JOURNAL OF PROPULSION AND POWER
Vol. 22, No. 4, July–August 2006

High-Altitude Electromagnetic Launcher Feasibility

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A theoretical study shows that it is feasible to erect an electromagnetic launch system to an altitude above 30 miles. Detailed calculations are given for a system that reaches that altitude and accelerates 100-ton vehicles to 3600 mph, effectively performing the role of a first-stage rocket. It uses adaptations of known technology and existing materials, albeit with some significant engineering challenges. The method is to project electromagnetic bolts from the ground through several evacuated tubes so that the bolts support the tubes and provide thrust to a vehicle. Some hazards are considered, including cross winds. An outline costing is given.

Nomenclature

A	=	effective surface area
a	=	radius of tube
B_1	=	magnetic flux density of a magnet
B_2	=	applied magnetic field
C_d	=	drag coefficient for a tube in wind
D	=	length of a bearer
d	=	gap between a bolt and the tube wall
F	=	force on a bolt in the ambit or in a tube (see text)
F_a	=	force on a bolt in the accelerator pair
F_b	=	drag force per bolt
F_d	=	normal force on a tube due to a deflection α
m	=	mass of a bolt
N	=	average number density of particles in a tube
R	=	radius of curvature in the ramp
R_0	=	radius of the Earth
r	=	distance from the center of the Earth
$\dot{r}$	=	rate of change of r with respect to time
s	=	separation between bolts
T_α	=	normal force due to tension in the tube at deflection angle α
V	=	velocity of a bolt
V_0	=	initial velocity of a bolt
v	=	lateral velocity of particles in a tube
v_w	=	wind speed
w	=	weight of tube per meter
α	=	deflection angle in a tube
ζ	=	latitude of the space cable
ξ	=	tilt of a support tube
ρ_A	=	air density
ϕ	=	total deflection of a tube due to jet-stream wind
χ	=	angle of inclination of the ramp to the horizontal
χ_G	=	angle of inclination of the tunnel and gantry to the horizontal
Ω	=	angular velocity of the Earth at the surface

I. Introduction

MAGNETIC levitation and linear drives are proven technologies in rail transportation. Their use has been limited by issues of cost effectiveness, but there are several systems in operation, notably in Shanghai.[1] Superconducting magnets are commercially available and have many uses. Recently, high-temperature superconductors (i.e., at liquid-nitrogen temperature) have been demonstrated successfully.[2,3] Permanent-magnet systems[4] are in development for quiet urban transport in some U.S. cities. The Swissmetro team[5] has been working on travel using magnetic levitation in a partially evacuated tube for many years.

Experiments with electromagnetic launchers[6] have demonstrated the principle of accelerating vehicles to about 500 mph along the ground, offering worthwhile savings in fuel and hence increasing payload capacity.

A system is proposed that takes these ideas further. Called the *space cable*, it consists of several pairs of evacuated tubes a few centimeters in diameter. In a case study, the system reaches a height of 50 km (over 30 miles) and covers a range of 150 km (over 90 miles). The tubes contain permanent magnets and are supported by bolts that travel inside them and contain permanent magnets, coils and electronic stabilization controls. At each end of the space cable, a surface station can accelerate bolts to velocities of 2.5 km/s. The surface stations can also turn incoming bolts around and return them to the tubes using a circular track or *ambit* that uses superconducting magnets. The combination of permanent and superconducting magnets ensures low energy consumption for the support of the tubes in continuous operation. Electromagnets are used for initial acceleration at startup, for stabilization, and for support of vehicles.

A vehicle is carried by means of a *bearer*, which is magnetically connected to the traveling bolts by means of induction coils. The available thrust is mainly a function of the length of the bearer and the number of tubes. A long forward section is proposed that pulls a rear section, where the vehicle is supported. A 150-m (500-ft) bearer can derive a thrust from five tube pairs of about 4.5 MN (10^6 pounds or 500 tons).

By comparison, the launch loop[7] is a continuous traveling belt protected by a sheath. It covers a range of 2000 km. It rises above the Earth's atmosphere because the belt's velocity of 14 km/s exceeds orbital velocity. It is capable of launching vehicles directly into orbit, whereas the space cable only replaces the first stage of a rocket, although that is by far the heaviest and most expensive part. The space cable is much smaller than the launch loop (150 km instead of 2000 km) and is therefore likely to cost much less. Furthermore, it provides an alternative to the development of new first-stage heavy-lifting rockets while allowing existing technology to be exploited for the second and subsequent stages of launch.

The space cable's use of separate bolts, rather than a continuous belt, is advantageous during erection and startup (see Sec. IV), when additional bolts are used to support the structure at lower altitude. Another proposal that uses traveling bolts, called pellets, is Starbridge,[8] which is also known as the space fountain.[9] It was conceived as an alternative to the space elevator,[10] the proposed cable supported by tension from geostationary orbit. The space elevator requires new superstrong materials to be discovered, whereas the space fountain, the launch loop, and the space cable can all be erected from the ground (or ocean) up using known materials and technology, albeit in new combinations. The space fountain is

Received 5 April 2005; presented as Paper 2005-4029 at the AIAA/ASME/SAE/ASEE 41st Joint Propulsion Conference, Tucson, AZ, 10–13 July 2005; revision received 8 November 2005; accepted for publication 15 November 2005.

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vertical and is supported by the retardation of rising pellets and the acceleration of falling pellets using electronically controlled coils. The losses in these coils are estimated at 20 GW (gigawatts) to hold the structure up in the idle state. The space cable in the idle state only needs coils for stabilization; a combination of permanent magnets and tension provides the main support (see Sec. II).

The main sections of the paper are as follows: II. Tube Levitation: trajectory, magnetic fields, stabilization, and required vacuum, III. Surface Stations: support, inclination, deflection, and cross winds, IV. Erection and Startup: raising tubes from the surface, vacuum pumping, V. Vehicle Levitation and Propulsion: thrust and other forces in the bearer, VI. Conclusion: some failure scenarios, outline costing, and further research and development.

II. Tube Levitation

Bolts in a tube follow the trajectory illustrated in Fig. 1. They hold up the tube by a levitation force normal to their direction of travel. Because the levitation forces are not vertical, some of the tube's weight causes tension, which is transmitted to the top, where the bolts support all the weight. There is only a little tension at the base.

The equations of motion of a bolt reduce to a differential equation of the form

$$\ddot{r} = f(\dot{r}, r) \tag{1}$$

Here, r is the distance from the center of the Earth. The equation can be solved numerically by the Runge–Kutta method. The details of Eq. (1) are in the Appendix.

In the case study, Kevlar® 149 is proposed to sustain the tension. (Kevlar is a DuPont registered trademark. See MatWeb Material Property Data at URL www.matweb.com.) It has strength 3450 MPa and density 1.47 g/cm^3. For the target height of 50 km, a suitable bolt velocity at the surface station when no launch is taking place is 2.3 km/s at 56 deg, giving a horizontal range of 150 km and a tube length of 190 km. At the top, the levitation force reaches a maximum of 570 N per 10-kg bolt.

A. Stable Magnetic Levitation

Permanent magnets offer a levitation method that is energy-efficient. The favored arrangement is the Halbach array.[11] The Inductrack[12] system employs a combination of permanent magnets in the vehicle and coils in the track, but the losses in the coils are too great for the space cable. Permanent magnets in both the vehicle and the track would be energy-efficient, but, according to Earnshaw's theorem,[13] levitation based solely on permanent magnets cannot be stable in all three dimensions.

Related studies of magnetic bearings for flywheels that store electrical energy show the feasibility of an energy-efficient method.[14] The application of this work to the space cable consists of permanent magnets arranged as Halbach arrays in both the tubes and the bolts, supplemented by coils in the bolts. The coils are arranged so that they carry no current in the stable position, but when they move away from the stable position, currents are induced in them and are amplified electronically to exert a restoring force.

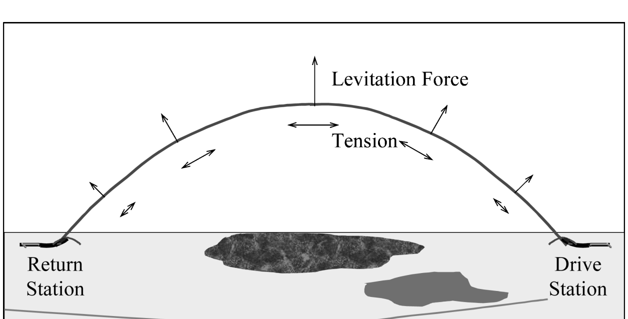

Fig. 1 Shape of curve indicating tension and normal forces.

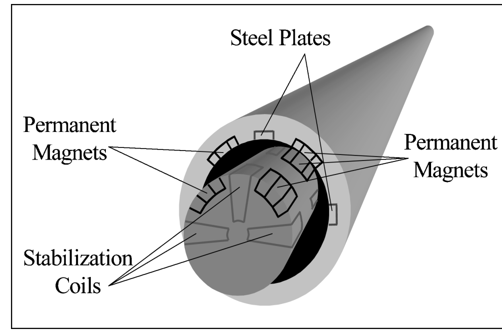

Fig. 2 Arrangement of magnets and stabilization coils in a bolt inside the tube.

The four Halbach arrays on a bolt (two at each end) are arranged to repel the continuous arrays in the tube, as shown in Fig. 2. This configuration of permanent magnets at right angles can exert both vertical and horizontal forces to bear the main external forces of gravity and winds. Stabilization is provided by three electronically controlled coils at each end of a bolt. They perform damping to prevent unwanted oscillations in the four degrees of freedom in which the magnets are effective—vertical, horizontal, pitch, and yaw. The coils also ensure that the bolt does not roll. The best available material for the magnets in the bolts is neodymium iron boron (NIB). (See properties at Integrated Magnetics Inc., "Neodymium Iron Boron Properties," URL www.intemag.com/magnetmaterials/neodymiumironboron/props.htm.) For the tubes, ferrites are preferred. Although ferrites are weaker, they are nonconducting and so do not suffer losses due to eddy currents. NIB is a conductor, but the bolts experience a steady field and so do not have significant eddy currents.

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

$$\frac{B_1 B_2 A}{8\pi \times 10^{-7}} \tag{2}$$

NIB is commercially available up to 1.2 T and ferrites up to 0.4 T. To achieve a maximum force of 570 N, we need $A = 30$ cm^2. In the case study, the bolts are 1 m long, and so four Halbach arrays 10×1.5 cm in area overachieve this.

B. Vacuum

The vacuum in the tube eliminates most of the aerodynamic drag on the bolts. The general formula for aerodynamic drag is applicable to a vehicle in open air rather than to objects moving in a tube. The air between bolts will collect immediately in front of and beside the following bolt, which will collide frequently with most of the air particles, accelerating them to its velocity. They will collide with the sides of the tube, which will decelerate them again. Thus, there will be a continual loss of momentum due to air friction with the sides. At low densities, these will be the dominant collisions, because particles will not often collide with each other.

In a tube of radius a, most of the air is concentrated in pockets within a distance $2a$ in front of a bolt. In effect, the moving bolts perform a supplementary pump action, pushing residual air from the tubes to the stations, where conventional vacuum pumps are installed. These could be cryogenic, diffusion, turbomolecular, or ion pumps.

The particles' lateral velocity v will be Maxwellian about an average determined by the temperature of the tube walls (300 m/s at 300 K). We need to consider the particles in front of a bolt and also those in the gap between a bolt and the walls of the tube. For the particles in front, the average time between collisions with the side is a/v. Typically, the bolt's velocity V will be much greater, and so the air particles will predominantly travel forward with velocity V and have their momentum exchanged every a/v seconds. If the average density is N particles per cubic meter and the separation between bolts is s, there will be $\pi a^2 s N$ particles exchanged every

a/v seconds. The rate of momentum loss will be

$$\frac{\pi a^2 s m_A N V}{a/v} \tag{3}$$

Here $m_A = 2.7 \times 10^{-26}$ kg is the mass of an air particle. To this must be added the effect of collisions in the gap at the side. Here, the average time between collisions with the side is d/v for a gap width d. There will be $\pi adsN$ particles exchanged every d/v seconds, and the rate of momentum loss is

$$\frac{\pi a d s m_A N V}{d/v} \tag{4}$$

In Eq. (4), the bolt separation s is used rather than the smaller bolt length, because particles will collect at the sides from all those available in the gap. Summing gives the force per bolt as

$$F_b = 2\pi a s m_A v N V \tag{5}$$

The power loss per meter length of tube is therefore

$$2\pi a m_A v N V^2 \tag{6}$$

A vacuum of 10^{-8} Torr (1.3×10^{-6} Pa, 1.3×10^{-8} mbar, 1.3×10^{-11} times atmospheric pressure) is well within the state of the art.[15] Here $N = 3.4 \times 10^{14}$ particles per cubic meter, and a is 2 cm, giving a drag force in the case study of about 0.2 μN and a power loss per tube (190 km long) of approximately 70 W, an acceptable level.

C. Oscillation Due to Passage of Bolts

As a bolt moves through a tube, it accelerates the tube upward, after which the tube experiences a downward acceleration due to gravity until the next bolt arrives. The period of this oscillation is s/V, which has a median value of 2 ms (frequency of 500 Hz) in the case study. The distance moved by the tube is 1.2 μm, well within the proposed millimeter-scale clearance between the bolts and the tube.

D. Rotation of the Earth

The Earth's rotation has a small effect in the case study, but it would be significant in a longer space cable. Consider first a space cable aligned with a line of latitude. If the bolts travel at the same speed relative to the Earth's surface in each direction, then those traveling from west to east will be faster than those traveling from east to west. For a bolt of mass m, this leads to a centrifugal force about the center of the Earth at latitude ζ equal to

$$\frac{m(V \pm \Omega R_0 \cos\zeta)^2}{R_0 \cos\zeta} \tag{7}$$

Here R_0 is the Earth's radius, and Ω is its angular velocity. The difference between the eastbound and westbound forces is $4\,mV\Omega$, giving a small tension of about 0.7 N in the case study at a temperate latitude.

For a space cable aligned with a line of longitude, there is an effect due to the faster rotation of the Earth's surface nearer the equator, the Coriolis force. The effect on southbound bolts and their associated tube counterbalances the opposite effect northwards, because the force is proportional to the north–south velocity. The force is $\pm mV\Omega \sin\zeta$, giving a net tension of about 0.2 N in the case study.

In the general case of different longitudes and latitudes, the two effects combine as a vector sum.

III. Surface Stations

There is a station on the surface at each end of the space cable, either on the ground or at sea. During startup (see Sec. IV), the drive station accelerates the bolts. Thereafter, in continuous operation, each station turns the bolts from the incoming tubes around and sends them back through the return tubes. The stations must balance the momentum used by the craft being launched (if any) and offset the effects of wind. A station has to ensure that the bolts are on a course to intercept the craft. The drive station imparts to the bolts the momentum required by the craft. The stations can trim the bolt velocities (speed and angle) to keep them in balance.

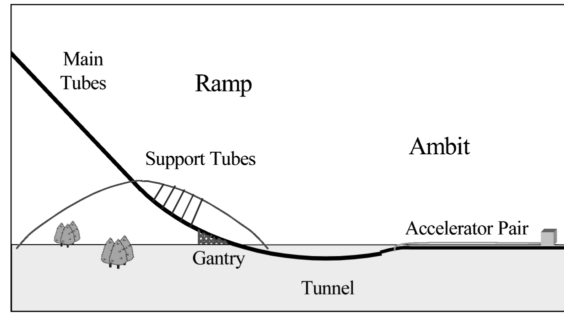

Fig. 3 Side view of ramp, ambit, and accelerator pair.

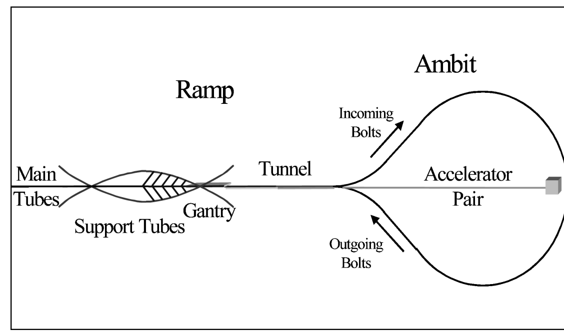

Fig. 4 Plan view of ramp, ambit, and accelerator pair.

In continuous operation, incoming bolts 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 Fig. 3, in which some of the ramp is in a tunnel, some of it is supported by a gantry, and some of it is 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.

There are an accelerator and decelerator (called an *accelerator pair*) at the drive station for starting up and taking down. The decelerator slows the incoming bolts to a speed at which they can be turned aside in a reasonable distance without successive bolts getting too close together; they can then be stored. The accelerator does the opposite. It would be possible to use the accelerator pair in continuous operation and have a much smaller ambit, but the coils required would cause considerable power losses.

As illustrated in the plan view (Fig. 4), there is a large ambit to avoid deceleration and acceleration. This allows powerful superconducting magnets to be used in the ambit, whereas the accelerator pair needs oscillating electromagnets (acting as the primary of a linear synchronous motor). Superconducting magnets have not so far been found capable of coping with the alternating current that would be needed in the accelerator pair.

Commercially available superconducting magnets can apply a 10-T field. Using Eq. (2), we obtain a force F in the ambit of about 190 kN if $A = 400$ cm^2, assuming NIB at 1.2 T for the bolts. The ambit radius is mV^2/F for a bolt of mass m and velocity V. If V is 2.5 km/s (as required during erection—see Sec. IV), the radius is about 330 m. In the accelerator pair, a force F_a of only 38 kN is available, because oscillating electromagnets can only deliver fields of about 2 T. The length, given by $\frac{1}{2}mV^2/F_a$, is about 800 m.

A. Support Above the Surface

The overall vertical extent of the ramp required (height plus depth of tunnel) is given by $2R\sin^2(\chi/2)$ for radius of curvature R and angle of inclination χ to the horizontal. To achieve the best radius, superconducting magnets are needed above and below ground, preferably cooled with liquid nitrogen. In the case study, χ is 56 deg, and R is as for the ambit, giving a vertical extent of 150 m. If the tunnel goes to 50 m depth, then the supporting tubes must rise above 100 m. Neglecting a small addition due to lateral deflection, the overall arc length of the ramp (above and below ground) is $R\chi$ (χ in radians), which comes to 325 m. Of this, 180 m is tunnel, 40 m is gantry, and the rest is supported by tubes. The tunnel and gantry achieve an inclination χ_G of about 38 deg.

Consider a mass m traveling at velocity V deflected by an angle α. The change of momentum is $mV\sin\alpha$. Spaced s apart, their rate of arrival is V/s. So the resultant force (rate of change of momentum) is

$$F_d = mV^2 \sin\alpha/s \tag{8}$$

The support tubes have to sustain a load of $mV^2\sin(\chi - \chi_G)/s$ per main tube, about 40 MN for 10 main tubes. Effectively, the support tubes are taking a fraction equal to $\sin(\chi - \chi_G)$ (about 0.3) of the total force. Because the supports only have to attain 100 m or so of height, they can enjoy a lower bolt velocity and ambit radius if there are several to each main tube. Using 10 times the minimum number of support tubes shares the load so that they only need a $\frac{1}{10}$ of the ambit radius (33 m) compared with the main ambit. Similarly, the ramps for the support tubes are $\frac{1}{10}$ the size (a vertical extent of 15 m); they may be underground, supported by pylons or a combination.

The angle of inclination of the main tubes can be varied by varying the bolt velocity in the support tubes. The support tubes are also used for lateral deflection.

B. Stabilization

To maintain the overall balance and minimize tension in the tube, the stations must adjust bolt velocities as vehicles take off. In addition, active controls are needed to take account of head, tail, and cross winds. The complexity of the control problem is comparable to that handled by automatic systems on sailing vessels, although the scale is obviously much greater.

Holding the tubes under moderate tension at the stations renders the space cable stable in the vertical direction; extra load lowers the tension. Lateral stabilization requires active control. Pending a detailed analysis, an informal argument is given as follows. There is an inherent form of stiffness due, not to the materials used, but to the momentum of the traveling bolts, which causes the effects of wind gusts to be propagated along the tubes at the velocity (direction and speed) of the bolts. These effects take the form of traveling waves, and they can be damped by providing damped connectors between pairs of tubes in which bolts travel in opposite directions. The resultant slow deflection of the tubes has to be countered by varying the deflection and inclination at the stations—turning into the wind. Sensors for motion and wind need to be placed along the length of the space cable, and the stations need to be able to vary the angles as wind gusts are experienced. The stations must deflect bolts in the outgoing tubes sufficiently to compensate for the forces experienced by bolts in the incoming tubes.

C. Cross Winds

This study does not attempt to analyze the oscillation modes, although that will be required, but it examines severe cases to verify that the forces needed are adequately provided. A particularly severe case that is of a strong gusting cross wind.

The pressure of wind on an object is given approximately by $\frac{1}{2}\rho_A v_w^2 C_d$, where ρ_A is about 1.25 kg/m^3 at sea level. A tube with circular cross section has a drag coefficient of approximately 1, although work on electrical power cables has shown that improved designs can reduce this to about 0.7 (Ref. 16). Assuming this improved drag coefficient, a hurricane-force wind ($v_w = 30$ m/s, force 11 on the Beaufort scale) at low altitude will exert a pressure of 400 Pa. However, at high altitudes in the jet stream, winds can reach 180 knots (110 m/s) at an air pressure of 300 mbar (0.375 kg/m^3 air density). The wind pressure is then 1600 Pa. It is reasonable to assume that one tube can partly shield others, so a mean wind pressure of 1000 Pa is suggested. On a tube of diameter 5 cm, this is a force per meter of 50 N or 250 N per bolt. Magnets in the bolts and tubes must handle this force. The bolt velocity in the case study allows for it. It is a factor of 30 below the maximum force achieved in the bearer. It sets an upper limit on the density of permanent magnets needed in the tube.

D. Deflection and Inclination

The jet stream does not operate at all altitudes but only between 20,000 and 40,000 ft (6–12 km). This affects a tube length of up to 20 km ascending and the same descending, giving a force per tube in the case study of 2 MN. From Eq. (8), the total deflection ϕ of a tube due to a strong jet stream is approximately 11 deg. Hence, the stations must be able to deflect the tube laterally by this angle, so that the tube above the adverse jet stream will follow the correct course, allowing for similar deflections in the rising and falling parts of the tube.

Steering at the stations, for both inclination and lateral deflection, is necessary to deal with winds and varying loads. Steering is carried out above the ground and needs to respond within a few seconds to changing wind conditions. To minimize tension in the tubes, the response time should be substantially less than the time a bolt takes to reach the station after it has been deflected by wind.

The support tubes are aligned with the main tubes, but they are tilted to either side and attached via cables. Varying the bolt velocities in the tilted support tubes deflects the main tubes and can affect the inclination. The force exerted is given by Eq. (8). The force is proportional to velocity V, and not V^2, because the spacing s is proportional to V. The velocity range, and hence the force, will be limited to 25% of maximum to avoid bolts getting too close to each other. Hence, the maximum and minimum forces satisfy $F_{\max} = 4F_{\min}$. The support tubes on either side exert the greatest deflection force F_{dfl} when one side is exerting the maximum force while the other is exerting the minimum. Therefore, $F_{\text{dfl}} = F_{\max} - F_{\min}$, and $F_{\text{dfl}} = \frac{3}{4}F_{\max}$.

A suitably positioned support tube tilted at angle ξ exerts orthogonal force components equal to $(\sin\xi, \cos\xi)$ times its total force. Hence the lift from the tilting tubes is $(F_{\max} + F_{\min})\cot\xi$, which is $\frac{5}{3}F_{\text{dfl}}\cot\xi$. In the case study, setting ξ to 45 deg means that the inclination and deflection forces are in balance. The total force to be exerted by the support tubes is $\sin(\chi - \chi_G)\max(\sec\xi, \csc\xi)$ of the load from the main tubes, a proportion of about 0.45. At a ratio of 10:1 with 10 main tubes, we use 46 support tubes (i.e., 23 pairs) so that they can have ambits $\frac{1}{10}$ the size.

The support tubes give a combined angle of both inclination and deflection of $\arccos(\cos(\chi - \chi_G)\cos\phi)$, about 21 deg in the case study, giving a supported arc length of 120 m covering a horizontal rectangle of approximately 85×20 m.

IV. Erection and Startup

The suggested method is to use an inflatable tube filled with helium gas. The inflatable tube is attached to a single pair of tubes for the length of the space cable. A diameter of 1.5 m at ground pressure will provide 7 kg of lift per meter length. The three tubes are laid out between the drive and return stations, and the helium tube is inflated. The tubes then rise to a level at which they can be supported by the bolts. In the case study, this point is reached at a central height of about 10 km.

To support the tube at this height, a greater number of bolts are needed than at the full height. Bolt spacing of about 1.6 m (instead of 5 m) achieves this at the top speed of 2.5 km/s. The accelerator pair at the drive station propels the bolts to this speed.

Once the tubes can be supported by the bolts, they can be raised by adjusting the angle of inclination, and the helium tube can be deflated. The initial inclination is only 15 deg, well below the 38 deg provided by the fixed part of the ramp (tunnel and gantry). Water ballast is proposed for the nearest parts of the tubes to keep them down to the required angle during erection. As the tubes rise further, the ballast can be drained out and the velocities of the bolts reduced to avoid excess tension. Expansion joints will be needed to allow for a 25% increase in length during erection.

The excess bolts used to erect the first tube pair are removed by the accelerator pair for use with further tubes. These tubes can be erected by dragging them along those already in place by means of *crawlers*, which are devices spaced at intervals along the new tube pair that crawl along the existing pair. Later, tubes can be taken down in a similar manner for servicing, maintenance, and repairs without having to bring down the whole structure.

It may be worth having a few startup bolts that are battery powered and capable of propelling themselves if their initial momentum is insufficient to carry them right through the tube. They could help to set the shape needed for smooth passage of bolts at high speed. They would also be useful in clearing the residual air from the tubes to reduce air drag during startup.

The stations need to maintain the vacuum by continual pumping. Normal practice is to use roughing pumps down to 10^{-2} Torr and use them as backup to high-vacuum pumps. Although the tubes have a wide bore (42 mm), they are long enough to sustain a considerable pressure gradient internally. Even though 10^{-8} Torr is reached at the station, there may be parts of the tubes at only 10^{-1} Torr. The first few bolts will encounter significant air resistance, on the order of 2 N.

The drag force of Eq. (5) causes the velocity to decay exponentially over time t as

$$V = V_0 e^{-2\pi asm_A vNt/m} \tag{9}$$

From this formula, we can compute the initial velocity V_0 that a bolt needs to traverse the length L of the tube before stalling as

$$V_0 = 2\pi asm_A vNL/m \tag{10}$$

Given a length of 190 km and a maximum initial velocity of 2.5 km/s, we need to be able to pump the tube down to a number density of $N = 5 \times 10^{22}$ or about 1.5 Torre. This is within the achievable vacuum without recourse to exceptional measures.

V. Vehicle Levitation and Propulsion

Above a moderate speed, the bearer has sufficient aerodynamic lift to support itself and a vehicle. However, at low speeds, the bearer can support the weight of vehicles by deflecting the bolts (and hence the tubes) downwards. To derive thrust, it retards the bolts. Thus it can obtain a force vector by controlling two independent directions.

The craft will separate from the bearer when it reaches the desired speed and altitude. The bearer will then decelerate and return to the drive station. The connection between the bearer and the bolts uses oscillating induction coils. It is a form of linear induction in which the bearer is dragged behind the passing bolts. The force calculation is similar to that for an accelerator pair at the stations (based on Eq. (2); see Sec. III), but this needs to be reduced, given the need for flexibility in the direction and rather less opportunity for optimization on the move. These considerations suggest a force F of 30 kN per bolt.

The available thrust FD/s depends on the length D of the bearer. Because the bolts are spaced $s = 5$ m apart, a 150-m bearer will supply 900 kN of thrust per tube. Five drive tubes will give 4.5 MN. For comparison, this is almost three times the thrust developed by the space shuttle's main engines (without the solid rocket boosters). It is sufficient to accelerate a 90,000-kg (100-ton) vehicle at $5g$ to 1.6 km/s (3600 mph) over a distance of 26 km. Retarding the bolts by a force F over distance D lowers the kinetic energy $\frac{1}{2}mV^2$ by an amount FD, causing a speed reduction (to first order) given by

$$\Delta V = FD/mV \tag{11}$$

In the case study, this subtracts between 125 and 300 meters/s from a bolt's velocity of 2.3 km/s.

To obtain lift, the deflection angle α is determined by Eq. (8) in Sec. III. The resultant deflection force normal to the tubes is also useful for balancing the torsion effect due to thrust that is offset from the center of gravity of the bearer and its payload. The deflection force is partly opposed by a tension force $T_\alpha = w(r - R_0)\alpha$ normal to the tubes, where w is the weight per meter and $r - R_0$ is the altitude. At high altitudes, the tension force can reach 30% of the deflection force.

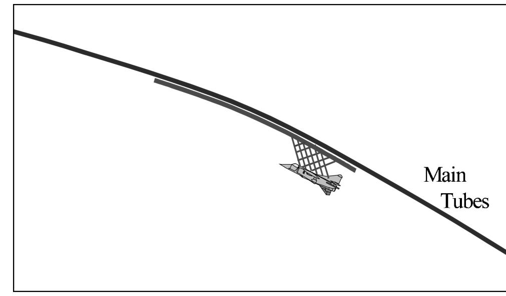

Fig. 5 Bearer supporting a vehicle during launch.

The bearer consists of a long forward section that obtains thrust and pulls a short rear section that carries the vehicle (Fig. 5). The rear section needs to be able to flex to obtain lift at low altitudes, until it reaches a speed at which it achieves aerodynamic lift. The bearer is suspended below the tubes, leaving the top and sides free for connectors and other equipment.

VI. Conclusions

All of the technologies used in this study are available today, but putting them together presents a major engineering challenge. Compared with the space elevator, the space cable has the advantage that it can be built from the ground up and may have applications to noise abatement in civil aviation. There may be other applications, such as constructing cable cars over wide chasms or expanses of water. In the following, we examine some failure scenarios, a preliminary outline costing, and directions for further research.

A system supported dynamically carries obvious risks of collapse. The space cable relies on redundancy between the tubes. In a system with five pairs of tubes, a failure of one or two can be contained. For comparison, consider a jet airliner. It has limited glide capabilities and needs power to land. The design relies on redundancy between the engines.

However, the following are a few scenarios where this is insufficient:

1) Ejection of Bolts: Breaking a tube will cause the high-speed bolts to fly through the air, where their kinetic energy will rapidly be converted into heat; they will heat to 20,000–30,000°C almost instantly due to atmospheric friction, well above their vaporization temperature. The only bolts presenting a danger on the ground will be those already traveling downward near a station. These will all fall short of the station, and so the ground under the space cable near a station will need to be kept clear in case of emergencies.

2) Loss of Vacuum: The tubes could start to leak. This would cause a localized drop in bolt speed, which is readily detectable, so that corrective maintenance can be planned before the leak becomes serious.

3) Attacks or Collisions: Generally, space launch sites are away from populated areas and have reasonable security, but an accidental collision or deliberate attack would lead to catastrophic failure. One way to limit the damage would be to have parachutes attached at intervals to slow down the fall. It may be worth designing the inflatable tube so that it automatically opens out to form a long narrow parachute in the event that it falls suddenly.

In these estimates, retail costs are used in an attempt to cover overhead. A 5-kg set of NIB magnets (for a 10-kg bolt) costs about $1250 retail. To this must be added control electronics in each bolt, estimated at another $100. In the case study, there will be 10 tubes, each 190 km long, containing 38,000 bolts, giving a total cost of $515 million. The tubes will need 1 kg of Kevlar per meter (see Appendix), costing about $90, giving a total of $170 million. There will be ferrites, expansion joints, and vacuum-tight materials, probably amounting to another $70 million. There are 46 support tubes at each station, costing $30 million in total. These figures sum to $785 million.

CERN in Geneva uses liquid-helium-cooled superconducting magnets. There, 27 km of tunnel are undergoing a reinstallation costing about \$2.5 billion. Each space-cable station has 2.5 km of comparable tracks, suggesting an approximate cost of \$250 million each. Using high-temperature superconductors may reduce this, but it is difficult to estimate; the saving in refrigeration equipment has to be balanced against the greater cost of the materials.

A bearer is comparable in complexity to an airliner and could cost \$150 million.

These figures total \$1.5 billion. To this should be added research and development costs, estimated at 20%, giving an overall estimate of \$1.8 billion.

A key idea of the space cable is the dynamic support of a structure using traveling bolts. The following are areas for further research and early development:

1) Magnetic levitation is a proven technology that has been used in several transport projects. As far as this author knows, it has not been tested at very high velocities (2.5 km/s as opposed to 600 km/h). The preferred technology uses arrays of permanent magnets made of NIB in the bolts, and the expected lack of flux change and consequent eddy currents needs to be confirmed experimentally.

2) Work is needed on the control systems for the stabilization coils in the bolts. Their ability to deal with buffeting cross winds must be modeled and laboratory tested. The informal arguments presented here must be validated both mathematically and experimentally.

3) Wind management at the macroscopic level will involve some complex systems for sensor input. The steering mechanism must be examined in more detail.

4) Oscillation modes and frequencies need investigation, particularly those caused by varying winds.

5) The coupling of the bearer to the traveling bolts requires detailed investigation to ensure that it can be achieved without upsetting the levitation of bolts within the tube.

6) There is not much experience in using high-temperature superconductors. Trials and evaluations will be necessary, and these may reveal possible cost savings.

7) The speed of the bolts will raise the energy, and hence temperature, of the residual air in the evacuated tubes to about 1.8 eV (electron volts). This may cause additional material to be dislodged from the walls of the tubes (i.e., sputtering) and needs to be investigated.

8) The control systems will require extremely high reliability, comparable to that of fly-by-wire systems in aircraft. The ability to achieve this at reasonable cost must be examined further.

9) Exhaustive testing of failure scenarios is needed.

10) Laboratory trials and wind tunnel tests will need to be followed by field trials, perhaps at a 1/100 scale.

Appendix

The derivation of Eq. (1) in Sec. II is given here. A dot denotes differentiation with respect to time, and r is the distance from the center of the Earth. The equation can be solved numerically by the Runge–Kutta method. The details of Eq. (1), shown as Eq. (A.1), are given in the following:

$$\ddot{r} = f(\dot{r}, r) \tag{A.1}$$

At any point (r, θ), in plane polar coordinates, the tube will have an inclination ψ, and its weight at that point will be supported partly by the bolts as they pass and partly by tension in the tube. In Fig. A.1, we can see that the tension increases with height and balances the normal force from a bolt. If the tube's weight per meter is w, the tension is $T = w(r - R_0) + T_0$, where R_0 is the Earth's radius, and T_0 is the tension at the surface station, which can be zero. To see this, consider a small section of tube of length δl from A to B. Its weight $w\delta l$ is supported by a levitation force of $w\delta l \cos\psi$ and a balancing tension $\delta T = w\delta l \sin\psi$; that is, $\delta T = w\delta r$. From there, assuming uniform weight, we obtain the tension

$$T = \int w \, \mathrm{d}r = w(r - R_0) + T_0 \tag{A.2}$$

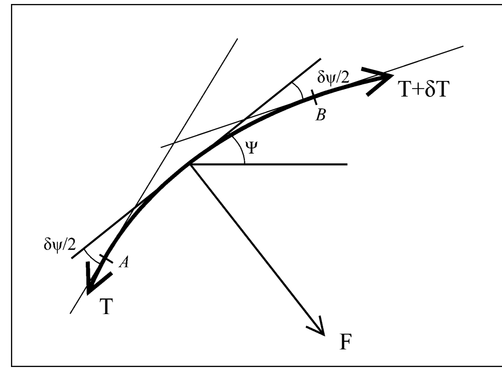

Fig. A.1 Forces over a small segment *AB* of the tube.

The mass of material of density ρ and tensile strength S required to support this tension is $\rho T/S$ per meter. Kevlar 149 has strength 3450 MPa and density 1.47 g/cm^3. At height 50 km and tube weight 70 N/m, the weight of Kevlar required is 14 N/m (i.e., about 1.4 kg out of 7 kg mass per meter of the tube). A factor of 40% has been added to w to allow for the effects of cross winds (see Sec. III).

The tube's weight results in a force $w\delta l \cos\psi$ on the bolts normal to the direction of motion. In addition, the tension causes a force: the slope of the tube changes by an angle $-\delta\psi$ over the length δl, yielding a force on the bolts of $2T \sin(-\delta\psi/2)$, which comes to $-T\delta\psi$, which is $-(w(r - R_0) + T_0)\delta\psi$. Hence, the force F on a bolt spaced s from its neighbors is

$$F = \int_0^s w \cos\psi \, \mathrm{d}l - \int_{l=0}^{l=s} (w(r - R_0) + T_0) \, \mathrm{d}\psi \tag{A.3}$$

Applying the chain rule and using $\dot{l} = V$, the velocity, this gives

$$F = sw \cos\psi - s(w(r - R_0) + T_0)\dot{\psi}/V \tag{A.4}$$

The spacing varies with velocity so that $s = s_0 V/V_0$, where s_0 and V_0 are values at the surface. Therefore, using the notation $wT_w = T_0$,

$$F = (s_0 w/V_0)[V \cos\psi - (r - R_0 + T_w)\dot{\psi}] \tag{A.5}$$

The equations of motion for a bolt of mass m, in the form for acceleration in polar coordinates, are

$$\ddot{r} - r\dot{\theta}^2 + g = -(F/m)\cos\psi \tag{A.6}$$

$$r\ddot{\theta} + 2\dot{r}\dot{\theta} = (F/m)\sin\psi \tag{A.7}$$

Here g is 9.81 m/s^2. To convert Eq. (A.6) to the form of Eq. (A.1), we obtain expressions for $\dot{\theta}^2$, $r\ddot{\theta}$, $\dot{\psi}$, and V^2 as follows. Note that the velocity vector is such that

$$V(\cos\psi, \sin\psi) = (r\dot{\theta}, \dot{r}) \tag{A.8}$$

Therefore

$$\dot{\theta}^2 = (V^2 - \dot{r}^2)/r^2 \tag{A.9}$$

Dividing Eq. (A.7) by Eq. (A.6), using Eq. (A.8), and simplifying gives

$$r\ddot{\theta} = -(\dot{r}/r\dot{\theta})(\ddot{r} + g) - \dot{r}\dot{\theta} \tag{A.10}$$

By differentiating $\tan\psi = \dot{r}/(r\dot{\theta})$ from Eq. (A.8) we get

$$\dot{\psi} = [\ddot{r}r\dot{\theta} - \dot{r}(r\ddot{\theta} + \dot{r}\dot{\theta})]/V^2 \tag{A.11}$$

The levitation force is normal to the direction of travel and so does not affect the bolts' speed, which is subject only to the gravity of their own weight. Hence, at a height $r - R_0$, their kinetic energy balances their potential energy, giving $\frac{1}{2}mV_0^2 = \frac{1}{2}mV^2 + mg(r - R_0)$. Therefore

$$V^2 = V_0^2 - 2g(r - R_0) \tag{A.12}$$

Substituting Eqs. (A.5), (A.8), (A.10), and (A.11) into Eq. (A.6), and writing $C = ws_0/mV_0$, we obtain

$$\ddot{r} = \frac{r\dot{\theta}^2 - g - C\left[r\dot{\theta} - (r - R_0 + T_w)(\dot{r}^2 g/r\dot{\theta}V^2)\right]}{1 - C(r - R_0 + T_w)[r\dot{\theta}/V^2 - \dot{r}^2/r\dot{\theta}V^2]} \tag{A.13}$$

Equations (A.9) and (A.12) provide the final substitutions needed to reduce Eq. (A.13) to the form of Eq. (A.1).

Acknowledgment

The author is grateful for informal discussions with Roger Goodall of Loughborough University, England.

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