N87-16781 D39-18
27P.
96555

1986

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER

THE UNIVERSITY OF ALABAMA

TETHER CRAWLER SYSTEM

Prepared by:	**Frank R. Swenson, Ph.D., P.E.**
Academic Rank:	Professor
University and Department:	Tri-State University Department of Mechanical and Aerospace Engineering
NASA/MSFC: Division: Branch:	 Program Development Advanced Systems Office
MSFC Colleagues:	Georg von Tiesenhausen James K. Harrison

T4725139

Date:	August 15, 1986
Contract No:	NGT 01-002-099 The University of Alabama

TETHER CRAWLER SYSTEM

by

Frank R. Swenson
Professor of Mechanical Engineering
Tri-State Univeristy
Angola, Inidana

ABSTRACT

A crawler system is designed to move a low-g/variable-g laboratory module along a tether between the Space Station and an attached space platform.

An analysis is made of the effects of control law parameter changes on the displacement, velocity and acceleration of the crawler system. The control law is then modified by the addition of a constant-velocity section and the new values of distance traveled, velocity and acceleration are analyzed as a function of time.

The power and torque equations are derived for a crawler system moving along a tether in orbit and numerical values of power and torque required for each prescribed movement are calculated versus time for four different cases using the control laws. All of the movement trajectories result in a requirement for power absorption or dissipation. The torque versus velocity data for the set of trajectories is used to define maximum required torque-speed envelope which can be used in the selection of the drive motor and the power supply.

A two-step control sequence is selected to permit initial location along the tether by distance traveled, followed by a vernier movement to reach the final desired constant net acceleration level. The components for the control system are identified and arranged in a block diagram configuration. The support subsystems are also identified.

The sections of this study have been integrated to develop a procedure for the determination of crawler system performance requirements and the initial design of tether crawler systems.

ACKNOWLEDGEMENTS

Guidance and definition to this project have been provided by Georg F. von Tiesenhausen and James K. Harrison of the MSFC Advanced Systems Office. A number of people in other areas of the Program Development provided direct and background inputs into this project. Background information on orbital mechanics were supplied by Vincent Dauro, Charles E. Hall, Herschel W. Harmon and John A. Mulqueen. An understanding of gravity-field variation and the techniques of gravity-field measurements was developed from discussions with Joe T. Howell and P. D. Nicaise. Stephen B. Hall helped develop the concept of Shuttle-based experiments. Jay H. Laue of the Tethered Satellite System Project provided background information on the properties of tether materials.

Insights into the opportunities and problems associated with ground testing of Tether Crawler Systems came from discussions with Charles E. Smith. An exposure to the facilities for the testing of large space structures was provided by Joe T. Howell. Henry Waites of the Systems Dynamics Laboratory provided information on self-erecting towers. Instruction in electrical power systems was provided by Harold H. Huie, Donald E. Williams, L. Whitt Brantley, Larry Hill and Bob Giudici. Discussions with Bob also provided insights into the longer-range dream of the NASA Team - The Mission to Mars.

A great deal of what has been achieved has been due to the encouragement and teachings of these and other NASA mentors. However, the responsibility for errors of detail or of the transmission and application of this knowledge and insights to the problems worked upon in this study rests with the author.

LIST OF FIGURES

LIST OF FIGURES
(Concluded)

<u>NOMENCLATURE</u>

Symbol		Meaning
$\alpha, \propto$	-	control law time parameter
Δ	-	interval
σ	-	proximity
γ	-	control law shape factor
Ω	-	angular velocity for circular orbit
A_g	-	net constant radial acceleration
c.m.	-	center of mass
c.o.	-	center of orbit
$C_F R$	-	diameter of the drive mechanism drive wheel
I	-	mass moment of inertia for the drive wheel
GM_E	-	gravitational constant for the Earth
H	-	elevation above the Earth
L	-	distance traveled along tether
L_{10}	-	initial distance along tether
ΔL_c	-	distance interval
ΔL_{cv}	-	constant-velocity distance interval
ΔL_c	-	acceleration-and-deceleration distance interval
L_F	-	final total distance traveled
$\dot{L}$	-	velocity along the tether
$\dot{L}_{max}$	-	maximum velocity during a movement along the tether
L_1	-	distance along the tether from the Space Station to the tether crawler system
L_2	-	distance along the tether from the tether crawler system to the end mass (tethered science platform)
$\ddot{L}$	-	acceleration along the tether
$\ddot{L}_{max}{}^{+}$	-	maximum positive acceleration during a movement along the tether
$\ddot{L}_{max}{}^{-}$	-	maximum negative acceleration during a movement along the tether
M	-	mass or tether crawler system/experiment module
N	-	rotative speed
P	-	power
R	-	radius of an orbit measured from the center of the Earth
T	-	time, torque
T_A	-	time to reach maximum velocity and time to the start of a constant-velocity section

NOMENCLATURE
(Concluded)

Symbol		Meaning
T_B	-	time to the end of a constant-velocity section
ΔT_{cv}	-	time interval of a constant-velocity section
T_1	-	time to maximum positive acceleration
T_2	-	time to maximum negative acceleration total
$T\sigma$	-	time to proximity
T	-	total time to proximity - reference case
$T_{\sigma}^{g,r}$	-	time for acceleration-and-deceleration for control law with a constant-velocity section
X	-	constant-velocity distance parameter
Y	-	radial distance from the center of orbit
$\dot{Y}$	-	radial velocity
$\ddot{Y}$	-	radial acceleration

Measurement Dimensional Units

g_o	-	one Earth gravitational acceleration unit (981cm/s^2)
kg	-	kilograms, mass
M	-	meters, length
N	-	newtons, force
s	-	seconds, time

INTRODUCTION

The Space Station of the 1990's is expected to provide an acceleration environment in the experiment modules of a low-g level for longer periods than is presently available to experimenters in the areas of fluid mechanics, biotechnology and materials science. However, even on the much larger capacity Space Station, the space and astronaut time available for man-monitored and interacted experiments will be limited. In addition, crew movements, equipment transfer movements, departures and arrivals of orbital, free-flyers, unmanned transportation and Shuttle vehicles, along with Space Station maneuvers for station-keeping and attitude adjustment will generate acceleration and vibration disturbances in the station structure which will be transmitted to the experiments. The conclusion is that there is a need for a low-g, even variable-g, experiment environment which is quiescent with respect to acceleration levels for long periods of time.

By the Shuttle era, there should exist many experiments and self-contained production processes which require long periods at very low-g levels but do not require frequent man-monitoring or interaction. These can be placed in an instrument module and moved out away from the Space Station along a deployed tether to be maintained in an isolated, controlled, very low-g acceleration environment. Another available option would be to move the instrument module through a programmed sequence of variable-g levels.

In summary, a crawler system is needed that will move a low-g/variable-g laboratory module along a tether between the Space Station and an attached space platform. The purposes for locating the module along the tether are (1) to isolate low-g experiments from the attitude changes and the vibrations of the Space Station structure, (2) to permit variable-g experiments without changing Space Station altitude, and (3) to reach and maintain controlled, constant net acceleration experiment environments in the range from 10^{-3}g to 10^{-6}g.

OBJECTIVES

The objective of this study is to complete a design study of the motion control laws and drive mechanism for a system to move a low-g/variable-g experiment module along a tether between the Space Station and an attached space platform.

The crawler should move along the tether to isolate the experiment module from the movements and vibrations of the Space Station and attain and maintain prescribed acceleration levels in the range of 10^{-3}g to 10^{-6}g.

Figure 1 shows the constraints-operations envelope for meeting the above objectives. The planning limit for the duration of the low-g experiments has been set at a nominal value of 1000 hours. This period is about half of the interval of 2160 hours (90 days) that is presently scheduled for Shuttle arrivals at the Space Station, a time of considerable activity on the Station and, therefore, acceleration disturbances. The nominal value is conservatively low, and in actual operation the available quiescent period may be longer.

BACKGROUND

One of the earliest recommendations for the applications of tethers in the United States space program was made by Colombo (1974). Many suggestions have been made since then and these have been reviewed and summarized by von Tiesenhausen (1982).

Arnold (1986) has recently prepared a thorough discussion of the dynamics of long tethers in space. Also, von Tiesenhausen (1984) has compiled a history of the proposals down through history and science-fiction for the uses of tethers in space. Both the prospects and the problems associated with a long, limber element in orbit are being identified and worked upon.

A problem that was identified early was the unsteady nature of tether deployment from an orbiting spacecraft. One of the first control laws for tether deployment was proposed by Rupp (1975). Although this problem is still under study, newer efforts have been made by Rupp and other investigators to develop an optimal control law for the movement of a tether crawler system (sometimes referred to as a Space Elevator) along an already deployed tether.

The most recent proposal of a crawler-motion control law was made by Lorenzini (1986). He both reviewed the development of crawler control laws and studied the dynamical response of the tether/crawler system to movements of the crawler. This present study will extend this work in the development of control laws for tether crawler systems.

BASIC CONTROL LAW

A control law having a continuous smooth motion has been proposed by Lorenzini (1986) as a distance traveled along the tether -

$$L(t) = L_{10} + \Delta L_c[\tanh(\alpha t)]^{\gamma} \tag{1}$$

which is plotted in Fig. 2. An increase in shape factor is seen to give a delayed acceleration.

For this control law the motion exponentially approaches the final point which would take an infinite time to reach, so as a practical matter, the motion is ended at a proximity distance to the end point. The time required to reach this proximity distance is shown in Fig. 3, which is a plot of -

$$T_\sigma = \frac{1}{\alpha}\left[\tanh\left(1 - \frac{\sigma}{\Delta L_c}\right)\right] \tag{2}$$

where,

$$\sigma = L_f - L(T_\sigma) \tag{3}$$

This time to proximity is seen to increase both for an increasing value of the control law shape factor and for decreasing proximity distance.

Figure 4 shows the velocity versus time for this control law. The velocity equation is -

$$L'(T) = \Delta L_c \alpha \gamma [\tanh(\alpha t)]^{\gamma-1}[\operatorname{sech}(\alpha t)]^{2} \tag{4}$$

and the maximum value of velocity is determined by -

$$L'_{max} = \Delta L_c \alpha [2\gamma/(\gamma+1)][(\gamma-1)/(\gamma+1)]^{\frac{\gamma-1}{2}} \tag{5}$$

The distance traveled and the time to reach maximum velocity are expressed as -

$$L(L'_{max}) = L_{10} + \Delta L_c[(\gamma-1)/(\gamma+1)]^{\gamma/2} \tag{6}$$

and

$$T(L'_{max}) = \frac{1}{\alpha}\sinh^{-1}[(\gamma-1)/2]^{0.5} \tag{7}$$

Acceleration along the tether is given by -

$$L''(t) = \Delta L_c \, \alpha^2 \gamma [\tanh(\alpha t)]^{\gamma-2} [\mathrm{sech}(\alpha t)]^4 \times \{(\gamma-1) - 2[\sinh(\alpha t)]^2\} \tag{8}$$

and is plotted for typical values of the shape factor in Fig. 7. Both the positive and the negative maximum values of acceleration decrease in magnitude with increasing values of shape factor and both reach limiting values - the maximum positive acceleration limit being approximately twice the maximum negative acceleration limit.

The times to reach maximum positive acceleration, zero acceleration (maximum velocity), and maximum negative acceleration are also a function of shape factor, as shown in Fig. 8.

The values for an example (reference, r) case are listed in Fig. 9. The shape factor value is high enough in this example that the limit values can be used in calculating the maximum velocity, the maximum positive acceleration and the maximum negative acceleration.

MODIFIED CONTROL LAW

The basic control law is smooth and continuous. However, it can be inefficient in the use of both time and velocity capabilities of the crawler system. A modification which can be made to improve the control law is the addition of a constant-velocity interval as shown in Fig. 10. This interval begins at the time maximum velocity is reached; i.e., when the acceleration is zero.

The equations for the three segments of the motion - acceleration, constant-velocity, deceleration - are:

$0<T<T_a$

$$L(T) = L_0 + \Delta L_c [\tanh(\alpha t)]^{\gamma} \quad (9)$$

$$L'(T) = \Delta L_c \alpha \gamma [\tanh(\alpha t)]^{\gamma-1} [\operatorname{sech}(\alpha t)]^2 \quad (10)$$

$$L''(T) = \Delta L_c \alpha^2 \gamma [\tanh(\alpha t)]^{\gamma-2} [\operatorname{sech}(\alpha t)]^2 \} \quad (11)$$

$T_a<T<T_b$

$$L(T) = L_0 + \Delta L_c [\tanh(\alpha t)]^{\gamma} + (T-T_A) L'_{max} \quad (12)$$

$$L'(T) = L'_{max} = \Delta L_c \alpha [2\gamma/(\gamma+1)][(\gamma-1)/(\gamma+1)]^{\frac{\gamma-1}{2}} \quad (13)$$

$$L''(T) = \phi \quad (14)$$

$T_b<T<T$

$$L(T) = L_0 + \Delta L_c [\tanh(\alpha(T-(T_B-T_A)))]^{\gamma} + (T_B-T_A)(L'_{max}) \quad (15)$$

$$L'(T) = \Delta L_c \alpha \gamma [\tanh(\alpha(T-(T_B-T_A)))]^{\gamma-1} [\operatorname{sech}[\alpha(T-(T_B-T_A))]]^2 \quad (16)$$

$$L''(T) = \Delta L_c \alpha^2 \gamma [\tanh(\alpha(T-(T_B-T_A)))]^{\gamma-2} \times [\operatorname{sech}[\alpha(T-(T_B-T_A))]]^4 \times \{(\gamma-1) - 2[\sinh(\alpha(T-(T_B-T_A)))]^2\} \quad (17)$$

The selection of a constant-velocity interval length can be done using the constant-velocity parameter X, the ratio of the net distance for acceleration and deceleration to the total distance to be traveled. Two cases of interest are (1) where the time to proximate distance remains the same as for the basic control law and (2) where the maximum velocity remains the same. The effects of changing the parametr X on the values of the other control law parameters and the values of maximum velocity and accelerations are shown in Fig. 11 for the case of constant time to proximity and in Fig. 12 for the case of constant maximum velocity.

Figure 13 shows an example case where the distance traveled versus time is plotted for X=1 and for X=0.336 and the same maximum velocity, distance traveled and control law shape factor. By adding the constant-velocity section the time to travel the same distance has been halved.

The considerations in the selection of a tether control law are listed in Fig. 14. The type of analysis that has been made on this control law can be made on other candidate control laws and the same parameters of the motion and the maximum velocity and maximum values of acceleration will be the principal considerations in selection of the optimal control law.

DRIVE MECHANISM

A drive mechanism provides both the contact of the crawler system with the tether and the forces on the tether to move the crawler/instrument platform along the tether. The major considerations in selecting a drive mechanism are listed in the top section of Fig. 15. A drive configuration meeting these considerations is shown in the bottom section of Fig. 15. The crawler system is toggle-latched onto the tether and the drive wheel-belt combination provides a large contact area and, therefore, low contact pressures on the tether. A larger force can be applied to the tether without damage to the tether from crimping or sliding forces.

The torque and power required for the motion of the crawler system and instrument module along the tether are given by the equations in Fig. 16 and below -

$$T = \left(\frac{mD}{2} + \frac{2I}{D}\right)\ddot{Y} + C_p R_c \dot{Y} + \frac{mD}{2}\left[\frac{GM_E}{(R+Y)^2} - (R+Y)\Omega^2\right] \tag{18}$$

$$P = T \times N = T \times \dot{Y}/D \tag{19}$$

Figures 17, 18 and 19 are plots of the required torques and power versus time for cases where the same distance is traveled but from different starting points relative to the center of orbit (where the net gravitational and centripetal acceleration is equal to zero). The variable Y is the measure of distance radially from the center of orbit. The basic control law is used in all three cases. One feature of all three cases is the large area under the negative power curve. These fairly large amounts of energy must be transmitted and stored or used elsewhere, be absorbed, or be dissipated to outer space.

The same analysis is applied to the constant-velocity example case and the results are shown in Fig. 20. The constant-velocity section is seen as central straight line curves. Again, a large negative power area is obtained. The velocity and acceleration curves for this case are shown in Fig. 21.

The selection of a drive motor is conventionally done from required torque versus speed data, so torque values are plotted versus speed for each of the four cases. A typical plot is shown in Fig. 22. An envelope which encloses all of the plotted points is then the required torque versus speed for that motion of the tether crawler system and instrument module.

The required torque-speed envelopes for all four cases are plotted in Fig. 23. The two cases of X=1, Y=0 to + 1000m are combined as the torque curves are nearly mirror images and the torque capabilities of drive motors are the same in both directions of rotation. The limit of speed is the maximum expected velocity which is the same for all four of these cases. The shaded region defines the values of required torque versus speed for any drive system which is to follow the basic and modified control laws to move the crawler system/instrument module. A drive system should be selected which has a torque-speed capability above this required torque versus speed envelope.

CONTROL SYSTEM

The components required to make a control system having the capabilities for coarse control by location on the tether and for vernier control by acceleration level are listed in Fig. 25. The constant acceleration levels versus distance from the center of orbit are plotted in Fig. 24 for the design altitude of the Space Station.

The control system block diagram containing these components is shown in Fig. 26. For the coarse location movement this control system controls the motion of the crawler system until it reaches the proximity distance and stops. The vernier control is then switched in and the small correction movement is made using acceleration level as the controlled variable. Three accelerometers are used to cover the range from a milli-g to a tenth of a micro-g.

CONCLUSIONS

A procedure for determining performance specifications and the initial design of tether crawler system is developed. The steps of the procedure are:

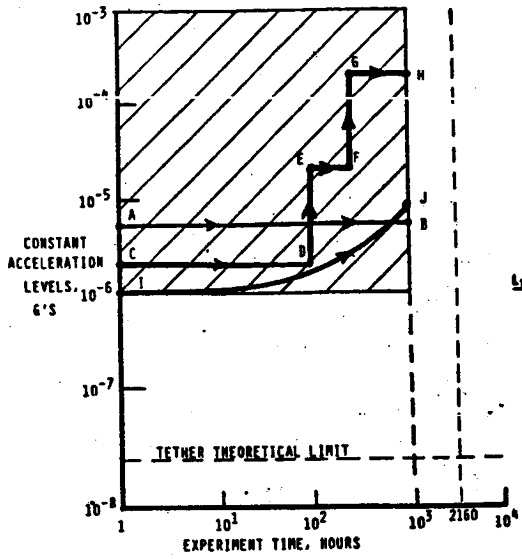
- Determine the desired acceleration levels and the corresponding trajectories
- Determine the mass to be transported
- Select the limiting trajectories and determine the distances to be traveled and the acceptable first proximity distance
- Determine the maximum time to move within proximity
- Select the acceptable levels for maximum velocity, maximum positive acceleration and maximum negative acceleration
- Determine the locations along the tether at which will occur the maximum positive acceleration, maximum velocity and maximum negative acceleration
- Select a time factor and shape factor based on the above considerations and simulation studies of tether response to Tether Crawler System movement
- Select a constant-velocity section to decrease either maximum velocity and acceleration or the time to move within proximity
- Determine the required torque versus speed envelope
- Select a drive motor, gearhead and electronic drive that provide a maximum available torque versus speed curve that is above the required torque-speed envelopes for all proposed trajectories
- Select a control system and the support subsystems.

RECOMMENDATIONS

The following are recommended as continuation studies:

- Simulation of Tether Response to Tether Crawler System Movement with Constant-Velocity Section
- Acceleration Filter Characteristics of Free-End and Fixed-End Tether
- Fixed-End Tether Crawler System Dynamics
- Ground-Based Tether Crawler System Demonstration Experiments
- Shuttle-Based Tether Crawler System Demonstration Experiments.

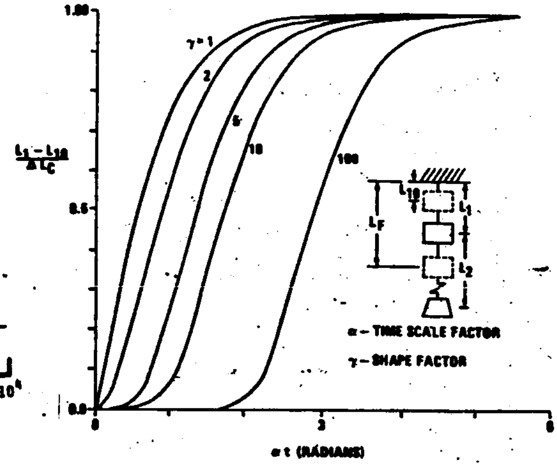
ORIGINAL PAGE IS OF POOR QUALITY



- 2160 HOURS BETWEEN SHUTTLE ARRIVALS
- 1000 HOURS PLANNING LIMIT.
- EXPERIMENT TRAJECTORIES
  - A-B CONSTANT G LEVEL
  - C-H STEPPED G LEVELS
  - I-J CONTINUOUSLY VARIABLE G LEVEL

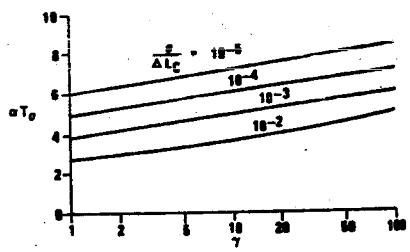
Fig.1

CONSTRAINTS - OPERATIONS ENVELOPE



DISTANCE TRAVELED VERSUS TIME

Fig.2



σ – PROXIMITY DISTANCE FROM FINAL POINT

L_F – σ – END POINT OF INITIAL TRAVEL

$T_σ$ – TIME INTERVAL TO END POINT

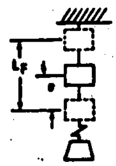
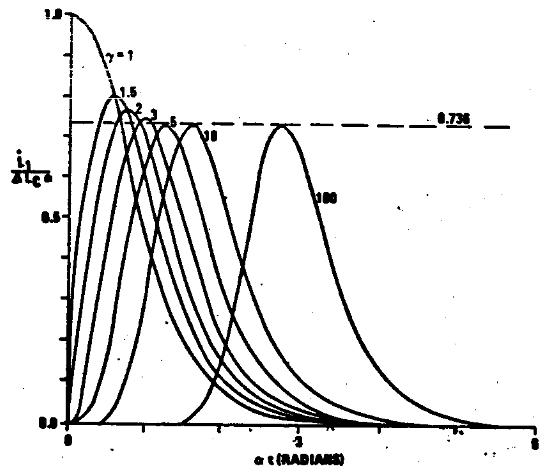
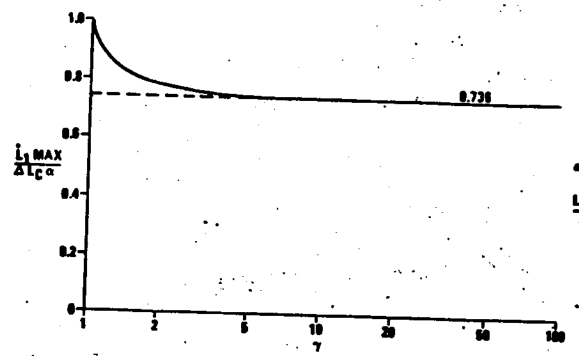


Fig.3



VELOCITY VS. TIME

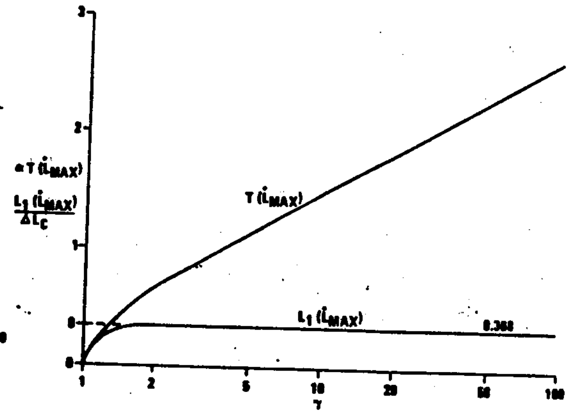
Fig.4



MAXIMUM VELOCITY VS. SHAPE PARAMETER

- MAXIMUM VELOCITY IS BOUNDED
- MAXIMUM VELOCITY IS DETERMINED BY PRODUCT OF ΔL_C AND α FOR $\gamma > 4$

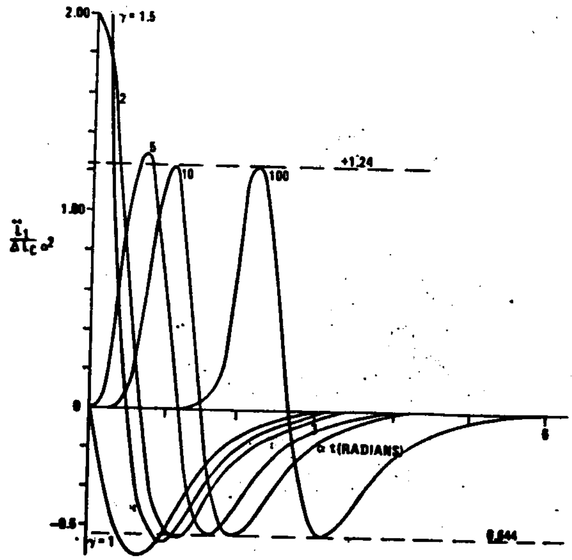
Fig.5



TIME AND DISTANCE TRAVELED TO REACH MAXIMUM VELOCITY

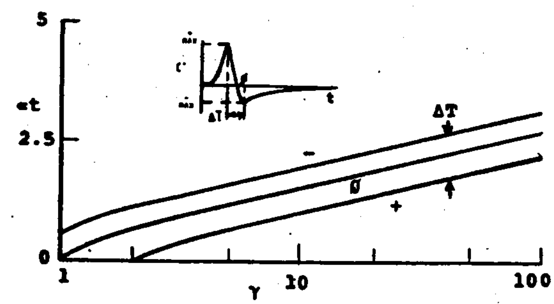
FOR $\gamma > 2$, RELATIVE DISTANCE TRAVELED TO REACH MAXIMUM VELOCITY

Fig.6



ACCELERATION VERSUS TIME

Fig.7



TIME TO REACH MAXIMUM POSITIVE ACCELERATION, ZERO ACCELERATION AND MAXIMUM NEGATIVE ACCELERATION VERSUS SHAPE FACTOR

- SHAPE FACTOR ACTS AS A TIME DELAY
- TIME INTERVAL, ΔT, BETWEEN MAXIMUM NEGATIVE ACC^LERATION AND MAXIMUM POSITIVE ACCELERATION REMAINS CONSTANT FOR SHAPE FACTOR GREATER THAN FIVE.

Fig.8

ORIGINAL PAGE IS OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

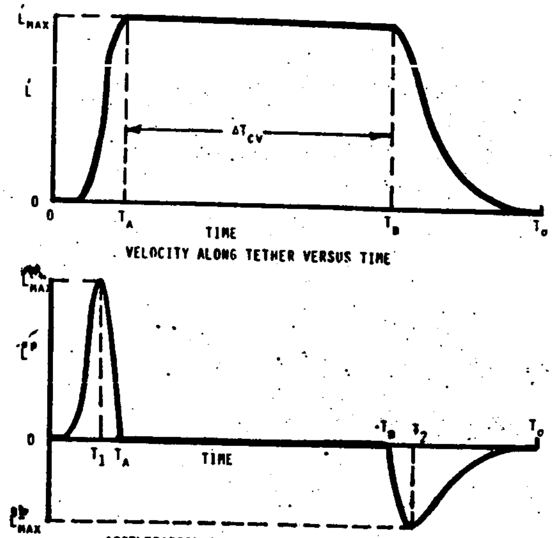
CONTROL LAWS: EXAMPLE

FOR: $L_{10} = 10M$
$\Delta L_C = L_F - L_{10} = 1KM$
$\sigma = 1M$

SELECT: $\omega = .001$ RADIANS PER SECOND
$\gamma = 10$

THEN: $L(T) = 10 + [TANH\,(.001T)]^{10}$
$T_0 = \frac{5}{\omega} = 5000$ SECONDS
$\dot{L}_{MAX} = 0.736\Delta L_C\,\omega = 0.736\ M/S$
$L_{\dot{L}_{MAX}} = L_{10} + 0.368\Delta L_C = 378M$
$T_1 = T_{\dot{L}_{MAX}} = \frac{1.5}{\omega} = 1500S$
$\ddot{L}_{MAX} = 1.236\Delta L_C\,\omega^2 = 1.236\times10^{-3} M/S^2$
$T_0 = T_{\ddot{L}_{MAX}} = \frac{1.0}{\omega} = 1000S$
$\ddot{L}_{\bar{MAX}} = -0.644\Delta L_C\,\omega^2 = -6.44\times10^{-4} M/S^2$
$T_2 = T_{\ddot{L}_{\bar{MAX}}} = \frac{2.0}{\omega} = 2000S$

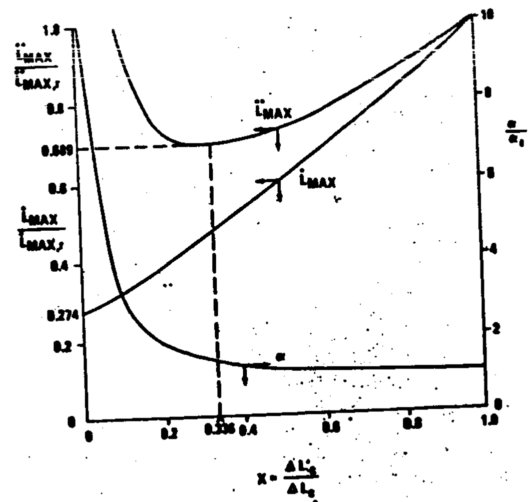
Fig.9



ACCELERATION ALONG TETHER VERSUS TIME
- CONSTANT-VELOCITY INTERVAL, ΔT_{CV}, IS INDEPENDENT OF ω AND γ.
- CONSTANT-VELOCITY INTERVAL PARAMETER, ΔT_{CV}, MAY BE VARIED TO CHANGE ΔL_C.

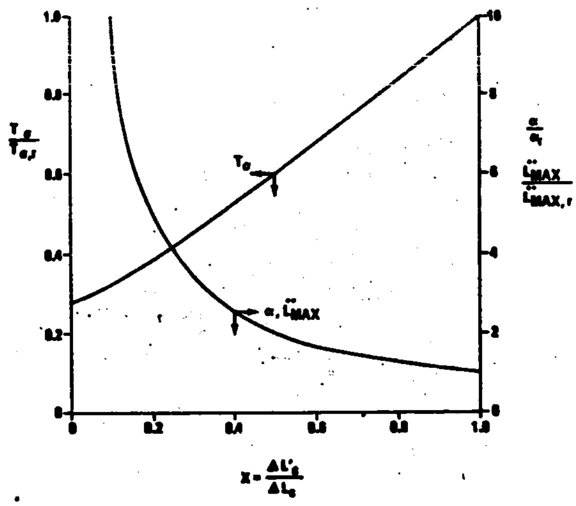
INSERTION OF A CONSTANT-VELOCITY INTERVAL

Fig.10



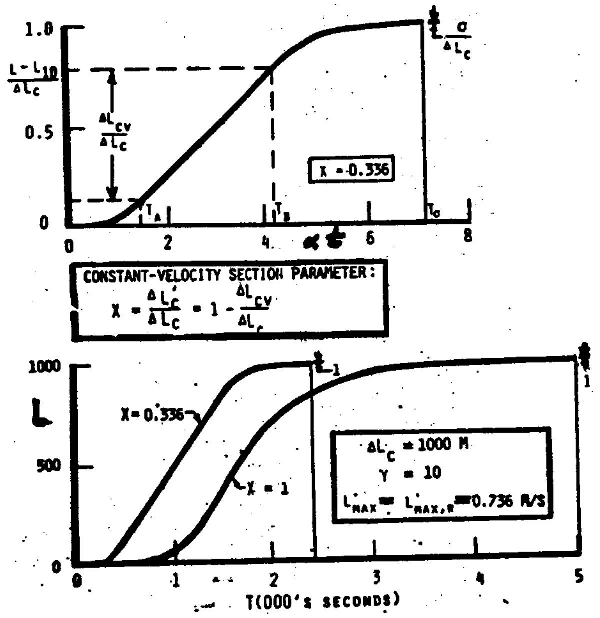
CONTROL–LAW CONSTANT–VELOCITY PARAMETER SELECTION FOR $T_o = T_{o,f}$

Fig.11



CONTROL LAW CONSTANT – VELOCITY PARAMETER SELECTION FOR $\dot{L}_{MAX} = \dot{L}_{MAX,f}$

Fig.12



ADDITION OF A CONSTANT-VELOCITY SECTION
— DISTANCE TRAVELED VERSUS TIME

Fig.13

ΔL_c - DISTANCE TO BE TRAVELED ALONG TETHER
ΔL_{cv} - DISTANCE TRAVELED AT CONSTANT VELOCITY
σ - PROXIMITY DISTANCE
T_σ - TIME TO MOVE DISTANCE $\Delta L_c - \sigma$
$\dot{L}_{MAX}$ - MAXIMUM VELOCITY
$\ddot{L}^{+}_{MAX}$ - MAXIMUM POSITIVE ACCELERATION
$\ddot{L}^{-}_{MAX}$ - MAXIMUM NEGATIVE ACCELERATION

CONTROL LAWS - SELECTION CONSIDERATIONS

Fig.14

DRIVE MECHANISMS - DESIGN CONSIDERATIONS:
- O MOTION CONTROL LAWS CONTROL L OR $\dot{L}$
- O LATCHING/UNLATCHING TO TETHER
- O NO CRIMPING OF TETHER - LOW CONTACT PRESSURES
- O NO SLIPPING ALONG TETHER - LARGE CONTACT AREAS

CONFIGURATION FOR DESIGN ANALYSIS:

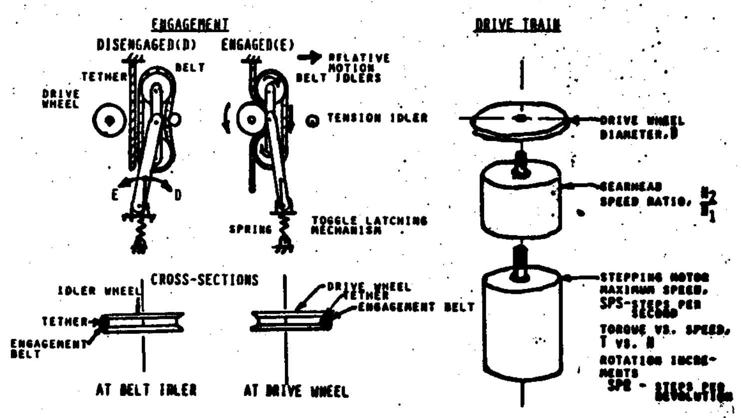


Fig.15

ICS DRIVE MECHANISM

TORQUE

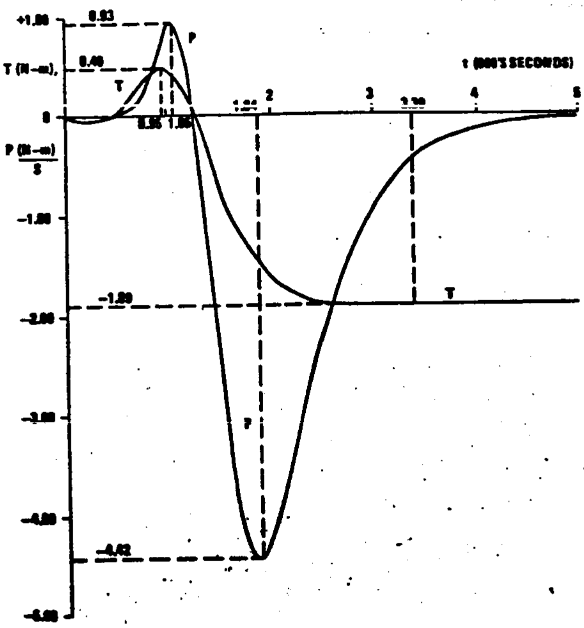
$$T = \left(\frac{MD}{2} + \frac{2J}{D}\right)\ddot{Y} + C_F R_R \dot{Y} + \frac{MD}{2}\left(\frac{GMr}{(R+Y)^2} - (R+Y)\Omega^2\right)$$

POWER

$$P = T \times N = T \times \frac{\dot{Y}}{\pi D}$$

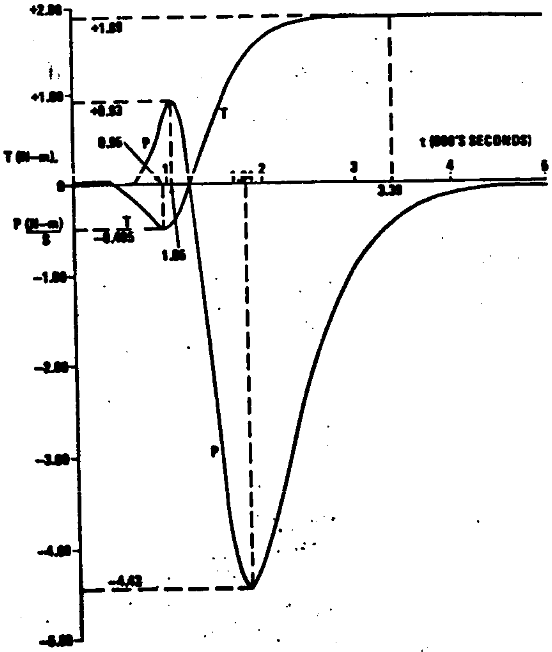
Fig.16

ORIGINAL PAGE IS
OF POOR QUALITY



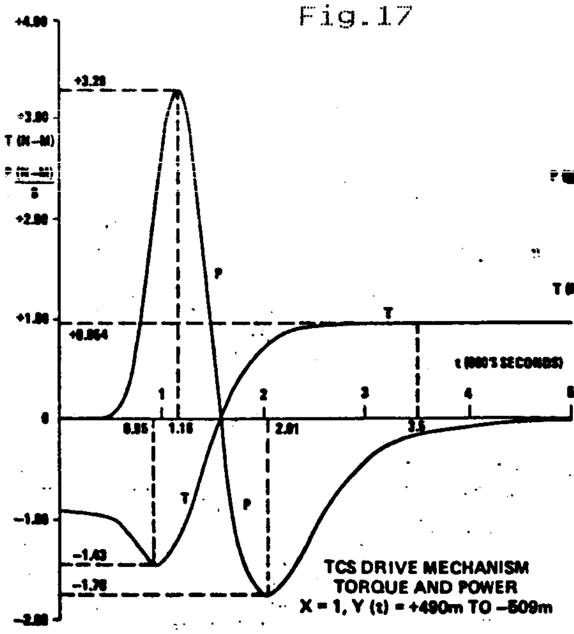
TCS DRIVE MECHANISM
TORQUE AND POWER
X = 1, Y (t) = +10m TO +1000m

Fig.17



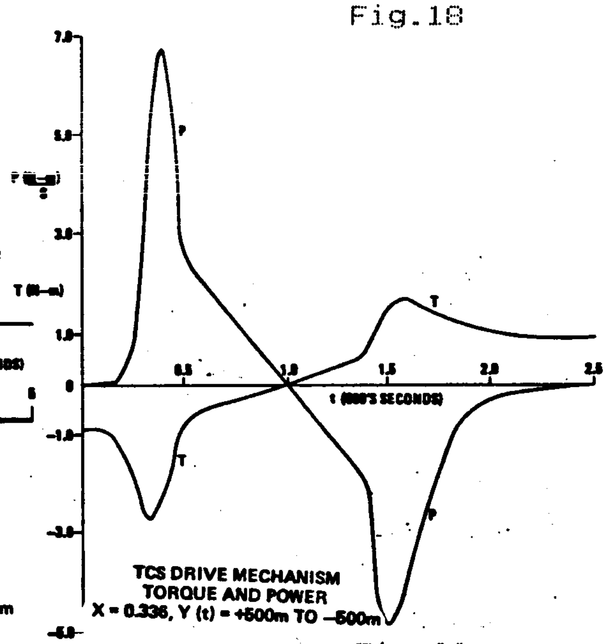
TCS DRIVE MECHANISM
TORQUE AND POWER
X = 1, Y (t) = −10m TO −1000m

Fig.18



TCS DRIVE MECHANISM
TORQUE AND POWER
X = 1, Y (t) = +490m TO −509m

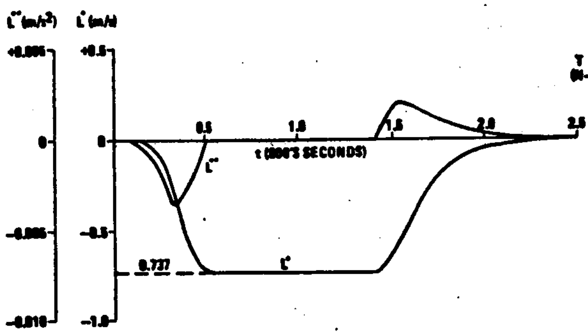
Fig.19



TCS DRIVE MECHANISM
TORQUE AND POWER
X = 0.336, Y (t) = +500m TO −500m

Fig.20

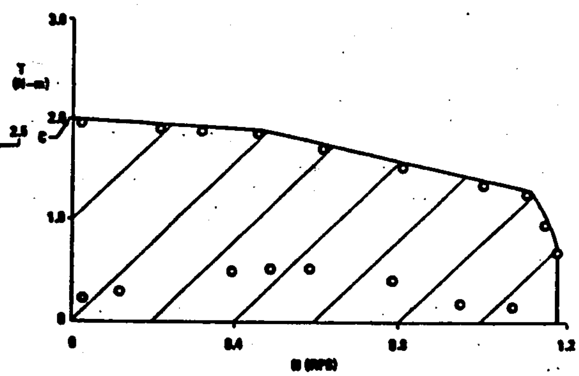
ORIGINAL PAGE IS
OF POOR QUALITY



TCS DRIVE MECHANISM
VELOCITY AND ACCELERATION
X = 0.336, Y = +500m TO –500m

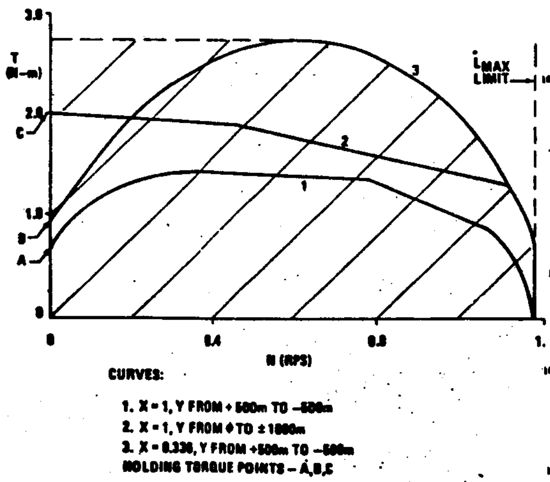
Fig.21

X = 1, Y FROM 0 TO ± 1000M



TORQUE–SPEED REGION FOR
TCS DRIVE MECHANISM

Fig.22



TORQUE–SPEED REGION FOR
TCS DRIVE MECHANISM

Fig.23

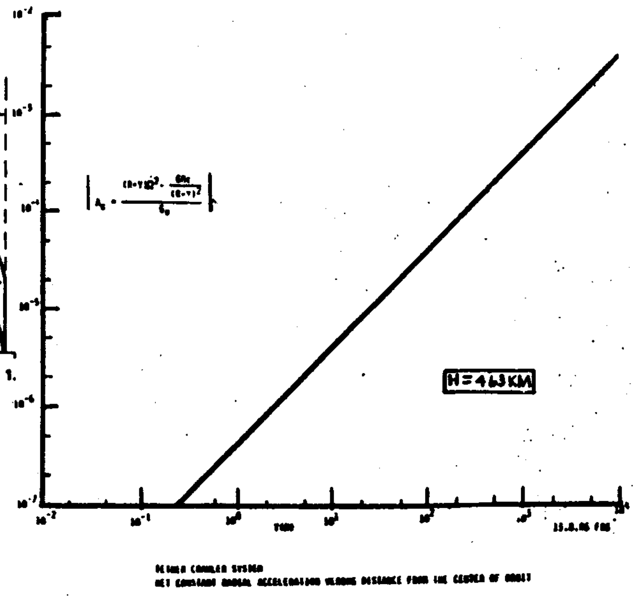


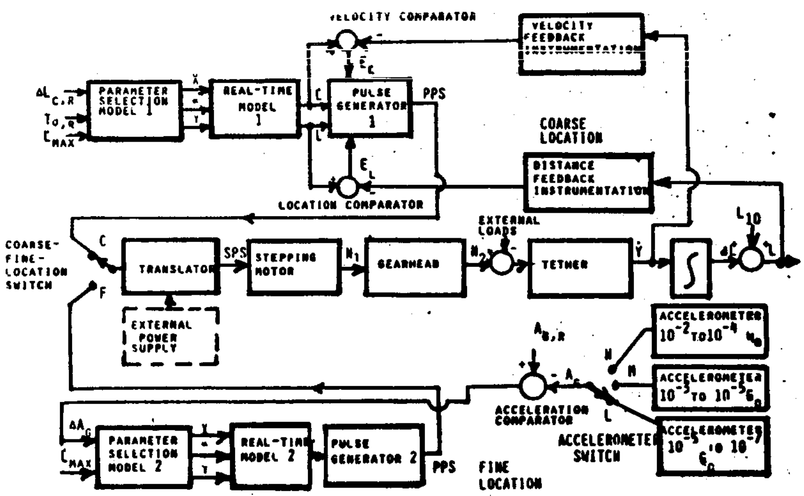
Fig.24

**ORIGINAL PAGE IS
OF POOR QUALITY**

- O REAL-TIME MODEL OF CONTROL LAW
- O ACCELERATION LEVEL INPUTS
- O LOCATION ON TETHER INPUTS
- O COMPARATOR FOR LOCATION ON TETHER (COARSE LOCATION)
- O COMPARATOR FOR CONSTANT ACCELERATION LEVEL (FINE LOCATION)
- O COMPARATOR FOR VELOCITY ALONG TETHER (MOTION)
- O PULSE GENERATOR
- O TRANSLATOR (PULSES TO STEPS PER SECOND)
- O FEEDBACK INSTRUMENTATION - LOCATION AND VELOCITY
- O FEEDBACK INSTRUMENTATION - CONSTANT ACCELERATION LEVEL
- O STEPPING MOTOR AND GEARHEAD

TETHER CRAWLER SYSTEM
CONTROL SYSTEM COMPONENTS

Fig.25



CONTROL SYSTEM BLOCK DIAGRAM

REFERENCES

1. Arnold, David A., The Behavior of Long Tethers in Space, submitted for publication, 1986.

2. Colombo, G., et.al., Shuttle-Borne "Skyhook": A New Tool for Low-Orbital-Altitude Research, Smithsonian Institutions' Astrophysical Observatory, September, 1984.

3. Lorenzini, Enrico, A Three-Mass Tethered System for Micro-g/Variable-g Applications, submitted for publication, 1986.

4. Rupp, C.L., A Tether Tension Control Law for Tethered Subsatellites Deployed Along the Local Vertical, NASA TM X-94963, Marshall Space Flight Center, September, 1975.

5. von Tiesenhausen, Georg F., Tethers in Space-Birth and Growth of a New Avenue to Space Utilization, NASA TM-82571, Marshall Space Flight Center, February 1984.

6. von Tiesenhausen, Georg F., Future Applications of Tethers in Space, AIAA 86-0053, American Institute of Aeronautics and Astronautics, January, 1982.