Preliminary Investigation of Dynamic Control of a Single Tethered Satellite System Using a Tether Crawler

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ABSTRACT
The preliminary investigation of the inclusion of a tether crawler in a free-flying, tethered system consisting of a mother-daughter pair is presented. A motor/reel mechanism provides control over system dynamics. A tether crawler can be included as a separate body which can move along the deployed tether between the two endmasses. The tether crawler may be used as a control actuator, a maintenance device or in other capacities in larger systems. As a control actuator, the crawler could provide a means of effectively damping disturbances on the system. The objective of this paper is to present data showing the effects of specific motion of the crawler on the system and the potential use of the crawler as a control actuator. Computer simulation has been used to investigate the effects of crawler motion on the system. The tethered system is modeled using a bead model for the tether. Preliminary results indicate the feasibility of adding the tether crawler to the system. The results show that crawler movement along the tether induces a disturbance which could counteract vibrations of the tether.

INTRODUCTION
The addition of a tether crawler, or elevator, to a two mass tethered system has been proposed by Lorenzini as a possible means of having an orbiting, micro and variable gravity laboratory which is separate from an orbiting space station. The system consisted of three large bodies: two endmasses and a mass which could move along the tether between the two endmasses. Control laws for tether deployment and station keeping were presented. Lorenzini, et al., have recently extended the study using a four mass system. Control laws for elevator control and station keeping were presented for the system. Optimization of motion control laws for tether crawlers has been recently addressed. These motion control laws were based upon the powers of a hyperbolic tangent function. The optimization approach used can be extended to include other control laws. The use of a crawler as a repair robot has also been proposed. It was suggested that the device would optically examine the tether and then would perform any necessary repairs, thus prolonging tether life in a dynamic system.

The present study investigates the effects of crawler motion on the system of the GetAway Tether Experiment (GATE). The GATE will be a free-flying, tethered system consisting of a mother-daughter pair. The mother will be a larger body than the daughter, and a motor/reel mechanism will provide the only means of control over system dynamics. The crawler will be a small body which can move along the tether under its own power. Simple acceleration and velocity profiles for the crawler are used. The results give a generalization of the effects of specific crawler motion on the system dynamics of any system with the same configuration. The purpose of this paper is to present data showing the type of disturbances caused by specific crawler motion and to propose that these disturbances can be used in the control of a single tether system.

COMPUTER SIMULATION
A previously developed tether bead model which can simulate disturbances on the tether due to applied forces was used. The equations of motion for the bead model tethered system were...
developed using Lagrangian formulations. The bead model is constructed by dividing the mass of the tether into concentrated points of mass, or beads. A spring and dashpot are placed between adjacent beads to model the dynamic characteristics of the tether. A portion of the tether bead model is shown in figure 1. The endmasses are modeled as beads with a spring and dashpot connecting them to the tether model. Additional code has been written to include the crawler in the model. The crawler is placed on the tether as a movable bead representing the mass of the crawler. Spring coefficients on either side of the crawler bead are adjusted proportionally to the changing lengths of tether on either side of the crawler. The forces applied to the tether due to crawler acceleration are accounted for in terms added to the equations of motion for the crawler and adjacent beads. The program is written in FORTRAN and the simulations have been carried out on an IBM Model 80 or on IBM compatible PCs. The results of the program are stored in inertial frame coordinates.

For the present study, the results were converted to a local vertical frame and tether frame coordinates. As seen in figure 2, the local vertical frame x-axis is in the direction of the vector from the center of the earth to the larger endmass (mother). The y-axis is in the orbital plane in the direction of the forward velocity, and the z-axis is perpendicular to the orbital plane. In the tether frame, the x-axis is in the direction of the vector pointing from the mother to the smaller endmass (daughter). The y-axis is in the orbital plane and the z-axis is perpendicular to the orbital plane. Using the local vertical and tether frames, the results give endmass motion with respect to a circular orbit, where the orbit center is located at the mother, and also give bead motion along the tether with respect to the x-axis of the tether frame.

Simulations were executed to study the effects of initial position of crawler, duration of crawler motion, and acceleration of the crawler on the tethered system. For all cases, the masses of the bodies on the tether are 50 kilograms for the mother, 15 kilograms for the daughter and 1 kilogram for the crawler. The total mass for the tether is 1 kilogram. The tethered system moves in a circular orbit 300 kilometers above the earth, with the orbit center located at the mother. The tether is fully deployed at one km in length with a spring constant of 10 N/m and a damping coefficient of 0.01 N-sec/m. Initially, the mother and daughter are aligned along the local vertical, with the mother closest to the earth.

The bead model used for the system has a total of 22 beads including the crawler and the two end bodies. A very simple acceleration profile for the crawler was used in the simulations. Assuming the crawler will use pinch rollers, with no freewheeling capability, to move along the tether, the acceleration profile takes into account the force of rolling friction the crawler must overcome. A constant acceleration profile is used to induce crawler motion and a constant deceleration is used to stop the crawler. The acceleration profile is shown in figure 3. For simplicity, the acceleration
component required to overcome the force of rolling friction is constant throughout. This acceleration component is omitted in the calculation of crawler velocity along the tether. An initial run was made to prove the assumption that the system remains aligned along the local vertical, with only slight deviation if the crawler remains immobile throughout the simulation. All simulations presented were run for a simulation time of 12,000 seconds (3 1/3 hours). Each simulation took 12 hours to run. By initializing the system to fly in a circular orbit with initial velocity components only in the y-direction of the inertial frame, motion is restricted to the x-y plane for ease of analysis.

RESULTS

Three cases were considered to give a general overview of the differences the initial position of the crawler, as measured from the mother, can make in the disturbances on the system induced by subsequent crawler motion. The effect of the direction of motion can also be seen in these three cases. The value of the acceleration component, \( a \), which is used in determining crawler velocity is 0.001 m/sec\(^2\), which results in a constant crawler velocity of 0.05 m/sec. The duration of the crawler motion is kept constant and the crawler moves a total distance of 62.5 meters. The results are summarized in Table 1.

<table>
<thead>
<tr>
<th>Initial Position</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 m</td>
<td>475 m</td>
<td>925 m</td>
<td></td>
</tr>
<tr>
<td>Direction</td>
<td>Toward Daughter</td>
<td>Toward Daughter</td>
<td>Toward Mother</td>
</tr>
<tr>
<td>Max Defl. Daughter</td>
<td>67.47 m</td>
<td>57.12 m</td>
<td>106.3 m</td>
</tr>
<tr>
<td>Max Defl. along tether</td>
<td>3.88 m</td>
<td>30.0 m</td>
<td>9.735 m</td>
</tr>
</tbody>
</table>

Table 1

In figure 4a, only the motion of the daughter is shown because it is indicative of the motion of all beads along the tether. The daughter is the point of maximum deflection in the local vertical frame. The pendulum motion of the daughter is highly irregular and eventually damps out. Note that Case 3 has the largest maximum deflections, and Case 2 gives deflections that are opposite those of the other cases. In figure 4b, the motion of bead 10 (the middle of the tether) is shown. The sinusoidal oscillations of the tether observed in the tether frame are the reason the pendulum motion of the daughter is irregular. The sense of the deflections along the tether are opposite those of the pendulum motion of the daughter. Maximum deflection along the tether in the tether frame occurs at the position of the crawler. The sinusoidal oscillations of the tether were found to have a frequency of 0.00018 Hz and to damp out over a very long period. These oscillations begin after the crawler has stopped moving. Note that Case 2 gives the greatest deflection. In all cases, the crawler causes the most significant deflection on the y-axis. Deflections along the local vertical and the length of the tether are negligible.

A series of simulations were run in which the total distance the crawler moved was varied. In all cases, the initial position of the crawler was 25 meters away from the mother. The magnitude of the value of \( a \) in the acceleration profile is 0.0001 m/sec\(^2\) and, the steady state speed of the crawler is 0.1 m/s. For each case, the duration of crawler motion at the steady state speed was varied to give a different total distance traveled. The results are presented in figure 5. Crawler position is measured from the mother and along the tether. The graph shows that as the total distance traveled is increased, the magnitude of the sinusoidal oscillations along the tether increases. The frequency of tether oscillation remains 0.00018 Hz in all cases. Due to the highly irregular nature of the
MOTION OF BEAD

Tether Frame

Figure 4. b) Y Deflection of tether in tether frame.

DEFLECTION ALONG TETHER VS. CRAWLER ACCELERATION

Tether Frame

Figure 5. Y Deflection of tether in tether frame as a function of total distance traveled.

Figure 6

CONCLUSIONS

The results obtained indicate that the addition of the crawler to the GATE is feasible, in that crawler motion will not induce disturbances which cause the system to become unstable. The disturbances produced by the crawler could be damped using the motor/reel mechanism of the system. For the specified acceleration profile, the disturbances crawler motion induces on the tether are a pendulum motion in the orbital plane accompanied by a sinusoidal oscillation along the tether occurring after the crawler stops moving. The sinusoidal oscillations along the tether are always the same frequency, and the point of maximum deflection of pendulum motion of the daughter, no generalizations can be made about the effect of the duration of crawler motion on the pendulum motion.

In order to study the effects of the acceleration of the crawler on the tethered system, a series of simulations were run in which the acceleration component, $\alpha$, was varied. For the acceleration profile, $T_1 = 30$ sec, $T_2 = 130$ sec, $T_3 = 130$ sec, and $T_4 = 230$ sec. (refer to figure 3) The results are presented in figure 6.

Varying the acceleration component, $\alpha$, over the range chosen had very little effect on the sinusoidal oscillation of the tether, but had considerable effect on the peak deflections of the pendulum motion of the tether. The peak positive deflection of the pendulum motion decreases with increasing magnitude of acceleration, while the peak negative deflection is affected in the opposite manner. The pendulum motion is similar to that of Case 1 presented in the first section. The pendulum motion observed is, of course, irregular, and it is hard to make significant generalizations about the effects of crawler acceleration on the pendulum motion. The frequency of oscillation of the tether is 0.00018 Hz for all cases.
the tether is at the final position of the crawler. Due to the oscillations along the tether, the pendulum motion is very irregular.

The pendulum motion of the daughter caused by crawler motion could be used to damp in-plane libration, if the crawler were moved to produce deflections opposite those of the libration. However, the oscillations on the tether make the pendulum motion unsuitable for control actuation, because it is very irregular. It is possible that the oscillations along the tether caused by crawler motion could be avoided by using a type of acceleration profile other than the one used in this study. The pendulum effect caused by crawler motion would be sinusoidal if the oscillations caused along the tether were nonexistent. A sinusoidal pendulum effect could be quite useful in settling in-plane libration of the tethered system during retrieval. For the given system and acceleration profile, it has been shown that the magnitude of the deflection of the daughter from the local vertical is directly related to the magnitudes of the acceleration profile. It has also been shown that the initial position of the crawler has an effect on the magnitude and sense of the deflections of the daughter from the local vertical. Further study must be done to investigate the use of the induced pendulum motion in control actuation.

The sinusoidal oscillations along the tether produced by crawler motion could be used to damp vibrations on the tether due to micro-meteorites or other bodies striking the tether. Since the disturbances caused by such applied forces tend to be sinusoidal oscillations, these oscillations could be damped by setting up oscillations which are 180 degrees out of phase with the unwanted disturbance. Note that for the given system, the oscillations produced by motion of the crawler toward the daughter are 180 degrees out of phase with the oscillations produced by motion toward the mother. This could aid in setting up the proper induced deflection at the proper time. The results also indicate that the duration of crawler motion has a direct effect upon the magnitude of the oscillations along the tether and, as was stated, an effect on when the oscillations start (Oscillations begin when the crawler stops moving). This effect could be used to provide the desired magnitude of oscillation or the desired time for the oscillations to start.

The preliminary results show that the possibility of using the crawler as a control actuator is very great, but more in-depth study of the effects of crawler motion is needed. Future work will include refining the crawler model and experimentation with other acceleration profiles. A thorough study of the use of the induced disturbances to damp in-plane libration and undesired oscillations along the tether will also be covered in future research.

REFERENCES