is shown in

figure 5. The NASTRAN model has 1062 degrees of freedom but only the first 89 modes for each body were computed within NASTRAN giving us the first rough cut model reduction. In the second stage of model reduction TREEFLEX was used to arbitrarily select the first 15 modes for body 1 and the first 50 modes for body 2. This produced a baseline TREETOPS model with 72 DOF's. (6 Rigid body for hinge 1, 15 flex for body 1, 1 rigid for hinge 2 and 50 flex for body 2). The third step was to perform component cost analysis using TREESEL and select a reduced subset of modes based on relative importance. This step reduced the model from 72 to 41 degrees of freedom and further reduction is quite likely for the control design problem. A comparison of the transient response for the 72 and 41 DOF models is presented in figure 6.

IMPORTANCE OF WORK TO COMMUNITY

For many years government funded software has been available to model, analyze and design complex spacecraft systems. Now these software codes have been integrated. With NASTRAN you can create and analyze complex finite element models. TREETOPS can combine these NASTRAN single body models into a multi-body model, add sensors and actuators and linearize the total for use in MATLAB. The controller can be designed in MATLAB and passed back to TREETOPS for verification via non-linear simulation.

Strict adherence to FORTRAN 77 standards enhances TREETOPS portability. All software has been installed on engineering workstations.

No user supplied code is required.

FUTURE DIRECTION

The major complaint against generic, multi-body simulations is run time. We are currently using three approaches to reduce run time: Order-N algorithms, symbolic programming and parallel processing. Order-N and symbolics can be done without compromising portability but parallel processing requires the proper hardware. Two orders of magnitude reduction in run time is feasible without resorting to approximate solutions. This puts a large class of problems in the realm of real time simulation.

The second area of advancement is graphical interfaces. A menu/mouse

method of building models is very desirable but hardware dependent. NASA funded software is already available for 3-D solid modeling and building NAS-TRAN input files. The same 3-D model built with the graphical preprocessor can be used in a graphical post processor to produce movies from your simulation. The simulation merely supplies the coordinate transformation for each of the graphic objects created with the preprocessor.

Last, but not least, a collection of MATLAB macros is being collected to solve the common controls problems.

C.2

Target
Vector

Body #2
Flexible Solar Panel

Pointing
Error

Aerodynamic
drag

Earth
Magnetic
Field

Gravity
Gradient

Rotating
Machinery
Disturbance

Body #1
Rigid Core Body

Rate
and
Attitude
Sensors

Body #3
Flexible Solar Panel

Magnetic
Actuator
Commands

Reaction
Wheel
Commands

Pointing
Control
System
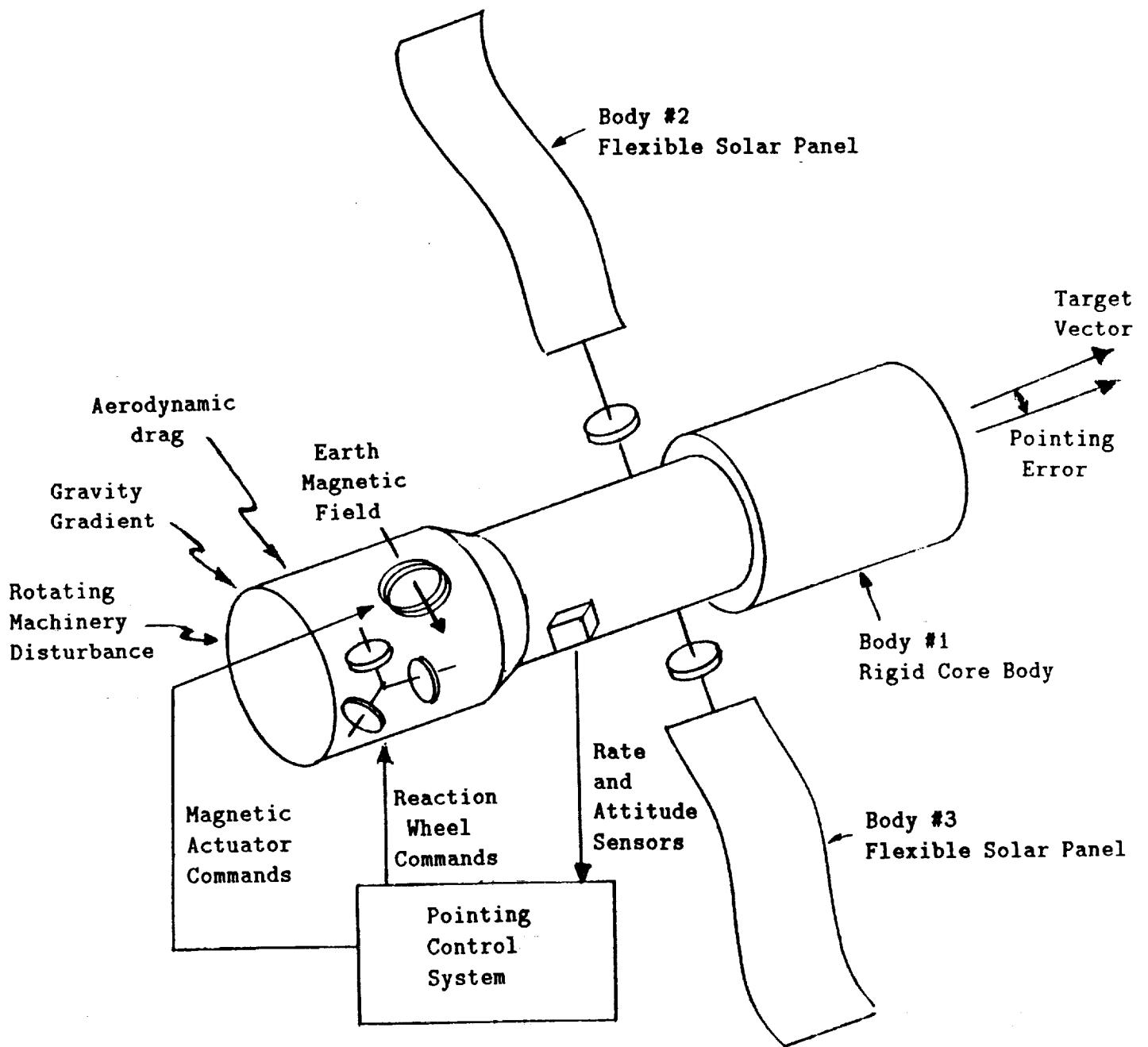
Figure 1   A 3-body representation of the AXAF spacecraft.
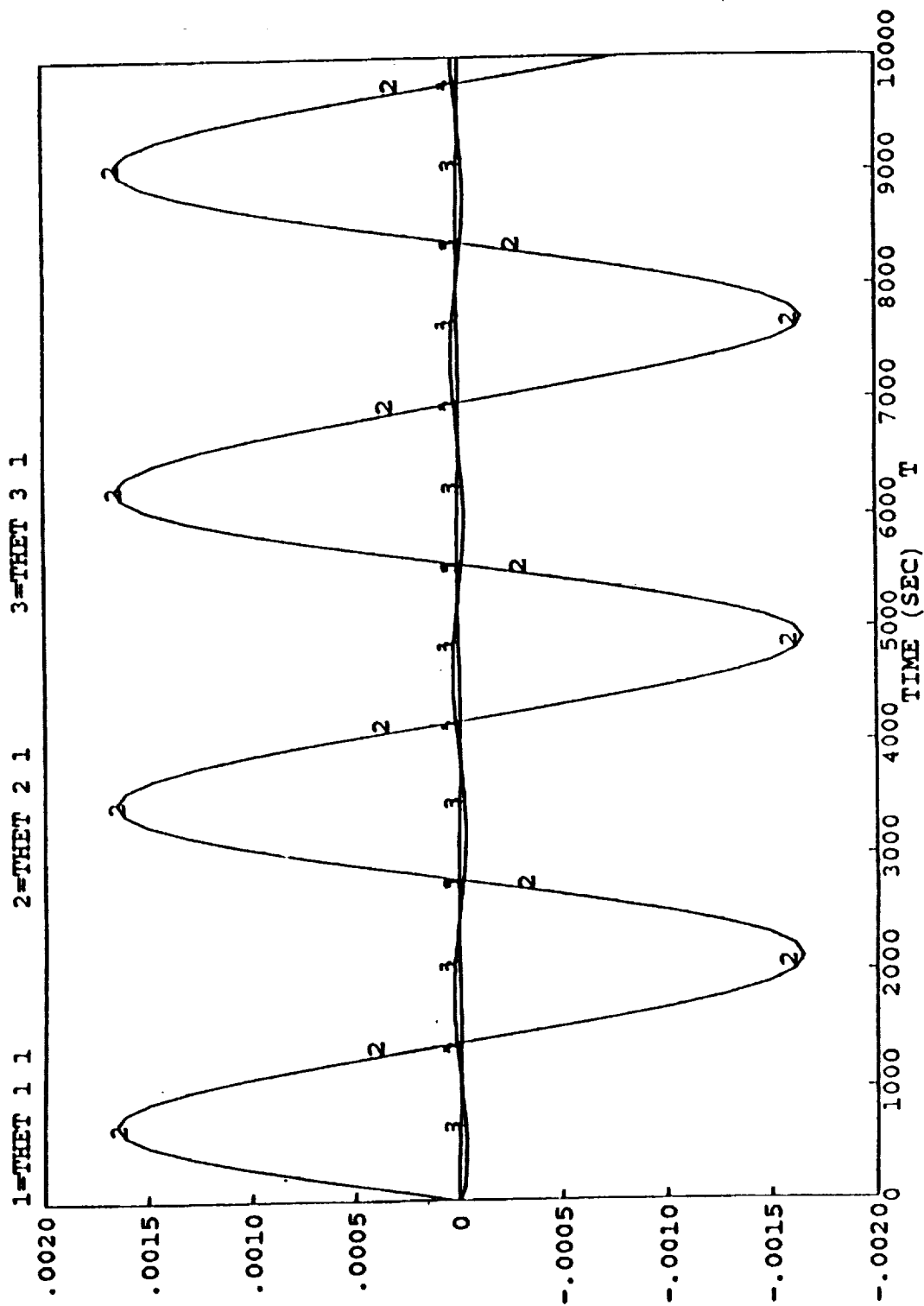
Figure 2   AXAF pointing error response to disturbance inputs.

Optical
Alignment
Controller

Motordrive
Actuator
Commands

Optical
Alignment
Sensors

Body #2
High Resolution
Mirror Assembly
(HRMA)

Body #1
Corebody including
Solar Panels
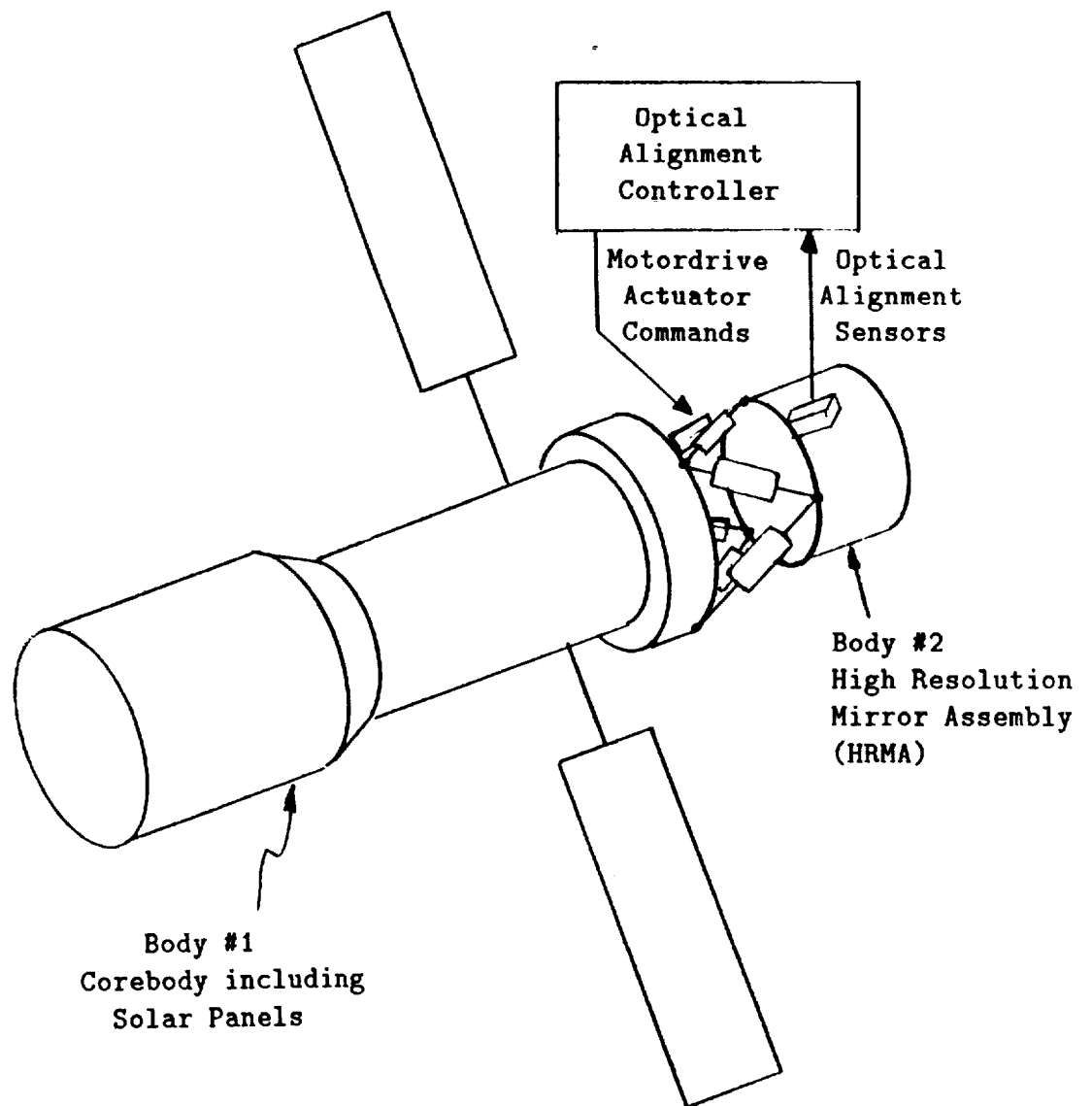
Figure 3   A 2-body representation of the AXAF spacecraft.

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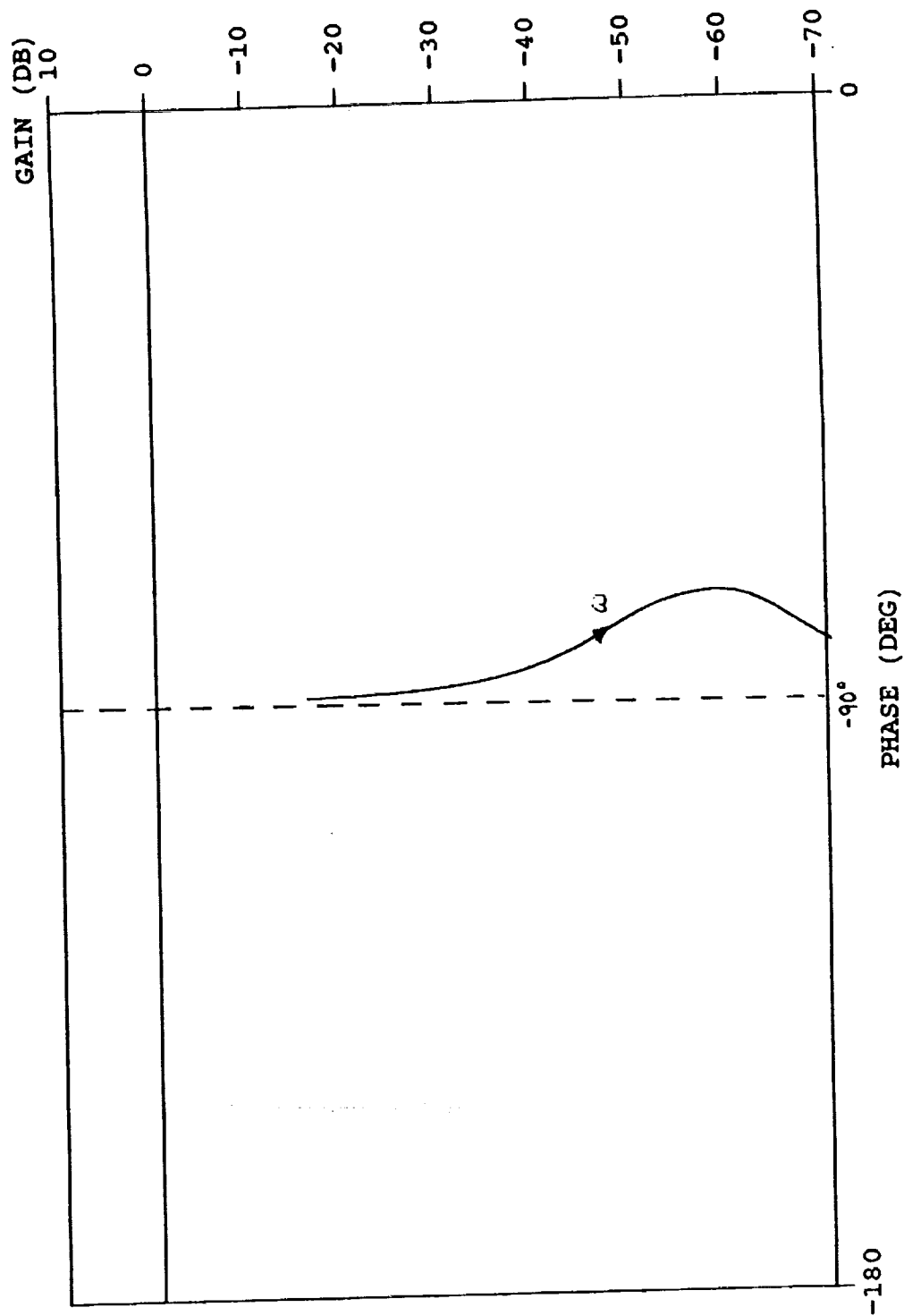
Figure 4   AXAF typical open loop frequency response.
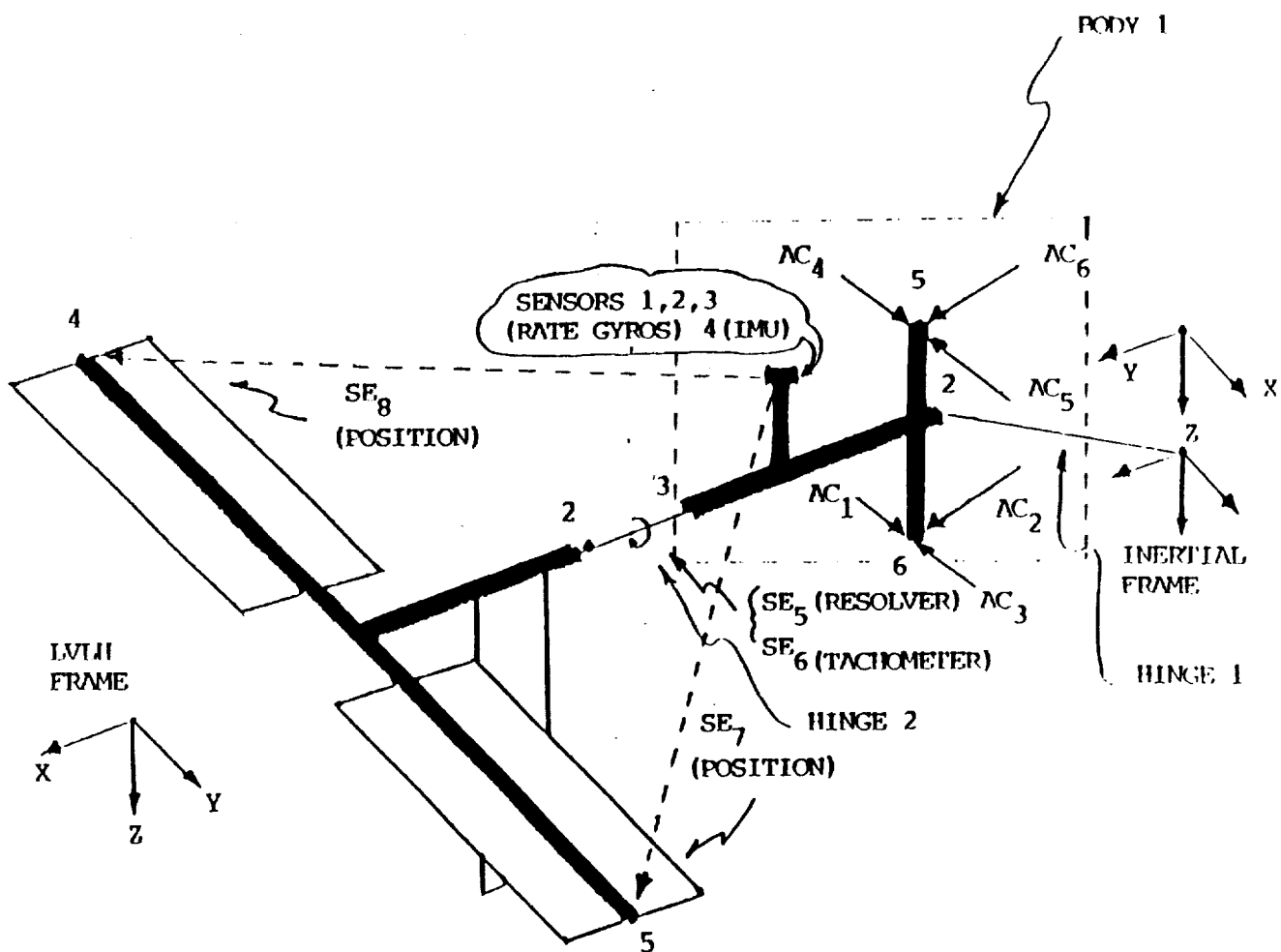
Figure 5   Space Station MB1 configuration.

MB-1.0

FULL (15+50) vs. RED. (15+19)

Flex Deformation (Body Coord.) +x Tip

Tue Jun 27 17:05:13 1989

1=1 UJB 1 2 6   2=2 UJB 1 2 6

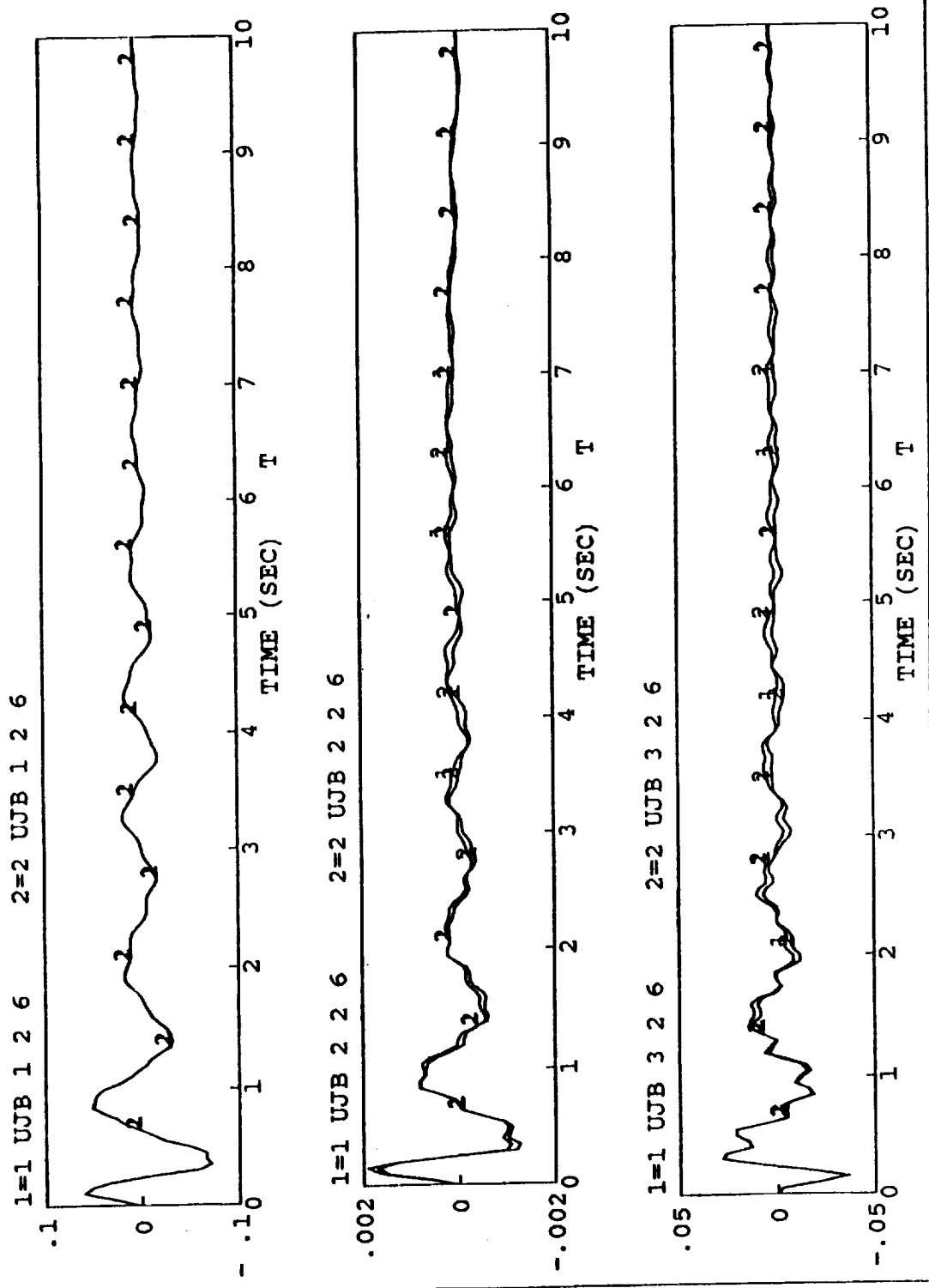1=1 UJB 2 2 6   2=2 UJB 2 2 6

1=1 UJB 3 2 6   2=2 UJB 3 2 6

TIME (SEC)

Figure 6 A comparison of Space Station reduced order models.