Report Number NPS 69-87-011

NAVAL POSTGRADUATE SCHOOL

Monterey, California

PROGRESS REPORT

INVESTIGATION OF THE SPIN STABILITY OF THE NPS MINI-SATELLITE (ORION)

by

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Period: July 5, 1987 - September 30, 1987

Approved for Public Release: Distribution Unlimited.

for: The Naval Postgraduate School Mini-Satellite (ORION) Project Office, and Air Force Technical Application Center.

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The work reported herein was supported by NPS Mini-Satellite (ORION) Project.

This report was prepared by:

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for Public Release Distribution Unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S): NPS 69-87-011	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION: Naval Postgraduate School; 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION: Air Force Technical Application Center
6c ADDRESS (City, State, and ZIP Code): Monterey, California 93943-5000	7b ADDRESS (City, State, and ZIP Code): Code TXN Patrick Air Force Base, FL 32925
8a NAME OF FUNDING/SPONSORING ORGANIZATION; 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: MIPR F62400-87-0004
8c ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO; PROJECT NO; TASK NO; WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification)

Investigation of The Spin Stability of the The NPS Mini-Satellite (ORION)

12 PERSONAL AUTHOR(S)
Kilsoo Kim and Young S. Shin

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Progress Report	FROM 1987 TO 1987	1987, 12, 4	27

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Satellite, Stability, Attitude Dynamics

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A preliminary design of the Naval Postgraduate School Mini-Satellite consists of a long cylindrical body and four radial booms and uses the single spin stabilization scheme for its attitude control. Stability conditions between design parameters for simple spinning motions of the satellite in space are investigated by applying Liapunov stability theory and using the natural modes as the admissible functions of internal coordinates. The stability diagram from this study shows that the internal stability conditions due to the flexibility of booms limit the angular velocity range of simple spins whlie the Maximum Axis Rule limit the minimum lengths of booms.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL: Professor Kilsoo Kim	22b TELEPHONE (Include Area Code): (408) 646-2288; 22c OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

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I. Introduction

The Naval Postgraduate School has started a project to design and build a mini-satellite (ORION). This mini-satellite bus will support a small payload for various space science, technology and military missions. The first specific payload is not determined, yet, and therefore, its major design parameters, such as, launch vehicle, attitude stabilization scheme, are not known. A feasibility study and a preliminary design of the mini-satellite were performed by Boyd (Ref. 1). In this preliminary design the launch of the satellite from the GAS (Get-Away-Specials) canister of a Space Shuttle and single spin stabilization were assumed

This preliminary design, as defined in Ref. 1, is investigated from the structural dynamics and attitude dynamics points of view. These include the survivability of the satellite under severe shock and vibration environment during launch periods, and the stability of the single spin attitude stabilization of the satellite. A rigorous investigation of the survivability satellite under shock and vibration environment is not possible in this preliminary design stage since the acceptible acceleration level of each electronic and mechanical components and detail design of connections and fasteners are not defined. However, it seems that the present design of bolts and nuts connection and no damping treatment (Figure 1) contains high failure probability areas considering the wide input frequency range (20-2000 Hz) of random vibration in GAS Canisters (Figure 2).

The main body of the NPS mini-satellite is long cylindrical shape (See Figure 1). The principal moment of inertia about the axial axis of symmetry is smaller than the principal moments of inertia about the radial axes of the main body without the four radial booms. It is well known that the attitude of a rigid body spinning about the axis of the minimum principal moment of inertia is unstable. Therefore, in the preliminary design of the NPS satellite, the lengths of booms and the masse of the magnetometer at the end of each boom are such that the total moment of inertia about the axial axis is the maximum, assuming the four radial booms are rigid. However, long booms are flexible and the flexibility of booms affects the attitude stability of a spinning body negatively. Therefore, each specific design of a spin stabilized satellite with flexible parts should be investigated to determine the stability conditions between design parameters.

Dynamic equations governing 3-dimensional motions of a body (especially a flexible body) in space are highly nonlinear and complicated. Therefore, a free or forced motion and the stability of the motion of a body in 3-dimensional space can be best investigated by the computer simulation for each specific case using a highly capable computer code such as DISCOS (Ref. 2), or TREETOPS (Ref. 3). In this preliminary design stage, and without an available code, the stability of the simple spinning motion of the NPS mini-satellite about the axial axis of symmetry is investigated analytically in Chapter II. The analytical study of the spin stability of free motions of elastic disspative systems was performed previously by Teixeira-Filho and Kane (Ref. 4). The results of this study were applied to the stability studies of a spinning rigid satellite that carries four elastically mounted rigid antennas (Ref. 5) and of a spacecraft consisting of a rigid body and four elastic booms using finite number of beam elements (Ref. 6). In the present investigation of the stability of free spinning motion of the NPS mini-satellite the basic results of the Ref. 4 are applied, using natural vibration modes of the booms as the admissble functions of internal coordinates.

II. Analysis

II-1 system Description

The NPS mini-satellite S to be analyzed consists of a rigid body B of cylindrical shape and four flexible booms C, D, E, F, as shown in Figure 3. B* is the mass center of B and X_1, X_2, X_3 are the principal axes of inertia of B. When undeformed, boom C and D lie on the opposite side of B in the X_1-X_2 plane and are parallel to X_2 while booms E and F lie on opposite sides of B in the X_1-X_3 plane and are parallel to X_3. The four booms are assumed to be rigidly attached on the cyclindrical surface of radius R of body B in the radial direction and are on the X_2-X_3 plane. Each boom has length L and rectangle-tubular cross section of flexural rigidities EI_1 about axis X_1 and EI_2 about axis X_3 (for C,D) or about X_2 (for E, F).

B has mass M and the mass distribution in B is assumed to be axisymmetric about X_1. Therefore among the principal moments of inertia B_1, B_2, B_3 of B for the mass center B* associated with X_1, X_2, X_3, respectively, B_2 and B_3 are the same. Each boom has mass m_b and the mass of a magnetometer attached at the tip of each boom is m.

The orientation of B, or the X_1, X_2, X_3, in a Newtonian reference frame N can be specified in terms of three external coordinates, θ_1, θ_2, θ_3. Let θ_1, θ_2, θ_3 be Euler angles such that X_1, X_2, X_3 coordinates system is brought into an orientation in N by successive rotations θ_1, θ_2, θ_3 about X_1, X_2, X_3 from the N_1, N_2, N_3 direction.

The deformed configuration of the satellite is described using 4n internal coordinates q_1, q_2, ... q_{4n}, in addition to the external coordinates. The general deformation of a boom C is described using the n internal coordinates.

$$W_c(x,t) = \sum_{i=1}^{n} \phi_i(x) q_i(t) \tag{1}$$

where $W_c(x,t)$ is the deflection of a boom cross-section at position x from the boom root in X_1 X_2 X_3 coordinates, and ϕ_i i = 1,2,...n are admissible functions chosen to be the same as the normal modes of the boom as a cantilever beam with an end mass in this analysis. The general deformation of booms D, E, F, are described using the same form of equation (1) with q_i, i = n+1,...,2n for boom D, with q_i, i = 2n+1,...,3n for boom E, with q_i, i = 3n+1,...,4n for boom F, respectively.

It is assumed that no external forces and moments are applied. Due to the internal forces of interaction between the particles of systems, it is presumed that energy dissipation can be described by functions $D_r(q,\dot{q})$ which are functions of $q_1,\ldots,q_{4n}$, $\dot{q}_1,\ldots,\dot{q}_{4n}$ such that

$$D_r(q,0) = 0, \qquad r = 1,2,\ldots,4n \tag{2}$$

$$D_r(q,\dot{q})\,\dot{q}_r \leq 0 \tag{3}$$

where the equality sign of equation (3) holds only when $\dot{q}_1,\ldots,\dot{q}_{4n}$ all vanish.

I-2 Stability Conditions

In torque-free motion, the satellite system S can move such that the angular velocity of B in the Newtonian reference frame N has a constant magnitude Ω and is parallel to X_1 which remains fixed in N while the booms remain normal to X_1. This motion is defined as a simple spin.

A simple spin is called stable if the system resumes this motion, or acquires a motion closely resembling it, subsequent to every sufficiently small disturbance that leaves the angular momentum unaltered. If the system returns to the original simple spin state after a disturbance as time t approaches infinity, then the simple spin is said to be asymptotically stable.

Stability conditions can be established by stating conditions under which the function $F(\theta, q, \dot{q})$ defined as

$$F \triangleq 2(E-E_o) \tag{4}$$

is a Liapunov function (Ref. 7), where E is the total energy of the system and E_o is the total energy of the system during the simple spin. It was shown in Ref. 4 that for a simple spin of an axisymmetric system,

$$F = \frac{H^2}{I_s^o}\left\{\frac{I_s^o - I_t^o}{I_t^o}(\theta_2^2 + \theta_3^2)\right\} + Z^o_{,rs}\, q_r q_s + M^o_{rs} q_r q_s + 0_3(\theta, q, \dot{q}) \tag{5}$$

where H is the magnitude of angular momentum, I_s and I_t are the principal moment of inertia of the system about the axial axis and about the transverse axis, respectively, $0_3(\theta, q, \dot{q})$ indicates terms of third or higher degree in its arguments, and superscript o means its value at the simple spin state.

M_{rs} is an element of an inertia like matrix defined as

$$M_{rs} = \langle mp,_r \cdot p,_s \rangle - \langle mp \times p,_r \rangle \cdot I^{-1} \cdot \langle mp \times p,_s \rangle \tag{6}$$

$$r,\ s = 1,2,\ldots\ldots\ldots\ldots,4n$$

where the symbol < > denote summation over all particles of the system S, p is the position vector of a particle relative to the mass center of F, $p_{,r}$ indicates its derivative about q_r, m is the mass of the particle, and I^{-1} is the inverse of the inertia dyadic I.

$Z_{,rs}$ is a second derivative of an energylike function Z(q) with respect to q_r and q_s, which is defined as

$$Z(q) = V(q) + \frac{1}{2} H^2 I^{-1}(q) \qquad (7)$$

where V(q) is the potential energy function of S.

From the Liapunov stability theory, the stability conditions are

$$\dot{F} \leqq 0 \qquad (8)$$

with equality sign holds only when $\dot{q}_1, \ldots, \dot{q}_{4n}$ all vanish,

$$I_s^o - I_t^o > 0 \qquad (9)$$

and

$$Z^o_{,rs} \text{ is positive definite.} \qquad (10)$$

The first condition, equation (8) is satisfied from the energy dissipation, equations (2) and (3). The second condition, equation (9), is the well known "Maximum Axis Rule" of the stability condition of a rigid body, and can be called the "external stability condition" of a deformable body system. This condition can be satisfied when the boom length L is longer than the critical length L_{min}, which is about 60 inches for the NPS mini-satellite (ORION).

The third stability condition, equation (10), is due to the flexible deformation of booms and can be called the "internal stability condition". It is shown in Ref. 4 that for a stress-free spin about axis X_1, that is,

$$V^o_{,r} = 0 \qquad ; \qquad r = 1,2,\ldots\ldots\ldots, 4n \tag{11}$$

or

$$I^o_{11,r} = 0 \qquad ; \qquad r = 1, 2,\ldots\ldots\ldots, 4n \tag{12}$$

from the associated eqations governing the internal coordinates, $Z^o_{,rs}$ can be expressed as follows with H replaced by $I_{11}{}^o \Omega$

$$Z_{,rs} = V^o_{,rs} - \Omega^2\{\frac{1}{I^o_s - I^o_t}(I^o_{12,r}\, I^o_{12,s} + I^o_{13,r}\, I^o_{13,s}) + \frac{1}{2} I^o_{11,rs}\} \; ; \quad r = 1,2,\ldots 4n \tag{13}$$

The simple spin motion of the NPS satelite system S is a stress-free spin, since it satisfies the condition, equation (11) or equation (12), by choosing the internal coordinates as in equation (1). Moreover, by this choice of internal coordinates using the normal vibration modes of the cantilevered boom, the components of $Z^o_{,rs}$ in equation (13) can be easily calculated, using the orthonormal relations between normal modes of the boom:

$$m\phi_r(L)\phi_s(L) + \int_L \phi_r(x)\phi_s(x)\,\mu\, dx = \delta_{rs} m_{rr} \tag{14}$$

$$\int_L EI\phi_r''(x)\phi_s''(x)\, dx = \delta_{rs} k_{rr} \tag{15}$$

where δ_{rs} is the Kronecker delta of r, s = 1,2,...,n, and m_{rr} and k_{rr} r = 1,2,...,n, are modal masses and modal stiffnesses of the vibration modes, μ is the mass per unit boom length.

$$V^{o}{}_{,rs} = k_{rr}\delta_{rs} + K_G$$

$$= m_{rr}\omega_r^2\delta_{rs} + \Omega^2\int_R^{R+L}\frac{x}{2}\,\{m+(R+L-x)\}\;\phi_r'(x)\;\phi_s'(x)\;dx \tag{16}$$

where K_G is the geometric stiffness of the boom due to the centrifugal force of the spin, and ω_r is the natural frequency of the r mode.

$$I^{o}_{12,r} = \int_R^{R+L} x\,\phi_r(x)\,\mu\,dx + L\,\phi_r(L)\,m \tag{17}$$

r = vibration modes in X_1- X_2 plane for booms C and D

$$I^{o}_{13,s} = \int_R^{R+L} x\,\phi_s(x)\,\mu\,dx + L\,\phi_s(L)\,m \tag{18}$$

s = vibration modes in X_1- X_3 plane for booms E and F

$$I^{o}_{11,rs} = m_{rr}\,\delta_{rs} \tag{19}$$

r = vibration modes in X_2- X_3 plane for booms C, D, E, and F

When all ingredients required for the evaluation of $Z^{o}{}_{,rs}$ are available using equations (13), (16-19), the internal stability conditions can be examinded as followes:

Define Δ_i, $i = 1,2,\ldots\ldots\ldots..4n$, as

$$\Delta_1 \triangleq Z^o_{,11} \tag{20,a}$$

$$\Delta_2 \triangleq \begin{vmatrix} Z^o_{,11} & Z^o_{,12} \\ Z^o_{,21} & Z^o_{,22} \end{vmatrix} \tag{20,b}$$

$$\Delta_3 \triangleq \begin{vmatrix} Z^o_{,11} & Z^o_{,12} & Z^o_{,13} \\ Z^o_{,21} & Z^o_{,22} & Z^o_{,23} \\ Z^o_{,31} & Z^o_{,32} & Z^o_{,33} \end{vmatrix} \tag{20,c}$$

and so on.

The internal stability condition is

$$\Delta_i > 0 \qquad \text{for all} \quad i = 1,2,3,\ldots\ldots.,4n \tag{21}$$

II-3 Stability of the NPS Mini-Satellite (ORION)

The stability conditions of the simple spinning motion of the NPS mini-satellite between the angular velocity Ω and the length of a boom L for other parameters defined in the preliminary design (See Ref. 1). The numerical value of these parameters are shown in Table 1.

Table 1 - Parameters of NPS mini-satellite

Radius of B	R = 9.5 inch
Mass of B	M = 7.542 slug
Axial moment of inertia of B	B_1 = 2.18 slug-ft
Transverse moment of inertia of B	$B_2 = B_3$ = 6.78 slug-ft
Area of a boom cross-section	A = 0.212 in
Area moment of inertia of a boom about $X_2 - X_2$ plane	I_1 = 0.01668 in
Area moment of inertia of a boom about $X_1 - X_2$ plane	I_2 = 0.06328 in
Young's modulus of the boom	E = 10.3 X 10 Psi
Mass of a boom per unit length	μ = 0.000415 (Slug/in)
Mass of a magnetometer at the end of a boom	m = 0.0621 slug

For the design value of L = 78.5 inches the cantilever beam model of a boom with an end mass was analyzed using the MSC/NASTRAN code for the natural frequencies and mode shapes. The natural frequencies are shown in Table 2, and the finite element model and the first 3 mode shapes are shown in Figures 4 to 7.

Table 2 - Natural Frequencies of a Boom

Mode	Natural Frequency (Hz)	Mode Shape
1	2.104	1-2 plane bending
2	4.097	2-3 plane bending
3	23.426	1-2 plane bending
4	45.569	2-3 plane bending
5	73.656	1-2 plane bending
6	142.980	2-3 plane bending

When the angular velocity of simple spin Ω is increased from very small value, it can be seen from stability conditions, equations (20-21) and from equations (13), (16-19) that the stability condition will be violated first when Ω approaches the first natural frequency ω_1, since for higher modes ω_i^2, i = 2,3,..., are much greater than Ω^2 and the matrix $Z^o_{,rs}$ become diagonally dominant. Therefore, the stability conditions can be examined simply by reducing the number of internal coordinates q_i to the first mode of each boom, q_1, q_2, q_3, q_4.

Inserting the expressions of its components, equations (16) - (19) into equation (13), the matrix $Z^o_{,rs}$ becomes the following form:

$$Z^o_{,rs} = \begin{bmatrix} \omega_1^2 - \alpha\Omega^2 & 0 & -\beta\Omega^2 & 0 \\ 0 & \omega_1^2 - \alpha\Omega^2 & 0 & -\beta\Omega^2 \\ -\beta\Omega^2 & 0 & \omega_1^2 - \alpha\Omega^2 & 0 \\ 0 & -\beta\Omega^2 & 0 & \omega_1^2 - \alpha\Omega^2 \end{bmatrix} \qquad (22)$$

where

$$\alpha = \frac{1}{I_s^o - I_t^o}\{\int_R^{R+L} x\,\phi_1(x)\,\mu\,dx + L\,\phi_1(L)\,m\}^2 - \int_R^{R+L} \frac{x}{2}\{m+\mu(R+L-x)\}\{\phi_1'(x)\}^2 dx \qquad (23)$$

and

$$\beta = \frac{1}{I_s^o - I_t^o}\{\int_R^{R+L} x\,\phi_1(x)\,\mu\,dx + L\,\phi_1(L)\,m\}^2 \qquad (24)$$

with $\phi_1(x)$ is the mode shape of the first mode.

The stability conditions, equations (20) - (21), become

$$\omega_1^2 - \alpha\Omega^2 > 0 \qquad (25,a)$$

$$(\omega_1^2 - \alpha\Omega^2)^2 > 0 \qquad (25,b)$$

$$(\omega_1^2 - \alpha\Omega^2)\{(\omega_1^2 - \alpha\Omega^2)^2 - \beta^2\Omega^4\} > 0 \qquad (25,c)$$

$$\{(\omega_1^2 - \alpha\Omega^2)^2 - \beta^2\Omega^4\}^2 > 0 \qquad (25,d)$$

Therefore, the internal stability conditions is reduced to the condition

$$\Omega^2 < \frac{\omega_1^2}{\alpha+\beta} \qquad (26)$$

from the condition (25,c).

As the length of a boom L increases, the first natural frequency ω_1 decreases as follows;

$$\omega_1 = \sqrt{\frac{3EI}{(m+0.23\mu L)L^3}} \tag{27}$$

The denominator in equations (23), (24), $I_s^o - I_t^o$ is proportional to $(L^2 - L_{min}^2)$ and increases from zero for $L > L_{min}$, which is the external stability condition. Therefore, the stability boundary in the stability diagram varies as shown in Figure 8. For the designed value of L = 78.5 inches the stability condition is

$$\Omega < 8.658 \quad \text{(rad/sec)} \tag{28}$$

However, it was assumed that each boom is a single piece and rigidly connected to the rigid main body B. Since each boom consist of three beam and the connection between the boom and the body B is not ideally rigid the critical angular velocity Ω_c may be much lower than the value calculated, equation (28), depending on the design of joints of booms.

III. Conclusions

The stability conditions of a simple spin motion of the NPS mini-satellite (ORION) are derived analytically using Liapunov stability theory and by choosing the natural vibration modes as admissible functions of internal coordinates of the system. By applying this conditions to the preliminary design of the satellite it is shown that the angular velocity of the simple spin should be limited to the value of 8.685 rad/sec for the boom length L = 78.5 inches. If the boom length is changed the critical angular velocity Ω_c also changes and the stability conditions should be re-examined using the results derived in this study.

It should be recognized that the stability conditions were derived for the simplified ideal model under the following assumptions; 1) the mass distribution of the cylindrical main body is axisymmetric; 2) the connections between the booms and the main body and the main body itself are rigid; 3) each boom acts as a single piece and the locking mechanism of the boom should be ideal.

Due to the highly nonlinear behavior of a three dimensional motion of a flexible body, the stability analysis is valid for only small disturbances. Therefore, stability of dynamic motion of a satellite for general environments should be investigated by dynamic simulation using computers and proper dynamic models.

IV. References

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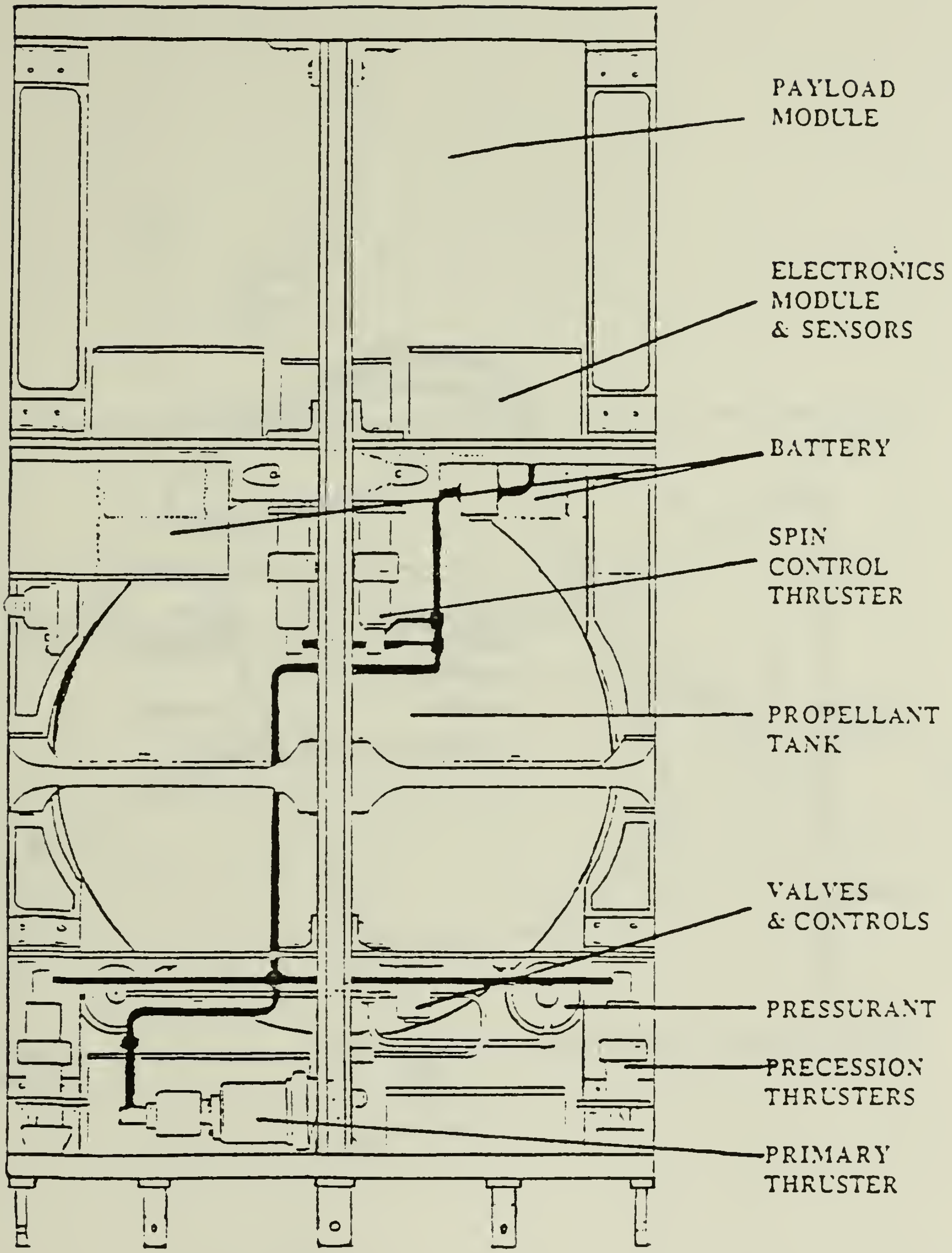

Figure 1. The NPS Mini-Satellite (ORION)

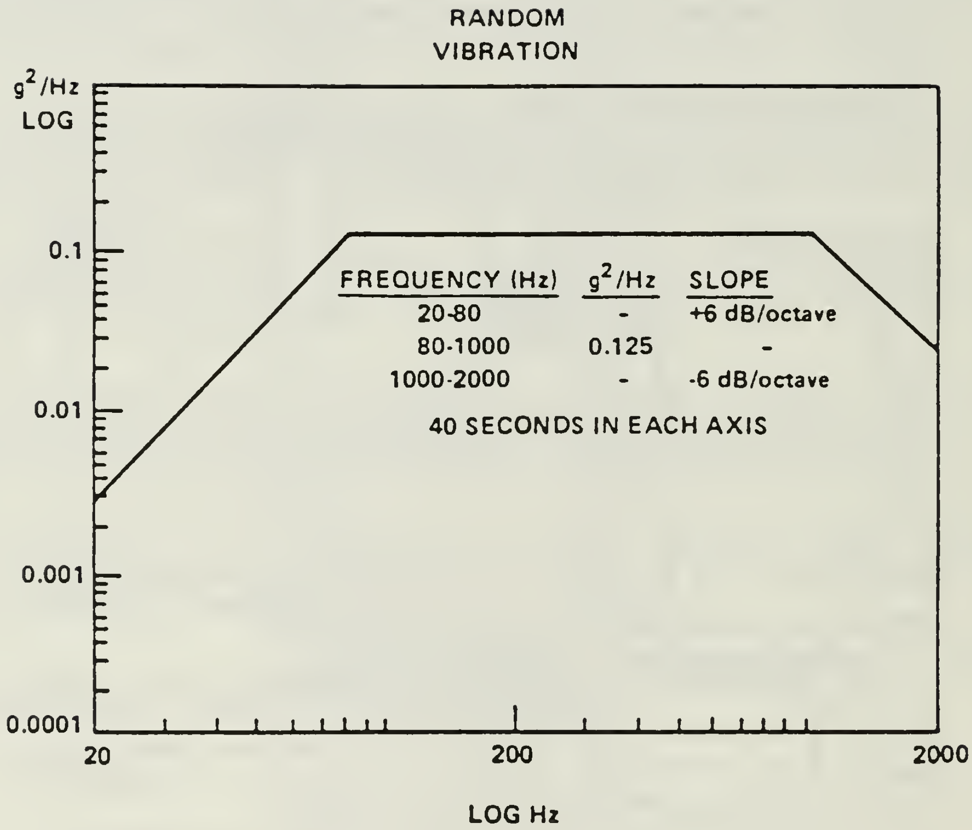

Figure 2. Random Vibration Level in GAS Canisters. (NASA G. A. S. Manual, 1984, P. 57)

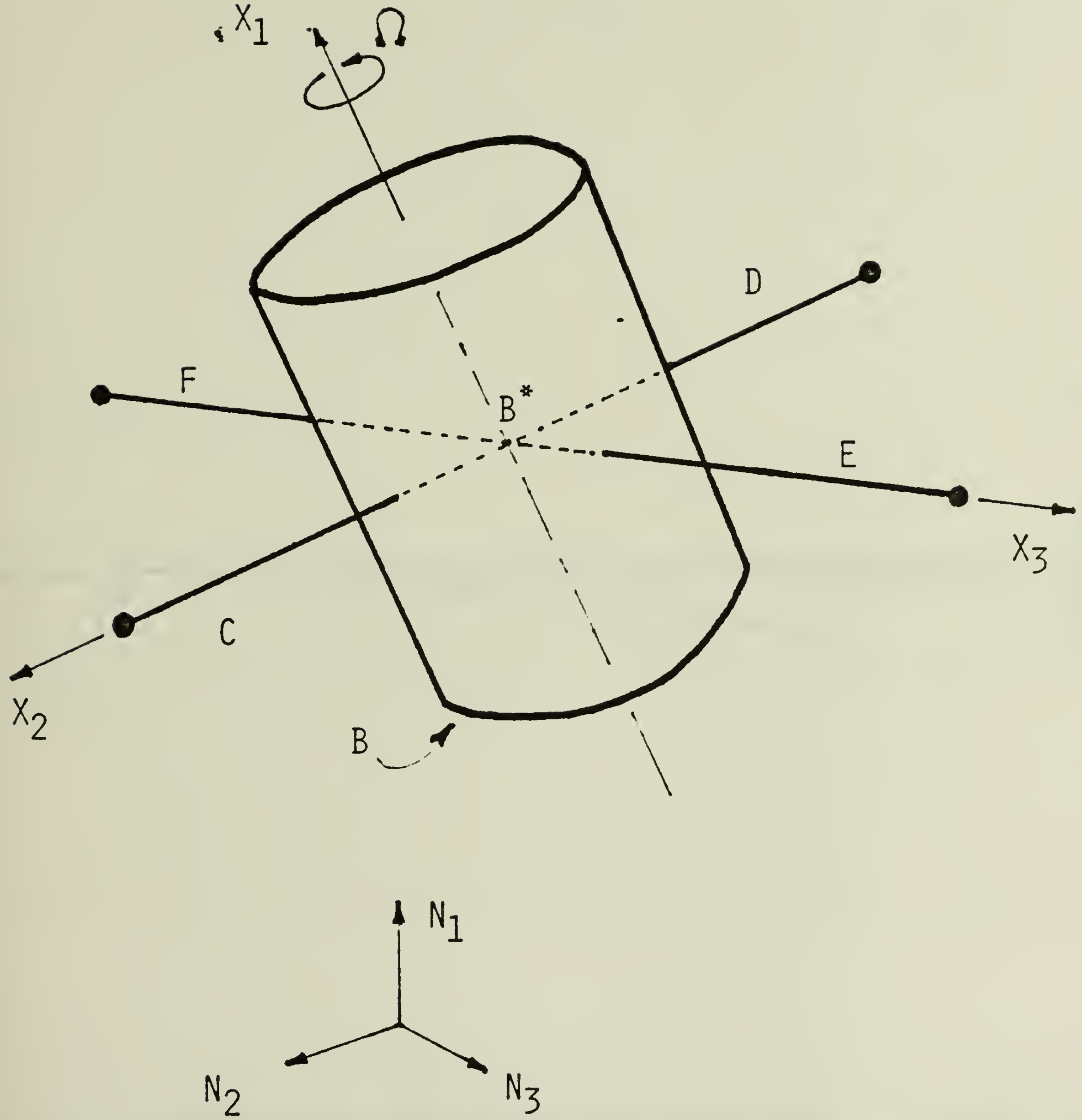

Figure 3. Dynamic Model of The NPS Satellite During a Simple Spin Motion in Space.

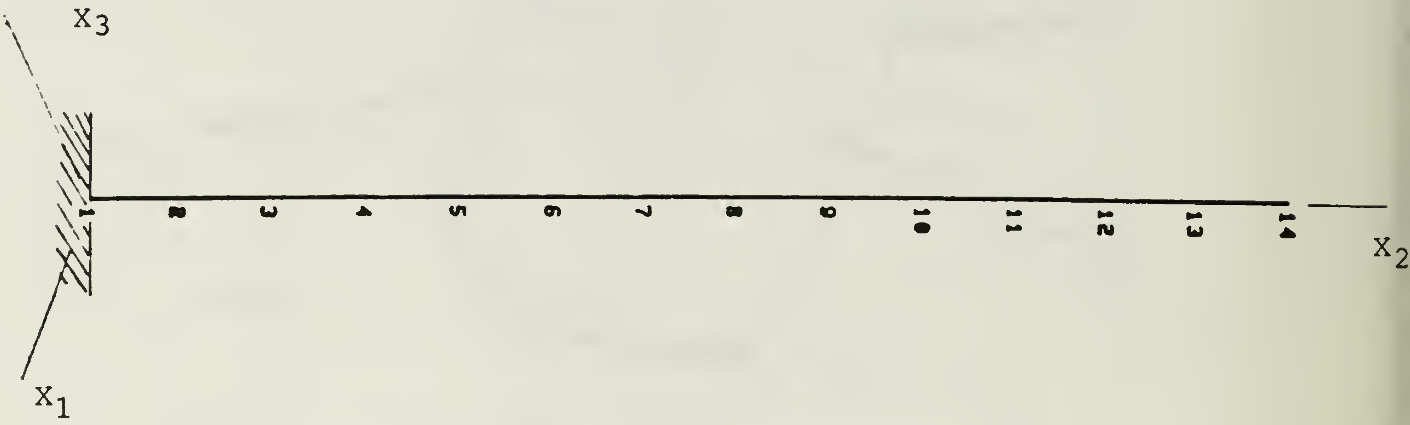

Figure 4. The Finite Element Model of a Boom
(X_1, X_2, X_3 show the Orientation of the Satellite)

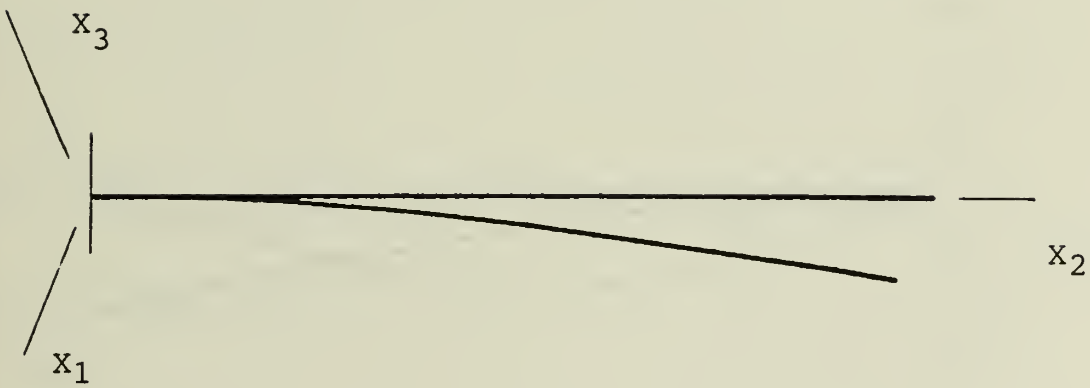

Figure 5. The Mode Shape of the First Mode (f = 2.104 Hz)

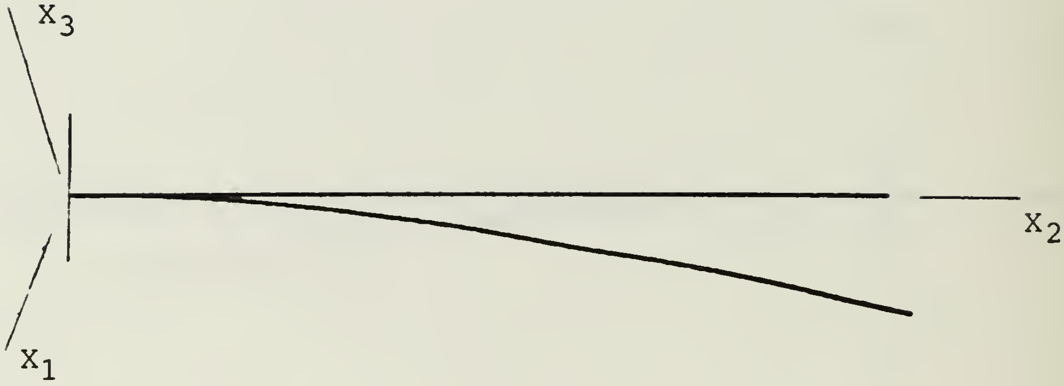

Figure 6. The Second Mode (f = 4.097 Hz)

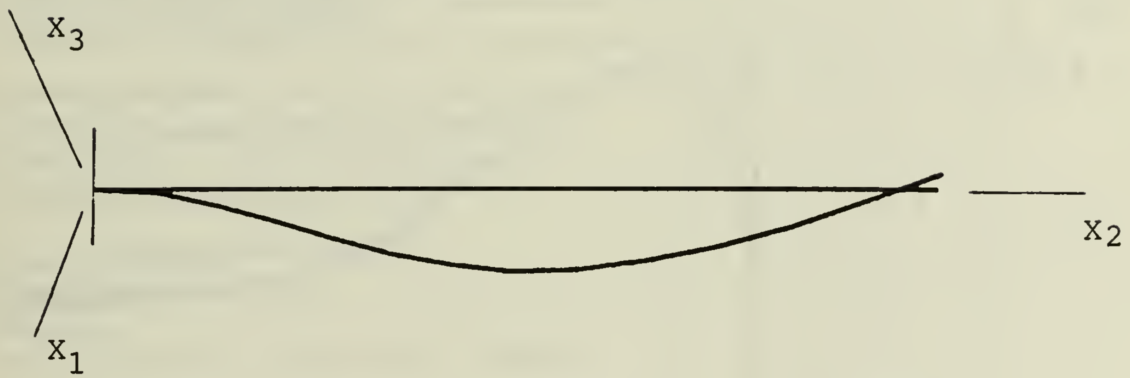

Figure 7. The Third Mode (f = 23.43 Hz)

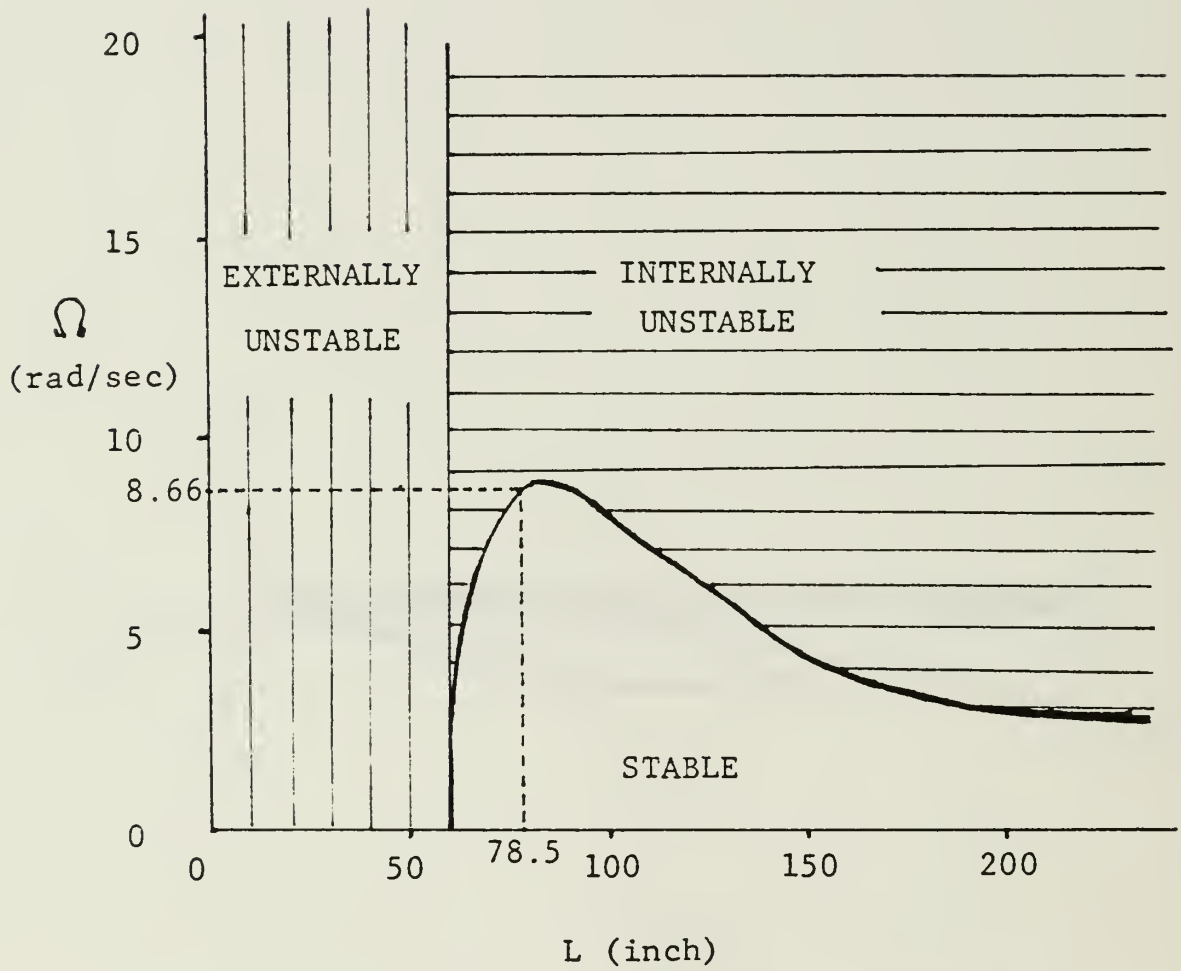

Figure 8. Stability Diagram of The NPS Mini-Satellite.

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