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MULTIDISCIPLINARY ANALYSIS OF ACTIVELY CONTROLLED LARGE FLEXIBLE SPACECRAFT

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Introduction

The COFS program has supported the development of an analysis capability at the Langley Research Center called the Integrated Multidisciplinary Analysis Tool (IMAT) which provides an efficient data storage and transfer capability among commercial computer codes to aid in the dynamic analysis of actively controlled structures. IMAT is a system of computer programs which transfers Computer-Aided-Design (CAD) configurations, structural finite element models, material property and stress information, structural and rigid-body dynamic modal information, and linear system matrices for control law formulation among various commercial applications programs through a common database. Although general in its formulation, IMAT was developed specifically to aid in the evaluation of the transient dynamic response and control of large flexible space structures. This paper contains a description of the IMAT system and results of an application of the system.

- **" Integrated Multidisciplinary Analysis Tool ", IMAT, Developed at NASA Langley Research Center.**
- **IMAT uses executive under interactive user control and common database to store and transfer structural and controls information between commercial codes.**
- **IMAT development supported by the COFS program for application to large flexible spacecraft under active control.**
- **Application to the reference space station and a growth version of the space station will be reviewed.**

Figure 1

Description of IMAT

IMAT consists of an assemblage of pre- and post- processors which, under the control of an interactive executive system, convert and transfer information between application programs through a relational database management program. A simplified schematic of the IMAT system is shown in Fig. 2. A commercial database manager, RIM (Boeing Commercial Services Inc.), forms the basis for storage and distribution of data using a database schema which accepts finite element model information, stiffness and mass matrices, linear system matrices for control studies, and analysis results such as displacements, stresses, and natural modes and frequencies. All data are stored in a generic format, which insures that the data can be shared among different application programs. These data are loaded into or extracted from the database by processors, written in FORTRAN, which format the data for specific applications programs. All input and output of data are controlled interactively by the researcher using a menu driven executive code. The executive control procedures, formulated to direct the transfer and storage of information, are complicated by the fact that the commercial applications programs involved in the creation or use of information reside and operate on computers of three different manufacturers, Control Data Corp., Digital Equipment Corp., and PRIME Inc, each with its own unique operating system. All computer systems are connected by a local area network which can transfer data at approximately 250,000 baud.

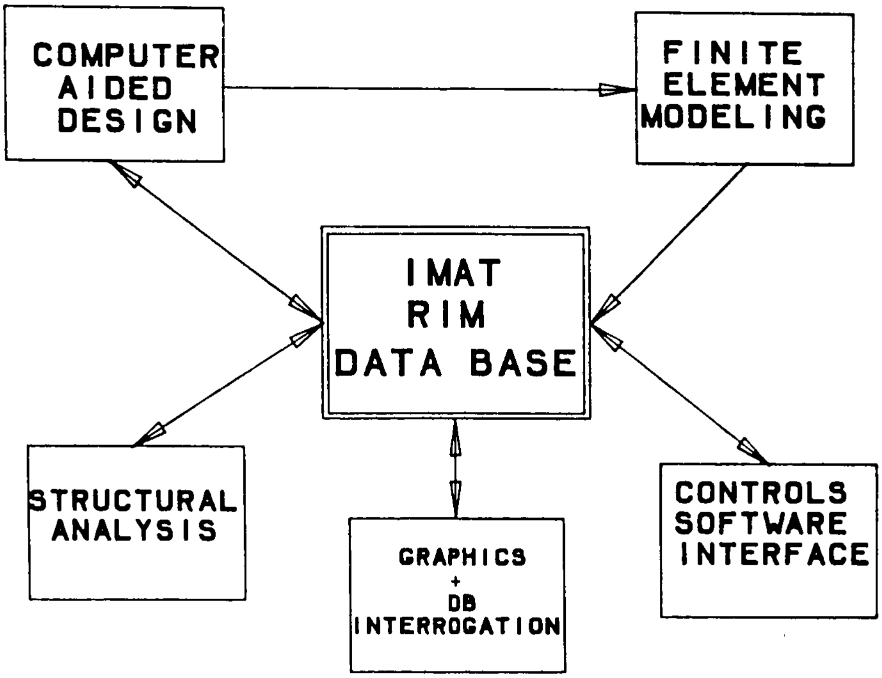


Figure 2

CAD, Finite Element Modeling and Analysis

Fig. 3 describes the codes and data paths available for computer-aided design and finite-element modeling. Wireframe geometry developed using the commercial computer-aided-design code ANVIL (MCS inc.) is converted to input for the commercial finite-element modeling code PATRAN-G (PDA Inc.). A processor stores finite-element model information from PATRAN-G in the database. The second commercial CAD capability available is the 3-D wireframe CAD system CALMA DDM (GE/CAE Inc.), which can transfer geometry information to GEOMOD (SDRC Inc.), a solid modeling code. This latter code can transfer three dimensional information to SUPERTAB (SDRC Inc.), a finite-element modeling code similar to PATRAN-G. A processor similar to that installed between PATRAN-G and the database has been developed to transfer a finite-element model description from SUPERTAB into the database. Entry into IMAT can occur at several different levels: at the CAD or modeling level or simply by loading finite- element model data prepared elsewhere through a processor into the database. Two commercial finite-element solver codes are available: MSC/NASTRAN (MacNeal Schwendler Corp.) and EAL (Engineering Information Systems Inc.). The finite-element data created by PATRAN G or SUPERTAB are stored in a generic format in the database. Processors have been developed which can create an MSC/NASTRAN bulk data input file or an EAL input file. Processors have also been developed which can convert an MSC/NASTRAN bulk data input stream to an equivalent EAL bulk-data input stream and vice-versa. Static and dynamic results obtained from the analysis codes are placed in the database, and are available for inspection or use in performing dynamic analyses or generating linear system matrices for controls analyses.

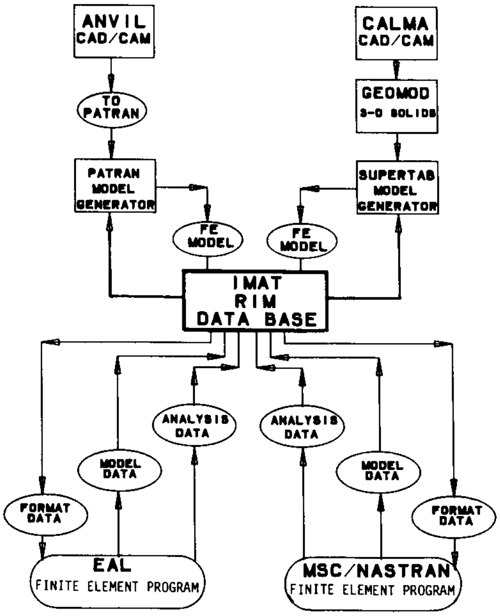


Figure 3

Linear System Matrix Generator

Fig. 4 is a schematic of the interactive capability provided in IMAT for generating linear system matrices for a controls design or analysis. The controls researcher has access to the modal, mass, inertia, and sensor and control influence information through the database interrogation capability. The researcher can use the information to evaluate the significant dynamic modes, select the modes and frequencies of interest used to define the state of the system and obtain the mass and inertia matrices necessary for development of linear system matrices. The user must provide sensor and actuator information as to type and location and must provide a modal damping value for each mode selected to define the state. A processor creates the system matrices which are then stored in the database or are fed directly to a commercial control design and analysis code called MATRIX_x (Integrated Systems Inc.). The controls analyst, external to the IMAT system, develops control laws, and creates state feedback matrices which are stored in the IMAT database.

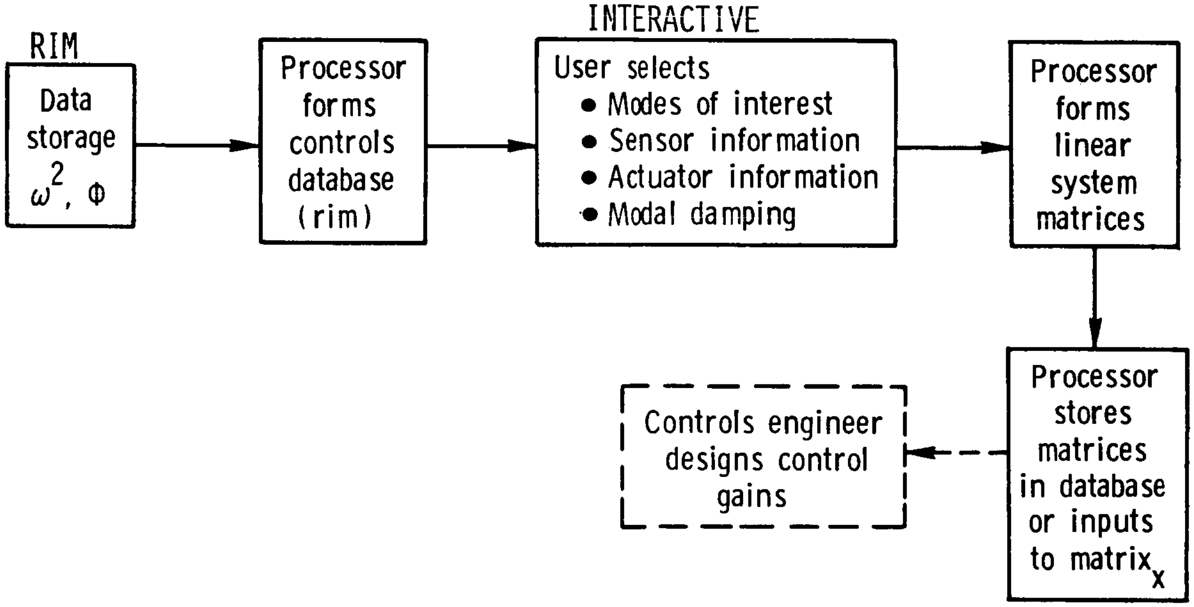


Figure 4

Dynamic Simulation in IMAT

With the control law and the natural modes and frequencies available in the database, the structural dynamicist can use the IMAT capabilities to investigate the dynamic closed-loop transient response of the structure to external disturbances and the control actuator forces. The user defines the information required for his state space matrices including disturbance locations and forces and any structural grid points of interest. The system matrices are computed and transferred to MATRIX_x. The time domain solution procedures of MATRIX_x are exercised to solve for the state vector amplitudes as a function of time. IMAT creates a solution file and transports the file to MSC/NASTRAN. The user can then call the old problem tape with the physical model information and the solution file and use the MSC/NASTRAN output routines to compute physical information such as stress and strain as a function of time in the elements of interest.

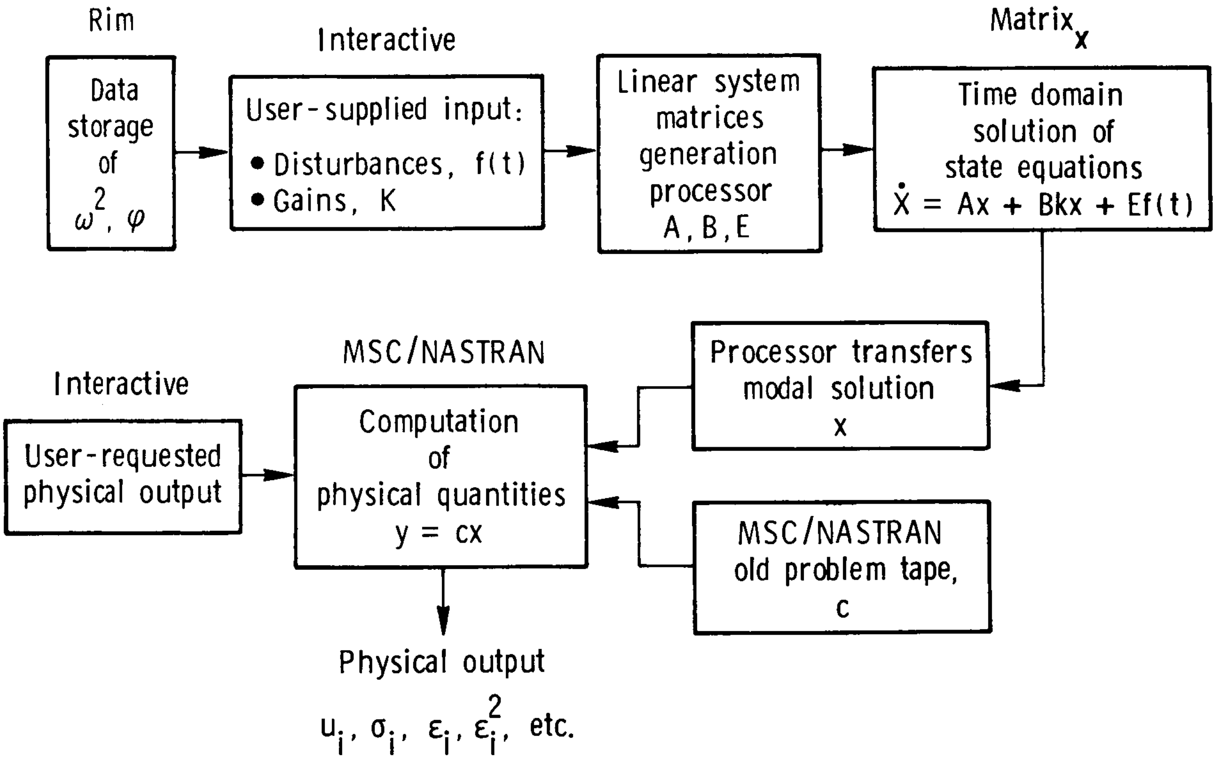


Figure 5

Application to Reference Dual-Keel Space Station

During the definition phase of the NASA Space Station program (Phase B), a reference configuration for the station was developed to serve as a baseline for investigation of the various technical criteria required to build and operate the station and for identification of system engineering and integration issues. One aspect of the phase B study was to evaluate the attitude control characteristics and the elastic dynamic behavior of the station for various expected internal and external disturbances and to investigate the possible interaction between the control system and the elastic response of the system. IMAT was used to define a finite element represenation of the station and determine and store the modes and frequencies preparatory to performing dynamic and control studies. The results of a study of the expected dynamic characteristics of the reference station, i.e. natural modes and frequencies, are presented here as an example of the application of IMAT and to present the frequency and mode characteristics of interest in the COFS 3 studies.

- **Reference station serves as a NASA baseline configuration to investigate technical criteria of the station.**

- **Our interest is to determine the:**
  - **Elastic dynamic characteristics of the station.**
  - **Attitude control characteristics with control sensors observing elastic as well as rigid body motion.**
  - **Closed-loop dynamic response of station to internal and external disturbances.**

Figure 6

Reference Dual-Keel Space Station

The reference station is a dual-keel station with a transverse boom supporting two types of solar power systems, photovoltaic and solar dynamic. The work area of the station is located at the center of the transverse boom and has four life supporting modules, the habitation, laboratory, European, and Japanese modules. The upper boom contains stellar experiment payloads and the lower boom contains earth resource payloads. Station attitude control is provided by control moment gyros located in the first bay of the port transverse boom outboard of the keel. Position and rate sensors are also located in this bay but not co-located with the gyros. Reboost control is provided by four Reaction Control System packages with nine 25 lbf jets in each package. The packages are located on the upper and lower keels.

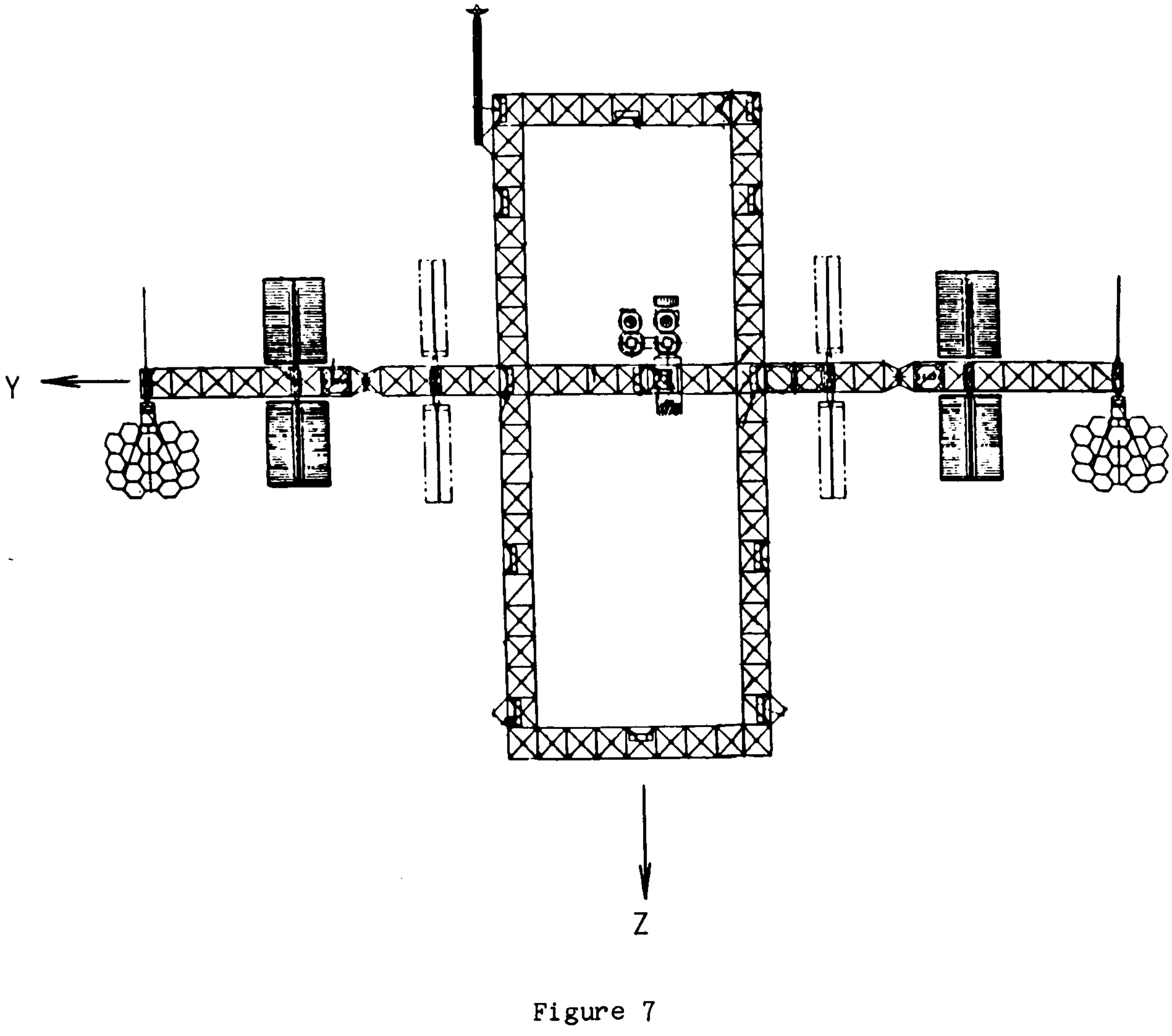


Figure 7

Finite Element Representation

The finite element model is composed of 1312 rod elements and 98 beam elements with 483 nodes and approximately 1700 dynamic degrees of freedom. Each element of the trusswork is represented by a rod element and the modules are represented by beam elements with the equivalent stiffness properties of the module cylinders and connecting components. The truss members are 2.0 inch outside diameter graphite epoxy tubes with a 0.06 inch wall thickness and a longitudinal modulus of elasticity of 40.0×10^6 psi. An approximation of the stiffness characteristics of truss joints is included in the stiffness of the rod elements by reducing the modulus of elasticity for rod element based on the length of the rod element.

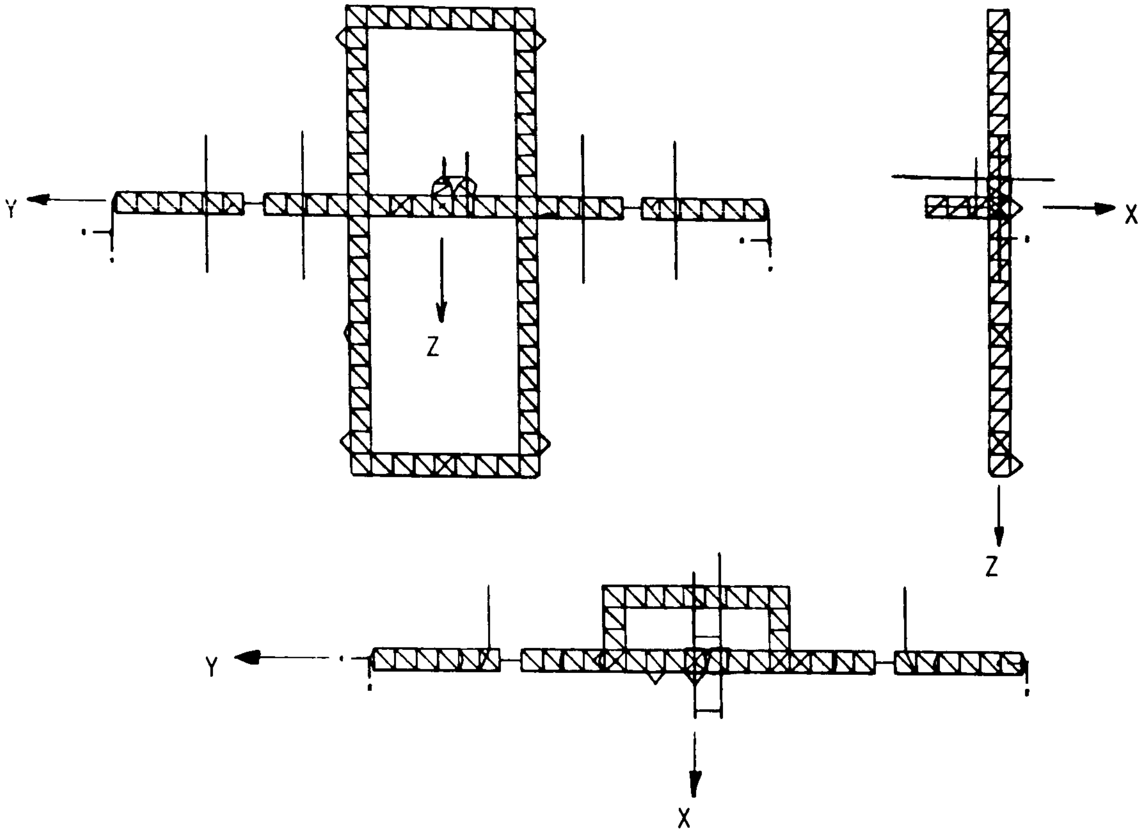


Figure 8

Mass and Inertia Characteristics of the Reference Station

The mass and inertia characteristics of the model are given in the figure. The origin of the coordinate system is located at the center of the central transverse boom between the keels and the positive x axis is taken along the flight direction as shown in figure 8.

FINITE ELEMENT MODEL

O NODES	483
O RODS	1312
O BEAMS	98

MASS AND INERTIA DATA

O TOTAL MASS 571800 LBM

O CG LOCATION

X	-117	INCHES
Y	-65	INCHES
Z	-242	INCHES

O MASS INERTIA AT BASIC COORDINATE SYSTEM OF THE MODEL

I_{XX}	1.00E12	LBM-IN**2
I_{YY}	5.61E11	LBM-IN**2
I_{ZZ}	5.63E11	LBM-IN**2
I_{XY}	1.25E10	LBM-IN**2
I_{XZ}	1.76E10	LBM-IN**2
I_{YZ}	1.71E10	LBM-IN**2

Figure 9

Modes and Frequencies

The natural modes and frequencies of the system below 2 Hz were computed using MSC/NASTRAN and brief descriptions of the modes are given in Fig. 10. Most of the modes encountered in this frequency range are appendage modes (thermal radiators and the photovoltaic power systems) and are of less interest than the framework modes in the evaluation of the overall response of the station due to external loads. The fundamental elastic mode for this model is a framework mode occuring at 0.22 Hz.

MODE	FREQUENCY (HZ)	DESCRIPTION
1-6	0	RIGID BODY
7,8	0.22	TRANSVERSE BOOM BENDING AND TORSION
9	0.25	TRANSVERSE BOOM BENDING AND TORSION
10-19	0.27 - 0.29	INBOARD RADIATORS BENDING
20	0.33	UPPER KEEL BENDING AND TORSION
21	0.36	KEEL TORSION AND TRANSVERSE BOOM BENDING
22	0.43	UPPER AND LOWER KEEL BENDING
23-30	0.45 - 0.47	PHOTOVOLTAIC BENDING
31-35	0.50 - 0.53	PV RADIATOR BENDING
36	0.64	HIGHER MODE TRANSVERSE BOOM BENDING
37-38	0.75, 0.76	ALPHA JOINT TORSION
39-42	0.93 - 1.32	COMPLEX BOOM AND KEEL BENDING AND TORSION
43-50	1.42 - 1.46	INBOARD RADIATOR BENDING
51-59	1.50 - 1.96	COMPLEX FRAME AND APPENDAGE MOTION

Figure 10

Representative Framework Modes of the Reference Station

Fig. 11A shows the fundamental elastic mode of the model which is characterized by transverse boom bending and torsion and occurs at 0.22 Hz. In Fig. 11B a higher upper keel bending mode coupled with transverse boom bending occurs at 0.33 Hz.

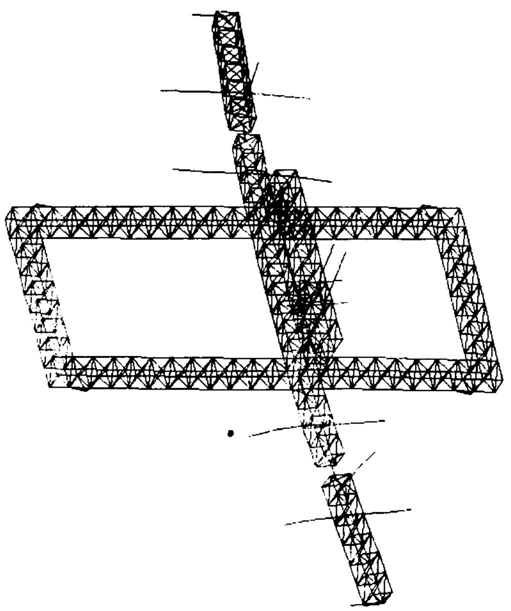


Figure 11A

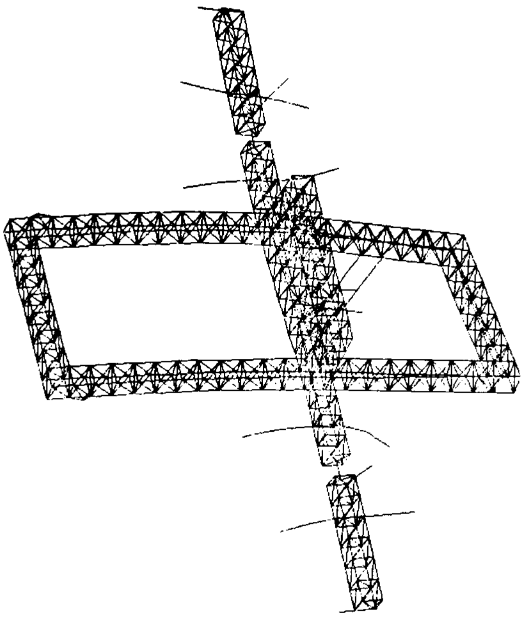


Figure 11B

Attitude Control Study of Growth Station

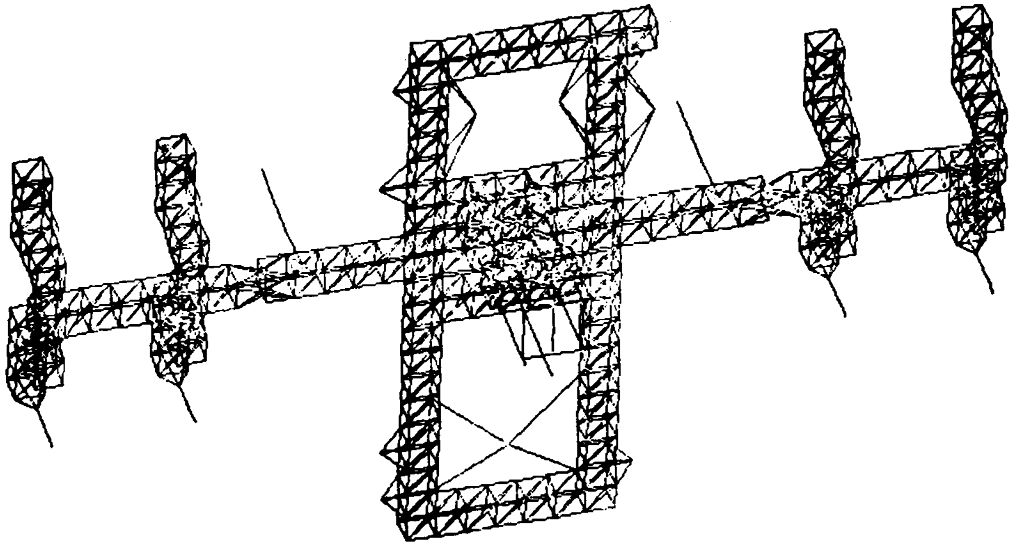
IMAT was used to study the control of a growth version of the dual-keel space station during an orbital reboost maneuver. Because of atmospheric drag, the space station must be reboosted periodically to maintain its desired operational orbit. This maneuver is performed using four constant-thrust reaction- control-system (RCS) jets. The purpose of the control system is to maintain station attitude during the maneuver. In the current study the stability of the attitude control system during reboost and the elastic response of the solar dynamic system sun-line axis are investigated.

- **Dual-keel station has over twice the mass of the reference station.**
- **Study was the response of a solar-dynamic power system to reboost loads.**

Figure 12

Finite Element Model of the Space Station

The growth space station configuration studied has over twice the mass of the reference station described above and is described in ref. 1 which gives a complete description of the masses and locations of the payloads, power systems, heat rejection radiators, subsystems, and the structural properties and dimensions of the truss components and support structures. The control sensors are located at the origin of the coordinate system at the center of the center bay. Four RCS jets are located on the keel structure to provide reboost propulsion and attitude control. To determine the natural modes and frequencies of the space station framework, a detailed finite element model of the station was developed using EAL. The model is shown in Fig. 13 and details of the model and the modes and fequencies are given in ref. 1. The finite-element model with 735 nodes connected by 235 beams and 2110 rods had 2238 dynamic degrees of freedom.



- 735 NODES
- 2238 DYNAMIC DEGREES OF FREEDOM
- 235 BEAM ELEMENTS
- 2110 TRUSS ELEMENTS

Figure 13

Reboost Control Law

Four 75-pound, constant-thrust RCS jets are located with two jets above and two jets below the center of mass of the station on the keels. The jets are aligned with the x-axis of the station so that the thrust is in the orbital direction. The upper- and lower-keel RCS thrusters are located at different distances along the y-axis from the station center of mass. Thus, a reboost maneuver with all thrusters active would produce an unbalanced moment about the y-axis, causing the station to rotate away from its vertical position. The station attitude is kept within desired limits by intermittent firing of the lower- keel RCS jets. The control logic which governs the firing of the lower-keel jets is given in Fig. 14. The logic is designed to hold the pitch attitude of the station within approximately one degree from the local vertical while applying the desired velocity increment along the flight path. The error signal (E) used to control the jet firing is a proportional-plus- differential signal consisting of pitch and pitch rate, $E = \theta_y + K\dot{\theta}_y$, measured at the sensor location. Two control studies were performed. The first study assumed that the error signal contained only rigid body motion, while the second study assumed that the error signal contained both the rigid body motion and the local flexible response at the sensor location. Following the control logic on Fig. 14, all jets are active until the control error reaches 1.0 degree plus a 0.05 degree hysteresis. At this point the lower jets are switched off and the station rotation decelerates and eventually reverses direction. When the error signal returns to 1.0 degree the lower jets are switched on and the process repeats as required.

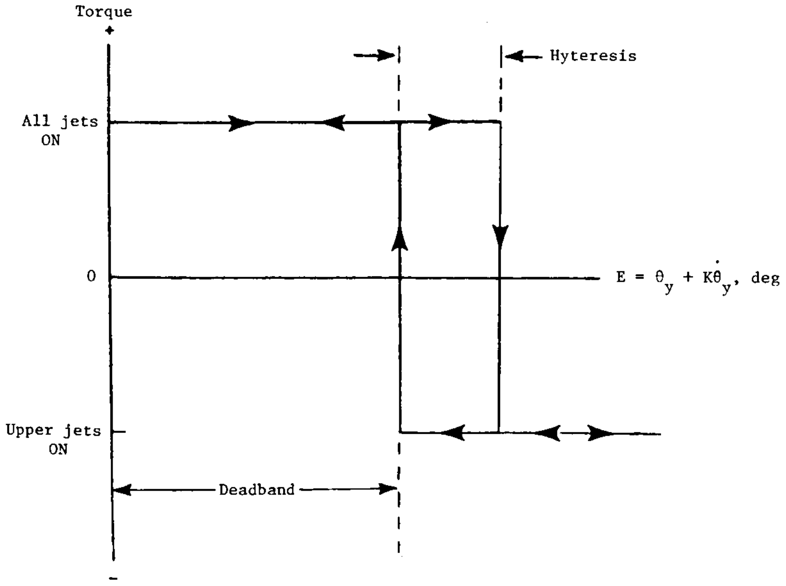


Figure 14

Control Stability

The stability of the reboost control system is illustrated on the pitch vs. pitch rate phase-plane plots of Fig. 15 considering rigid body motion only and with both rigid-body and flexible response included. The inward spiral of the plots indicates that both methods of error signal measurement lead to a stable control system during the time investigated.

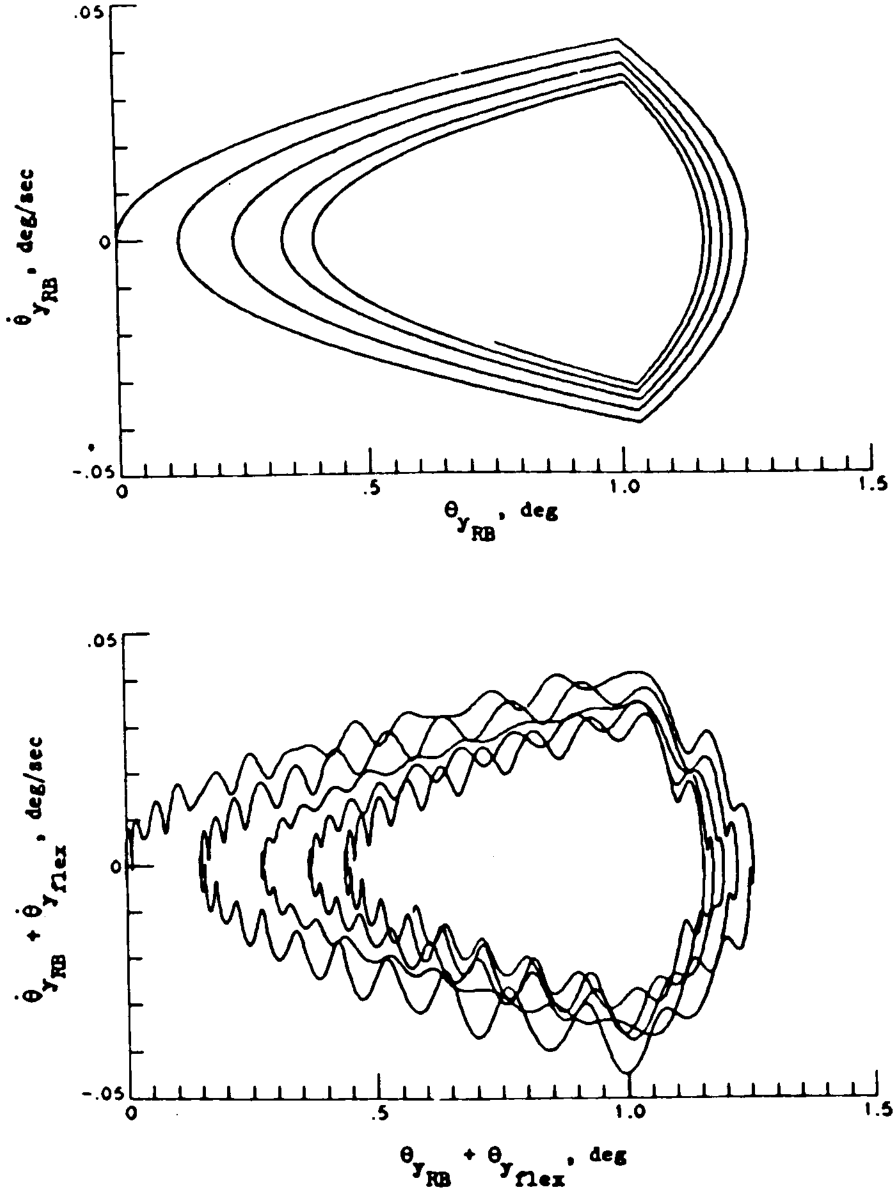


Figure 15

Solar Dynamic System

The station is powered by eight solar dynamic systems located on support structures attached to the transverse beams. A typical solar dynamic system is shown in Fig. 16. For maximum efficiency, the direction of the symmetry axis of each of the solar dynamic systems must be held to within 0.1 degree of the solar vector, even during an orbital reboost maneuver. This is done by controllers which command rotary joints located on the transverse truss and a vernier joint attached to the reflector symmetry axis. For the current study, these controllers are assumed inactive. Of particular interest in the study was the elastic response of the outboard solar dynamic system support structure and its effect on the pointing accuracy of the solar dynamic unit. Accordingly, no attempt was made to define in detail the structure of the solar dynamic system itself or to consider local dynamic response of the components of the systems. The system was represented instead by a rigid frame with the total mass and mass moments of inertia assigned on the frame at the center of mass of each system component. To simplify the problem, the sun-line vector and the x-axis are assumed to be coincident, although in actual practice the sun-line vector is continually rotating at orbital frequency.

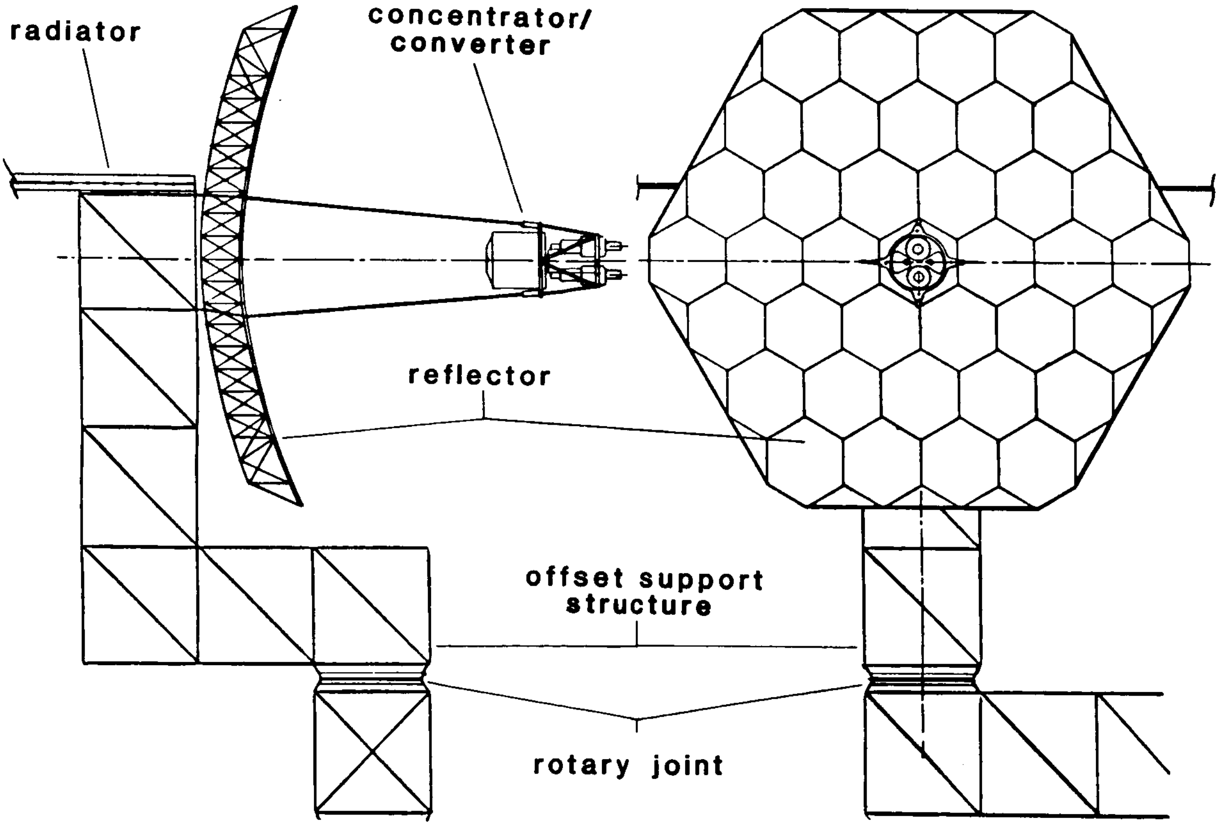


Figure 16

Solar Dynamic System Response.

Shown in Fig. 17 is the flexible component of the rotation of an outboard solar dynamic system symmetry axis during the first 500 seconds of an orbital reboost maneuver. The responses shown are for a rigid body control switching logic. Because of the one-degree deadband requirement in the control logic, the total y-axis pitch always exceeds the 0.1 degree pointing requirement. However, if the rigid body pitch angle were known, it could be nulled using the rotary joints on the transverse boom of the space station. The higher frequency flexible rotation response is well within the 0.1 degree rotation limit imposed for efficient operation of the solar dynamic system. A more complete discussion of the control analysis is given in reference 2.

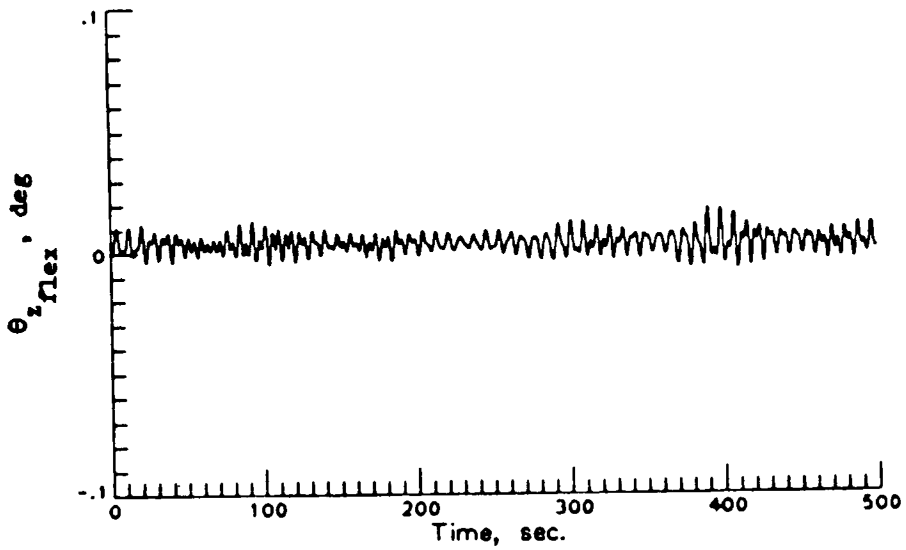


Figure 17

Concluding Remarks

The paper describes a computerized data distribution capability, IMAT, in place at the NASA Langley Research Center for the multidisciplinary analysis of the dynamics and control of large flexible space structures. The paper includes results obtained in using IMAT to investigate the dynamic characteristics of the NASA Dual-Keel Reference Space Station and the influence of structural response of the space station framework on the control of a growth version of the station during an orbital reboost maneuver. The method of control, using a proportional-plus-differential control law, led to a stable control system even with local flexible response measured at the control sensor location included as a part of the control error signal. The flexible response at the outboard solar dynamic system sun-line axis was well within the maximum rotation allowed for efficient operation. The IMAT system can be used to support the COFS program by providing an efficient means for simulating response to given linear control laws for the MAST structure in COFS I and to develop and analyze a scaled space station model for COFS III.

References

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2. Young, John W.; Lallman, Fredrick J.; Cooper, Paul A. and Giesy, Daniel P.: Controls/Structures Interaction Study of Two 300 KW Dual-Keel Space Station Concepts. NASA TM-87679, March 1986.