12/12/2016

Reusability of space systems and space elevators

ENAE283H

Instructor: Dr Becnel

Abstract

This paper will be split into two main parts. Before these however, a discussion of the importance and history of reusable space systems is presented, in order to provide context for the paper. The first main part of the paper is an analysis of some technical challenges regarding reusability in space systems. The second part will focus on specific technologies which will increase reusability and make space access easier, specifically space elevators. The paper will conclude with recommendations for future research.

Noah Jarrah

114182524

Contents

Table of figures

Preface

Someone once made the point to me that a space shuttle required five months of maintenance between missions while a commercial airplane can land, refuel, exchange passengers and be on its way again in about twenty minutes. This is why there is so much development into "space planes" like the Virgin Galactic SpaceShip2. That concept intrigued me, leading to the conception of this particular paper. However my research uncovered that the main preclusions to reusability lay in launch and so the methods of avoiding launch became central to my internal concept of "reusability".

Introduction:

When the United States first began the Space Race during the Cold War, our mission was simple: get to space as fast as we can. Money was almost of no object: after the USSR beat it into space NASA got all the resources and funding that it needed. John F Kennedy requested, and received, from congress in his 1961 speech "to provide the funds which are needed to meet the following national goals"; landing a man on the moon and creating the first iteration of GPS, among others. of (at least partially) reusable space systems (Kennedy, 1962) . There was little to no consideration of the environmental impacts or long term operation of those actions.

That choice was perhaps prudent, but the point of this paper is not to pass judgement either way. As time went on, the Space Shuttle program proved to the world the feasibility of (at least partially) reusable systems, with the OV-103 *Discovery* claiming 39 missions and 27 years in service (Chow, 2011). Studies on the space shuttle program made it evident that space systems must be reusable, partially for the economic benefits reaped. It has eventually become industryaccepted that reusable systems are the future of space travel. However, this is easier said than done.

Barriers to reusability

There are untold amounts of issues surrounding the issue of reusability. Inherently, every aerospace system is a complex balance of payload capacity, aerodynamics, weight, thrust, safety and many other factors. Therefore, to gain benefits in one area, other areas may be sacrificed. This paper will focus on two of these issues: fatigue and fuel use.

Fatigue in materials

Materials have max stress vs number of loading cycles as described in figure 1. In this example the S-n graph of 6061-T6 aluminum is given but a similar curve can be found for most materials. Note that the curve levels off below a certain S – this is the Endurance Stress and any material subjected to stress less than this will last "infinitely", ideal for static structures. The aerospace engineer *must* design in the "high risk" portion of the graph shown as weight must also be considered. This design will have a lesser life than static structures, and therefore impedes reusability.

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 1 A S-n curve for 6061-T6 Al (Yahr, 1993)

Furthermore, a rocket launch is perhaps one of the most stressful events possible (both for the materials and launch control)! A g-force graph is given by figure 2 for the Saturn V rocket launch profile. G-forces up to 4 are applied, and this does not even consider vibrations or thermal loads that are present. In fact, in 1971 NASA estimated that vibrations at launch (from waves reflecting off the ground, being significant in the "first 10 seconds of launch") caused 30-60% of launch failures. Vibrations can reach up to 200Hz and can cause "serious structural and equipment failures or complete mission failure" on their own. (Caimi, Margasahayam, & Nayfeh, 2001). So high vibrations combined with high accelerations (meaning higher forces and higher component stresses) lead to significant design considerations.

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 2 A typical acceleration profile for a Saturn V rocket launch (Hill, Kotys-Schwartz, Yakacki, Yowell, & Zarske, 2004)

The primary purpose of any launch is of course to deliver a payload into orbit, say a satellite. That satellite now not only must be designed for its own function, for example as a GPS satellite, but also to withstand the stresses that it will be exposed to at launch. This is commonly done (in relation to electronics) with vibration isolators. A single vibration isolator may around 215g – which doesn't seem like a lot (Li & al, 2014). However, mass is extremely costly when it is trying to get to space – around $25,000 per kilogram. This lowers the actual *mission-designated* mass fraction. Considering that the initial mass fraction is only usually around 0.07 to 0.09, this becomes a real issue when every "useful" component of the payload must be protected in this way and "overdesigned" just to survive launch conditions (Anderson Jr, 2010).

The rocket itself also does not fare well in a satellite launch. All of the "structural" components like the fairing, tanks and internal supports must also be engineered for launch. Combustion chambers, in particular, go through high-to-low pressurizations during launch. An advanced copper-nickel combination tank analyzed by NASA in 1974 indicated that the tank had a mean like of 35 firings but the testing was completed only with thermal loads – no mechanical loads at all (Miller, 1974)! A similar analysis for a copper/stainless steel combustion chamber used by the ISRO yielded a life of merely one use (Asraff, Sunil, Muthukumar, & Ramanathan, 2010).

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 3 Design of the ISRO Copper-nickel thrust chamber (Asraff, Sunil, Muthukumar, & Ramanathan, 2010)

These high stresses have (partially) led to very high payload rockets like the Saturn V (the record holder for maximum payload delivered to LEO, at 144,000kg) to be completely disposable.

Fuel use

Another constraint to reusability is the amount of rocket fuel used in each rocket launch. Figure 4 summarizes the types of propulsion currently available and estimates for available thrust. As can be seen, chemical rocket fuels are the only option for large payload delivery into space as large thrust is required for liftoff and acceleration to orbital velocity (Hill, Kotys-Schwartz, Yakacki, Yowell, & Zarske, 2004).

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 4: Table of typical rocket propulsion methods and their related Sis and Thrusts (Hill, Kotys-Schwartz, Yakacki, Yowell, & Zarske, 2004).

The other types of propulsion are acceptable once orbit has been reached and for deep-space propulsion but are completely ineffective for liftoff. Therefore, chemical fuels are, as of now, *completely necessary* for space missions. This presents an issue in the scope of this paper: materials are not infinite. A SpaceX Falcon 9 launch uses about 400,000 kg of propellant (LOX and RP-1) which costs around $200,000 per launch according to Elon Musk (Space Flight 101, 2016). LOX, the oxidizer for RP-1, has a boiling point of 90.19K meaning it must be stored under cryogenic conditions. It also must be fractionally distilled from air in huge scales. RP-1 is a distilled form of kerosene which must go through many forms of processing before it can be used (AOGHS, 2016). These include removing sulfur and alkenes in the base oil, which itself must come from select fields with good-quality raw oil – and it is clear that heavy oil use is not sustainable.

Other considerations

Rocket launches cost around $225 million (ULA, 2015). However, from above, the actual cost of propellant is a very small percentage of this – the rest of the costs come from personnel, R&D of the system, satellite testing and many other factors, including profiteering. Although not a monopoly, there are a small number of corporations (SpaceX, ULA) that provide private access to space which, while not quantifiable, likely drives up costs.

Summary of technical challenges

We can conclude from the above information that a large barrier to effective and reusable space systems that are optimized for their mission is rocket launch. During launch there are many stresses that will never again be present in the systems' life (especially for satellites) leading to overdesign. Therefore, logically the best way to drastically increase the reusability and mission effectiveness of space systems is to remove the requirement for launch. So how can this be achieved?

Space elevators

Consider a large pylon extending 36 kilometers above the earth's surface (at the level of geosynchronous orbit) from which you release a small sphere. The sphere will simply stay exactly where you left it – with no fuel required at all. You have just created a satellite that will – in theory – remain in orbit infinitely (discounting atmospheric drag). Once there, the energetic cost to remove this satellite from Earth orbit and send it wandering the solar system is 1.4 times less than it would have been to put it there via propellant only (Anderson Jr, 2010). This is a space elevator – potentially the simplest form of energetic reduction. Of course, the scenario just described has many issues, the primary one being: how can one possibly build a 36-kilometer-tall structure? Current construction techniques can barely break 800m tall (Burj Khalifa) (Emaar, 2016). The solution is quite innovative: instead of a structure in compression (as all current buildings) the elevator would be a cable in tension, with a counterweight

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 5: A typical space elevator design (Swan & et, 2013)

in space. The tensile force is provided by the centripetal forces acting on the counterweight and "pulling" the cable into space!

Related physics, equations and design considerations

The material in this section is sourced from The Physics of the Space Elevator *by Professor P. K. Aravind of Worcester Polytechnic Institute, an article published by the American Journal of Physics.*

The design of the space elevator is highly conceptual as the technology required is simply not present now, as will be seen. A column design is taken as an example. First, the stresses in the elevator must be calculated.

If T is the stress in the shaft, R_g is the height of geostationary orbit, ρ is density of the material and r is the radius from the center of the earth then the following equation is true for an elevator:

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

Then the maximum T occurs when $r = R_g$ and is

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

Where R is the radius of the earth (this solution is obtained by integrating the above expression from R to R_g). Then given that each tip of the elevator must have T=0, the total height may be solved for. This height represents the height of a space elevator in equilibrium.

$$RH^2 + R^2H - 2R_g^3 = 0,$$

This gives H=144,000 kilometers.

Now given the above equations, certain material properties can be tested (noticing max stress is only dependent on density of the material) and then compared to the maximum allowable stress for those materials. The results are tablated in figure 6.

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 6: A table showing the SF of conventional materials. Properties taken from (Engineer's Edge, 2000).

As can be seen, from a cylindrical design even the strongest materials cannot even come close to the required strength for the elevator. Therefore more creative approaches were required. Figure 7 shows an element of the cable with height dr and change in area from one end to the other as dA. As stress is force per unit area, the idea is to thicken the column at places of most force (ie, at GEO) and have less thickness at places with least force (at the ends) – a tapered design. This also reduces total column weight. Therefore area proportional to the force in the element (in order to keep stress constant throughout) is

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 7: A tapered cable design (the tapering is exponential but shown as linear for simplicity). (Aravind, 2007)

$$A(r) = A_s \exp\left[\frac{\rho g R^2}{T}\left\{\frac{1}{R} + \frac{R^2}{2R_g^3} - \frac{1}{r} - \frac{r^2}{2R_g^3}\right\}\right]$$

Which is an exponential increase to R_g and then exponential decrease. It is dependent on the cross sectional area of the elevator at the surface, A_s, and density. Therefore the required taper ratio (Area at GEO, the thickest part divided by the area at the surface, the thinnest part) can be calculated again for certain materials. Figure 8 shows the results (L_c is simply a rearragement of previous variables, the *characteristic length*).

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 8: A table showing density, max applied stress, characteristic length, and taper ratio of certain materials. (Aravind, 2007)

Therefore we still find that typical and non-typical contruction materials still require ridiculous taper ratios and are infeasible. Hoowever we can see that carbon nanotubes provide a viable solution!

Given some assumptions about the weight of the actual crawler at one metric ton (the part that climbs the cable to deliver payloads) and the maximum stress allowed to be borne at 50GPa, A_s can be fixed at $1.5 * 10^{-7}\ m^2$ and the taper ratio can be calculated to be 4.28. Furthermore, the length of the cable can be shortened to 100,000 km with addition of a counterweight at the end, of around 53 tons . These are relatively reasonable values for carbon nanotubes, which may have a tensile strength of up to 300 GPa (although some more conservative studies say 130 GPa).

Therefore we can conclude that, theoretically at least, space elevators are a physical possibility.

Getting up the "elevator"

Now that we have a "reasonable" elevator design we must consider how to "climb" it. A conventional counterweight system would not be feasible due to the simple length of the elevator. One idea is a "crawler" (see figure 9) that clings to the cable via friction and rolls up the elevator via mechanical means. However, since we are considering a rotating body, we must reevaluate the accelerations that act on the crawler. Normally the gravitational acceleration on the body of the earth is $g = \frac{GM}{R^2} = 9.81\frac{m}{s^2}$. Now the "imaginary" centripetal force term comes into play.

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 9: Artist's impression of a microwave-powered crawler (Gajitz, 2009)

$$g_{apparent} = -\frac{GM}{r^2} + \omega^2 r$$

And so $g_{apparent} = 0\ for\ r = GEO$, $g_{apparent} < 0\ for\ r < GEO$ and $g_{apparent} > 0\ for\ r > GEO$. This shows that as the crawler gets higher, the forces dragging it downwards will be reduced more quickly than those on a rocket, because of the forces inherent in circular motion! In fact, it will drag itself upwards after GEO! This reduces the differnece in energy costs between getting from GEO to HEO to 0J.

Powering the crawler

If the crawler is to climb mechanically it will need a power source to do so. It would be impractical to have a conventional form of energy on board as this would reduce payload weight available significantly. Instead, the crawler could have a very energy-dense power source on board like nuclear fusion, or alternatively could carry microwave receivers to collect microwaves transmitted from a generator station at the bottom of the tower. A similar concept has the counterweight redirecting solar rays to a receiver panel on the crawler (ISEC, 2011).

Construction techniques

Conventional construction techniques quake at the thought of building the elevator. It would be impossible to build support structures tall enough – otherwise the elevator would not be necessary! One thought is that a "spool" of the material would be launched into GEO by conventional rocketry and then lowered onto the surface at a desired location. This is feasible given that the example cable mentioned previously would only weigh 97.7 tons – within the tolerance of the Saturn V rocket (Aravind, 2007). Then, specialized crawlers could thicken the cable to the required thickness. Other concepts involve a tether building to decrease the length of cable required.

Once one elevator is constructed, it would be much easier to construct others using the techniques described above as the other spools would not need to be launched into orbit.

Space Junk

The space elevator faces numerous other challenges. Space junk is a primary one. There is currently 500,000 pieces of space debris in LEO (figure 10 is a computer model of this). This poses a significant threat to a space elevator, thin as it may be. Multiple solutions have been proposed to this. One is an interlocking "lattice" of cables to increase strength, or making the cable ribbon shaped with one extremely (microns) thin edge to minimize impact chances (Artsutanov, 1960). Furthermore, the

DRUM note:
Image has been removed from this paper due to copyright restrictions.

Figure 10: a computer simulation of space junk (exaggerated) (BBC News, 2016)

problem of space junk has begun to be solved. A Japanese company recently launched a 700m long magnetic cable to slow and deorbit space debris (BBC News, 2016).

Conclusions and future research

As can be seen, technology must progress in many areas before space elevators are a realistic concept. However, the International Academy of Astronautics conducted a lengthy review of this technology and concluded that "space elevators seem feasible" (Swan & et, 2013). A space elevator would enable more focused space vehicle planning, easier access to space and simple transitions into escape velocities (via slingshot maneuvers) from the Earth and the Solar System (Aravind, 2007). Finally they may lower per kilogram costs of sending a payload into orbit to as little as $500 (ISEC, 2011)!It is the belief of the author that they are the best option for facilitating future space exploration.

In order to make this concept possible, more research is required into carbon nanotube technology, as well as remote energy transmission or nuclear energy. Also, the issue of space debris must be adequately addressed, preferably in a permanent manner such as the magnetic decelerator.

Bibliography

Anderson Jr, J. D. (2010). *Introduction to Flight* (6th ed.). New Delhi: McGraw-Hill Education (India).

AOGHS. (2016). *Kerosene Rocket Fuel*. Retrieved December 11, 2016, from American Oil and Gas Historical Society : http://aoghs.org/products/kerosene-rocket-fuel/

Aravind, P. (2007, February). The physics of the space elevator. *American Journal of Physics, 75*(2), 125-130.

Artsutanov, Y. (1960). *To the Cosmos by Electric Train.* Leningrad: Leningrad Technological Institute.

Asraff, A., Sunil, S., Muthukumar, R., & Ramanathan, T. (2010, April). Stress analysis & life prediction of a cryogenic rocket engine thrust chamber considering low cycle fatigue, creep and thermal ratchetting. *Transactions of the Indian Institute of Metals, 63*(2), 601-606.

BBC News. (2016, December 9). *Japan tests innovative magnetic tether for slowing space junk*. Retrieved December 12, 2016, from BBC News: http://www.bbc.com/news/world-asia-38265676

Caimi, R., Margasahayam, R., & Nayfeh, J. (2001). *Rocket Launch-Induced Vibration and Ignition Overpressure Response.* Titusville: NASA Kennedy Space Center.

Chow, D. (2011, July 5). *The 3 Most Flown Space Shuttles of NASA's Fleet.* Retrieved December 12, 2016, from Space.com: http://www.space.com/12173-nasa-space-shuttles-miles-flown.html

Emaar. (2016). *Burj Khalifa*. Retrieved December 10, 2016, from Burj Khalifa: http://www.burjkhalifa.ae/en/index.aspx

Engineer's Edge. (2000). *Yield Strength.* Retrieved December 10, 2016, from Engineer's Edge: http://www.engineersedge.com/material_science/yield_strength.htm

Gajitz. (2009). *Sci-Fi Surprise: Real Space Elevator Closer Than You Think*. Retrieved December 11, 2016, from Gajitz: http://gajitz.com/sci-fi-surprise-real-space-elevator-closer-than-you-think/

Hill, G., Kotys-Schwartz, D., Yakacki, C., Yowell, J., & Zarske, M. S. (2004). *Lesson: Get Me Off This Planet*. Retrieved December 10, 2016, from TeachEngineering: https://www.teachengineering.org/lessons/view/cub_mars_lesson04

ISEC. (2011, April). *Space Elevator FAQs*. Retrieved December 12, 2016, from ISEC: http://www.isec.org/index.php/2016-05-29-06-04-13/space-elevator-faq

Kennedy, J. F. (1962). Rice Stadium Moon Speech. [mp3]. Houston, Texas, United States of America. Retrieved November 25, 2016, from https://er.jsc.nasa.gov/seh/ricetalk.htm

Li, W., & al, e. (2014, December). Design and experiments of an active isolator for satellite micro-vibration. *Chinese Journal of Aeronautics, 27*(6), 1461-1468.

Miller, R. W. (1974). *Cyclic Fatigue Analysis of Rocket Thrust Chambers.* Cleveland: NASA Lewis Research Center.

Reagan, R. W. (1986). Explosion of the Space Shuttle Challenger. [mp3]. Washington D.C., United States of America. Retrieved November 25, 2015, from http://history.nasa.gov/reagan12886.html

Space Flight 101. (2016). *Falcon 9 v 1.1*. Retrieved December 10, 2016, from Space Flight 101: http://spaceflight101.com/spacerockets/falcon-9-v1-1-f9r/

Swan, P., & et, a. (2013). *Design Considerations for Space Elevator Tether Climbers.* Seattle: ISEC.

ULA. (2015). *FREQUENTLY ASKED QUESTIONS - LAUNCH COSTS*. Retrieved December 10, 2016, from ULA: http://www.ulalaunch.com/faqs-launch-costs.aspx#What-does-a-single-launch-cost

Yahr, G. (1993). Fatigue design curves for 6061-T6 aluminum. *1993 American Society of Mechanical Engineers (ASME) pressure vessel and piping conference.* Denver: Oak Ridge National Lab.