Design of a Reel Mechanism for Control of an Orbiting Single Tether System

David A. Gwaltney and Michael Greene
Department of Electrical Engineering
Auburn University, Auburn, AL 36849

ABSTRACT

The preliminary design of a reel mechanism for the control of the GetAway Tether Experiment (GATE) is presented. The GATE is now part of the Tether Dynamics Explorer Series (TDE) and consists of a small subsatellite tethered to a large body (Delta II second stage). A reel mechanism is housed in the subsatellite and used as the primary means of attitude control of the tether and subsatellite. Concepts used for the implementation of control software are discussed and preliminary testing procedures are described. Results showing the capability of the prototype are presented and discussed.

INTRODUCTION

The Getaway Tether Experiment (GATE) is a single tether satellite system which will test and develop technology for tethered system applications. Originally, GATE was to be a free-flying tethered system released from GetAway Special canister on the orbiter. The system is now one experiment in the Tether Dynamics Explorer (TDE) series which uses a Delta II launch vehicle. The system is shown in figure 1 and consists of a mother (Delta II second stage) and a smaller daughter connected by a single tether. The daughter contains a motorized reel mechanism which will be the primary means of control actuation.

Four flights using GATE components and technology are planned as part of the TDE series. The first two flights will use a Small Expendable-tether Deployer System (SEDS). SEDS

This work was supported in part by a grant from the National Aeronautics and Space Administration, Marshall Space Flight Center, AL.

TH0301-2/90/0000/0363$01.00 © 1990 IEEE
This control is performed after the tether has been deployed, or retrieved, to the desired length. The "yo-yo" type motion required to perform out-of-plane libration damping is shown in figure 2. This control scheme requires very quick deployment and retrieval rates in relation to the frequency of the out-of-plane libration.

![Fig. 2 Control of out-of-plane angle](image)

A prototype reel mechanism has been constructed to investigate methods of implementing the developed tethered system control schemes. The reel mechanism was designed to be used in the GATE system. Simple deployment schemes and the out-of-plane libration control scheme proposed by Davis and Banerjee have been implemented. The control was performed with tether length and length rate available as feedback.

**Prototype Design**

The basic reel mechanism consists of a spool and a level wind mechanism, as seen in figure 3. Both are driven by independent stepping motors. The spool is designed to hold 1.8 kilometers of 0.75 cm diameter tether. The entire structure is of dimensions 41.3cm x 30.5cm x 21.0cm (16.25in x 12.0in x 8.25in).

Stepping motors are used to meet space qualifications. Since a stepper remains in position unless commanded to step, it allows the tether to be held at a constant length provided the holding torque of the motor is not exceeded. The motor chosen to drive the spool has a holding torque of 28 N-cm. The holding torque is not exceeded during tether station keeping unless a very large disturbance is placed on the tether. Two motors are used to provide a design with no

![Fig. 3 Diagram of the reel mechanism](image)

Fig. 3 Diagram of the reel mechanism

Mechanical connections between the level wind and the spool shaft. Figure 4 is a simplified block diagram of the control system. The motor driver requires a pulse frequency modulated (PFM) signal to command the desired stepping rate. The stepper motor coupled to the level wind is electronically "geared down" to drive the level wind at the appropriate rate. Both motors use the same PFM signal. This signal is passed through a frequency dividing circuit before being sent to the level wind motor driver. Optical switches are used to trigger direction logic circuitry for the level wind mechanism. The direction logic provides the level wind motor with the appropriate direction signal based on the present spool motor direction and level wind motor direction.

An optical encoder connected to the spool shaft is used to provide length and length rate feedback. Pulses from the encoder are used to produce a count which can be related to

![Fig. 4 Block diagram of the reel mechanism](image)

Fig. 4 Block diagram of the reel mechanism

Instantaneous tether length. The encoder signals are also used to provide a direction of rotation signal, via logic circuitry, which is used as an up/down signal to the counter circuitry.

**Control Software**

An IBM PC is used to control the reel mechanism. The mechanism is interfaced to the
IBM PC through an IBM Data Acquisition and Control Adapter. The sixteen bit count from the counter circuitry is obtained by the computer through the digital input port on the adapter. Command signals are sent to the stepping motors using the digital output port and the 8253 timer which are also part of the adapter.

Control software is written in "C" language and is software interrupt based. Interrupts occur at the rate of 50 Hz. At each interrupt, the tether length and length rate are calculated, and new commands are formulated before interrupts are enabled again.

For preliminary testing, the control is analogous to that of a simple dc servo motor system. A desired tether length is input to the control program. Using the error between the actual length and desired length, a motor step rate command, proportional to the error, is formulated. The step rate command is converted to a count word which is used by the 8253 to produce the PFM signal for the motor drivers.

TESTING AND RESULTS

For testing purposes, the prototype was configured as shown in figure 5. A mass of 22g was placed on the end of the tether to produce a static tension in the tether which is slightly larger than the static tension the actual system will experience when fully deployed. (According to projected TDE Series payload mass.)

In this configuration, the equations of motion governing the system are analogous to those of the system model used by Rupp. There is an equation governing length dynamics, and an equation governing angle dynamics in one plane. The major difference is the absence of contributions from a constant orbital rate in the Earth-based system. However, the equations are similar in form and the equations for the Earth-based system are;

\[ \ddot{i} = g \cos \theta + \dot{i} \theta - F_i/m \]
\[ \ddot{\theta} = -(g \sin \theta)/I - (2 \dot{i} \theta)/I \]

These equations are easily verified using a Lagrangian formulation. With the system in this configuration, control algorithms can be tested to determine if the control system can respond as desired.

A deployment from 4 meters to 10 meters is shown in figure 6a. This deployment was performed with approximately 70 meters of tether on the spool. A deployment of such short duration would probably not be used in a space borne deployment of great length, but is useful in other situations and can be used to illustrate important system parameters. In figure 6b, it can be seen that the maximum length rate obtained during deployment was about 1.0 m/sec. With 70 meters of tether on the spool, the diameter of wound tether was very close to the diameter of the empty spool traverse. If the spool were fully loaded with approximately 1 km of tether, the maximum length rate during deployment would be about 3 m/sec provided the maximum motor stepping rate remained the same. Also note that the motor required 0.76 seconds to achieve the maximum length rate. In previous work by Greene, et al, in which a control law of the form developed by Rupp is used, it was projected that the system would complete a full deployment to 1 km in 2.5 orbits, or about 4 hours, and achieve a maximum tether length rate of about 1.2 m/s. The results presented in figure 6 indicate that prototype response time was more than adequate and that length rate requirements for proper deployment were met.

The control used in the deployment was very useful in implementing the out-of-plane libration control as proposed by Davis and Banerjee. With
the tether deployed to a length of 10 meters, a pendulum motion was induced with an initial amplitude of 7.0 degrees (.122 rad). The time to damp to a maximum amplitude of 1.3 degrees (.0227 rad) with no control was 53 seconds. The control scheme proposed by Davis and Banerjee uses tether angle feedback to trigger the required deployment, or retrieval, at the proper time (refer to fig. 2). Since a tether angle sensor was not part of the prototype control system, a computer simulation of the system was performed to determine the time at which deployment and retrieval must occur to perform the desired damping. A change in tether length of 5% of the initial length was used for tether retrieval and deployment. The results of the computer simulation are shown in figure 7. Libration damping to the desired limit was achieved in 43 seconds. When the control scheme was implemented using the prototype, similar results were obtained with damping achieved in 41 seconds. Better results were obtained with the hardware setup by using a "phasing" technique. This refers to beginning each deployment and retrieval at an earlier time than prescribed by the control scheme. Retrieval was begun before the tether angle reached its maximum amplitude, and deployment was begun before the amplitude of the tether angle changed sign. The desired damping was achieved in 36 seconds using this "phasing" technique. Results were not nearly as good as those predicted by Davis and Banerjee due to the faster rate at which the Earth-based system oscillated. The change in tether length in the Earth-based system was far from instantaneous in relation to the period of tether oscillation.

In the space borne system, out-of-plane librations would have a period of close to 3000 sec. So, the maximum tether length rate produced by the reel mechanism would be more than adequate for space borne implementation of the out-of-plane libration control scheme.

A series of length error tests have been performed an an attempt to determine the magnitude of tether length error that can be expected. These tests consisted of deploying and retrieving the tether between two lengths 5 times before making deployment and retrieval length error measurements. This process was performed at least 10 times for each of several different total changes in length. It was found that the magnitude of the length error increased as the magnitude of the total change in length was increased. For deployment, a length error of about 0.5% to 0.7% of the total change in length was measured, and an error of 1% to 2% was measured for retrieval. This error was attributed to differences in tether in tether winding geometry.

The deployed tether length calculation in software is made using an equation based on
tether winding geometry on the spool. It is assumed that the tether winds on the spool in an orderly fashion in which each tether wrap lies next to the previous wrap. It is further assumed that each layer of tether wrappings lies on top of the layer of tether wrappings under it. The tether does not always wind on the spool in this manner despite the action of the level wind mechanism. Thus, the deployed tether length is not necessarily equivalent to the deployed length which is calculated in software.

CONCLUSION

In conclusion, it can be seen that testing the reel mechanism in the lab provides a means of evaluating the ability of the control system to perform desired control schemes in space. From the results obtained, it can be concluded that the mechanism should be able to perform as required. Control system response time and dynamic ability is well within the constraints set by the desired control schemes.

The results of the libration damping tests indicate that the reel mechanism will be able to perform the control schemes in the space borne system, provided tether angle feedback is integrated into the control system software.

Results from the length error tests show that the expected errors in tether length will have little or no detrimental effect. These errors are very small in relation to the total length deployed or retrieved, but could be large enough to be undesirable in retrievals involving large changes in length; such as a retrieval of 1 km of tether. It would be possible to reduce this error with a more reliable level wind system or to remove the error by using a pinch roller device. The tether would move through the pinch roller device before being wound on the spool. An encoder could be coupled to one of the rollers, thus giving a more reliable means of calculating length and length rate.

Future testing will include the implementation of Rupp's tether tension control law and tether length rate control laws. Also, the ability of the control system to recover from induced disturbance will be evaluated. A flight quality reel mechanism is envisioned by 1992.

REFERENCES