The Hypersonic Skyhook: Enabling an Impossible Idea

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Abstract

A "skyhook" is an orbiting platform which extends a tether down towards the Earth, enabling the transportation of payloads to orbit by cable car, instead of by rocket. While the skyhook concept is intrinsically attractive, as it offers the potential for enormous reductions in Earth to Orbit transportation costs, both the geostationary and rotating skyhooks proposed in the past have been found to be infeasible due to excessive strength to weight ratio required for the tether material. In this paper, an alternative skyhook concept, termed the "hypersonic skyhook," is proposed which has the potential of relieving the severe strength-of-materials demands which have thus far prevented the implementation of a practical skyhook. The hypersonic skyhook accomplishes this by keeping the tip of the extended tether outside of the tangible atmosphere and allowing it to move at hypersonic velocities with respect to the ground. This allows the skyhook's center of mass to be lowered from geostationary altitude, reducing the length of the tether, and cutting its mass and taper ratio by many orders of magnitude. Delivery of payloads to the tether is accomplished by hypersonic (Mach 10-15) trans-atmospheric vehicles capable matching horizontal velocity with the tether and utilizing vertical rocket thrust to negate gravity during rendezvous.

This paper presents a derivation of the equations governing the required size, taper ratio, and mass of hypersonic tethers. Results flowing from these equations are presented, and the design and operation of a sample system is described. It is shown that the hypersonic skyhook is a potentially feasible, and may offer an attractive means of transporting payloads to orbit.

Introduction

In 1960, the Soviet engineer Y. N. Artsutanov[1] published a description of a novel means for Earth to Orbit transportation. In the Artsutanov scheme, a satellite placed in geostationary orbit would simultaneously extend cables down towards the Earth and in the opposite direction, keeping its center of mass, and thus its orbit, constant. This procedure would continue until the lower cable reached the surface of the Earth, where it could be anchored, and used to support elevator cabs. These cabs in turn, could then be used to transport payloads up to the satellite where they could be released into geostationary orbit. Alternatively, if allowed to proceed out along the outward cable, the payloads could be released with greater than orbital velocity, so that at different stations along the outward cable, payloads could be released to proceed on trans-Lunar, trans-Mars, trans-Jupiter and other trajectories of interest. This concept, while published in both Russian and English, was widely ignored and promptly forgotten, only to be re-derived, and published by a group of American oceanographers[2] in 1966, after which it was forgotten again. The concept was revived for a third time in 1975, by Jerome Pearson[3], of the Wright Patterson Air Force Base, who published a series of papers going into much greater detail than the earlier authors, including derivations for system mass, tether taper configuration, and allowable limits to the rates that payload could be moved along the tether without exciting dangerous vibrational modes. Subsequently, the geostationary skyhook concept was widely publicized by Arthur Clarke, who employed such a device as a central feature of his novel "The Fountains of Paradise."

While offering the exciting prospect of a simple cable car-to-orbit system, the geostationary skyhook described by Pearson and the others suffered from one little flaw: it was impossible. The reason why it was impossible was this: If one places a load at the bottom of the geostationary tether, the bit of tether holding it must be thick enough to support that load. The next bit of tether must then be thick enough to support, not only the load, but the load plus the bit of tether supporting it. Thus, as it proceeds from the ground towards geostationary altitude, the tether must get thicker and thicker, and it fact its diameter expands exponentially. Depending on the strength-to-weight ratio for the tether assumed, the final result would be that the cross sectional area of the tether at

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the satellite would be 6 to 20 orders of magnitude greater than its area at its base, with similar fantastic ratios holding between the tether system mass and the mass of the payload it is required to lift. In answer to this problem, Pearson could only propose that in the future, ultra-strong materials, such as single crystal graphite fibers, might become available with orders of magnitude improvement in strength-to weight over current materials, resulting in exponential reductions in taper diameter ratio and system mass. Until such futuristic materials became available, skyhook applications would have to be limited to lower gravity bodies, such as the Earth's Moon, where while the problems faced by skyhook engineering are greatly reduced, the imperative for an alternative to rocket transportation is correspondingly less compelling.

A potential means of bringing the skyhook back down to Earth was offered in 1977, by Hans Moravec[4], who proposed that the skyhook be placed in an orbit lower than geostationary, and the two tethers extending from it be made to rotate, or "roll" so that during its descent through the atmosphere, the tether tip would be moving backwards at an equal speed to the skyhook's orbital velocity. This would cause the tether tip to briefly possess a ground track velocity of zero, at low altitude, thus enabling a payload on the ground or on a slow flying aircraft to be transferred to the tether for a ride into space. By bringing the skyhook to a lower orbit, the length of the skyhook is reduced, creating the potential for a large reduction in system mass. The realizing of the mass reduction potential in the rolling skyhook concept is restricted however, by the fact that as the two tethers spin about the system center of mass, centrifugal force is generated which is additive to gravity while a tether is in the downward position and negative to it when the tether is in the upward position. This adds both static and dynamic loads to the tether system, requiring tether thickening and mass increases. The result is that futuristic materials are still required for the construction of a practical system. As an operational system, the rotating tether suffers in comparison to the geostationary tether by the brevity of potential access, and by the fact that in while a payload can reach a stable orbital condition can be reached by climbing the tether to the skyhook center prior to release, and injection energies for interplanetary velocities are easily attained during release from the tether during its upward, forward moving swing, useful injection orbits may be difficult to attain due to the lack of correspondence between the tether's motion and the proper orbital phasing for payload release (i.e. the tether will generally not be moving through its upward arc at the right moment to throw the payload where it is supposed to go.)

In this paper we present a third type of tether-skyhook system, which we call a hypersonic skyhook. (Fig.1). As we shall show, the hypersonic skyhook has potential of relieving the severe strength-of-materials demands which have thus far prevented the implementation of a practical skyhook of either the geostationary or rotating varieties. The hypersonic skyhook accomplishes this by keeping the tip of the extended tether outside of the tangible atmosphere and allowing it to move at hypersonic velocities with respect to the ground. This allows the skyhook's center of mass to be lowered from geostationary altitude, reducing the length of the tether, and cutting its mass and taper ratio by many orders of magnitude. Unlike the rotating skyhook, however, the hypersonic skyhook does not spin about its satellite center of mass, but keeps both tethers aligned along a constant radial direction towards and way from the center of the Earth. This causes the centrifugal force term along the tether to be constant in time and always counter to the stresses induced by gravitational loads. This eliminates the dynamic stresses faced by the rotating tether and causes a further exponential reduction in tether mass, as the gravity term driving the tether mass expansion is negated more and more as the tether's orbital velocity increases. The result is that tether systems with masses only 1 or 2 orders of magnitude greater than the payloads to be lifted become possible using present day or near term materials, for hypersonic tethers moving with ground track velocities in the Mach 10-15 range. Because the atmospheric drag caused by travelling through the atmosphere at such velocities is unacceptable, the base of the hypersonic skyhook must travel outside the atmosphere, perhaps at an altitude of about 100 km. Access to the hypersonic skyhook would have to be provided by trans-atmospheric vehicles capable matching horizontal velocity with the tether and utilizing vertical rocket thrust to negate gravity during rendezvous. While the design of such vehicles is certainly a significant challenge, it is much less formidable than the development of transatmospheric vehicles with full orbital (Mach 25) capability. The hypersonic skyhook, moreover, allows the payload to be sent from suborbital trajectories, not only to orbit, but to any destination in the solar system without the further use of propellant.

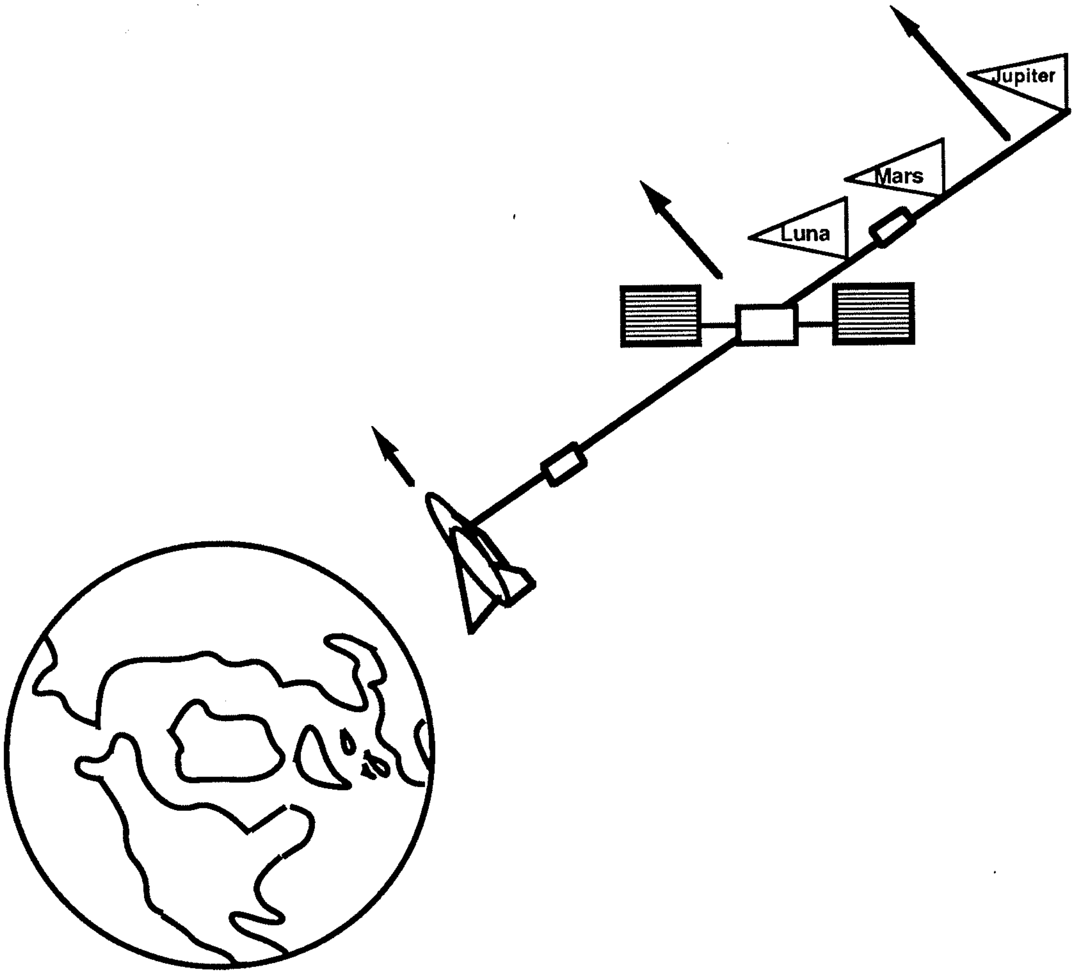

Fig. 1 The Hypersonic Skyhook

Derivation of Equations

In this section we derive the relevant equations governing the performance of a hypersonic skyhook.

The amount of mass in a given segment of the tether is given by:

$$dm = \rho a dl \qquad (1)$$

where ρ is the the density and a is the cross-sectional area.

The amount of additional load added to the tether due to this segment is given by:

$$dF = g dm - \omega^2 (R_1 + l) dm \qquad (2)$$

where g is the gravitational acceleration at the altitude of a given tether location, R_1 is the distance of the base of the tether from the center of the Earth, l is the distance along the tether from the base, and ω is the angular velocity of the tether with respect to the center of a fixed (non-rotating) Earth.

The local gravitational acceleration, g, is given by:

$$g = g_1 \frac{R_1^2}{(R_1 + L)^2} \qquad (3)$$

where g_1 is the gravitational constant at the base of the tether.

Putting equations (1), (2), and (3) together and integrating along the length of the tether, we can obtain an equation for the total load that must be reacted by a tether of length L.

$$F = \sigma a = M_1 g_1 + \int_0^L \rho a \left(g_1 \left(\frac{R_1}{R_1+L}\right)^2 - \omega^2 (R_1 + L)\right) dl \tag{4}$$

Here M_1 is an initial load placed at the end of the tether. Differentiating equation (4) with respect to L we obtain:

$$\sigma \frac{\partial a}{\partial L} = \rho a \left(g_1 \left(\frac{R_1}{R_1+L}\right)^2 - \omega^2 (R_1 + L)\right) \tag{5}$$

Equation (5) can be rearranged and integrated, resulting in:

$$\int_0^L \frac{da}{a} = \frac{\rho}{\sigma} \int_0^L \left(g_1 \left(\frac{R_1}{R_1+L}\right)^2 - \omega^2 (R_1 + L)\right) dL \tag{6}$$

The solution of equation (6) is:

$$a = a_0 \exp\left[\left(\frac{\rho L}{\sigma}\right)\left(\frac{g_1 R_1}{R_1 + L} - \omega^2 \left(R_1 + \frac{L^2}{2}\right)\right)\right] \tag{7}$$

Equation (7) is the expression which yields the required taper ratio for an orbiting, non-rotating, tether skyhook of any given length, L. It can be seen that the tether taper ratio is an exponential function of the material density to strength ratio, ρ/σ, multiplied by a the length of the tether, L, multiplied by a term which decreases strongly as the angular velocity, ω, increases.

It can be shown from the laws of orbital mechanics that:

$$(R_1 + L)^3 = \mu/\omega^2 \tag{8}$$

where μ is the mass of the Earth times the universal gravitational constant.

Now as the velocity of the tether with respect to the ground increases, so does ω, which, as equation (8) shows, has a strong inverse relationship to the length of the tether from its bottom tip to its thickest (orbital center of mass) position. As equation (7) shows, *each* of these effects tends to reduce the required tether taper ratio exponentially, so it may be expected that taken together, the resulting reduction in required taper ratio will be extremely strong. As we shall see in the presentation of results given below, this is indeed the case.

A tether skyhook starts with a certain cross sectional area, a_0 at its base, which increases to a maximum cross sectional area, A, at its orbital center of mass. The tether then continues outward beyond its center of mass, tapering off again as described by equation (7). The tether will reach its initial, minimum, cross sectional area, a_0, again when the exponential factor in equation (7) goes to zero, or:

$$\frac{g_1 R_1}{R_1 + Z} = \omega^2 \left(R_1 + \frac{Z}{2}\right) \tag{9}$$

Here Z is the total length of the tether, including the segments both above and below the center of mass, i.e. $Z = L_1 + L_2$, where L_1 is the length of the tether from its base to its orbital center of mass (previously described as simply "L"), and L_2 is the maximal allowable length (from the standpoint of tether stress) from the orbital center of mass to the outward tether tip. Maintaining symmetry about the orbital center of mass will, however, generally require truncating the upper tether length shorter than L_2.

Discussion of Results

The strength to weight ratio of tether materials is ordinarily given in terms of the tether's characteristic velocity (CV), which is simply the square root of the strength (in pascals) to density (in kg/m^3). Kevlar with a CV of 1.2 km/s has been available on the commercial market for some time, while state of the art high-strength kevlar type materials with a CV of about 1.6 km/s are now becoming available. Advanced materials with CV's of somewhat over 2 km/s will probably be available in the near future.

In Fig. 2 we show the taper ratios resulting from equation (7) for hypersonic skyhooks with CV's of 1.2, 1.6, and 2.0 km/s. The case of a ground-track velocity of zero is simply the classic Artsutanov-Pearson geostationary skyhook. It can be seen that, postulating present day or near-future materials, such devices require taper ratios that are astronomical, making their construction infeasible. The merit of allowing the skyhook to move at hypersonic velocities can, however, also be seen. For example, assuming a CV of 1.6 km/s, the geostationary skyhook requires a ludicrous taper ratio of 10^8, while one whose base is allowed to

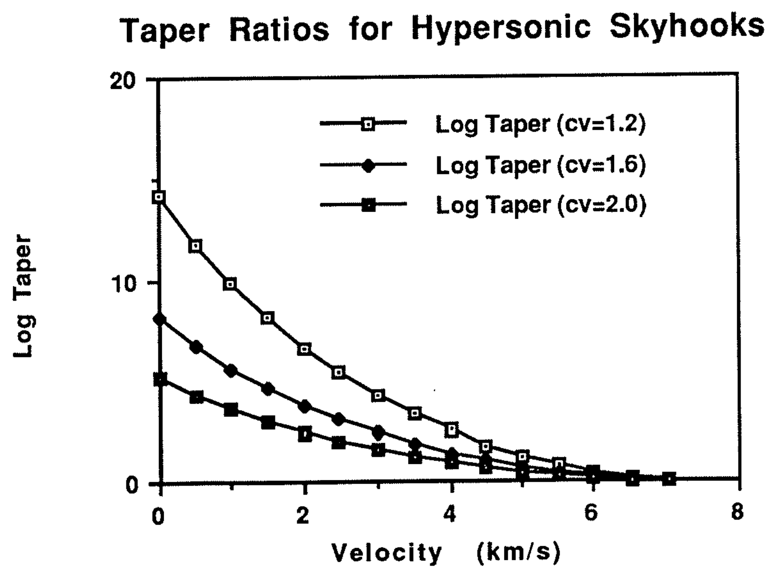

Fig.2 Taper Ratio for Hypersonic Skyhooks

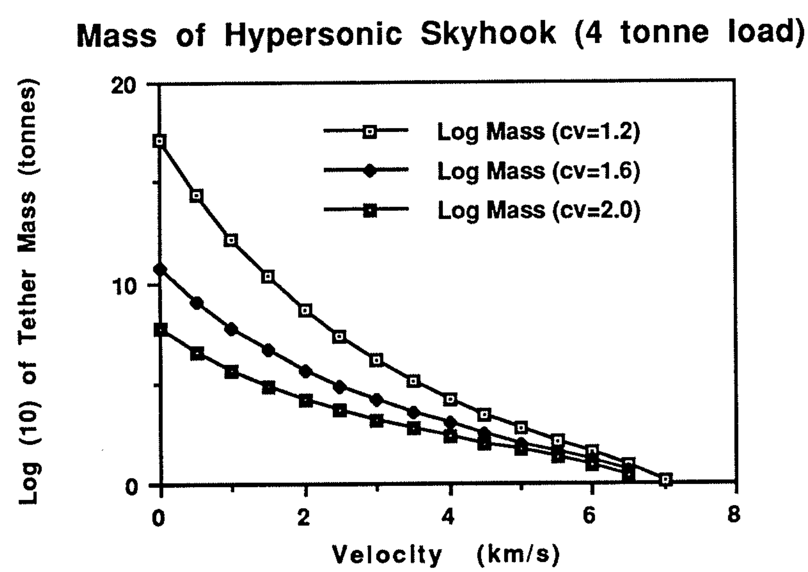

Fig. 3 Mass of Hypersonic Skyhook Tether Lifting 4 tonne Payloads

move at 4 km/s (Mach 12) only requires a quite reasonable taper ratio of 10^2.

In Fig. 3 we show the mass of a hypothetical hypersonic skyhook system capable of lifting loads of 4 metric tonnes. The skyhook mass was estimated by integrating equation (7) from the bottom of the tether to its orbital center of mass (to calculate the mass of the lower tether directly), doubling this to account for the additional mass of the strand of the tether beyond the orbital center of mass (this is an approximation - there is a certain amount of design freedom in the configuration of the tether upper strand), and multiplying the result by 1.25 to allow for margin. Once again the drastic reduction in mass of the hypersonic skyhook compared to the geostationary variety is readily seen.

In Table 1. we give the lower tether length (essentially skyhook central platform orbital altitude) and the total tether mass (both upper and lower strands) for hypersonic tether skyhooks capable of

Table 1. Hypersonic Skyhook Performance for 1 tonne Payloads

Velocity (km/s)	Lower Length (km)	Skyhook Tether Mass (tonnes)			Upper End C3 (km^2/s^2)
		CV=1.2	CV=1.6	CV=2.0	
0.0	35727	3.68 E 16	1.40 E 10	1.34 E 7	21.9
1.0	13275	3.23 E 11	1.26 E 7	102,250	32.1
2.0	7501	1.22 E 8	117,000	4200	30.0
3.0	4667	325,000	3,425	375	21.4
4.0	2936	3,575	224	55	8.1
5.0	1751	122	26	11	-8.8
6.0	880	31	3.8	2.1	-29.1
7.0	208	0.33	0.19	0.12	-52.4

lifting 1 tonne loads, again with a safety margin of 1.25. It can be seen that while a geostationary skyhook with a CV of 2.0 km/s requires a total (upper and lower sections combined) tether mass of more than 13 million tonnes, a hypersonic skyhook with a ground track velocity of 4 km/s only requires 55 tonnes of tether mass.

Also shown in Table 1 is the energy (C3) the payload will have if released from the upper end of the tether, assuming that the tether is constructed symmetrically, with the upper strand identical to the lower strand. Since a C3 of 8 is about what is required for a minimum energy trajectory to Mars or Venus, after which a planetary gravity assist can be obtained, it can be seen that a hypersonic skyhook with a base velocity of 4 km/s or less can be used to transfer payloads from a suborbital condition to a trajectory to any planetary destination in the solar system. While it cannot achieve Earth escape, a payload released from the 5 km/s skyhook has more than sufficient energy to achieve an elliptical orbit whose apogee is at geostationary altitude (i.e. a GTO orbit.)

A Hypersonic Skyhook System

We now consider a sample hypersonic skyhook system. Based upon the results given in Table 1, we assume a 1 tonne payload delivery design with a ground track velocity of 4 km/s and CV=2.0 km/s. The required tether thus has a mass of 55 tonnes. A power source will also be required to lift the payloads up the tether by a cable car mechanism; we assume 40 kWe. This can be provided by either photovoltaic panels or a nuclear reactor. Assuming near term space power technology, we assume a mass of 3 tonnes for the power source and its power conditioning system. While moving up the lower strand of the tether, the 1 tonne payload has an initial weight of about 9700 N, decreasing to 0 at the orbital center of mass. If we assume an average weight of 5000 N, the average speed that the payload can be moved is (40,000 W/5000 N) = 8 m/s. Since the lower strand of the tether is 2936 km long, it will thus take about (2936000/[(8)3600)] = 102 hours to move the payload from the tether lower tip to orbital altitude at the skyhook center of mass. Raising the payload beyond the orbital center so that it can be released at some point along the upper strand of the tether requires no power at all, as beyond the orbital center of mass, the outward centrifugal force term along the tether is greater than the inward pulling force of gravity. Effectively, a payload being transferred out along the tether upper strand is being lowered away from the Earth.

While the bottom of the tether has a ground-track velocity of 4 km/s, it has a velocity of 4.471 km/s with respect to a fixed (non-rotating) Earth (assuming a tether bottom altitude of 100 km). The tether center of mass is moving at a velocity of 6.497 km/s with respect to a non rotating Earth. Moving a 1 tonne payload from the tether base to its orbital center of mass thus increases the payload's angular momentum about the Earth by (6.497*9414)-(4.471*6478) = 22295 tonne-km^2/s. Since the angular momentum of the total skyhook-payload system about the Earth must be conserved, thrust will be required or the skyhook will lose altitude. If we adopt the approximation that the total mass of the skyhook (about 70 tonnes, accounting for various miscelaneous subsystems and micrometeorite protection) is concentrated at its orbital center of mass, we find that a total ΔV of [22295/(70*9414)] = 0.034 km/s will be required for the tether to maintain altitude. If this is provided by ion engines with a specific impulse of 5000 s, then 48 kg of propellant will have to be expended to enable the skyhook to maintain altitude after the lifting of each 1 tonne payload. Alternatively, part of the tether could contain an aluminum wire, whose current, interacting with the Earth's magnetic field could be used to produce thrust without the expenditure of any propellant. Based upon existing studies[5], a 20 km long electromagnetic (10 km above the orbital center of mass and 10 km below) tether operating in an equatorial orbit at an distance from the Earth's center of 6778 km and consuming 40 kWe would have a mass of about 800 kg and be able to generate as thrust of 5.0 N. Our skyhook operates in an equatorial orbit at a distance from the center of the Earth of 9414 km, and since the Earth's magnetic field falls off as the distance from its center cubed, this implies that such a design would exert a thrust of 1.86 N if used to propel the skyhook. This amount of thrust would be sufficient to provide the required compensatory ΔV for the skyhook in about 15 days. If more frequent use of the skyhook were desired, part or all of the ΔV could be provided by lifting a high thrust propellant to the orbital center of mass as part of the payload. For example if hydrogen/oxygen propellant with a specific impulse of 450 s were used to provide half of the required 34 m/s ΔV, then 272 kg of the 1000 kg payload would have to be propellant, but the tether could provide the rest of the re-boost electromagnetically in a period of 7.5 days, thus allowing it to be used about 40 times per year.

Payloads would be delivered to the skyhook by a trans-atmospheric vehicle, perhaps similar to the National Aerospace Plane (NASP) or Single Stage to Orbit (SSTO) vehicles currently being developed. Vehicle performance requirements would be far more modest, however, since only suborbital (Mach 12) flight would be needed, instead of the Mach 25 speeds entailed for both flight to orbit and orbital re-entry. The trans-atmospheric vehicle would match speeds with the skyhook bottom (which is hanging at an altitude outside of the tangible atmosphere), and use vertical thrusters to negate gravity during the period of rendezvous. During rendezvous the trans-atmospheric vehicle would hover below the tether, open its cargo bay, and allow its payload to be hooked by a cable car mechanism which rides upon the tether. After the payload is hooked, the trans-atmospheric vehicle would drop away, close its cargo bay, and return to Earth. Assuming that 30 seconds of thrust-negated gravity are required for the hooking operation, and hydrogen/oxygen thrusters with a specific impulse of 450 s are used, then an amount of propellant whose mass is about 7% of the trans-atmospheric vehicle will have to be expended during rendezvous.

Using its own electrodynamic thrust capability, the skyhook could deliver itself from LEO to its design altitude of 3036 km in about 300 days, without requiring any propellant. The system's total initial mass in LEO would thus be the same as its operational mass, i.e. about 70 tonnes, and either three launches of a 24 tonne to LEO launch vehicle, such as a Shuttle or an upgraded Titan IV, or a single launch of a 70 tonne to LEO launch vehicle, such as a Shuttle-C or an NLS-1 would be sufficient to launch the system. If a more rapid delivery was required from LEO to the destination orbit, a high thrust system could be used. Since the total ΔV required to move the system by Hohmann transfer from a 300 km launch delivery orbit to its final 3036 km operational orbit is only about 1.23 km/s, a hydrogen/oxygen stage could be used for transfer and the mission initial mass in LEO would still be under 95 tonnes.

Conclusions

We have shown that the concept of a hypersonic skyhook, which keeps the tip of the extended tether outside of the tangible atmosphere and allows it to move at hypersonic velocities with respect to the ground, has the potential of relieving the severe strength-of-materials demands which have thus far prevented the implementation of a skyhook of the pure geostationary variety. We have presented the derivation of the equations governing the required size, taper ratio, and mass of hypersonic tethers. Results flowing from these equations show that the reduction in length due to lower orbital altitude of a hypersonic skyhook, and the reduction in tether stress caused by the strong anti-gravitational centrifugal force operating along the tether of the hypersonic skyhook each cause an exponential reduction in the required tether mass and taper ratio. The net result is found to reduce the tether mass and taper ratio by many orders of magnitude, making an otherwise impossible concept at least theoretically feasible. We have described a sample hypersonic skyhook system, and have shown that a practical system capable of launching 1 tonne payloads from a Mach 12 suborbital trajectory to any destination in the solar system can be launched and delivered to orbit with an initial mass in LEO of less than 100 tonnes. We conclude that such a system is potentially practical and offers high-leverage for the human exploitation of space, and recommend that further investigations be undertaken to define the characteristics of such a system in greater detail.

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