DYNAMIC CHARACTERISTICS OF SPACE STATION FREEDOM MARS & LUNAR EVOLUTION REFERENCE CONFIGURATIONS

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Introduction

One concept for a manned mission to Mars uses an evolutionary version of Space Station Freedom (SSF) as a transportation node. The station is modified by the addition of dual keels, an upper and lower boom, additional laboratory and habitation modules, increased power and an assembly platform. With these modifications the station is called the Mars Evolution Reference Configuration (MERC). The mass of the station is 65 percent greater than the mass of SSF and its moments of inertia through the mass center are greater by approximately a factor of four. Over a period of months, several flights from Earth to low-Earth-orbit carry the components of a manned Mars piloted vehicle (MPV) to the MERC where the vehicle is constructed on the assembly platform. After each flight the station is reboosted to an appropriate altitude, such that the orbit decay due to atmospheric drag forces lowers the spacecraft to the proper altitude at the appropriate time for rendezvous with the next assembly flight. When the assembly process is completed, the MPV, which has a mass of approximately 200,000 lbm, is situated on the evolutionary station. The mass increase of the MERC with MPV system over SSF is 112 percent and the moments of inertia about axes through the mass center increase by up to a factor of 12. When the MPV is assembled, inspected and verified, the mission is ready to proceed and the MPV is moved from the station to a staging area and mated with fueled trans-Mars injection stages for the flight to Mars.

This presentation describes a finite element model of the MERC formulated to investigate the expected low frequency modes and its variation with the addition of a large payload. A basic reboost procedure using near-continuous firing of reaction control system jets is proposed with off-modulation of the jets used to control flight attitude. The reboost procedure is described with the closed-loop attitude control dictating jet on/off cycling based on feedback signals which contain both the rigid body rotation information and the elastic rotations local to the attitude sensor. The presentation contains a description of the dynamic response at critical points of the station during the reboost and concludes with results of a brief study of the dynamic characteristics of a Lunar transportation node configuration.

INTRODUCTION

- O EVOLUTIONARY CONCEPTS OF SPACE STATION FREEDOM WILL HAVE MORE MASS AND BE MORE FLEXIBLE THAN THE ASSEMBLY COMPLETE CONFIGURATION.

- O FUNDAMENTAL STRUCTURAL FREQUENCIES WILL BE REDUCED AND WILL APPROACH THE CONTROL BANDWITH OF THE ATTITUDE CONTROL SYSTEMS.

- O THE CURRENT STUDY EVALUATES THE STRUCTURAL, DYNAMIC AND CONTROL CHARACTERISTICS OF EVOLUTIONARY CONFIGURATIONS CONSISTENT WITH TRANSPORTATION NODE CONCEPTS.

- O THE PRESENTATION DESCRIBES:
  - FINITE ELEMENT MODEL OF A MARS EVOLUTIONARY REFERENCE CONFIGURATION
  - STRUCTURAL DYNAMIC MODES AND FREQUENCIES OF THE CONFIGURATION WITH AND WITHOUT A MARS PILOTED VEHICLE
  - A BASIC REBOOST PROCEDURE WITH ACTIVE ATTITUDE CONTROL
  - THE DYNAMIC RESPONSE AT CRITICAL POINTS OF THE STRUCTURE DURING REBOOST

- O THE PRESENTATION CONCLUDES WITH RESULTS OF A BRIEF STUDY OF THE DYNAMIC CHARACTERISTICS OF A LUNAR TRANSPORTATION NODE CONFIGURATION

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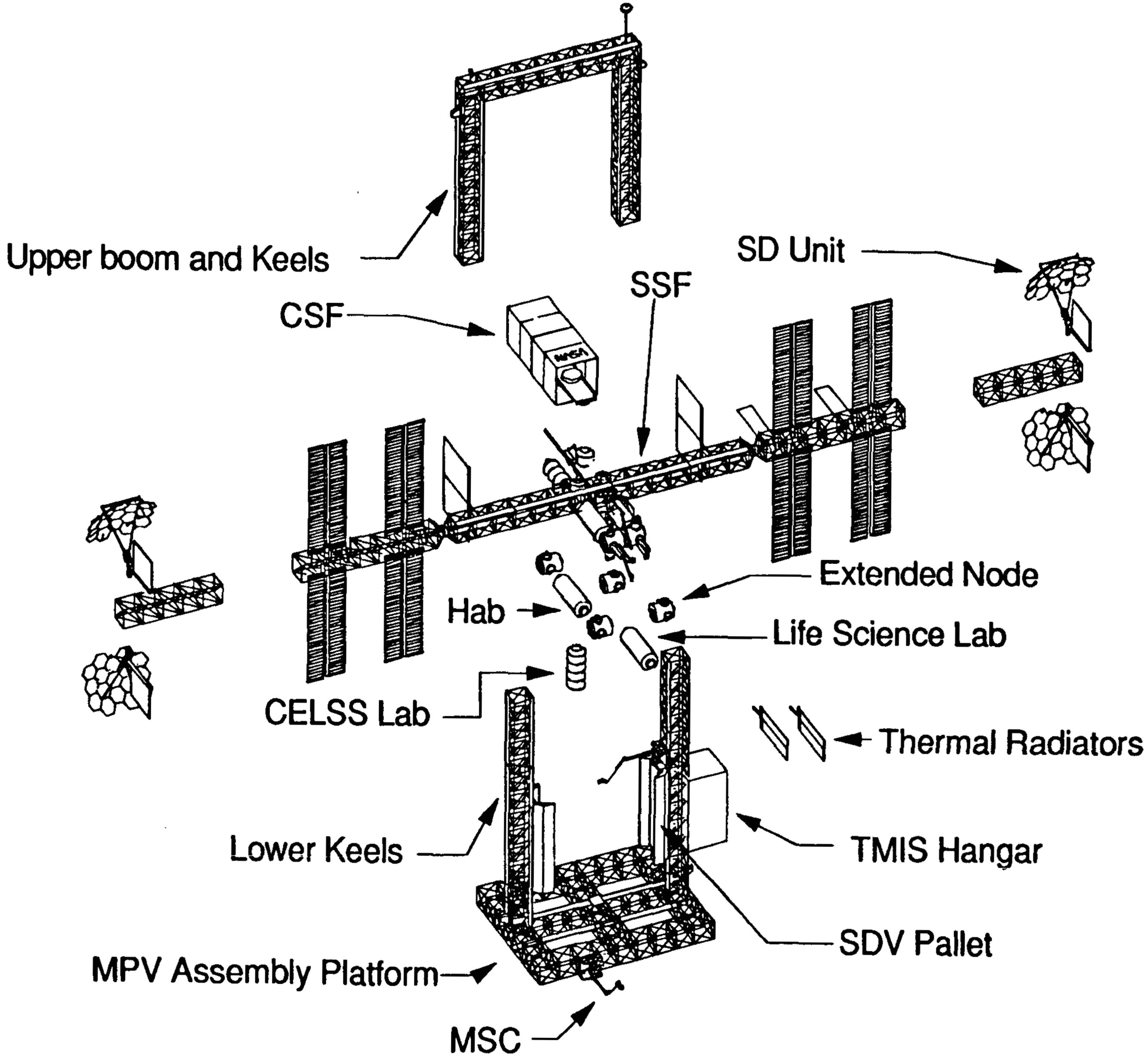
MERC ADDITIONS TO SPACE STATION FREEDOM

The MERC is an evolutionary version of Space Station Freedom configured to provide assembly and verification facilities for the Mars evolution mission. The SSF is modified by the addition of dual keels, an upper and lower boom, additional laboratory and habitation modules, the customer servicing facility (CSF), a trans-Mars injection stage (TMIS) hangar, increased power, and a MPV assembly platform with a mobile service center (MSC) as shown in the figure. The planar dimensions of the MERC are approximately 215 m by 135 m. The primary truss structure is constructed using 5 m square orthogonal tetrahedral truss bays. The truss structure supports the pressurized modules, a combined photovoltaic (PV) and solar dynamic (SD) power generation system, the vehicle assembly and verification subsystems, and a central thermal radiator system. The habitable area of the MERC is located at the center of the transverse boom and consists of seven modules: the US habitation module, the US laboratory module, the European Space Agency module, the Japanese experiment module, the life science lab, the closed environmental life support lab (CELSS), and a dedicated Mars habitation module. The lower keels and the MPV assembly platform provide docking/berthing areas for Mars mission vehicles and their associated equipment.

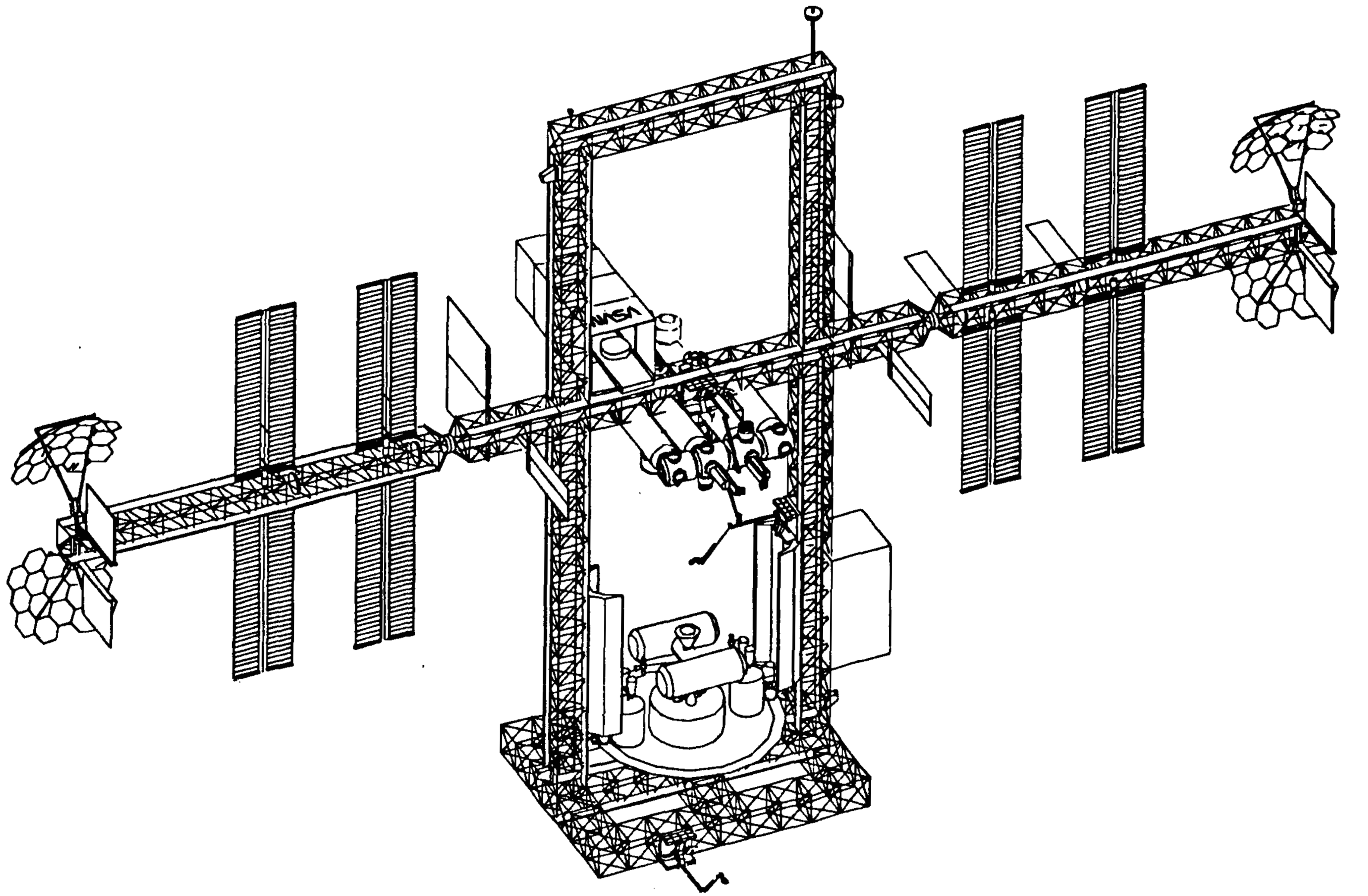
MERC Additions to Space Station Freedom



MERC WITH MPV

In the months prior to the launch of the second flight in the Mars evolution scenario several flights from Earth to low-Earth-orbit carry the components of the MPV to the MERC and the vehicle is constructed and verified on the assembly platform

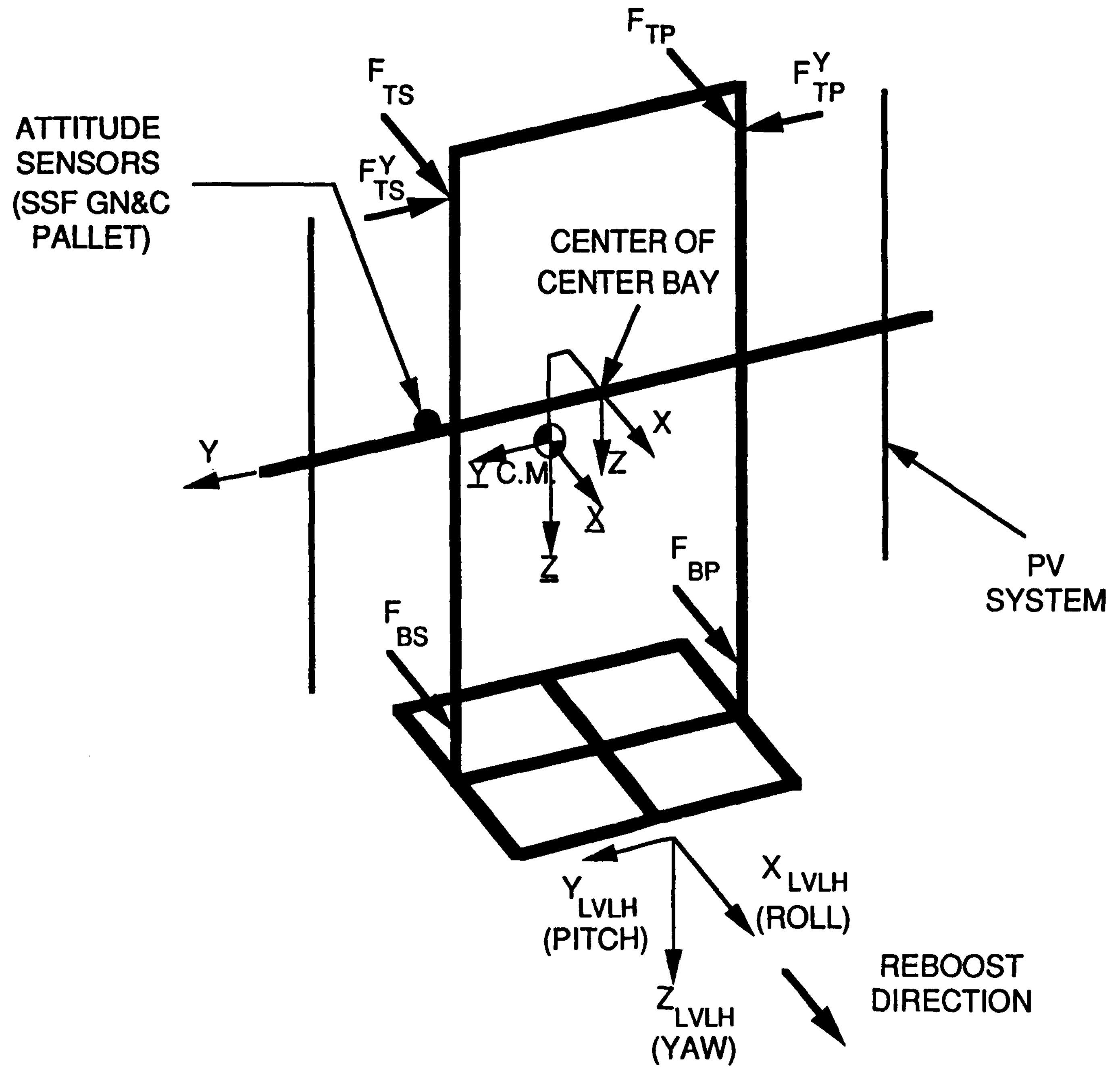
Mars Evolution Reference Configuration (MERC) with Mars Piloted Vehicle (MPV)



Locations of RCS Jets, Sensors, and Center of Mass

Three different coordinate systems are employed to characterize the geometry, dynamics, and orientation and location on orbit of the station. As shown in the figure, the geometrical coordinate system (X-Y-Z) has its origin at the center of the center truss bay. A body-fixed coordinate system ($\underline{X}$-$\underline{Y}$-$\underline{Z}$) at the center of mass with axes parallel to the geometrical coordinate system is used to describe the dynamics and the orientation of the station with respect to the local vertical, local horizontal (LVLH) coordinate system. The LVLH coordinate system is used to describe the position of the station on orbit with respect to an earth-fixed inertial coordinate system. The LVLH system is defined as follows: X_{LVLH} is parallel to the flight direction and coincides with the $\underline{X}$ axis, Z_{LVLH} is directed toward the center of the earth, and Y_{LVLH} is normal to the orbit plane composing a right handed coordinate system. Attitude control for the MERC is provided by a combination of control moment gyros and a hydrogen-oxygen reaction control system (RCS). The gyros are located outboard of the starboard keel on the guidance, navigation, and control (GN&C) pallet as shown in the figure. The four clusters of on/off type RCS thrusters, used for control moment gyro spin-up and desaturation, and altitude reboost, are located on the upper and lower keels and provide a total of 200 lbf thrust in the flight direction.

Locations of RCS Jets, Sensors, and Center of Mass

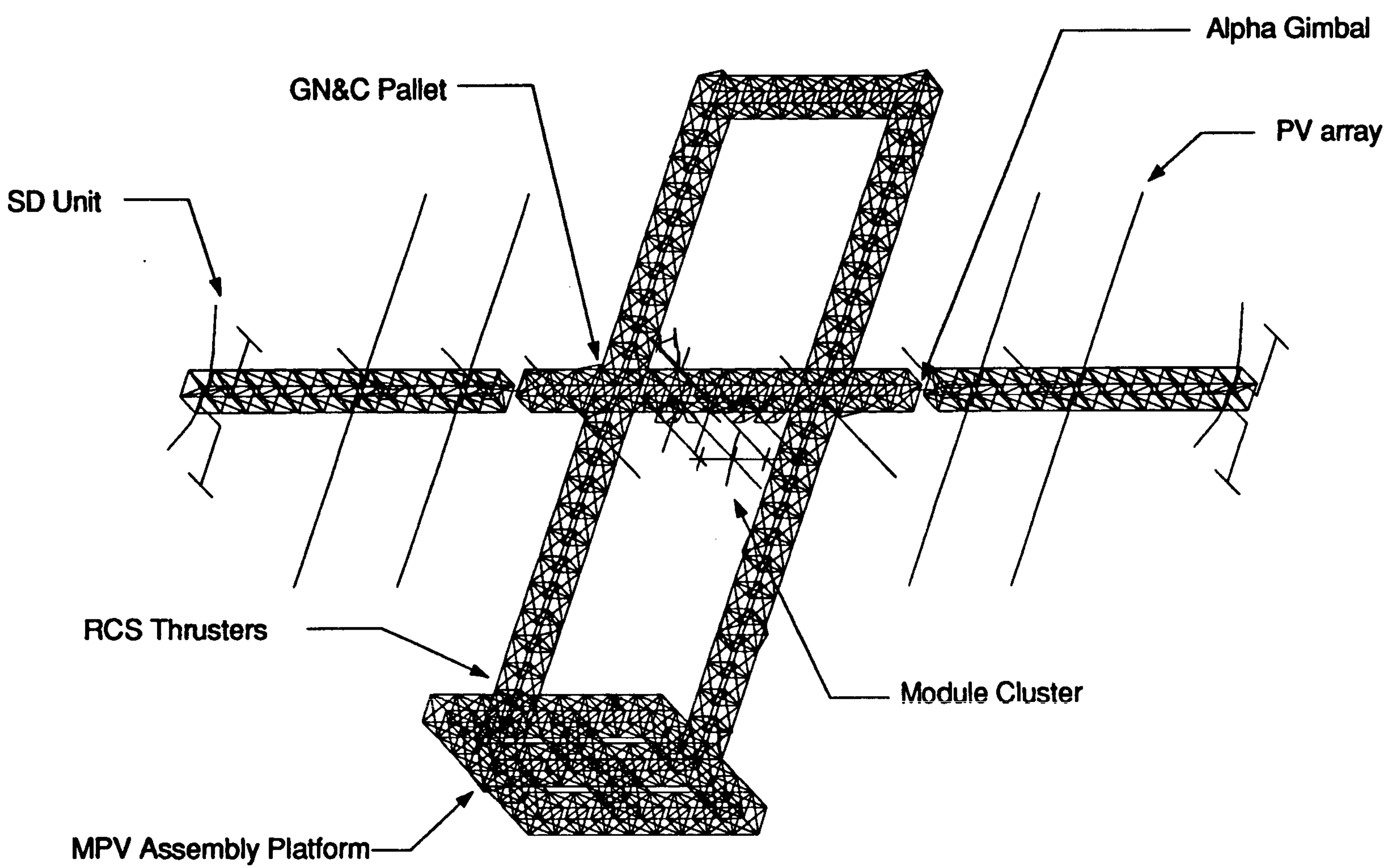


Structural Model

Detailed finite element models of the MERC and the MERC with MPV were developed. The MERC finite element model is shown in the figure. These models were based on a recent NASA baseline structural model of SSF. The truss members are aluminum coated graphite-epoxy tubes with a 2.0 inch outside diameter, a wall thickness of 0.067 inches, a modulus of elasticity of 13.77×10^6 psi, and a material density of 4.05×10^4 $lbf\text{-}s^2/in^4$. These members are represented by beam elements. Joint effect stiffness reduction is accounted for by modulus reduction. The pressurized modules are located on the positive z side of the center of the transverse boom. The modules are modeled as beam elements with structural and non-structural mass distributions. The local module mass inertias are represented by concentrated masses. The module interconnects are represented by translational and rotational springs which model the properties of the module berthing mechanisms. The pressurized module cluster is connected to the transverse boom by a series of truss tube members, utilizing rigid-link offsets from the elastic centerline of the modules. The alpha gimbals, which provide solar vector tracking, are located symmetrically about the z axis on the transverse boom. The gimbals are modeled as beam elements using lineal mass distribution (equal mass per unit length). The central station thermal radiators and PV systems are located symmetrically about the z axis on the port and starboard transverse boom. These components are modeled with beam elements using lineal mass distribution, and a bending stiffness tuned for a first bending natural frequency of 0.15 Hz for the radiators and 0.10 Hz for the PV system assuming a clamped-free boundary condition. The solar dynamic units are located on the positive and negative z faces at the outer edges of the port and starboard transverse boom. The units are modeled as rigid elements with discrete mass representations of the receiver, collector, and deployment mechanisms.

Various other structures, which include RCS, GN&C pallet, MPV, trans-Mars injection stage hangar, shuttle derived vehicle (SDV) pallets, and communications antennas, are represented as offset masses with inertia matrices about their centers of mass. Other non-structural components (utility trays, thermal control system, joint nodal clusters, and RCS tank farms) are represented by concentrated masses applied at the appropriate model nodes. The MERC finite element model has 2420 beam elements, 434 concentrated mass elements, 57 rigid elements, 1000 nodes, and approximately 5800 dynamic degrees of freedom. The addition of the MPV to the MERC model adds two concentrated mass elements, two rigid elements, and twelve dynamic degrees of freedom.

Mars Evolution Reference Configuration Finite Element Model



Rigid Body Properties of Finite Element Models

The mass characteristics and rigid body properties comparisons between the MERC, MERC with MPV, and SSF are shown in the Table. The mass of the MERC is 65 percent greater than the mass of SSF and its moments of inertia through the mass center are greater by approximately a factor of four. The mass increase of the MERC with MPV system over SSF is 112 percent and the moments of inertia about axes through the mass center increase by up to a factor of 12.

Rigid Body Properties of Finite Element Models

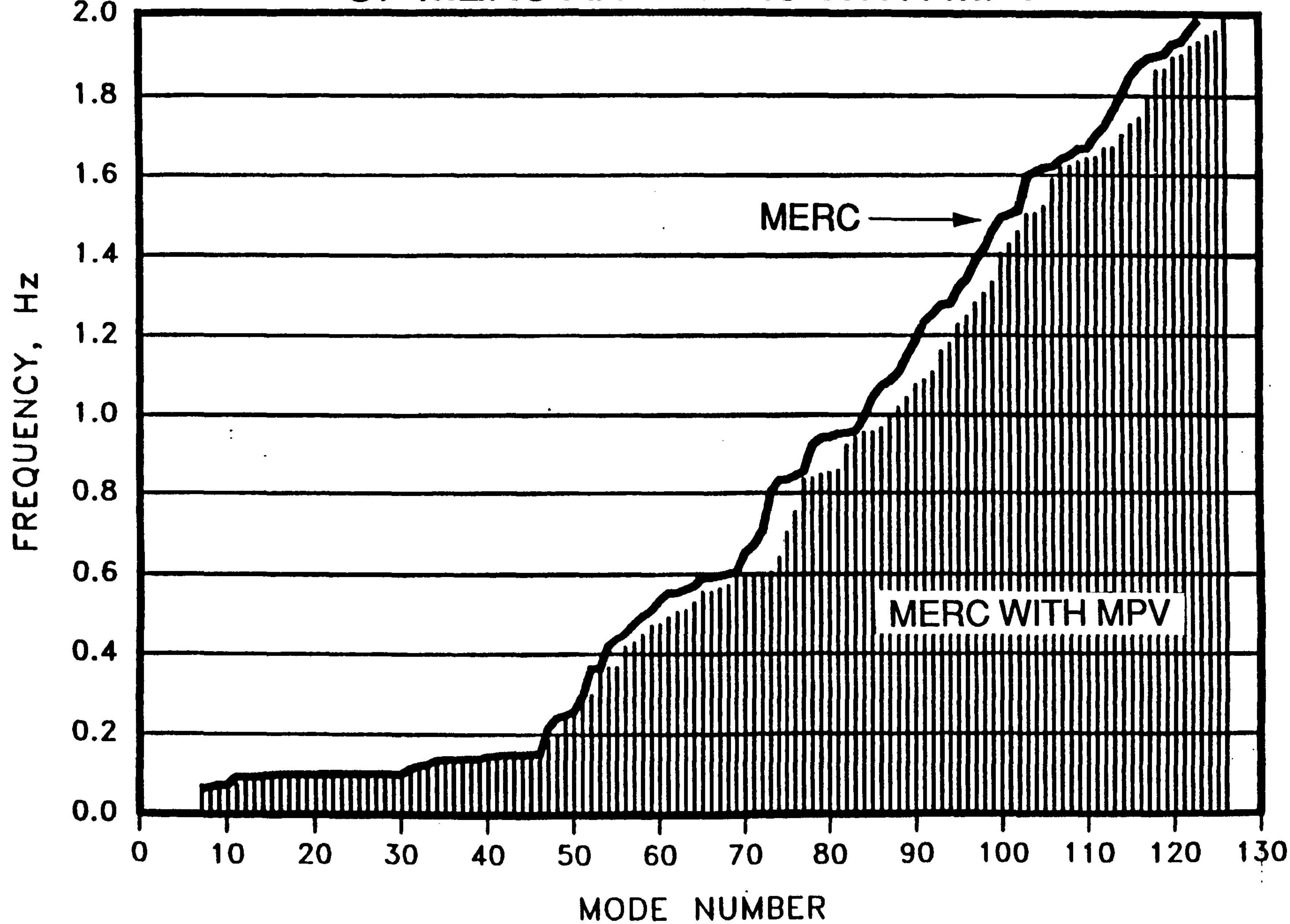
Configuration	Mass (lbf-sec ^{2}/in) (Wt. on Earth, lbf)	Center of Mass (in) *			Moment of Inertia (10^6 lbf-sec ^{2}-in) **			Product of Inertia (10^6 lbf-sec ^{2}-in) **		
		X	Y	Z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
SSF	1,548 (598,000)	-78.7	25.1	132.6	1132	299	1214	6.0	-8.3	-9.7
MERC	2,552 (986,000)	-44.6	10.3	270.9	4801	1302	4045	23.5	-40.5	73.1
MERC with MPV	3,282 (1,268,000)	-39.4	-16.4	714.7	7202	3615	4182	18.7	-82.7	177.7

*Measured from the center of center bay. ** About the center of mass.

Structural Analysis

The finite element code MSC/NASTRAN, with the Lanczos method of eigenvalue extraction, was used to obtain the undamped natural frequencies of the MERC and the MERC with MPV below 2.0 Hz. The distributions of natural frequencies for the MERC and the MERC with MPV are shown in the figure. The attachment of the MPV to the MERC system adds three natural frequencies below 2.0 Hz and causes a general lowering of most frequencies above 0.25 Hz.

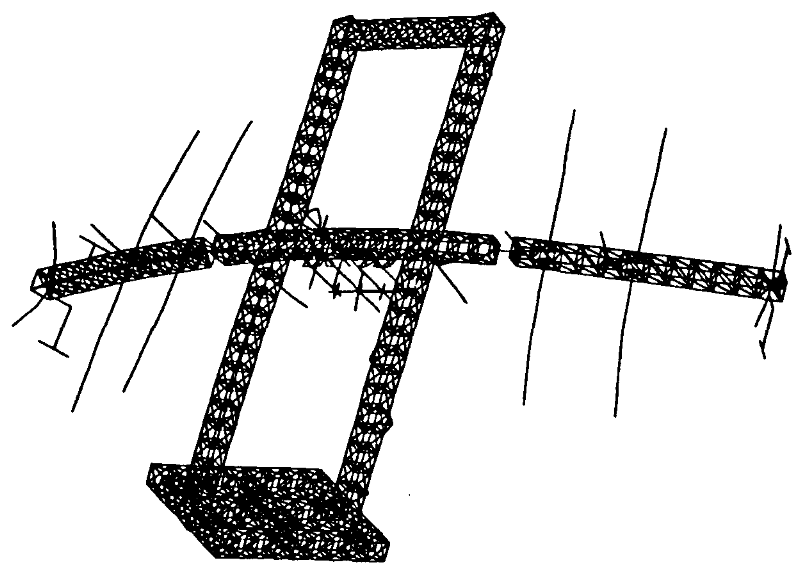
UNDAMPED NATURAL FREQUENCY COMPARISON OF MERC AND MERC WITH MPV



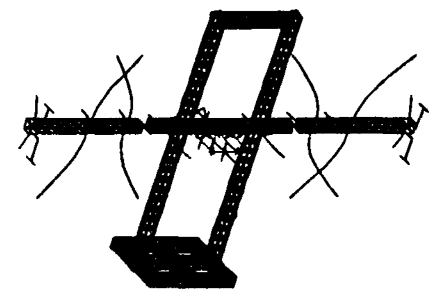
Undamped Natural Modes

The fundamental modes for both configurations (first flexible mode) occur at 0.064 Hz. The MERC with MPV fundamental mode is shown in the figure. An example of an appendage mode, in this case MERC photovoltaic array first bending, is also shown. The first occurrence of MPV assembly platform bending of the MERC with MPV system occurs at 0.36 Hz and is shown. In general the modes show a complex motion with strong coupling of the truss structure with various power, radiator, and payload components. The majority of the modes exhibit similar behavior in that the module cluster region, which has the bulk of the mass, acts as a node point for most modes and the stiff MPV assembly platform moves as a rigid body.

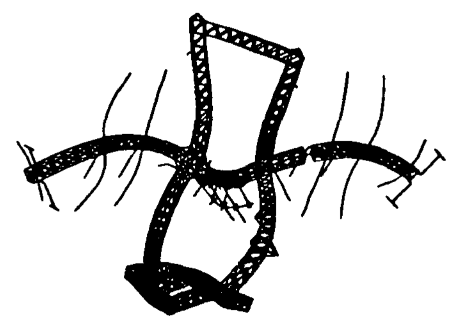
Typical Modes of the MERC and the MERC with MPV



MERC with MPV Fundamental Framework Mode Shape at 0.064 Hz



MERC Appendage Mode Shape at 0.099 Hz



MPV Assembly Platform Bending Mode Shape at 0.36 Hz

Lowest Frequency Occurrence of Component Modes

A comparison of component mode occurrences between MERC, MERC with MPV, and SSF is shown in the table. The undamped frequencies of the major truss framework modes are significantly reduced with the addition of the MPV.

Lowest Frequency Occurrence of Component Modes

Mode Shape	SSF Frequency (Hz)	MERC Frequency (Hz)	MERC/MPV Frequency (Hz)
PV Bending	0.090	0.099	0.095
Transverse Boom Bending	0.144	0.064	0.064
Lower Keel Bending	N/A	0.155	0.111
Lower Keel Torsion	N/A	0.219	0.103
MPV Assembly Platform Bending	N/A	0.672	0.362

Reboost Analysis

To reboost the MERC and the MERC with MPV, the RCS composed of four clusters of jets, located on the dual keels, fires its jets in the negative X_{LVLH} direction to accelerate the station in the flight direction. Since the jets are not located the same distance from the center of mass, the station will begin to yaw about the Z_{LVLH} axis and pitch about the Y_{LVLH} axis. Inertia coupling will also cause a roll motion about the X_{LVLH} axis. For the current study the station is required to maintain a rigid body flight attitude to within three degrees of the nominal flight path, i.e. about the LVLH axes. The attitude and attitude rate are sensed at the GN&C pallet. An error signal, composed of the measured attitude summed with the measured attitude rate, is used with a Schmitt trigger to off- or on-modulate the jets at the appropriate locations to control the attitude. A 50 lbf RCS jet force is used in a given direction at each RCS cluster. It is assumed that the station is assembled in a 220 nautical mile (NM) circular orbit. Altitude changes due to RCS jet firings for reboost in one orbit were studied. Orbital mechanics are incorporated to compute the orbit trajectory subject to time varying jet firings for the attitude control during reboost.

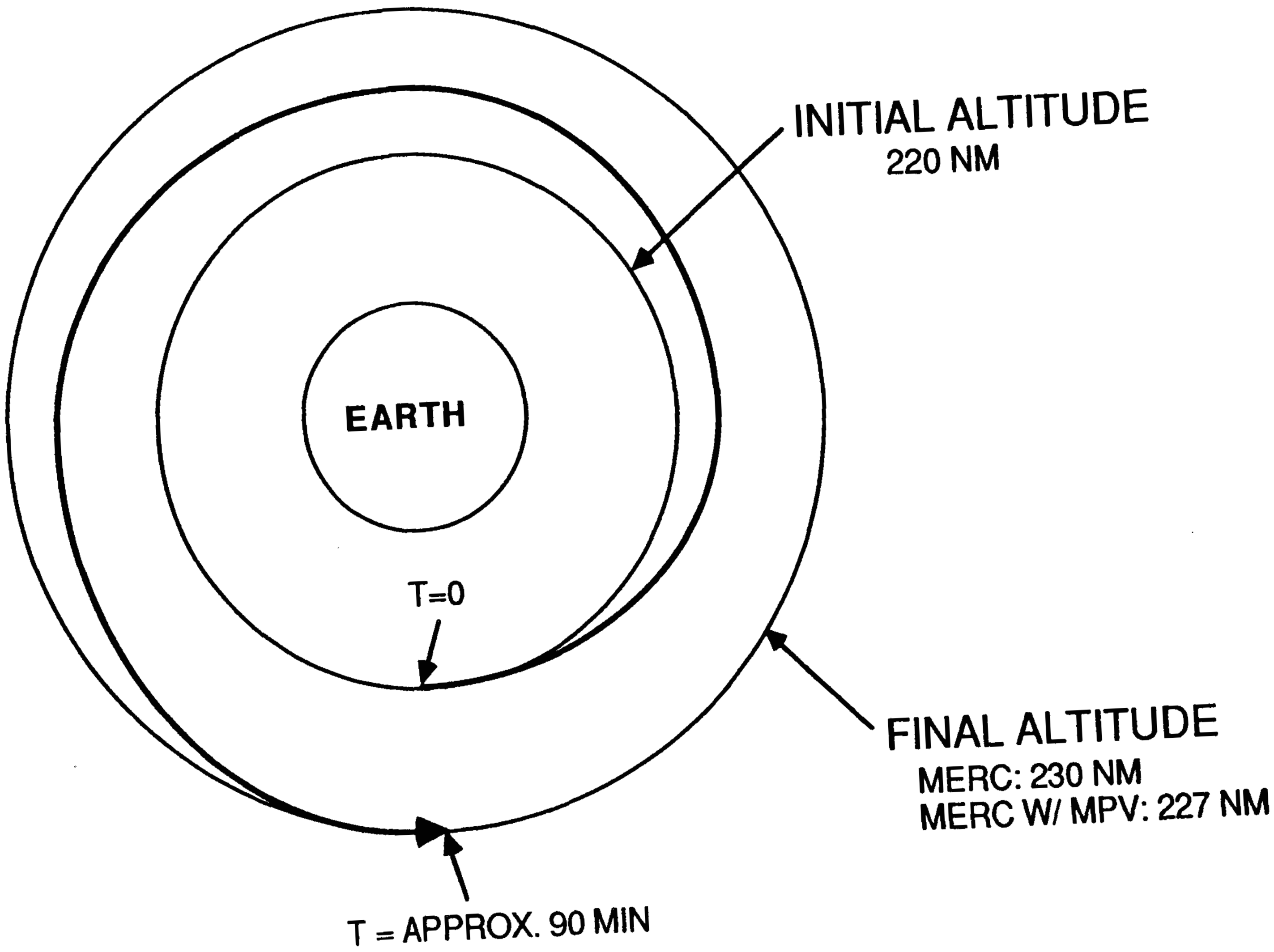
The dynamic characteristics of the MERC and the MERC with MPV are represented as a combination of rigid body and flexible structural dynamics. In order to obtain the equations of motion for the rigid body dynamics, a few assumptions are made. Environmental torques generated by atmospheric drag, solar radiation, and gravitational gradient are assumed to be negligible compared to torques generated by RCS firings during the reboost maneuver. Also, since the attitude change maintained is small, the orientation of the station is represented by a time integral of angular rate. Flexible structural dynamics are modeled by incorporating all flexible modes below 2 Hz. One-half percent of critical damping is assumed for modal damping for each mode. Based on laboratory tests of similar structures, the damping levels assumed are probably lower than the actual damping which will occur so that computed response levels at the sensor location should be conservative.

Reboost Assumptions

The study of a reboost maneuver of a Mars reference configuration is based on the following assumptions:

- RCS jet force magnitude of 50 lb at each RCS pod
- Thruster selection based on an attempt to minimize limit cycle rigid body frequencies to prevent excessive controls/structure interactions
- Rotation limits about each axis assumed to be $\pm$ 3 degrees without rotation rate limits
- The environmental torques (drag, gravity gradient, solar radiation pressure) assumed negligible compared to the torques generated by RCS firings during reboost
- Pitch, and yaw attitudes are controlled by off-modulation of X-axis jets
- Roll attitude controlled by on-modulation of Y-axis jets

REBOOST ANALYSIS



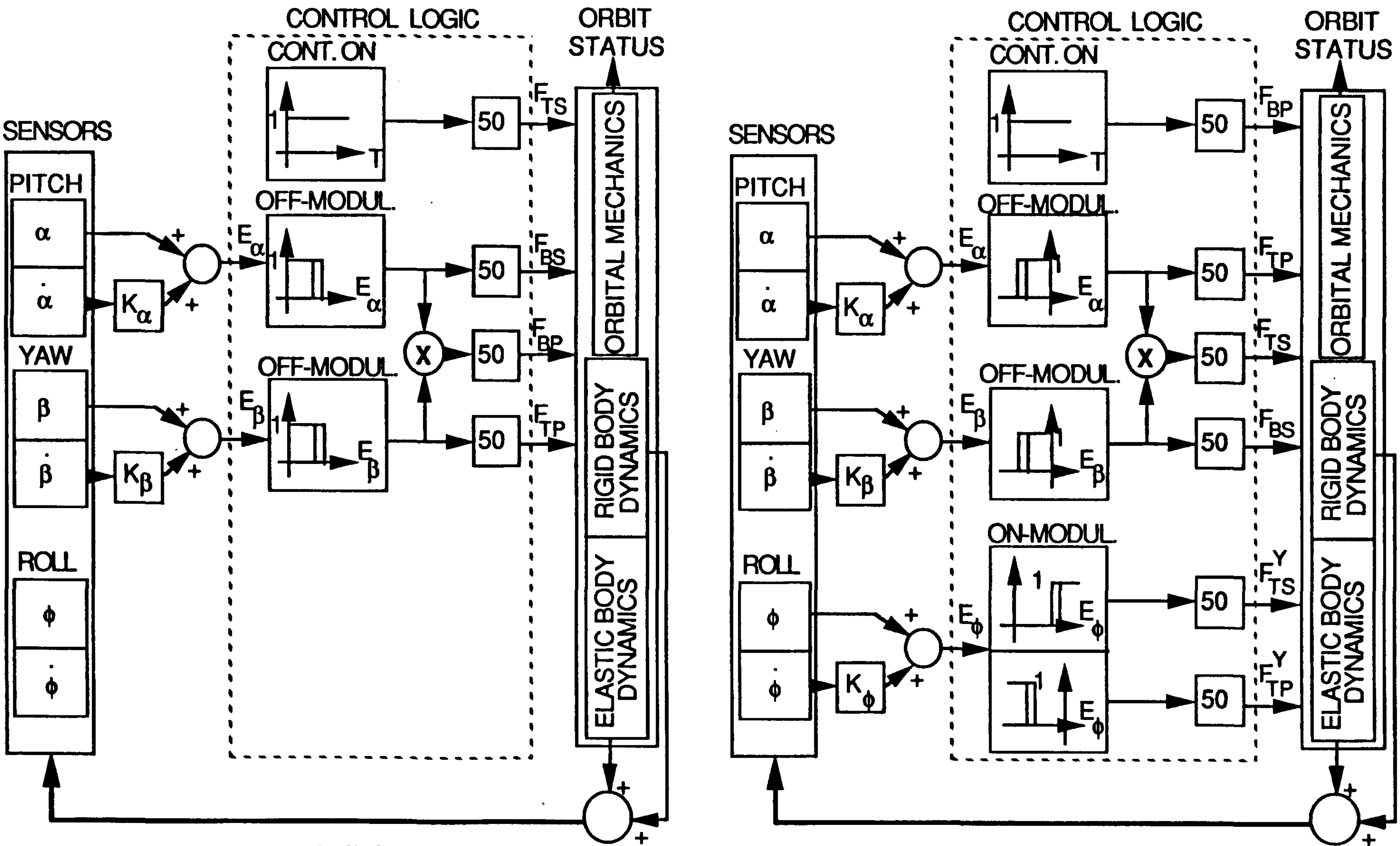
Attitude Control System

Closed-loop attitude control using the RCS jets is performed in order to maintain the attitude of the station within ± 3 degrees. Schematic diagrams of the closed-loop attitude control systems are shown in the figure for the MERC and the MERC with MPV, respectively. The sensors located at the GN&C pallet measure the total attitude and the attitude rate about each axis. This measured motion is the sum of rigid body motion and flexible structural responses at the sensor location. A proportional-derivative feedback control is employed. The error signal drives the Schmitt trigger logic to produce an on-off modulation of the RCS jets.

Since there were significant changes in the inertia properties and center of mass locations, due to assembling the MPV on the MERC , the MERC and the MERC with MPV require different attitude control logics. The changes in the control logic involve not only the adjustment of the control parameters such as deadband and hysteresis but also the complete reorganization of the firing sequences. Therefore, control systems using RCS jets for the MERC should be designed to accommodate control logic changes as the MPV is assembled on the MERC.

When the error exceeds the deadband plus hysteresis, the jet is turned off until the error becomes smaller than the deadband. This modulation creates an eventual limit cycling of jet firings. The deadband and the hysteresis are designed so as to keep the attitude excursion within the required bounds and to reduce the frequency of limit cycling without losing stability of the attitude control system. As the separation between the limit cycle frequency and the fundamental frequency increases, the elastic response caused by the jet firing modulation decreases. Also, the hysteresis is adjusted so that the flexible component of the error signal will not cause an RCS jet chattering instability when the error signal approaches the boundary of the deadband. An iterative design procedure is employed to select control parameters which satisfies the design objectives.

Block Diagram of Closed Loop Attitude Control During Reboost



(a) MERC

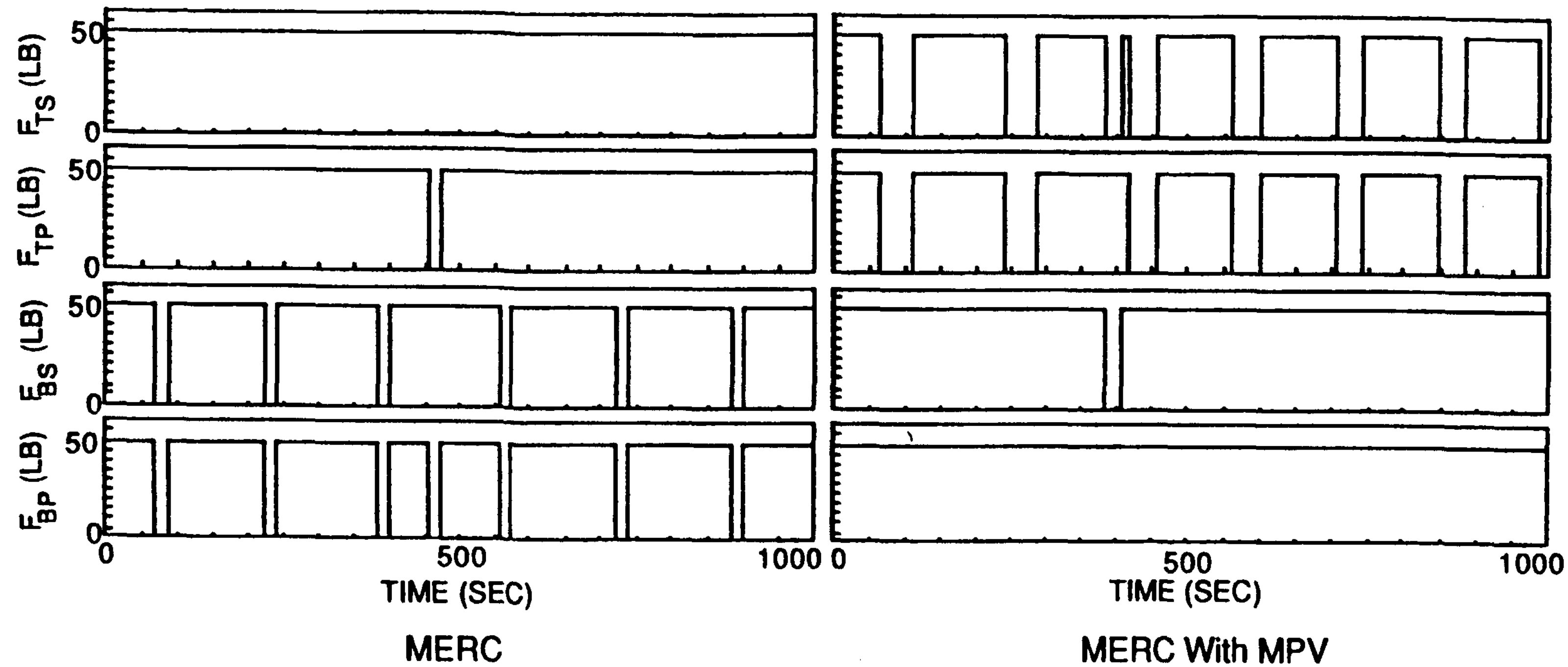
(b) MERC with MPV

Reboost Results

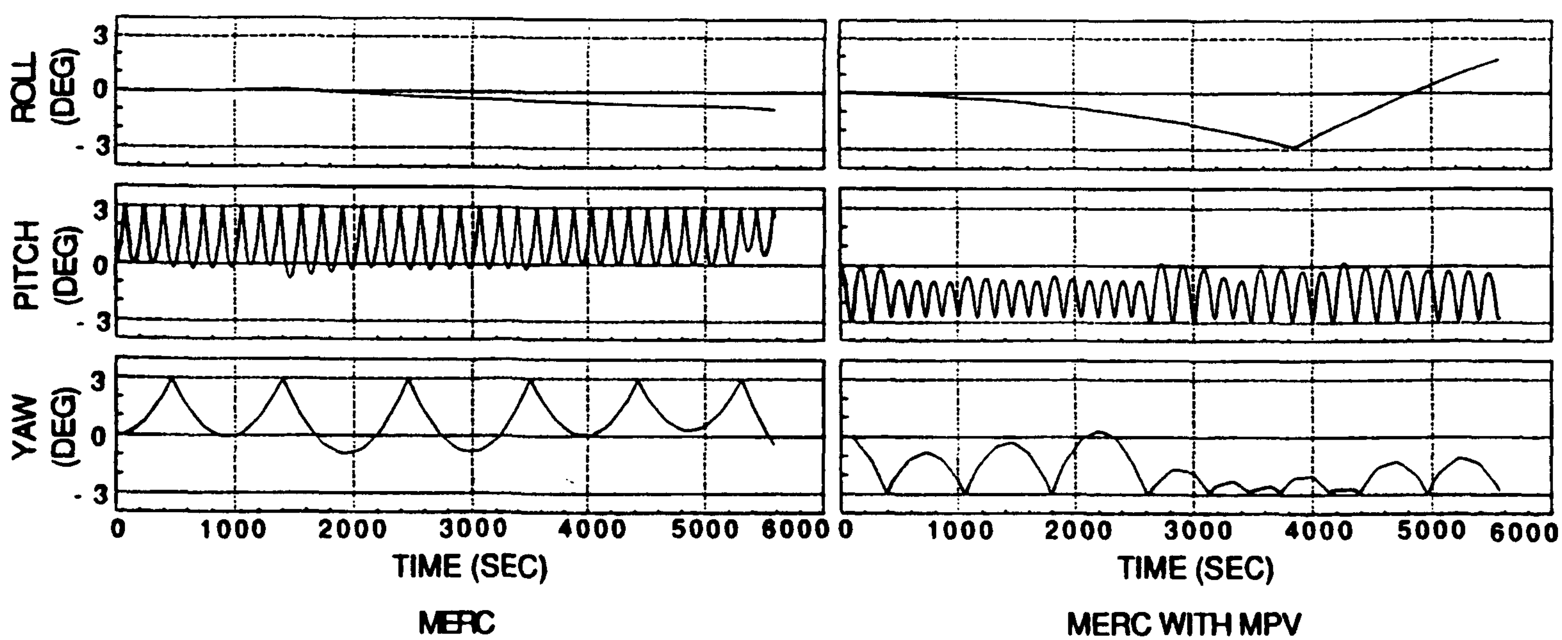
The resultant RCS firing sequences for the first 1000 seconds of the reboost maneuver of the MERC and the MERC with MPV are shown in the figure. To prevent a chattering instability, which could be caused by elastic rotation in the vicinity of the sensors, the hysteresis of the Schmitt trigger was made as large as possible while maintaining rigid body attitude control stability. Although attitude rate is not controlled, the magnitude of the rate is maintained small and never exceeds 0.09 deg/sec and 0.094 deg/sec about each axis for the MERC and the MERC with MPV, respectively. The approximate limit cycle frequencies of 0.0010 Hz and 0.0018 Hz in the yaw axis and 0.0062 Hz and 0.0063 Hz in the pitch axis for the MERC and the MERC with MPV, respectively, are well below the fundamental structural frequency of the MERC and the MERC with MPV which is 0.064 Hz. With this separation of frequencies, the dynamic loadings due to jet cycling should not cause excessive structural response during the reboost.

Reboost Results

RCS Jet Firings During the First 1000 Sec Reboost



Total Error at the Sensor Location



Dynamic Response

The elastic dynamic behavior of certain critical points of the MERC and the MERC with MPV during reboost are summarized in the table. These results indicate that the MERC with MPV is more responsive in certain areas than the MERC, to the reboost forcing function. There are several factors which lead to this result. The responses are driven by totally different reboost pulses, due to configurational mass distribution differences. The primary MERC reboost pulse is from the lower RCS jets and excites the lower regions of the station to a greater extent than do the MERC with MPV system RCS pulses. The primary MERC with MPV RCS pulses are from the upper jets and excite the transverse boom area components to a greater extent than the MERC RCS pulses.

Maximum Displacements and Accelerations at Critical Points

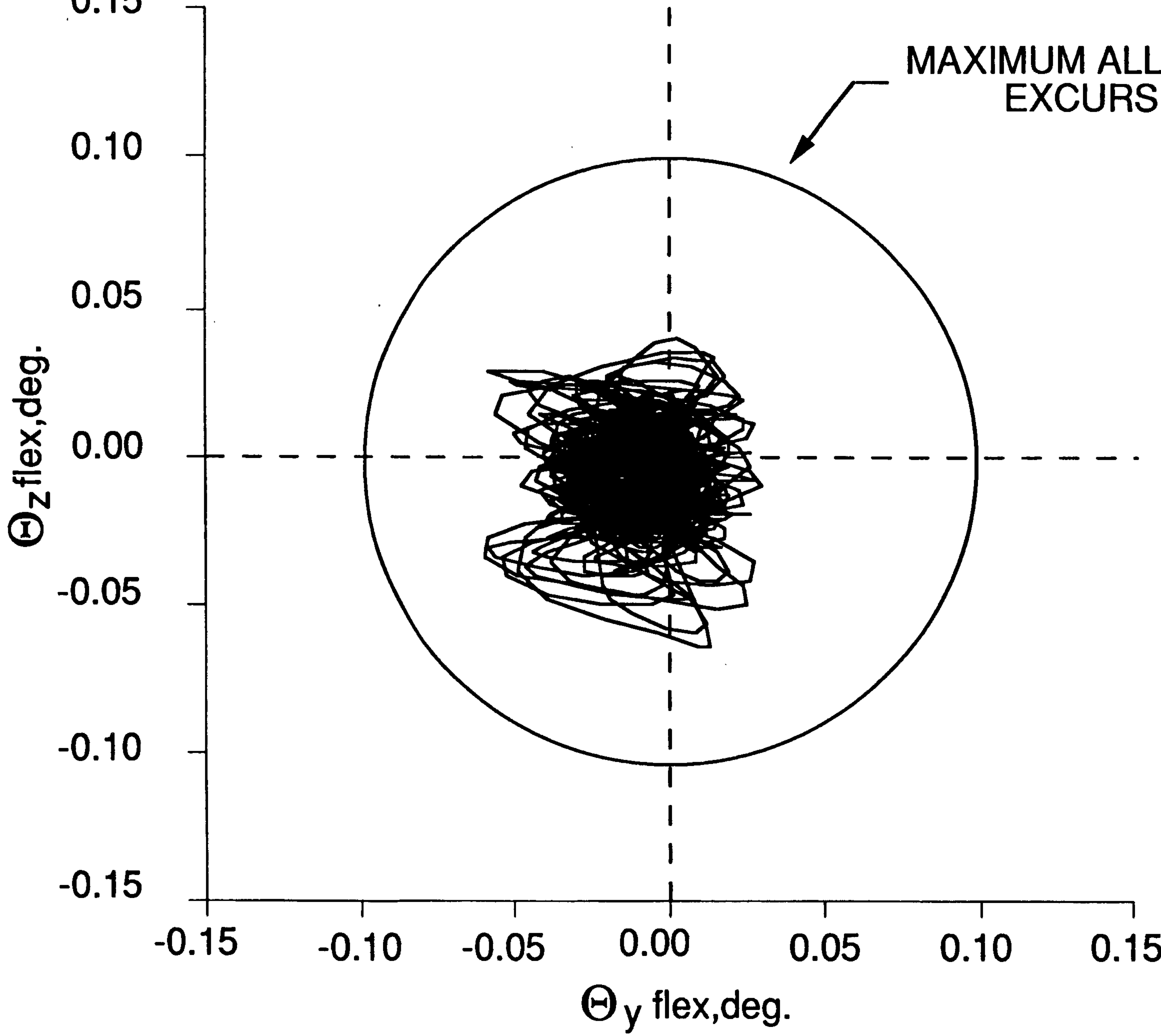
Location	MERC		MERC with MPV	
	Displacement (inches)	Acceleration (milli-G's)	Displacement (inches)	Acceleration (milli-G's)
GN&C Pallet	0.24	0.89	0.34.	0.70
SD Collector	0.88	1.75	2.26	2.14
PV base	0.37	1.49	0.96	1.05
PV tip	1.90	2.48	4.97	6.47
Hab Center	0.19	0.32	0.28	0.36
MPV Assembly Platform	1.05	2.60	0.48	1.44

Elastic Response at the Solar Dynamic Power System

An area of particular concern is the elastic rotation local to the SD systems at the port and starboard tips of the transverse boom. The SD system uses a concentrator to focus solar radiation energy on a receiver assembly which increases the pressure of a gas working fluid. The fluid drives a turbine connected to an electrical alternator and compressor. The concentrator requires a $\pm$ 0.1 degree solar vector pointing accuracy during orbital daylight. A combination of alpha and beta joint rotational control is provided to accomplish this pointing accuracy during nominal orbital operations. Since the station is allowed a $\pm$ 3.0 degree rigid body rotation during reboost, a local SD pointing control system is used to maintain pointing. The low frequency rigid body excursions from the LVLH axes ($\pm$ 3 degrees at 0.006 Hz) for the MERC and the MERC with MPV system are easily controllable and should present no pointing problems. The higher frequency local elastic motions of the SD systems were investigated to determine the extent of elastic motion which must be countered by active control. As a measure of elastic motion, plots of the flexible component of sun line variation in the YZ plane over the time of the reboost maneuver were generated. The MERC with MPV system result, shown in the figure, exhibited greater motion than the MERC configuration since the top RCS jets located closer to the SD were cycled to control attitude. The local elastic motion of the SD location never exceeded the 0.1 degree requirement and should present no control problems.

Results indicate no excessive displacements or accelerations at the critical points investigated. These results are based on the current mass distributions and elastic representations and are highly dependent on the NASA baseline alpha joint stiffness used in the structural modeling. This stiffness is subject to change as the design of SSF approaches maturity.

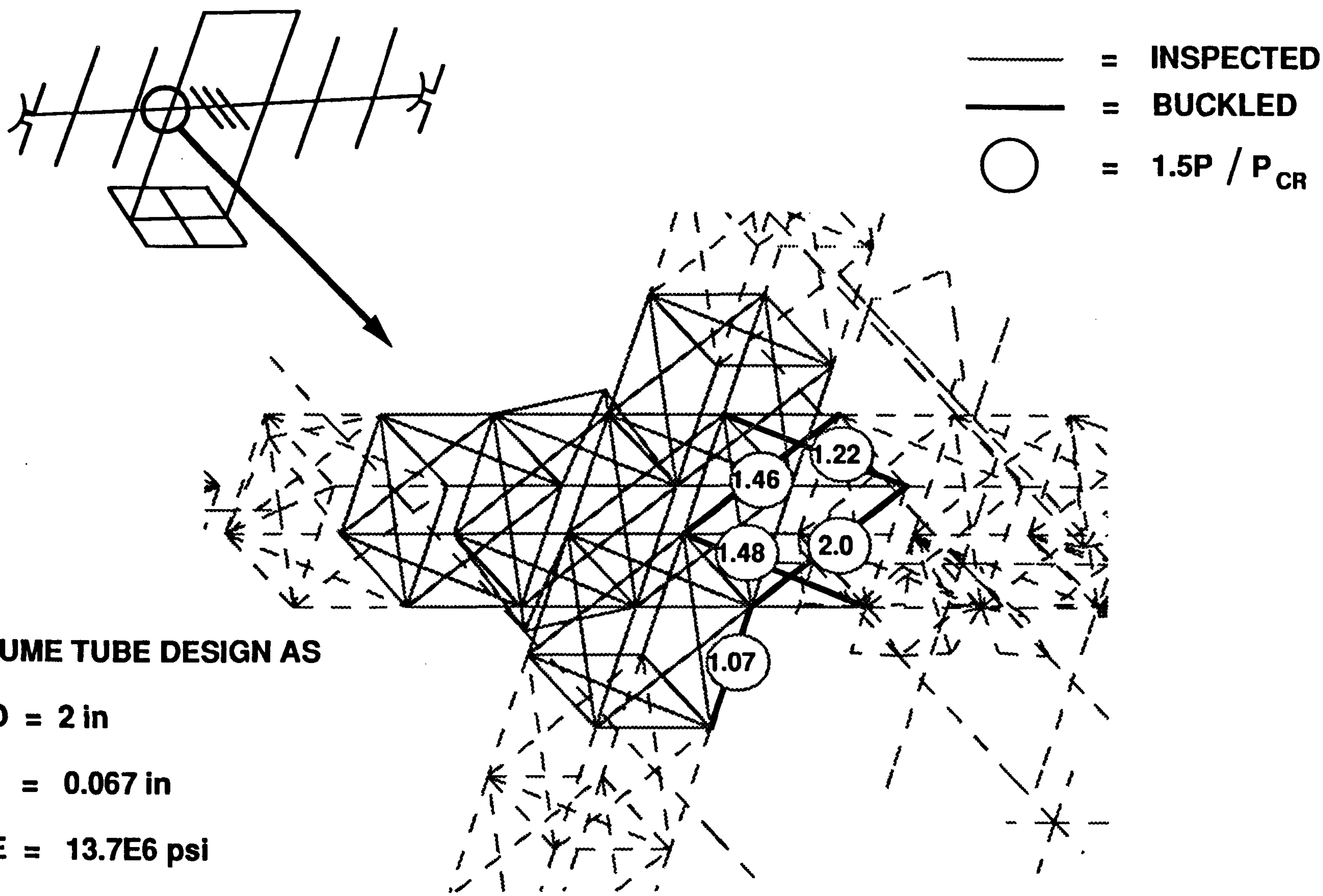
FLEXIBLE COMPONENT OF SUN LINE VARIATION AT SOLAR DYNAMIC COLLECTOR



Elements at Stbd Keel-Boom Interface Which Require Stiffening to Prevent Buckling During Reboost

A transient analysis was performed to calculate member loads at selected critical locations during a reboost maneuver. Critical buckling loads were calculated for longerons, battens and diagonals, and compared to the maximum compressive axial force in the selected truss members. Assuming a safety factor of 1.5, four diagonals and one longeron at the starboard keel-boom interface should be stiffened to prevent buckling during the reboost. One method of stiffening the tubes would be to increase the tube wall thickness from the nominal 0.067 inches to 0.153 inches or increase the thickness a lessor amount but increase the percent of axial fibers in the composite layup. The outside diameter must remain at 2 inches since that is the maximum diameter which allows for comfortable handling by an astronaut in a space suit.

ELEMENTS AT STBD KEEL-BOOM INTERFACE WHICH NEED STIFFENING TO PREVENT BUCKLING DURING REBOOST



ASSUME TUBE DESIGN AS

$D = 2$ in

$t = 0.067$ in

$E = 13.7E6$ psi

Safety Factor = 1.5

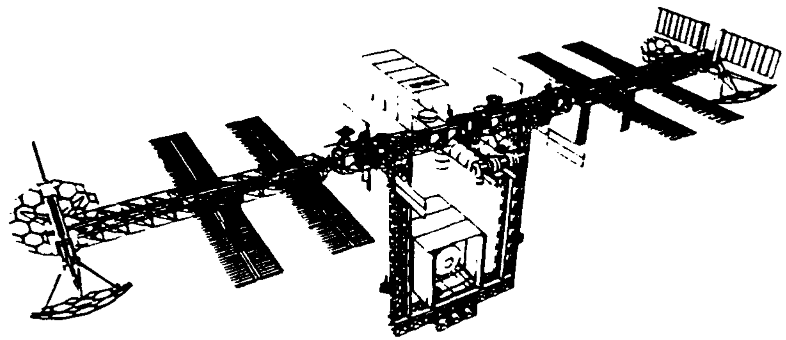
DYNAMIC CHARACTERISTICS OF THE LUNAR TRANSPORTATION NODE CONFIGURATION

A preliminary study was made of the dynamics of an evolutionary concept of Space Station Freedom consistent with use of the spacecraft as a transportation node for a manned Lunar mission. In this concept, lower keels are added to the assembly complete configuration.

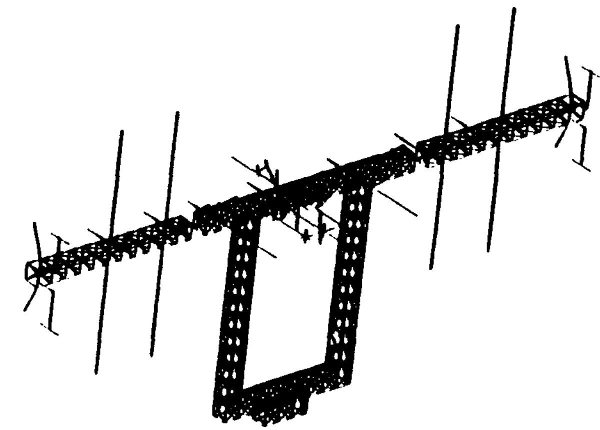
The finite-element model of the Lunar Transportation Node, which was developed from the Level II finite-element model of the Assembly Complete configuration, contains almost twice as much mass as the Assembly Complete model. Most of the increased mass is due to the addition of the solar dynamic power system and the Lunar Assembly Hanger and Lunar Transfer Vehicle (LTV). Addition of the mass of the Lunar Assembly Hanger and LTV, which accounts for 35 percent of the total station mass, causes the center of gravity of the station to shift approximately three bay lengths further away from the centerline of the transverse boom.

The eigenvalue analysis of the model of the structure yielded 113 flexible modes below 2 Hz. The fundamental frequency of 0.07 Hz corresponding to a transverse boom bending mode is 50 percent lower than the comparable Space Station Freedom first transverse boom bending mode due to the added masses of the solar dynamic systems.

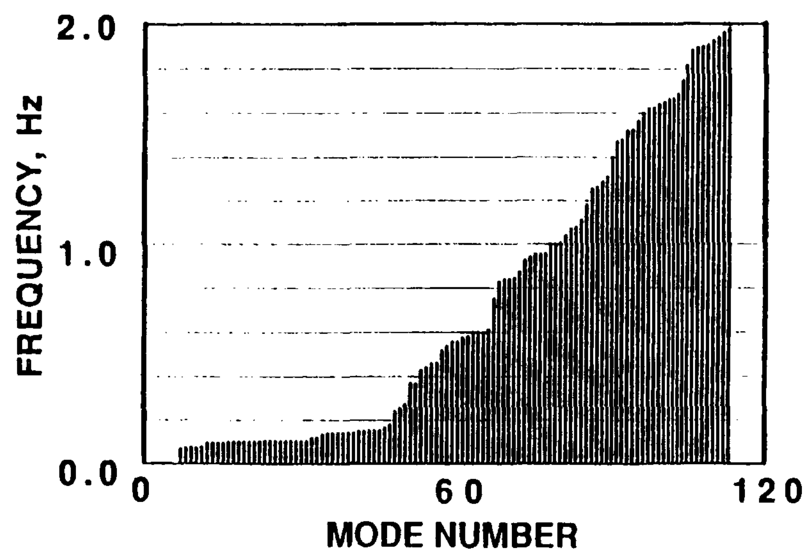
DYNAMIC CHARACTERISTICS OF THE LUNAR TRANSPORTATION NODE CONFIGURATION



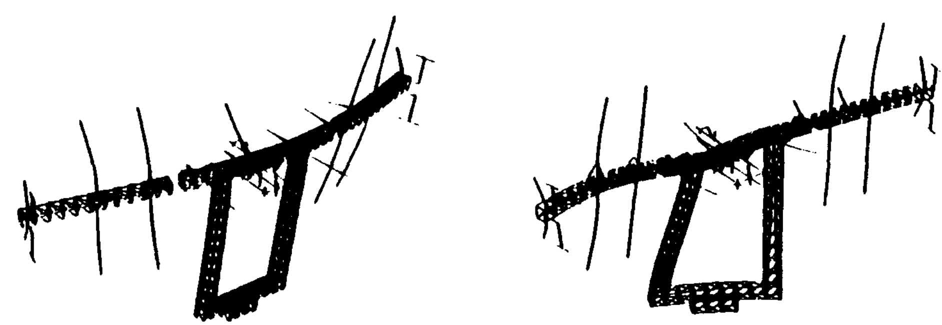
LUNAR TRANSPORTATION NODE CONFIGURATION



FINITE ELEMENT MODEL



FREQUENCY DISTRIBUTION



FUNDAMENTAL (0.07 Hz)

KEEL BENDING (0.51 Hz)

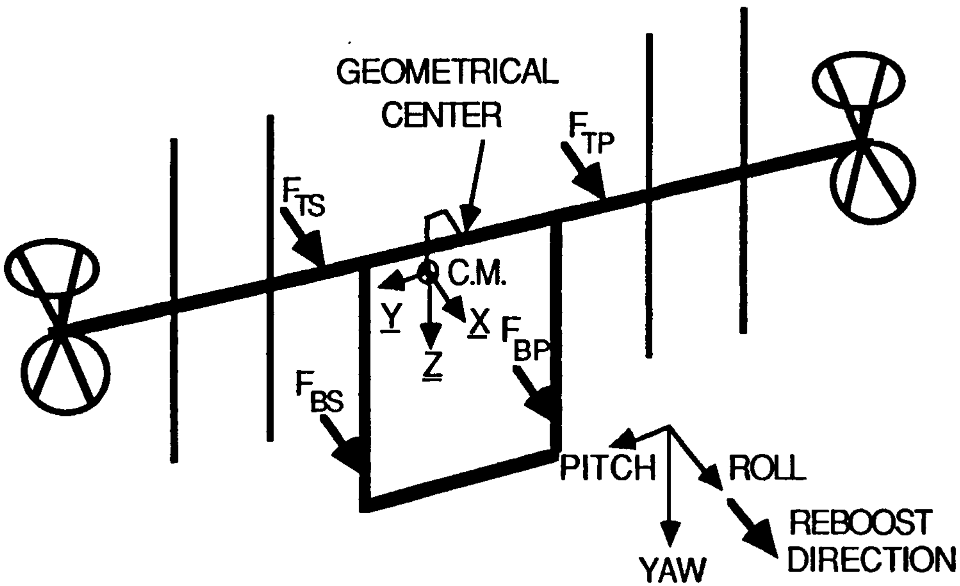
TYPICAL MODES

Reboost Excitation

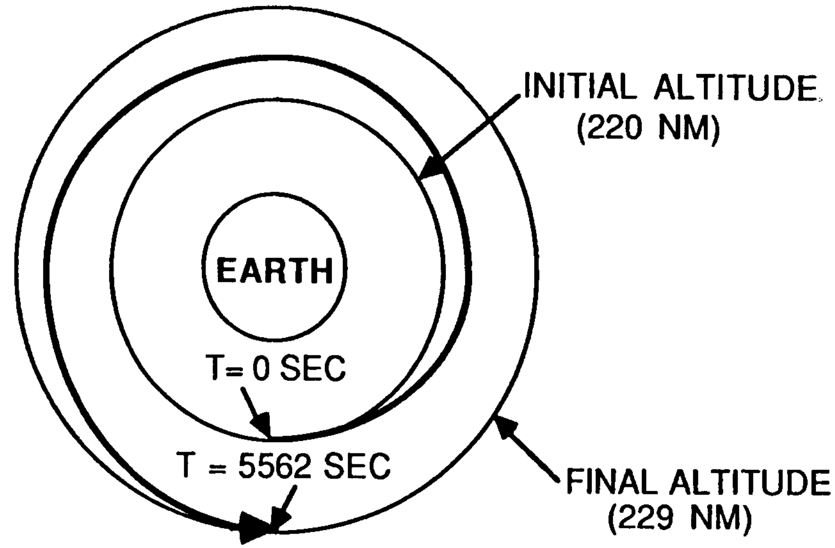
To reboost the Lunar transportation node, a Reaction Control System (RCS) composed of four clusters of jets, located on the transverse boom and the lower keels as shown in the figure, fires its jets to accelerate the station in the reboost direction. Since the jets are not located at the same distance from the center of mass, the station will begin to yaw about the $\underline{Z}$ axis and pitch about the $\underline{Y}$ axis. For the current study the station is required to maintain a rigid body flight attitude to within $\pm$ 3 degrees of the nominal flight path. Closed-loop attitude control using the RCS jets is performed in order to maintain the attitude of the station. An error signal, composed of the rigid body attitude summed with the rigid body attitude rate, is used with a Schmitt trigger to off-modulate the jets at the appropriate locations to control the attitude. A 50 lbf RCS jet is used in a given direction at each RCS cluster.

The resultant RCS firing sequences and the rigid body pitch and yaw attitude for the first 1000 seconds of the reboost maneuver are shown in the figure. Orbital mechanics were incorporated to compute the orbit trajectory subject to time varying jet firings for the attitude control during reboost. Assuming that the station is assembled in a circular orbit at 220 nautical miles (NM), approximately 9 NM altitude is picked up by reboost RCS jet firings in one orbit.

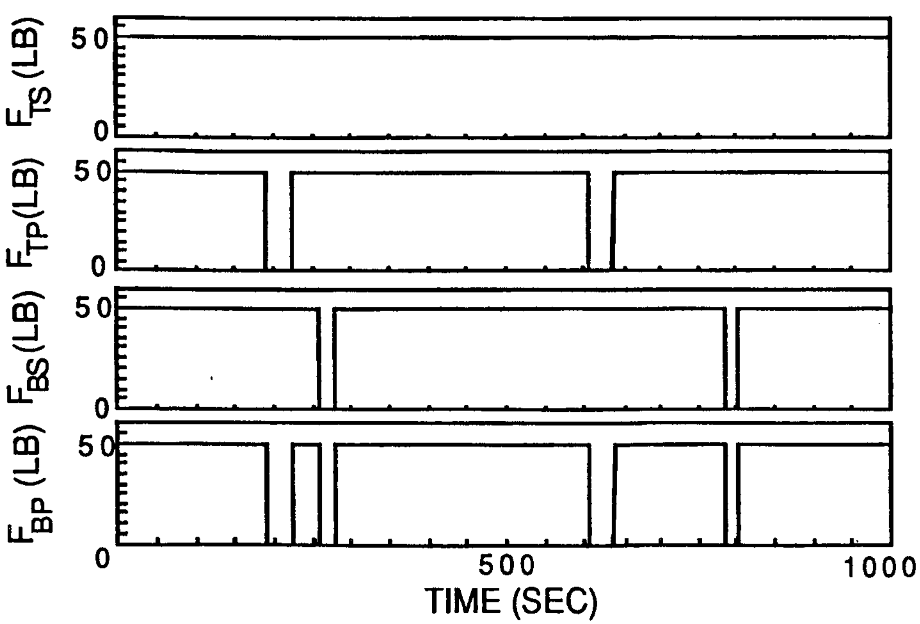
EXCITATION DURING REBOOST OF LUNAR TRANSPOTATION NODE



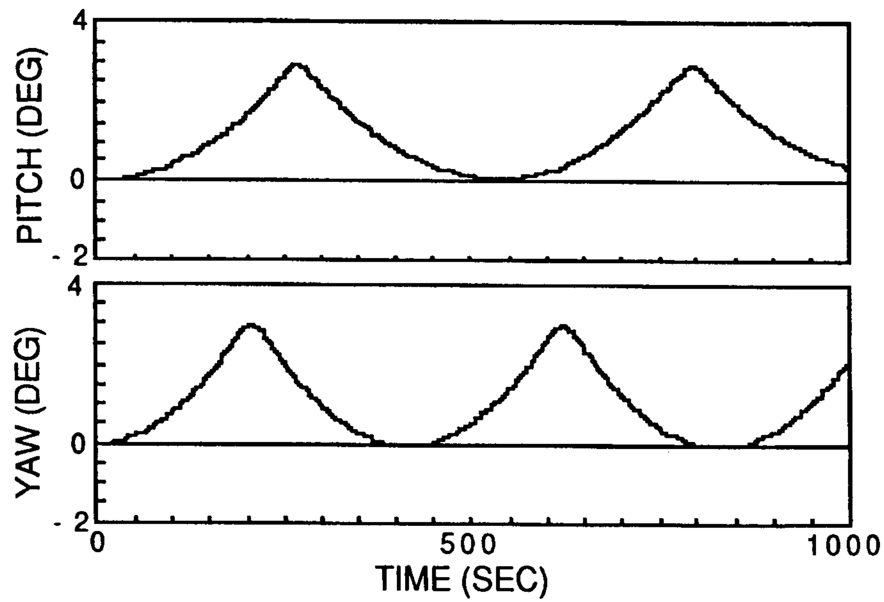
LOCATIONS OF RCS JETS AND C.M.



ORBIT ALTITUDE



RCS FIRINGS



RIGID BODY ATTITUDE

STRUCTURAL RESPONSE TO REBOOST

The elastic dynamic behaviour of certain critical points of the lunar transportation node is summarized below. The loads used in this study are based on the off-modulated Reaction Control System jet firings used for attitude control while reboosting the station from its assembly orbit. Preliminary investigation of buckling loads in the truss members at the interface between the transverse boom and the keels indicates that buckling failure (1.5 factor of safety) occurs in several of the truss batten/longerons. The baseline truss tubes modulus of elasticity, and wall thickness were 13.7×10^6 psi and 0.067 inches respectively. The buckling failure may be eliminated by increasing the truss tube stiffness either by increasing the tube wall thickness or the modulus of the material.

An area of particular interest is the elastic rotation local to the SD systems at the port and starboard tips of the transverse boom. The SD system concentrator requires a $\pm$ 0.1 degree solar vector pointing accuracy during orbital daylight. A combination of alpha and beta joint rotational control is provided to accomplish this pointing during nominal orbital operations. The higher frequency local elastic motions of the SD systems were investigated to determine the extent of elastic motion which must be countered by active control. As a measure of elastic motion, a plot of the flexible component of sun line variation in the YZ plane over the time of the reboost maneuver (shown in the figure) was generated. The local elastic motion of the SD location never exceeded the 0.1 degree requirement and should present no control problems. These results are highly dependent on the NASA baseline alpha joint stiffness used in the structural modeling. This stiffness is subject to change as the design of SSF approaches maturity.

Results at the remaining critical points indicate no excessive displacements or accelerations.

Structural Response To Reboost

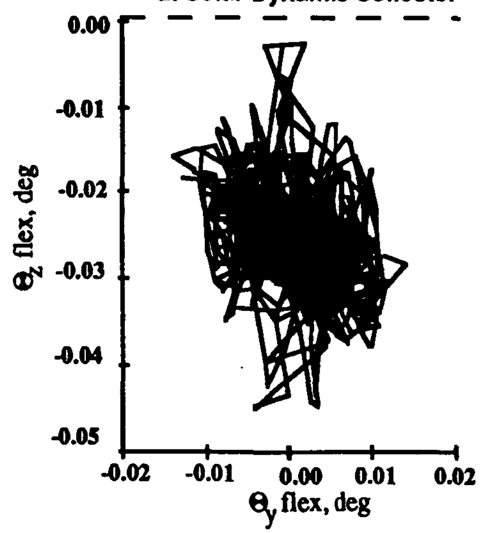
LOADS

o Buckling loads in truss members were investigated at interface between Boom and Keels ($E = 13.7 \times 10^6$ psi, 1.5 safety factor) :

- Max. load experienced in truss diagonal - **(1.5)** x **P/P_{cr}** = 0.29
- Max. load experienced in truss batten/longeron - **(1.5)** x **P/P_{cr}** = **1.19** **(Buckling Failure)**
- Structure at interface between Booms and Keels will have to be stiffened.

RESPONSE

Flexible Sun Line Variation at Solar Dynamic Collector



Location	Disp. (Inches) X	Y	Z
Tip of PV	2.40	1.03	0.29
Base of PV	0.96	0.09	0.29
SD Collector	1.66	0.44	0.54
Center of Hab. Module	0.25	0.13	0.09
Center of Lab. Module	0.30	0.12	0.07
Vehicle Attachment	0.04	0.14	0.13

o Peak accel. at modules = 621 µG (Lab.)

o No pointing problems at the SD collector or excessive displacement or acceleration occurred during reboost.

ATTITUDE CONTROL OF LUNAR TRANSPORTATION NODE CONFIGURATION

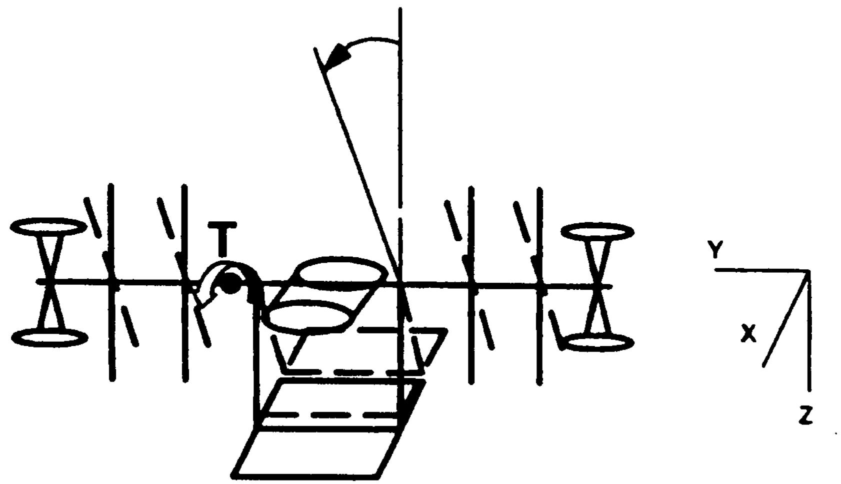
A simple, rigid body, attitude control system was designed for the Lunar Mission Node using control moment gyros (CMG) and based on a proportional plus differential (PD) feedback control law. The same control performance characteristics (i.e. 70.7% closed-loop system damping and 0.01 Hz bandwith frequency) were used as baselined for the space station Freedom. A second order Butterworth compensator designed for the Space Station Freedom assembly complete configuration (of 0.032 Hz break frequency) was included in the control loop for response simulation purposes.

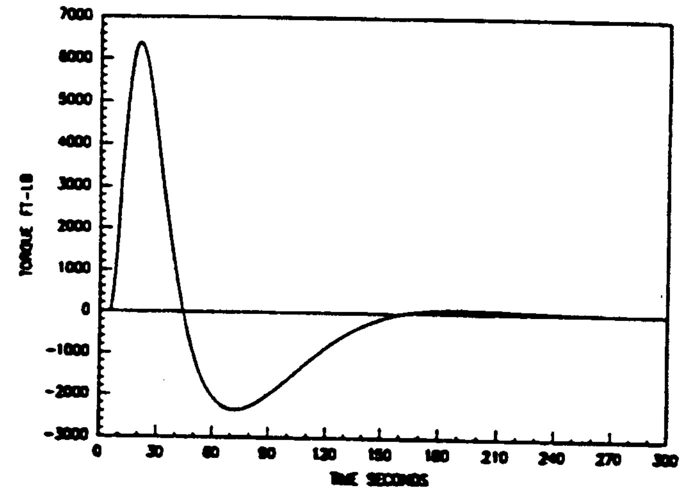
The figure shows the maximum control torque and the corresponding number of CMG's required to control the attitude of the Lunar Mission Node with the same control performance characteristics as the space station and for a one degree commanded attitude change about each axis.

The number of CMG's required to perform a 1 degree attitude change about a given axis is up to 10 times greater than the number on S.S. Freedom for the same response performance. A practical approach would be to reduce response performance requirements rather than to install a large number of CMG's.

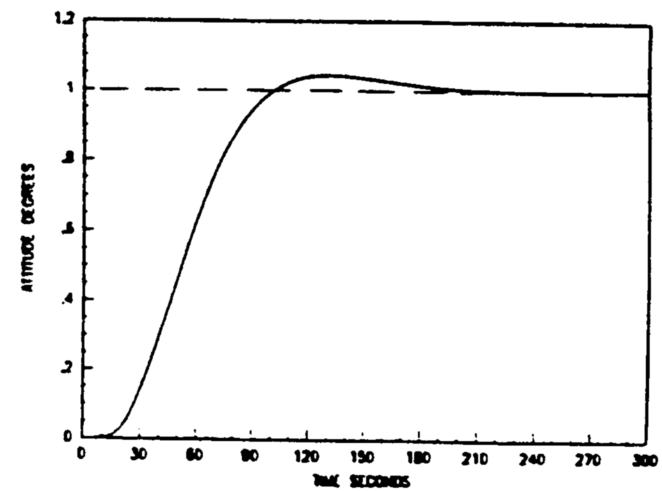
PRELIMINARY STUDY

CMG MAXIMUM TORQUE IN FT–LB AND NUMBER OF CMG'S TO CONTROL ATTITUDE OF LUNAR MISSION NODE WITH SAME CONTROL PERFORMANCE CHARACTERISTICS AS S.S. FREEDOM





Control torque time history about X axis



Attitude response time history

COMMANDED ONE DEGREE ATTITUDE CHANGE ABOUT EACH AXIS

TORQUE	MAGNITUDE	NO. OF CMG'S
Tx	6400	32
Ty	2800	14
Tz	4210	22

Concluding Remarks

A concept for a manned mission to Mars uses an evolutionary version of Space Station Freedom as a transportation node. This modified station with a Mars piloted vehicle installed has more than twice the mass of Space Station Freedom and up to a twelvefold increase in the moments of inertia. The lowest framework frequency of the modified station both with and without the Mars piloted vehicle is more than 50 percent below the lowest framework mode of the Space Station Freedom configuration. The low frequency modes have a complex motion with a strong coupling of the truss structure with the various power, radiator, and payload components. All modes exhibit similar behavior, in that the region of the modules, which has the bulk of the mass, acts as a node point for most modes and the region of the stiff Mars piloted vehicle assembly platform moves as a rigid body.

To reboost the station, a reaction control system composed of four clusters of jets, located on the dual keels fires its jets opposite to the flight direction. The jets are off-modulated at the appropriate locations to control the pitch and yaw attitude. The added mass, change in location of the center of mass and increase in inertia caused by the addition of the Mars piloted vehicle to the evolutionary station lowered the global keel frequencies significantly changing the character of the response of the station and required an adaptability in the jet firing logic for attitude control. The off-modulation pulsing of jets provided sufficient control to maintain station attitude to within three degrees yaw and pitch during the reboost maneuver. Study results indicate that there is sufficient separation between the reboost jet firing limit cycle and the fundamental frequency of the station to prevent excessive structural response to reboost loads. The attitude control is not significantly influenced by the elastic dynamic response at the sensor during the reboost maneuver.

One particular area of concern, the elastic rotation local to the solar dynamic systems at the tip of the transverse boom was investigated to determine the extent of the motion which must be countered by an active control system. The local elastic rotation at the solar dynamic system location never exceeded the 0.1 degree pointing requirement and should therefore present no control problems. These results are based on the current mass distribution and elastic model representation and are highly dependent on the NASA baseline stiffness of the alpha joint used in the structural modeling. This stiffness is subject to change as the design of Space Station Freedom matures.

CONCLUDING REMARKS

- O LOWEST TRANSVERSE BEAM FREQUENCY REDUCED 55% WITH INSTALLATION OF SD SYSTEM.

- O JET PULSING DURING REBOOST CAUSED NO SERIOUS ELASTIC DYNAMIC RESPONSES.

- O THE CURRENT BASELINE TUBE DESIGN IS NOT STIFF ENOUGH TO PREVENT BUCKLING OF TRUSS MEMBERS DURING REBOOST.

- O OFF-MODULATION PULSING OF JETS PROVIDES SUFFICIENT CONTROL TO MAINTAIN ATTITUDE DURING REBOOST.

- O LARGE VARIATIONS IN MASS AND STIFFNESS PARAMETERS DURING STATION OPERATIONS REQUIRES:

  - O UP-TO-DATE KNOWLEDGE OF MASS CHARACTERISTICS
  - O HIGHLY ADAPTIVE CONTROL SYSTEMS.
  - O ROBUST CONTROL SYSTEMS

- O CONTROL PERFORMANCE REQUIREMENTS FOR EVOLUTIONARY CONFIGURATIONS MIGHT HAVE TO BE RELAXED BECAUSE OF PRACTICAL LIMITATIONS IN AVAILABLE CONTROL AUTHORITY.