Tuned Mass Damping System for a Pendulum in Gravity and Microgravity Fields

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Abstract:

A tuned mass damper system, for short we refer to it as tilger, is suggested as damper of oscillations of tethers in satellites as they orbit the Earth while traversing the Earth's ionosphere and magnetic field. Variable Lorentz forces occur on the tethers, which will cause them to oscillate and may go out of control, which may de-orbit the satellite and fall to Earth. A system composed of a tuned mass damper and a simple pendulum simulating the tether is constructed. 350 sets of experimental trials were done on the system, while it is installed inside a drop tower capsule first resting on the ground, in order to pick four optimum setup experiments that will undergo a series of microgravity experiments at the Bremen Drop Tower in Bremen, Germany. We found that the oscillations of the simple pendulum will not be affected by the tilger during the free fall experiment, except if a feedback mechanism is installed between the simple pendulum and the tilger. In this case, the tilger will dampen the simple pendulum oscillations during free fall.

Introduction:

Schwinungstilger is the German name for a tuned mass damper system, which is also known as harmonic absorber. It is a device consisting of a mass, and a spring that is attached to an object in order to reduce the dynamic response of the object[1]. The concept of the Tilger is illustrated using the two-mass system shown in Figure 1. Where the spring system (M_T, C_T) is the damping oscillator and (M_R, C) is the oscillator to be damped. Once a force is applied to (M_R), (M_T) will start oscillating, and the energy will be dissipated by the damper inertia force keeping (M_R) stable.

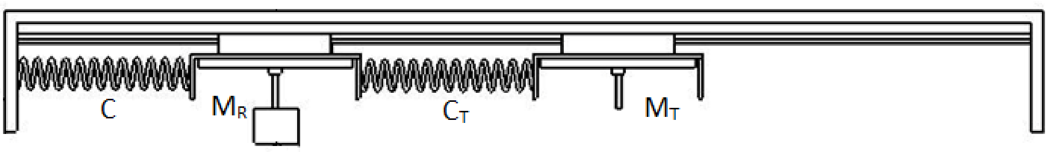


Figure 1 – A Tuned Mass Damper

This system has been widely deployed in the structure of many buildings[2]. To minimize the effects of earthquakes it was deployed in the foundations of the building[3]. To reduce the effect of vibrations from wind motion it is also deployed in towers and tall buildings[4]. There are numerous applications of this system that in reality we cannot cover all of them. However, one new application may be considered in the field of tethered satellites[5].

Usually, to move a satellite or a space station into a desired orbit, a huge amount of energy is needed. However, various natural forces cause satellites to drift out of orbit, these are; earth's and moon's gravity, variations in the earth's magnetic field, and the effect of the solar wind. Therefore, an additional amount of energy is also needed to be used in the small thrusters to keep the satellite in that orbit.

In order to find a cheap and viable solution to this problem, an electro-dynamic tether is hung from the satellite while it orbits the Earth. There are three fundamental concepts that tethers have; momentum exchange, gravity gradient and electro-dynamics. Electro-dynamic tether is a long conducting wire which can act as a generator or motor by inducing an electro-dynamic force as it traverses the ionosphere and crosses the earth's magnetic field. This situation produces an induced current in the tether, which can be usefully used as a propulsion system in space and makes it potentially significantly cheaper.

Tethers present a small or negligible rigidity since they are long and thin cables. On instability of the electro-dynamic tether on the other hand, they are subjected to a distribution of lateral forces. As the tether crosses the Earth’s magnetic field it will be subject to a Lorentz force acting in a direction perpendicular to both the magnetic field and the tether. As it is illustrated in figure 2 this force act perpendicularly on the tether and will move it from its local vertical to a new instantaneous equilibrium position. Where:

$$\boldsymbol{F} = q[\boldsymbol{E} + (\boldsymbol{v} \times \boldsymbol{B})]$$

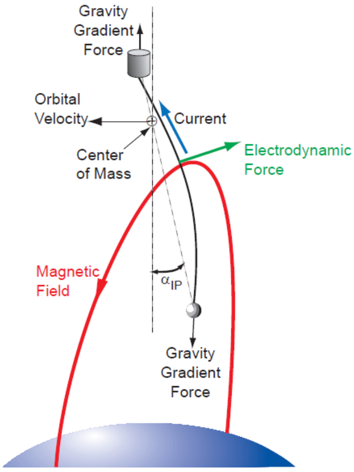


Figure 2 – Illustration of Electro-dynamic Tether[6]

However, this force changes depending on the strength of the Earth’s magnetic field and on the concentration of the charged ions in the ionosphere, which will make the equilibrium position changing over time. Therefore, this will create unwanted oscillations in the tether, which may build up to go out of control and jeopardize the satellite motion itself. In order to circumvent such a scenario, we developed a tuned mass damper connected through its main mass to simple pendulum simulating the tether.

In this paper, we shall investigate this system under Earth’s gravitational conditions, and obtain the best optimum conditions under which we get maximum damping of the simple pendulum oscillations. The setup resulting from optimum ground experiments will undergo a series of drop tower experiments simulating outer space conditions of weightlessness (microgravity conditions). Behavior of many systems under gravity may change drastically under microgravity conditions[7,8,9]. A recent theoretical paper by Bezglasnyl and Piyakina[10] studied the planar motion of a space tether system (STS) simulated by a massless rod with two diametrically opposite fixed masses on the edges of the rod and a third sliding mass along the rod. They studied the stability of the system using classical stability theory through constructing the corresponding Lyapunov functions.

The aim of our paper to establish that in principle the tether oscillations may be quenched through a feedback mechanism when in free fall. In this paper we shall first present the equations of motion for the tuned mass damping system, then present the experimental set-up, and state the results and discuss them. Finally, we shall conclude our work.

Theory:

In order to model the tilger system a simplifying assumption is made where the runner blocks (gliders) and the guide rails (track) are considered frictionless. Also the tether is simulated by a simple pendulum with mass M_B.

Tilger without Tether:

The Tilger system without the tether has been tackled by several books with the recent one being: Engineering Vibration by D.J. Inman and published by Pearson in 2007, Third edition[11]. The normal mode frequencies that were obtained in reference [11] on page 277 were:

$$\omega_{total} = \pm\sqrt{\frac{\left[\left(\omega^2+\omega_T^2+\omega_T^2\frac{M_T}{M_R}\right)\pm\sqrt{\left(\omega^2+\omega_T^2+\omega_T^2\frac{M_T}{M_R}\right)^2-4\omega^2\omega_T^2}\right]}{2}} \quad \dots\dots\dots (1)$$

With $\omega = \sqrt{\frac{C}{M_R}}$, and $\omega_T = \sqrt{\frac{C_T}{M_T}}$

In Ref [11] the normal mode frequency was obtained through applying Newton's second law equations. The same equations can be obtained through Lagrange's equations. Looking at Fig. (3) below we find the Lagrangian for the Tilger system without the tether as:

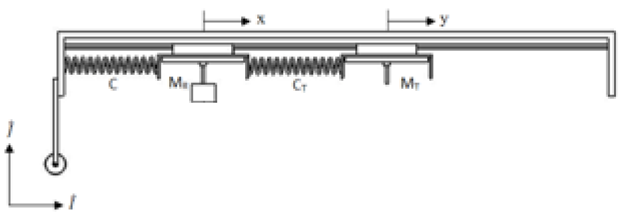


Figure 3 – A Tuned Mass Damper

$$L = K - U$$

Where the Kinetic Energy K is given by:

$$K = \frac{1}{2}M_R(\dot{x})^2 + \frac{1}{2}M_T(\dot{y})^2$$

And the potential energy U given by:

$$U = \frac{1}{2}Cx^2 + \frac{1}{2}C_T(y-x)^2$$

Setting up the Lagrangian L:

$$L = \frac{1}{2}M_R\dot{x}^2 + \frac{1}{2}M_T\dot{y}^2 - \frac{1}{2}Cx^2 - \frac{1}{2}C_T(y-x)^2 \quad \dots\dots\dots (2)$$

and applying Lagrange's equations

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0$$

Where q_i is the coordinate and $\dot{q}_i$ is the velocity and i runs over the independent coordinates.

We get the required equations of motion, which are:

$$M_R\ddot{x} + (C + C_T)x - C_T y = 0 \ \ldots\ldots\ldots\ (3)$$

$$M_T\ddot{y} + C_T(y - x) = 0 \ldots\ldots\ldots\ (4)$$

Imposing the simple harmonic motion in time recipe with the frequency ω_{total} (i.e. $ue^{j\omega_{total}t}$ $where\ j\ is\ \sqrt{-1}$) and imposing the condition to get the eigenvalues through the secular equation we get the normal mode frequencies mentioned above for ω_{total} in equation (1). The eigenvectors are obtained which represent the column vector made of the x and y displacements. In order to get a very small x displacements (amplitudes) the conditions on the spring constants and the masses should meet the conditions: $M_T=M_R/10$, and $C_T=C/10$. However adding the tether will complicate the situation as explained in the following section.

Tilger with Tether:

Looking at Figure (4), we set up the Lagrangian for the Tilger system with the tether:

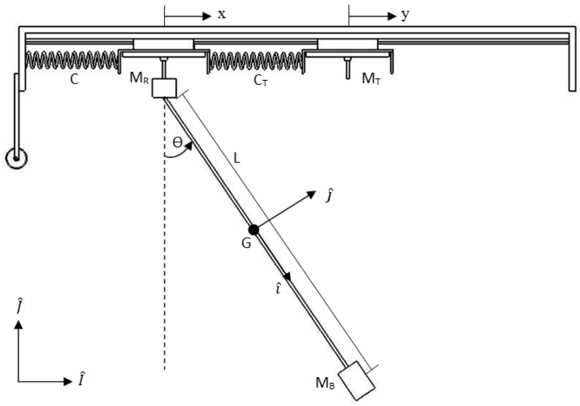


Figure 4 – Tilger System with a Pendulum (Tether)

$$L = \frac{1}{2}(M_R + M_B)\dot{x}^2 + \frac{1}{2}M_T\dot{y}^2 + \frac{1}{2}M_B L^2\dot{\theta}^2 + LM_B\dot{\theta}\dot{x}\cos(\theta) - \frac{1}{2}Cx^2 - \frac{1}{2}C_T(y - x)^2 - M_B gL(1 - \cos(\theta)) \ldots\ldots\ldots\ (5)$$

As a check on this Lagrangian if we set the Tether mass M_B equal to zero we get back the Lagrangian for the Tilger system without the tether mentioned above.

In this case applying Lagrange's equations we get three coupled nonlinear equations which do not lend themselves easily to an analytical solution as in the case of the tilger system without the tether. These equations are:

$$(M_R + M_B)\ddot{x} + LM_B\ddot{\theta}\cos(\theta) - LM_B\dot{\theta}^2\sin(\theta) + Cx - C_T(y - x) = 0 \ \ldots\ldots\ldots\ (6)$$

$$M_T\ddot{y} + C_T(y - x) = 0 \;\; \dots\dots\dots \; (7)$$

$$LM_B\ddot{x}\cos(\theta) + M_BL^2\ddot{\theta} + M_BgLsin(\theta) = 0 \;\; \dots\dots\dots \; (8)$$

Again setting $M_B = 0$ in the above equations (6), (7) and (8) we get back the equations (3) and (4) as expected. Equations (7) and (4) are identical however equations (6) and (8) contain nonlinear terms that need either numerical techniques to solve them or some simplifying asymptotic assumptions to find some analytical asymptotic solutions. This will be the basis for future work on these equations. So our aim is to look for the best sets of experimental data that will quench the oscillations in the pendulum when the setup is on the ground.

Experimental set-up

The set-up is shown in Figure 5. It is composed of two 55.5x60 mm low friction runner blocks sliding on a 42x500 mm guide rail which is mounted on a stainless steel platform. The main glider A has a main mass M_R attached to it and a main spring connects the main mass to the fixed side of the track with main spring constant C. Glider B has a tilger mass M_T attached to it, and the two gliders A and B are connected by a tilger spring of spring constant C_T. A simple pendulum is hung from the main mass A of mass M_B using ring ball bearings. And a 6 volt solenoid was used as a hold/release mechanism for the pendulum. Our aim is to find out experimentally the conditions under which the tuned mass damper will reduce the simple pendulum oscillations amplitude to a small value in a very short period of time that will be compatible with the time of free fall.

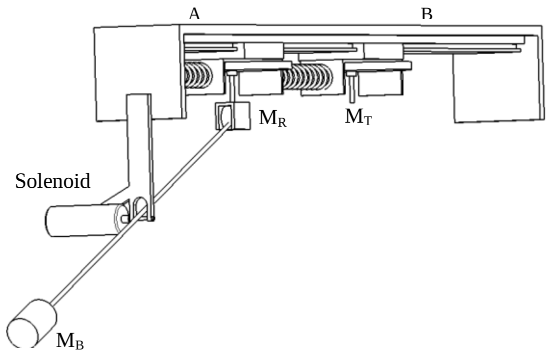


Figure 5- Schematic of the Set-up Experiment

The desired masses and springs were installed into the system using nuts and washers. The pendulum was locked in a certain angle using the solenoid. And by using a specially designed computer interface, the start button was pressed to start the experiment sequence, the data logging from the sensors and the recording of the high speed cameras.

The pendulum was released by the actuation of the solenoid. The data logging stops after 10 seconds of initiation. All data was stored as txt. files to be plotted using MATLAB.

To measure the linear displacement of the tilger mass and the main mass two 1-d accelerometers were utilized. A high precision potentiometer was connected to a Wheatstone bridge amplifying circuit to measure the pendulum angle. Two high speed-cameras with different orientations and with frame rates of 1000 frames per second assisted by background LED lights were also installed.

More than 350 trials, on the ground, were made in order to find the optimum conditions. It was found from the trials that the 1/10th ratio between the tilger and main mass according to the tilger theory (when acting alone) was not the optimum solution. The reason for that was that the pendulum was installed as an additional component.

It was also found that the effect of changing springs constants was bigger than the effect of changing the masses, and has a greater impact on damping of the oscillations. This is an advantage because this will make it cheaper for the satellite when orbiting in space, since the masses can be replaced by useful payloads instead.

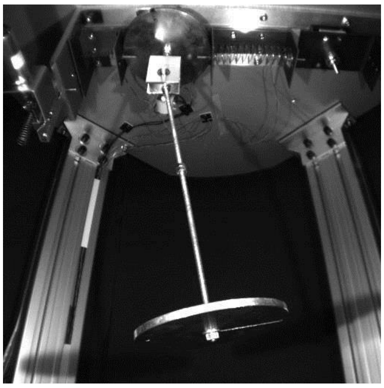
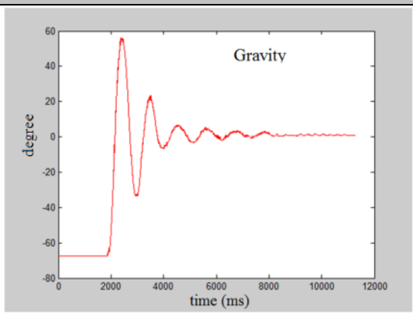
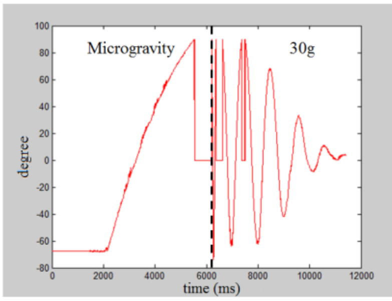
Results and Discussion:

After performing several ground experiments first in our home laboratory in Jordan and later inside the drop tower capsule setup at the Center of Applied Space Technology and Microgravity (ZARM) in Bremen, Germany, four microgravity experiments were conducted in the drop mode of ZARM's drop tower facility, the Bremen Drop Tower, providing 4.7 seconds in conditions of high-quality weightlessness at 10^{-6} g (microgravity).

In order to see the damping effect of the tilger system on the simple pendulum during the free fall period, we need to look for optimum conditions and a combination of the masses and spring constants that will make the damping of the simple pendulum oscillations occur in an interval of about 4 seconds.

In the following when we mention that the tilger mass is zero we are not mentioning the tilger holder mass which is 0.45 kg, which is the same for all other cases.

In our first optimum ground experiment shown in figure 1-r that gives the best damping in an interval of around 4s we found that the following set shown in table 1 of data applies and we refer to it experiment 1 hereafter.

<table>
<tr><td colspan="6">Experiment 1Data</td></tr>
<tr><td>Figure 1-r</td><td colspan="5">Table 1</td></tr>
<tr><td rowspan="5"></td><td>Main Mass</td><td>Tilger Mass</td><td>Pendulum Mass</td><td>Main Spring Constant</td><td>Tilger Spring Constant</td></tr>
<tr><td>1kg</td><td>0kg</td><td>0.5 kg</td><td>20N/m</td><td>60N/m</td></tr>
<tr><td colspan="3">Graph 1-g</td><td colspan="2">Graph 1-m</td></tr>
<tr><td colspan="3">
</td><td colspan="2">
</td></tr>
<tr><td colspan="3">Graph of the simple pendulum oscillations for experiment 1 with capsule at rest on the ground</td><td colspan="2">Graph of the simple pendulum oscillations for experiment 1 with capsule dropped from top of the tower (microgravity experiment 1)</td></tr>
<tr><td>Setup for Experiment 1</td><td colspan="5"></td></tr>
</table>

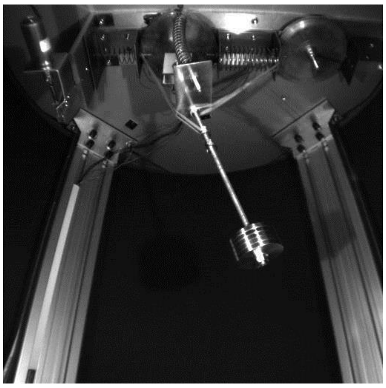
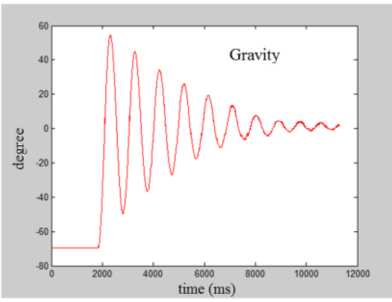
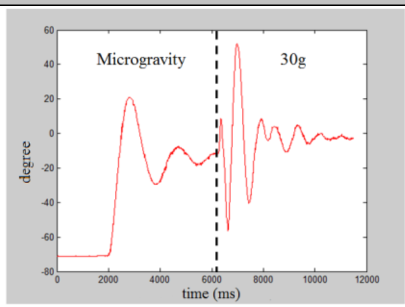
*Results and setup of experiment 1 during the ground and microgravity experiments

Figure 1-r above shows the setup according to the data labeled experiment 1. In graph 1-g we display the simple pendulum oscillations, where the horizontal axis represents time in milliseconds (ms) and the vertical axis correspond to the angular displacement of the simple pendulum in degrees. We notice the fast damping of the simple pendulum amplitude in a time

interval of 4 seconds. This means that the tilger system was successful and was able to dampen the oscillations very quickly. That means experiment 1 setup is suited for a microgravity experiment and to drop it from the top of the tower. Let us define the damping ratio, r, as the ratio of the second peak amplitude to the first peak amplitude. This damping ratio from graph 1-g is r = 0.41. We have chosen this definition because of the time interval in which we carry out our experiments during free fall.

Anticipating that the release mechanism will not work in the microgravity, a vertical spring was installed with the release mechanism solenoid in order to give an initial push to the simple pendulum. In this experiment we found out that there was a total decoupling between the pendulum and the main mass (tilger system). It is obvious from the graph 1-m how the pendulum was moving without oscillations in the first 4 seconds and how it changed its behavior once the capsule decelerated, with a deceleration of the order 30 g. This result suggests that the tilger will not function as a tuned mass damper in free fall. Therefore, we have to look for a feedback mechanism between the simple pendulum and the tilger system in order to dampen the simple pendulum oscillations. So, we have no oscillations and therefore no damping ratio.

In our second ground experiment we thought about a feedback mechanism to look into the possibility whether it will activate the tilger system and dampen the simple pendulum oscillations during free fall. A simple feedback mechanism was devised in which two rubber bands were attached to the arm of the simple pendulum, where one band is attached to the support screw on the left of the main mass as shown below in figure 2-r, which is also to the left of the simple pendulum. The other band attached to the support screw to the left of the tilger mass and as shown in figure 2-r to the right of the simple pendulum.

<table>
<tr><th colspan="6">Experiment 2 Data</th></tr>
<tr><th>Figure 2-r</th><th colspan="5">Table 2</th></tr>
<tr><td rowspan="4"></td><td>Main Mass</td><td>Tilger Mass</td><td>Pendulum Mass</td><td>Main Spring Constant</td><td>Tilger Spring Constant</td></tr>
<tr><td>1kg</td><td>0.5 kg</td><td>0.25 kg</td><td>100N/m</td><td>80N/m</td></tr>
<tr><th colspan="3">Graph 2-g</th><th colspan="2">Graph 2-m</th></tr>
<tr><td colspan="3">
</td><td colspan="2">
</td></tr>
<tr><td>Setup for Experiment 2</td><td colspan="3">Graph of the simple pendulum oscillations for experiment 2 with capsule at rest on the ground</td><td colspan="2">Graph of the simple pendulum oscillations for experiment 2 with capsule dropped from top of the tower (microgravity experiment 2)</td></tr>
</table>

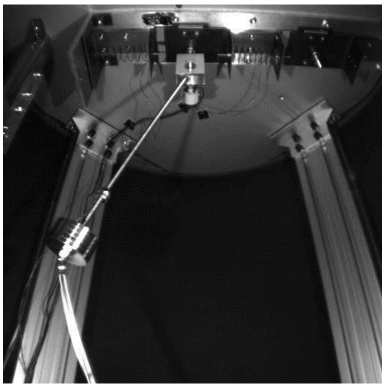
*Results and setup of experiment 2 during the ground and microgravity experiments

In this second optimum ground experiment that gives the best damping in an interval of around 4 seconds we found that the following set of data shown in table 2 applies and we refer to it experiment 2 hereafter. Experiment 2 data are different from experiment 1 except that the main mass of 1kg is the same.

In this experiment, the Pendulum was attached by rubber bands from both sides as explained above and shown in figure 2-r above. In the ground experiment where the capsule is at rest, we notice that the damping is not as fast as in experiment 1. Of course the damping is still occurring but over an interval of 6 seconds instead of 4 seconds. However, there is a significant and noticeable damping in the first 4 seconds, which will allow us to examine whether the elementary feedback mechanism works or not during the free fall experiment. Also, we notice that the number of oscillations is higher than that in experiment 1, graph 1-g, which is attributed to the fact that we are imposing two oscillatory regimes, the Earth's gravitational force, and the restoring forces of the two rubber bands. The damping ratio from graph 2-g and according to the definition stated above is r = 0.81.

In the free fall of the capsule we notice that the feedback mechanism of the two rubber bands is activating the tilger system and the oscillations are damped in the given time interval of the free fall as shown in graph 2-m above. In the freely falling reference frame of the capsule the gravitational force is absent and only two restoring forces are acting due to the two rubber bands and they are not equal. That is why there is an offset and graph 2-m is not symmetric about the time horizontal axis. The offset is around 15 degrees. If we measure the damping ratio r about this equilibrium horizontal axis r comes out to be r = 0.2. This result has to be checked whether it is a true effect or a spurious one. In order to check this result we shall carry out experiment 4 below where the tilger system shall be fixed by fastening the gliders to the track, and this ensures that any damping occurring similar to the results in graph 2-m above cannot be attributed to the tilger system. Next we shall do experiment 3 to try and see whether some other feedback mechanism may work other than the one tested in experiment 2 above.

As mentioned above we tried a different feedback mechanism where from the bottom of the pendulum mass we attached a rubber band that is fastened to the lower platform of the capsule. Experiment 3 data are displayed below.

<table>
<tr><td colspan="6">Experiment 3 Data</td></tr>
<tr><td>Figure 3-r</td><td colspan="5">Table 3</td></tr>
<tr><td rowspan="4"></td><td>Main Mass</td><td>Tilger Mass</td><td>Pendulum Mass</td><td>Main Spring Constant</td><td>Tilger Spring Constant</td></tr>
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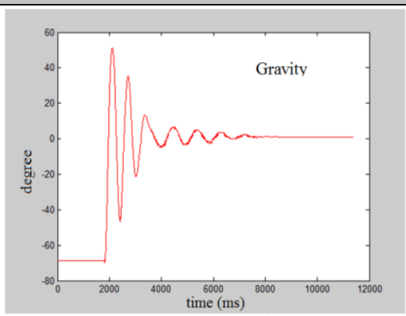
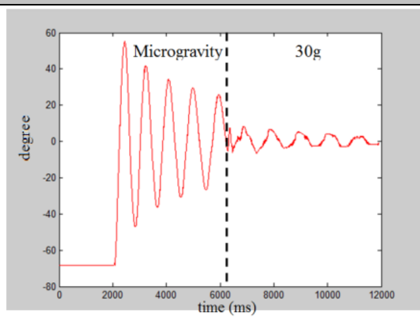
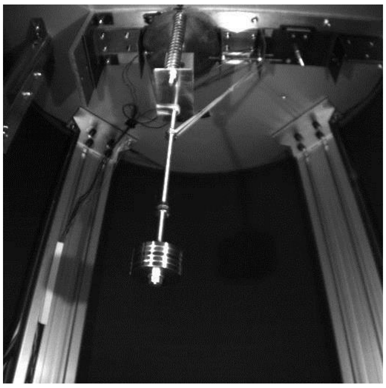
<tr><td colspan="3">Graph 3-g</td><td colspan="2">Graph 3-m</td></tr>
<tr><td colspan="3">
</td><td colspan="2">
</td></tr>
<tr><td>Setup for Experiment 3</td><td colspan="3">Graph of the simple pendulum oscillations for experiment 3 with capsule at rest on the ground</td><td colspan="2">Graph of the simple pendulum oscillations for experiment 3 with capsule dropped from top of the tower (microgravity experiment 3)</td></tr>
</table>

*Results and setup of experiment 3 during the ground and microgravity experiments

In this experiment, the bottom mass of the pendulum was attached by a rubber band to the lower platform as shown in figure 3-r above. In the ground experiment where the capsule is at rest, we notice that the damping is quite noticeable and better than the damping occurring in graph2-g above. The damping ratio from graph 3-g is r = 0.72. Since the damping was noticeable we shall carry out a free fall experiment on this setup and see whether it will be better than experiment 2 results. The same parameters were installed inside the capsule during the drop.

As shown in graph 3-m the results show that the tilger system did not dampen the simple pendulum oscillations as fast as it did in the ground experiment 3 as was shown in graph 3-g. The damping ratio is r = 0.76. In this case, there is equilibrium both in the ground experiment and the free fall experiment. However, the damping ratio came out to be worse than the ground experiment which was 0.72. This point needs further investigation in the future.

In our forth experiment, we have a similar setup to experiment 2 in terms of the two rubber bands. However, the tilger system is now inactive through fixing the gliders to the track. Therefore, experiment 4 data need not be the same like the ones in experiment 2 data, for the masses and spring constants. We would like to emphasize the result that the tilger system did indeed operate and damp the free fall pendulum oscillations that we found in experiment 2 results above.

<table>
<tr><th colspan="6">Experiment 4 Data</th></tr>
<tr><th>Figure 4-r</th><th colspan="5">Table 4</th></tr>
<tr><td rowspan="4"></td><td>Main Mass</td><td>Tilger Mass</td><td>Pendulum Mass</td><td>Main Spring Constant</td><td>Tilger Spring Constant</td></tr>
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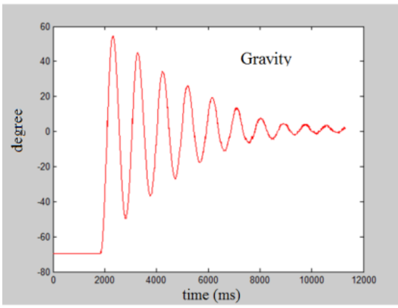
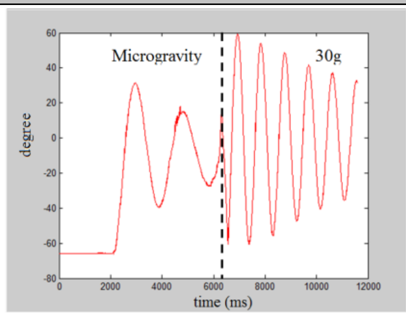
<tr><th colspan="3">Graph 4-g</th><th colspan="2">Graph 4-m</th></tr>
<tr><td colspan="3"></td><td colspan="2"></td></tr>
<tr><td>Setup for Experiment 4</td><td colspan="3">Graph of the simple pendulum oscillations for experiment 4 with capsule at rest on the ground</td><td colspan="2">Graph of the simple pendulum oscillations for experiment 4 with capsule dropped from top of the tower (microgravity experiment 4)</td></tr>
</table>

*Results and setup of experiment 4 during the ground and microgravity experiments

In this experiment, the Pendulum was attached by rubber bands from both sides as explained above and shown in figure 4-r above. In the ground experiment where the capsule is at rest, we notice that the oscillations are similar to the results of graph 2-g above, where damping is not as fast as in experiment 1. Also, the tilger system is now completely disabled. Of course, the damping is still occurring but over an interval of 6 seconds instead of 4 seconds. However, there is a significant and noticeable damping in the first 4 seconds which will allow us to examine whether the elementary feedback mechanism works or not during the free fall experiment. Also, we notice that the number of oscillations is higher than that in experiment 1 (graph 1-g), which is attributed to the fact that we are imposing two oscillatory regimes, the Earth’s gravitational force, and the restoring forces of the two rubber bands. Concerning graph 4-g the damping ratio is r = 0.83.

In the freely falling reference frame of the capsule the gravitational force is absent and only two restoring forces are acting due to the two rubber bands and they are not equal. That is why there is an offset and graph 4-m is not symmetric about the time (horizontal axis). The offset is around 8 degrees. This discrepancy between the offset of graph 2-m and this graph is due to the fact that we are looking for a qualitative and semi quantitative answer to whether the tilger system works during free fall with a feedback mechanism or not. The offset will not be the same since we have the setup done at a later stage and the rubber bands were not set in exactly the same positions as in experiment 2, because we are interested in establishing the fact that the damping seen in experiment 2 during the free fall is genuine and not spurious. If we measure the damping ratio r about this equilibrium (horizontal axis) it comes out to be r = 0.79. This means that the free fall results of experiment 2 displayed in graph 2-m are genuine and if a well designed feedback system is installed, we will be able to dampen the simple pendulum oscillations while the system is in free fall.

Conclusions

Electrodynamic tether technology has many useful future applications including satellite de-orbit, upper stages, and satellite reboost. However, the new proposed method for stabilizing the tether dynamics by using tilger was designed to handle its behavior and tested.

350 sets of ground experiments (capsule at rest on ground) were done in order to find the optimum conditions that will generate the values for a set of masses and spring constants that will achieve the damping of the simple pendulum oscillations in the range of maximum 6 seconds. This range is dictated by the given free fall period of 4.7 seconds.

It was found that the effect of changing springs constants was bigger than the effect of changing the masses, and has a greater impact on damping of the oscillations. This is an advantage because this will makes it cheaper for the satellite when orbiting in space, since the masses can be replaced to useful payloads instead.

This investigation led us to four optimum experiments that were explained above. Experiment 1 stationary on the ground gave ample results concerning the damping of the simple pendulum oscillations in a range of 4 seconds. The damping ratio is r = 0.41. However, dropping the capsule in free fall with the experiment inside it gave a result that the pendulum and the tilger system behave as completely independent systems with no correlation between them. This led us to see whether a feedback mechanism may activate the tilger system during the free fall period and dampen the pendulum oscillations. This was done and the results were very encouraging. At least, we were able to establish in principle that a feedback mechanism may set the tilger system into work and dampen the pendulum oscillations which could simulate the tether in orbiting satellites which will be experiencing sideways Lorentz forces as it traverses the Earth’s ionosphere and the Earth’s magnetic field. Also, we made a trial in experiment 3 to see whether other feedback mechanisms could work but this needs further investigation in the future.

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