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A GENERIC MULTI-FLEX-BODY DYNAMICS, CONTROLS SIMULATION TOOL FOR SPACE STATION

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ABSTRACT

An order (n) multi-flex body Space Station simulation tool is introduced. The flex multibody modeling is generic enough to model all phases of Space Station from build up through to Assembly Complete configuration and beyond. Multibody subsystems such as the Mobile Servicing System (MSS) undergoing a prescribed translation and rotation are also allowed. The software includes aerodynamic, gravity gradient and magnetic field models. User-defined controllers can be discrete or continuous. Extensive preprocessing of body-by-body NASTRAN flex data is built in. A significant aspect, too, is the integrated controls design capability which includes model reduction and analytic linearization.

1.0   INTRODUCTION

The buildup of the International Space Station Freedom evolves through a series of widely differing configuration each with its own unique mass property distribution and ensuing stability and controls issues. Even the relatively mature Assembly Complete configuration can itself undergo significant variation in mass properties when the MSS is in transit and/or carrying out payload maneuvers or during Orbiter docking. In addition to the complications introduced by the multibody articulated nature of these configurations, there is the fact that each component assembly is not rigid but possesses a degree of structural flexibility. To support the controls design and verification for such complex orbiting dynamic systems requires a versatile and high fidelity simulation capability.

This paper describes a dynamics, controls time history simulation software package (SSSIM Rev. 2.0)‡ that specializes a very generic multibody topology to the needs of Space Station with flexibility effects included and is a significant extension of the rigid model described in Ref. 1. Flex modeling is based on a finite element 'nodal' representation compatible with NASTRAN. An efficient preprocessor is used to extract the necessary mass, stiffness and damping characteristics as well as the dynamic rigid/flex coupling coefficients. Calculations can be simplified considerably depending on the nature of the boundary conditions. To minimize the system order, a model reduction feature is built into the code. An interactive setup program aids the user in constructing the data file.

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The intent overall is to have a complete controls design analysis capability, hence, the code includes a series of idealized sensor options and a range of actuator types. The design process is assisted too by a newly developed analytic linearization capability which can linearize about nontrivial states and yields output in a form directly compatible with standard linear analysis tools such as MATLAB. Such features, when combined with a user-defined controller (continuous or discrete), provide a full closed loop large angle transient dynamic analysis tool for Space Station.

An overview follows of basic features and capabilities embodied in the software. As well, an outline is given of the approach used for the flex dynamics formulation and for the solution algorithm (numerous steps are taken to minimize simulation execute times). Preliminary results and run time performance are given for representative Space Station configurations.

2.0 CONFIGURATION AND FLEX DYNAMIC ANALYSIS

2.1 TOPOLOGY

The generic "tree" configuration topology forming the basis for the code is shown in Fig. 1. Any body that has more than one outboard body attached to it is labelled as a "base" body. A "leaf" body has no bodies outboard of it. A "branch" is made up of a chain of adjacent bodies starting with a base body innermost and ending with another base body or a leaf body. The "level" of a branch is a measure of how many base bodies there are between the branch base body and the reference (level 1) base body. Each body is defined on a stand-alone basis without regard to the rest of the bodies in the tree. The sensors, actuators and joints are connected to the bodies at specific locations called node points. Each individual body may be rigid or flexible.
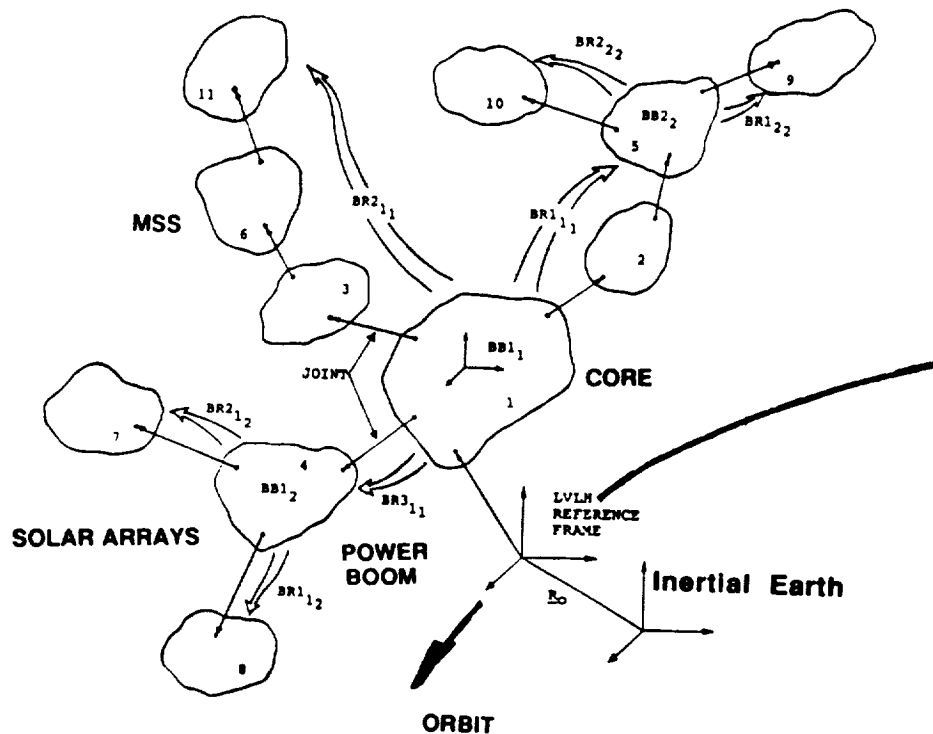

Fig. 1 Generic multibody configuration with a multiple branch, multiple base body hierarchy, point-connected interbody joints and a prescribed orbiting LVLH reference applied to Space Station.

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For applications to Space Station, the structure is assumed to have a core body undergoing up to 3 translational and up to 3 rotational (attitude) degrees of freedom (DOF) relative to the local vertical, local horizontal (LVLH). The frame fixed to LVLH is, in turn, following some predetermined orbital trajectory. All other bodies can have up to one rotational degree of freedom or can have prescribed motions that can occur along one axis for rotation and along up to 3 axes in translation. As indicated in Fig. 1, for example, base body 1 (BB1) can represent the core body and base body 2 (BB2) can be a power boom with leaf bodies 7 and 8 being pairs of solar arrays.

The MSS itself is a complex multibodied subassembly which, when operational, can significantly alter the overall mass properties of the Space Station. MSS-related activies can also generate significant disturbance loads.Consequently, it has served as somewhat of a focal point in development of the SSSIM software. One objective is to have the code generic enough to capture the major dynamic impact of the MSS during its many different configurations and missions. The current software can represent the MSS as an assembly of any number of point-connected bodies. There is no restriction as to body location or as to individual body mass properties. Prescribed motions are possible at joints both in rotation and in translation and are general enough to allow plane change maneuvering. The base body must be rigid if prescribed motions are involved since there are no suitable NASTRAN flex modes available for a translating structure. Payload release is also readily accomodated.

2.2   DYNAMICS FORMULATION OVERVIEW

The order (n) dynamics developed in Ref. 2 for rigid multibody cases is extended to include elastic deformations. Now accelerations associated with the outboard body vibrations are first shifted inboard along with outboard body acceleration. It is beyond the scope of this presentation to go into full detail (Refs. 3, 4) but the basic impact of flexibility on displacement field is shown here in order to appreciate the fundamental nature of the model.

Figure 2 provides a description of body pairs j and $L(j)$. As seen in Figure 2, a "nodal" body representation for flexible bodies is assumed. The nodal body, b_{jo}, will facilitate representation of
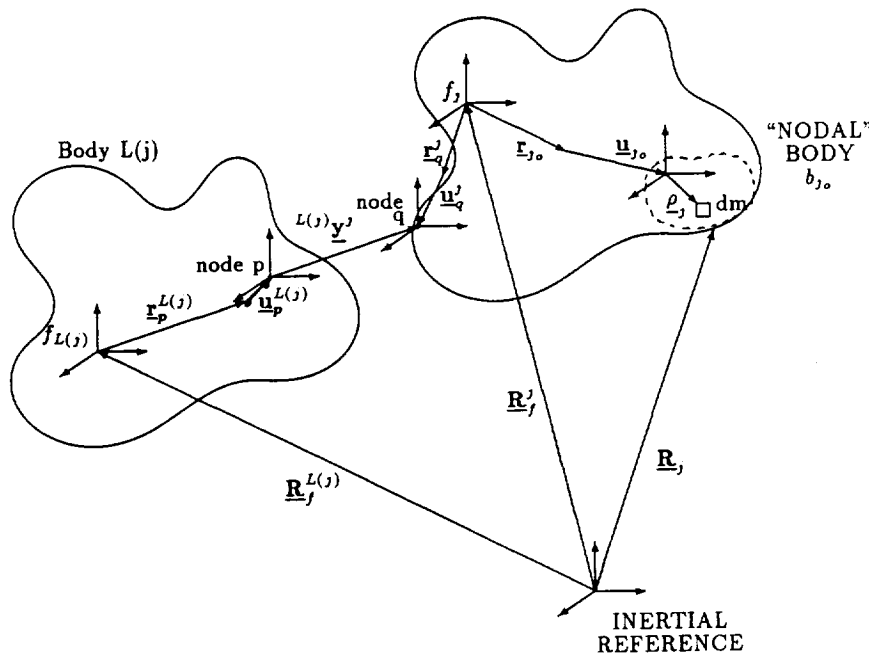

Figure 2   Inboard $(L(j))$ outboard (j) 2-body geometry forms the basis for the recursive kinematics.

discrete nodal data from finite element program NASTRAN, and provides means of accounting for effects such as mass center offset and eccentricity in the dynamics. These effects can arise when, for example, lumped masses are attached at nodes when running NASTRAN. For a consistent finite element formulation, effects such as these result in a coupled nodal mass matrix. In addition to the effects such as eccentricity, it is worth pointing out that this nodal body concept also introduces an additional rotation for mass elements as evident in Figure 2 where the nodal body, b_{jo}, has its' own reference frame. Throughout this text, it will be assumed that the nodal body reference frames are aligned with the body reference frame when the generalized modal coordinates are zero. It is also assumed that the deformations are small so that linear, time invariant, modal data is used.

With the multibody description provided, it is evident that required body data (mass properties, geometry, modal data, etc.) is defined for each body separately in its own reference. The vector location of the mass element, dm, of nodal body b_{jo} of body j is in inertial as follows:

$$\underline{R}_j = \underline{R}_f^j + \underline{r}_{jo} + \underline{u}_{jo} + \underline{\rho}_j$$

where:

$$\underline{R}_f^j \equiv \text{Vector locating body } j$$
$$\text{reference in inertial space}$$

$$\underline{r}_{jo} \equiv \text{Undeformed location vector of}$$
$$\text{nodal body } b_{jo} \text{ reference wrt body } j \text{ reference}$$

$$\underline{u}_{jo} \equiv \text{Vector of linear deformation}$$
$$\text{associated with nodal body}$$
$$b_{jo} \text{ reference wrt body } j \text{ reference}$$

$$\underline{u}_{jo} \overset{\Delta}{=} \sum_{i=1}^{NMj} \underline{\phi}_i^j \, (\underline{r}_{jo}) \, \eta_i^j$$

$$\underline{\rho}_j \equiv \text{Vector locating dm of nodal body } b_{jo} \text{ wrt nodal body}$$
$$b_{jo} \text{ reference (fixed in nodal body } b_{jo} \text{ basis)}$$

The location vector of body j reference in inertial space is defined in a recursive sense via the location of its inboard body and relative joint displacements.

$$\underline{R}_f^j = \underline{R}_f^{L(j)} + (\underline{r}_p^{L(j)} + \underline{u}_p^{L(j)}) + {}^{L(j)}\underline{\gamma}^j - (\underline{r}_q^j + \underline{u}_q^j)$$

where:

$$\underline{R}_f^{L(j)} \equiv \text{Vector locating body } L(j)$$
$$\text{(body directly inboard of body } j)$$
$$\text{reference in inertial space}$$

$$\underline{r}_p^{L(j)} \equiv \text{Vector locating undeformed reference point } p \text{ (point fixed}$$
in Body L(j) for defining joint j)
wrt body L(j) reference, fixed in body $L(j)$

$$\underline{u}_p^{L(j)} \equiv \text{Vector of linear deformation associated with}$$
point p wrt body L(j) reference, fixed in body $L(j)$

$$\underline{u}_p^{L(j)} \triangleq \sum_{i=1}^{NML(j)} \underline{\phi}_i^{L(j)} (\underline{r}_p^{L(j)}) \eta_i^{L(j)}$$

$$^{L(j)}\underline{y}^j \equiv \text{Vector of linear joint } j \text{ displacement of}$$
reference point q in body j wrt
reference point p in body $L(j)$, fixed in reference p
of body $L(j)$

$$^{L(j)}\underline{y}^j \triangleq \sum_{i=1}^{NTj} \underline{g}_i^j y_i^j$$

$$\underline{r}_q^j \equiv \text{Vector locating undeformed reference point}$$
q (point fixed in body j for defining joint j)
wrt body j reference, fixed in body j

$$\underline{u}_q^j \equiv \text{Vector of linear deformation associated with}$$
reference point q wrt body j reference, fixed in body j

$$\underline{u}_q^i \triangleq \sum_{i=1}^{NMj} \underline{\phi}_i^j (\underline{r}_q^i) \eta_i^j$$

The coefficients of h, $\underline{\phi}$, are referred to as "Mode Shape" vectors and are provided via NASTRAN. The model shape vectors are assumed to be time invariant consistent with the assumption that deformation, u, is small. The second generalized coordinate was that associated with joint j displacement, y. The relative displacement of point q in body j with respect to (wrt) point p in body $L(j)$ is written in terms of the orthogonal unit vectors, $\underline{g}^i$ (fixed in the material frame at point p in body $L(j)$) and the generalized translation coordinate y, where i is from 1 to the number of translational degrees of freedom of the joint, NTj.

NMj is the number of modes of body j, NTj is the number of translational degrees of freedom for joint j, and NRj is the number of rotational degrees of freedom for joint j.

Velocity and acceleration follow by differentiation. Here though, only velocity is presented. The acceleration is even more complex. Local material frames will have a relative, local angular velocity with respect to body reference frames due to rotational deformation. For the most part, local rotation due to deformation at the nodal bodies will be neglected in as much as the associated coordinate transformations are not introduced (which would give rise to higher order terms). However, the relative orientation of reference frames particular points will include rotation due to deformation, for example, in computing body j to body $L(j)$ coordinate transformation. Like linear deformation and mode shape vectors, rotation deformation for local angular velocity will use the "Mode Slope Vectors", ϕ' also available from NASTRAN.

Inertial velocity of mass element, dm, of nodal body b_{jo} of body j follows. An open dot above a vector will be used to denote local velocity, whereas a solid dot above a vector will be used to denote an inertial velocity.

Performing the differentiation of the displacement field, the inertial velocity of the mass element is as follows.

$$\dot{\underline{R}}_j = \dot{\underline{R}}_f^j + \underline{\omega}^j \times (\underline{r}_{j_o} + \underline{u}_{j_o}) + \dot{\underline{u}}_{j_o} + \underline{\omega}_o^j \times \underline{\rho}_j$$

where:

$$\dot{\underline{R}}_f^j = \dot{\underline{R}}_f^{L(j)} + \underline{\omega}^{L(j)} \times (\underline{r}_p^{L(j)} + \underline{u}_p^{L(j)}) + \overset{\circ}{\underline{u}}_p^{L(j)} + \underline{\omega}_p^{L(j)} \times {}^{L(j)}\underline{y}^j$$

$$+ \, {}^{L(j)}\overset{\circ}{\underline{y}}^j - \underline{\omega}^j \times (\underline{r}_q^j + \underline{u}_q^j) - \overset{\bullet}{\underline{u}}_q^j$$

$\underline{\omega}^j \equiv$ Angular velocity vector of body j reference in inertial space

$$\underline{\omega}^j \triangleq \underline{\omega}^{L(j)} + \overset{\circ}{\underline{u}}_p^{\prime L(j)} + {}^{L(j)}\underline{\omega}^j - \overset{\circ}{\underline{u}}_q^{\prime j}$$

$\underline{\omega}^{L(j)} \equiv$ Angular velocity vector of body $L(j)$ reference in inertial space

$\underline{\omega}_p^{L(j)} \equiv$ Angular velocity vector of reference at point p in body $L(j)$ wrt inertial space

$$\underline{\omega}_p^{L(j)} \triangleq \underline{\omega}^{L(j)} + \overset{\circ}{\underline{u}}_p^{\prime L(j)}$$

$$\overset{\circ}{\underline{u}}_p^{\prime L(j)} \triangleq \sum_{i=1}^{NML(j)} \underline{\phi}_i^{\prime L(j)}(\underline{r}_p^{L(j)}) \, \dot{\eta}_i^{L(j)}$$

$$^{L(j)}\overset{\circ}{\underline{y}}^j \equiv \sum_{i=1}^{NTj} \underline{g}_i^j \, \dot{y}_i^j$$

$^{L(j)}\underline{\omega}^j \equiv$ Angular velocity vector of reference q wrt reference p

$$^{L(j)}\underline{\omega}^j \triangleq \sum_{i=1}^{NRj} \underline{\ell}_i^j \, (\theta^j) \, \dot{\theta}_i^j$$

$\underline{\omega}_o^j \equiv$ Angular velocity vector of nodal body b_{j_o} reference in inertial space

$$\underline{\omega}_o^j \triangleq \underline{\omega}^j + \overset{\circ}{\underline{u}}_{j_o}^{\prime}$$

$$\overset{\circ}{\underline{u}}_{j_o}^{\prime} \triangleq \sum_{i=1}^{NMj} \underline{\phi}_i^{\prime j}(\underline{r}_{j_o}) \, \dot{\eta}_i^j$$

Also,

$$\overset{\circ}{\underline{u}}_q^{\prime j} \triangleq \sum_{i=1}^{NMj} \underline{\phi}_i^{\prime j}(\underline{r}_q^j) \, \dot{\eta}_i^j$$

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Clearly, flexibility introduces considerable additional algebraic detail, augmenting not just the displacement field but contributing significantly to both translation and rotational velocity.

The Newton, Euler dynamic equation can now be formulated for a 2 body point-connected pair and solved for recursively. The kinematics, dynamics is transformed successively body by body from outermost to the most inboard body frame (which need not be situated at the mass center). Accelerations are then determined for this innermost body based on augmented inertia properties. This solution is propagated outboard to solve for the accelerations of all other bodies. The net effect is a solution algorithm that avoids the need for direct numerical inversion of a high order system mass matrix. Consequently, run time is proportional to number of degrees of freedom (n) - i.e. order (n) - and not to n^2 or n^3 say [2].

3.0   OVERVIEW OF CAPABILITY

3.1   BASIC SUPPORT FEATURES

In addition to high fidelity modeling of the multibody dynamics, the SSSIM Rev. 2.0 software provides the same basic support features common in Ref. 1. These include detailed models of the primary environmental loads in orbit. i.e. the Earth's gravitational effect (including oblateness) and low density aerodynamics (1970 Jacchia atmosphere) applied to flat plate or cylindric surfaces. A magnetic field model is available too and is in use for passive damper studies for early configurations. For controls design purposes, the code includes a series of idealized options such as position sensors, single-axis rate gyros and accelerometers, resolvers, tachometers as well as a control moment gyro (CMG) resolver. Similarly, a range of actuator types are provided which include: reaction jets, torque motors, torque devices, magnetic torques and double-gimbal CMG's. User defined controllers can be continuous or discrete.

The basic simulation capability described above is complemented by a series of enhancements that model disturbance associated with:

- solar radiation pressure
- CMG, torque motor friction effects
- fuel slosh (3 DOF point mass and nonlinear stiffness, damping)
- static, dynamic imbalance for rotating bodies
- fans
- fluid flow (pumps, heat exchangers, throttles)
- start/stop friction of solar array drives, antenna pointing mechanisms
- crew actions (kick-off, sneezing, walking).

Such detailed modeling makes it possible to assess impact of such disturbances on acceleration level at any specified location (i.e. micro "g" impact).

3.2   SUMMARY OF MODELING CAPABILITIES AND LIMITATIONS

Structure. The structure is composed of bodies and joints connected in an open tree topology. You can have any number of bodies. There are two limitations on topology. The joints between adjacent bodies are pin connected and no closed loops ar are allowed.

Bodies. The bodies in SSSIM may be rigid or flexible. All of the data for each individual body is defined in that body's reference frame. For flexible bodies the boundary conditions are arbitrary, i.e., fixed-free, etc. The finite element models for flexible bodies can have point masses or rigid bodies called nodal bodies at each one of the node points. There are 3 limitations on the definitions of bodies. The first is that only normal modes may be used, the second is that deformations must be small, and the third is that the third degree terms in deformation are neglected.

Joints. Each joint connects two adjacent bodies. The degrees of freedom at each joint can be prescribed, free, or locked and large angle rotations and translations are allowed. Initial values of the coordinates for locked degrees of freedom are allowed. Joint 1 connects the core body to the local vertical reference frame and is treated differently from all the remaining joints. The number of prescribed and free degrees of freedom is limited as defined in Table 1. An additional limitation is that for each joint with prescribed translation, the inboard body must be rigid.

<div align="center">

TABLE 1   JOINT DOF

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	Allowable Number of DOF's	
	Joint 1	Joints 2-N
Free Rotation	0,1,2,3	0,1
Prescribed Rotation	0	0,1[a]
Free Translation	0,3	0
Prescribed Translation	0	0,1,2,3

[a]If the ith joint has 1 free rotation DOF then it must have 0 prescribed rotation DOF's

Sensors and Actuators. Sensors and actuators are generic in their types and placement. Your can select the types of sensors and actuators from a menu and place them at any node in the structure. The sensors and actuators are limited in that they do not include dynamics or noise with the exception of CMG's and torque motors. CMG dynamics are included and fully coupled with the structure dynamics. Both the CMG and the torque motors have a friction model which may be considered a noise source.

Controllers. The controllers have unlimited capability because they are user supplied subroutines. The continuous controller is called inside the fourth order Runge-Kutta integration loop and the discrete controller is called outside the loop at discrete instants in time. Controllers are limited to only one controller per simulation.

Orbiter Environment. The orbit environment includes a standard NASA atmosphere and magnetic field model. The atmosphere model includes the diurnal bulge and the effect of solar flux and magnetic activity. The primary limitation on the orbit environment is that the orbit is fixed and defined a priori. This means that any forces and moments acting on the structure due to reaction jets, aerodynamic drag, etc. will not change the orbit. The orbital equations are uncoupled form the dynamic equations and solved assuming zero disturbance acceleration. The effect of gravity gradient on the multi-body structure is modeled as a point force and moment applied at the reference frame of each individual body, where the distributed effect of the gravitational disturbance on flexibility has been neglected.

3.3   SPECIAL FEATURES AND ADDED CAPABILITY

The basic SSSIM software has been enhanced considerably in order to support the flex modeling; in order to create a controls analysis tool and in order to improve user friendliness and efficiency. This section outlines the major areas of enhancement.

SETUP Program

A considerable volume of data can be required to run SSSIM Rev. 2 as the number of bodies and joints grow and with full-up implementation of controllers. A single error in the data file can stop a run and it can be a painstaking process to track down. Program SETUP is designed to assist the user interactively in building up an error-free data file. Data is entered block by block, e.g. body 1, body 2, ...; joint 1, joint 2, ...etc. The user can add, delete and modify any given block of data and error checking is provided.

PREFLX Program

The flex model, as shown earlier, is based on a linear assumed mode representation of the elastic displacement. During solution, the deformation is separated into a space dependent part and a time dependent part. Furthermore, the spatial modal component is discretized into displacements
  for a series of interconnected 'nodal' mass elements analogous to the finite element models used in NASTRAN. This type of modeling ensures compatibility with contractor-supported structural data.
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The purpose of the PREFLX program is to interface with NASTRAN data to form all the modal coefficients and terms needed by SSSIM Rev. 2 to accommodate flex degrees of freedom and to ensure rigid, elastic coupling.

Standard terms include the zeroth order terms $\underline{\alpha}_i^j$, $\underline{h}_i^j$ and the rigid body inertia dyadic, $\underline{I}_{rigid}^j$. The optional terms include the first and second order terms $\underline{M}_i^j$, $\underline{Y}_{ki}^j$ and $\underline{P}_{ki}^j$.

Quantities computed by PREFLX are expressed in the nodal body formulation as:

Zeroth Order Terms

$$\underline{\alpha}_i^j = \frac{1}{m_j} \left\{ \sum_{0=1}^{NNB_j} \int_{b_{jo}} \underline{\phi}_{o_i}^j + \underline{\phi}_{o_i}'^j \times \rho_j \, dm \right\}$$

$$\underline{h}_i^j = \sum_{o=1}^{NNB_j} \int_{b_{jo}} (\underline{r}_{jo} + \underline{\rho}_j) \times \underline{\phi}_{o_i}^j + (\underline{r}_{jo} + \underline{\rho}_j) \times (\underline{\phi}_{o_i}'^j \times \underline{\rho}_j) \, dm$$

$$\underline{I}_{RIGID}^j = \sum_{0=1}^{NNB_j} \int_{b_{jo}} \left((\underline{r}_{jo} + \underline{\rho}_j) \cdot (\underline{r}_{jo} + \underline{\rho}_j) \right) \underline{U} - (\underline{r}_{jo} + \underline{\rho}_j) \cdot (\underline{r}_{jo} + \underline{\rho}_j) \, dm$$

First Order Terms

$$\underline{M}_i^{j} = \sum_{0=1}^{NNB_j} \int_{b_{jo}} (\underline{r}_{jo} + \underline{\rho}_j) \cdot \underline{\phi}_{o_i}^j) \underline{U} - (\underline{r}_{jo} + \underline{\rho}_j) \underline{\phi}_{o_i}^j \, dm$$

$$\underline{N}_i^{j} = \underline{M}_i^{jT}$$

$$\underline{Y}_{ki}^j = \sum_{0=1}^{NNB_j} \int_{b_{jo}} \underline{\phi}_{o_k}^j \times \underline{\phi}_{o_i}^j + \underline{\phi}_{o_k}^j \times (\underline{\phi}_{o_i}'^j \times \underline{\rho}_j)) \, dm$$

Second Order Term

$$\underline{P}_{ki}^j = \sum_{0=1}^{NNB_j} \int_{b_{jo}} (\underline{\phi}_{o_k}^j \cdot \underline{\phi}_{o_i}^j) \underline{U} - \underline{\phi}_{o_k}^j \underline{\phi}_{o_i}^j \, dm$$

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where,

$$m_j = \text{Mass of } j^{th} \text{ Body}$$

$$\underline{\rho}_j = \text{Location of } dm \text{ wrt nodal body refrence frame}$$

$$\underline{r}_{jo} = \text{Undeformed location of nodal body refrence frame}$$

$$\underline{\phi}_{oi}^j = \text{Mode Shape of } i^{th} \text{ Mode at } o^{th} \text{ Node on } j^{th} \text{ body}$$

$$\underline{\phi}_{oi}^{\prime j} = \text{Mode Slope of } i^{th} \text{ Mode of } o^{th} \text{ Node on } j^{th} \text{ body}$$

$$\{\cdot\} = 3 \times 1\text{column matrix}$$

$$\{\tilde{\ }\} = \text{Skew symmetric matrix}$$

$$nj = \text{The number of NASTRAN structural nodes}$$

$$nm = \text{The number of retained flexible modes}$$

$$r_c = \text{Rigid body mass center location wrt the body refrence frame}$$

$$M_{nm \cdot nm} = \text{Modal mass matrix}$$

It is evident that considerable computational effort can be required. PREFLX is currently designed to accommodate 2500 node points and up to 250 modes per body.

LINEAR Program

Much control design is based on analysis of a linear systems model. An independent code LINEAR is in place which provide linear analytic modes (about zero or nonzero states). The topology is provided by SETUP. The analytic approach is considerably more accurate and more computationally efficient than its numerical counterpart. The output of this program is deliberately formatted for compatatibility with linear analysis tools such as MATLAB.

MODRED Program

MODRED performs model reduction on the linearized multi-flex-body output fro LINEAR at the component or system level. Three options are provided the user: (1) modified Component Cost Analysis (CCA); (2) CCA with special choice of parameters that yield costs based on controllability, observability Grammians; and (3) system model reduction using a p-q Covariance Equivalent Realization projection approach. Note that component model reduction preserves original coordinates allowing trace back to original flex body source data.

RESTART Option

Long duration runs are typical for Space Station, sometimes just to let the controller establish steady state. With this in mind, a RESTART option is provided to allow a run to be extended. At the end of a run the final system state is stored and used to initialized the data file for the next starting time.

3.4   COMPUTATIONAL CONSIDERATIONS

High fidelity dynamic simulation for an orbiting multibodied system such as Space Station can be computationally intensive. Run times can easily stretch into many hours even for the all-rigid cases. The problem becomes much more serious for flex modeling. Hence, the importance of order (n) modeling and solution. It is the flex cases that require the really high order models.

Other methods are needed to control run times too because of the higher flex frequencies which tend to dictate smaller integration step size. The number of modes retained can be kept to a minimum by carrying out model reduction. The software also provides 'options' to compute only up to zeroth, to first or to second order flex effects. A further innovation is the separate and independent coding of flex equations for differing boundary conditions.

The controls design is sped up too for flex cases by having an 'analytic' as opposed to a 'numeric' linearization. At all stages of development great care is exercised in storing and accessing the potentially large amount of flex data.

In addition to the flex-related steps taken above, the software also minimizes coordinate transformations by allowing only the core body to have up to 6 degrees of freedom whereas all other joints can have up to 1 rotation only (in addition to prescribed motions).

The RESTART capability does not speed up a run but it can remove the need to rerun time histories. Previous runs can be used to start up other longer term case studies as needed.

4.0 THE INTEGRATED SIMULATION, CONTROL SOFTWARE ENVIRONMENT

The capabilities and features discussed are integrated to provide a single time history simulation as well as a frequency domain controls analysis environment as shown in Fig. 3. The Space Station data can include multi-rigid-body configuration and mass properties and/or multi-flex-body NASTRAN structure models.
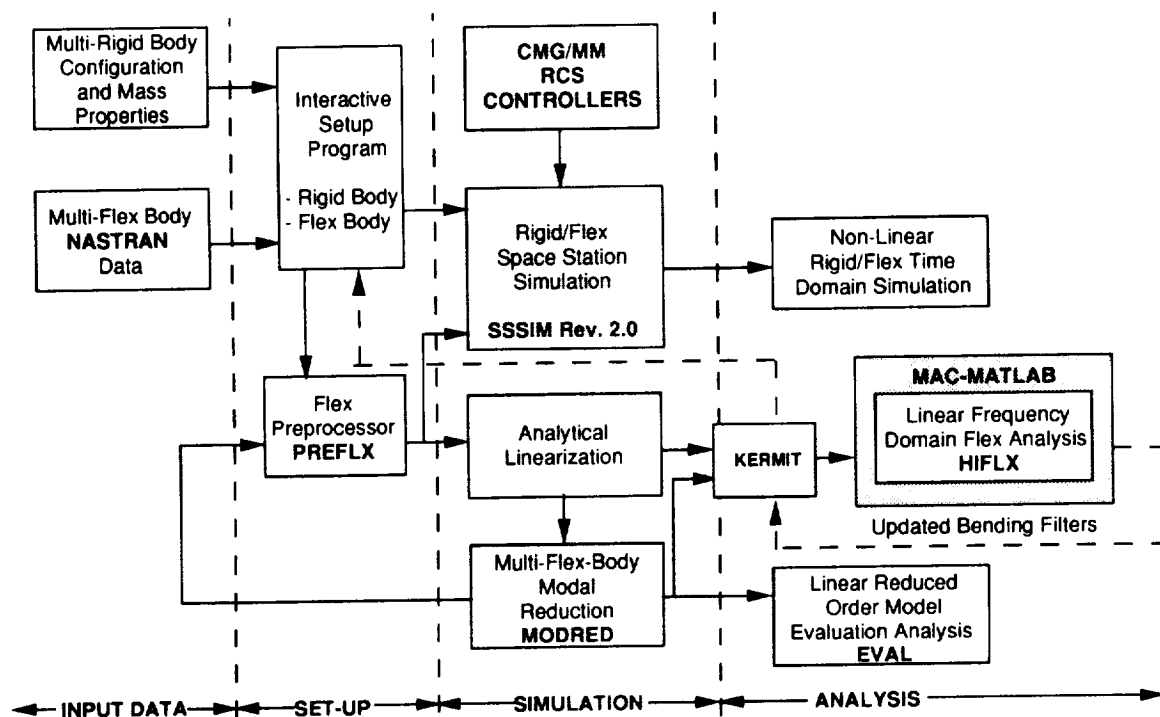

FIG. 3   MULTI-RIGID/FLEX-BODY DYNAMICS AND CONTROLS
ANALYSIS/SIMULATION OVERVIEW

The separate stand-alone programs SETUP, PREFLX, SSSIM Rev. 2, LINEAR, MODRED, EVAL AND HIFLX that make up the SSSIM analysis environment can be applied in various combinations to perform 1. non-linear time history simulation, 2. model reduction, 3. linear system analysis, or 4. micro-gravity studies. The 6 programs are connected via data files that are created by one program and read by another without any user interaction. Three of these programs are interactive: SETUP is the basic model building program, MODRED and EVAL are used for model reduction and prompt the user for model reduction criteria. It is to be noted that all programs reside on a single VAX computer except for HIFLX, which is Macintosh (MAC) based. Data transfer between the VAX and MAC is carried out via the KERMIT program which is a file transfer protocol.

Non-linear, Time-history Simulation. Time-history simulation is primary a three step process using SETUP, PREFLX AND SSSIM. The first step in this process is to define a model and enter the data using SETUP. The structure model is composed of bodies, joints, sensors and actuators.

The second step is to create the flex body data files. The bulk of the data for flexible bodies is handled automatically by PREFLX. A finite element model is created and used by NASTRAN to produce a modal model. PREFLX will read the modal model, compute the necessary modal integrals and form the flex data input file for the SSSIM Rev. 2 core. Once the number of nodes and modes are selected in SETUP, PREFLX takes over.

The third step is to simply execute the time-history simulation program, SSSIM.

Model Reduction. Model reduction is an iterative process. The first step is to create a full order model by running SETUP and PREFLX for the time-history simulation. Then instead of running SSSIM to do the simulation LINEAR is run to create a linear model of the system. The reduced order model is created by truncating flex modes from the full order model just created. MODRED and EVAL rank the modes and help select the retained bodes for the reduced order model. PREFLX is then re-run to create the flex data files for the reduced order model.

Linear System Analysis. A linear model of the system is created by running SETUP, PREFLX AND LINEAR to produce a linear model in the ABCD matrix quadruple format. HIFLX then can add the orbital dynamics, rigid body state estimator dynamics and Control Moment Gyro (CMG), Reaction jet Control System (RCS) controller effects to produce open and closed loop frequency domain as well as linear time domain response (via MATLAB). Any changes in control and filtering, can be fed back to the VAX through KERMIT to perform time-domain simulation.

Micro-Gravity Studies. Micro-gravity analysis is performed by measuring accelerations at one point on the Space station structure caused by forces and moments exerted at different points on the structure. SSSIM has a special provision for performing this analysis. You can select the points at which you want to compute the Micro-gravity accelerations, and you can locate actuators at the points where you want to insert the forces. Time history simulation can be run by connection function generators to the actuators.

5.0   APPLICATION TO SPACE STATION

Preliminary results are presented showing flex time history response and a linear controls design Nichols plot. An earlier Assembly Complete flex configuration is chosen as part of the validation process because of the availability of earlier test case data.

5.1   Simulated Space Station Flex Response

5.1.1   Time History Response

The objective is to simulate the reponse overall and to assess run time performance for a multibodied Space Station with a large number of flex models. The configuration is shown in Fig. 4 divided into 11 separate interconnected segments.

The core truss structure (body 1) is allowed 3 attitude rotations and 3 translations relative to LVLH. Each of the power booms (bodies 2, 3) undergoes a single rotation about a local 'y' axis (a gimbals) while each of the solar arrays (bodies 4 through 11) ar are kept locked (f gimbals). The NASTRAN flex models include: 12 'free-free' modes for the core, 12 'fixed-free' modes for each of the 2 power booms and 12 'fixed-free' modes for each of the 8 solar arrays. Damping ratios of 0.5% are assigned all modes. The simulation is run open-loop without aero drag or gravity. Excitation is by applying an initial 500 lb. pulse over 0.1s along the x axis.

Inertial 3-axis attitude rotations are shown in Fig. 5(a). They are, as expected, quite small (< 0.04 degrees) and there is an oscillatory perturbation induced by the combined flex effect. Generalized coordinates associated with the first three modes of body 1 are plotted in Fig. 5(b). The frequencies are quite low, especially when compared with mode 11 of body 11 (Fig. 5(c)). Overall the results
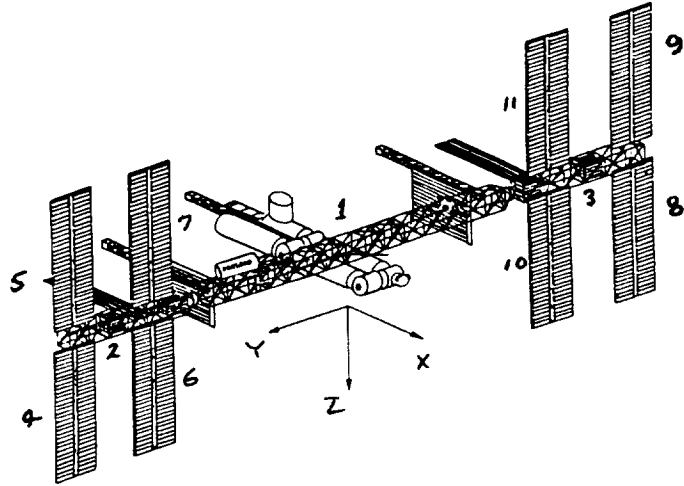
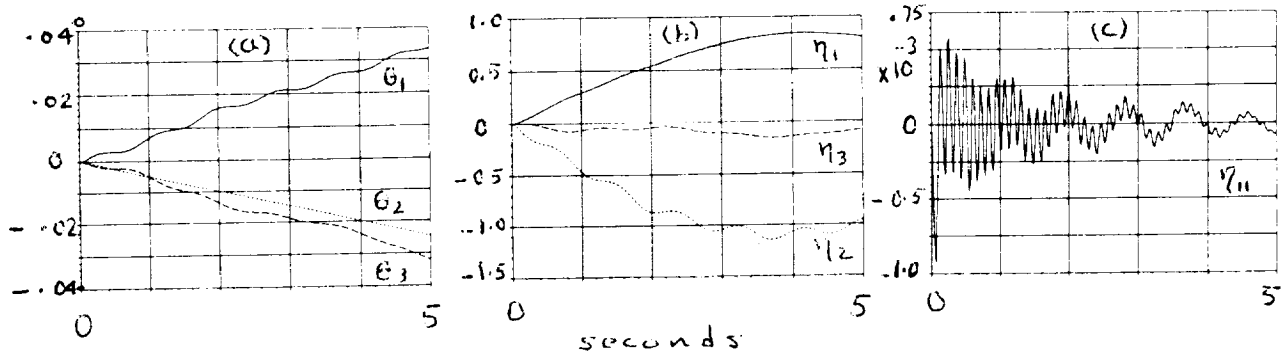Fig. 4 Representative AssemblyComplete Configuration

Fig. 5 Preliminary time history response demonstrating the flex capability of SSSIM Rev. 2.0: (a) attitude of core body relative to LVLH axes (b) generalized flex coordinate for first 3 modes of core body, and (c) generalized flex coordinate of mode 11 of solar array (body 11).

appear to be consistent and all indications are that the flex coupling effects have been captured. The same results are found using the TREETOPS software but much more computer CPU time is needed as discussed below.

5.1.2 Run Time Performance

The 5s simulation for the above case is carried out;t using a 4 term Runge-Kutta integrator at a step size of 0.025s. When run on a Sun Work Station SSSIM Rev. 2.0 requires 36 minutes as opposed to the 13 hours needed to run TREETOPS. The improvement by a factor of at least 20 to 1 is dramatic enough to be evidence of a new era in multibody flex simulation. The improvement is almost as dramatic too by changing hardware to Digital Equipment VAX 6410 processor which completes this 140 DOF run in 3 minutes.

5.2   Linear Controls Analysis

SSSIM Rev. 2.0 also provides the linear models needed to carry out frequency response studies. For example, Fig. 6 shows a typical Nichols diagram generated for reaction jet control (RCS) along the roll (x) axis of an Assembly Complete configuration. The first order state estimator filter operates at 1 radian/s. All flex modes appear to be stable.
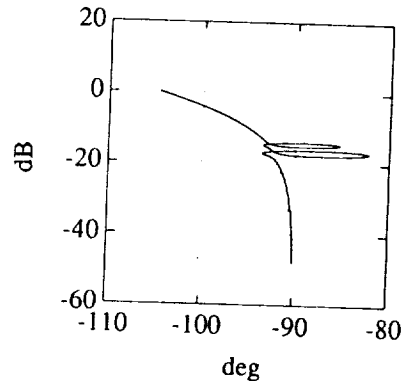

Fig. 4 Typical Assembly Complete 'roll' axis Nichols diagram for RCS.

6.0   CONCLUDING REMARKS AND FUTURE DEVELOPMENT

An order (n) nodal flex multibody model has been successfully developed for Space Station. The improvement in run time performance is significant, exceeding by at least an order of magnitude the existing generic codes (TREETOPS). To accommodate the flex modeling, an efficient preprocessor is built in which converts NASTRAN source data directly to the required input format and computes all additional rigid flex coupling coefficients.

A second major development is integration of the controlsdesign support programs into the SSSIM Rev. 2.0 environment. Analytic linearization and model reduction can now tie in directly with linear analysis software such as MATLAB.

Ongoing efforts include introduction of symbolic processing into solution of equations and into describing elements of the controller as well as of the environmental loads, such as gravity gradient. Alternate integration algorithms and strategies are under investigation, too, as possible means of improving run times.

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2.   Singh, R.P., Schubele, D., and Sunkel, J.W., "Computationally Efficient Algorithm for the Dynamics of Multi-Link Mechanisms," AIAA Guidance, Navigation and Control Conference, Boston, MA, Aug. 14-16, 1989.

3.   Space Station Simulation SSSIM Rev. 2.0 USERS MANUAL, DYNACS Engineering Co. Inc., Clearwater, FL, March 29, 1990.

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5.   Singh, R.P., Vandervoort, R.J., and Likins, P.W., "Dynamics of Flexible Bodies in Tree Topology - A Computer-Oriented Approach." J. Guidance, Control and Dynamics, Vol 8. No. 5, Sept-Oct. 1985, pp. 584-590.
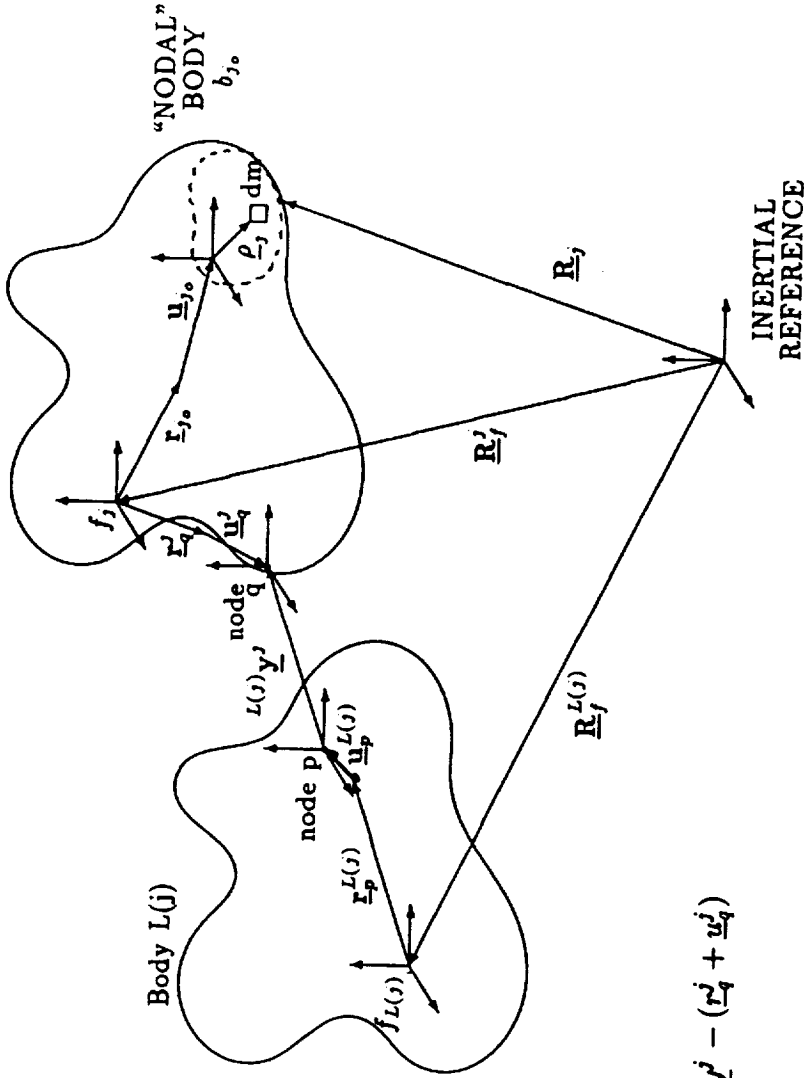
SSSIM REV. 2.0
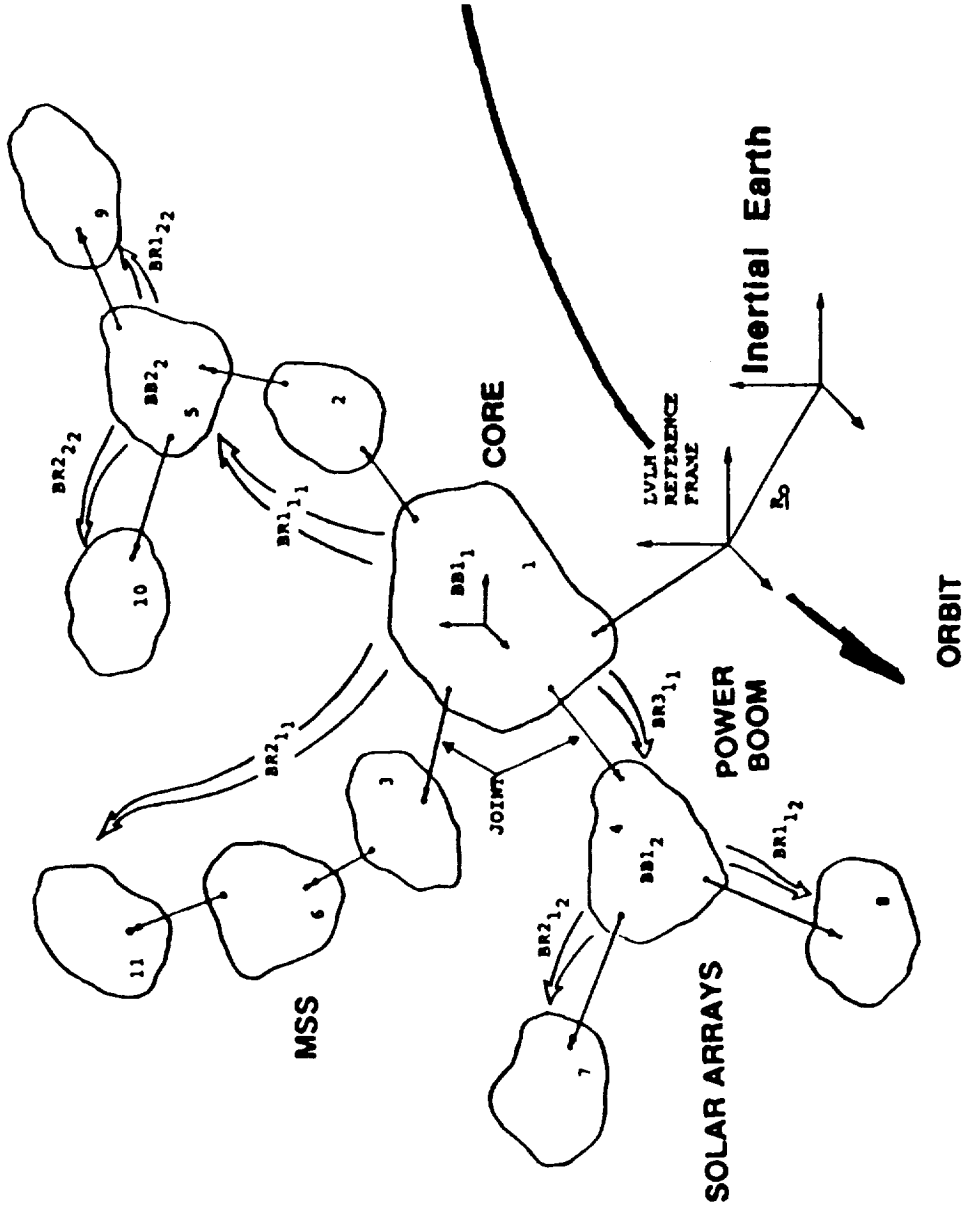
Generic multibody configuration with a multiple branch, multiple base body hierarchy, point-connected interbody joints and a prescribed orbiting LVLH reference applied to Space Station.

SSSIM   REV. 2.0

"NODAL" BODY b_{j_o}

$\square$ dm

ϱ_j

u_{j_o}

r_{j_o}

f_j

u_q^j

r_q^j

node q

${}^{L(j)}y_j$

node p

$u_p^{L(j)}$

$r_p^{L(j)}$

$f_{L(j)}$

Body L(j)

$R_f^{L(j)}$

R_f^j

R_j

INERTIAL REFERENCE

$$u_{j_o} \triangleq \sum_{i=1}^{NMj} \phi_L^i (r_{j_o})\, \eta_i^j$$

$$\underset{=}{u}_{j_o}^{\prime} \triangleq \sum_{i=1}^{NMj} \phi_L^{\prime j} (r_{j_o})\, \eta_i^j$$

$$R_j = R_f^j + r_{j_o} + u_{j_o} + \varrho_j$$

$$R_f^j = R_f^{L(j)} + (r_p^{L(j)} + u_p^{L(j)}) + {}^{L(j)}y_j - (r_q^j + u_q^j)$$

2 BODY GEOMETRY FORMS BASIS FOR RECURSIVE KINEMATICS:
[L(j) = INBOARD
j = OUTBOARD]

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SSSIM REV. 2.0

Multi-Rigid Body Configuration and Mass Properties

Multi-Flex Body **NASTRAN** Data

Interactive Setup Program
- Rigid Body
- Flex Body

Flex Preprocessor **PREFLX**

CMG/MM RCS CONTROLLERS

Rigid/Flex Space Station Simulation
SSSIM Rev. 2.0

Analytical Linearization

Multi-Flex-Body Modal Reduction **MODRED**

Non-Linear Rigid/Flex Time Domain Simulation

MAC-MATLAB
Linear Frequency Domain Flex Analysis **HIFLX**

Updated Bending Filters

KERMIT

Linear Reduced Order Model Evaluation Analysis **EVAL**

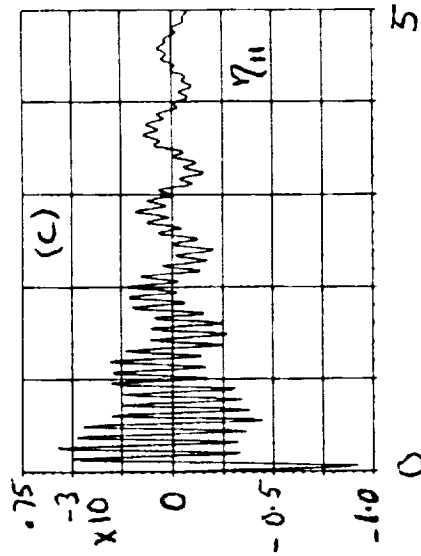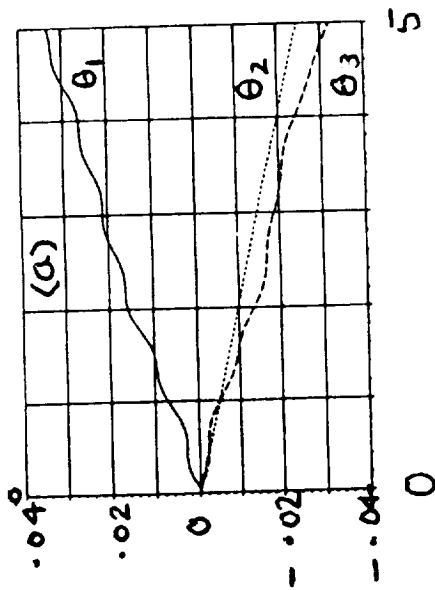←— INPUT DATA —→ ←— SET-UP —→ ←— SIMULATION —→ ←— ANALYSIS —→

INTEGRATED MULTI-RIGID/FLEX-BODY DYNAMICS, CONTROLS SIMULATION, ANALYSIS CAPABILITY

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SSSIM REV. 2.0

B9

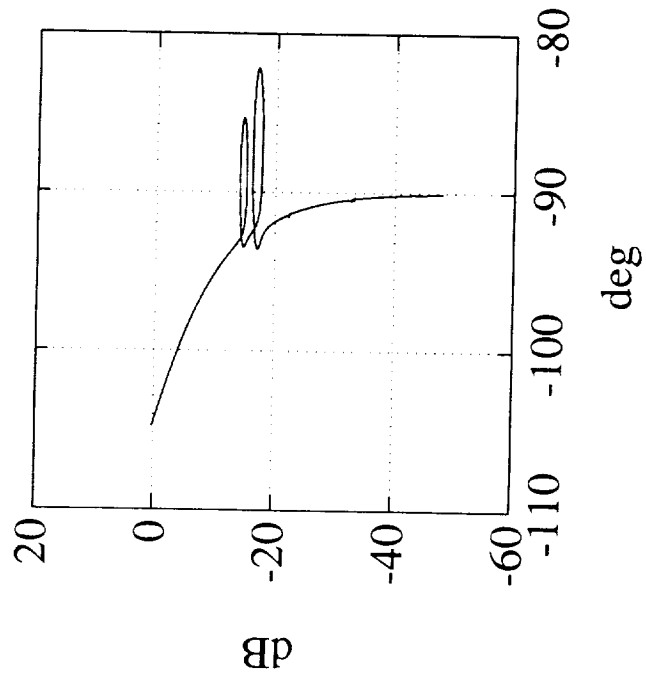B3

B8

B11

B10

B1

B7

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B6

B5

B4

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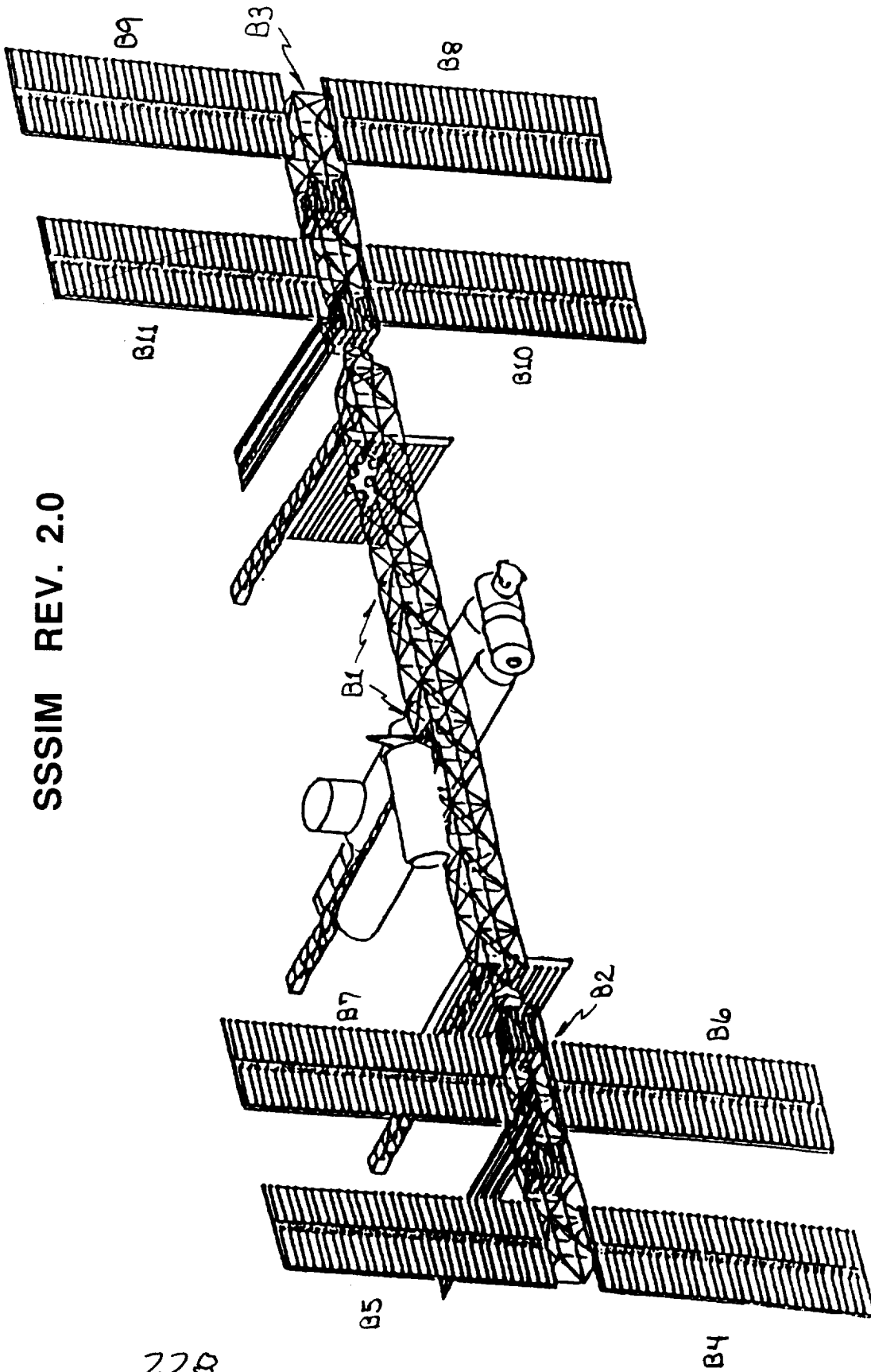
11-BODY BREAKDOWN FOR ASSEMBLY COMPLETE
SPACE STATION TEST CASE

SSSIM REV. 2.0
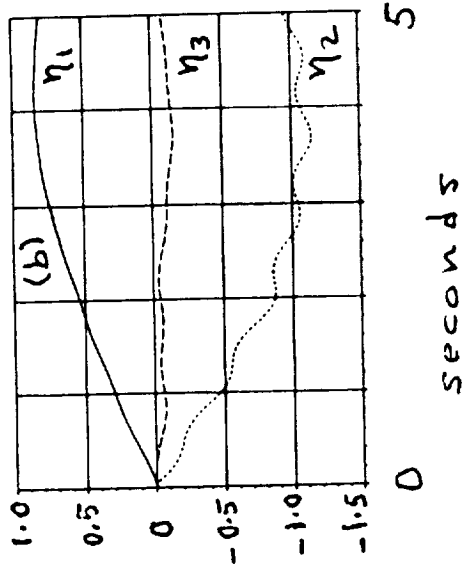
SSSIM REV. 2.0 RESPONSE FOR II-FLEX BODY SPACE STATION
(a) CORE BODY ATTITUDE; (b) CORE BODY GENERALIZED FLEX
COORDINATES; AND (c) BODY II (SOLAR ARRAY) MODE II
GENERALIZED FLEX COORDINATE.

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SSSIM REV. 2.0

NICHOLS DIAGRAM FOR RCS ROLL ('X') AXIS
CONTROL OF ASSEMBLY COMPLETE CONFIGURATION

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