A winding solution to the space elevator power problem

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***Abstract*— A solution to the space elevator power problem is proposed. Climbers are attached to a constant section cable and the cable is wound and unwound on demand at both ends. Both winches are powered by electricity, the top one being driven by photovoltaic solar panels.**

I. INTRODUCTION

Today's most probable space elevator design is based on a carbon nanotube ribbon cable and lifters climbing it with electric motors powered by energy transmitted by ground-based laser beams. We describe a way to do away with the need for laser beams to transmit energy to the lifters in order to propel them up along the space elevator ribbon.

We assume here that the space elevator (SE) cable has a safety coefficient of at least two and is constructed from a constant section CNT material with a tensile strength of 152 GPa from the ground up to 150,000 km. The 'reference S.E.' from the NIAC phase II report cost is US$6 billion, of which one third is to power the climbers through laser beaming.

Our proposed solution is somewhat different: Our ribbon will be heavier and longer (about 150,000 km) and the lifters will not climb the ribbon but will simply be attached to it. The climbing movement will be done by the ribbon itself. Let's explain: we suppose that the ribbon is initially deployed without any load and the lower 35,900 km of the ribbon reeled-in on a large spool at the ground station. Due to the presence of a counterweight at the top end, the ribbon's centre of gravity is farther than the geostationary orbit (GEO) and it will remain stressed under all load conditions. Then we attach a lifter to the ribbon and release it by unwinding our spooled ribbon. Under the centripetal forces applied to the counterweight (CW), the lifter climbs away from the earth up to the geostationary orbit, where it can be released and a new cycle restarted. A similar method can be used to bring down payload.

The problem is that as the counterweight recedes, the ribbon is more and more stressed due to the increasing centrifugal force applied to the ribbon and to the counterweight. To reduce the stress to acceptable values, at the same time as we unwind the ribbon at the earth level, we wind it on a large storage spool inside the counterweight. Thus, as the payload climbs up to the GEO, the counterweight lowers itself from 150,000 km to 71,500 Km while its weight increases twentyfold from 15.6 to 313 tons. The needed energy is provided by solar panels at the CW level. As the system needs a 15 ton minimum counterweight in any case, the best use we can put this mass to is to use it as a maintenance station including a large solar power source and a giant winch to store the ribbon.

During the descent phase, the CW will unreel its spool and recede again while the ribbon is reeled in once again on the ground. In this phase, uncoiling the ribbon at the top end provides a large amount of unwanted energy that will be dissipated through large heat radiators. Of course, it could also be used to recharge batteries and to provide energy to the station ancillaries.

The obvious advantage of the method is that we no longer need complex laser beaming to power the climber, saving US$2 billion and a lot of complexity. With a properly designed deployment phase the saving is more than enough to finance the extra ribbon manufacturing and launch cost.

II. RIBBON MAINTENANCE

As already established in the NIAC study, the lower 5,000 km or so of the ribbon are the most exposed to various risks such as wind, thunderstorms, low earth orbit debris and atmospheric oxygen corrosion. With the proposed reel-in space elevator concept the repair and maintenance work needed by the lower 35,800 km of the ribbon can now be done in a safe place, on Earth, greatly simplifying the repair and splicing equipment. The upper part of the ribbon may also need repairs but, once again, the whole ribbon top part is periodically stored and released from the CW station, where maintenance operations could take place more easily than on board the climbers themselves as in the 'reference SE' model.

In case of major damage to a large part of the ribbon above 35,900 km, the system can be used without payload, uncoiling fresh new ribbon at the ground level and cutting and discarding the extreme top part of the ribbon at the same time at the CW. This continuous process can be done as long as needed.

Compared with the NIAC ribbon, our cable will be repaired, reinforced and even replaced in two locations only. The lower 20% of the cable will be cared for on Earth with unlimited access to human workforce and technology. The remaining 80% will be accessible from two specific locations: at the end counterweight, where the top 60% of the ribbon will be periodically coiled and uncoiled, and at the GEO, where an arbitrary size station could be build over time. The GEO station will see at each cycle the central part of the ribbon passing by.

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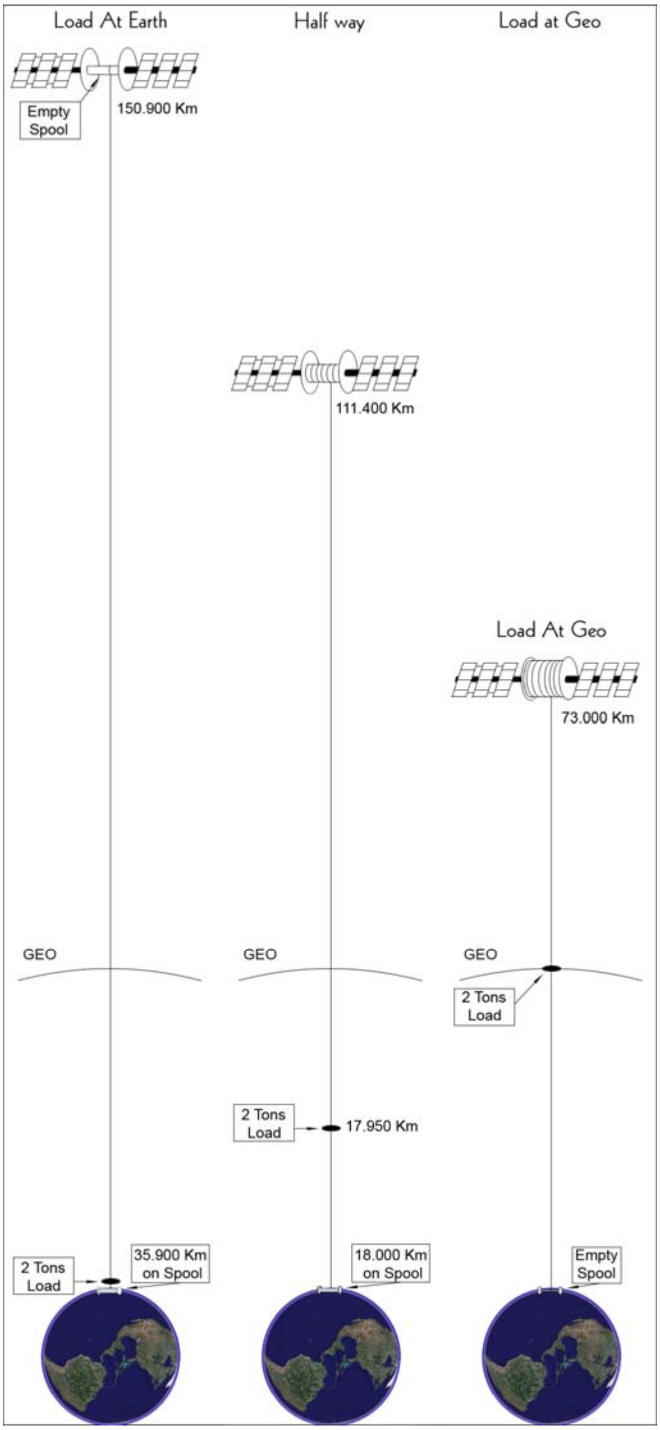

Fig 1. The Reel-In Space Elevator at Earth, half-way and at the end of the climbing process.

Even without any maintenance station at GEO, 80% of the cable is accessible from one of the extremities and the last 20% may be partially replaced by fresh ribbon segments coming from the ground if Earth produces more ribbon than needed and the CW discards the same amount at the other end at the same time.

III. CONSTANT CABLE SECTION

The most obvious drawback of the described method is that the ribbon shape and coating cannot be adapted to the threats encountered at various altitudes. In the Edwards reference design [1], the payload is 20 tons with 89 tons for the tapered ribbon. In our constant section design, the total cable mass is 483 tons for a 3 ton payload. To achieve our system, we need a super strong ribbon cable with a tensile strength of 152 GPa, twice as strong as the one envisioned in the NIAC study at around 65 GPa, but still well behind the carbon nanotube’s (CNT) theoretical strength limit of 300 GPa.

The deployment phase of a constant section cable may also be complex, but as the progressive increase in cable section and weight can be done easily with simple operations at the ribbon’s ends, the related mechanisms will be simpler and more reliable.

Some optimization of the final reel-in space elevator should be possible by allowing a tapered ribbon for the part above GEO that is always less stressed than the allowed maximum. However, this will cancel most of the advantages of a constant section ribbon all along, such as easy maintenance.

IV. RIBBON CABLE ELASTICITY

Taking elasticity into account slightly modifies the SE simulator behavior. The data obtained are not only more realistic but also more optimistic. According to recent research efforts on CNT mechanical behavior, we can assume that the elastic lengthening of the ribbon will reach several percent when stressed. Five percent seems to be a good estimate. The net result of introducing elasticity in our Reel-in SE model is that the payload can be increased by around half the maximum elastic lengthening, thus around 3%. However, the model also shows that the ribbon acts as an energy storage device by accumulating and releasing energy when the specific stress changes.

The total energy balance remains unchanged after a whole cycle since, during the cycle, the energy spent to stretch the ribbon is recovered when it is relaxed. Another consequence is that acceleration of moving parts such as climbers and the counterweight are lower than in the unelastic model, which increases the overall comfort and lowers the vibration level. The stress on all mechanical elements such as winches and clamping mechanisms is also deadened.

V. STABILITY AND DEBRIS AVOIDANCE

According to the reference book in space tether systems [8] and the recent stability study by Prof. Pugno [5], any space elevator is unstable if it is not taut enough. Without going into the details, almost impossible stiffness and strength will be needed to ensure full stability of the elevator system under natural forces only. Prof. Pugno suggests adding a large mass at GEO along the cable to increase the stability. In any space elevator system, the ideal location for a space station is obviously at the geostationary orbit. For many reasons, the station will be equipped with ribbon winding and unwinding capacity. This mechanical setup will give the station control over its own precise location and the ability to interact with the ribbon.

Equipped with small directional rockets, the station will be able to move the ribbon north-south and east-west to avoid flying orbital debris detected by space or ground radars and to regain stability if needed. Vertical position adjustment of the station will be done by mechanical displacement relative to the ribbon itself.

It is well known that the most dangerous altitude range for the SE is between the ground and 2,000 or so km because of atmospheric interaction and low Earth orbit debris. To ensure a quick reaction and avoid space debris detected at the last minute, moving the ribbon Earth base could be way too slow, with a lateral move taking hours if not days to have any influence on the high-altitude location of the ribbon. Quick reaction could come with far greater efficiency from several small 'impulsers' attached to the cable. Our moving ribbon could be fitted with such devices weighting only a few dozen kg every 5,000 km. or so. Each 'impulser' will be equipped with a four control rocket thrusters and the related transmission, command and control electronics. They will be able to give the ribbon section where they are implanted the needed impulsion to avoid an incoming thread some at least ten times faster than by using base movements alone.

VI. CHEAP CLIMBERS

One advantage of the reel-in space elevator is that the climber can be almost 100% payload, as it doesn't need any motor, energy source or any other high-power systems. The supporting structure needs only a simple clamping and unclamping mechanism to move to the GEO. Of course, climbing 'down' beyond GEO will require some kind of controlled braking during the movement along the cable. The most obvious solution that comes to mind is an electrical brake system with heat dissipation by radiant panels.

VII. ENERGY

In the proposed system, two energy sources are needed to feed the two active elements of the elevator; the winches at both ends. On the ground, a large facility to store and repair the ribbon could be easily installed at the anchor station. The electric winch that reels the ribbon in could be powered by a local power station. When the cable unwinds, a mechanical braking force has to be applied to control the winch speed. This will be easily done by using the electric motor of the winch as a generator. The electricity produced during this operation could be reused by the anchor base power grid. As a large part of the electric energy is recuperated when the ribbon is unwind, the energy balance of the system is very good. The net energy provided to the system for a full cycle corresponds only to the efficiency losses in the various mechanical devices. In any case, the required energy will be produced and converted on the ground at the same costs as in a large industrial plant, not at spaceship costs.

On the counterweight station, the whole installation will be unmanned and working automatically. The simplest setup will be similar to the one at the anchor station but with electricity provided by a large set of solar panels for reeling in the ribbon when the counterweight comes back toward Earth when a payload is lifted. During the other phase of the cycle, when the ribbon is reeled in on the ground, it is unreeled from the counterweight at the same time, producing electricity while the counterweight escapes partially the earth gravitational field.

The storage capacity at the counterweight station will be too limited to store the energy produced. Once the batteries are refilled and the inertial wheel storages spinned to their maximum, the surplus energy will be radiated outwards by black panels fitted with large resistors. The radiating panels will of course be oriented perpendicularly to the solar panels to radiate toward the cold sky background and to avoid being heated by the sun.

VIII. DEPLOYMENT

In the NIAC reference design [1], deployment is done by launching a minimal 1/10th capacity version of the elevator with an initial maximal payload of 2000 kg. The first launches will have additional ribbon thread spools as payload. This additional material is spliced with the existing ribbon during the travel from Earth to the counterweight, reinforcing the existing ribbon by a small fraction at each pass. After two years and 230 incremental reinforcements, the ribbon will reach its full capacity. The initial ribbon and the necessary system to lift it to GEO and then unreel the two ends toward Earth and outwards will be sent in low Earth orbit by several conventional rocket launches.

In our space elevator system the deployment phase will be more difficult. Because of its tapered design, the reference SE will be lighter and thus easier to launch. In our case, the launch scenario will, however, follow the same line, albeit with several significant variations. The initial ribbon initially deployed will be very small, representing around 5 percent of the final ribbon cross-section and mass of the final one. A large ribbon spool will be lifted to low Earth orbit and then pushed to GEO using standard rockets where it will be deployed toward earth and toward space simultaneously. Once the lower end is attached to the ground station and the counterweight is in place at 150,000 km from Earth, the reinforcing process will start.

In the reference design, the climbers add new threads to the ribbon as they climb. Each climber increases the ribbon mass and strength by around 1%. In our reel-in SE, the ribbon being unwound from Earth will be slightly thicker than the one already deployed. This will give its lower third increased weight and strength. At the same time, at the counterweight end the ribbon is reeled in on a large spool. The CW weight increases and its altitude drops to 73,000 km. During the second half of the cycle, the counterweight goes up and unwinds the cable to reach its starting position again, but during the process, it keeps a fraction of the ribbon on the top spool. At the same time, the Earth station releases the same amount of fresh thicker ribbon. After several cycles the whole ribbon is thicker than the original one along its full length and the counterweight is heavier than initially. The cycle can be repeated over and over as long as needed to reach the final thickness and strength.

Of course, the increase in cable section will be very gradual and after a while the optimal mass of the counterweight will be reached and compensation will be made for an additional ribbon arriving at the top end by discarding the same weight from the original smaller section elements and letting it fly freely to become the largest interplanetary body ever made. Of course this will need a careful design of the winch and spools within the counterweight.

A more clever way of using the unneeded ribbon elements could be to use them to reinforce the top part of the existing ribbon but this would require a very complex mechanical setup. That solution may also reduce the overall system reliability, so we are not considering it in the initial scenario deployment. At a more mature stage of space exploration by space elevator we will have a manned station operating at the counterweight and many clever uses of CNT material will become possible, such as reuse for the construction of another SE, on Earth, on Mars or on the moon.

The constant section of the ribbon in our design will suffer an exception in its initial configuration. The part of the initial 'seed' ribbon could be tapered from GEO to the upper end, saving a substantial portion of its weight as this part of the ribbon will never be reused with the maximum stress applied after the initial deployment. This fact and the small initial section of the cable gives us a starting weight for the initial 'seed' ribbon of less than 25 tons, which is a high but acceptable value.

IX. CONCEPT HYBRIDIZATION

The reference space elevator is designed around a tapered cable with maximum thickness at GEO altitude. This has the advantage of minimizing the weight of the whole structure and optimizing the CNT material usage. However, the fact that the ribbon is fixed at both ends implies that the unavoidable cable maintenance must be done 'in situ' and thus while on board the moving climbers. Considering our own version of the space elevator and its advantages -mainly the ability to perform maintenance tasks at fixed locations- we can also imagine a hybrid concept where the reference space elevator is still designed around a tapered fixed cable. Adding a limited reel-in and reel-out capability to both ends of the cable as explained earlier in this paper, we will end up with a solution where the climbers continue to ascend the cable by auto-propulsion, but only after, for example, 5,000 km. The first 5,000 km of the journey will be done by reeling in the lower part of the ribbon, attaching to it the climber and unreeling the ribbon again, let it leave the ground without any self-propulsion.

This hybrid solution will make it possible to perform all maintenance tasks, such as ribbon repair and reinforcement for the first part of the cable that is stored periodically in the anchor station, on the ground. As several authors have noted [1 and many others], the lower part of the ribbon is the most exposed to atmospheric storms, high altitude free oxygen corrosion, and low Earth orbit objects and meteors collisions. The most complex repairs to the ribbon are likely to take place in the lower 1,000 km due to the increased risk in this lower section. Thus the hybrid scheme may save more than half the service interruption that could be required because of extensive damage from LEO objects and atmospheric corrosion.

Notice also that at 5,000 km the force of gravity is already reduced to 30% of its ground value. The traction power required from the climber's motors and its energy collecting panels is thus also reduced to one-third their values in the reference design.

Altitude in km above Equator	Applied force in m/s^2	Force in % of ground value
0	9.765	100.0
1,000	7.384	75.6
5,000	3.046	31.2
10,000	1.408	14.4
20,000	0.435	4.5
35,785	0.000	0.00
71,500	- 0.346	- 3.6
100,000	- 0.528	- 5.4
150,000	-0.812	-8.3

X. CONCLUSIONS

We presented an alternative space elevator concept that seems usable and far simpler to use and deploy than the reference design [1]. The underlying principle is to reel in and reel out the ribbon at both ends to move the payloads around the cable, removing the need to provide energy to the moving climbers. However, a major obstacle has to be overcome, namely, the cable material should be stronger with a tensile strength slightly above 150 GPa if we consider the same safety factor of 2 as in the reference design.

Considering a hybrid between our reel-in SE and the reference SE may remove most of the disadvantages of both versions, such as the need to provide large amounts of energy to the climbers and the very high tensile strength of the ribbon. The hybrid version will largely ease maintenance and repairs to the most critical part of the system: the lower part of the ribbon exposed to atmospheric and low Earth orbit debris.

XI. REFERENCES

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