Analytical Investigation of the Dynamics

of Tethered Constellations in Earth Orbit (Phase II)

Contract NAS8-36606

Quarterly Report # 9

For the period 1 April 1987 through 30 June 1987

Principal Investigator

Dr. Enrico C. Lorenzini

July 1987

Prepared for
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

Analytical Investigation of the Dynamics of Tethered Constellations in Earth Orbit (Phase II)

Contract NAS8-36606

Quarterly Report # 9

For the period 1 April 1987 through 30 June 1987

Principal Investigator
Dr. Enrico C. Lorenzini

Co-Investigators
Mr. David A. Arnold
Dr. Mario D. Grossi
Dr. Gordon E. Gullahorn

July 1987

Prepared for
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory is a member of the Harvard-Smithsonian Center for Astrophysics

CONTENTS

CONTENTS (Cont.)

Summary

In summary the content of this Quarterly Report is as follows:

A new control law has been developed to control the Elevator during short-distance-maneuvers.

This control law (called retared exponential or *RE*) has been analyzed parametrically in order to assess which control parameters provide a good dynamic response and a smooth time history of the acceleration on board the Elevator. The short-distance-maneuver under investigation consists of a slow crawling of the Elevator over a distance of 10 m that represents a typical maneuver for fine tuning the acceleration level on board the Elevator.

The contribution of aerodynamic and thermal perturbations upon acceleration levels has also been evaluated and acceleration levels obtained when such perturbations are taken into account have been compared to those obtained by neglecting the thermal and aerodynamic forces.

With regard to the tasks supervised by G.E. Gullahorn, the preparation of a tether simulation questionnaire is illustrated. Analytic solutions to be compared to numerical cases and simulator test cases are also discussed.

Figure Captions

Figures 1a-1g. The dynamic response obtained by adopting an *MHT* (modified-hyperbolic-tangent) control law is compared to that obtained by adopting an *RE* (retarded exponential) control law. Control parameters are as follows: total distance traveled by the Elevator $\Delta\ell_{2T}$ = 10 m, time constant $1/\alpha$ = 400 sec, shape parameter γ = 4 and, for the *RE* control law, time-delay-parameter Δt = 1000 sec. The aerodynamic and thermal effects are neglected.

Figures 2a-2z. Parametric analysis of the *RE* control law for the same control parameters as in the previous set of figures except for the time constant and the time-delay-parameter which are varied as follows: a) $1/\alpha$ = 100 sec and ΔT = 500 sec. 2) $1/\alpha$ = 200 sec and Δt = 500 sec. 3) $1/\alpha$ = 400 sec and Δt = 1000 sec. In all these three simulation runs the aerodynamic and thermal effects are neglected.

Figures 3a-3n. The Elevator is controlled according to an *RE* control law with control parameters as in the first set of figures. The dynamic response when the aerodynamic and thermal effects are taken into account are compared to the dynamic response when such effects are neglected.

1.0 INTRODUCTION

This is the ninth Quarterly Report submitted by SAO under contract NAS8-36606, "Analytical Investigation of the Dynamics of Tethered Constellations in Earth Orbit (Phase II)," Dr. Enrico C. Lorenzini, PI. This report covers the period from 1 April 1987 through 30 June 1987.

2.0 TECHNICAL ACTIVITY DURING REPORTING PERIOD AND PROGRAM STATUS

2.1 Short Length Crawling Maneuvers Of Space Elevator

2.1.1 Introductory Remarks –

The previous report (Quarterly Report #8) dealt with the dynamics of a 4-mass tethered system when the elevator moves along the tether over distances of a few kilometers. This quarterly report investigates the dynamics of the same tethered system when the elevator moves over distances as short as a few meters. These short maneuvers are required for fine tuning of the acceleration level on board the elevator. In the case of the short, as opposed to long, maneuvers the dynamics of the system (and the accelerations on board the elevator) are dominated by the elasticity of the tether along which the elevator is crawling. The lengths traveled by the elevator along the tether in order to reach the desired distance from the Space Station, for example, are shorter than the elastic deformations of the tether itself. A parametric analysis of suitable control laws to perform such short maneuvers has been carried out and the results are presented in this quarterly report.

2.1.2 An Alternative Control Law For Elevator's Crawling Maneuvers –

The modified-hyperbolic-tangent control law that was illustrated in the previous quarterly report (Quarterly Report #8) proved to be very effective in performing crawling maneuvers over long distances. The modified-hyperbolic-tangent law, however, has one minor drawback: the modulus of the maximum acceleration is higher than the modulus of the maximum deceleration. The maximum acceleration has a tolerable effect on the acceleration level on board the elevator when the traveled distance is long because the motion-induced-acceleration on board the elevator is small compared to the overall variation of the gravity-gradient-acceleration from the start to the end of the maneuver. In the case of short maneuvers the overall variation of the gravity-gradient-acceleration is small and the motion-induced-acceleration becomes much more important. In order to maintain the same ratio between the above mentioned accelerations, time constants equal to those adopted for long length maneuvers should also be adopted for the short length maneuvers. This strategy would result in very slow maneuvers to cover a distance of only a few meters. We decided, therefore, to modify further the control law with the goal of reducing the maximum acceleration induced by the elevator's motion without having to increase the value of the time constant.

The variation of the traveled tether length $\Delta\ell_c$ according to the new control law is

$$\Delta\ell_c = \Delta\ell_{cT} \left[\frac{1}{1+e^{\alpha(\Delta t-t)}}\right]^{\gamma} \tag{1}$$

where $\Delta\ell_{cT}$ is the total traveled tether length, α is the rate parameter, γ is the shape factor and Δt is a delay time. The delay time has the purpose of reducing the value of the motion-induced-acceleration at the start of the maneuver to a value close to zero. From now on we will call this control law retarded exponential (*RE*), while we will use the acronym *MHP* for the modified-hyperbolic-tangent control law. By taking the time derivatives of equation (1) we obtain the expression of the crawling velocity

$$\Delta\dot{\ell}_c = \Delta\ell_{cT} \left\{\alpha\gamma\left[1+e^{\alpha(\Delta t-t)}\right]^{-(\gamma+1)} e^{\alpha(\Delta t-t)}\right\} \tag{2}$$

and of the crawling acceleration or motion-induced-acceleration

$$\Delta\ddot{\ell}_c = \Delta\ell_{cT} \left\{\alpha^2\gamma\left[1+e^{\alpha(\Delta t - t)}\right]^{-(\gamma+2)} \cdot \left[\gamma\ e^{\alpha(\Delta t - t)} - 1\right] e^{\alpha(\Delta t - t)}\right\} \tag{3}$$

It is clear from equation (3) that for $\Delta t = 0$ and $t = 0$ the acceleration is different from zero and is given by

$$\left\{\Delta\ddot{\ell}_c\right\}_{\substack{t=0 \\ \Delta t=0}} = \Delta\ell_{cT}(\gamma-1)(2\alpha^2\gamma)^{-(\gamma+2)} \tag{4}$$

By increasing Δt the acceleration at $t = 0$ becomes smaller and smaller.

We have run a simulation to compare the dynamic response of a 4-mass tethered system, when the elevator crawls according to a *RE* control law, to the case when the elevator crawls according to a comparable *MHP* law. The elevator starts at a distance of 1 km above the Space Station and moves upwards covering a distance of 10 m. We have adopted a time constant $1/\alpha = 400$ sec (the reason for this choice will become clear later on in this report) and a shape factor $\gamma = 4$. The time delay Δt for the *RE* law is equal to 1000 sec in order to provide a smooth start of the maneuver. In the *MHP* control law we have adopted a constant-velocity-phase that covers 80% of the maneuver $(1 - \chi = 0.8)$. The crawling maneuver of the elevator starts, in both cases, after a time lag of 1000 sec that allows for the settling down of the initial transient oscillations.

Figure 1a depicts the controlled and the actual tether length of tether segment 2 (that connects the Space Station to the Elevator) for the *RE* and *MHP* control law respectively. The difference between the controlled and the actual length is the sum of the elastic stretch and the deformation of the longitudinal damper. Since the longitudinal dampers are tuned to the frequencies of the associated tether segments at the start of the maneuver, the elastic stretch of tether segment 2 is equal to the deformation of longitudinal damper 2 at the start of the maneuver. Figure 1a also points out that the sum of the elastic stretch and the damper's deformation is comparable to the variation of the controlled length during the maneuver. Figure 1b shows the velocity of tether 2 for the two control laws. The maximum speed for the *RE* control law is greater than for the *MHT* control law, and no constant velocity phase is used for the *RE* control law.

The acceleration on board the elevator for the two control laws is shown as follows: the front component (perpendicular to the tether in the orbital plane) in Figure 1c, the side component in Figure 1d and the longitudinal component (along the tether) in Figure 1e. The minimum (negative) value of the front component for the *RE* law is slightly greater than for the *MHT* law. This peak acceleration can be reduced by introducing a constant-velocity-phase in the *RE* control law. This modification, however, was not deemed necessary because the front and side components are orders of magnitude smaller than the longitudinal component of the acceleration and the behavior of the latter is satisfactory. Figure 1c also shows that the ringing of the system is much greater for the *MHT* control law than for the *RE* law. The greater ringing is most probably caused by the faster acceleration phase of the *MHT* law with respect to the *RE* law. Figure 1d shows the side component of the acceleration. Comments stated with regard to the front acceleration component apply to the side component.

Figure 1e depicts the longitudinal component of the acceleration. The superiority of the *RE* control law with respect to the *MHT* law is evident. By adopting the latter control law the acceleration measured on board the elevator overshoots soon after the beginning of the maneuver because of the relatively fast acceleration phase. There is also a ringing of the system that takes a long time to be damped out. These two phenomena disappear when the *RE* law is adopted. The steady-state sinusoidal oscillation of the longitudinal acceleration in Figure 1e (when the Elevator is standing still) is caused by the J_2 component of the gravity field.

Finally, Figures 1f and 1g show the three components of the acceleration on board the Space Station as a consequence of the Elevator's motion for the *RE* and *MHT* control laws respectively. The comparatively large oscillation of the longitudinal component is caused by unbalanced initial conditions: the Space Station is initially at the system *CM* and the initial conditions have been computed by linearizing the gravity potential and therefore by assuming that the initial acceleration on board the Space Station is (incorrectly) equal to zero.

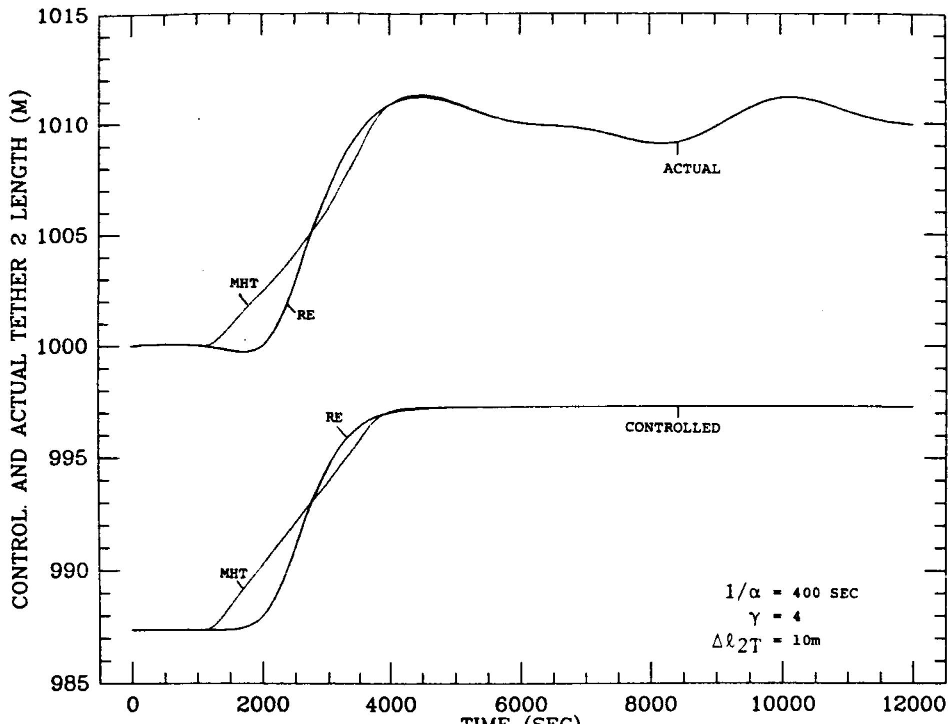
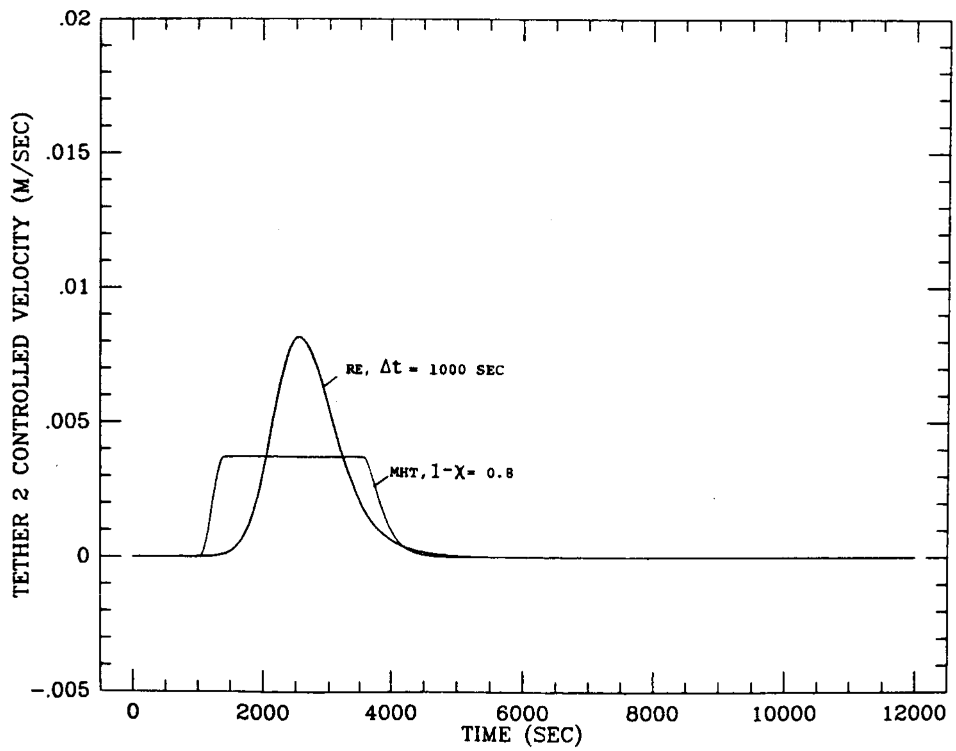


Figure 1a ↑ Figure 1b ↓



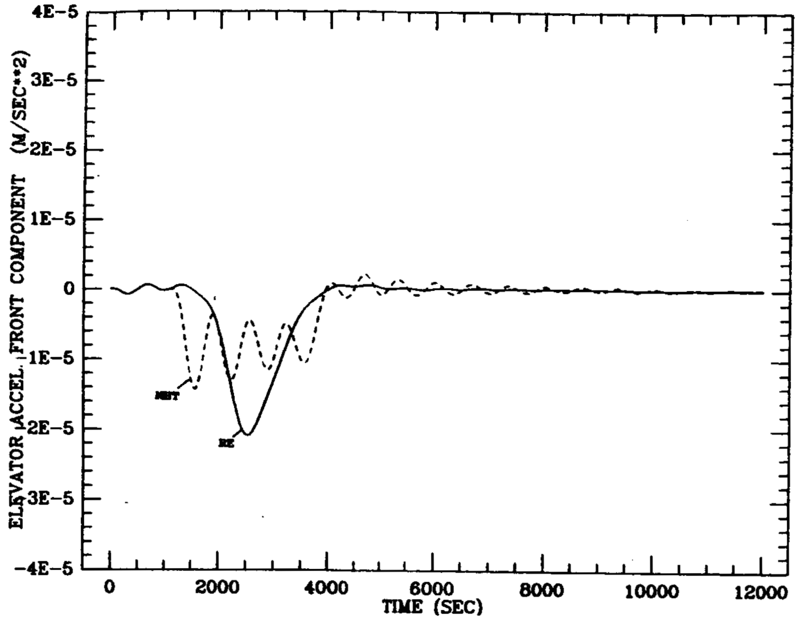


Figure 1c

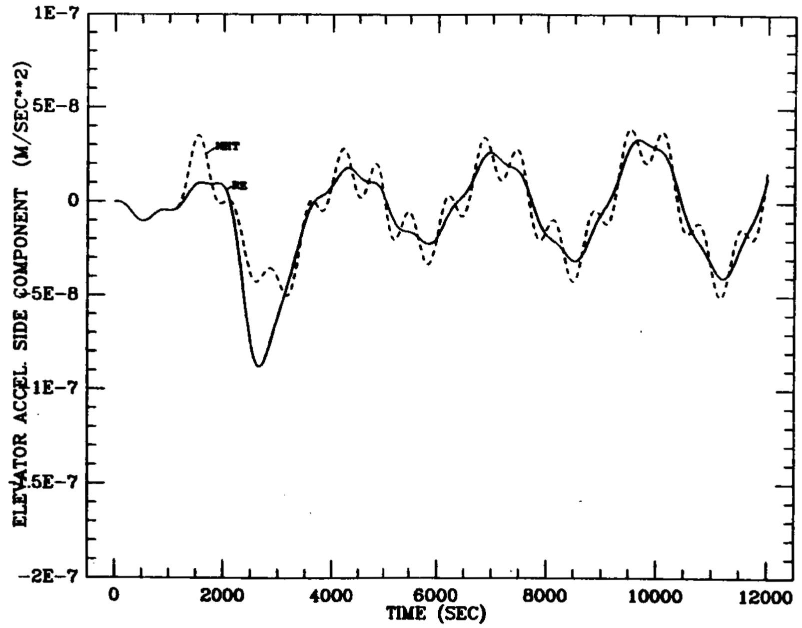


Figure 1d

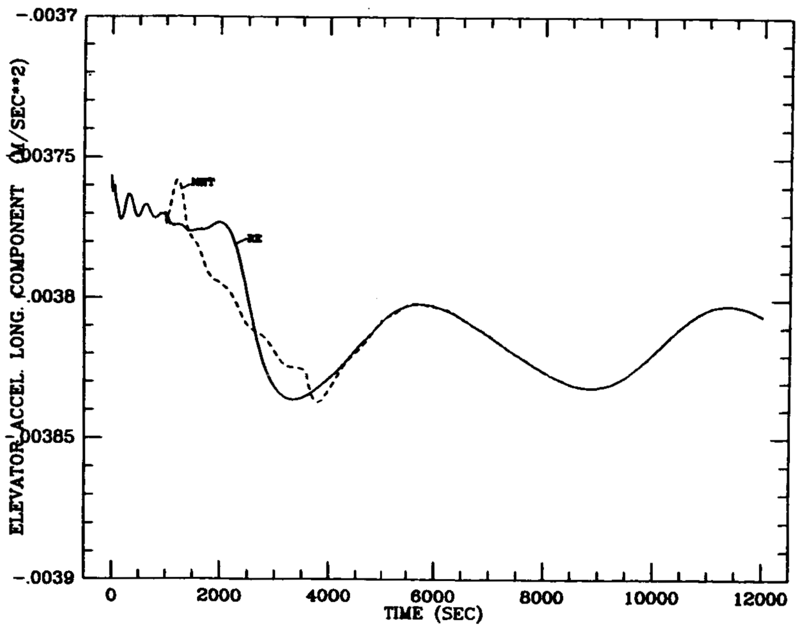


Figure 1e

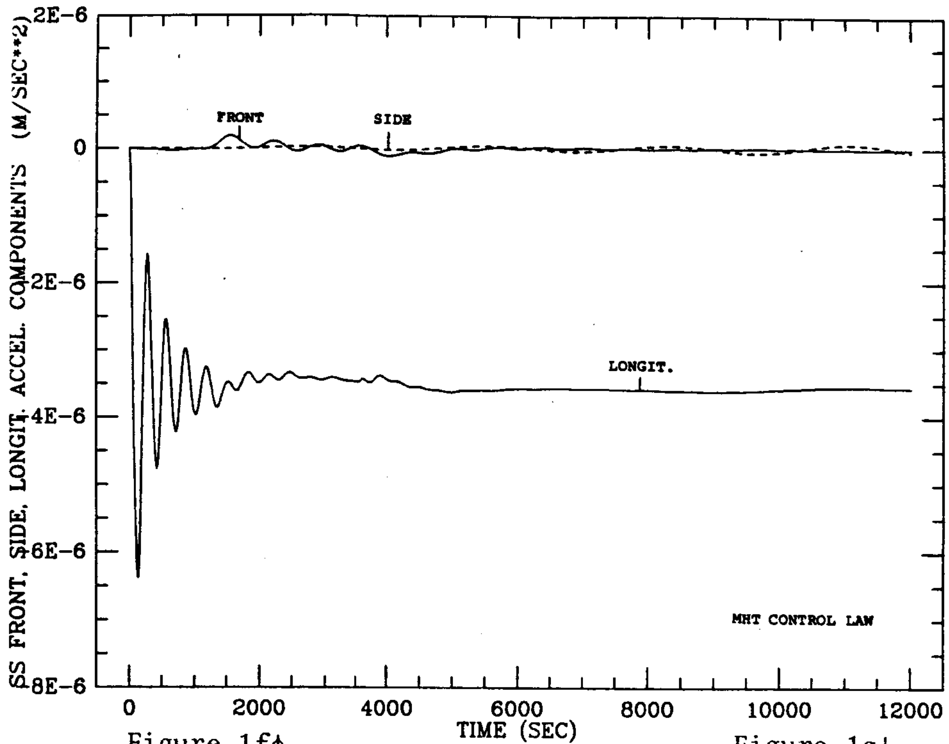
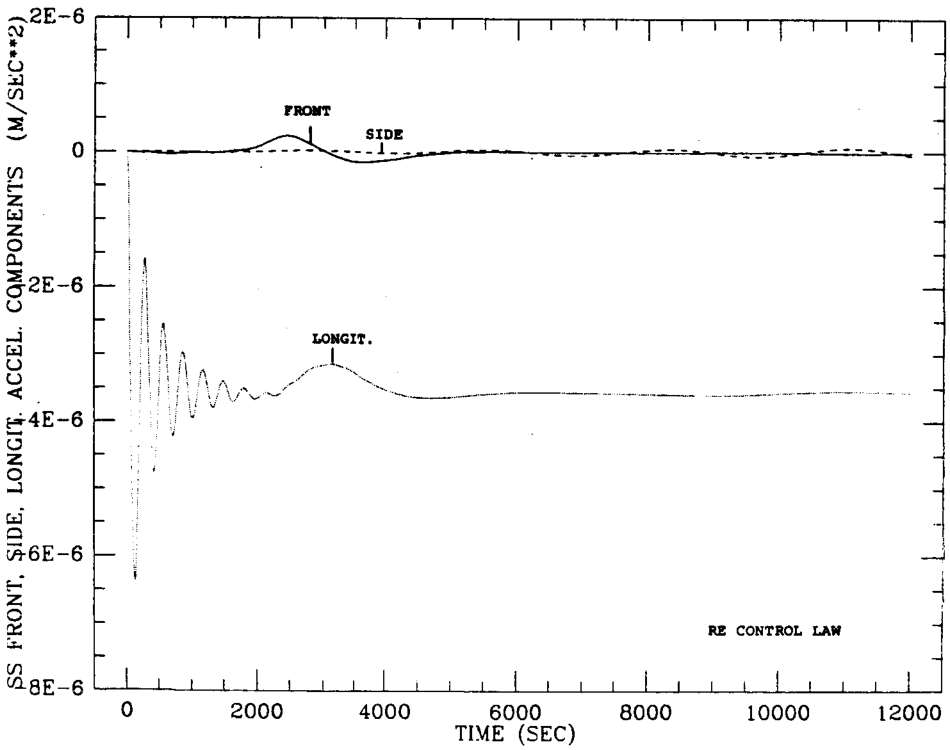


Figure 1f↑

Figure 1g↓



2.1.3 Parametric Analysis Of Short Length Crawling Maneuvers –

As a consequence of the conclusions stated in the previous subsection the *RE* control law has been adopted to perform crawling maneuvers over short distances.

This subsection analyzes the effect of varying the control parameters upon the dynamics of the system and the acceleration levels on board the Elevator and the Space Station. In the following simulation runs the distance covered by the Elevator is 10 m long. Because of the tethers' elasticity and the longitudinal dampers the controlled tether length (or length crawled by the Elevator along the tether) is shorter than the traveled distance. The controlled length that provides an actual traveled distance of 10 m is computed beforehand by the computer code.

In the following set of simulation runs the time constant $1/\alpha$ is respectively equal to 100 sec, 200 sec and 400 sec while the shape parameter $\gamma = 4$ for the three cases. The delay-time-parameter $\Delta t = 500$ sec for the first and the second case ($1/\alpha = 100$ sec and 200 sec respectively) while $\Delta t = 1000$ sec in the third case ($1/\alpha = 400$ sec) in order to have a small acceleration at the start of the maneuver in the three cases. The delay-time-parameter Δt should not be confused with the time lag between the beginning of the simulation and the start of the crawling maneuver. Such time lag is equal to 1000 sec for the three cases and it allows for the initial transient oscillations to be damped out.

In the next three simulation runs the aerodynamic and the thermal effects have been set equal to zero in order to speed up the *CPU* time to perform the simulation. The effect of aerodynamic and thermal perturbations is negligible when compared to the variations of the acceleration level on board the Elevator in the case of long-distance-maneuvers. In the present case of short-distance-maneuvers the aerodynamic and thermal induced accelerations are more important than in the previous case. The next subsection addresses this issue.

Figure 2a depicts the controlled and actual tether lengths of tether 2 for the three case mentioned before. The Elevator starts to crawl at the initial time t_I = 1000 sec and it reaches the final distance on the tether at the final time t_F = 2330 sec, 3160 sec and 5320 sec respectively. The simulation runs, however, are continued until t = 10,000 sec for the first two cases and until t = 12,000 sec for the third case in order to show the steady-state oscillations of the system. The duration of the crawling maneuver for the *RE* control law $t_c = t_F - t_I$ is given by

$$t_c = \Delta t - \frac{1}{\alpha}\ell n\left[1-(1-\tau)^{-1/\gamma}\right] \tag{5}$$

In equation (5) $\tau = \sigma/\Delta\ell_{cT}$ where σ is the cut off distance and $\Delta\ell_{cT}$ the total variation of the controlled tether length. If we select $\tau = 10^{-3}$ and Δt = 500, 500 and 1000 sec equation (5) gives t_c = 1330, 2160 and 4320 sec for the three cases respectively. The actual length of tether 2 differs from the controlled length because of tether elasticity and longitudinal damper's stretch. In particular (see Figure 2a): a) The initial difference between the controlled and the actual tether length is greater than the variation of the controlled tether length during the maneuver. b) The fastest maneuver ($1/\alpha = 100$ sec) excites (longitudinal/lateral) oscillations which are not excited in the other two cases. c) The comparatively large steady-state oscillation experienced by the actual tether length is caused by the J_2 gravity term which forces the system to librate and eventually stretch the tethers according to the libration frequency.

Figure 2b shows the rate of change of the controlled length for tether 2. It is readily clear from the figure that the maximum speed is directly proportional to the rate parameter α. Figure 2b also indicates that the *RE* control law can be easily modified in order to include a constant velocity phase in between the acceleration and the deceleration phase. For short maneuvers, however, this additional modification has been deemed unnecessary because the maximum tether speed is low enough. The controlled speed of tether 3 (not shown here) is like that of tether 2, with an opposite sign. The controlled speed of tether 1 (not shown here) can be obtained by scaling down the speed of tether 2 by a factor of two. It should be reminded that the length of tether 1 (the downward tether) is controlled, during the Elevator maneuver, in such a way as to maintain the system *CM* at its initial position.

The three components of the acceleration on board the Elevator for the three cases are depicted as follows: the front component in Figure 2c, the side component in Figure 2d and the longitudinal component in Figure 2e. The front component is generated primarily by Coriolis forces. It is interesting to notice that for $1/\alpha$ = 100 and 200 sec (longitudinal/lateral) oscillations are excited by the Elevator's motion. The same oscillations are not excited in the case $1/\alpha$ = 400 sec, and the front component of the acceleration has a smooth time history. The side component is much smaller than the front component. Since, as pointed out in Section 2.3 of Quarterly Report #7, it is not convenient to damp the out-of-plane oscillations, the side component of the acceleration shows an undamped behavior. The value of such component, however, is so small that it can be neglected. The longitudinal component (Figure 2e) shows a large overshoot for $1/\alpha$ = 100 and 200 sec. Higher frequency oscillations are also excited in those two cases. For $1/\alpha$ = 400 sec the behavior is very smooth and the initial overshoot is quite small. The acceleration reaches steady-state conditions as soon as the Elevator stops and the higher frequency oscillations are not excited (the settling down time is zero).

The components of the acceleration on board the Space Station are shown in Figures 2f, 2g and 2h for $1/\alpha$ = 100, 200 and 400 sec respectively. As previously stated the (damped) oscillation of the longitudinal component before the Elevator starts moving is caused by the initial conditions at the start of the simulation run. The fluctuations of the acceleration once the Elevator starts crawling are more relevant to our analysis. In all the three cases such fluctuations are much smaller than 10^{-5} g (that is the required limit value for microgravity experiment on board the Space Station). Such fluctuations decrease as the time constant of the control law increases. For short maneuvers of the Elevator the acceleration levels at the Space Station are not a critical issue.

In order to complete the presentation of data about the dynamic response Figure 2i shows the in-plane (θ) and out-of-plane (φ) libration angles vs. time. The libration dynamics of the system is the same for the three cases under investigation (within the resolution of the plot) and only one plot is, therefore, presented.

Figures 2j, 2k and 2ℓ depict the in-plane components of the lateral deflections ϵ_{1i} (Space Station) and ϵ_{2i} (Elevator) with respect to the line through the end masses for the cases $1/\alpha$ = 100, 200 and 400 sec respectively. The increase of the time constant has a dramatic effect on these degrees of freedom and such effect is eventually reflected in the acceleration level on board the Elevator. Figure 2m shows the out-of-plane components of the deflections ϵ_{10} and ϵ_{20}. Such components are not (appreciably) affected by the variation of the time constant. This plot is therefore valid for the three cases. The moduli of the lateral deflections ϵ_1 and ϵ_2 are shown in Figures 2n, 2p and 2q for $1/\alpha$ = 100, 200 and 400 sec respectively. The moduli reflect the variations, already pointed out, of the in-plane components.

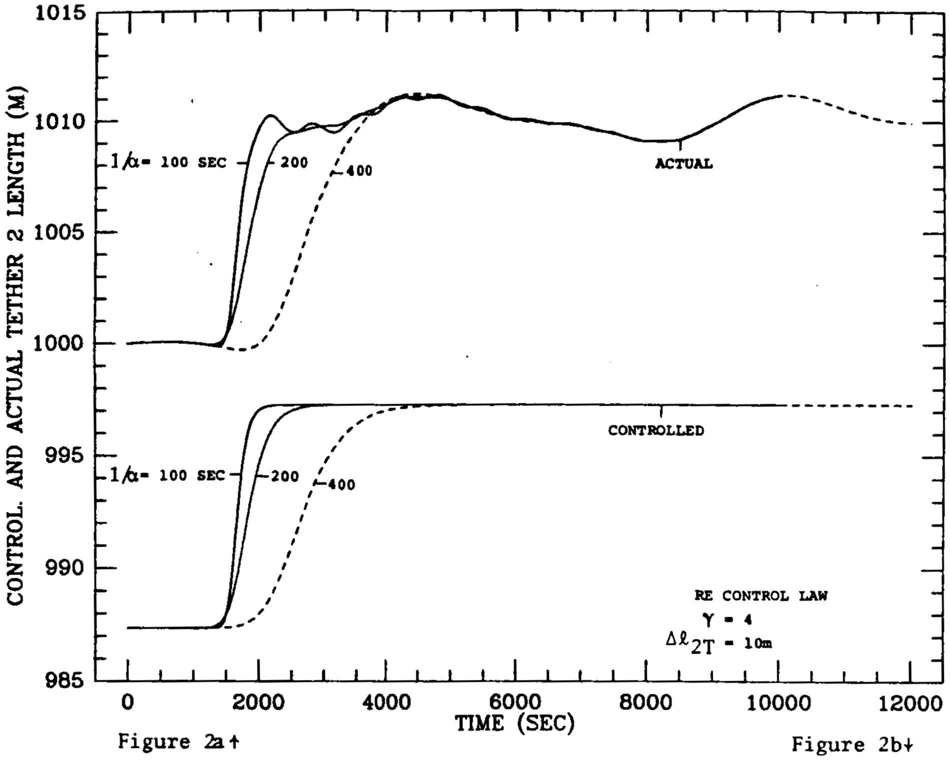
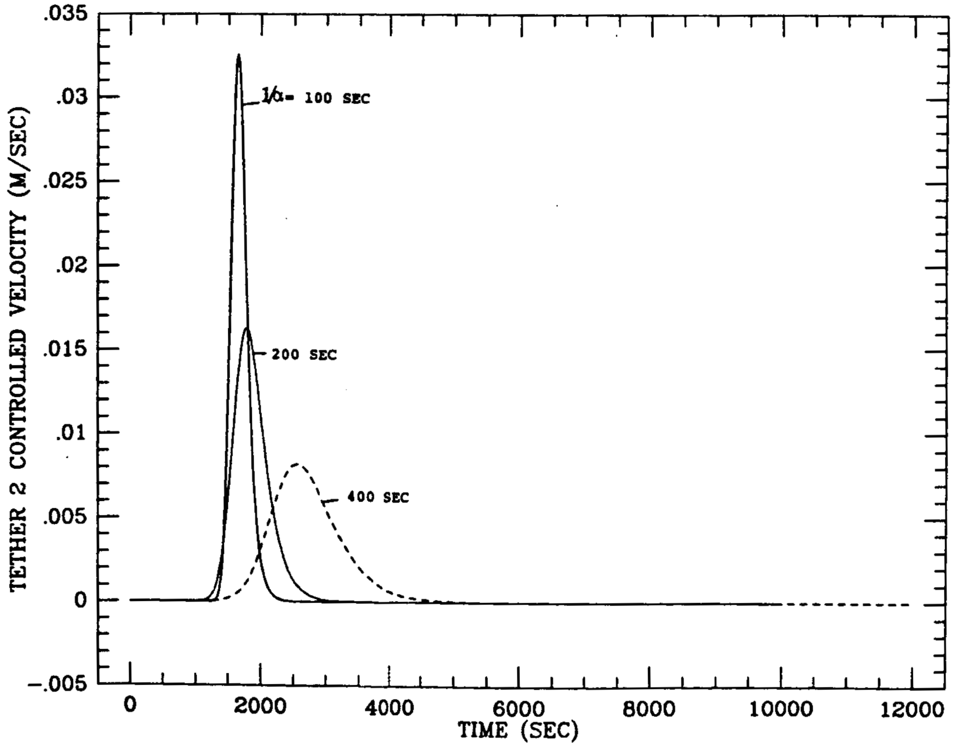


Figure 2a↑

Figure 2b↓



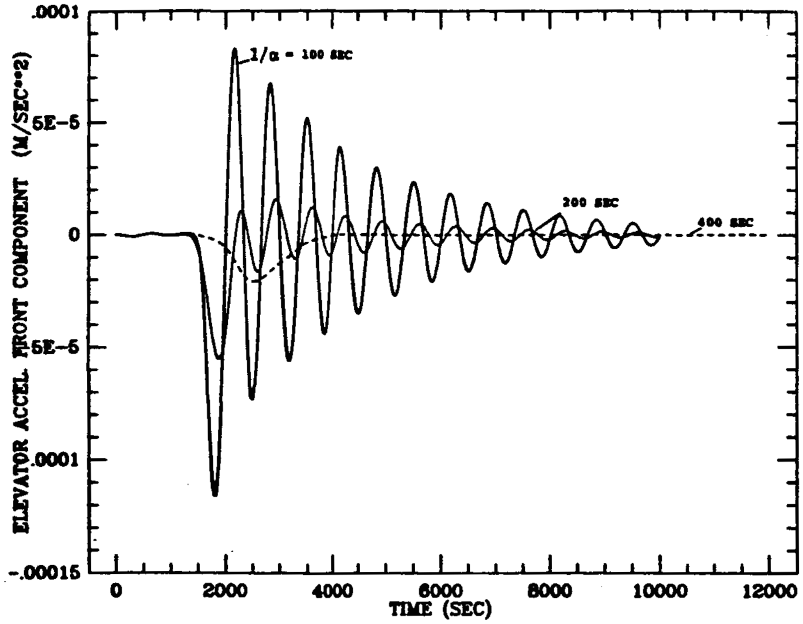


Figure 2c

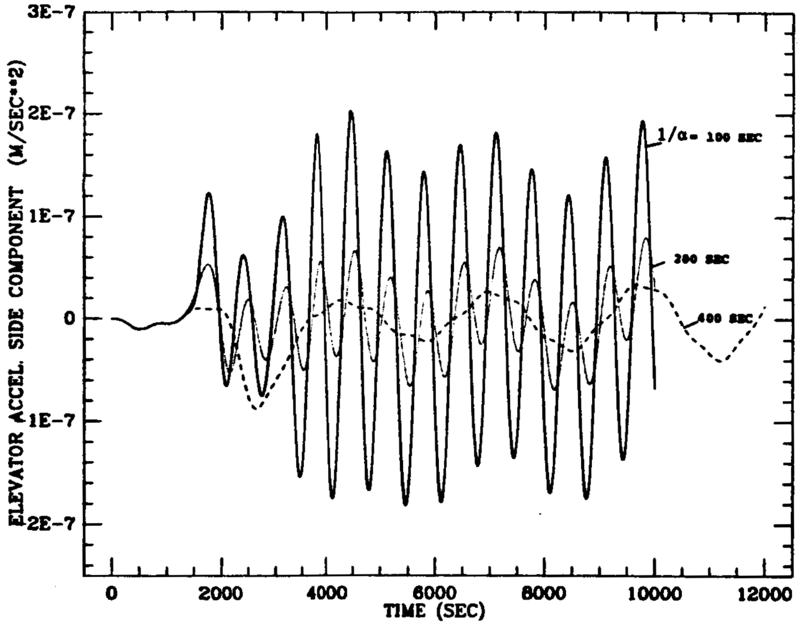


Figure 2d

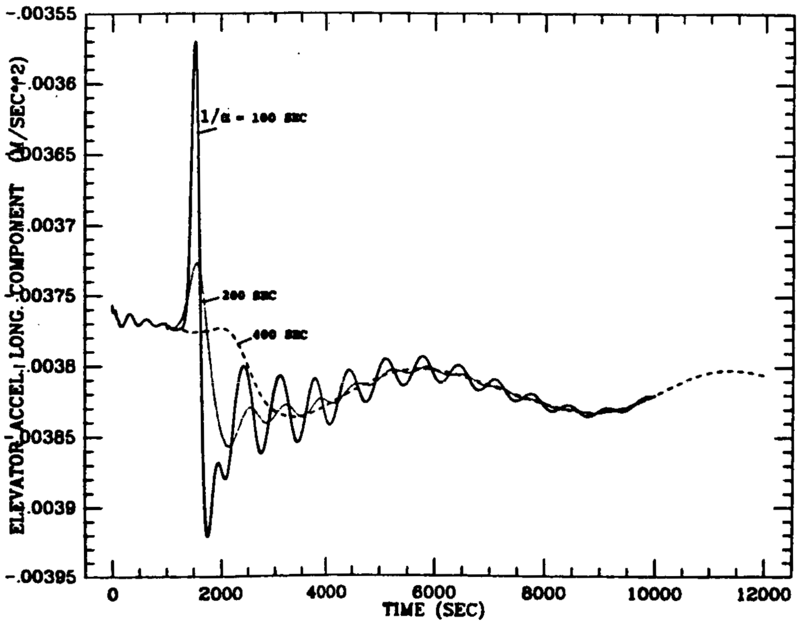


Figure 2e

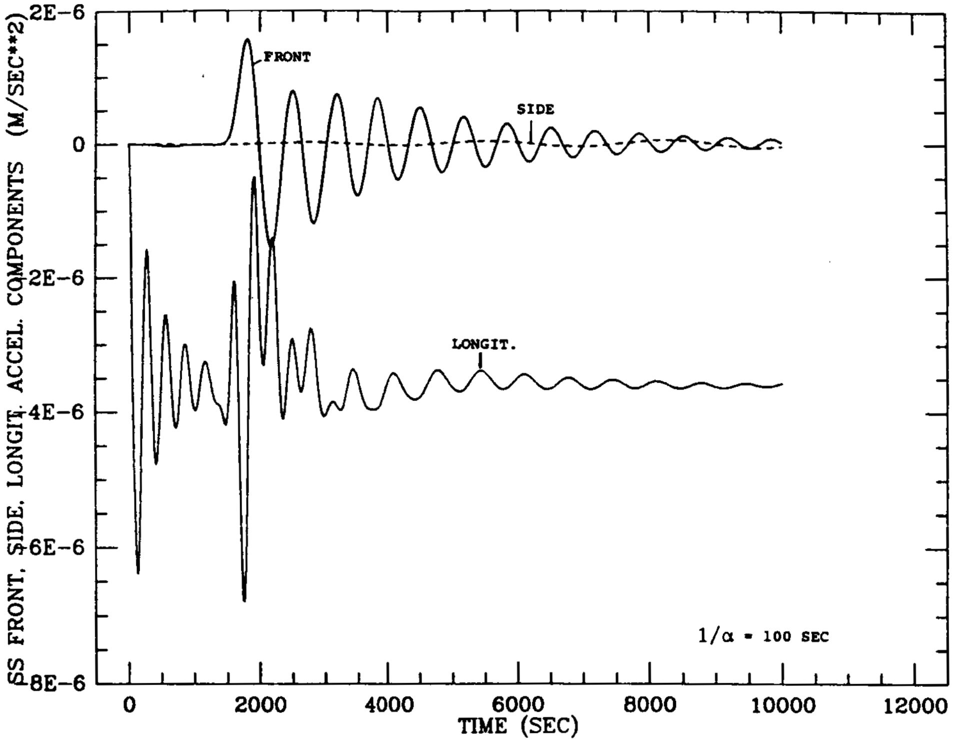
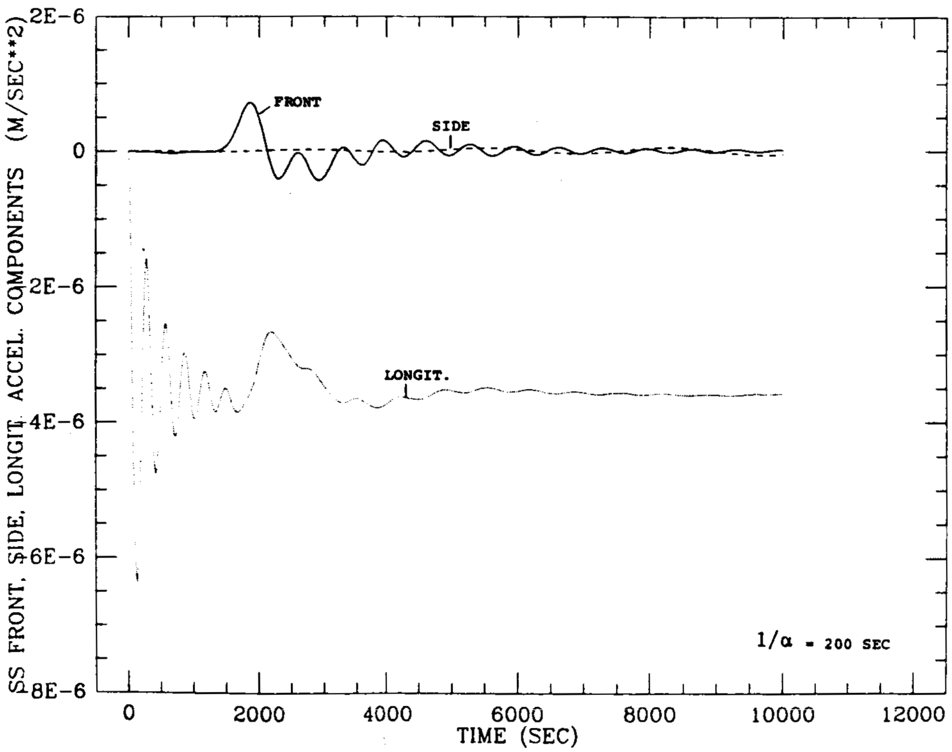


Figure 2f↑

Figure 2g↓



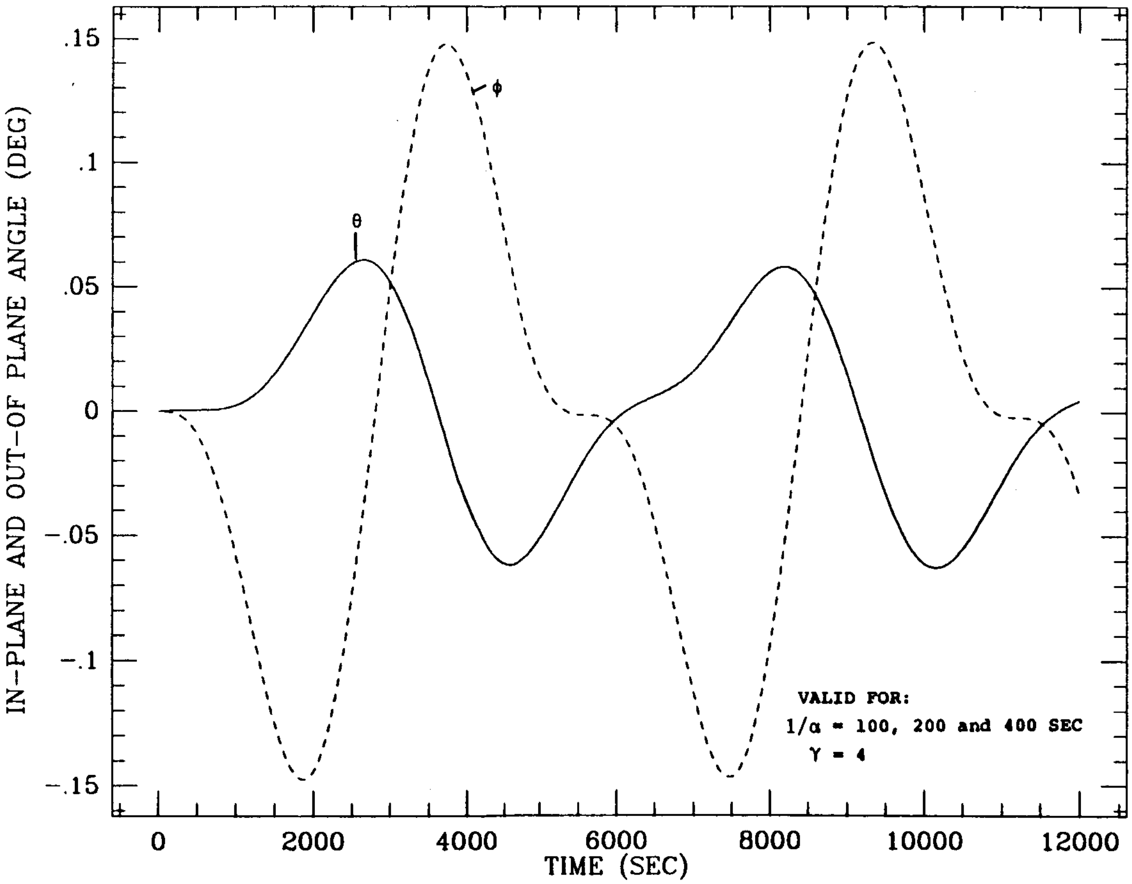

.15
.1
.05
0
-.05
-.1
-.15
IN-PLANE AND OUT-OF PLANE ANGLE (DEG)
0
2000
4000
6000
8000
10000
12000
TIME (SEC)
θ
φ
VALID FOR:
1/α = 100, 200 and 400 SEC
γ = 4

Figure 2i

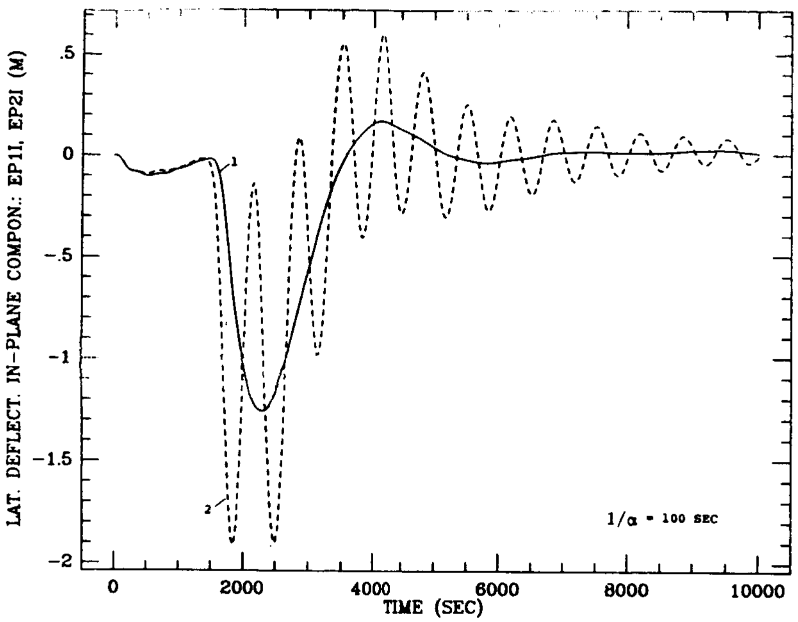


Figure 2j

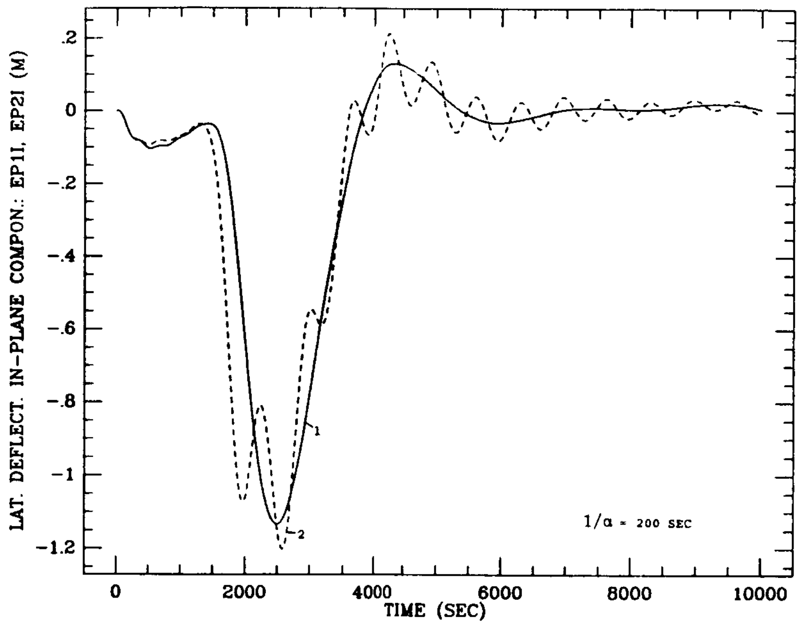


Figure 2k

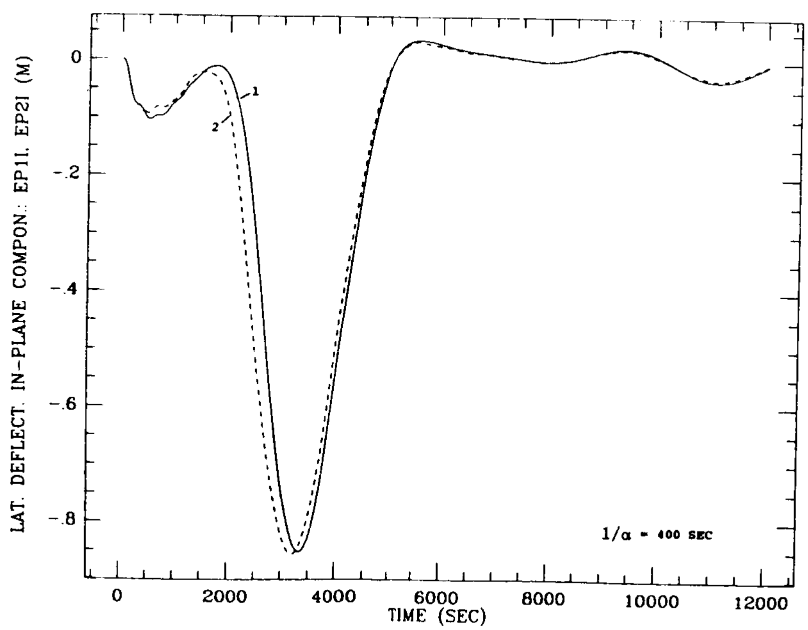


Figure 2ℓ

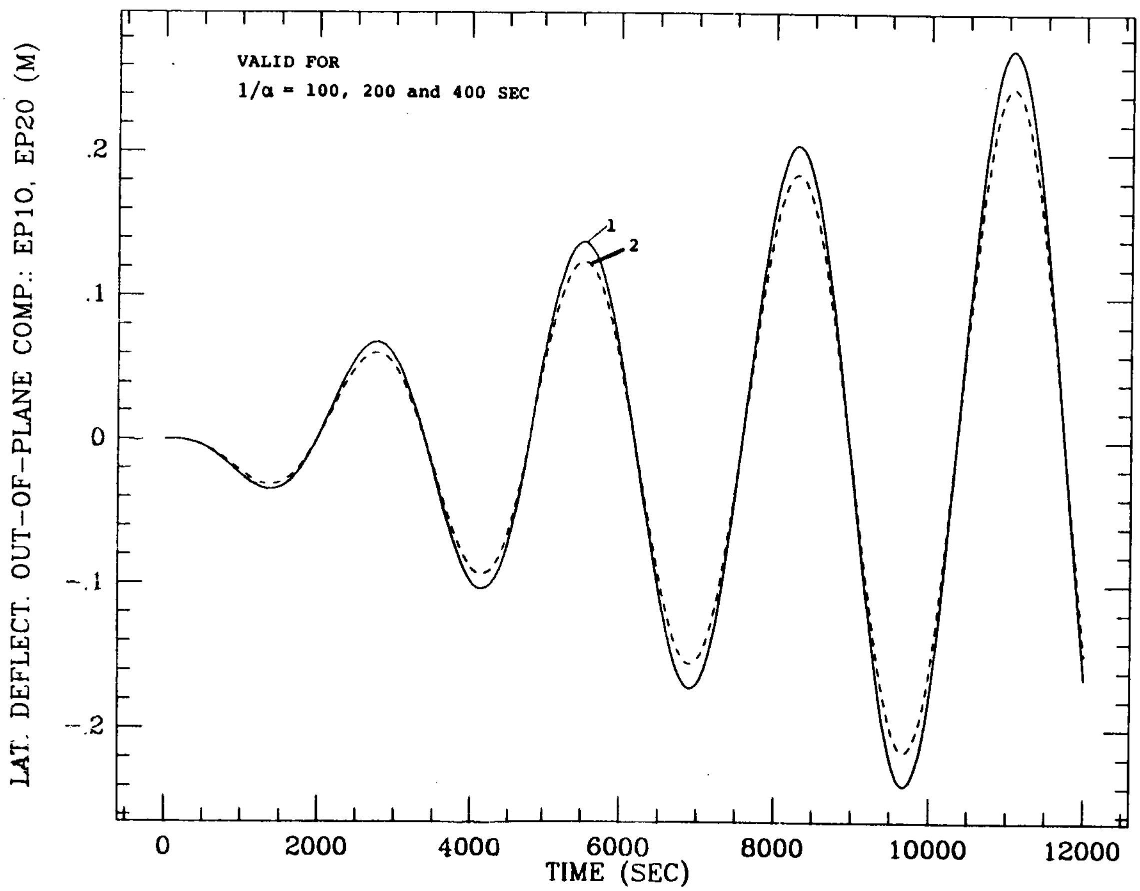

VALID FOR
1/α = 100, 200 and 400 SEC
1
2
LAT. DEFLECT. OUT-OF-PLANE COMP.: EP10, EP20 (M)
.2
.1
0
-.1
-.2
0
2000
4000
6000
8000
10000
12000
TIME (SEC)

Figure 2m

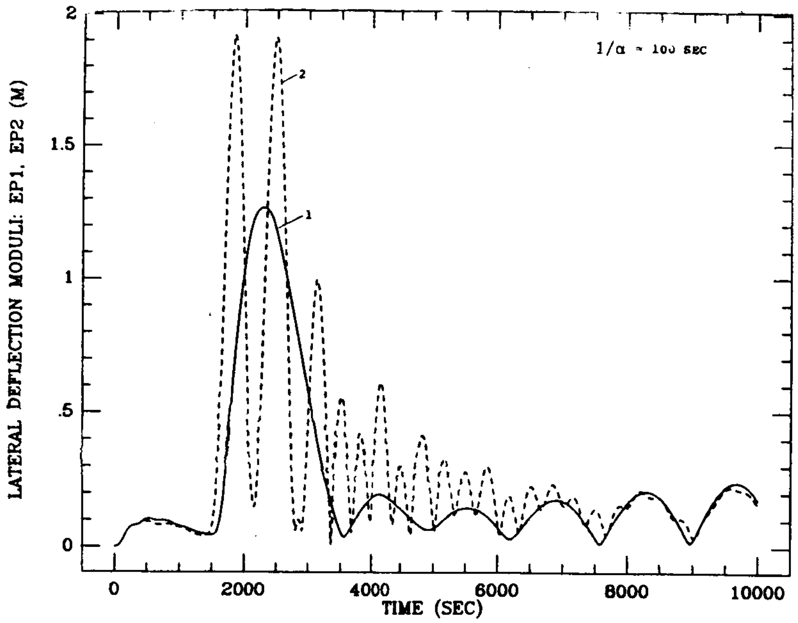


Figure 2n

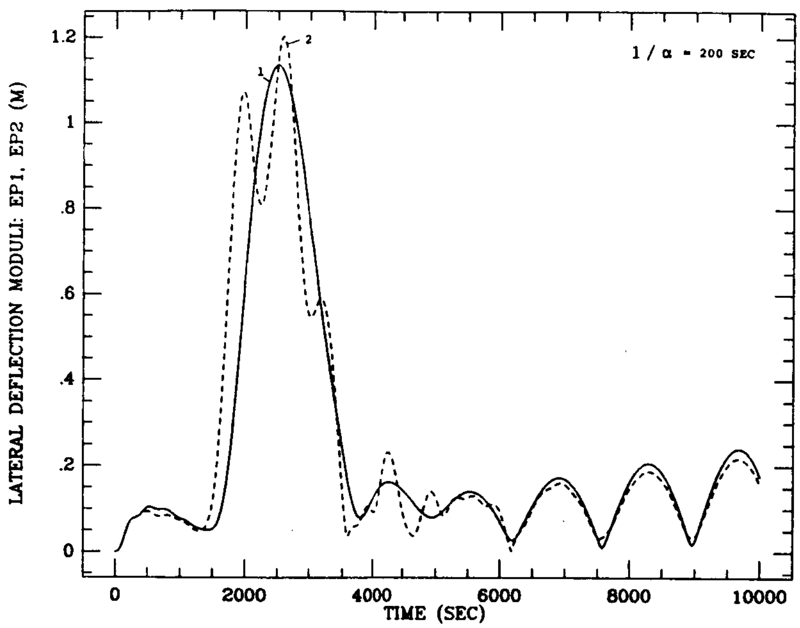


Figure 2p

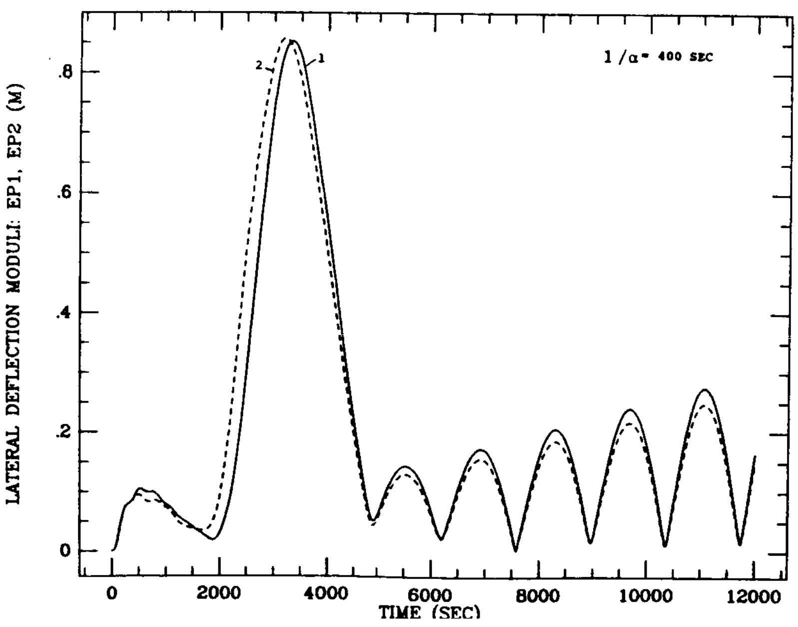


Figure 2q

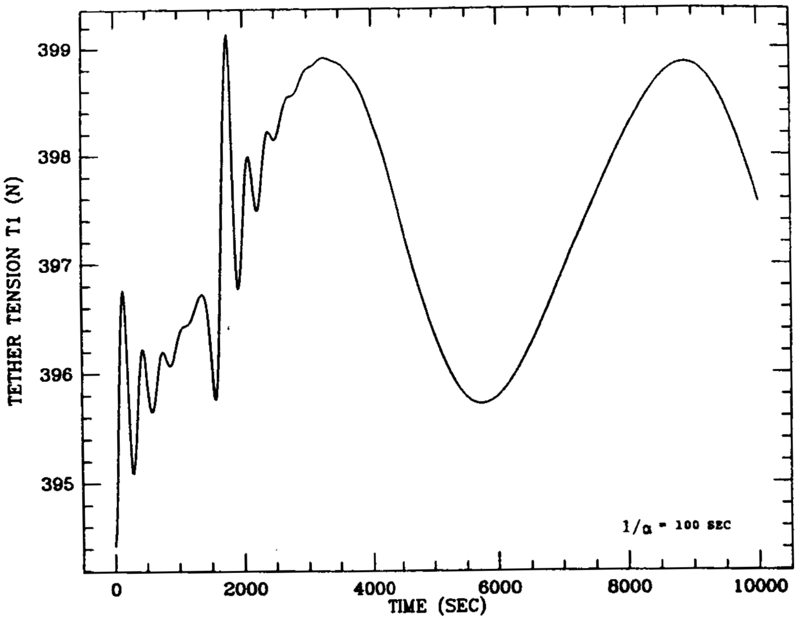


Figure 2r

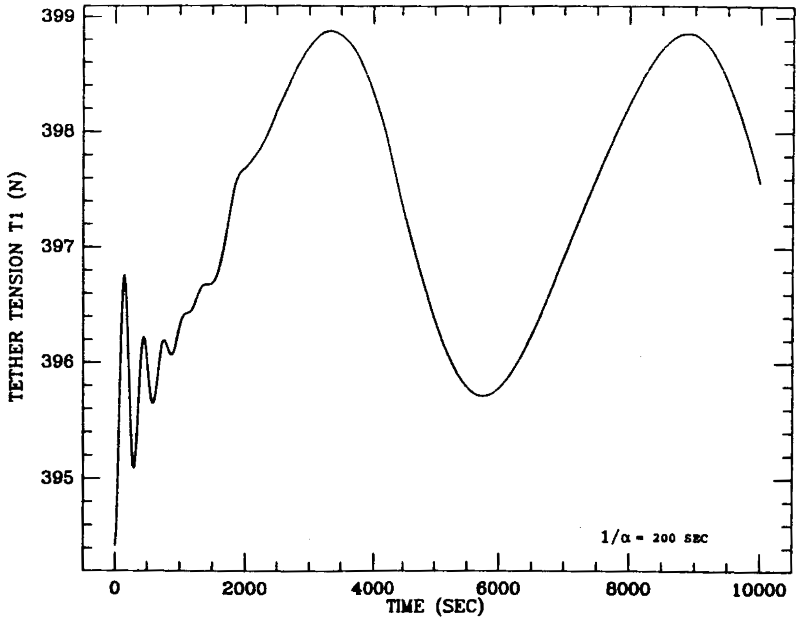


Figure 2s

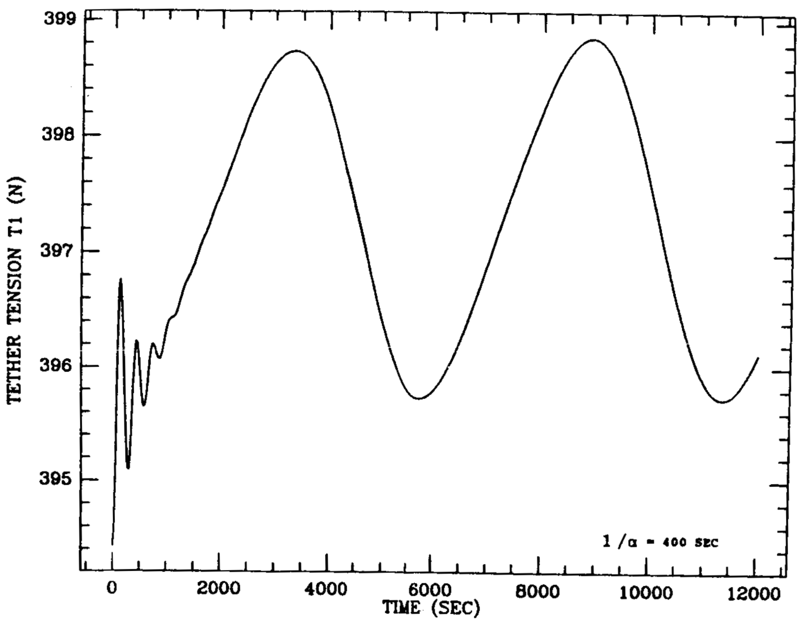


Figure 2t

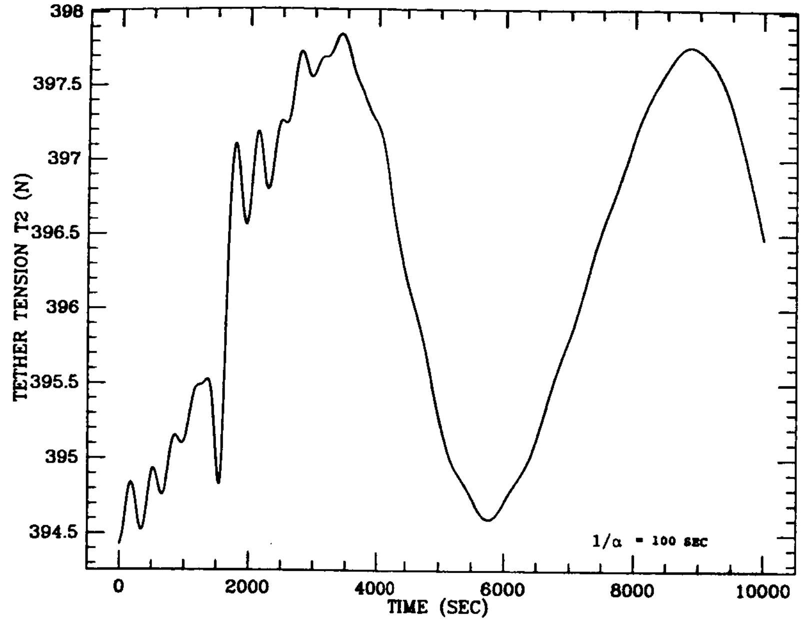


Figure 2u

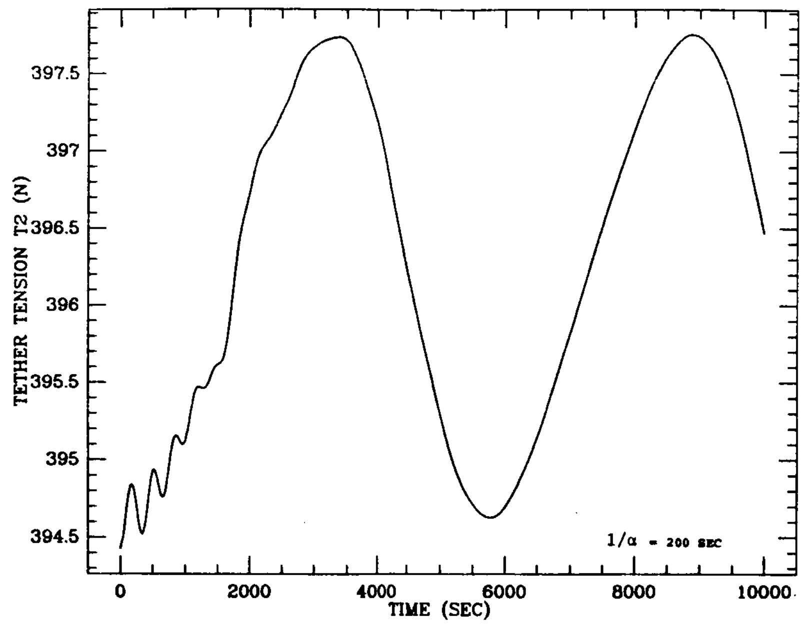


Figure 2v

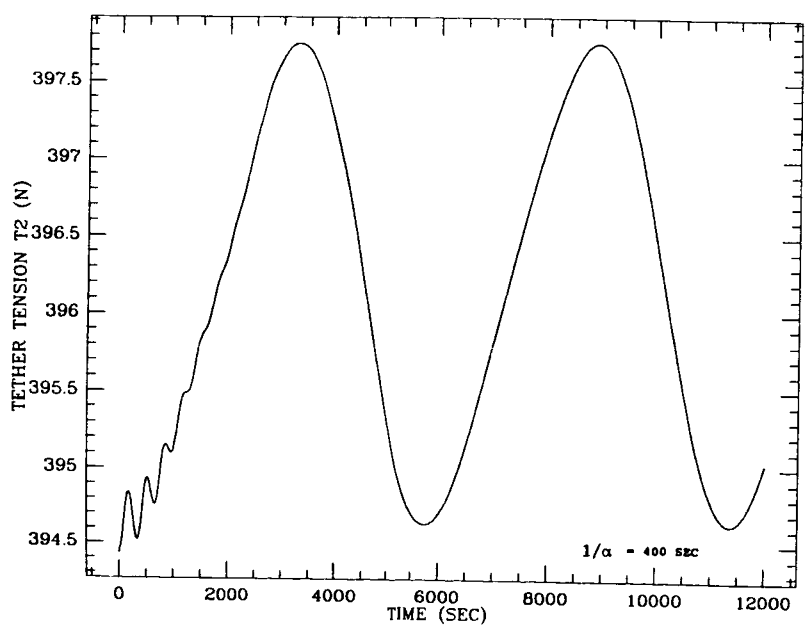


Figure 2w

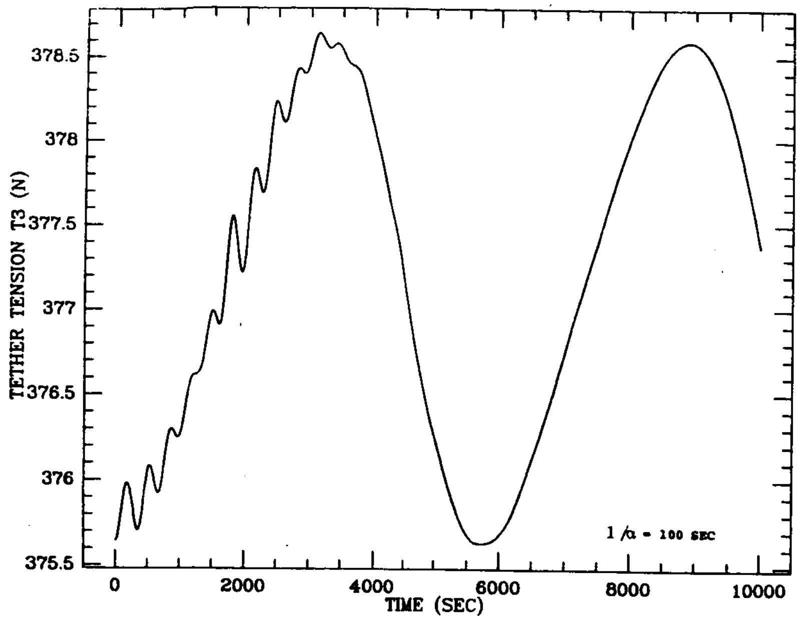


Figure 2x

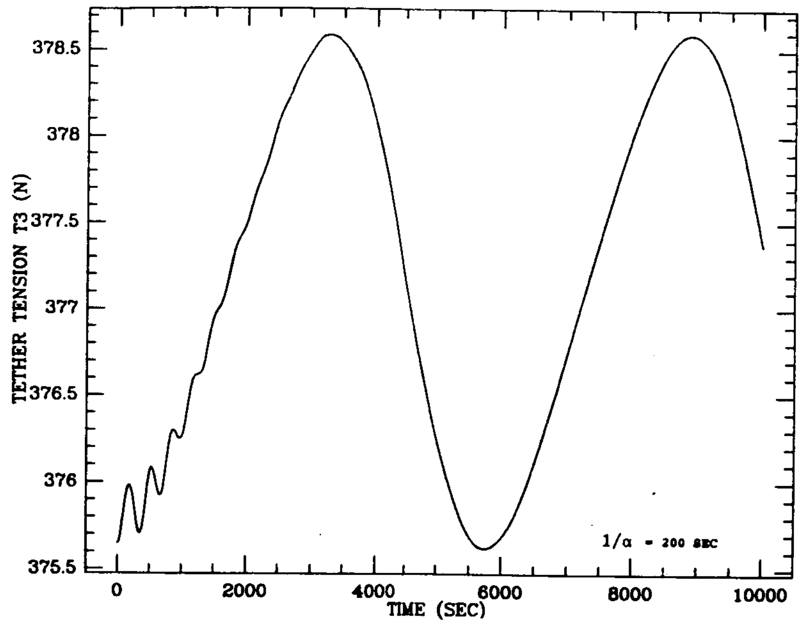


Figure 2y

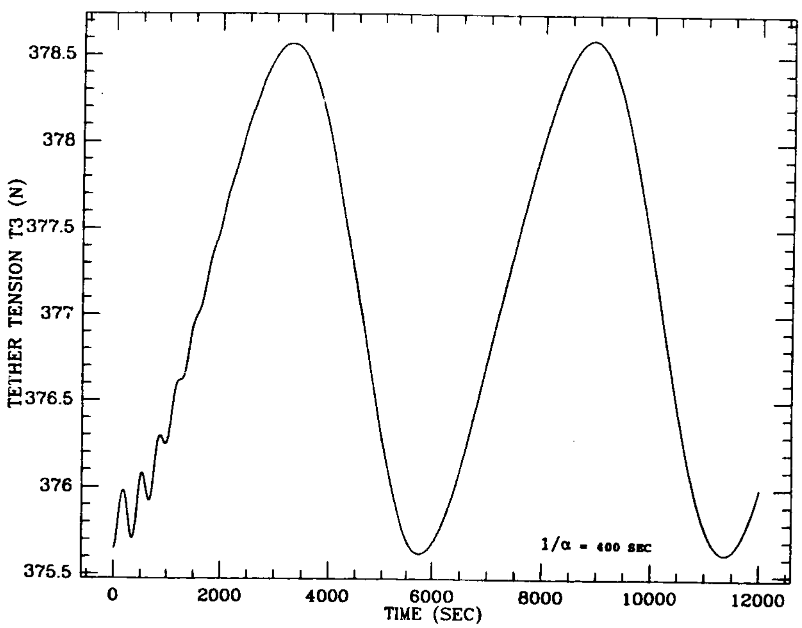


Figure 2z

Finally the tether tensions are shown as follows: tether 1 tension in Figures 2r, 2s and 2t; tether 2 tension in Figures 2u, 2v and 2w; tether 3 tension in Figures 2x, 2y and 2z for the three values of the time constant respectively.

2.1.4 Aerodynamic And Thermal Contributions To The Acceleration Levels –

The last case ($1/\alpha$ = 400 sec), examined in the previous subsection, has been rerun by adding aerodynamic and thermal effects. The results are compared to those obtained without taking into account such effects in the following figures.

Figure 3a shows the controlled and the actual tether length of tether segment 2. The controlled length is the same for both cases whereas the actual length experiences an additional stretch that is caused primarily by the thermal expansion and secondarily by the aerodynamic forces. The initial temperature of the tethers is arbitrarily assumed equal to 290 °K. As the tethers cool to achieve the thermal equilibrium the tether lengths increase because of the negative expansion coefficient of the tether material. This small variation of tether lengths result in a slight increase of acceleration level on board the Elevator. This latter effect may be compensated by modifying slightly the distance traveled by the Elevator along the upper tether (this distance is also called controlled tether length of tether segment 2). The components of the acceleration on board the Elevator are compared, for the two cases with/without aerodynamic and thermal effects, in the following figures: the front component in Figure 3b, the side component in Figure 3c and the longitudinal component in Figure 3d. The aerodynamic deceleration (since we are plotting the acceleration on board the vehicle, a deceleration is plotted as positive) is primarily responsible for the differences in the front component of the acceleration between the two cases. The side component is almost unaffected by the thermal and aerodynamic forces. The effect of thermal perturbations upon the longitudinal component is evident in Figure 3d: at each crossing of the terminator a sudden thermal contraction or expansion of the tethers takes place and a longitudinal oscillation is initiated. This oscillation causes an appreciable variation of the longitudinal component of the acceleration measured on board the Elevator. In the case of short-length-maneuvers, therefore, the effect of thermal and aerodynamic perturbations is important and can not be neglected when evaluating the acceleration levels on board the Elevator.

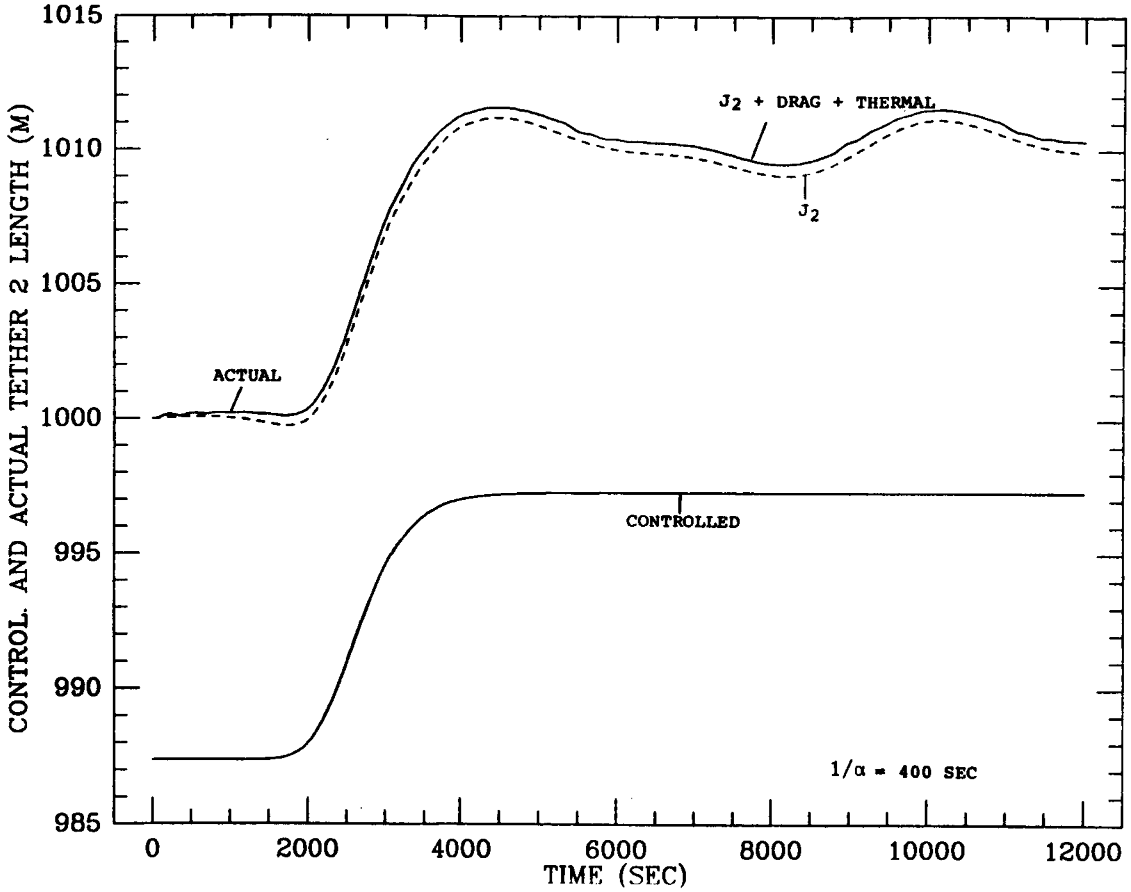
Figures 3e and 3f show the components of the acceleration on board the Space Station for the two cases without and with thermal and aerodynamic perturbations respectively. The effect of the aerodynamic drag upon the front component and the effect of thermal perturbations upon the longitudinal component of the acceleration is immediately seen by comparing the two figures.

The following figures show the remaining dynamic quantities for the simulation run with thermal and aerodynamic forces: The in-plane (θ) and out-of-plane (φ) libration angles in Figure 3g. The in-plane components of the lateral displacements ϵ_{1i}, ϵ_{2i} in Figure 3h. The out-of-plane components of the lateral displacements ϵ_{10}, ϵ_{20} in Figure 3i and the moduli ϵ_1, ϵ_2 in Figure 3j. The tether tensions in Figures 3k, 3ℓ and 3m for the three tether segments respectively. The temperature of tether segment 2 (the temperature of the three tether segments is almost the same) in Figure 3n. By comparing Figure 3n with Figures 3d and 3f it is readily seen that the thermal shock (at the crossing of the terminator) is the cause of the ripples in the longitudinal components of the accelerations on board both the Elevator and the Space Station.

2.1.5 Concluding Remarks –

The new control law (retarded exponential or *RE*), developed during this reporting period, has proved to be more effective than the *MHT* (modified hyperbolic tangent) control law for the short-distance-maneuvers of the Elevator. When the *RE* control law is adopted the dynamic response of the system and the acceleration level on board the Elevator are smoother than for a comparable *MHT* control law.

The results of a parametric analysis of the *RE* control law, over distances covered by the Elevator of 10 m, indicate that a time constant $1/\alpha = 400$ sec, a time-delay-parameter $\Delta t = 1000$ sec and a shape factor $\gamma = 4$ provide a



1015
1010
1005
1000
995
990
985
CONTROL AND ACTUAL TETHER 2 LENGTH (M)
J2 + DRAG + THERMAL
J2
ACTUAL
CONTROLLED
1/α = 400 SEC
0
2000
4000
6000
8000
10000
12000
TIME (SEC)

Figure 3a

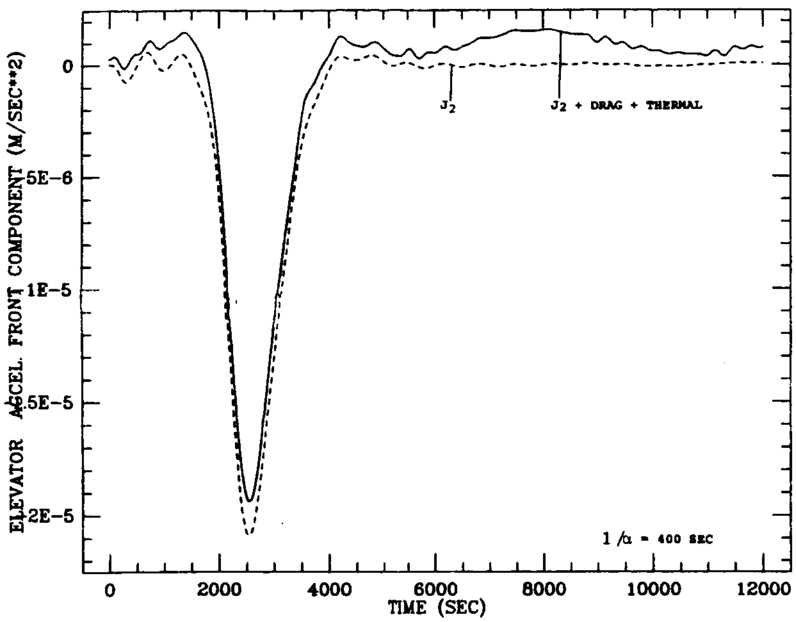


Figure 3b

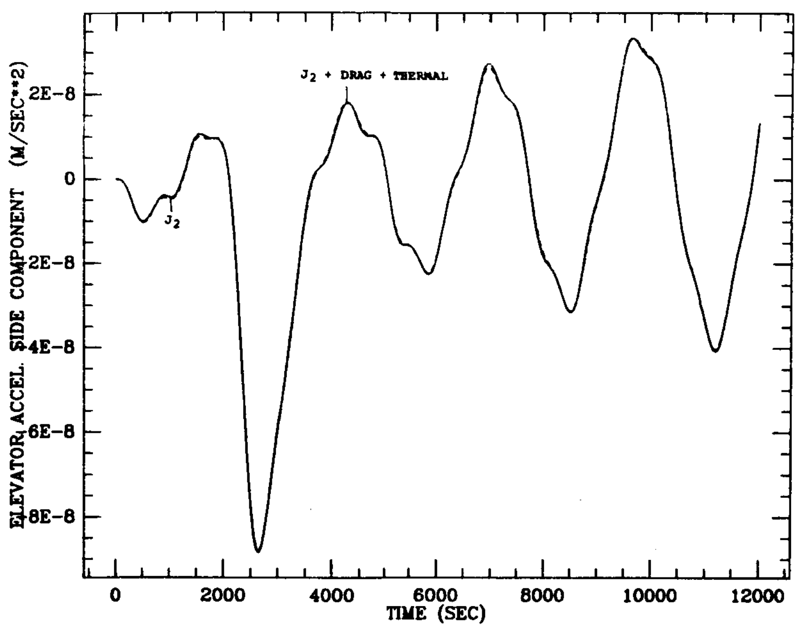


Figure 3c

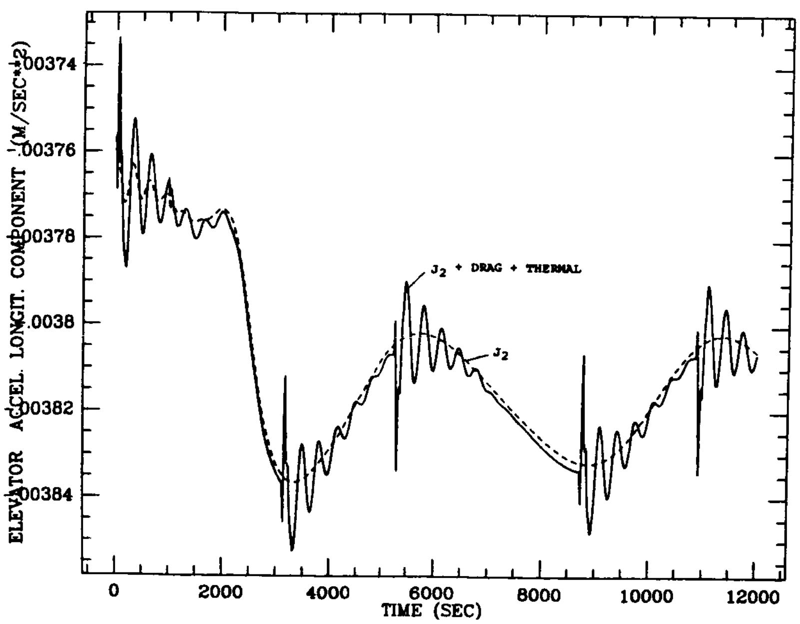


Figure 3d

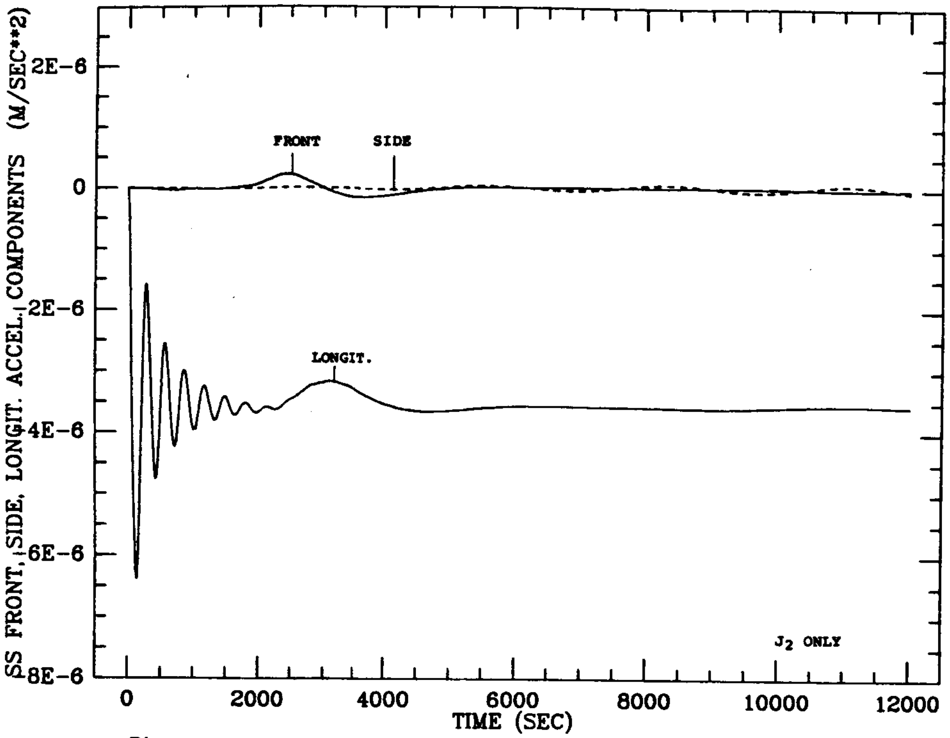
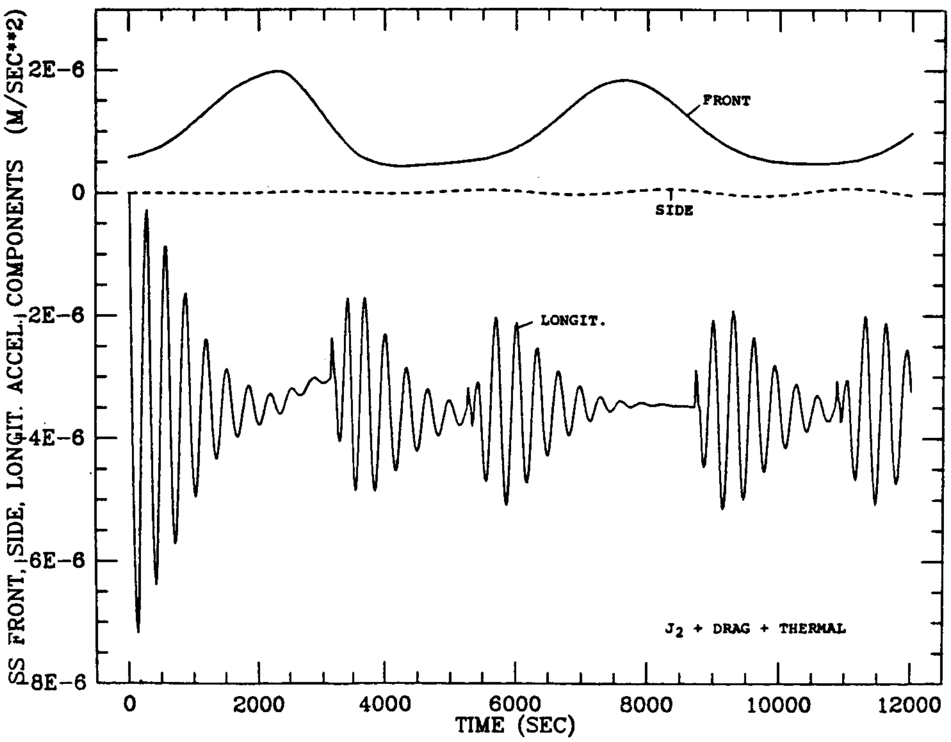


Figure 3e↑

Figure 3f↓



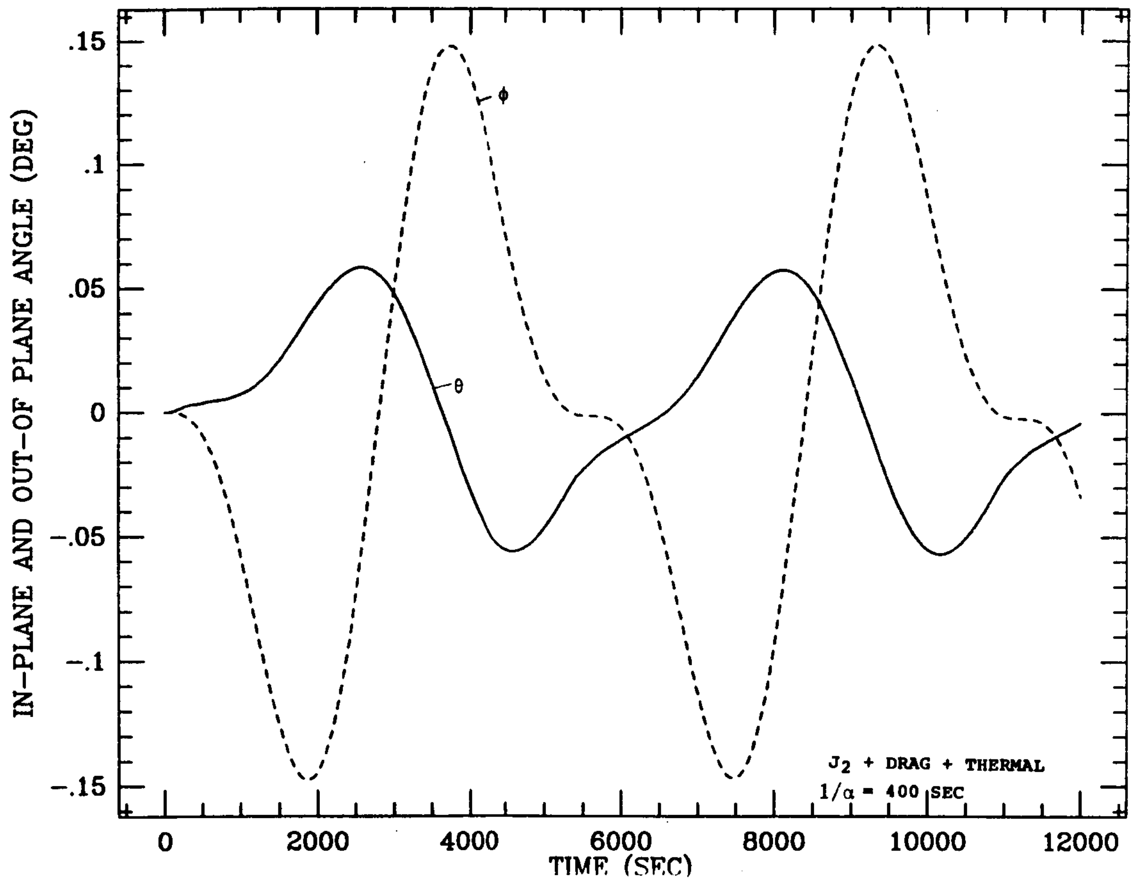

IN-PLANE AND OUT-OF PLANE ANGLE (DEG)
.15
.1
.05
0
-.05
-.1
-.15
0
2000
4000
6000
8000
10000
12000
TIME (SEC)
φ
θ
J2 + DRAG + THERMAL
1/α = 400 SEC

Figure 3g

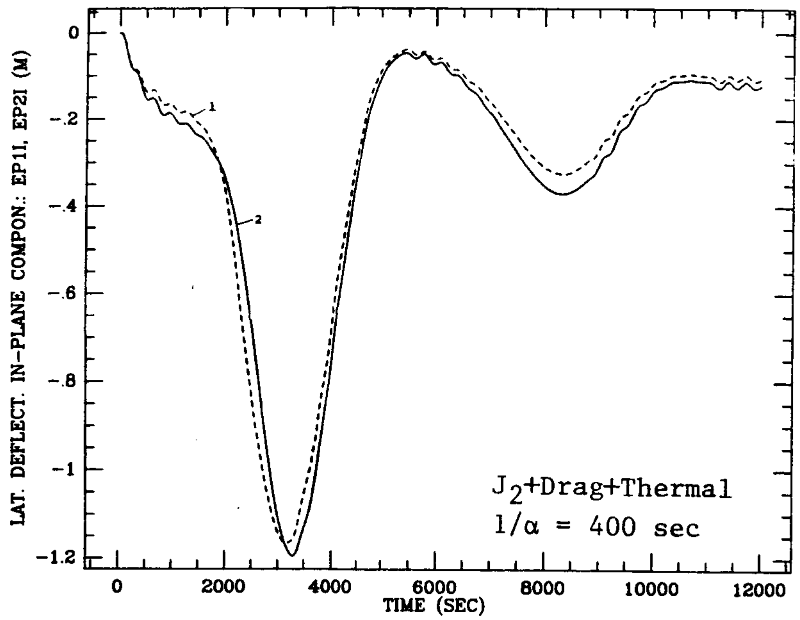


Figure 3h

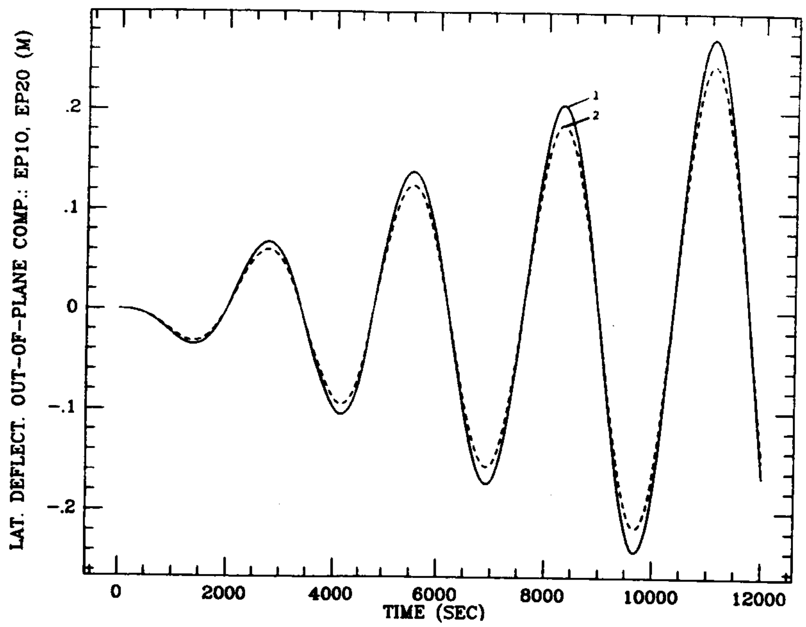


Figure 3i

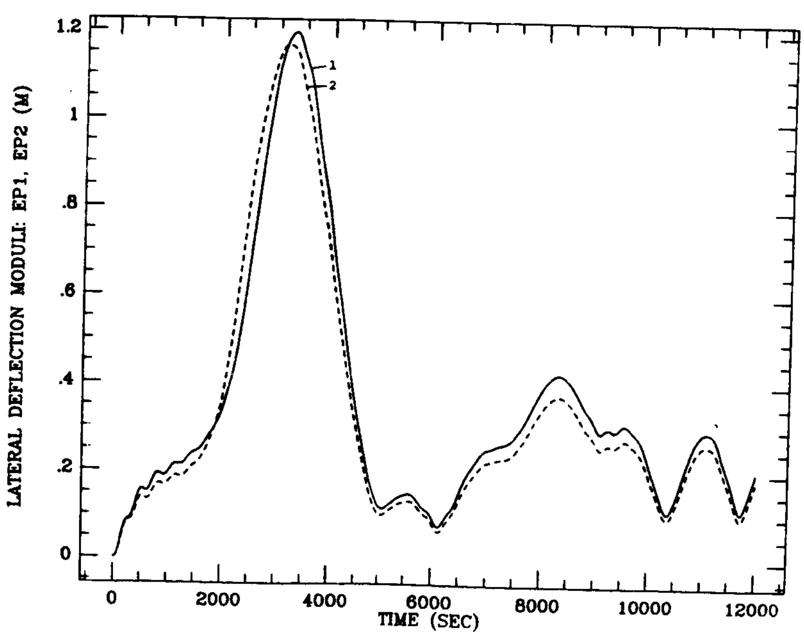


Figure 3j

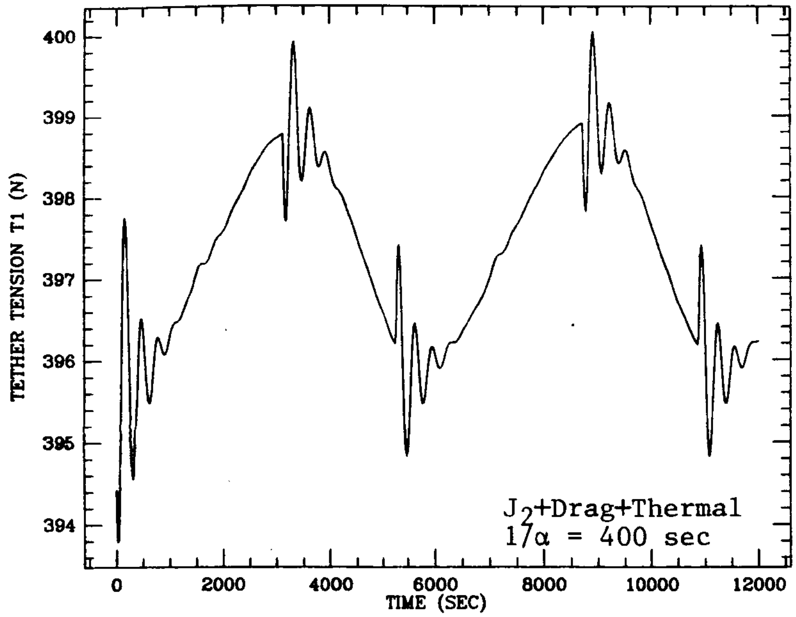


Figure 3k

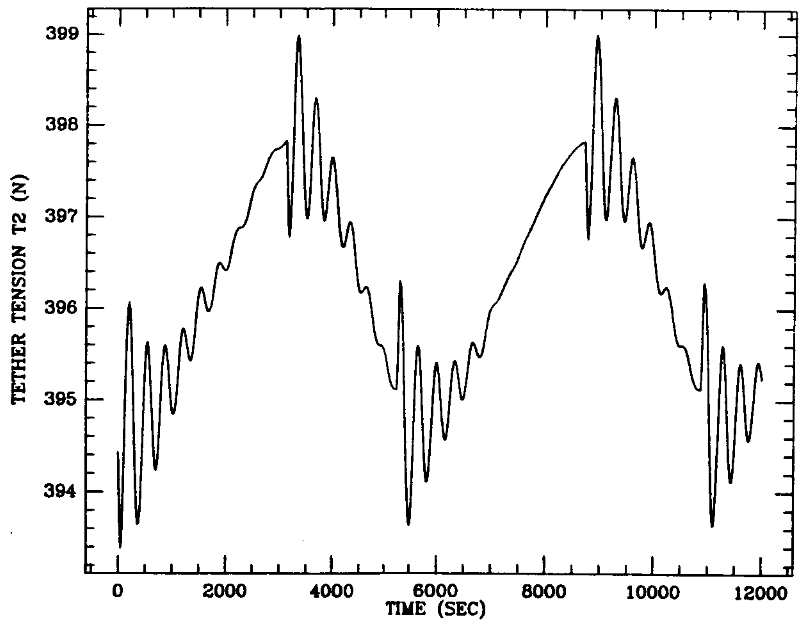


Figure 3ℓ

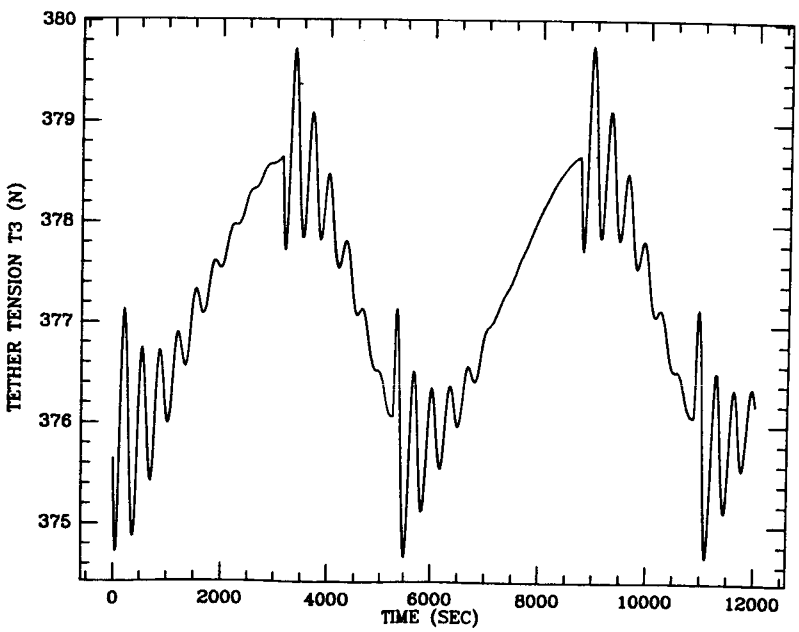


Figure 3m

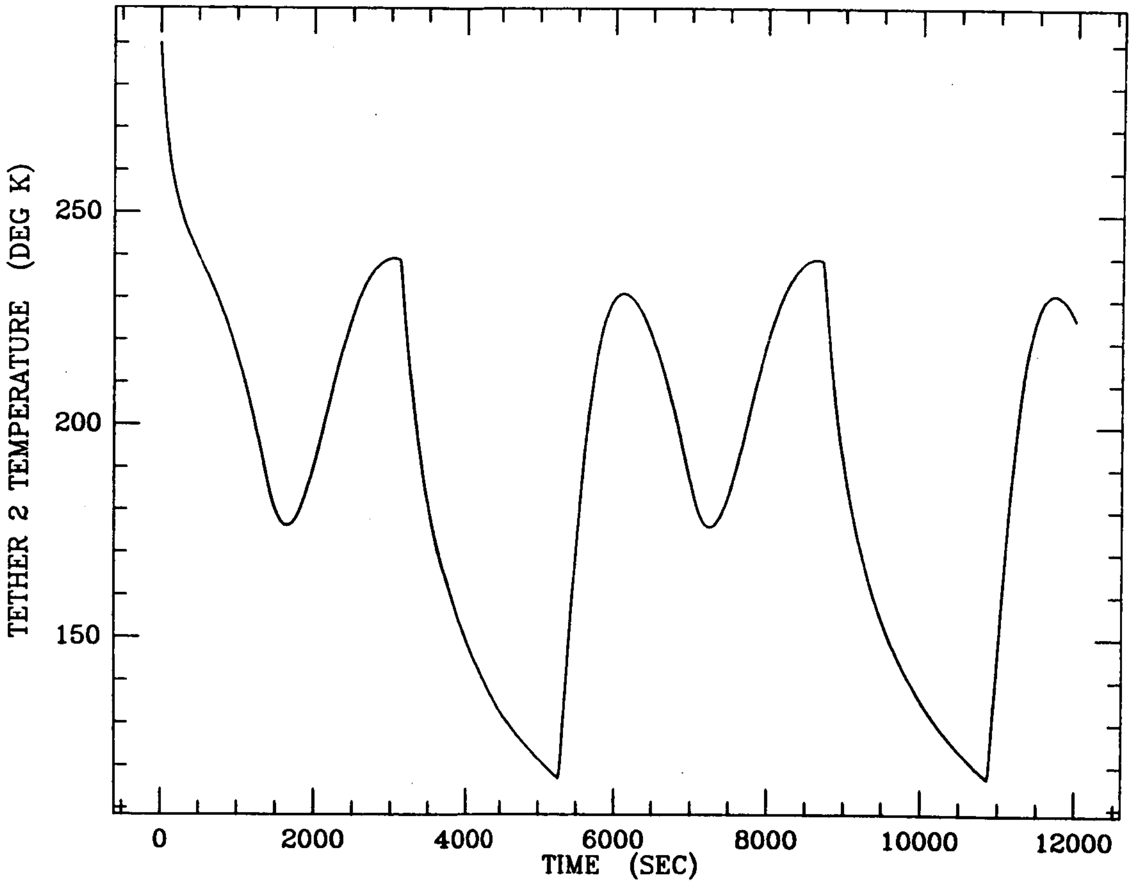

TETHER 2 TEMPERATURE (DEG K)
250
200
150
0
2000
4000
6000
8000
10000
12000
TIME (SEC)

Figure 3n

smooth dynamic response.

In the case of short-distance-maneuvers, thermal and aerodynamic perturbations can not be neglected since their effect upon the acceleration levels on board the Elevator is comparable to the variation of the gravity gradient acceleration during the Elevator's crawling maneuver.

2.2 Tether Applications Simulation Working Group Support By G.E. Gullahorn

2.2.1 Introduction –

One of the co-investigators (Gullahorn) is working in support of the Tether Applications Simulation Working Group. He has attended the two meetings of the Group at General Research Corporation in McLean, VA, and is working on a variety of tasks. In particular, he has been made chair of two subcommittees, one to circulate a questionnaire to ascertain the variety and status of simulation programs, and the other to provide a number of analytically precise solutions to TSS dynamics problems to which numerical solutions can be compared. He is also working in support of a committee to provide suggested test cases for intercomparison among the various simulators, and sample results in these cases. A further task shall be to define suggested environmental models for inclusion in current and future simulators, both simple ones (such as spherical or J_2 gravity models) for rapid calculation and more complex realistic models.

2.2.2 Questionnaire Subcommittee –

On the basis of reaction to a preliminary questionnaire and cover letter presented at the 29 May committee meeting, a new questionnaire and letter have been designed. The questionnaire is designed (1) to be as specific as possible so that answers will be truly comparable, and (2) to ease the burden of filling it out by using as many simple "check off" responses as possible. The questionnaire and cover letter are shown in Appendix A.

It is intended that a matrix in which the features of the various simulators are displayed will be compiled. A preliminary version has been prepared on the basis of response to a previous questionnaire, and is being sent with the questionnaire package; the matrix and an abbreviation key are also in the Appendix.

Experience in filling out this matrix indicates that the features displayed (rows) and options (abbreviations) will require substantial modification. It will also be desirable to devise a scheme to categorize simulators: e.g., general purpose, control, etc.

The questionnaire package is in the process of being mailed to some 350 organizations on a mailing list provided by General Research. For distribution to European groups, a sample package and mailing labels are being sent to Dr. Alberto Loria of PSN/CNR, who has volunteered to handle the European mailing.

2.2.3 Analytic Solutions Subcommittee –

The purpose of the "analytic solutions" is to provide precise basemarks against which numerical simulations (suitably restricted) can be compared. (We put "analytic" in quotes because numerical work must still sometimes be done, though the computations are more precise and simpler than in a full simulation.)

Often it will be the case that when the degree of computational effort is increased, as when the number of masses in a bead model is increased, the theoretical solution should be approached. E.g., the modal frequencies of a <mass, linear tether, fixed or infinite mass> system can be precisely calculated; by making the Shuttle mass very large and allowing the simulation to ring in response to an initial perturbation, these modal frequencies should be discernable by Fourier analysis. In such cases, the rapidity with which the true solution is approached with increased effort would make for a measure of program efficiency.

In other cases, the analytic solution should be approached as the simulation parameters become in some sense small: e.g., librations become analytically known in the limits of short, rigid tethers and small angular displacements from vertical equilibrium.

A third group of analytic solutions should be precisely simulated unless there are program bugs (or other known effects, which should have been consciously and judiciously chosen). E.g., a system started in the equatorial plane of a planet with cylindrically symmetric gravity field and with no out-of-plane velocities should remain in this plane.

It should be noted that these analytic solutions primarily provide consistency checks in various limits, and cannot by their nature provide validation in the cases where simulations are most necessary, with complex behavior and fully non-equilibrium and non-linear configurations. These latter situations will require inter-comparison of results from several simulators.

A preliminary outline of analytic solution categories was prepared and presented at the 29 May meeting. This outline is included with the documents in Appendix A. A list of references to analytic solutions is being prepared, as well as simply writing down explicitly the solutions in simple cases (e.g. librations). These references will be annotated placed in context in the outline. There was discussion at the 29 May meeting as to whether simply providing references was sufficient, or whether providing summary detail would also be desirable. It appeared to be the sense of the Group that such detail would be desirable, complete and explicit enough to allow someone writing a simulator to perform validation activities without actually referring to the original reference. Time and resources permitting, such summaries will be prepared for selected solutions (references); we envision one or two pages each, explicitly setting forth the physical problem and system, and restrictions involved (e.g. short tether), and the solution.

2.2.4 Simulator Test Cases –

In a telecon on 16 June the test case subcommittee made several recommendations for the SAO team (Arnold, chair, and Gullahorn) to follow up. (1) The cases should be specified as physical situations, with the simulation performer free to simulate them as s/he sees fit. (2) A "data base" of such items as c.m. orbit height and inclination and system characteristics should be prepared, to be used in all simulations. (3) A uniform output format should be specified to allow for as nearly direct comparison as possible; the implementation (whether directly in the program or through post processors) is to be left to the simulator. (4) The simulations should be chosen so that as many groups as possible can perform them. (5) The results should concentrate on the TSS itself, that is on the end masses and tether shape rather than, say, the ground track. (6) Test cases should be chosen so that each simulation will demonstrate several phenomena.

Suggested test cases were: (1) Large out-of-plane initial condition, at rest with zero tension. This would demonstrate out-of-plane librations, coupling to in-plane librations, and tether bobbing. (2) Masses vertical, but tether bowed in a combination of in- and out-of-plane initial configuration. (3) An impulse to the subsatellite from an initial hanging equilibrium configuration.

Further discussion and recommendations are in a series of memoranda among members of the subcommittee.

Effort to define such test cases is beginning. The test cases will be distributed following an initial telephone canvassing of possible respondents. The cover letter to the questionnaire asks respondents if they will be willing to perform such test runs. SAO will perform the test case simulations with SKYHOOK and other available programs.

2.2.5 Concluding Remarks –

The preparation of the questionnaire and cover letter are complete. Distribution is in process. Relevant documents are in Appendix A. Work on the accumulation and elucidation of analytic solutions for program validation is underway, and results will be reported in the next quarterly. One document is included in the Appendix.

Appendix A: Documents in Support of Tether Applications Simulation Working Group

Center for Astrophysics
60 Garden Street
Cambridge, Massachusetts 02138

Harvard College Observatory
Smithsonian Astrophysical Observatory

Mail Stop 59
8 July 1987
(617)495-7419

Dear Colleague:

Pursuant to the recommendations of the Tether Dynamics Simulation Workshop held 16 September 1986 in Arlington, VA, a Tether Applications Simulation Working Group has been formed by NASA and PSN.

The Working Group has undertaken to assemble yet another catalog of tether simulation programs. The experience of previous efforts has resulted in an updated -- more explicit and detailed -- questionnaire, a copy of which is enclosed. We would appreciate your response even if you have replied to previous surveys, and apologize for any duplicated effort this may require. Copies of previous responses we are aware of are enclosed; please feel free to "cut and paste" if appropriate. Note that many items can be completed by simply checking off the corresponding response.

Note that we are interested in programs under development as well as mature simulators; a response is provided to indicate stage of development.

Please use a separate form for each program for which you respond. We suggest you keep a copy of the questionnaire in case you develop new programs or substantially update a current program.

We also encourage you to distribute copies of the questionnaire (and this letter) to others you are aware of who have or are developing tether simulators.

The responses to the questionnaire will be edited and issued as a report early next year. Respondees (and other interested parties) may requeste a copy by filling out the form on the last page of the questionnaire. This report should help keep you abreast of developments in tether simulation.

A preliminary report will be presented at the Second International Conference on Tethers in Space in Venice, October 5-8. For inclusion in this Venice report please responde within two weeks.

Also at the Venice meeting we shall be presenting results of various simulators for a set of standardized test cases; we also hope to continue this activity. If you would be willing to perform such comparison runs (and possibly present the results in Venice) please contact either myself at the number above or Mr. David Arnold at 495-7269.

In parallel with this effort, the Working Group will be preparing "standard" or "recommended" environmental models (atmosphere, gravity, etc.) for use in simulation programs. We envision two categories: simple models, for comparison with theory and for economy; and "best possible" models. If you have been actively involved in selection or implementation of environment models in your programs, any input you may have as to criteria used, relative merits, etc., would be greatly appreciated.

Part of the report will consist of a matrix of simulators vs. attributes. A sample portion of a preliminary matrix is included, along with a key for its interpretation.

Sincerely yours,

Gordon Gullahorn

GEG/gg

TETHER SIMULATOR QUESTIONNAIRE

Tether Applications Simulation Working Group
May 1987

- Please fill out a separate questionnaire for each simulator.
- Many questions have a number of likely responses listed; check off choice(s) given or expand as appropriate.
- Mail to the address at the end of questionnaire; if you have any questions, write or telephone.
- Distribution of this form is encouraged.

PROGRAM/SIMULATION NAME:

INSTITUTE:
Address:

Person responding:
phone
Contact person(s):
phone

SUMMARIZE, BRIEFLY, THE DISTINCTIVE FEATURES OF THIS SIMULATOR:
(I.e., why did you write this program?)

IS YOUR PROGRAM:
BASED ON
ADAPTED FROM
AN IMPLEMENTATION OF
ANOTHER PROGRAM?

If so,
Original program name and source:

Differences in your version:

Should your version be considered:
a new program? or
an added implementation of the original program?

DEVELOPMENT STAGE:
Mature.
Operational, but still under development.
Under development, programming.
Under development, specification (writing equations, etc.).

SYSTEM BEING MODELED:
End Masses:

	"Shuttle"	"satellite"
fixed position		
point mass		
attitude dynamics		
simple drag		
aerodynamics		
other (specify)		

Tether:

Internal structure

- none ("massless","rigid")
- finite element, physical
- partial differential equ's
  - finite element
  - finite difference
  - modal synthesis

Properties

- axial elasticity
- axial damping
- bending stiffness
- torsional stiffness
- thermal
- conducting

Control: Does the program simulate:
- reel motion
- current control

What algorithms are used?

ENVIRONMENT MODELS:

	Simple	Complex *
atmosphere ________		
plasma ________		
magnetic field ____		
earth gravity _____		
lunar/solar grav __		
radiation ________		
other (specify)____		

* if readily available, please provide (complex) model names, references, descriptions, etc.

PROGRAM VARIABLES WHOSE EVOLUTION IS COMPUTED:

OTHER RESTRICTIONS, LIMITATIONS, DEFICIENCIES, PROBLEMS:

Short tether?
Small angles (from vertical)?
Other?

TYPICAL TETHER APPLICATIONS SIMULATED:

PROGRAMMING LANGUAGE(S):

Language:

Does your code meet a portable standard, e.g. Fortran 77?

COMPUTER/OPERATING SYSTEMS ON WHICH IMPLEMENTED:

At this institute:

Other known implementations:

AVAILABILITY:

Listing?	
Executable?	tape, floppy disk (what format?), punch cards
Source code?	tape, floppy disk (what format?), punch cards
Contract work?	perform runs, studies; modify programs

PRE/POST-PROCESSORS USED :
(e.g. for generating initial conditions or plots)

INPUT REQUIRED:
(i.e., what is needed to run the program? or, how do you specify the input?)

OUTPUT / PRESENTATION OF RESULTS:

Program itself:

- tabular file for inspection/plotting
- direct screen display
- other

Postprocessor:

IS THERE ANY INTERACTIVE CAPABILITY?

For simulation setup and execution?

To change course of simulation (e.g. control parameters) during run?

NON-STANDARD HARDWARE, SOFTWARE:
(Specify if used for main program or for post-processors.)

Commercial or other software libraries, e.g. IMSL or NAG:

Graphics terminals:

Plotters:

TYPICAL PROGRAM EXECUTION TIME(S):

E.g., computer time per orbit. If tether is finite mass, use ten masses/elements/modes:

Other typical situations, ranges:

DOCUMENTATION AVAILABLE:

Physical model:

Numerical/computational techniques:

Program structure:

Program use:

Source for documents:

ANY OTHER COMMENTS:

Please return to: Gordon Gullahorn Mailstop 59
Center for Astrophysics
60 Garden St.
Cambridge MA 02138

Phone: (617)495-7419 or FTS 830-7419
Bitnet: GORDON@CFA2 SPAN: CFA2::GORDON
Telefax: Call above number to arrange.

Fill in name and address below to receive a copy of summary report:
(You need not fill out a questionnaire to receive the report.)

ORIGINAL PAGE IS
OF POOR QUALITY

	SKYHOOK	SLACK3	TSSIM	BEADSIM	LOW-TENSION	RECOIL	GTOSS	SES TSS	TETHER	STOCS	HIFITS	SATP
MODEL:												
Shuttle	D, P	*	P	F!	F!	F	A	* A	?	AE	A	A
Satellite	D, A	–	P	P	P	P, D	A*	AE	?	AE	A	*
Tether	L	L	FE/FD!	L	–	–	L, M	R	?	L, M	?	?
Tether Prop	E, D, TH, EL	E, D	E, B	?	–	–	?	–	E, DR	EL, DR	–	?
Control	R, C	*	R	R	R	–	–	*	R, T	E	R	*
ENVIRONMENT:												
atmosphere	C	S	S, C	S	–	*	C	?	S	?	C	–
plasma	–	–	–	–	–	–	–	–	–	–	–	–
magnetic field	C	–	–	–	–	–	S	–	–	C	C	–
earth gravity	S, C	S	S, C	S	S	–	S	C	S	S, C	C	S
lun/solar grav	C	–	–	–	–	–	–	–	–	–	–	–
radiation	S	–	–	–	–	–	–	–	–	–	–	–
RESTRICTIONS:	–	*	–	*	*	*	–	*	–	–	–	–
LANGUAGES:	F+	F	F+	P+	–	–	F+	–	F	–	–	–
COMPUTER:	VAX	VAX	VAX, PC, *	*	MAC	MAC	*	*	*	*	*	–
AVAILABILITY:	S, C	S, C	–	–	–	–	–	–	–	–	–	–
OUTPUT:	N, P	N, P	N, P, S	N, S	N, S	N, S	N	N, S	N, P	N, P	N, P	N
INTERACTIVE:	–	S	–	–	C, S	C	?	C	–	–	?	–
DOCUMENTATION:	M, N, P, U	M, N, U	–	–	–	–	–	–	–	–	–	–

SLACK3 : SHUTTLE IS SPECIFIED, SUBJECT TO CONTROLS; TETHER IS DETENSIONED
TSSIM : ALSO HP9000, PDP 11/23
BEADSIM : IN-PLANE MOTION ONLY; NORTHSTAR HORIZON;
LOW-TENSION: IN-PLANE ONLY
RECOIL : EFFECT OF SHUTTLE THRUSTERS ON FREE MASS
GTOSS : ARBITRARY COLLECTION OF BODIES + ~~SHUTTLE~~ TETHERS; MANY SYSTEMS
SES TSS : SHUTTLE COCKPIT + CONTROL SIMULATOR FOR MANUAL CONTROL; TETHER <1.2KM; GOULD SEL-32-8780
TETHER : AMDAHL 5850
STOCS: CYBER 830
HIFITS : CYBER, HP9000
SATP : TETHER CRAWLER

KEY FOR ABBREVIATIONS IN MATRIX

MODEL:

Shuttle	Fixed; Point; Attitude; Drag; AErodynamics
Satellite	Fixed; Point; Attitude; Drag; AErodynamics
Tether	Rigid; Lumped mass; FiniteElement; FiniteDifference; Modal
Tether Prop	Elastic; Damped; Bending; Torsion; THermal; ELectrodynamic; Drag
Control	Reel; Current; Thrusters

ENVIRONMENT: Simple; Complex
atmosphere
plasma
magnetic field
earth gravity
lunar/solar gravity
radiation

RESTRICTIONS:	SHort tether; small Angles; nearly STraight tether
LANGUAGES:	Fortran C PAscal Assembler (+ = portable)
COMPUTER:	VAX; IBM mainframe; PC (ibm); Macintosh
AVAILABILITY:	Listing; Source code; Executable image; Contract work
OUTPUT:	Numerical file; Plots; Screen display
INTERACTIVE:	Setup; Control
DOCUMENTATION:	physical Model; Numerical methods; Program; User's guide

3.0 PROBLEMS ENCOUNTERED DURING REPORTING PERIOD

None.

4.0 ACTIVITY PLANNED FOR NEXT REPORTING PERIOD

During the next reporting period, as requested by the technical monitor, a new control law will be implemented in our computer code. This control law, developed by F.R. Swenson of Tri-State University, is called mirror image motion control law or MIMCL. The MIMCL will be tested in the dynamics simulation computer code in a variety of cases involving long traveled distances (4 km) and short traveled distances (2 m and 9.75 m). Results will be compared to those obtained previously with the *MHT* and *RE* control laws.

Regarding the tasks supervised by G.E. Gullahorn the activity for the next reporting period will be as follows. Effort on definition of the comparison test cases is beginning, and progress will be reported in the next quarterly. Preparation of a list of suggested environment models will be aided by the response to the questionnaire; effort on this task will begin in the next quarter.