IMPROVING THE STABILIZATION OF TETHERED SUBSATELLITE SYSTEM DURING ITS RETRIEVAL TO SPACE SHUTTLE

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الملخص

خلال مرحلة رجوع سلك طويل يحمل قمر اصطناعي إلى المركبة الفضائية هناك مشاكل عدم استقرار نتيجة الحركات الدوارنية والاهتزازات الطولية والعرضية، ويتم عادة التحكم في هذه الحركات والاهزازات عن طريق محركات نفاثة.

في هذا البحث نتطرق إلى تعديل جديد على طريقة التحكم بالمحركات النفاثة ونوضح أن هذا التعديل ينتج عنه توفير كبير في كمية الوقود التي تحتاجها المحركات بالإضافة إلى تحسن ملحوظ في استقرار السلك أثناء مرحلة الرجوع.

ABSTRACT

During the retrieval of very long tether carrying subsatellite to space shuttle, instability problems occurr due to rotational motions as well as the longitudinal and transverse vibrations. Usually, a thruster augmented control system is used to control these motions and vibrations. In this paper, a new modified thruster control law based on this system is proposed which results in saving a large amounts of thruster fuel and improved the stability modes of the tether.

KEYWARDS: Space shuttle; Subsatellite; Tether; Thruster; Control.

INTRODUCTION

Tether connected two-body systems have a great potential for space applications, of particular interest is the shuttle supported tethered subsatellite system. The primary scientific and engineering deploy stabilize, and retrieve a tethered satellite in space and operate it as an electrically conducting system within Earth's magnetic field. With this system a variety of fascinating uses (Figure (1)) have been proposed in the last decades such as:

i)- Upper atmospheric experiments;
ii)- Electrodynamics uses;
iii)- Radio astronomy and low frequency communications uses;
iv)- Transportation and space constellation uses;

Manipulating a satellite on a tether from the orbiter turned out to be a unique engineering challenge. Because gravity, centrifugal acceleration, and atmospheric drag vary with altitude, each of the two bodies in a tethered system, one orbiting above the other, is subject to different magnitudes of influence [1-3]. Many problems are associated with the system dynamics and control, especially during the retrieval stage.

The rotational motions as well as the longitudinal and transverse vibration of the tether grow with time [4-5].

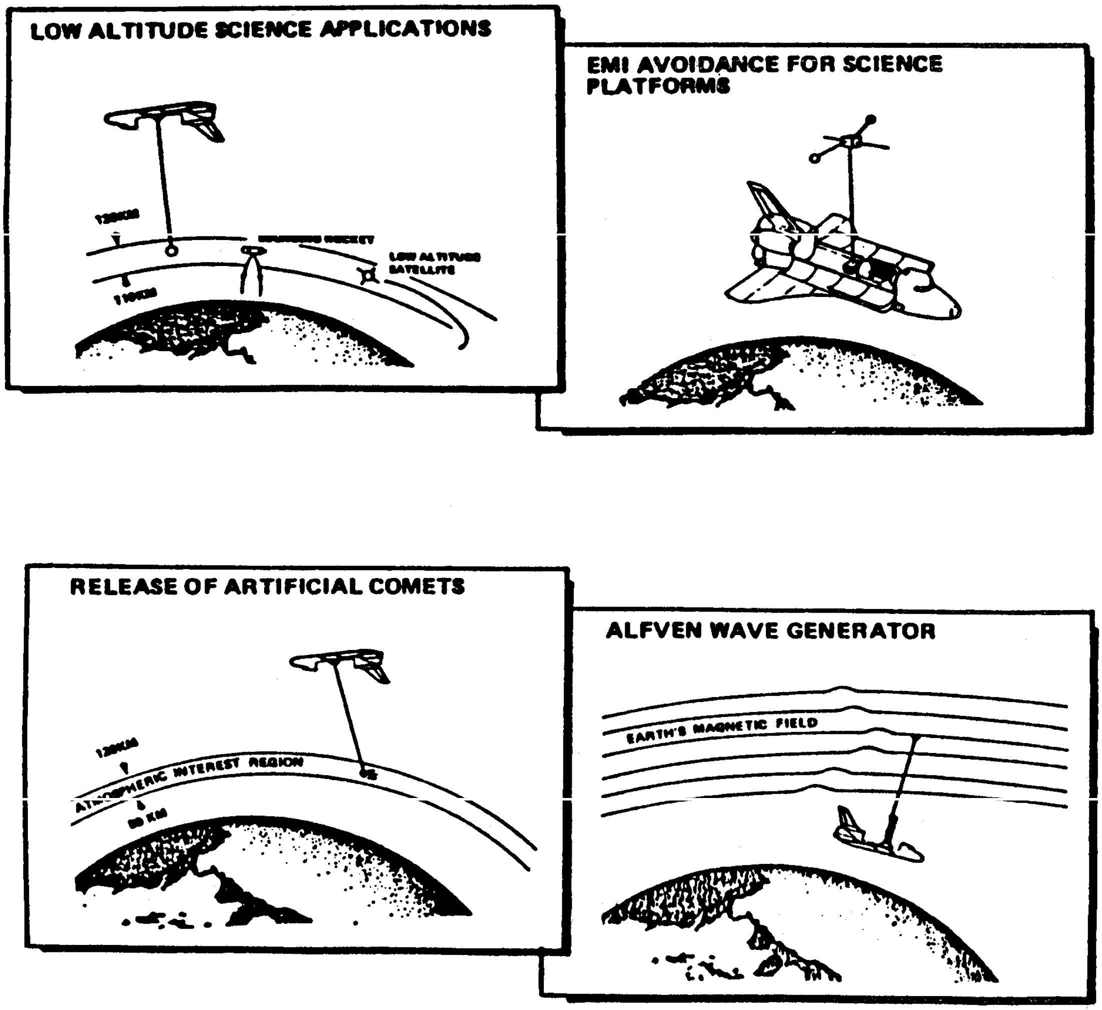


Figure 1: Tether system science applications [8]

A significant effort has been concentrated on this problem. To alleviate this problem, Banerjee and Kane [6] have proposed using a set of thrusters to control the retrieval dynamics Figure (2). Xu et al [7] proposed appropriate functional forms of the thrusts required for control of all components of motion at the retrieval stage. The analysis in this paper uses this type of control law.

In previous study [2], the motion was stabilized around the local vertical, where a large amount of thruster fuel was consumed. The objective of this paper is to stabilize the tether around a steady state configuration (a line inclined to the local vertical) with an aim of saving the thruster fuel.

It must be emphasized that the objective is not the optimization of the thruster impulse for a given retrieval procedure. Instead the objective is to decide on an appropriate procedure by comparing the thruster impulse for various procedures.

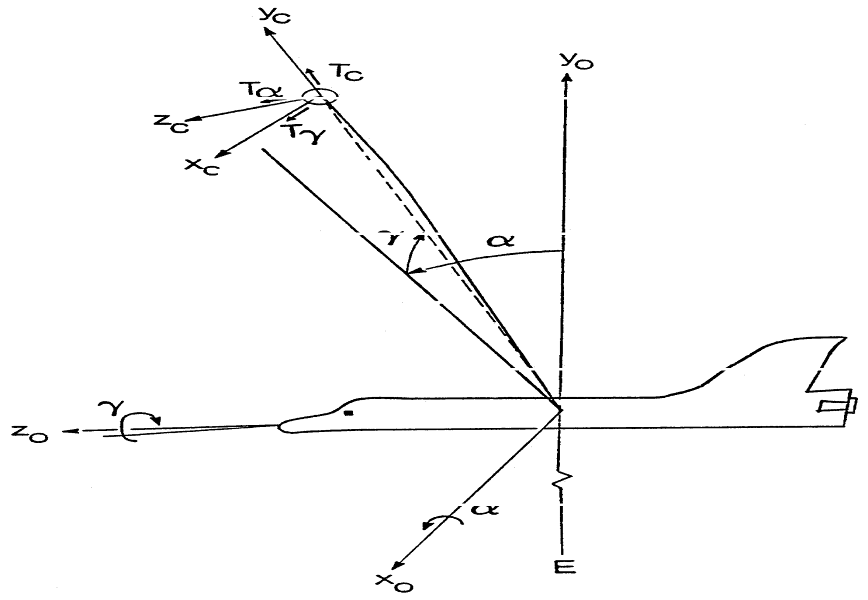


Figure 2: Arrangement of the thrusters

SYSTEM DESCRIPTION AND MODELLING

The system under consideration consists of a subsatellite of mass m_s supported by a shuttle through a tether having a mass per unit length ρ_t and instantaneous nominal length L Figure (3).

The rotational motion or the tether is described by two angles α (pitch) and γ (roll), given in that order in and out of the orbital plane, respectively. Also there are two types of vibrations of the tether, one is longitudinal and the other is transverse.

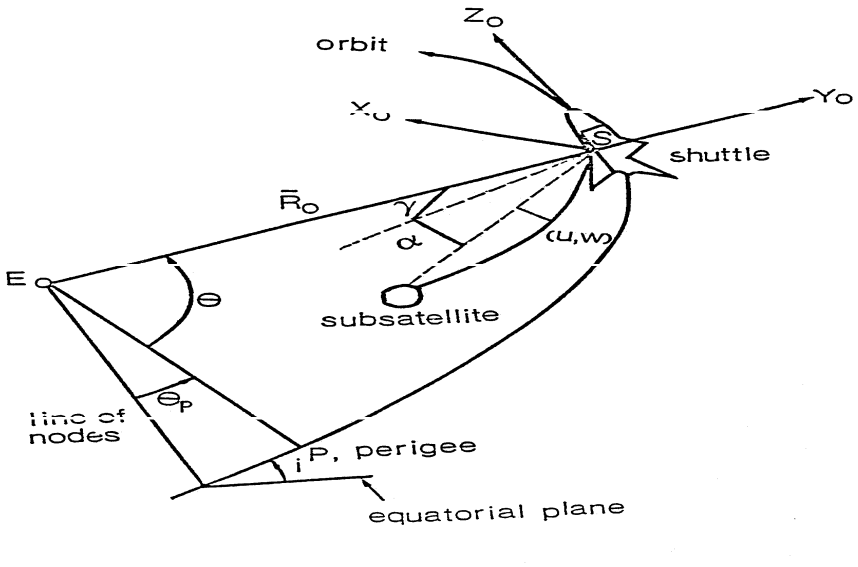


Figure 3: Illustration of the system

The transverse displacements are denoted by u and w in and perpendicular to the orbital plane, respectively, while the longitudinal displacement is v. By using Galerkin method, u, v, and w are expressed approximately as

$$u = \sum_{i=1}^{n} \widetilde{A}_i(t)\phi_i(y,t), \qquad A_i = \widetilde{A}_i / L \tag{1}$$

$$w = \sum_{i=1}^{n} \widetilde{B}_i(t)\phi_i(y,t), \qquad B_i = \widetilde{B}_i / L \tag{2}$$

$$v = \sum_{i=1}^{p} \widetilde{C}_i(t)\psi_i(y,t), \qquad C_i = \widetilde{C}_i / L \tag{3}$$

Here ϕ_i and ψ_i are a set of admissible functions satisfying at least the geometric boundary conditions. Note that n and p are limited to 2.

MATHEMATICAL MODELING

The equations of motion and the possible forms of thrusters which are used in these analyses are given and used without going into the details of derivation since this can be found in [8].

ANALYSIS OF THE EQUATIONS OF MOTIONS

Before starting the analysis of the equations of motion, I should mention that, there are two types of retrieval for which the length variation is specified;
(i)- Exponential retrieval in which

$$L = L_i e^{\widetilde{c}\theta} \tag{4}$$

where $\widetilde{c} = c/\omega$ clearly the velocity is

$$L' = \widetilde{c}L \qquad \text{or} \qquad \dot{L} = cL \tag{5}$$

(ii)- Uniform retrieval (constant velocity) here

$$\eta'' + \eta'^2 = 0 \tag{6}$$

or

$$L = L_i(1 + \widetilde{c}\theta) \tag{7}$$

then the velocity

$$L' = \widetilde{c}L_i \qquad \text{or} \qquad \dot{L} = cL_i \tag{8}$$

ANALYSIS OF ROTATIONAL MOTIONS

Recognizing that inplane and out of plane rotations represent the most important variables of the problem, therefore, these motions will be studied first ignoring the vibrations.

The equations of rotations after ignoring vibrations are

$$(1+\nu/3)c^2\gamma\alpha'' - 2s\gamma c\gamma\gamma'(1+\alpha')(1+\nu/3) + (1+\alpha')(2+\nu)\eta' c^2\gamma$$

$$+3(1+\nu/3)s\alpha c\alpha c^2\gamma = \tilde{T}_\alpha \tag{9}$$

$$(1+\nu/3)\gamma'' + (2+\nu)\eta'\gamma' + \{(1+\alpha')^2 + 3c^2\alpha\}(1+\nu/3)s\gamma c\gamma = -\tilde{T}_\gamma \tag{10}$$

The control forces are

$$\tilde{T}_\alpha = (k_0 + k_\alpha \alpha')\eta' \tag{11}$$

$$\tilde{T}_\gamma = -k_\gamma \gamma'\eta' \tag{12}$$

Equations (9) and (10) in very simplified case when no control forces, the angles are small and mass of tether is negligible are

$$\alpha'' + 2\eta'(1+\alpha') + 3\alpha = 0 \tag{13}$$

$$\gamma'' + 2\eta'\gamma' + 4\gamma = 0 \tag{14}$$

During exponential retrieval, η' is constant, that means $-(2+\nu)\eta'$ is nearly constant (ν is very small). The two equations (13) and (14) are greatly simplified; one may note the difference between deployment and retrieval. During deployment, length L is always increasing i.e, η' is positive, thus the equations involve positive damping and the motions are stable. On other hand during retrieval, length L is decreasing η' is negative and the equations involve negative damping, thus both α and γ are unstable. Physically, this can be explained in terms of the Coriolis force. This force associated with pitch and roll in such that it is along a direction opposite to the velocity of the subsatellite during deployment thus making the motion stable. On the other hand, during retrieval this force is in the direction of the velocity of the subsatellite pushing it to instability.

Figure (4) shows the dynamical response corresponding to the rotational motions during deployment Equations (9-10) without control forces). It can be seen that all motions are damped out in the absence of control forces which clearly demonstrates the stability of rotational motions during deployment.

Figure (5) shows a different behavior of rotational motions during retrieval. It clearly indicates that the motion becomes unstable as the tether is reeled in retrieval phase and no control forces are used. This is the main reason for studying the control of the motions of the tether during retrieval of the subsatellite to the space shuttle.

From Equation (9) the steady state of α is

$$\alpha_{eq} = -2\eta'/3$$

The function of the $k_0\eta'$ term in T_α expression is to cancel the steady state effect of the term $-2\eta'$ on the left hand side of Equation (9).

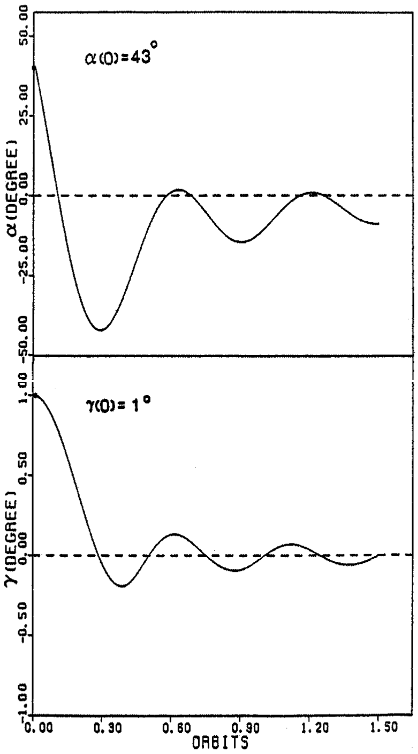


Figure 4 Dynamical response of rotational motion during deployment

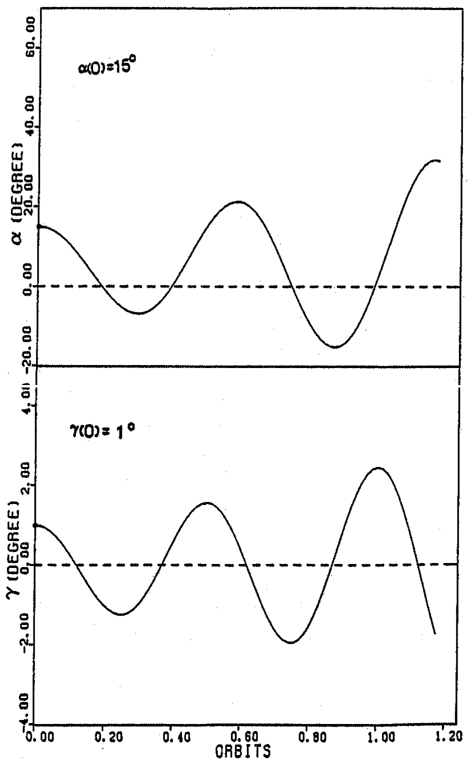


Figure 5 Dynamical response of rotational motion during retrieval

By dropping the k_0 term from the T_α expression, the inplane angle can be stabilized around the steady state configuration (a line inclined to the vertical $\alpha_{eq} = 14^0$). The reason of doing so is an attempt to achieve reduction in the total thruster impulse required for this type of retrieval.

NUMERICAL RESULTS FOR ROTATIONAL MOTIONS

The numerical calculation based on Equations (9) and (10) with control forces Equations (11) and (12) is performed during the retrieval stage.

For numerical calculation, a spherical satellite with projected area 1 m^2 and mass 170 kg is considered. The orbit of Shuttle is assumed to be circular and polar with an orbital rate of $\omega = 1.1 \times 10^{-3}$ rad/s and $c = -4 \times 10^{-4}$ s^{-1}. The diameter and fully deployed length of stainless steel tether are 0.325 mm and 100 km. respectively. The initial generalized displacements are $\alpha = 15^o$, $\gamma = 1^o$, while the initial generalized velocities are all equal to zero. The coefficients of thrusters are chosen as follows

$$k_0 = 2 + \nu, \qquad k_\alpha = k_\gamma = 2 + \nu - 2/\tilde{c}$$

The maximum thrust provided by any of the thrusters is limited to ± 5 N. Figure (6) shows the results when exponential retrieval is used from length of 100 km up to 200 m. With k_0 term in inplane control force, it is estimated that the total thruster impulse required is about 25,000 Ns. Note that the thruster providing T_α works quite hard at the beginning, consuming much more thruster fuel than that providing T_γ.

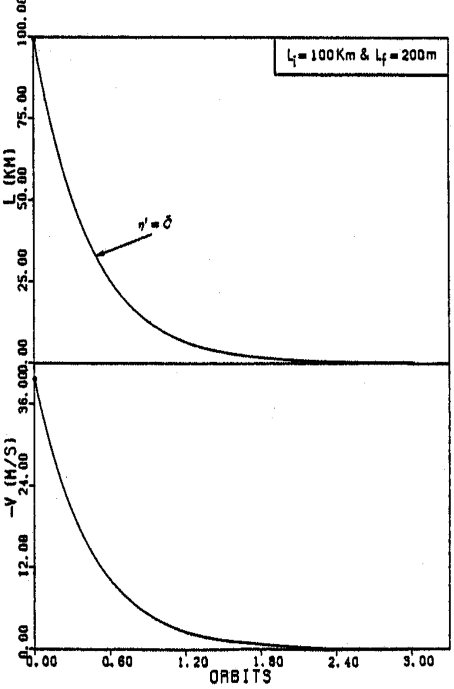
In other hand when no k_0 term added, (i.e. the tether is stabilized on a line inclined to the local vertical at approximately 14 degrees. With the new modified inplane thruster equation, it can be noted that the thruster providing T_α does not work as hard as it did with the k_0 term. It is estimated that the total thruster impulse is only about 1,500 Ns, which is much smaller than the amount with the k_0 term, which means less fuel consumption resulting in less weight. The time of retrieval from length of 100 Km to 200 m is approximately 3 orbits (4.5 hours).

Figure (7) shows the results when the retrieval process is divided into two parts, i.e. from 100 km to 10 km, exponential retrieval is used. The second part from 10 km to 200 m a uniform retrieval is used in order to avoid the slow retrieval process, hence to reduce the retrieval time.

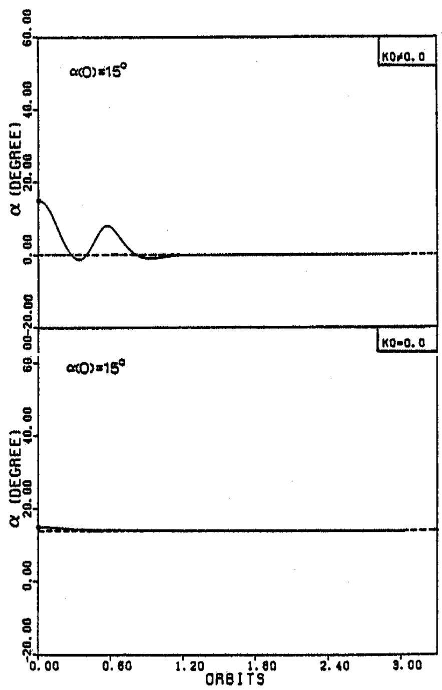
Note that during the uniform retrieval η' is changing giving rise to higher negative damping. In this stage k_0 term must be added when length is reduced to 5 km (this length is chosen arbitrarily), to bring back the inplane angle closer to the local vertical.

With k_0 term, the total thruster impulse required from length 100 km to 200 m is about 25,000 Ns, while the total thruster impulse is approximately 4,000 Ns without k_0 (for $L \geq 5$ km). Finally inplane motion goes to zero. The retrieval time for this type of retrieval is approximately 1.4 orbits (2.5 hours).

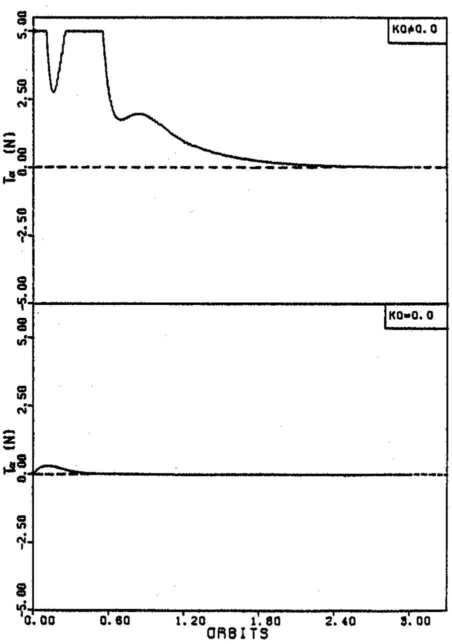
Examining the results from the two different cases, with the new modified inplane thruster equation, the total thruster impulse was reduced from 25,000 Ns to 1,500 Ns when solely exponential retrieval was carried out and 4,000 Ns when exponential retrieval was followed by uniform retrieval. If the latter scheme is used, the retrieval time from 100 km to 200 m is reduced from 3 orbits to 1.4 orbits.



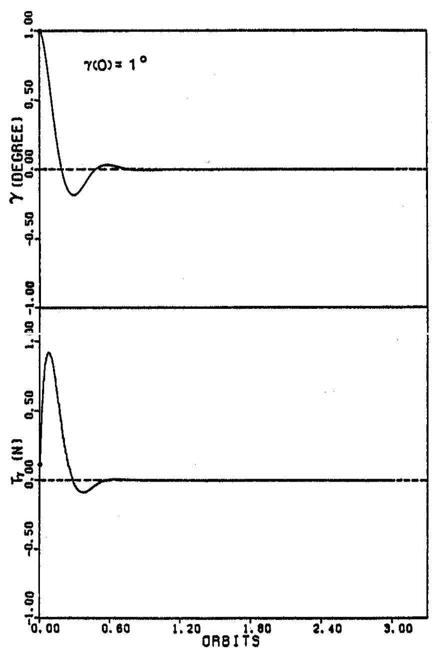
(a) Variation of length & velocity



(c) Variation of inplane angle

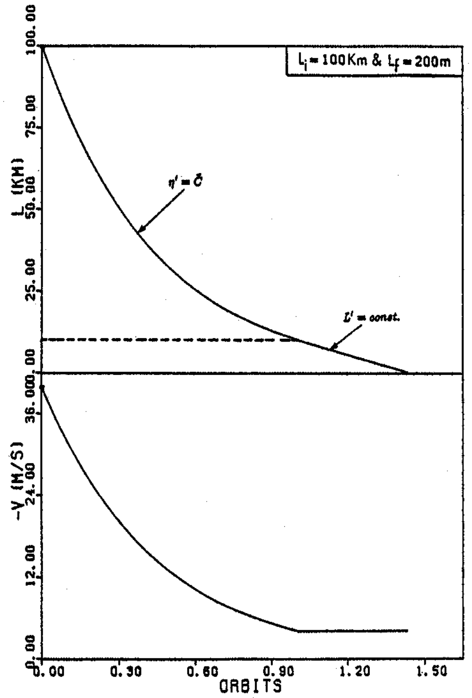


(b) Variation of inplane thruster

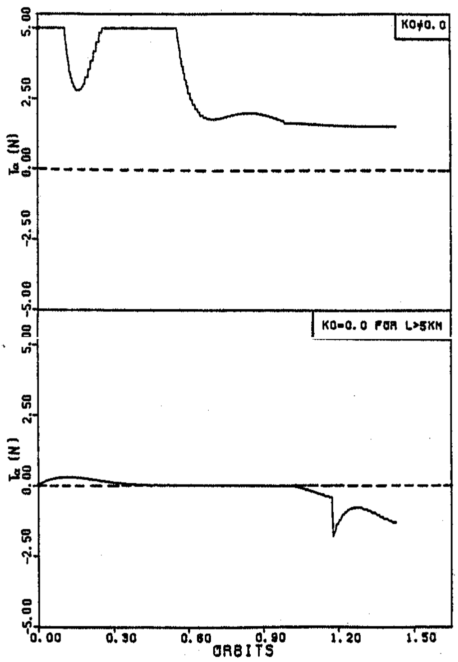


(d) Variation of out of plane angle and thruster

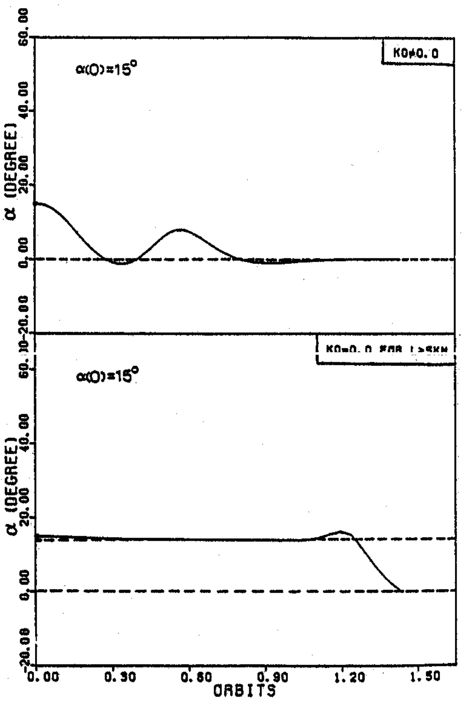
Figure 6: Dynamical response during retrieval from 100 km using thrusters



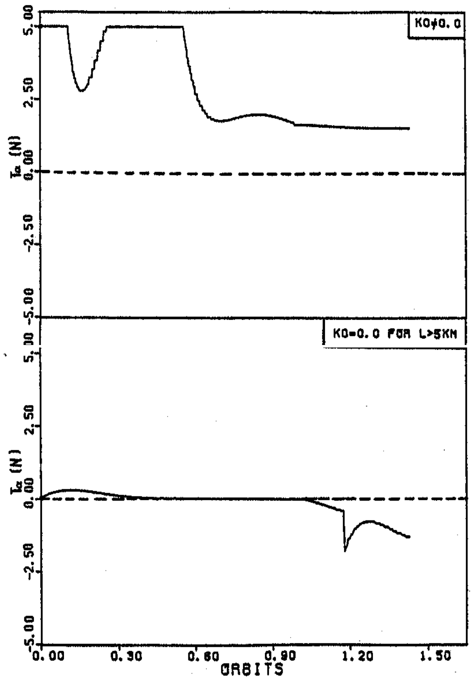
(a) variation of length & velocity



(b) variation of inplane thruster



(b) variation of inplane angle



(d) variation of out of plane angle and thruster

Figure 7: Dynamical response during retrieval from 100 km using thrusters.

GENERAL DYNAMICS INCLUDING ROTATIONS AND VIBRATIONS

So far the rotations have been examined at the terminal place of retrieval ignoring the vibrational motion. This section brings the vibrations (both longitudinal and transverse) and rotations together. Thrusts as well as length change control laws are used.

The retrieval process is divided into three parts; from 100 km to 10 km the retrieval is exponential. The second part from 10 km to 1 km, a constant velocity is carried out. During these two parts, thrusts control laws are used. From a length of 100 km up to 5 km, no k_0 term in inplane control force (mainly to reduced thruster impulse) then beyond length of 5 km, k_0 term is added to bring the inplane rotation close to zero. Finally in the third part of retrieval, from 1 km to 200 m, thrusts stop firing; instead a length change law is used. The equation of motion of the general dynamics and the thrusts forms are used as given in [2].

The physical parameters and initial conditions are

$E = 2.1x10^6 N/m^2$, $\rho_t = 0.658 kg/km$, $\alpha = 15^0$, $\gamma = 1^0$, $c_1 = 0.47x10^{-2}$, $c_2 = -0.19x10^{-3}$, $A_1 = 0.5x10^{-4}$, $A_2 = -0.5x10^{-4}$, $B_1 = -0.16x10^{-2}$, $B_2 = 0.48x10^{-3}$, while the initial generalized velocities are all equal to zero.

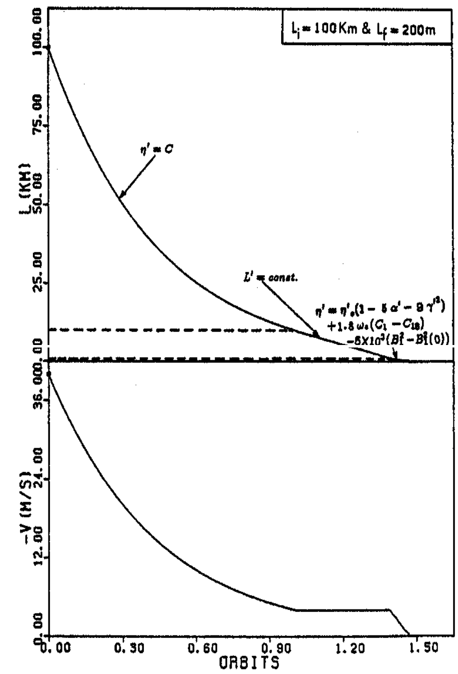
NUMERICAL RESULTS FOR GENERAL DYNAMICS

Figures (8) and (9) show the results of the general dynamics; finally α rotation reduced to zero from a constant value of about 14 degrees after k_0 has been added when length reduced to 5 km. All other rotation and vibrations are damped out except c_1 which approaches positive value which indicates that there is still tension in the tether, which is the tether does not become slack. However the value of c_1 at the end of retrieval is quite small, therefore length change law is not recommended to be used beyond L = 200 m to prevent slacking of the tether.

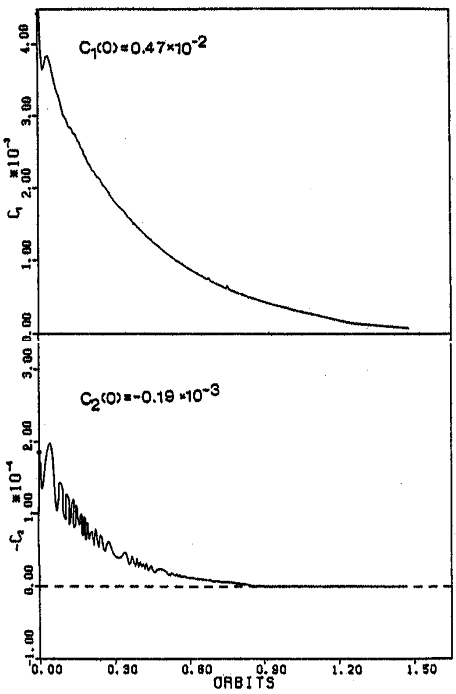
With the new modified thrust equations, it is estimated that the total thruster impulse is about 7,000 Ns.

up to L = 5 km, the thruster T_α is fired only when the inplane angle was less than 12 degrees or greater than 16 degrees allowing a deviation of ± 2 degrees around the steady state configuration, this variation of α is expected to require less T_α. Note that from the beginning of retrieval and up to about L = 5 km, α is oscillating between 12 and 16 degrees around equilibrium line, Beyond 5 km, α starts dropping in value (k_0 added) toward zero, all other variables finally go to zero except c_1.

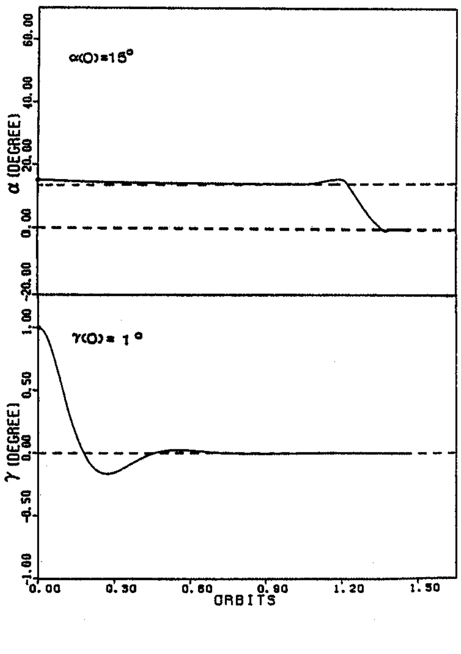
It is also noted that from the beginning or retrieval up to L = 20 km, α is oscillating between 12 and 16 degrees in the absence of control force. Therefore, T_α is not required in the beginning and is zero unlike T_c and T_γ. It is estimated that the total thruster impulse is about 5,000 Ns which is about 30 % less the amount estimated in Figure (8). The retrieval time for both cases is the same and it is about 1.5 orbits (2.5 hours).



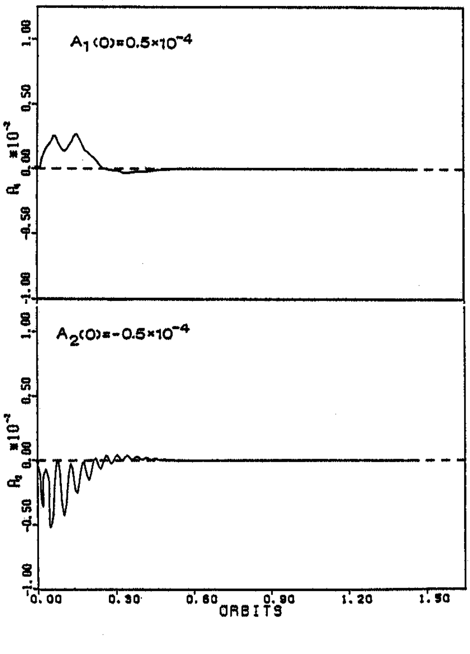
(a) variation of length and velocity



(c) Behavior of longitudinal generalized co-ordinates

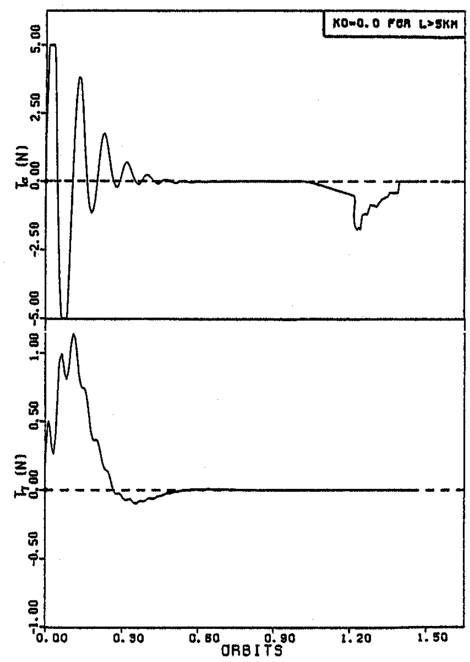


(b) variation of rotational motions

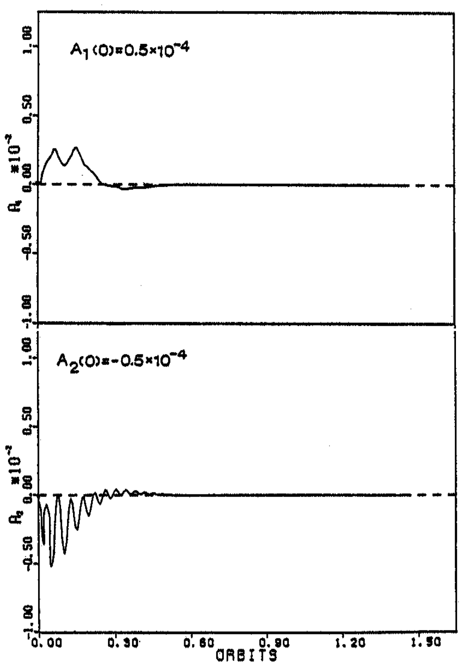


(d) behavior of out-of-plane transverse modal co-ordinates

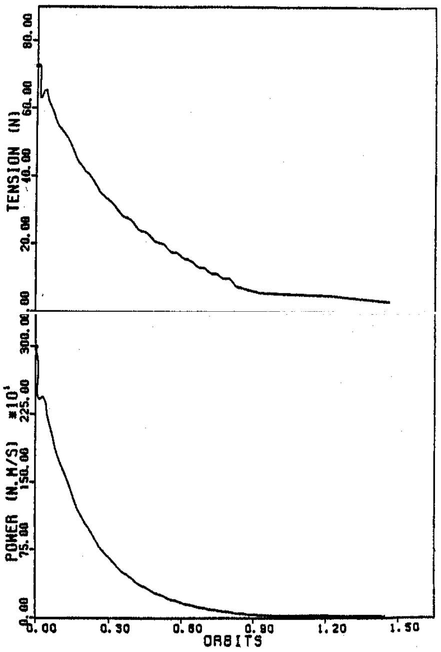
Figure 8: Dynamical response during retrieval from 100 km using thrusters followed by length change control law



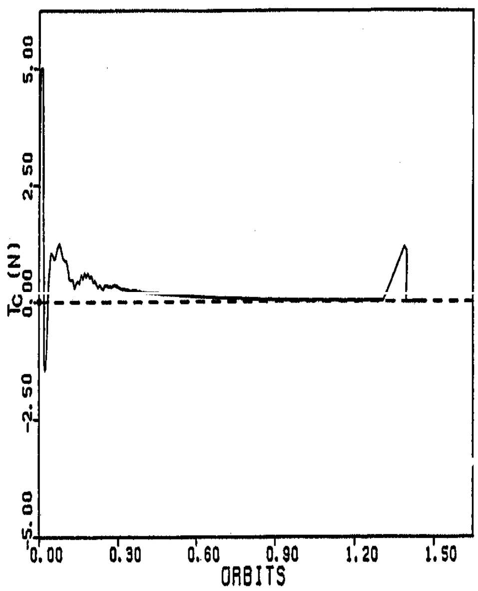
(a) behavior of inplane transverse modal co-ordinates



(b) variation of inplane and out of plane thrusters

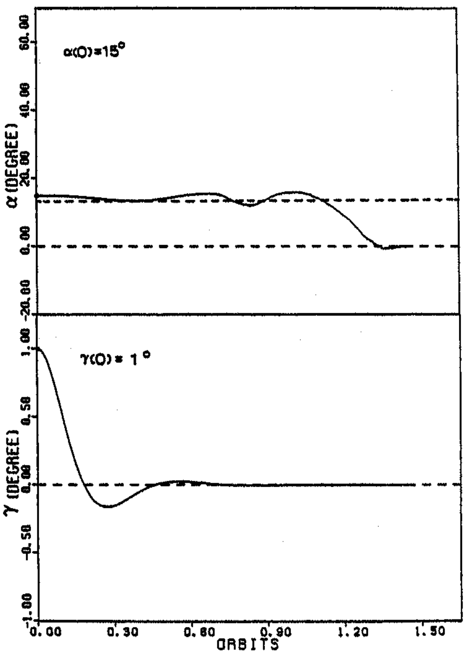


(c) variation of tension and power thruster

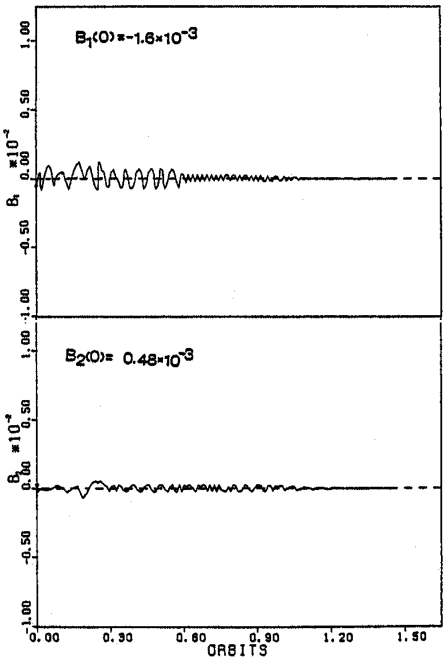


(d) variation of longitudinal

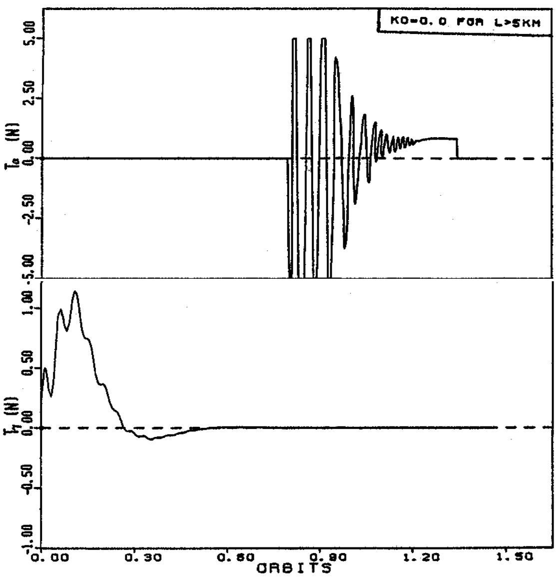
Figure 9: Dynamical response during retrieval from 100 km using thrusters followed by length change control law



(a) variation of inplane and out of plane angles



b) Bahavour of iplane transverse modal co-ordiates



(c) Variations of inplane and out of plane thrusters

Figure 10: Dynamical response during retrieval from 100 km using thrusters followed by length change control law

Figure (10) shows the results of the same stages of retrieval, but from the beginning. It may be noted that in the study of pure rotational motion and in the study of general dynamics, all efforts are directed to reduce T_α and trying to improve the corresponding thruster impulse without any attention focused on T_c and T_γ. The reason of doing so is that α has the larger value between the two rotational motions and B_1 represents the largest among the transverse vibrations. Therefore, T_α that eliminates these two, is much higher than T_γ or T_c.

Table (1) shows summarized results obtained in this paper compared with the ones [8,10]> As can be seen the with the proposed method, for first case of study when k_o- term not included in thruster equation, the thruster impulse only 500Ns compared to 24,000 Ns with k_o – term. Therefore, a large amount of thruster fuel can be saved.

Table 1: Comparison of retrieval time and impulse required to stabilize rotations for various schemes

Type of retrieval	Firing of T_α	k_0 - term	Thruster impulse	Retrieval time
Exponential ($\eta' = \tilde{c}$)	100≥L≥ 0.200	2 + ν 0	24,000 Ns 500 Ns	3 Orbits (4.5 hrs)
Exponential + Uniform (L' = constant)	100≥L≥ 0.200	2 + ν 0	24,000 Ns 300 Ns	1.4 Orbits (2.5 hrs)
Exponential + Uniform	Only if α =14^0 ± 2^0	0 For L ≥ 5 Km	2,000 Ns	1.4 Orbits
Exponential + Uniform	100≥L≥ 0.200	0	1,500 Ns	1.4 Orbits

CONCLUSION

The equations of motion have been analyzed numerically using the proposed control schemes during the retrieval stage. Steps are taken to improve the numerical efficiency of control schemes. The most important conclusions based on this study are summarized below:

- With the new modified thruster control law, the rotations and the vibrations can be stabilized around the steady state configuration instead of the local vertical during retrieval. This method saves a large amount of thruster fuel.
- A combination of thruster control laws at the beginning of retrieval, followed by length change law for very short tether, successfully damps out both rotations and vibrations and maintaining a certain amount of tension in the tether.
- To avoid slacking of the tether (be able to maintain a certain amount of tension in the tether) when the length of tether reduces to a small value, the retrieval process should be speeded up towards the end.

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NOMENCLATURE

$\widetilde{A}_i, \widetilde{B}_i$ = coefficients of ϕ_i in the expansion of u and w, respectively.

c = retrieval constant

$\widetilde{c}$ = non-dimensional retrieval constant, $\widetilde{c} = c / w$

c, s = cos and sin, abbreviations as in Eqns. (9) & (10)

$\widetilde{C}_i$ = coefficient of ψ_i in the expansion of v

E = Young's modulus of the tether material

i = inclination of the orbit to the equatorial plane

k = a constant, $\sqrt{2} / \pi$

K_i = gains, $i = \alpha, \gamma$, A_1, A_2, B_1, B_2, C

L, L_i = unstretched length of the tether at any instant and at the begining of retrieval, respectively

T_c, T_α, T_γ = components of the thrust vector

$\widetilde{T}_c, \widetilde{T}_\alpha, \widetilde{T}_\gamma$ = nondimensional values of the thrust components $T_c = \widetilde{T}_c / m_s L \dot{\theta}^2$, etc.

x_0, y_0, z_0 = orbital coordinate system.

α = inplane rotation of the tether (pitch)

γ = out of plane rotation of the tether (roll)

η = non-dimensional length, $\eta = \ln(L / L_i)$

θ = true anomaly

m_s = mass of subsatellite

θ_p = argument of the perigee

ν = mass ratio, $\rho_t L / m_s$

ρ_t = mass per unit length of the tether

ϕ_i, ψ_i = admissible functions used in expansion of u, v, w
ω = mean orbital rotational velocity

Superscripts
(.) = differentiations with respect to t
$(\ )'$, $(\ )''$ = differentiation with respect to θ