Designing space elevator as a low-cost transportation to space

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Abstract

Space exploration helps to address fundamental questions about our place in the universe and the history of our solar system. However, getting to space is very costly as it takes around 500$ million in launch cost to get a satellite to geosynchronous orbit. A space elevator could reduce the cost and would create a permanent Earth to space connection. This would make trips to space more frequent and would open up space to a new era of development. The original idea came in 1895 from a Russian physicist Konstantin Tsiolkovsky which identifies the concept that a space station could be built beyond geosynchronous orbit that would support the portion of the tower below geosynchronous by using an outward force due to Earth's rotation. In this paper, I will address the basic technical components of a space elevator as well as redressing the need and potential of having a space elevator for space development. A space elevator model will also be created by using a commercial software NX Siemens PLM version 12 and further analysis of the model will be discussed in this paper.

Keywords: Space elevator; Carbon nanotube; Free-standing tower; Tensile strength; Tether; Climber; Anchor; Counter weight; Siemens NX12; Geosynchronous orbit.

I. Introduction

The original idea came in 1895 from a brilliant Russian physicist Konstantin Tsiolkovsky which identify the concept that a space station could be built beyond geosynchronous orbit that would support the portion of the tower below geosynchronous by using an outward force due to Earth's rotation [1].

In September 2018, a group of engineers from Shizuoka University held a research and launched two ultrasmall cubic satellites into the space from the International Space Station (ISS) [2]. Each cubic satellite was connected by a 10-metre steel cable with a small container acting as an elevator car to move along the cable. A camera is attached on the container to study the movements and behavior of the container while operating in space.

This article will explain the basic mechanical principles of the space elevator and also investigate the basic technical requirement for an operating space elevator. Later, a space elevator model will be designed and a short analysis will be done.

II. Physics of space elevator

a) Theory of a free-standing tower

A free-standing tower will only able to withstand itself if the force upward is equal to the force downwards. Therefore, in this case the weight of the tether and climber need to be counterbalanced by the outward centrifugal force due to the rotation along the geostationary orbit.

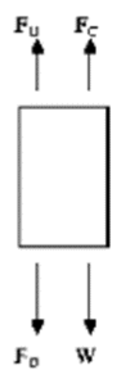

Figure 2.1 Summation of the forces acting on the tower at the geostationary height. Source: [3].

There will be a few forces that is applied to this system which is gravitational force, centrifugal and tension forces acting on it.

$$F_U + F_C = F_D + W \qquad (1)$$

Where:

F_u: upward force due to the upper element of the tower [N]
F_c: upward centrifugal force [N]
F_D: downward force due to the lower element of the tower [N]
W: weight of the tower due to gravity [N]

For a tower at a geostationary height, the weight and centrifugal force taking account that the height is at a distance from the Earth's center equal to the radius of the stationary orbit, the forces should be ($F_c = W$) and therefore the other equation should be ($F_u = F_D$) for an equilibrium to be achieved.

For an element below the geostationary height, the weight force **W** is greater than F_c and thus the other equation ($F_u > F_D$) for it to be in equilibrium. On the contrary, the equation ($F_u < F_D$) should be met for the element above the geostationary height for it to be at equilibrium.

In both cases, the forces will be at maximum at the geostationary height and the tension drops at zero at both ends. This will only occur if any of the following case is satisfied. Firstly, the tether should end further than the geostationary orbit to counter the forces pulling downwards.

The other option would be building a terminus station which is a bit further than the geostationary height that can be used for other purposes such as creating a livable environment and space for human to live and can also serve as a rest and service areas for space craft. Figure 2.2 is a representation of the forces that is acting on the tower at the geostationary height.

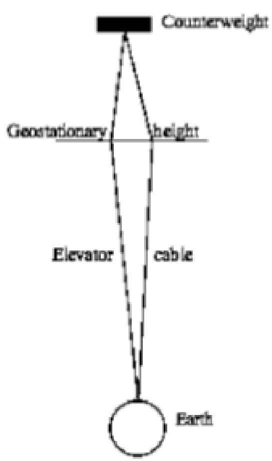

Figure 2.2 Representation of the summary of forces along the cable. Source: [3].

b) Mass and length of a space elevator

In this part, the steps and calculation for the length and mass of the space elevator was calculated by P.K. Aravind [3].

$$m_c = \frac{\rho A_s L_c \, exp\left[\frac{R^2}{2L_c R_g^3}\left\{\frac{2R_g^3 + R^3}{R} - \frac{2R_g^3 + (R_{g+h})^3}{R_g + h}\right\}\right]}{\frac{R^2(R_g + h)}{R_g^3}\left[1 - (\frac{R_g}{R_g + h})^3\right]} \quad (2)$$

Where:
m_c: mass of counterweight [kg]
ρ: mass density of elevator cable [kg/m3]
T: stress (or force per unit area) in elevator cable [GPa]

Note that mc →∞ as h→0 and decreases with increasing h. The value of the parameters in this calculation is as following; ρ= 1500kg/m3, T= 100GPa and As= 1.5×10^{-7} m^2. A further calculation of the maximum distance a spacecraft could reach if released from the counterweight was done by using a 107,000 km length of space elevator. The obtained distance for the maximum distance for a spacecraft is 7.95x1011 km which is equivalent to 5.3 AU (Astronomical unit) which is a little larger than the mean orbital radius of Jupiter.

A cable of about 100,000 km in length is generally a good choice for the proposed idea. Therefore, the height of the space elevator is assumed to be about 100,000 km in this and the upcoming chapters. By using the previous equation, and incorporating a safety factor of 2 into the design, it is found that the mass of the counterweight to be 52.7x103 kg. The stress in the cable is only 50 GPa everywhere which is half from the maximum stress allowed.

III. Major components of the space elevator

In this chapter, the basic requirements and specifications of the components of space elevator based on latest technology will be explained and discussed. The four main components in a space elevator consist of an anchor, tether, counterweight and climber.

a) Anchor

Earth's rotation creates an upward centrifugal force on the counterweight hence a base station is needed to held down the cable and keep the cable in taut. It also anchors the whole system to the surface of the Earth.

Locating a base station on a movable ocean-based platform outweigh the advantages over a land-based anchor. The advantages include:

1. Excellent mobility to move the cable from low Earth orbit objects and storms.
2. Can be located near the equator with less lightning strikes and calm weather.
3. Can be located in international waters.
4. Impose less threat to the local community in case of a break in the ribbon.
5. Easier to ship large scale objects on sea compare to the land.

It is also wise to locate the base station at the equator. This is because all types of winds such as hurricanes, tornados, and cyclones will never occur at the equator. At the equator the winds can rotate in any directions but cannot sustain the high concentrations of angular momentum required for the formation of destructive windstorms.

The base of the space station should be developed as a floating platform and not be anchored or supported from the ocean floor. This method of anchoring will allow the space elevator to be mobile so that it can be placed at the safest location away from lightning strikes and other potential threats.

The space elevator ribbon could be anchored on a refurbished oil platform. For example, an old mobile drilling rig can be converted into self-propelled semi-submersible mobile base station. This has been the case for LP Odyssey which undergo renovation from late 1995 to May 1997 [1].

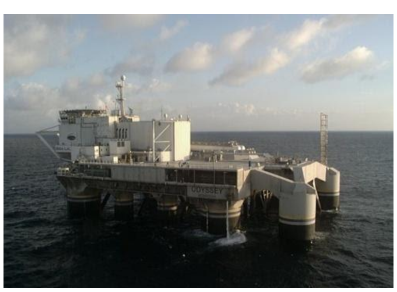

Figure 3.1 LP Odyssey, mobile spacecraft launch platform refurbished from an oil platform. Source: [4]

This platform has sufficient mass not to be affected by the total mass of the ribbon and on top of that, has a self-propelled speed of 12 knots which provides sufficient mobility to avoid collision with objects.

b) Tether

The ribbon design proposed by Brad Edwards will have a 3 mm2 cross sectional area of 10-micron diameter fibres or roughly 30,000 fibres at the anchor width [1]. The cable will consist of many individual fibres that are arranged in parallel with cross-connections, or straps, across the ribbon at 10 cm interval or more. The connections between fibres will be made up of composite materials which are 60% nanotubes and 40% epoxy.

As a result, when one of the fibre breaks, it will contract, pulling through the cross connectors until the tension drops below 1 GPa at each cross-connections. When this happens, the tension is transferred from the severed fibre to the neighbors through many cross-connectors and dissipating the energy.

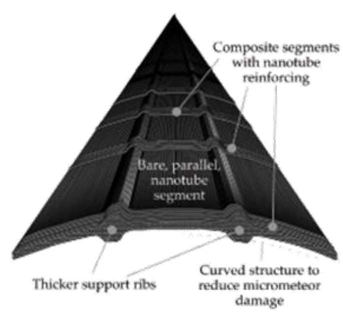

Figure 3.2. Cut-away view of the proposed ribbon. **Source: [5]**

c) Counter weight

The function of a counter weight is to compensate the weight of the system with a centrifugal force that is acting on the counter weight due to the Earth's rotation and keeping the cable taut.

A space elevator that is extending beyond geosynchronous orbit could provide escape velocity for propellant-free transfer orbits to the nearby planet such as Mars or the Moon. This is done by using the tower's rotational energy to launch spacecraft. A dock is built at the top of the space station so that spacecraft can be tethered and launched by using the Earth's rotation.

One might be wondering, what is the furthest distance from the sun that a spacecraft can reach if released at rest from the top of a tower. A calculation was done by P.K Aravind, which considered the height of the tower to be 100,000 km, obtained a distance of 7.95×10^{11} km [3]. The distance is equivalent to 5.3 AU (Astronomical unit) which is a little larger than the mean orbital radius of Jupiter. Therefore, a spacecraft released at rest from the top of the space elevator tower would be able to reach Jupiter.

The International Berthing and Docking Mechanism (IBDM) will be used at the space station. This is because the European mating system is capable of docking and berthing large and small spacecraft [6]. The IBDM is also designed to be compliant with the International Docking System Standard (IDSS) and is hence compatible with any future or current space facilities. The dock has a circular transfer passage with 800 mm diameter.

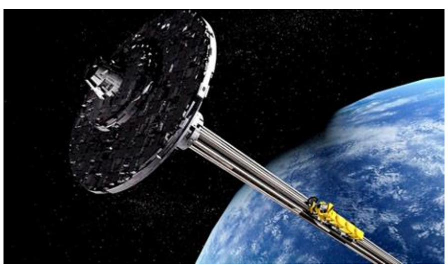

Figure 3.3 A space station at the upper end of the cable. Source: [7]

There are few other possible long-term applications of the space station other than using the counterweight to launch spacecraft. A space facility that is built on GEO station could lead to many new space industry developments such as travel and tourism, entertainment, medical facilities and materials development. The space station could also be used as a research facility that could identify and realistically deal with any potential threat to Earth from large asteroids.

d) Climber

There a few types of climbers needed in building and maintaining the space elevator which are regular climber, malfunctioning climber and repair climber. The first 200 climbers design is slightly different than the main commercial climber. The main job of these climbers deployed are to strengthen the existing ribbon. Each climber will add a few additional ribbons to the edge of the initial ribbon.

In the following part, I will focus solely on the components on the commercial climber because there are a lot of variations of climbers. All of them serve different purposes and therefore the design and size of each climbers differs from each other. List of the basic components in the climber:

1. Motor
2. Track and roller system
3. Power system
4. Thermal control system
5. Control system
6. Communication system

IV. Space elevator model

There are four components of the space elevator as explained in the previous chapter. The components that I will be focusing in this chapter are the climber, tether and the counter weight. A simplified version of the base station (anchor) will be used to replace the complicated model of the base station. The requirements of the base station of the space elevator is as discussed in previous part which is a semi-submersible mobile base station. In figure 4.1 is the final model of the space elevator

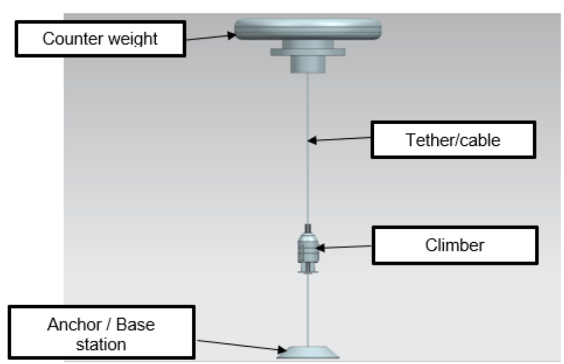

Figure 4.1 Side view of the assembled space elevator [own source].

In figure 4.2 is the side view of the assembled space elevator with dimension. The cable was not modelled according to scale with respective to the other components of the space elevator. This is because if modelled with the same scale with the other components, it is impossible to have a picture of the assembled space elevator due to the cable being extremely long. Therefore, the total length of the space elevator is 110,522 km with the counter weight attached to the upper end and anchored at the base. The length of the cable itself would be 100,000 km.

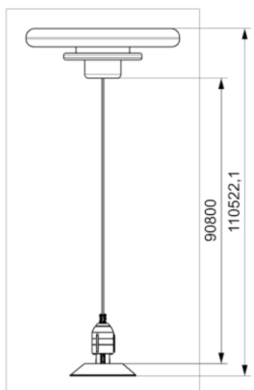

Figure 4.2 Side view of the assembled space elevator with dimensions (km) [own source].

a) Climber functionalities

In figure 4.3 is the prototype of the climber. The space elevator consists of 5 main components as labelled in the figure. Visible on top of the climber is the track and roller system that is designed to hold the cable while ascending it. At the top part of the climber is where the secondary motor is located.

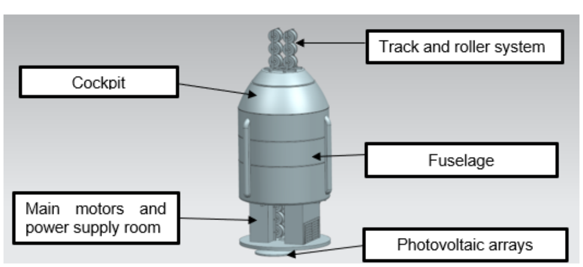

Figure 4.3 Isometric view of the climber [own source].

The fuselage is the centremost piece of the climberº. It is responsible for the structural integrity of the climber. The pilots will sit in the cockpit in front of the fuselage. Passengers and cargo are carried in the middle and rear section of the fuselage.

At the bottom part of the main body is the compartment for the main motors, power supply and thermal control. Attached at the bottom plate are the photovoltaic arrays which are responsible of receiving laser beam from power stations on Earth. The purpose of the side fin is for easier docking process at the anchor or the counter weight.

In figure 4.4, we can see the dimension of each compartment of the climber. The middle section of the fuselage will be the living space for the passengers. It is 6.82 m in height and the interior will be divided into two level. The number of passengers will be explained in the following part. In figure 4.5, we can see the diameter of the fuselage which is 6.80 m with a 1 m diameter circle at the centre of the body to allow the cable to pass through during ascending and descending. Both figures 4.4 and 4.5 were drawn according to scale and shown in the figures are the dimension in millimetre.

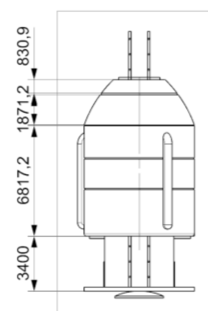

Figure 4.4 Side view of the climber with dimensions (mm) [own source].

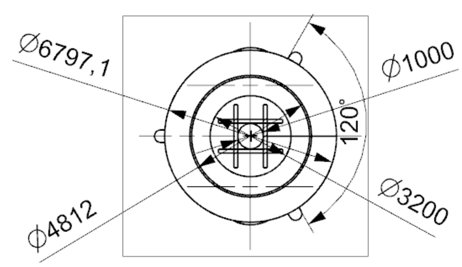

Figure 4.5 Top view of the climber with dimensions (mm) [own source].

Number of passengers

In order to figure out the room capacity for the passenger in the climber, the area of the fuselage is calculated beforehand. The fuselage of the climber will be divided into four levels. The uppermost level will be the cockpit for the pilots operating the climber. Located on the same level is the control room serving as a central space where a large physical facility dispersed service can be monitored and controlled.

At the middle part of the fuselage is where the passengers and cargo are located. The middle fuselage will be divided into 3 levels. The two upper level will be the assigned space for the passengers and the lower part will be for the cargo. The assigned space for the passengers will have 2.5-meter height and the cargo room will have 2-meter height. The width of the room consistent throughout the climber which is 2.9-meter. For more detail of the dimension of the climber can be found in appendix.

The calculation of the area for the assigned space for the passengers by using the modified formula of area of the circle is as follow;

$$\boldsymbol{A = \pi(R^2 - r^2)} \quad (3)$$

$$A = \pi(3.398^2 - 0.5^2)$$

The available area in a level of the fuselage is 35.49 m^2. For two level of assigned space for passengers, the area obtained in the previous part is to be multiplied by 2 which resulted in 70.98 m^2 of space available.

Considering the flight duration and the comfortability of passengers in the case of space elevator, the type of room selected for the climber will be similar to hotel room with 5 m^2 per person.

By using the 5 m^2 for the area per person, it is assumed that every passenger will be placed in an individual cabin. The maximum number of passengers that can be carried on the climber at a time can be calculated by using the data obtained;

$$\text{Area per person} = 5\, m^2/\text{person}$$
$$\text{Total area available} = 70.98\, m^2$$
$$\text{Max number of passengers} = 70.98\, m^2 \times \frac{1}{5m^2/person}$$
$$\text{Max number of passengers} = 14.2 \approx (14\, passengers)$$

Therefore, the maximum number of passengers that can be carried at a time is 14 passengers including the pilots and space elevator crews.

b) Counter weight functionalities

In figure 4.6 is the prototype of the space station which is located at the higher end of the tether. The space station which is also acting as a counter weight consists of three main components as labelled in the figure. At the top part of the space station is where the living space are located and at the middle part is the control room. Located at the bottom part of the space station is the docking port for the space elevator. The docking port for the space shuttle can be seen at the upper side of the space station in figure 4.7.

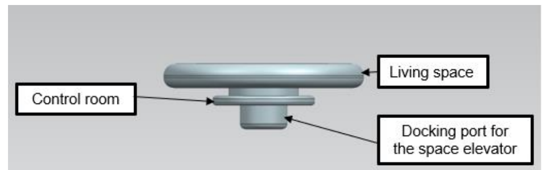

Figure 4.6 Side view of the space station [own source].

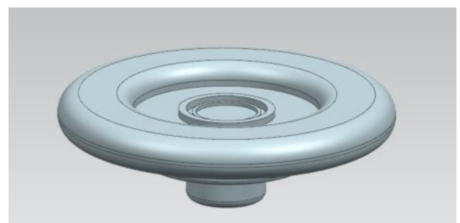

Figure 4.7 A docking port for space shuttle at the centre of the space station [own source].

Figure 4.8 was drawn according to scale and shown in the figure is the dimension in millimetre. The middle section of the counter weight will be the control room for the space station which is also directly above the docking platform for the space elevator. The total height of the counter weight is 15.8 m with 11.6 m in diameter for the living space. The depth of the climber's docking platform is 5.8 m with 7.6 m in diameter which can fully fit the climber inside the docking platform. At the top part of the space station is the docking platform which is used to provide the escape velocity for spacecraft by using Earth's rotational velocity.

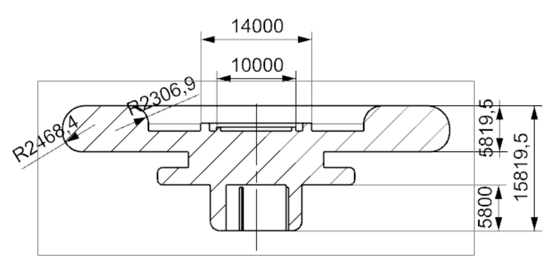

Figure 4.8 Side view of the counter weight with dimensions (mm) [own source].

V. Conclusion

The massive scale and the complexity of the space elevator is often cited as impossible to build which left the idea from being developed. The detailed study of the system for the space elevator was done in this paper which indicate that is indeed complex but comparable to other high rise building on Earth. The physics theory behind a free-standing tower was also discussed and calculated in the earlier chapter.

A space elevator model was also done by using NX12 Siemens PLM Software based on the criteria discussed. A further analysis of a possible operating system was also done based on the design created. The design proves that the construction of the space elevator can be initiated in near future with available technologies while relying on the future materials with a more desirable property.

The development of the counter weight as a space station can be started since the requirements are already known such as the minimum weight of the counter weight, the docking system for spacecraft and the docking system for the space elevator. A space station that is built at the higher end of the cable will create the construction capabilities needed for major developments beyond LEO which is absent in other space elevator design.

Furthermore, the operating analysis of the designed climber model was discussed and further development of photovoltaic arrays and power storage capacity are needed so that it can operate at high efficiency and travel for a long distance compared to other space elevator model using a conventional combustion engine.

In future work, the limitations in this project will be addressed and improved. These are the few recommendations for further development of the project. More study and research should be done to understand the requirement for the space station that is located at the higher end of the tether because of the artificial gravity that is acting on the space station. The internal design and how it operates will greatly differ than any high-rise building because of the outward force due to Earth's rotation.

In addition, the mechanism and the design of the climber should also be improved by taking account the difference in the gravity felt at different altitude during the climb to the space station. The internal design should incorporate the method of transporting the passenger in order to avoid the effect of negative g-force effect to human body that occurred during the climb to the space station.

Acknowledgments

I would like to express my deepest appreciation to my supervisor, Manuel Moreno Lupiáñez for his advice and support throughout the development of the project. His guidance and patience helped me in all time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my study.

I also would like to express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of writing this thesis. This accomplishment is dedicated to them and it would not have been possible without their help.

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