Acoustic Wave Powered Climbers

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***Abstract*—The space elevator tether makes an excellent acoustic conductor for megawatts of audio frequency sound. The acoustic wave power can be transmitted from electric motors or heat engines powering transmitters at the bottom and GEO end of the tether, at 25 km/s. Acoustic power, with frequencies of 360 Hz, wave displacement speeds of 100 m/s, and force levels of 200 kN, can be mechanically converted into linear climber thrust and velocity, without conversion to electricity. This corresponds to acoustic power levels of 10 MW. With power feeds on the ground and at GEO, the system capable of lifting more than 10 tonnes of climbers to GEO per day, limited by the capacity of the lowest 3000 km of tether.**

There is no need for solar cells on the climber, so 24 hour operation is possible, and climbers can have high payload mass fractions.

I. Introduction

Robert Hooke experimented with the first wire-coupled mechanical telephone in 1665. Wire-coupled mechanical telephones were in common use in the late 1800s, with ranges up to 3 miles. Carbon nanotube tether, if and when we learn how to crosslink shear force between slippery carbon nanotubes, will be far stiffer and less dispersive than the metal wires used for those historic mechanical telephones.

It is surprising, perhaps even embarrassing, that in the half century after Yuri Artsutanov's 1960 proposal for a space elevator, nobody has considered the acoustic properties of a space elevator tether. The tether is rigid, strong, and can carry huge amounts of acoustic power, enough to lift a climber at high speed.

The following short paper is a vague sketch of the possibilities. It will hopefully inspire clever mechanical engineers to create designs for optimized, robust, high throughput acoustically powered space elevators.

II. Acoustically Powered Climbers

We do not know how to make long, ultra-strong tethers from carbon nanotubes. When we learn how (presumably by replacing zero-shear van der Waals forces between CNT with materials that create virtual ionic crosslinks that cannot slide down the tube), the mechanical properties of the ultra-strong composite material offer a surprise - they can carry high velocity, high power acoustic energy with low dispersion for long distances. The acoustic power transmitted is ample to lift climbers at high velocity, and scales with tether mass. This eliminates the need for heavy, expensive photovoltaics, electrical power conversion, and primary power electric motors on the climber, replacing them with a receiver that directly converts the mechanical-acoustic power on the tether to mechanical climber thrust.

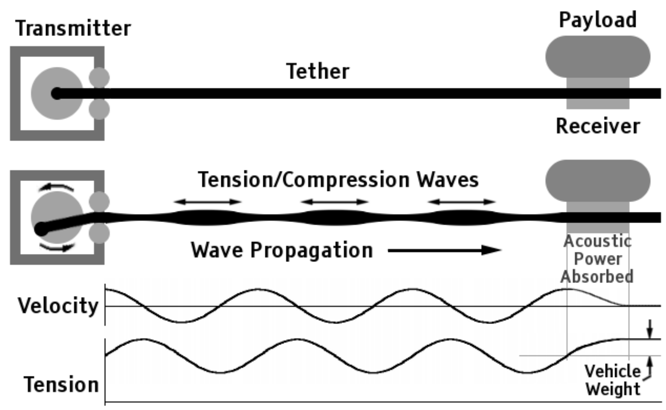

Fig. 1. Generation and propagation of acoustic wave energy in the space elevator tether, here shown completely absorbed by the acoustic power receiver on the climber.

Fig. 1 is a schematic example. The transmitter (possibly as simple as a high-RPM offset cam) converts megawatts of electricity into transverse mechanical motion, which propagates up the tether at very high speed. This is the key point - the tether can store a lot of mechanical energy in a wave, and the waves move very fast - energy density times speed is power, and a thin CNT tether can move megawatts of wave power, with small absolute displacements. Centimeter scale or smaller discontinuities in the tether will not disperse these long wavelength waves; 25 meters wavelength for a 1000 Hz vibration.

What we can add, we can take back out. A mechanical receiver, like the half-wave dipole receive antenna on a radio, can absorb this mechanical energy. Like the radio, resonances can be used to impedance match and speed translate the acoustic waves into reciprocating and then rotary motion, velocity, and thrust on a climber. This paper does not offer a practical design for this receiver - the author is not a talented mechanical engineer - but a few hours with such an engineer, translating concepts from radio to mechanism, is likely to yield many candidates for such a receiver.

Candidate receivers can be tested on a large test track, somewhat longer than a climber and tiltable from vertical to horizontal to simulate changing gravity during the climb to GEO. Unlike solar photovoltaic designs with their vast solar arrays, a complete journey for a full-sized acoustic climber can be simulated inside a multistory vacuum chamber.

Fig. 1 shows the power transmitted horizontally into a tether; in reality, power will be transmitted from the ground in the beginning, and payload throughput will be low. However, the first payloads delivered to GEO can be the components of a larger solar powered transmitter at GEO, where microgravity permits gossamer solar photovoltaics, or heavy motors and counterweights, without gravitational forces complicating the problem. Climbers can move very fast with power arriving from above and below.

At higher altitudes, power from GEO will be more than ample for 200m/s climb. The highest altitude climber in a series of climbers can pick off a fraction of the power, letting most of it continue down to other climbers below. Climbers will need some electricity and motors to reconfigure the receiver for reduced thrust in reduced gravity, permitting partial extraction of power.

III. Tether Acoustics near GEO

With a Young's modulus of 1 TPa, and presuming some magic "crosslinkium" filler which increases the effective mass of the tether to 1600 kg/m^3, the acoustic propagation speed (the "speed of sound") is $v_s = \sqrt{1e12/1600}$ = 25 km/s .

The acoustic impedance, the ratio of wave force to wave displacement speed, is proportional to the mass per length times the speed of sound. $Z = \rho\ v_{sound}$ in units of kg/s .

The wave displacement speed is far lower than the acoustic propagation speed. Think about a tsunami wave in mid-ocean - frequencies of 3 cycles per hour, amplitudes of about a meter, rising and falling slowly, not noticeable among the higher frequency wind waves. However, this long amplitude wave is moving at 800 kilometers per hour (220 m/s), and carries a huge amount of energy, enough to push thousands of cubic kilometers of water onto land. Propagation speed in CNT tether will be more than 100 times faster, and displacements much faster, so CNT waves can carry vastly more energy per kilogram than an ocean.

The acoustic impedance Z = 0.08 $\times$ 25 000 = 2000 kg/s for a 0.08 kg/m tether at GEO. 100 m/s of wave displacement speed corresponds to 200 kN of peak mechanical wave stress, added to or subtracted from the static structural tether stress.

If the tether is stressed to 27 MYuri, then the static stress is 27M $\times$ 0.08, or 2.2 MN at GEO, 11 times the peak wave stress.

The acoustic power in a unidirectional wave with zero "standing wave ratio" is the wave energy per meter times the speed of sound. For a 0.08 kg/m tether with a longitudinal wave displacement speed of 100 m/s second (or equivalently, the spring energy corresponding to a peak dynamic stress of 200 kN in that tether, the wave energy per meter is 0.5 $\times$ 0.08 $\times$ 100^2 or 400 Joules per meter. Propagating at 25 km/s, that is 10 megawatts. The very large tensile strength and the very high speed of sound combine to allow very high acoustic power transmission levels.

A climber needs a LOT of energy to climb out of the lower gravity well. It is desirable to do so quickly for high throughput, since the lower tether cannot support more than one climber. The power needed is the force times the speed, so higher speeds and lower altitudes (with higher gravity) require more power, as shown in fig. 2

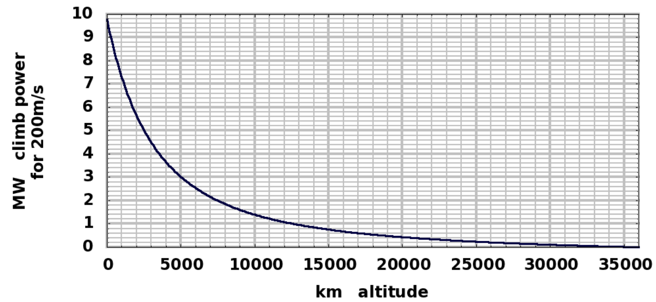

Fig. 2. Power needed for a 5 ton climber climbing at 200 m/s

At the bottom of the tether, at 9.8 m/s^2 with a taper ratio of 6, the tether is 0.013 kg/m, the static tether stress is 350 kN, and the acoustic impedance is 325 kg/s, so a 150 m/s wave corresponds to acoustic power of 2.0 MW and a dynamic stress of 40 kN.

A 5 tonne climber corresponds to about 50 kN of gravitational weight. 2 MW will lift it from the bottom of the tether at 40 m/s. As the climber rises and the tether gets thicker and more massive, the power is attenuated from below, but power may also be provided from above, at GEO. It may be possible to double the speed off the ground, although we must be careful.

If a climber fails, or falls off the tether, and its acoustic load vanishes, the power sources at top and bottom should change from power transmission to power absorption. However, the acoustic power may take as much as an hour to drain from the tether, and unexpected resonances may stress the tether to the breaking point. Failure modes will require much further study.

This analysis assumes that the "crosslinkium" is strong enough to prevent creep and slip between nanotubes. Average atomic scale thermal vibrations of carbon atoms are 830 m/s [1] at 330K (the black body temperature of a two sided flat surface facing the sun), and peak thermal speeds are many times that. This suggests that creep (the stretching and gradual failure of the tether) caused by acoustic vibration will be much smaller than creep caused by thermal vibration and high static loading.

Note: There will also be extreme low temperatures on the tether in eclipse [2].

IV. Tether Taper, Reflections, and Standing Wave Ratio

Fig. 3 shows a simplified tether cross section increasing with altitude towards GEO. The real cross section will be small, the lengths will be vastly longer, and the taper change will be nonlinear with distance. The important point is that the acoustic propagation velocity stays constant, as does the wave tension, but because the acoustic impedance increases with altitude, the velocity and wave energy and acoustic power decreases, inversely proportional to the tether density, for a wave propagating from the ground transmitter. "Standing waves" emerge on the tether below the climber, vibrations

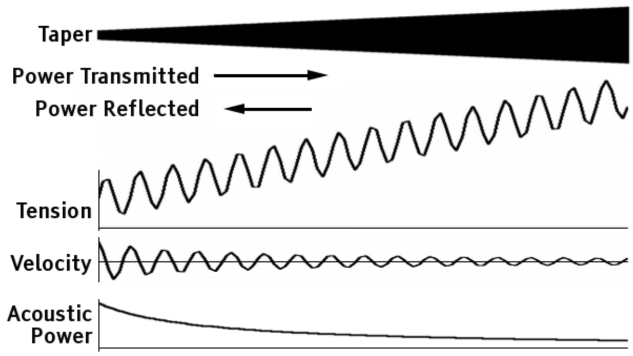

Fig. 3. Tether acoustic power from the bottom transmitter is attenuated and reflected off the denser taper above. This limits climb power, approximately proportional to the gravity on the tether.

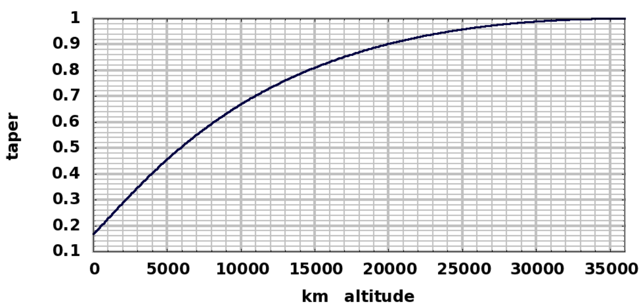

Fig. 4. Tether taper versus altitude. Reduced gravity at higher altitudes reduces the rate of taper increase, so the attenuation of ground transmitted power is reduced.

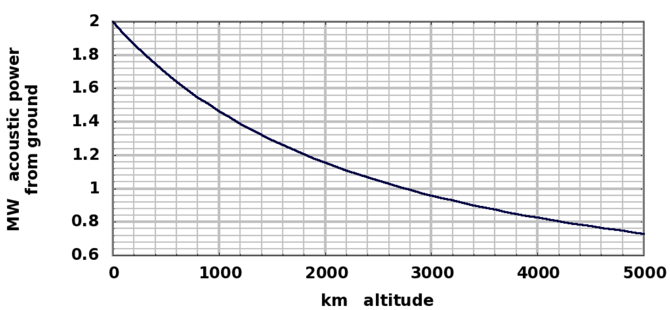

Fig. 5. Climber power versus altitude, 2 Megawatts from the bottom, assumed top speed 200m/s for 5000 kg climbers. These numbers will increase greatly at middle altitudes when a second transmitter is added at GEO

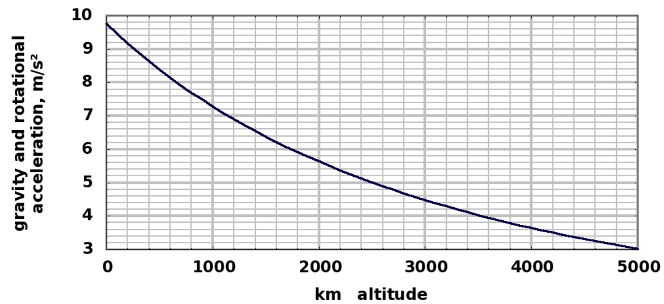

Fig. 6. Gravity minus centrifugal acceleration versus altitude

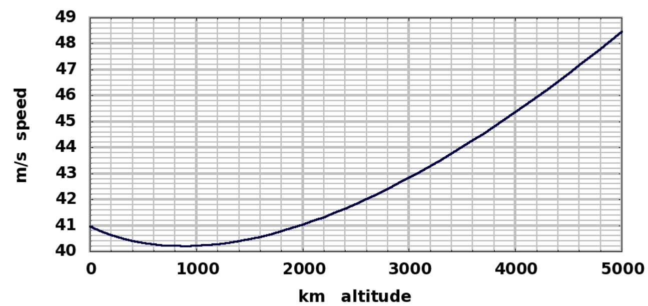

Fig. 7. Speed versus altitude, power from the ground transmitter only. Speed is proportional to power divided by gravity and the 5 tonne climber mass. When the GEO transmitter is constructed, and power can also be supplied from above, the power can be proportional to tether cross section, increasing with altitude as gravity decreases. Speed can increase to 200 m/s at 3000 kilometers altitude.

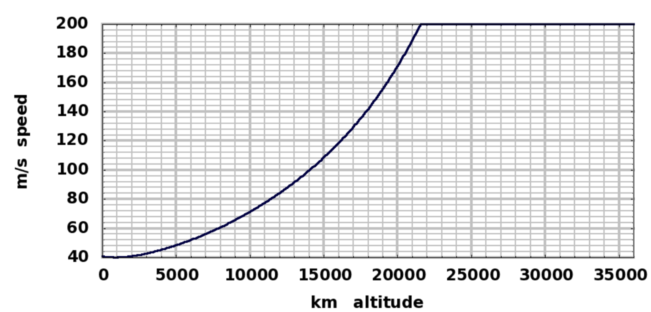

Fig. 8. Speed versus altitude, power from one transmitter at the bottom only. The maximum climb speed is presumed to be limited to 200 m/s. Below 22 000 km altitude, climb speed is power limited. When a 6 MW transmitter is added at GEO station, sending power downwards, climbers may be able to climb at the presumed 200 m/s speed limit from 3000 km altitudes and above.

that still contain energy, but are the sum of upwards and downwards waves, transmitting less total power for capture by the receiver on the climber.

As luck would have it, this effect is approximately proportional to the inverse square reduction of gravity with altitude - less power is transmitted, but less power is needed to move a climber. The actual tether taper versus altitude is shown in fig. 4. The ground-transmitted power versus altitude over the lower 5000 kilometers is shown in fig. 5.

The gravity versus altitude in the lower 5000 km is shown in fig. 6, and the resulting speed - the power divided by the gravity and climber mass, is shown in fig. 7. For this paper, I assume mechanical limits on climber speed to 200 m/s (720 km/hr or 450 m.p.h.). Staged climbers, with payload hand-off from high gravity low speed climber designs to low gravity high speed climber designs, may improve top speed in the upper tether, and total throughput, but will add complexity, and perhaps unacceptable accumulated wear. Again, a clever mechanical engineer may have better solutions.

As shown in fig. 8, above 22 000 km (for this design), the acoustic power is more than ample to keep a climber climbing at 200 m/s, the assumed top speed. That suggests that another

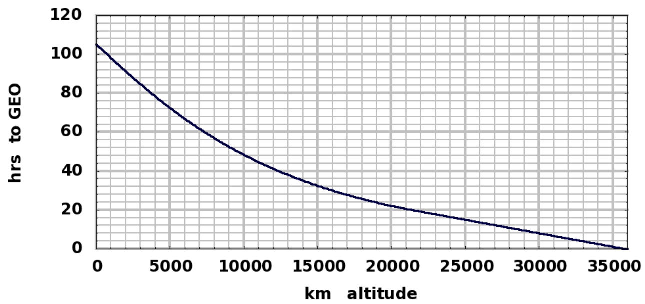

Fig. 9. Climber time to GEO from lower altitudes, assuming only one 2 MW transmitter at the bottom, attenuated by the taper to single climbers higher up. When a 6 MW transmitter is added at GEO, throughput increases to one climber every 10 hours, while climb time drops below 56 hours.

climber can start up the tether when this point is reached, passing some power upwards. However, this is complicated by the fact that the peak acoustic wave tension of the energy passed upwards is added to the tension of the climber weight, increasing stress beyond design limits.

A more prudent course is to pair climbers - letting the first negotiate the transit to 22 000 kilometers and coast to a stop, then sending a second climber up to join it, with the pair traveling in tandem, perhaps an hour apart, at half speed initially, with speed for the pair increasing as they climb into lower gravity. The delay will increase average transit time, but also increase throughput - we can launch climbers more rapidly

With a lower transmitter only, the climb time for a single climber is shown in fig. 9. If we add a 6 MW upper transmitter, this time reduces rapidly, because climbers can move at 200 km/s from above 300 kilometers altitude, and up to 3 MW of downward-transmitted power can reach the climber as it ascends into the wider-tether, lower-gravity zone.

Above 3000 kilometers, the tether is wider and gravity is lower. The tether can support many climbers, and the power needed for each climber to achieve 200 meters per second against the remaining gravity is small, too. If each climber receiver is agile enough, they can pass unneeded power to a climber below, and many 200 m/s climbers can be powered by the same 6 MW upper transmitter.

V. Acoustic transmitters

The first acoustic transmitter will be at the bottom of the tapered tether, and waves will be attenuated by the taper ratio on the way up the tether. The first payloads delivered to GEO will be another transmitter, solar powered, perhaps a simple rotary or piston heat engine, or a more sophisticated solar power and electric solenoid arrangement. With transmitters at both ends, a wide range of frequencies, amplitudes, and phase velocities can be created in the tether. The acoustic propagation delay from High Stage One to GEO is 22 minutes, resulting in a long delay between power transmission and power pick-off by climbers.

360 Hz is an interesting acoustic frequency, because it can be efficiently created from 3 phase 60 Hz grid power. However, 2 megawatts of ground power at 20 cents per kilowatt hour is an annual expense of only $3.5M, very small compared to other operating expenses, so efficiency is not the prime consideration. Power frequencies should be chosen for optimal climber performance and reliability, and may be adjusted dynamically as climber velocity changes with altitude.

Descending climbers must somehow dissipate gravitational descent energy. By depositing energy through the same mechanism, on the “downbeat” of the wave, a descending climber can transmit power back to the surface, or to GEO, where it can be converted to electricity by reversing the transmitter.

Transmitters provide another advantage with an inclined tether; they can change the average tension on the tether, and hence its north-south profile versus altitude. This allows the tether to dodge accurately tracked space debris, given some warning. An debris object at 1000 kilometers altitude can be avoided with a large vertical displacement wave launched from the lower transmitter 40 seconds before.

VI. Receiver design

The receiver converts acoustic power - strain waves and phase-offset velocity waves - into vertical thrust and linear motion. The process resembles the capture of electrical energy with an antenna, resonant circuit, and rectifier. Low frequency vibrations have long wavelengths, which may be easier to rectify, but require bigger resonators to store energy over a cycle, and longer wavelength ”antennas”. High frequency vibrations require fast response from ”rectifiers” - ratchets, or electronically activated solenoid clutches.

All receivers will require impedance transformation - for wide tethers carrying high static stress loads, the impedance is high, and large mechanical strains translate to small displacement velocities. The waves move extremely fast up (or down) the tether, and deliver many pulses of energy rapidly, but each pulse must be transformed into ”slow energy” for a climber moving much more slowly than the propagation speed.

The ”resonator” might be a flywheel, storing 20 cycles of climb power with power densities of 20 KJ/kg; about 2 kg/msec .

Table I assumes a 5000 kg climber climbing at 40 m/s and a climb force of 50 kN, climb power of 2 MW. The vibration distance is how far mass can drop in a 10 m/s^2 acceleration plus gravity field in one cycle.

Table II assumes a 5000 kg climber climbing at 200 m/s at 3000 kilometers altitude, assuming 0.9 MW acoustic power from the ground and 3.6 MW acoustic power arrives from GEO, after most is picked off by climbers above. The region between 5000 kilometers and GEO at 35 786 kilometers altitude is where most climbers will be, and the most transit time elapses.

Table III assumes a 5000 kg climber climbing at 200 m/s and close to the geostationary station at 35786 kilometers altitude. 4 or 5 climbers between 3000 km altitude and GEO will tap off only part of the acoustic energy sent from GEO, passing most of it to climbers below.

Formula One race cars, moving cranks and valves and cams and completing combustion cycles, are limited by racing rules

ground, 13.7 g/m, 2 MW tether			
impedance Z	342 kg/s		
vibration energy	80 J/m		
vibration velocity	108 m/s		
vibration stress	37 KNewton		
static stress	370 KNewton		
local gravity	9.8 m/s^2		
climber mass	5000 kg		
climber speed	40 m/s		
climber stress	49 KNewton		
climber power	2 MW		
frequency (Hz)	100	360	1000
RPM	6000	21 600	60 000
period (ms)	10.0	2.78	1.0
wavelength (m)	250.0	69.4	25.0
vibration distance μm	490	38	5
energy per cycle (KJ)	20.0	5.6	2.0
acceleration (km/s^2)	68	244	680
displacement (cm)	17.2	4.8	1.7

TABLE I
ACOUSTIC POWERED CLIMBER NEAR THE GROUND

3000 km, 29 g/m, 4.5 MW tether			
impedance Z	725 kg/s		
vibration energy	180 J/m		
vibration velocity	111 m/s		
vibration stress	76 KNewton		
static stress	950 KNewton		
local gravity	4.5 m/s^2		
climber mass	5000 kg		
climber speed	200 m/s		
climber stress	22.5 KNewton		
climber power	4.5 MW		
frequency (Hz)	100	360	1000
RPM	6000	21 600	60 000
period (ms)	10	2.78	1.0
wavelength (m)	250	69.4	25
energy per cycle (KJ)	45	12.5	4.5
acceleration (km/s^2)	70	251	700
displacement (cm)	17.7	4.9	1.8

TABLE II
ACOUSTIC POWERED CLIMBER AT 5000 KM ALTITUDE

to 18 000 rpm, but can turn much faster with cutting edge technologies. The Volvo S60 braking energy storage flywheel turns at 60 000 RPM. The numbers above (scaled for extreme tether strength) are not out of line with current engineering practice.

Actuator frequencies using high power drive solenoids can (presumably) move as fast as an audio speaker - 20 kHz or faster. These will presumably be resonant, unlike speakers or ”voice coil” heads for disk memory, so electrical power shapes movement but does not drive it.

Fig. 10 shows elements of an acoustic power receiver. The

near GEO, 80 g/m, 6 MW tether			
impedance Z	2000 kg/s		
vibration energy	240 J/m		
vibration velocity	78 m/s		
vibration stress	155 KNewton		
static stress	2160 KNewton		
local gravity	near zero		
climber mass	5000 kg		
climber speed	200 m/s		
climber stress	near zero		
climber power	near zero		
frequency (Hz)	100	360	1000
RPM	6000	21 600	60 000
period (ms)	10	2.78	1.0
wavelength (m)	250	69.4	25
energy per cycle (KJ)	60	16.7	6.0
acceleration (km/s^2)	49	176	490
displacement (cm)	12.4	3.4	1.2

TABLE III
ACOUSTIC POWERED CLIMBER NEAR GEO

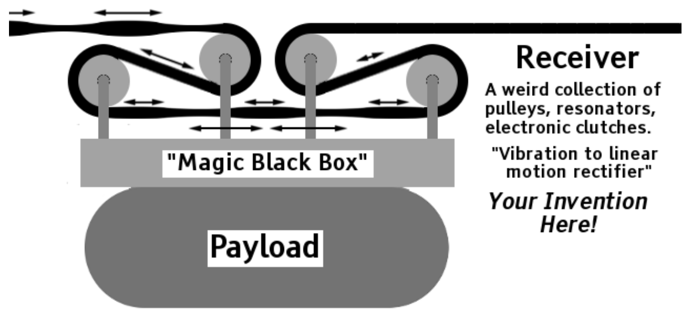

Fig. 10. A hypothetical receiver, transforming and rectifying longitudinal acoustic energy into vertical climb power. The actual mechanism is not yet designed, but will use resonance and flywheel power storage to amplify the velocity and reduce the force.

actual design requires more mechanical imagination than the author of this paper has. We can assume that the payload is vibration-isolated from the acoustic receiver, and that the tether makes multiple loops through a set of pulleys on the receiver so that a significant fraction of an acoustic wavelength is contained in the system. Here, the pulleys are assumed to vibrate and remove acoustic power from the tether, turning that power into linear motion of the vehicle using clutches and resonances inside the ”magic black box”.

VII. PAYLOAD RATES

When fully deployed, with a transmitter at GEO, climbers above 3000 km altitudes can ascend at 200 meters per second, making the transit to GEO in a little over two days. The limit on throughput will be the weight of a single climber on the lowest 3000 km of the tether, limiting throughput to perhaps 2.4 five tonne climbers per day. Climber mass and speed should be optimized for quick passage through this region. Lighter climbers put less stress on the tether, allowing more of the peak stress to be used for moving acoustic power.

The climbers will be much simpler than photovoltaic climbers, consisting of a few hundred kilograms of mechanical mass and a few tens of kilograms of more-expensive electronics. The electronics might be worth re-using. Rather than send empty receivers back to earth all the way down the tether, it may be easier to separate the electronic packages, bundle hundreds up into a reentry capsule with a heat shield, lower them to 12 200 kilometers below GEO, and release them into an atmosphere-skimming 10 km/s reentry. Lowering the reentry packages at 200 meters per second will only require 17 hours. Two or three up-bound climbers can wait below that altitude, where gravity is 3% of surface gravity, and the 3 tonnes of additional tether can support 15 tonnes of waiting climber. This recycles the expensive part of a climber receiver without reducing system throughput; wheels and other mechanical climber parts will probably be worn, and would require expensive refurbishing even if they were returned to Earth.

VIII. Space-to-Space Tether Power Transmission

Before a space elevator tether becomes possible, acoustic power transfer, and "tin-can-telephone" signaling, can be used between two satellites connected by a Kevlar tether, tensioned by the gravity gradient.

Let's use the example of TSS-1R, a 500 kg satellite deployed on a tether 20 km below the STS-75 space shuttle mission, orbiting at 300 km altitude. The tidal acceleration gradient is $3\omega^2 L$, or 0.08 m/s^2 for 20 km of tether in a 90 minute orbit. The tidal force on the tether is 400 Newtons.

We will diverge from the story there - the tether for TSS-1R was not a pure structural tether - it carried electrical current inside insulating plastic, and that made it far heavier than our example. How much pure structural tether would we need just to support 400 N?

Assume a Kevlar 149 tether - density is 1470 kg/m^3, tensile strength is 3450 MPa, and the modulus is 179 GPa. With a pure Kevlar-only structural tether, with a safety factor of 2 (1725 MPa), the tether cross section to support 400 N is 2.3e-7 m^2, and the entire 20 km tether would weigh 7 kilograms. The acoustic propagation speed in Kevlar is $\sqrt{179e9/1470}$ = 11 km/s, and the mass of the tether is 3.5e-4 kg, so the impedance Z is 3.8 kg/s . Assuming a 100 N acoustic tension wave, the acoustic wave displacement speed would be 26 m/s, and the energy per meter would be 0.12 J. Multiplied by the propagation speed of the tether, this is about 1.3 kW.

The real TSS-1R tether was heavier - a slower propagation speed, and higher acoustic impedance, lower vibration speed, all conspiring to move far less acoustic power. For electrical tethers, it is probably better to use a parasitic voltage drop at one end to extract power from the large magnetically-induced voltages and plasma-coupled currents.

However, in much higher orbits, where the plasma density and magnetic fields are both low, an acoustic tether can be a practical way to move power between widely separated end masses.

IX. Conclusion

CNT tethers are extremely strong, allowing them to carry huge amounts of power as longitudinal acoustic vibrations. The vibration can be transmitted from power sources on the ground and also at GEO station, sent through the tether with high efficiency, and converted to climber velocity and thrust with mechanical receivers on each climber.

Acoustic power transmission is a preliminary and incomplete idea. It will need much more development to be practical, requiring a clever and durable design for an efficient acoustic receiver that produces mechanical thrust without an expensive intermediate conversion to electricity. A mostly-mechanical system can be vastly cheaper, lighter weight, and more efficient.

However, even a low efficiency system will be less expensive and weigh far less than solar panels supporting themselves in gravity. Some control electronics may be needed, but those packages will be relatively low power and light weight; those expensive parts can be removed from used climbers, then bundled and reentered for reuse without interrupting the upward flow of climbers, while the worn (and low cost) mechanical parts of the climber can be stockpiled at GEO station, or added to the apex anchor.

The space elevator is a mechanical system - it will be cheaper and more reliable if the climbers are almost purely mechanical as well.

References

[1] The temperature is highest if the tether is flat to the sun. The power absorbed is the albedo times 1366W/m^2, the power emitted (on each side of an approximately flat surface) is the albedo times σT^4, where σ is the Stefan-Boltzmann constant, 5.67e-8 W/m^{2}K^4 . Thus T^4 = 683 W/m^2 / 5.67e-8 W/m^{2}K^4 and T = 330K . However, the tether can twist and face with any angle towards the sun; if it has a slight curvature, the area facing the Sun is not zero, but reduced. If the tether is perpendicular to the sun, with 20% curvature, it will cool to 220K. We can expect a tether to twist with altitude - there are no significant restoring forces keeping it flat, except during the temporary transit of a climber. That will create regions of varying temperature over the length of the tether, presumably with varying mechanical characteristics. Those may be acoustically dispersive and reduce the power reaching a climber far from the transmitter.

[2] During the spring and fall equinoxes, the tether will be in full eclipse for an hour every day, and the tether temperature will drop to about 35 Kelvin. The only heat source is the 250K night sky of the earth, appearing as 3.67e-4 of the Lambert-law-weighted night sky at GEO. The rest of the sky, including the sky perpendicular to the tether (with a Lambert law weighting of 1) is 2.7K deep space. 35K $\approx$ 250K $\times$ $\sqrt[4]{3.67e-4}$.

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