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SPACE ELEVATOR STAGE I

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One of the challenges of building the space elevator is to deal with the effects of Earth's turbulent atmosphere without adding substantially to the weight that has to be supported by the rest of the structure. A particular challenge is varying wind pressure in the upper troposphere and lower stratosphere. A solution is to adapt the Lofstrom Loop or Launch Loop as the first stage, supporting a platform at 50 km altitude to which the main space-elevator ribbon is anchored. From this platform, payload and passengers can transfer to the ribbon. The structure stands on floating platforms at sea, and it puts no weight on the ribbon. It uses magnetic levitation with fast-moving continuous belts traveling in evacuated tubes. This proposed Space Elevator Stage I can be built using materials and technology available today.

I. INTRODUCTION

The space elevator has to deal with the effects of Earth's turbulent atmosphere without adding substantially to the weight that has to be supported from geosynchronous orbit. It helps to choose a site near the equator where there are no recorded tropical storms, such as the area of the Pacific to the south west of the Galapagos Islands or the Atlantic near Ascension Island. It is still necessary to cope with wind pressure in the stratosphere. Using tethers for stabilization or increasing the tension in the space-elevator ribbon will cause strong variable forces that would have to be supported from the top.

The proposed solution is to adapt the Lofstrom Loop,[1] also known as the Launch Loop or the Space Cable,[2] as stage I of the Space Elevator. Stage I will stand on *surface stations* floating 240 km apart. It will support a *transfer platform* 50 km above the Earth's surface. Stage I will lift payloads, and eventually passengers, to the transfer platform for onward travel up the space-elevator ribbon to geosynchronous orbit or beyond (Figure 1).

The Lofstrom Loop is capable of propelling a vehicle into orbit electromagnetically, but the technology can be adapted to act as a high-altitude support structure. It is held aloft by fast-moving belts called *rotors* traveling inside evacuated tubes. To minimize friction and energy consumption, they use magnetic levitation with permanent magnets stabilized with electromagnets. The levitation force causes the rotors to change the direction of their momentum vectors, which provides sufficient force to support the weight of the tubes and transfer platform. The rotors continue in an indefinite loop via the transfer platform from one surface station to the other and back again.

To maintain stability in the presence of gusting cross winds, a technique called active curvature control transmits the forces to a set of tethers near each surface station. The support structures at the surface station are designed to accommodate the consequent movement of about 150 metres in any horizontal direction. This structure is feasible using Kevlar as the main load-bearing material and Neodymium Iron Boron (NIB) in the magnets. Because these materials are available today, the space elevator stage I can be built now and so provide valuable experience of reaching space using a fixed infrastructure. Hence it can be stage I chronologically as well as the lowest stage physically.

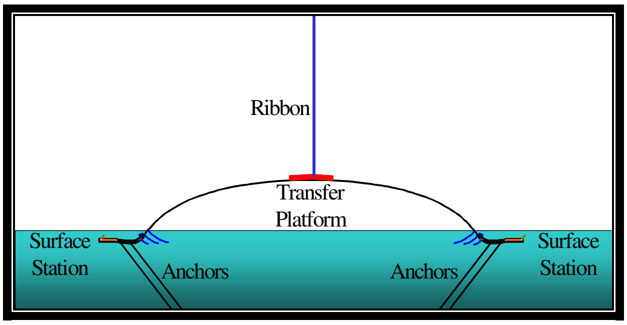

Figure 1 Space Elevator Stage I with surface stations and transfer platform

I.I Previous Work

Version 1 of the space cable was designed to replace a first-stage rocket by accelerating large vehicles (up to 100 tons) to 1.6 km/sec at 50 km altitude. The aim is to reduce substantially the cost of space launch by replacing the biggest and most expensive stage. Version 1 is similar in design and appearance to the space elevator stage I except for the transfer platform anchoring the ribbon. However, version 1 does have a small platform for astronomy and other scientific purposes.

Bigger and smaller versions have been described.[3] For comparison, Figure 2 shows a 15-km-high version suitable for accelerating a ramjet aircraft that could fly from London to Tokyo in three hours. In the figure, this version appears beneath the launch loop, which is 2000 km long and 80 km high. Stage I appears to the left.

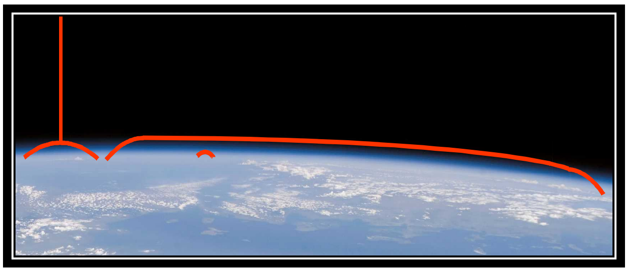

Figure 2 Space Elevator Stage I beside the Launch Loop and a Space Cable 15 km high

One difference between the space cable and launch loop is that the space cable uses separate bolts with space between them instead of a continuous rotor per tube. The launch loop's rotor consists of iron with some simple expansion joints. The electronics, electromagnets and permanent magnets are in the tubes. By contrast, the bolts in the space cable are electronically sophisticated, with both permanent and electromagnets, while the tubes are relatively simple; inside the tubes, there are two tracks of permanent magnets.

The advantages of separate bolts are that (a) the spacing can be varied by a factor of three or more, which is helpful during initial erection on land, and (b) the bolts can be manufactured off site and are replaceable. The advantages of the rotor are that (a) it can be used as a large heat sink, and (b) it is less liable to sputtering and related problems if there should be a flaw in the vacuum through which it is traveling.

I.II Advantages and Disadvantages

Stage I uses known technology and materials that are already available. It can therefore be built without having to wait for new materials. Initially, it can support astronomical telescopes and other scientific instruments 50 km high at a fraction of the cost of launching them into orbit. They will be easy to access for service and upgrade. Later, tourists will be able to visit the platform, and this will build experience and generate income that can be reinvested in the higher parts of the space elevator.

The platform can support power beaming to climbers using lasers or microwaves without the diffusion caused by the Earth's atmosphere and without blocking caused by clouds or storms.

The main disadvantage is an increase in conceptual complexity of the space-elevator project.

I.III Propulsion

One focus of recent work on the space elevator has been to use weaker materials than first envisaged.[4] This is possible by increasing the taper ratio, that is, the ratio between the mass per metre at the centre of gravity and at the ends. One effect of this increase is to require a greater mass of ribbon material to be launched during initial erection. The Lofstrom Loop and variations were designed for launching vehicles. In particular, a hybrid of stage I with version 1 of the space cable can accelerate as much as 100 tons to 2.7 km/sec at 50 km altitude. From here, a single-stage rocket could take a substantial payload of ribbon to orbit at moderate cost. The final lift to geosynchronous orbit can be done with ion engines, as suggested by Edwards.[5]

I.IV Stage I Variations

Research has been published on versions of the Lofstrom Loop as high as 140 km or as low as 300 metres. The preferred altitude of 50 km is low enough to avoid significant risk of damage due to space debris but high enough that there is no risk of wind damage to lightweight solar panels that may power the climbers.[6]

The transfer platform is big enough to support more than one laser power transmitter at altitude. If the climbers use lightweight solar panels, a single transmitter is enough, and it is only required for use at night. Having the transmitter at altitude eliminates the dispersion caused by the atmosphere, but adds the complexity of cooling the laser. A good compromise is to place it at 15 or 20 km altitude, where cooling is somewhat easier and there is little atmospheric dispersion.

The surface stations can be sited on land. Alternatively, one station could be on an island or near a coast while the other station is at sea, provided there is sufficient depth. Having at least one surface station at sea allows for it to be moved, which makes erection of stage I easier.

It is possible to use a different shape for stage I by having the surface stations closer together, but the 240 km separation is easier to stabilize. Another design is to have four surface stations with the tubes forming a cross. A three-cornered arrangement is also possible, and both these arrangements help with stability. However, solutions are available to the problem of stability with two surface stations, and they avoid the significant cost of extra stations. The cross arrangement may be useful when moving the space-elevator ribbon to avoid space debris. Further work is needed on the speed and forces needed for moving the ribbon.

II. FACILITIES

The facilities consist mainly of the surface stations, the transfer platform, the mechanism to move the ribbon to avoid space debris, and one or more laser power transmitters.

II.I Surface Stations

There is a station on the surface at each end of stage I, either at sea or on the ground. During startup, the surface stations accelerate the rotors. Thereafter, in continuous operation, each station turns round the rotors from the incoming tubes and sends them back through the return tubes. It can build up a reserve of speed, and hence energy, by allowing the tension in the tubes to increase so that it is non-zero at the surface. This also simplifies the task of maintaining stability.

In continuous operation, the incoming rotors arrive on the *ramp* that turns them to the horizontal. Then they proceed to the *ambit* that turns them around, after which they go back up the ramp. These are illustrated in Figure 3, in which the ramp is below sea level, and a submarine pipe brings the rotors back near the surface for the ambit and accelerator. It is possible to have the ambit submerged more deeply, thus shortening the pipe, but that would make servicing more difficult.

On land, some of the ramp is in a tunnel, some of it supported by a gantry and some of it supported by short *support tubes* (as distinct from *main tubes*). This represents a compromise between depth of tunneling and height of support tubes. The ambit and accelerator pair are at surface level or in shallow trenches. The details will depend on site conditions.

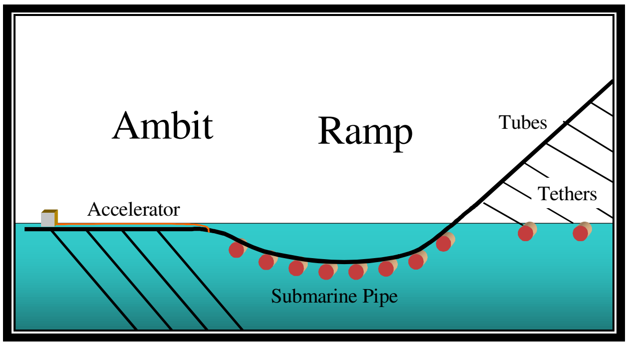

Figure 3 Side View of Ramp, Ambit and Accelerator Pair

As illustrated in the plan view (Figure 4), there is a large ambit to avoid deceleration and acceleration. This allows powerful magnets to be used in the ambit. These may be permanent or superconducting magnets. An ambit using permanent magnets is large but reliable. Powerful electromagnets are available, but they consume substantial power. Superconducting magnets cooled with liquid helium are preferred, because of their field strength. Where the Lofstrom Loop is used for launching to orbit, the rotor can become very hot, which risks warming the liquid helium but, in the space elevator stage I, the rotor will not absorb much heat, and so we can benefit from a compact ambit.

The force on a magnet of flux density B_1 with effective surface area A in a field B_2 is given by

$$F = \frac{B_1 B_2 A}{8\pi \times 10^{-7}}$$

Commercially available superconducting magnets can apply a 10 T (Tesla) field. Using this equation, we obtain a force F in the ambit of about 60 kN if A=100 cm^2, assuming an induced field in the iron rotor of 2 T. This result is confirmed by a simulation using *Finite Element Method Magnetics, Version 4.2.* The ambit radius is mv^2/F for a rotor mass m kg/metre and velocity v. If v is 3.5 km/sec and m is 3 kg/metre, the radius is about 615 metres. If Neodymium Iron Boron (NIB) permanent magnets were used instead of superconducting magnets, the field strength would be about 1.2 T. Taking the induced field as 0.9 T, the force comes to approximately 4.3 kN, and the radius of the ambit would be 8.5 km.

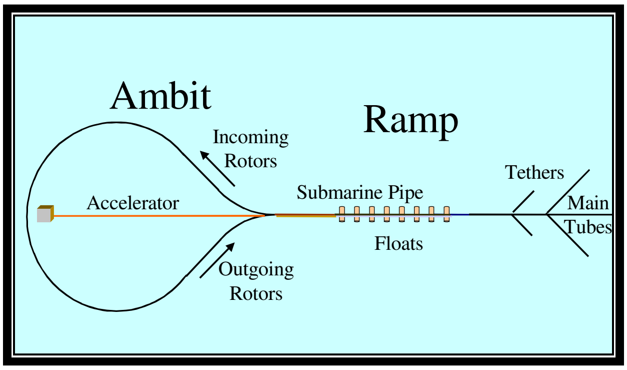

Figure 4 Plan View of Ramp, Ambit and Accelerator Pair

II.II Extent of the Ramp

The overall vertical extent of the ramp required is given by $2R\sin^2(\theta/2)$ for radius of curvature R and angle of inclination θ to the horizontal. To achieve the best radius, superconducting magnets are needed in the ramp, cooled with liquid helium. Now θ is 38°, and R is as for the ambit, giving a vertical extent of 145 metres, which is the required depth of the submarine pipe. Its length is roughly $2R\chi$ (χ in radians), which is about 860 metres. The angle of inclination of the main tubes can be varied by varying the buoyancy of the floats.

II.III Location of the Surface Stations

Erecting stage I at sea has some advantages, because the surface stations can be brought closer together as the tubes rise. On the other hand, siting it on land is likely to simplify the overall logistics. Having one station on an island and the other at sea is quite appealing. The location must be away from human habitation in view of the experimental nature of the project. We are dealing with novel technology. At the required scale, a very large amount of energy is stored in the moving parts, and stringent safety precautions must be taken.

The distance between the two surface stations is approximately five times the altitude of the transfer station at the top. For 50 km altitude, the distance is about 240 km.

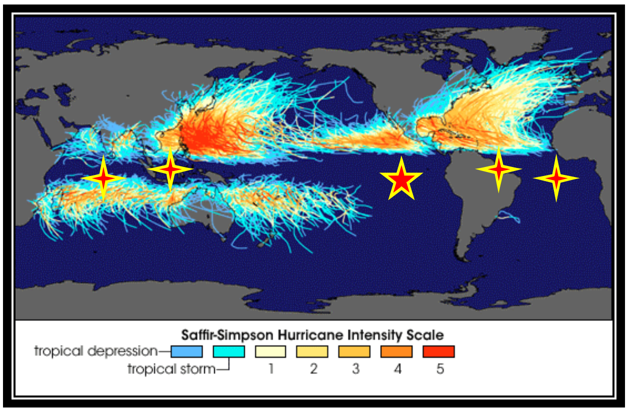

Figure 5 Recorded tracks of tropical storms over the last 150 years

The equatorial area of the Pacific Ocean west of the Galapagos Islands at longitude 100°W has particularly calm weather and is the favored site. Ascension Island in the Atlantic at longitude 14° W and latitude 8° S is possible. Another possibility is the Salomon Islands, part of the British Indian Ocean Territory; this uninhabited atoll is at 5°S and 72°E. A surface station could be based on the largest island, Boddam, which is about 2 km long. The second surface station would be at sea.

Sites on land include French Guiana at 4°N and 53°W and Brunei at 5°N and 115°E. All five sites are marked by stars in Figure 5 and Figure 6.

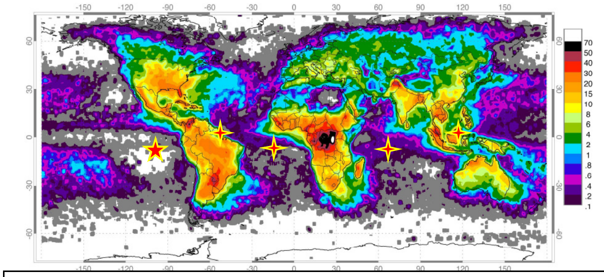

Figure 6 Annual rate of lightning flashes observed by NASA satellites: Apr 1995-Feb 2003

II.IV Facilities at a Surface Station

Apart from the infrastructure needed to support and operate the space elevator stage I, facilities include a floating airport capable of handling regional jets that link to the nearest international airport, which is at Quito in Ecuador in the case of the site west of Galapagos. A runway about 1200 metres long is suitable for this class of aircraft. Passengers will disembark from an aircraft and transfer to a vehicle that is lifted up the tubes to the transfer platform.

The surface station floats and includes a floating dock for cargo and resupply as well as sufficient accommodation of reasonable quality for passengers and crew, bearing in mind that a flight could be cancelled or delayed as at any other airport.

III. TRANSFER PLATFORM

It is likely that most passengers will want to stop at the transfer platform to admire the view, much as most visitors to the Eiffel Tower like to pause at the intermediate stages. The tubes up to the platform vary in slope, and so a vehicle designed for passenger comfort could vary the tilt of seating areas. On the other hand, the climber that ascends the ribbon from the platform does not need that adaptation but does need to be suitable for micro gravity. The methods of supplying power are quite different: either the stage I vehicle draws power from the tubes and propels itself, or it is winched up. The climber ascending the ribbon may be powered either by ultra lightweight solar panels or by receiving power from a laser transmitter. To avoid wind damage, the lightweight solar panels should not be brought into the atmosphere but held at the transfer platform.

Therefore, it is proposed to have two different classes of vehicle: one for the vehicle traveling between the surface and the platform, and one for the climber going up and down the ribbon. Passengers will transfer at the platform, and they will have the use of an observation lounge. Cargo transfer can be automated. There will be storage and handling facilities for several climbers, including the possibility of removing or replacing their solar panels and transferring them to the ground for maintenance and repair.

III.I Space Debris

The altitude of the transfer platform is chosen so that the risk of being hit either by space debris or a natural meteor is negligible. On the other hand, the space-elevator ribbon will be exposed to these hazards. It is designed to withstand collision with objects up to 10 cm. Larger objects can be tracked, and the ribbon must be moved to avoid them. One method of doing this is to pay out an additional length of ribbon and initiate a transverse wave from the platform. According to a recent study, up to 100 metres of ribbon may be required, which would permit lateral movement up to that distance in any direction.[7] It is sufficient to thrust the ribbon at the desired velocity using winches, so long as it is timed to set up a resonant traveling wave. It is not necessary for the winches themselves to pull the ribbon the whole distance.

The winches or a similar mechanism are to be built on the transfer platform. When more information is available on the frequency and forces required to move the ribbon, it will be possible to finalize this part of the design. If the forces are greater than anticipated, it may be desirable to go for a cross arrangement of stage I with four surface stations instead of two.

III.II Power Beaming

The platform can support the power supply to the climbers, avoiding the dispersion caused by the atmosphere and the risk of occlusion by cloud. However, it is preferable to place the laser power transmitters lower down at 20 km altitude. Then the transmitters are displaced 90 km horizontally, well out of the way of any ribbon movements required for avoiding space debris.

With the advent of very lightweight solar panels, the climber may be able to obtain the power it needs from the sun during daylight (ref. 6). A climber starting at dawn and traveling at 300 kph reaches an altitude of 3600 km after 12 hours, where it enjoys an additional 2 hours of sunlight to reach 4200 km. Initially, the power required is 16 MW. At 4200 km, gravity is reduced by 64%, and the power required is 6 MW. Assuming 20% of the laser output is captured and converted into mechanical power, the laser beam output is 30MW. We assume 2 MW of waste heat per MW output.* So we need 90MW of power, 60MW of which has to be disposed of in cooling. At a ratio of 3 kg/kW, the estimated weight is 300 tons.

If such lightweight solar panels do not become available in time for the space elevator, there remains the solution of installing three laser transmitters emitting 50 MW of power each, sufficient to supply three vehicles at different points on the space-elevator ribbon, each traveling at 200 kph. On the same assumptions as above, the total power including losses is 450 MW, and the weight estimate is 1400 tons.

III.III Cooling a Laser

Cooling a laser at altitude presents unique challenges. Water cooling requires water to be lifted from the surface, with a commensurate expenditure of power. The latent heat of boiling water is 2380kJ/kg, and so water is needed at 25 kg per second to dispose of the 60 MW heat produced by the 30 MW laser. Lifting water to 20 km at that rate requires an additional 5 MW of power.

There remains the option of placing the laser power transmitters on the ocean surface, where water cooling is relatively straightforward.

IV. LEVITATION FORCES

The rotors traveling inside the evacuated tubes are able to support the weight of the transfer platform, as well as the tubes' weight, by changing the direction of their momentum vectors. However, they maintain their kinetic energy. The rotors only lose kinetic energy due to residual friction and due to gravity. They make up the effect of gravity when they descend. The surface stations give them a boost to make up for friction losses.

Permanent magnets deflect them without affecting their speed, thus creating a force orthogonal to the direction of travel but without taking any of the rotors' kinetic energy. Because of the inherent instability of levitation by permanent magnets, electronically controlled electromagnets in the tubes are used to maintain a clearance of about 1 mm between the rotors and the tubes. Careful design of the permanent-magnet arrays and the electronics allows the currents in the electromagnets to be kept very small.

As illustrated in Figure 7, the levitation force at the top of the curve supports the weight of the platform and the greater part of the tubes. Lower down, the levitation force is not vertical, and it only supports part of the weight. Tension in the tubes supports the other component of weight. Because tension in a curve causes a net orthogonal force inward, the tension transmits the tube weight to the top.

If the mass density of a rotor is m kg/metre and it changes direction by an angle ϕ over a distance l, then the change in momentum is $mlv\sin\phi$, where v is the speed. This happens in the time the rotor travels the distance l, which is l/v seconds. Hence, the rate of change of momentum is $mv^2\sin\phi$, and this is the resultant levitation force. If ϕ is 5°, m is 3 kg/metre, and v is 3.5 km/sec, the force is 3.2×10^6 N (Newtons) per tube. Thus ten tubes would support 3100 tonnes weight. However, using permanent magnets, the available force is about 1600 N per metre per tube in addition to the 160 N needed to support the tubes themselves. Thus a 250-metre length with 10 tubes can support 400 tonnes. By contrast, suitably designed electromagnets can support 10000 N per metre per tube. A length of 300 metres is sufficient to support a 3000-tonne platform.

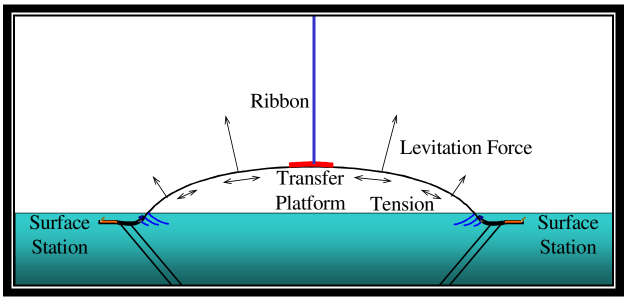

Figure 7 Shape of Curve indicating Tension and Orthogonal Forces

For the sake of redundancy, six pairs of tubes are used so that one pair can be quiesced and taken down for maintenance while the other five pairs continue to support the platform. Different numbers are possible, depending on the desired degree of reliability and the weight to be supported.

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* Jordin Kare, personal communication

V. WINDS AND STABILIZATION

Cross winds and other disturbances will tend to cause instability. There is a natural stability in the vertical direction due to the effect of gravity offset by the curvature of the tubes and rotors. This stability is enhanced by adding moderate tension to the tubes to allow the necessary variations in the rotors' speeds without the structure sagging. Laterally, however, the structure is inherently unstable, and corrective measures are needed.

The technique known as active curvature control (ref. 2) uses electronic methods to correct for changes in curvature and adjust them so that they match the curvature required to counteract lateral forces. It is designed to maintain stability at higher altitudes by transmitting movements down to the Earth's surface. There are some practical implementation details still to be worked out. It requires the time derivative of curvature to be measured and the results to be acted on as the rotor passes at high speed. Assuming these details can be resolved, the complexity of the control problem is comparable to that handled by automatic systems on sailing vessels, although the scale and speed is much greater.

The maximum deflection due to wind is calculated based on previous work showing that a tube is subject to a maximum wind force of 50 N/metre.[8] Winds are significant at elevations up to about 12 km. At these elevations, the rotor speed is 3.4 km/sec and the maximum deflection angle is 0.8°. This translates to a maximum deflection near the surface station of 220 metres in any direction. At 3 km elevation, the movement is about 150 metres.

The alternative solution is to attach tethers at periodic intervals up the tubes. These tethers would be anchored at the surface and would inhibit lateral movement. Small-scale movements between tethers are suppressed by the natural stiffness of the rotors and tubes. The drawback is that the tethers add considerably to the overall weight that the rotors must support through magnetic levitation, and this load scales non-linearly with altitude.

If there were no stage I, the space-elevator ribbon would experience these wind forces. It would need similar tethers to keep it stable, which would require a substantial increase in ribbon strength.

V.I Tethers Below 3 Km

Using active curvature control removes the need for most of the tethers, but they are still required up to a height of 3 km in order to draw the tubes back from their maximum deflection so that they line up with the surface stations. Triples of tethers are placed at regular intervals along a tube, as in Figure 8. Each tube is anchored at the surface station and is under tension, so that each triple of tethers complements the tube in a stable four-cornered arrangement. The lateral wind forces that the tubes experience are stronger than those in the vertical plane of the tube by a factor $1/\sin\theta$, where θ is the tube's tilt to the horizontal. Only a factor $1/\sin\theta$ of this is experienced as a force orthogonal to the tube in the vertical plane, and so the angles of the tethers reflect that combined factor of $1/\sin^2\theta$.

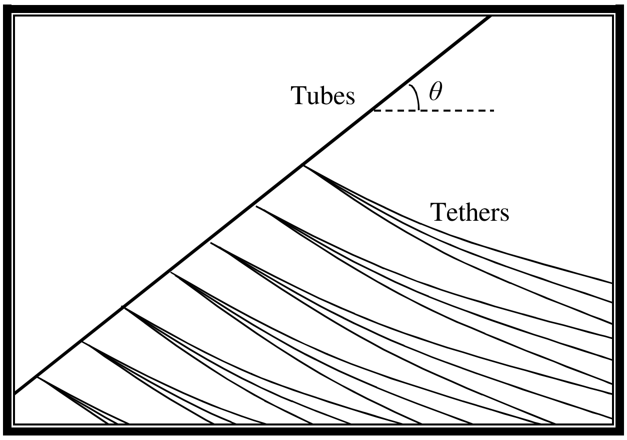

Figure 8 Side view of triples of tethers along the tubes

The following calculations assume there are three tethers per metre of tube, one in the vertical plane of the tube and the other two arranged symmetrically on either side. The actual tethers may be spaced more widely than this, so long as the force density per metre fits the calculations. Figure 9 shows the arrangement viewed from above.

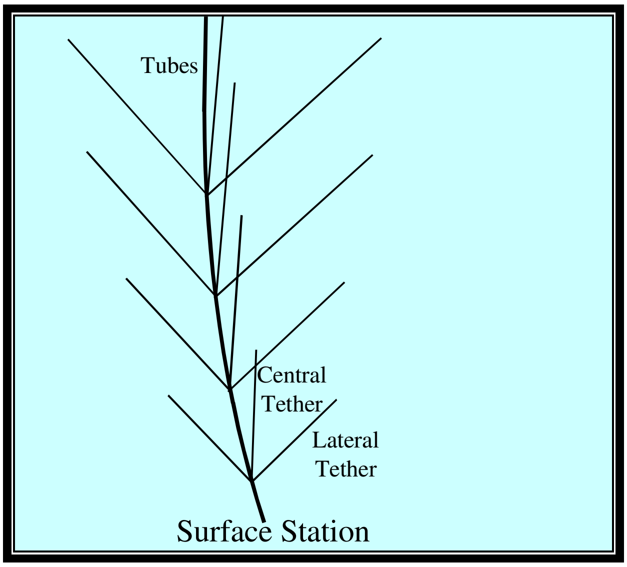

Figure 9 Plan view of triples of tethers along the tubes

At 3 km height, the tubes will move laterally as much as 150 metres to either side as the cross winds fluctuate. The vertical movement may be as much as 60 metres up or down. The tethers will change their tension by ±300 N. At lower altitude along the tethered tubes, the movement is less but the forces are the same. The tethers form catenaries with tension up to a maximum of 2000 N. The lateral tethers weigh 0.1 N/metre; the central tether weighs 0.35 N/metre. The longest tethers extend horizontally over 3.4 to 3.6 km. The slope at the junction with the tubes is approximately 35°; at the bottom it is approximately 17°. As the tethers need to extend or shorten, a winding mechanism is needed at the surface to maintain tension. No power need be supplied, as the movements are driven by the wind; in principle it is possible to draw some power from wind movements, although it is doubtful whether this would be worthwhile in practice.The tension in the tethers adds to the force that the rotor and tube must support using magnetic levitation. Each lateral tether imposes a force of 1215 N in the vertical plane in the direction orthogonal to the tubes. The central tether adds 405 N, giving a total of 2835 N. This is a little high for permanent magnets, and electromagnets will be needed in the tubes for the 4 to 5 km where these forces can occur.

V.II Derivation

At the junction with the tube, each lateral tether has tension T_L and hangs at an angle ξ to the horizontal; the components of the tension are $T_L(\cos\xi, \sin\xi)$. The tether lies in a vertical plane at an angle ψ to the vertical plane of the tube, and the tube is tilted at an angle θ. Hence the tension in the coordinate frame aligned with the tube is

$$\begin{aligned} T'_L = T_L(&\cos\xi\cos\psi\cos\theta - \sin\xi\sin\theta, \\ &-\sin\xi\cos\theta - \cos\xi\cos\psi\sin\theta, -\cos\xi\sin\psi) \end{aligned} \quad (1)$$

The central tether has tension T_C and hangs at an angle χ to the horizontal. The components of the tension are $T_C(\cos\chi, \sin\chi)$. It is already aligned with the plane of the tube. Hence the tension in the coordinate frame aligned with the tube is

$$\begin{aligned} T'_C = T_C(&\cos\chi\cos\theta - \sin\chi\sin\theta, \\ &-\sin\chi\cos\theta - \cos\chi\sin\theta, 0) \end{aligned} \quad (2)$$

The movement and force needed in the vertical plane orthogonal to the tube is proportional to the lateral force by a factor $\sin^2\theta$. Therefore the sum of the y-component of the forces in equations (1) and (2) from the three tethers needs to match the z-component in this proportion:

$$\begin{aligned} &2T_L(\sin\xi\cos\theta + \cos\xi\cos\psi\sin\theta) \\ &+T_C(\sin\chi\cos\theta + \cos\chi\sin\theta) \\ &= 2T_L\cos\xi\sin\psi\sin^2\theta \end{aligned} \quad (3)$$

Make the simplifying assumption that $\chi = \xi$. Then the equation becomes

$$\cos\psi = \sin\psi\sin\theta - b \quad (4)$$

where

$$b = \tan\xi\cot\theta + \frac{T_C}{2T_L}(1 + \tan\xi\cot\theta)$$

Equation (4) is quadratic in $\sin\psi$. The slope of the tube is chosen to be $\theta = 38°$. The slope of each tether needs to be such that the force along the tube opposes the tension in the tube, i.e., so that the sum of the x-component of the forces in equations (1) and (2) is positive:

$$\begin{aligned} &2T_L(\cos\xi\cos\psi\cos\theta - \sin\xi\sin\theta) \\ &+ T_C(\cos\chi\cos\theta - \sin\chi\sin\theta) > 0 \end{aligned} \quad (5)$$

Choosing $\chi = \xi = 35°$ and $T_C = T(0.345)$, equation (4) has solution $\psi \approx 45°$, which also satisfies inequality (5).

The catenary equation can be written

$$x = \frac{H}{w}\cosh^{-1}\left(1 + \frac{wy}{H}\right) \quad (6)$$

Here y is the height above the origin (the lowest point) of the catenary curve, H is the horizontal tension, w is the weight per metre, and x is the horizontal displacement. The tension $T = H + wy$. The slope ξ is given by

$$\tan\xi = \sinh\frac{wx}{H} = \sinh\cosh^{-1}\left(1 + \frac{wy}{H}\right)$$

Hence

$$H = \frac{wy}{\cosh\sinh^{-1}\tan\xi - 1}$$

The maximum height is 3000 metres, but the value of y needs to be greater to allow variation in slope at the bottom – that is, the origin of the catenary is below the surface. Taking $y = 600$ metres at the bottom, we find $y = 3600$ metres at the top. With $w = 0.1$ N/metre and $\xi = 35°$, the estimate of H is 1360 N, and T is 1720 N. The maximum tension is computed for Kevlar from the strength $S = 0.875$ GPa (assuming a 4:1 safety margin), density $\rho = 1.47\times10^3$ kg/m^3, and $g = 9.81$ m/s^2 as 6070 N using

$$T \le \frac{wS}{g\rho}$$

These calculations apply to the lateral tethers. The central tether has w, T, and H reduced in proportion by a factor 0.345.

VI. INITIAL ERECTION

Initially, a pair of tubes is laid out flat on the surface of the ocean between the two surface stations. Slowly, the surface stations accelerate the rotor to full speed, which will take several days. The next step is to begin to raise the angle of the ramps. One surface station is at a fixed location, but the other is movable. The movable station is in two widely separated parts, the ramp and the ambit. The ambit is at the furthest point away from the fixed station, but the movable ramp starts close to the fixed station and slowly moves towards the movable ambit as the ramps raise their angle, causing the tubes and rotors to elevate between the two ramps. The movable ambit moves slowly towards the movable ramp to allow for the shortening of the surface distance as the tubes rise.

The magnetic forces required in the ramp are stronger than those needed in the bulk of the tubes, and sufficiently powerful electromagnets must be installed along the entire length of this pair of tubes. These magnets are adjusted while the movement of the floats supports the moving ramp. It can be calculated that the ramp length is about 12 km and it drops to a depth of 1.5 km below the ocean surface. The next (optional) step is to convert the ramp to using superconducting magnets. These must be installed along the 12-km length of tube that serves as the ramp once it has joined with the ambit. The superconductors can then be adjusted to exploit their power by shortening the ramp.

Once the first pair of tubes has been installed, the second pair is raised along it using crawlers. Next, the surface stations accelerate the rotor in the second pair until it can support itself. Further pairs of tubes are erected in the same way. It is possible to take the first pair down if desired in order to salvage the magnets that are no longer required.

Finally, the transfer platform is taken up in sections and assembled at the top.

A method using a helium-filled tube has been described (ref. 8) for use when both surface stations are on land.

VI.I Capturing the Ribbon

Once stage I has been erected, it is necessary to capture the initial threads of the space-elevator ribbon. These will be lowered from geosynchronous orbit. It is possible to think of ingenious methods of capturing the threads at altitude using a lasso or some form of hovering rocket. However, there seems to be no justification for spending significant time or money on such a one-off endeavour. The simple approach is to lower the threads to the ocean, where a team can gather them up using a small boat or launch. The crew can carry the threads to the surface station, where they will attach them to a vehicle to transport them to the transfer platform.

When the threads are secure, further construction of the ribbon can proceed from the transfer platform by means of the small crawlers.

VII. CONCLUSION

There are many benefits to building stage I while we are waiting for strong enough material for the space-elevator ribbon. It will provide valuable experience in operating infrastructure for space access and will generate a revenue stream, initially from scientific investments and later from tourism. It could even be used to lower the cost of launching the initial ribbon threads for the elevator.

Stage I will solve the problems of winds and storms that would otherwise present significant challenges to the space elevator, because stage I can carry the additional weight and forces involved without loading the ribbon itself. Moving the ribbon from the Earth's surface to avoid space debris would be very difficult if there were strong winds blowing in the stratosphere at the same time. Stage I will be able to do this from the transfer platform, which is above 99.9% of the atmosphere.

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