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Development of a Ground Based Testbed for Studying the Libration Dynamics of Orbiting Tethered Satellite Systems

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Abstract— This paper discusses the development of a ground based experimental environment that can mimic the libration dynamics of tethered satellite systems. The setup consists of an Air-Bearing Inclinable Turntable (A-BIT), whose inclination and rotation rate can be adjusted independently. Appropriate scaling factors help compare the tethered system in the experiment to that in orbit, both of which experience vastly different magnitudes of forces. The two scenarios also differ in their physical parameters including the length of the tether, the mass of the satellite, and the tension along the tether. The scaling factors are used to compare the behavior of these two tethered satellite systems.

Keywords- space tethers; air bearing table; inclinable turntable; ground based testing; tether deployment; scaling tether deployment; tether dynamics.

I. Introduction

Tethers are long ropes or tapes that connect two satellites orbiting at different altitudes in space. They are usually constructed using a bare metal like aluminum, however, depending on their application they may have a part or the entire tether covered with insulating material. Tethers have numerous applications in space including power generation, attitude stabilization, momentum transfer, and de-orbiting the satellite at the end of its mission [1] [2] [3] [4]. When a tethered satellite is launched, the tether is folded and stowed inside of the satellites. Once the satellites are in orbit, the tether is deployed and stabilized in the desired orientation. In fact, all successful tethered satellites rely on the successful deployment and stabilization of the tether, while the missions that fail to achieve this struggle to complete their objectives. This fact is evidenced by missions such as the Tethered Payload Experiment (TPE) I & II, launched in 1980 and 1981, respectively. The TPE I mission deployed only 38 m, instead of the planned 400 m tether deployment, while the TPE II faired marginally better, deploying 103 m out of its 500m long tether [2] [4]. Onboard cameras showed that the under-deployed tether wasn't under tension all the time, which resulted in the tether coiling up. Similarly, the Small Expendable Deployer System (SEDS-I), launched in 1993, failed to slow down the deployment of the tether, which caused the satellites to recoil at the end of deployment [1] [2] [3]. The unsuccessful deployment of the tether in all such missions inhibited the payload onboard from completing the mission objectives. This presents a serious challenge for tethered satellite missions, as a tremendous amount of resources are wasted if the tether does not deploy properly. Although it is not possible to completely eliminate the possibility of mechanical failure of the deployment and stabilization mechanism, an experimental verification of the behavior of the satellite, given the mission parameters, can help fine-tune the deployment process in order to ensure a smooth and complete deployment of the tether.

This research focuses on the development of a testbed that is capable of imitating the behavior of a tethered satellite system orbiting in a circular Low Earth Orbit. The testbed utilizes an Air-Bearing Inclinable Turntable or *A-BIT*, whose inclination and rotation rate can be adjusted independently. A similar experimental technique was employed by [5] [6], focusing on the dynamics of a climber attached to a pre-deployed tether. The *A-BIT* aims to provide insight into the libration dynamics of a tethered satellite and provide a platform to test control strategies that stabilize the libration of the tethered satellite system.

II. Experimental Setup

The proposed experimental setup of the *A-BIT* is shown in Fig. (1). The table is 2m long and 1 m wide. There are two dummy CubeSats on the table. The mother satellite is anchored near the edge of the table furthest from the rotation axis, while the daughter satellite is free to move across the table. There are three air blowers mounted on the rotating frame that allow the satellite to float on the testbed. The mother and daughter satellite are connected by an aluminum tape tether which has a width of 1cm and a thickness of 50 μm.

Prior to deployment, the tether is folded and stored in a stowage box placed above the daughter satellite [7], and both satellites are held together by an electromagnet mounted on the mother satellite. The electromagnet latches on to a threaded steel rod which passes through a spring mounted on the daughter satellite. As the daughter satellite is pushed together with the mother satellite, this spring get compressed between the two satellites. To deploy the daughter satellite, the electromagnet is remotely deactivated, converting the potential energy of the spring into the kinetic energy of the daughter satellite. The stowage box of the tether includes a passive braking mechanism

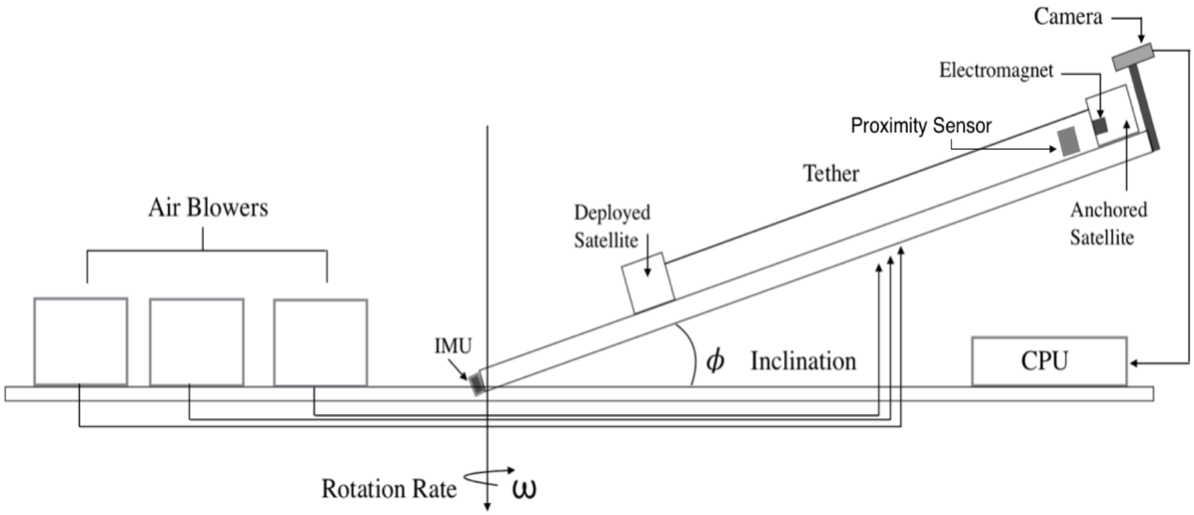


Figure 1: An Overview of the Experimental Setup

which uses friction to slow down the deployment process and avoid recoil. There are two cameras mounted on the table, one on either side of the mother satellite in order to track the motion of the daughter satellite. A proximity sensor is placed on the table near the mother satellite to measure the deployment speed of the daughter satellite.

The inclination of the *A-BIT* with respect to the local horizontal Φ, and its rotation rate ω can both be adjusted independently. An Inertial Measurement Unit (IMU) is mounted on the turntable to measure the values of Φ and ω. The inclination of the table emulates the gravity gradient along the tether, while the table's rotation emulates the centrifugal and Coriolis forces acting on the daughter satellite.

III. Scaling Experimental Parameters

In order to emulate the behavior of an orbiting tether using the *A-BIT* experiment properly, the forces acting on the daughter satellite in the experiment should be similar to those in orbit, namely, the gravitational gradient, the centrifugal force and the Coriolis force. Since the magnitude of these forces are not the same as those in orbit, they need to be appropriately scaled. This can be achieved by equating the net torque and the net angular momentum of the two systems. This provides a relationship between the libration angle of the tether in the experiment to the same in orbit, as expressed in Eq. (1)

$$\sin\theta_e = \frac{3L^2\Omega^2 M}{2ml(g\ sin\emptyset - \omega^2 r\ cos^2\emptyset)} \sin 2\theta_o \tag{1}$$

where $\theta_e$is the libration angle of the tether on the *A-BIT*, θ_o is the libration angle of tether in orbit, *g* is the acceleration due to gravity, *r* is the distance of the mother satellite to the rotation axis, and Φ is the inclination of the *A-BIT* as defined before. The terms *M*, *L*, and *Ω* represent the mass of the daughter satellite, the length of the tether and orbital rate of the tethered satellite system respectively in orbit, while the terms *m*, *l*, and *ω* represent the same, but in the experiment.

Similarly, the relation between the tension along the tether in orbit and the tension along tether in the experiment, is expressed in Eq. (2) [8]:

$$T_o = \frac{ML}{I_o^2}\left[\Omega^2 + f\ \pm 2\Omega\sqrt{f} + 2\Omega^2 I_o^2\right] \tag{2 a}$$

$$f = \frac{I_e^2}{ml}\left[T_e - mg\ sin\Phi + mk\omega^2 cos^2\Phi(r - l)\right] \tag{2 b}$$

where T_e and T_o are the tensions along the tether in the experiment and in orbit respectively, while I_e and I_o are the moments of inertia of the system in the experiment and in orbit respectively. The moment of inertia is measured about the center of mass of the mother satellite.

The following expression is introduced in order to relate the orbital rate of the tethered satellite system with the rotation rate of the air-bearing table [6] [8]:

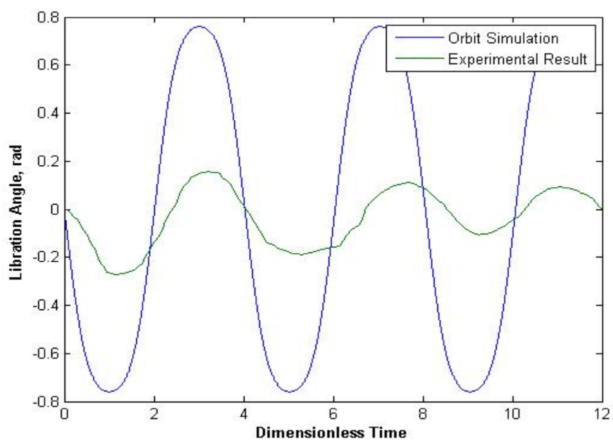
$$\omega = \sqrt{\frac{ML^2\Omega^2}{kml^2}} \tag{3}$$

where *k* is a dimensionless constant used to limit the inclination and rotation rate of the *A-BIT*. It should be noted that this expression holds true for small libration angles only.

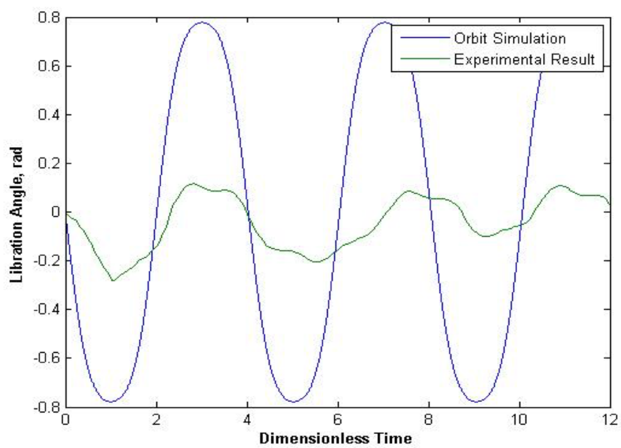
As with the forces, the timescale of the tether libration in orbit and in the experiment, is not the comparable. In order to overcome this, both timescales can be resolved into dimensionless time by using the orbital rates as a normalizing factor.

IV. Experimental Results and Analysis

Once the orbital parameters to be simulated have been decided, the experiment is setup using the parameters developed in the previous section. Figures (2a) and (2b) show the experimental results along with the numerical simulation of an 800m long tether orbiting at 1440 Km and 1450 Km above the Earth's surface, respectively. The results show that the time periods of libration, in orbit and in the experimental setup, are comparable. The results of the experiment show a 3% longer time period than the simulation. This is most likely caused by the damping experienced by the system in the experiment, but not in orbit. However, this damping can be measured and its effects can be accounted for. As mentioned in the previous section, the scaling factors have been developed such that the amplitude of libration matches only for small libration angles. Since no control law has been applied to the simulation of the tether in the orbit, the amplitude of libration is very high and thus does not match up to that in the experiment.



(a)



(b)

Figure 2: Tether Libration Dynamics. *Emulated orbital height (a) 1440 Km (b)1450 Km*

V. Conclusion

The results serve as a preliminary indicator that the *A-BIT* can be utilized to study the behavior of the tethered satellites in orbit. They show that the scaling factors have been implemented effectively and that these factors can be used to scale up the libration dynamics measured in the experiment to those expected to be observed in orbit. Future work on the experimental setup would include measurement of the extent of damping experienced by the system and model it out of the resultant motion observed. Sensors would be put in place to measure the tension along the tether. A wide-angle camera would be mounted on top of the table. This would provide better position estimation and reduce the drag experienced by the daughter satellite due to the change in orientation of the mounted target that is being tracked. The experimental setup will be modified to include various control strategies, whose behavior in orbit is known. Implementing these control laws will reduce the libration angle of the tether. Comparing the behavior of the tethered satellites in the experiment to that in orbit should provide details about the effectiveness of the experimental setup to measure amplitude of the libration as well, instead of just its time period. A successful imitation of both these parameters in the experiment will allow this setup to be used for validating the effectiveness of new control strategies to stabilize tethers in orbit.

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