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Design of A Space Elevator as an Alternative Transport to Space

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Abstract

The idea of space elevator has existed for more than a century when Konstantin Tsiolkovsky first discovered the concept back in 1895 [1]. However, the concept only lies in the science-fiction realm since it has never been technologically feasible until now. From both scientific study and science-fiction resources, different designs will be analysed and then the best design is chosen based on suitable justifications. The outcome of this paper leads to the reveal of the best material to build the cable of the space elevator up to this day which is carbon nanotubes. The study about the cable of the space elevator has revealed the importance of incorporating taper design to prevent collapse. Another result from this paper also reveals the possibility of incorporating electromagnetic propulsion as the main driver mechanism of the climber, instead of the commonly proposed track and roller system. Other than technical aspect, this paper will also enclose the possible threats to the space elevator which are mainly caused by environmental factors such as the weather and atmospheric surroundings.

Keywords: Space elevator; Carbon nanotubes; Cable of space elevator; Climber; Electromagnetic propulsion; Standard; Hoytether design; Counterweight; Geostationary orbit; Space elevator in science-fiction.

I. Introduction

The origination of the space elevator concept has started since the late of 19th century, when a Russian scientist Konstantin Tsiolkovsky was inspired by the Eiffel Tower in Paris [1]. According to the record, he imagined creating a compression structure that outstretches all the way up to the geostationary orbit. Years after that many organizations took part in the research to make space elevator become a reality. The progress would even been better if there is a material that is extremely strong and thin enough to make the tether. Until then, space elevator might never be technologically feasible. The main component that makes up a space elevator includes a strong lightweight cable, a ballast weight, a geostationary station and also a climber unit**.** In the standard setting of a space elevator, the whole structure is under an equilibrium state, with no resultant force coming downward or upward from the system. Since the end of the cable extends up to the geosynchronous orbit, the whole assembly will synchronize exactly with the Earth's rotational speed. The main gain from space elevator is that it is believed to be a much cheaper alternatives for transportation than a conventional rocket that is still being utilized until this day.

II. Rocket has flaws

In order to travel from the Earth to space, an enormous amount of energy is essential for rocket launching. The need of a strong propulsion mechanism is crucial to defy the gravitational pull on the rocket thus makes it heavily dependent on propellant. For instance, the Venus Express spacecraft of the ESA which was launched on 9th of Nov 2005, had a total mass of about 1270 kg when it was sent on its way and not less than 570 kg of this was propellant [2]. This shows that the propellant itself makes up a big proportion of the vehicle's mass.

Apart from that, rockets are expendable, which is they can only be used once. Along the journey, rockets will deploy their empty stages so as to discard the dead weight of the rocket. These parts will then fall back down to the Earth and either splash into the ocean or burn up in the atmosphere. Thus, no component of the vehicle is left to be reused. Even though we can incorporate retrieval equipment such as parachute, the additional mass will be unfavorable to the launcher.

The environmental effect originated from rocket launchings are sickening. According to the Journal of Cleaner Production, rocket launches are the only source of ozone-depleting chemicals that are deposited directly into the stratosphere [3]. In addition, launch emissions have the potential to impact climate changes through the release of black carbon into the stratosphere. They also can impact ecosystem and human health through the release of toxic chemicals that can enter the surface of water and persist in the soil. Therefore, space elevator is believed to be a better transportation to space than a conventional rocket.

III. Space elevator concept

The concept of space elevator can be simplified down to a structure that has its bottom end tethered to a point on the Earth's surface and the other end located at the geosynchronous orbit. These two parts of the structure will be connected via a thin light-weight cable which will happen to be the most critical component of a space elevator. To summarize the force that will act on the space elevator at the geostationary height, a free-body diagram is illustrated as follows.

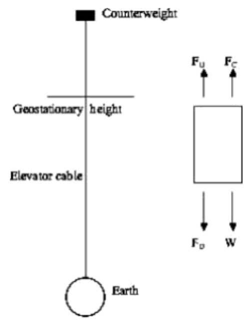

Figure 3.1. Summation of the forces acting on the space elevator at geostationary height. Source:[4].

The equation to express the forces acting on the space elevator at geostationary height is shown as follows.

$$F_U + F_C - F_D - W = 0 \quad (1)$$

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

There will be a few forces involved. Starting from the bottom side, the forces acting on the satellite are the weight of the space elevator component below geostationary altitude and the tension of the cable. This weight covers the weight of the cable, climbers and all other lower parts of the space elevator. On the upper side, the satellite will experience tension force from the cable and also centripetal force.

It is crucial to maintain the balance between the upward and downward forces since any disproportion could lead to lethal tragedies. If the centripetal force exceeds the gravitational force, the cable may break thus swinging the satellite away at great acceleration to the space. On the contrary, the structure may collapse down to the Earth in the case when gravitational force is greater.

IV. Height of space elevator

In accordance with the free body diagram shown earlier in this research, the forces need to cancel each other so as the structure stays in a static equilibrium. Assuming a differential element of the length of the cable, *dr*, where its lower end has a distance of *r* from the center of the Earth. Recalling the previous equation (1), we substitute F_U-F_D as *AdT*. In this case, the term *T* represents the tensile stress of the cable. Given that *M*, *R* and ω are the mass, radius and rotational angular velocity respectively.

$$m = Adr\rho \qquad (2)$$

$$F_u - F_D = W - F_C \qquad (1)$$

$$AdT = \frac{GM(Adr\rho)}{r^2} - (Adr\rho)\omega^2 r \qquad (3)$$

where
G: Newton's constant of gravitation [Nm^2/kg^2]
M: mass of the Earth [kg]
r: radius of Earth [km]
ρ: mass density of elevator cable [kg/m^3]
ω: rotational angular velocity of Earth [s^{-1}]

Suppose we divide both side of the equation by *Adr*, a differential equation is created as follows.

$$\frac{dT}{dr} = \frac{GM\rho}{r^2} - \rho\omega^2 r \qquad (4)$$

Since $R_g = (GM/\omega^2)^{1/3}$, we can rewrite the equation.

$$\frac{dT}{dr} = GM\rho\left[\frac{1}{r^2} - \frac{r}{R_g^3}\right] \qquad (5)$$

By integrating Eq. (5) from r=R to r=R_g, where T(R) = 0 results to the tensile stress at geostationary altitude R_g as:

$$T(R_g) = GM\rho\left[\frac{1}{R} - \frac{3}{2R_g} + \frac{R^2}{2{R_g}^3}\right] \qquad (6)$$

If the distance of the top of the cable from the Earth center is represented by letter H, it can be calculated by integrating Eq. (5) from r=R_g to r=H where T(H)=0 indicates that the tension falls to zero at the upper and lower end of the cable.

$$T(R_g) = GM\rho\left[\frac{1}{H} - \frac{3}{2R_g} + \frac{H^2}{2{R_g}^3}\right] \qquad (7)$$

If we solve both Eq. (6) and Eq. (7) to find the T(R_g) and note that H=R is a solution of the resulting cubic H. The equation can then be further simplified to a quadratic equation.

$$RH^2 + R^2H - 2R^3g = 0 \qquad (8)$$

Solving H as the subject resulting with

$$H = \frac{R}{2}\left[\sqrt{1 + 8\left(\frac{R_g}{R}\right)^3} - 1\right] = 150\ 000\ \text{km}$$

Hence, the height of the cable above Earth's surface can be figured out by subtracting the Earth radius from the value of H, which resulting in 144 000 km after rounded up to three significant figures.

V. Carbon nanotube

Apart from its strength, an ideal taper ratio is one of the factors that makes carbon nanotubes the best material of choice for the space elevator cable. A cable with taper design is believed to be more practical than a uniform cross section cable. This is due to the fact that the forces acting on the cable is not the same at every height. Since a cable will be experiencing the weight of it below, the top of the cable therefore is subjected to the greatest tension force.

By having a taper ratio of as small as 1.9, there will not be a huge difference between the lower and upper end of the cable in term of cross-sectional area. For example, a cable with 10 mm thickness would only thickens up to 19 mm at geostationary altitude. This advantage gives possible chance to widen the thickness of the cable as necessary to support the electromagnetic systems needed for the climb. In addition, the capability of transporting electricity is absolutely beneficial to the operation of the space elevator since the material can be utilized as a good power conductor for the systems.

VI. Cable design

The key concept in determining the design of the cable focuses on minimizing the mass so that the structure is as light as possible whereas the strength is maximized axially.

In the Standard Model design, thousands of individual fibers with small diameter are interlinked together by cross-connections. These connectors are tape sandwiches, which allows the fiber to support a maximum of 1 GPa tension for a 10 microns diameter fiber.

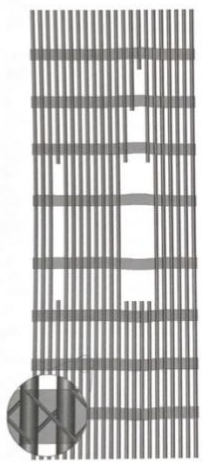

Figure 6.1. Proposed ribbon-design. Source: [1]**.**

In the Hoytether design, the carbon nanotube fibers are arranged in a vertical configuration while having a supporting fiber in between them. The support is provided by placing cross shaped fibers which can distribute the load in any debris encounter. This arrangement makes this Hoytether a reliable design in preventing any damage to the space tether. However, space tether with a Hoytether structure will most probably carry a heavier weight than the original Standard Model.

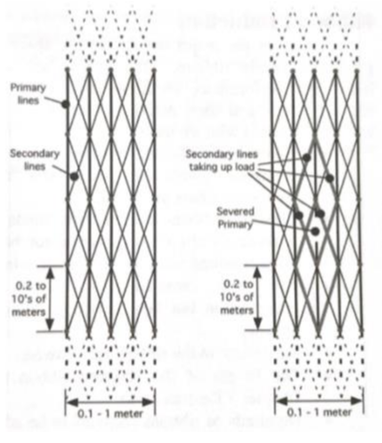

Figure 6.2. The Hoytether design. Source: [1].

Based on the strength analysis done through Siemens NX, the stress in the cable can be illustrated according to the color distribution. Based on Figure 6.3, it can be seen that the vertical strands are bearing a greater amount of stress than the horizontal connectors. In addition to that, the horizontal connectors are more closely packed than the vertical fiber, which result in greater surface area. Consequently, the horizontal connectors experience a significantly less stress distribution.

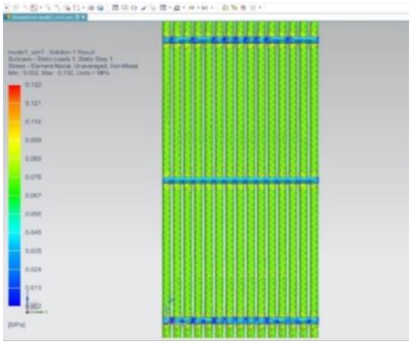

Figure 6.3. Stress distribution of a Standard model design. Source: [own source].

As for the Hoytether design, it can be seen that most of the stress is concentrated at the joints of the cable. In comparation to the strength of the Standard model, the Hoytether is relatively weaker based on the stress distribution diagram below.

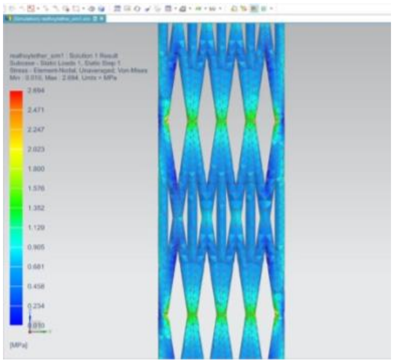

Figure 6.4. Stress distribution of a Hoytether design. Source: [own source].

VII. Space elevator components

a. Climber

The climber is portrayed as the moving component carrying the payload back and forth to the geostationary station. The climber is equipped with a docking port at both upper and bottom end of the vehicle to facilitate the docking process. Other than that, portholes are also included considering the possibility of the passenger to have viewports inside the climber. The window will be made up of aluminum silicate glass which is the most common material used for space craft windows. The porthole feature will consist of 4 panes of glass to provide extra protection.

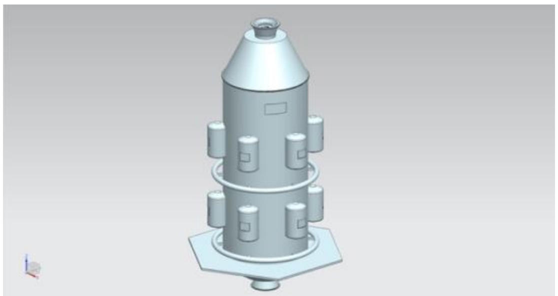

Figure 7.1. An isometric view of the climber. Source: [own source].

Furthermore, a Gallium Arsenide (GaAs) photovoltaic panel is also included to the climber. The panel is located at the lower part of the climber so as to assist the power beaming process which will be the main power source of the climber. As a protection against the space debris, the climber's fuselage will be equipped with a multi-walled system as described in the previous subtopics. In this case, the pressure wall will be made up from graphite/epoxy material while the inner bumper will be made up of Spectra/epoxy materials.

In contrast to mechanical climbers, electromagnetic climber provides a faster transportation while maintaining no contact with the railing system. Zero contact will prevent both the climber and cable structure from wearing down due to friction and subsequently saving a lot of maintenance cost. Electromagnetic climber incorporates the same mechanism as the bullet train which is MagLev. It is a system in where the vehicle will be levitated at short distance from the guide rail for thrust production powered by electromagnets. However, further development in material technology might allow magnetic dopants to be directly included into the cable structure itself, so that there is no need to individually attach the large number of individual magnets along the cable.

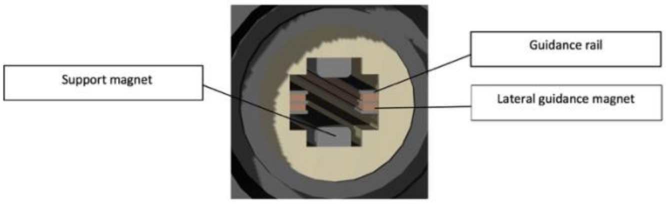

Figure 7.2. A magnified view of the magnetic drive system. Source: [own source].

In the core of the climber where the propulsion mechanism takes place, the climber will be equipped with a pair of lateral guidance electromagnets as well as a pair of support magnets for levitation. The guidance electromagnet will keep the climber move in the right track as it operates. Future research is still needed to determine the accessibility of this new technology in space industries.

b. Counterweight

The counterweight is created to provide balance to the structure. Without this component, the space elevator will collapse to the Earth because the gravitational pull will be the resultant force. For that reason, a counterweight will compensate the force by introducing a centripetal force which acts in the opposite direction to the gravitational force, thus keeping the space elevator in equilibrium state. The mass of the counterweight can be determined by the following equation [4].

$$m_c = \frac{\rho A_s T exp\left[\frac{R^2 \rho g}{2TR_g^3}\left\{\frac{2R_g^3+R^3}{R} - \frac{2R_g^3+(R_g+h)^3}{R_g+h}\right\}\right]}{\frac{R^2(R_g+h)}{R_g^3}\left[1-\frac{R_g}{R_g+h}^{3}\right]\rho g} \quad (9)$$

Where m_c is the mass of the counterweight in kilogram and h is the height of the counterweight above geostationary orbit in meter. Based on the equation, note that m_c approaches infinity as the value of h reaches zero.

In the science-fiction space elevator concept, the counterweight is commonly made up of big asteroid that is already exist in the space. However, that may not be practical for a real-life situation and for that reason, a heavyweight space craft is proposed to take the role as the counterweight.

c. Base anchor

An anchoring point is the point where the cable will be tethered on the Earth's surface. Previous researches have shown that the location of this base point must be at the equator for some reasonable justifications. First, the location will have the same angular velocity relative to that of the center of the Earth. Therefore, the station at geostationary altitude will always hang about the same point above the equator as the Earth rotates on its axis and the cable will always be stationary and vertical. Other than that, the equatorial region often experiences very mild climate if compare to those of the southern and northern region. It is indeed an ideal zone for space elevator construction and operation since the weather hazard is at minimum level.

Since most of the region at the equator is made up of oceans, mobile platform is an ideal choice since there is a vast location to choose from. Most importantly, a floating platform situated on a remote location can provide an assurance of safety in the case of the first attempt of space elevator operation went bad. In a worst-case-scenario, a failed structure would not have imposed as much damage as it would have been if the base is located on land, where any other facilities and infrastructure can be found nearby. Moreover, placing the platform on a remote location also give efficient protection against any attempt of sabotage or terrorist attack. A previous oil exploration base or drilling ship is most likely to be a preferrable platform since it provides living amenities and power supply.

d. Geostationary station

This specific station is conveyed as the main space hub where all the major transportation between the Earth and the space will take place. For that reason, the geostationary station will be equipped with amenities such as docking port to facilitate connection with other space vehicles. In addition to that, there is also a designated area in the station for the living space. This area includes the accommodation for the all the staff at the station and guests, control office, research laboratories and space elevator terminal. Just like the climber, the geostationary station will incorporate a multi-walled system to provide protection against space debris impact.

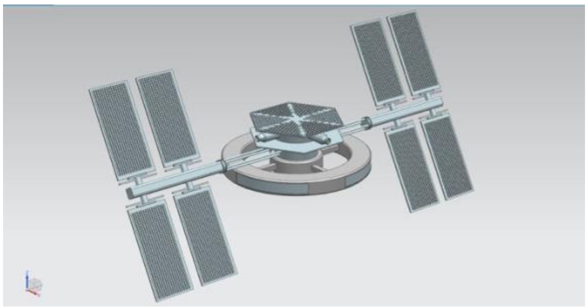

Figure 7.3. An isometric view of the geostationary station. Source: [own source].

The main power supply used for the station is solar energy. For that reason, a wide number of solar panels is incorporated to the system to maximize the direct absorption of sunlight for electric generation for the on-board usage. The design of the solar panel is inspired by the one used in the International Space Station by NASA [5].

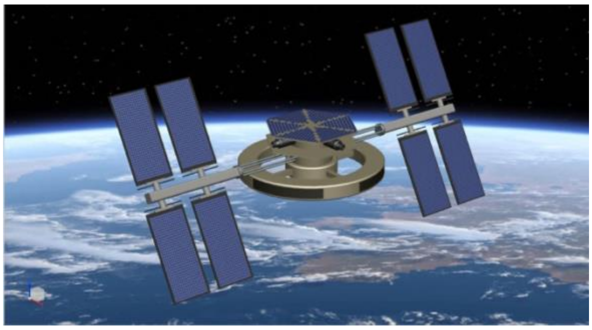

Figure 7.4. A realistic 3D model of geostationary station of the space elevator. Source: [own source].

VIII. Space elevator model

Component	3D model dimension	Main features	Ratio of 3D model to real scale
Climber	Height= 264,4 mm Diameter= 80 mm	I. Electromagnetic drive system II. Photovoltaic cell III. Docking ports IV. Multi-walled system	1:1000
Geostationary station	Height= 42,5 mm Outer diameter= 586 mm Inner diameter= 436 mm	I. Docking ports II. Solar panels III. Living space IV. Multi-walled system	1:1000
Cable	Length= 2880 mm Upper end diameter= $2,28x10^{-5}$ mm Lower end diameter= $1,2x10^{-5}$ mm	I. Tapered cable II. Protective layer coatings	1:50000000
Counterweight	Diameter= 800 mm	I. Initial cable deployment before serves as counterweight	1:10000

Table 8.1. A brief summary of the proposed space elevator design. Source: [own source].

Figure 8.1. A 3D assembly of the space elevator excluding the base anchor. Source: [own source].

IX. Challenges

a. Mechanical resonance

One of the main challenges in the safety of the space elevator is mechanical resonance [3]. Even though the structure will be stationary, the cable will still be subjected to oscillation, be it transverse or longitudinal. Whereas any compression and tension force along the cable will result in longitudinal oscillation, any force that causes the perpendicular movement of the cable creates transverse oscillation. These movements may not be noticeable by visual observation, but they are present along the cable. On top of that, there is also torsion. These oscillations and torsion are categorized as the internal movement of the system.

When there is an external force applied to the system, there might be a possibility of the cable to move similar to its resonance frequencies. Subsequently, this phenomenon will cause the cable to move vigorously due to an increase in amplitude. The main concern that can possibly provide an external force to the space elevator is the wind from the Earth atmosphere. Apart from that, the ultra-speed movement of the climber back and forth to the geostationary altitude can also be one of the factors that contributes to external force. For that reason, the climber will be prohibited to travel at certain speeds to avoid transverse oscillation of the cable. Another initiative to reduce vibration along the cable is by installing dampeners at the anchor base.

b. Environmental issues

Since the space elevator connects both the Earth and the space, the structure will be exposed to various atmosphere which can potentially cause damage to its components. In this context, the lower part of the space elevator is exposed to the Earth atmosphere, in which the main concern is the weather condition such as cloudy and windy. Apart from that, the upper part of the space elevator will be subjected to outer space, where the environment is much more extreme in term of temperature and radiation damage. There are numerous threats in the space environment such as meteoroids, space debris, ultraviolet radiation and atomic oxygen. These factors are significant enough to cause harm to the material used for space elevator components such as material erosion and collision. For that reason, it is essential to study the space environmental effect before designing each component of the space elevator to ensure a prolong survivability of the structure. Aside from space surrounding, lightning strike in the Earth atmosphere could likely destroy the cable. This is due to the fact that an average lightning bolt consists up to one billion volts of electricity which is enough to snap the cable.

X. Conclusion

The concept of space elevator would be a great development in the space technology. The reason behind this statement is that the space elevator will be known as a better transportation system between the Earth and the space, which offers the same service as conventional rocket, but at cheaper price point. However, the construction of this structure comes at a price. Prior to building space elevator, the parties involve should carry out an in-depth research for every inch of the space elevator concept due to its complexity. Based on the study done in this paper, there is a wide range of challenges that could result in the failure of the structure such as external threat, unavailability of suitable material for the construction and even the lack of appropriate technologies for the development of the space elevator.

Based on the study, some conclusion can be made for the design of the space elevator. For the cable design, the Standard model design is chosen since it has a greater strength than the Hoytether design. This can be proved by a better stress distribution for the cable when it is put under the stress analysis through Siemens NX. This cable will be made up of the most suitable material for space elevator to date, which is carbon nanotubes. A protective layer coating made up of silicon containing material or metal is necessary to overcome the risk of atomic oxygen erosion.

As of the design of the climber, the component will incorporate an electromagnetic propulsion mechanism while using power beam as the power source. An electromagnetic propulsion mechanism which is inspired by the ultra-speed bullet train is believed to be a better choice than a conventional track-roller system which depends on mechanical propulsion. Since electromagnetic driver system is more commonly used as the climber propulsion in the science-fiction publications, there is still a wide room for exploration under the topic. For example, further discoveries are needed to incorporate long stator to the cable. In addition, the climber will incorporate a multi-walled system to its fuselage as a protection measure against space debris impact. In this case, the pressure wall will be made up from graphite/epoxy material while the inner bumper will be made up of Spectra/epoxy materials.

For the geostationary station, the main power supply would be solar energy which will be absorbed by the solar panel installed to the station. The station will also be equipped with amenities such as docking adapter to facilitate connection with other space vehicle.

In the future work, more specification is required in the details of the climber. For example, the weight limit of the climber and its payload is not discussed in this study. This vague fact will bother the determination of maximum number of passengers on the climber during the journey up to geostationary station.

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