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

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- Schwinungstilger is the German name for a tuned mass damper system, which is also known as harmonic absorber.

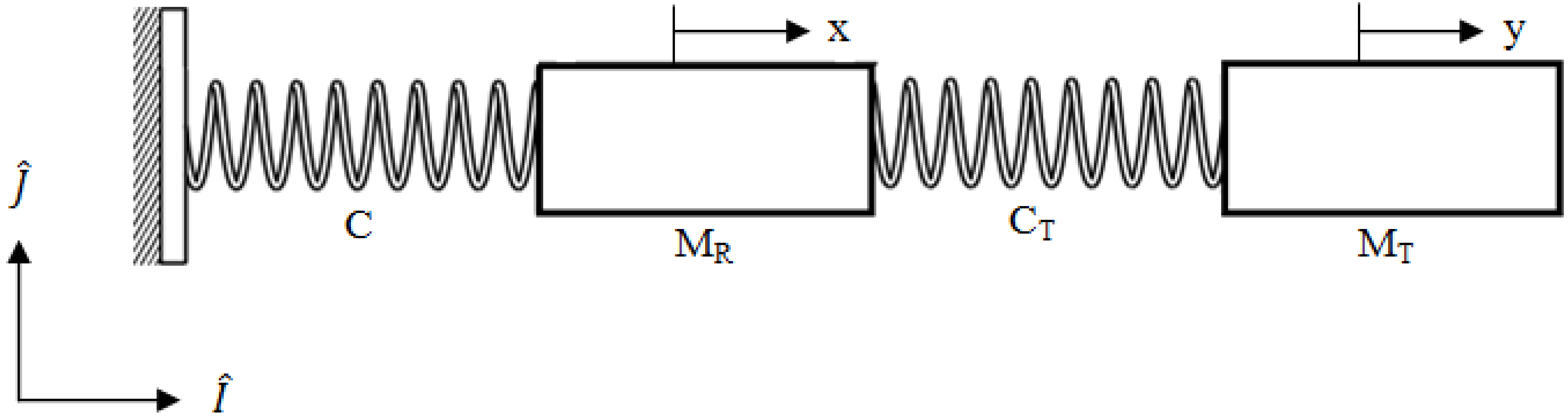


Figure 1 – A Tuned Mass Damper

- 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.

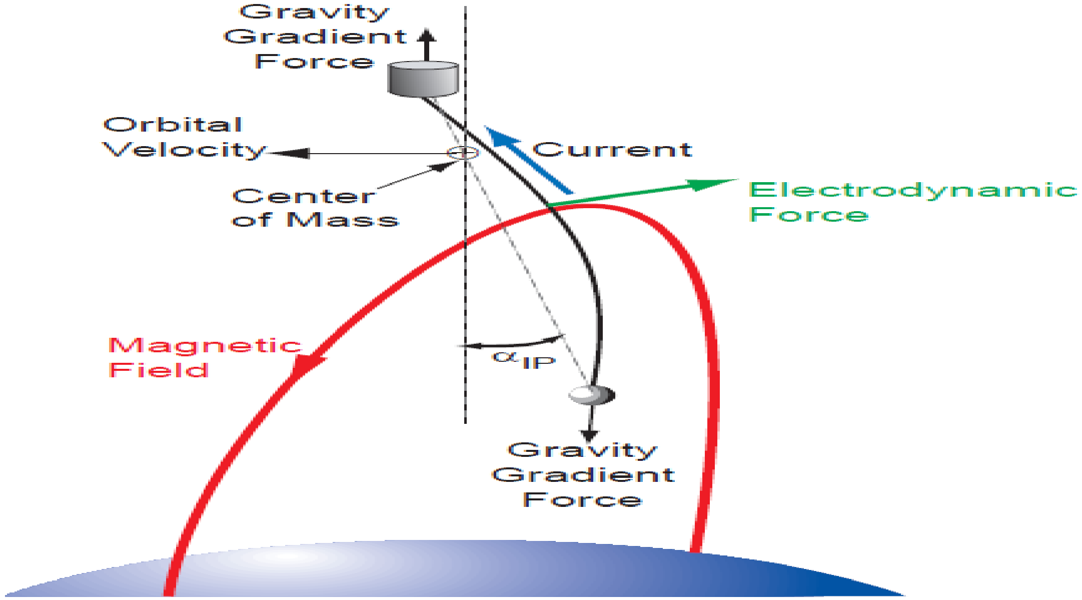


Figure 2 – Illustration of Electro-dynamic Tether[6]

- 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.
- On instability of the electro-dynamic tether on the other hand, they are subjected to a distribution of lateral forces.
- As the charged particle ***q*** in the tether moves with a velocity ***v***, crosses the Earth’s magnetic field ***B***, it will be subject to a Lorentz force ***F*** 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:
- $\boldsymbol{F} = q[\boldsymbol{E} + (\boldsymbol{v} \times \boldsymbol{B})]$
- Where ***E*** is the total local electric field due to the charges creating it and the induced electric field created by the variable magnetic flux at the location.
- 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 project, 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].
- The aim of our project to establish that in principle the tether oscillations may be reduced, through a feedback mechanism when in free fall.
- Also our aim in this work is to reduce the amplitude of oscillations.
- One of the previous works (Columbo, 1981)[11], have observed that the instability of the tether is only a concern if the oscillations exceeded 45° within twelve hours.
- They have found that under this degree of angle the electrodynamic forces will later damp and decay the oscillations.

- Therefore, the purpose of adding the tilger was to reduce the oscillations under the angle of 45° of the electrodymanic tether in space.
- **Theory of Tilger without Tether (without damping friction):**
- 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[12]. The normal mode frequencies that were obtained in reference [12] on page 277 were:
- $$\omega_{total} = \pm\sqrt{\frac{\left[\left(\omega^2+\omega_T^2+\omega_T^2\frac{M_T}{M_R}\right)\pm\sqrt{\left(\omega^2+\omega_T^2+\omega_T^2\frac{M_T}{M_R}\right)^2-4\omega^2\omega_T^2}\right]}{2}} \quad \text{Equation (1)}$$

- With $\omega = \sqrt{\frac{C}{M_R}}$, and $\omega_T = \sqrt{\frac{C_T}{M_T}}$
- Looking back at Figure 1 we find the Lagrangian for the Tilger system without the tether as:
- $L = K - U$
- $L = \frac{1}{2} M_R \dot{x}^2 + \frac{1}{2} M_T \dot{y}^2 - \frac{1}{2} C x^2 - \frac{1}{2} C_T (y - x)^2$ Equation (2)

and applying Lagrange's equations

- $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0$
- $M_R \ddot{x} + (C + C_T)x - C_T y = 0$ Equation (3)
- $M_T \ddot{y} + C_T (y - x) = 0$ Equation (4)
- Solving Eqs. (3) and (4) we end up with solution in Eq. (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.
- **Theory of Tilger with Tether (without damping friction):**
- Looking at Figure (3), we set up the Lagrangian for the Tilger system with the tether (w/o damping friction term):
- $L = \frac{1}{2}(M_R + M_B)\dot{x}^2 + \frac{1}{2}M_T\dot{y}^2 + \frac{1}{2}M_B d^2\dot{\theta}^2 + dM_B\dot{\theta}\dot{x}\cos(\theta) - \frac{1}{2}Cx^2 - \frac{1}{2}C_T(y-x)^2 - M_B g d(1-\cos(\theta))$ Equation (5)

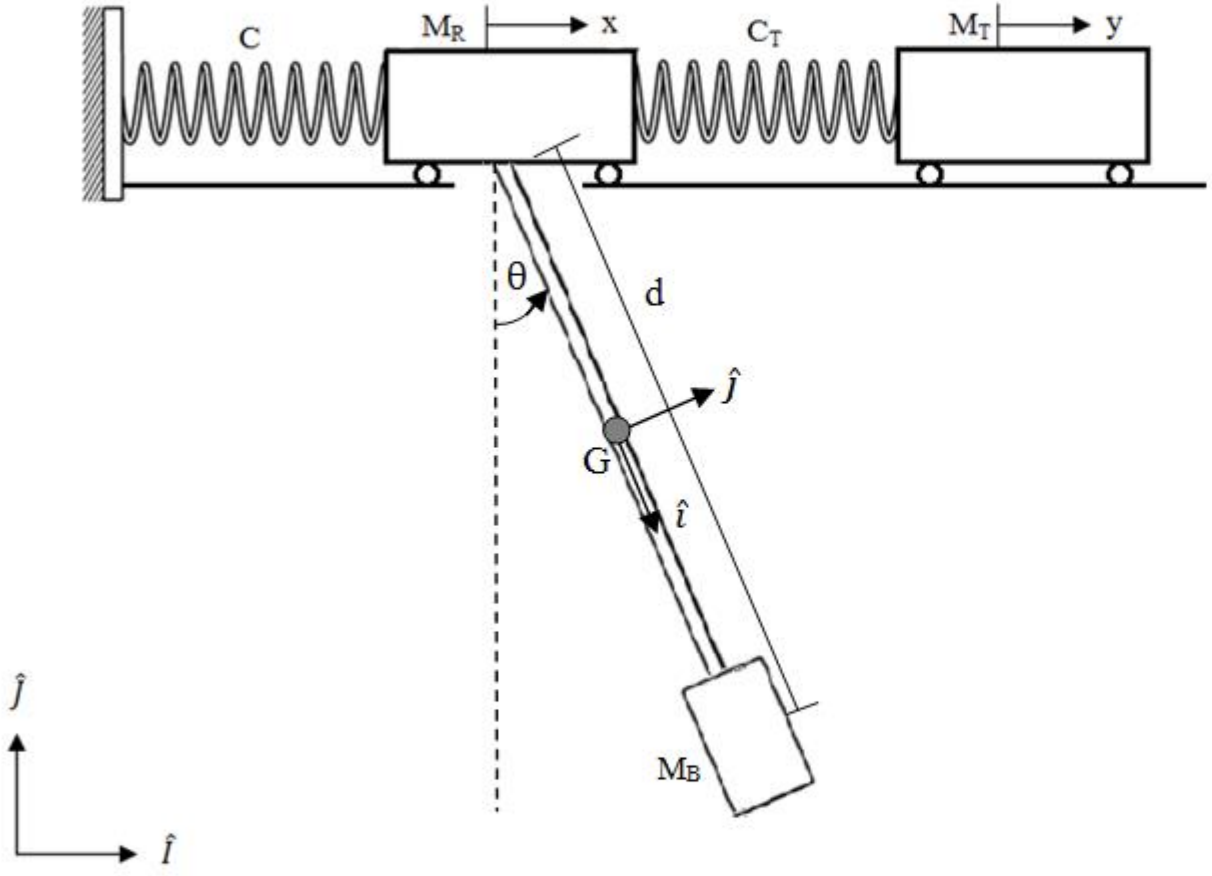


Figure 3 – Tilger System with a Pendulum (Tether)

- We look only for motion along the horizontal direction which is restricted by the gliders track. These equations of motion are true for the tilger with pendulum on Earth and not in orbit. We use an inertial frame of reference. If the problem to be formulated in orbit then we need an accelerated frame of reference and we must have transformation from an inertial frame into a rotating frame of reference. Under these conditions the equations of motion under gravity and without any frictional damping term are:
- $(M_R + M_B)\ddot{x} + dM_B\ddot{\theta}\cos(\theta) - dM_B\dot{\theta}^2\sin(\theta) + Cx - C_T(y - x) = 0$ Equation (6)
- $M_T\ddot{y} + C_T(y - x) = 0$ Equation (7)
- $dM_B\ddot{x}\cos(\theta) + M_Bd^2\ddot{\theta} + M_Bgdsin(\theta) = 0$ Equation (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. We have opted for the simplest assumptions and under gravity conditions. However tackling the more realistic situation is beyond the capabilities of undergraduate students knowhow. So our aim is to look for the best sets of experimental data that will reduce the oscillations in the pendulum when the setup is on the ground.

Experimental Setup

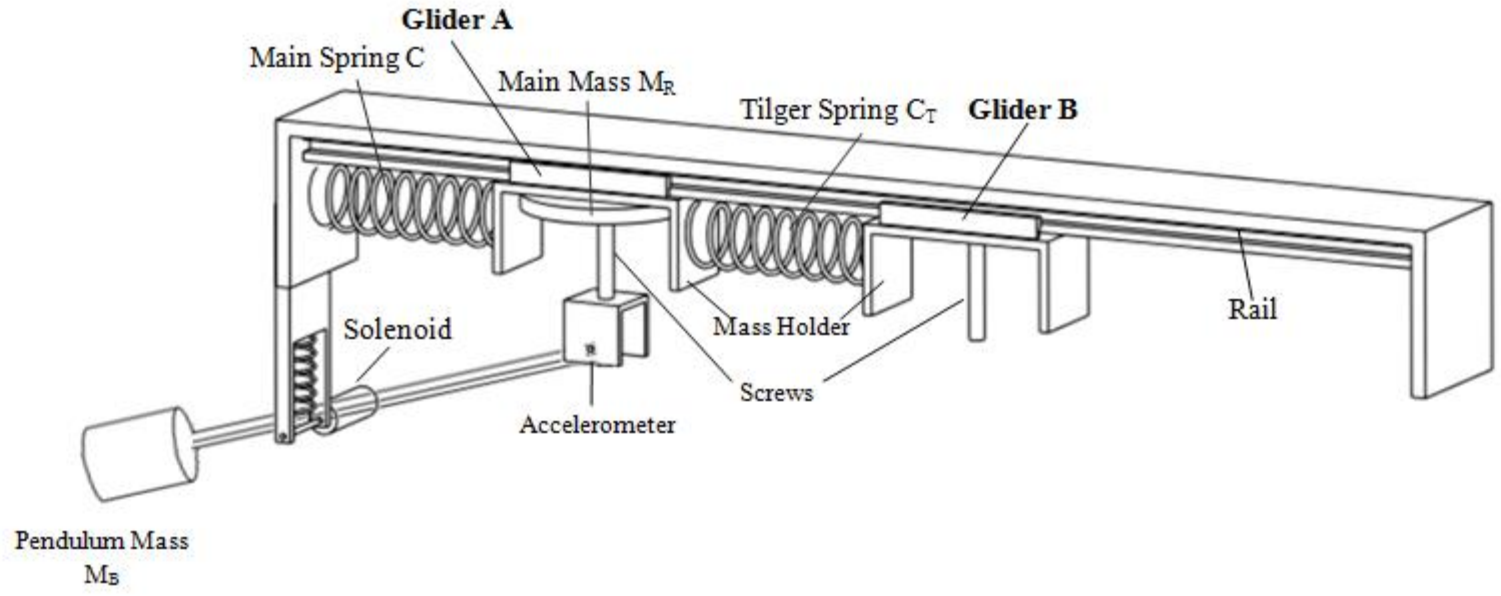


Figure 4- Schematic of the Set-up Experiment

Experimental Setup

- The set-up is shown in Figure 4. 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.

Experimental Setup

- 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.

Experimental Setup

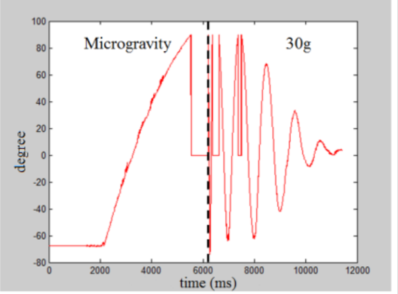
- It was also found that the effect of changing springs constants was bigger than the effect of changing the masses, and has a greater impact on damping of the oscillations. This is an advantage because this will make it cheaper for the satellite when orbiting in space, since the masses can be replaced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

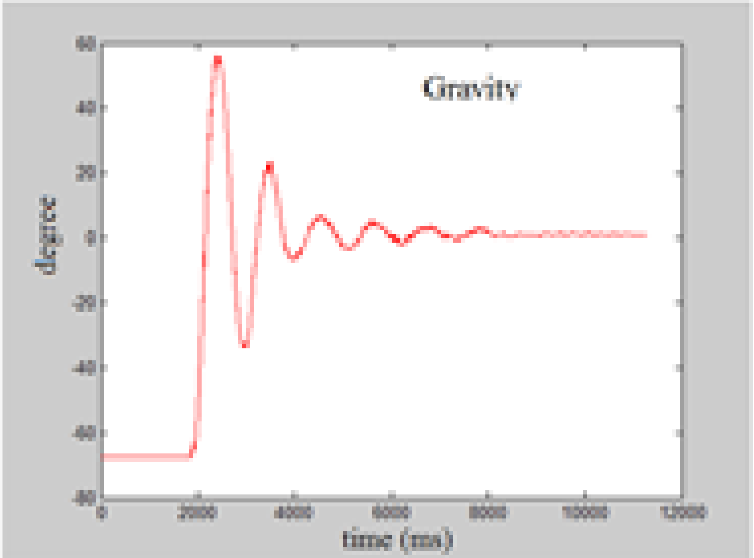
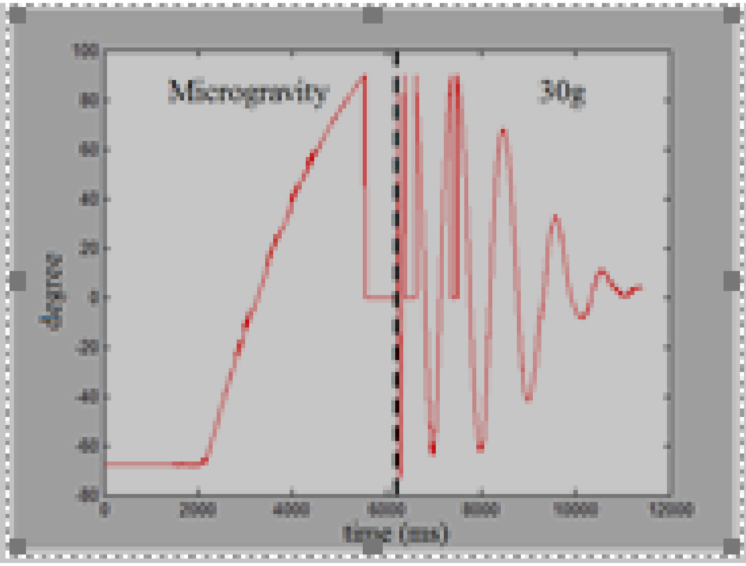
10^{-6} g.

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.



Results and Discussion

periment 1Data				
Table 1				
Main Mass	Tilger Mass	Pendulum Mass	Main Spring Constant	Tilger Spring Constant
1kg	0kg	0.5 kg	20N/m	60N/m

Graph 1-g	**Graph 1-m**
	
Graph of the simple pendulum oscillations for experiment 1 with capsule at rest on the ground	Graph of the simple pendulum oscillations for experiment 1 with capsule dropped from top of the tower (microgravity experiment 1)

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

Results and Discussion

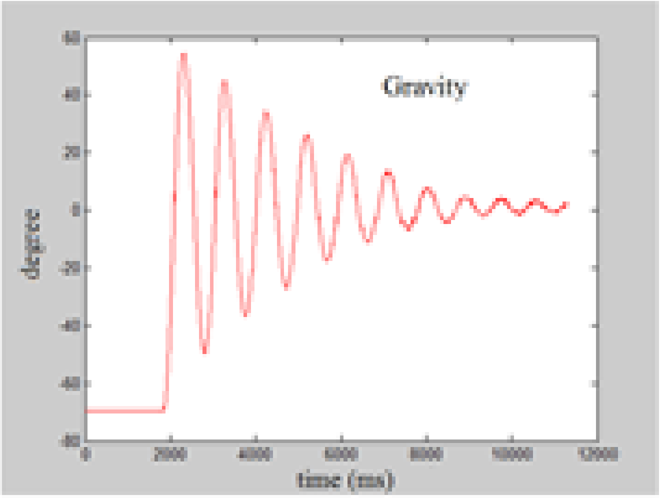
- In graph 1-g we display the simple pendulum oscillations, where the horizontal axis represents time in milliseconds (ms) and the vertical axis correspond to the angular displacement of the simple pendulum in degrees. We notice the fast damping of the simple pendulum amplitude in a time interval of 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.

Results and Discussion

Experiment 2 Data

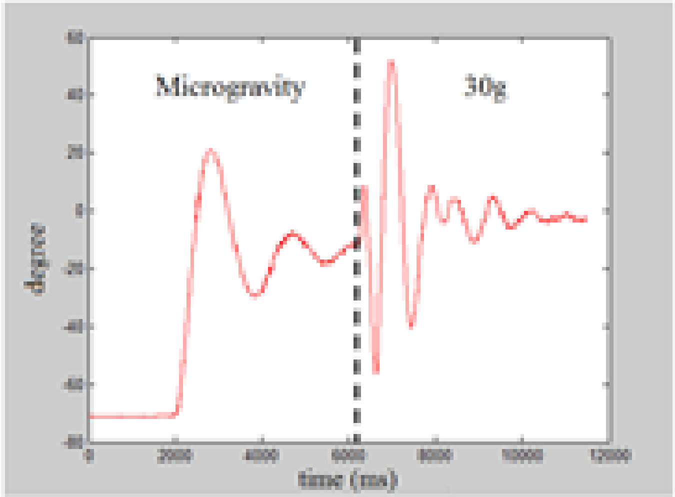
Table 2				
Main Mass	Tilger Mass	Pendulum Mass	Main Spring Constant	Tilger Spring Constant
1kg	0.5 kg	0.25 kg	100N/m	80N/m

Graph 2-g



Graph of the simple pendulum oscillations for experiment 2 with capsule at rest on the ground

Graph 2-m



Graph of the simple pendulum oscillations for experiment 2 with capsule dropped from top of the tower (microgravity experiment 2)

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

Results and Discussion

- 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 5, 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 5 to the right of the simple pendulum.

Results and Discussion

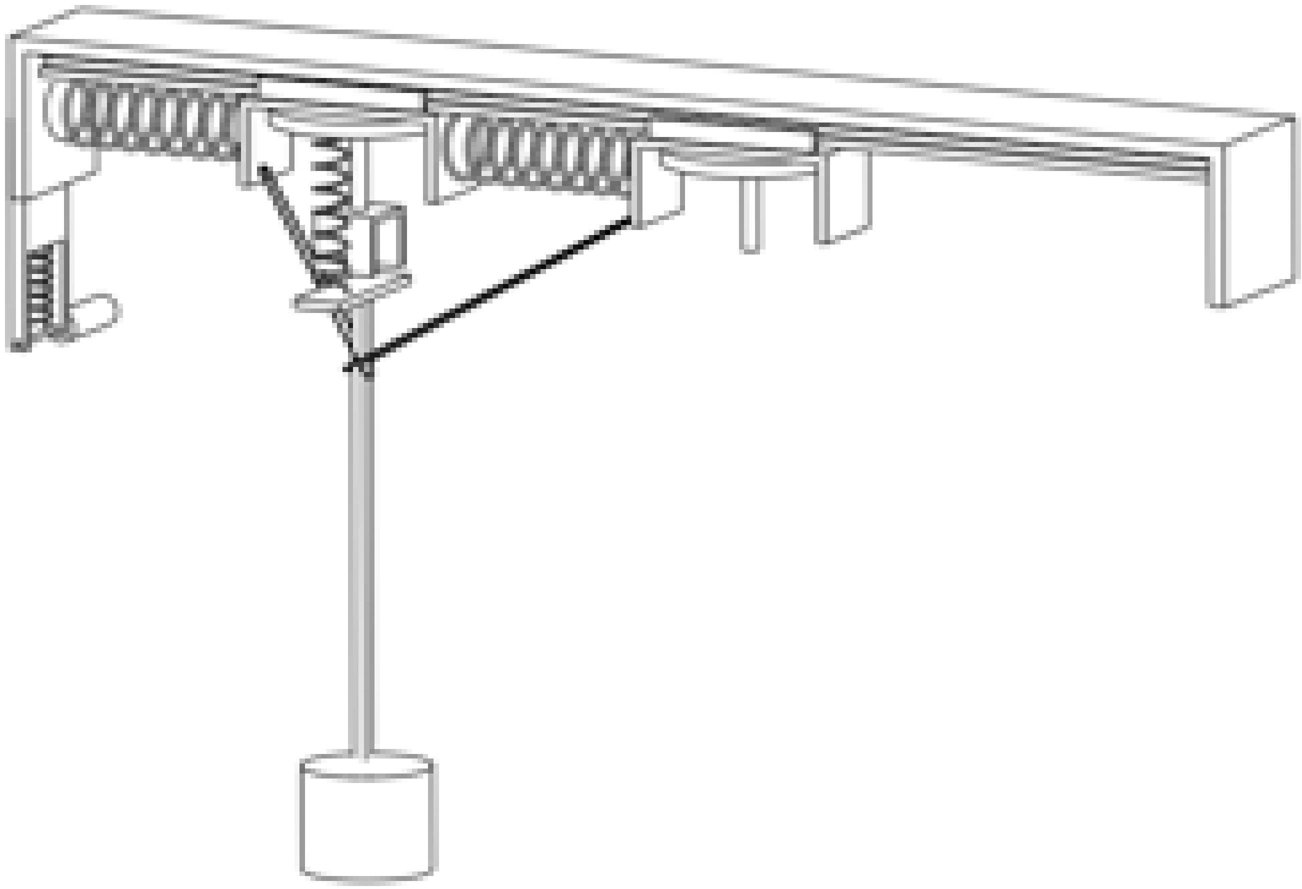


Figure 5- Schematic of Experiment 2 Set-up

Results and Discussion

- In this experiment, the Pendulum was attached by rubber bands from both sides as explained above and shown in figure 5 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 $r = 0.81$.