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Synchronous Satellite at Less Than Synchronous Altitude

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I. Introduction

THE establishment of a synchronous (stationary) satellite at less than synchronous altitude was first examined in 1967[1] where it was found that a high-strength tapered cable (boron fiber with a 0.5×10^6 psi yield stress) could support a payload at near half synchronous altitude. The results of that study showed that the mass of the cable plus counterweight (above synchronous altitude) would be about 80 times that of the payload. It was recognized, however, that the problems of deployment and stabilization could be serious.

Potential uses of a synchronous satellite at less than synchronous altitude may include communication, navigation, and surveillance missions. If, for example, an omni or broad beam antenna is utilized then the transmitted power (and weight) is only a fourth that at the synchronous altitude (inverse square law). Or, if the same power is available then a fourfold increase in the amount of information transmitted is possible. Other potential benefits may include a signal to noise ratio increase for Earth observation missions and a linear sensor resolution improvement with the decrease in altitude. Night time illumination of selected Earth areas may also be feasible with the intensity of illumination being proportional to the mirror diameter and inversely proportional to the orbital altitude. For example, an 80-m diam mirror which is flat to within a small fraction of the sun's angular diameter and which is located at one-half the distance from the Earth to the synchronous altitude could provide full moon illumination ($\sim10^{-2}$ lm/ft^2) over a 100-square-mile area.

This note extends the results of Ref. 1 and examines the possibility of using a viscoelastic organic material Kevlar which has nearly twice the strength-to-weight ratio of boron steel fibers. It will be shown that a significant reduction in the total satellite weight can be achieved. Also considered will be possible deployment and stabilization methods.

II. Cable Equlibrium Equations

The schematic diagram of the cable-connected satellite system in equlibrium is shown in Fig. 1. Using the notation of Ref. 1, the derivative of cable tension T with respect to the radial coordinate r is

$$\frac{dT}{dr}=\rho A\left(ga^2/r^2-\omega^2 r\right) \tag{1}$$

where ρ = mass density of cable, g = gravitational constant at the Earth's surface, ω = orbital angular velocity, $A=T/\sigma$ = cross-sectional area of cable, σ = cable design stress, and a = Earth's radius.

Integration of Eq. (1) yields

$$T/T_m=\exp-\gamma(1-s)^2(1/2+1/s) \tag{2}$$

where $\gamma=\rho(ga^2\omega)^{2/3}/\sigma$ and $s=r/\lambda$. The cable mass M_c and the counterweight mass M_2 can be given as (Ref. 1)

$$\frac{M_c}{M_1}=\gamma\left[\frac{1}{s_1^2}-s_1\right]e^{\gamma(1-s_1)^2(1/2+1/s_1)} \times\int_{s_1}^{s_2}e^{-\gamma(1-s)^2(1/2+1/s)}ds \tag{3}$$

$$\frac{M_2}{M_1}=-\frac{(s_1^2-s_1)\exp\gamma(1-s_1)^2(1/2+1/s_1)}{(s_2^2-s_1)\exp\gamma(1-s_2)^2(1/2+1/s_2)} \tag{4}$$

Here

$$s_1=r_1/\lambda,\ s_2=r_2/\lambda$$

At

$$r=r_1,\ T_1=M_1(ga^2/r_1^2-r_1\omega^2)$$

III. Numerical Evaluation

Equations (3) and (4) were integrated numerically and plotted in Fig. 2 for boron steel ($\gamma=6.56$) and Kevlar ($\gamma=3.81$) as a function of radius s_2. It is apparent that the lowest overall mass ratio is obtained at $s_2=1.4$ and that a considerable reduction results from the use of Kevlar. Similar results can be observed from Fig. 3 which is a plot of Eq. (4). The crossing of curves indicates that the heavier material (steel) is more effective for longer cables above ths synchronous altitude. These results show, for example, that for a Kevlar ($\gamma=3.81$) cable extending from 10,000-n. mi altitude to about 28,000 n. mi (18,000 n. mi long) the cable plus counterweight $(M_2+M_c)/M_1$ ratio is 25 and $M_2/M_1=5$ which implies considerably lower total satellite weight than would be required for the boron steel material. The tensile strength of resin impregnated Kevlar strands is 525,000 psi and its density is 1.45 g/cm^3 compared to 500,000 psi and 2.4 g/cm^3 for the boron fiber. The strength to weight advantage of Kevlar is thus apparent although its somewhat increased sensitivity to uv radiation may require the development of a protective coating or its replacement by a graphite or fiber glass material with similar properties.

IV. Deployment and Stabilization Considerations

The deployment of a gravitationally stabilized 10,000-20,000-n. mi cable in orbit is likely to be a difficult process at best. Several studies, for example, have considered the deployment of cables 1-3 n. mi long. The approach of Ref. 2 was a two-stage deployment process consisting of a spring imparted separation velocity to the two end masses which are separated to a preset length of cable. Capture by the gravitational gradient occurs and the librational motion is then removed without dissipative damping by a "deadbeat" process of inertia adjustment initiated at a predetermined time. This begins during the first swing toward the vertical with the release of a second preset length of slack tether. The end bodies again move apart in separate coplanar orbits until the tether (cable) runs out of slack and the line joining the bodies approaches the local vertical at near zero angular rate. Tension-limited snubbing with modest energy absorption is required for this method of deployment.

The deployment of the present cable-connected satellite and its stabilization relative to the local vertical in the synchronous

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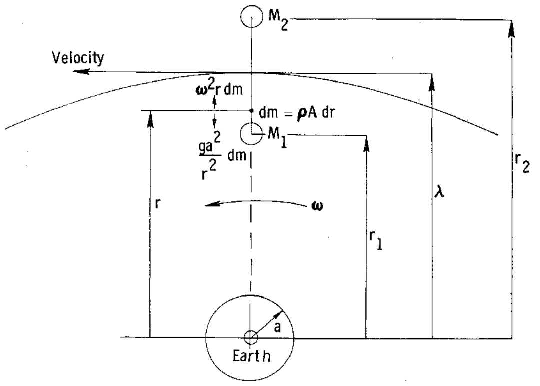

Fig. 1 Satellite configuration.

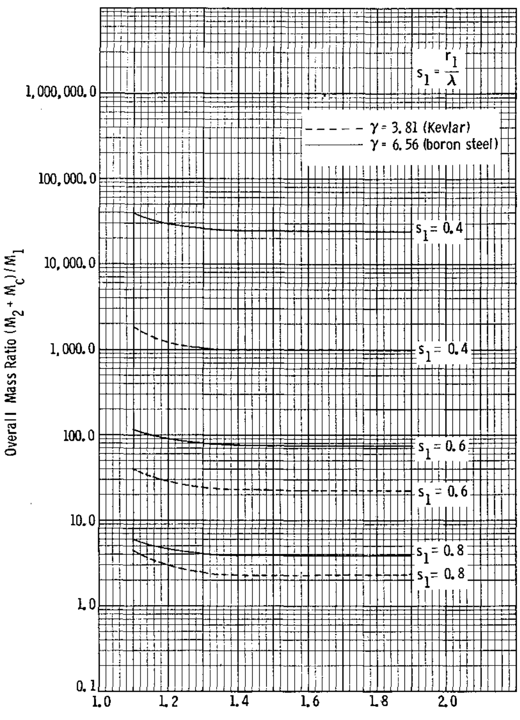

Fig. 2 Overall mass ratio vs radius s_2.

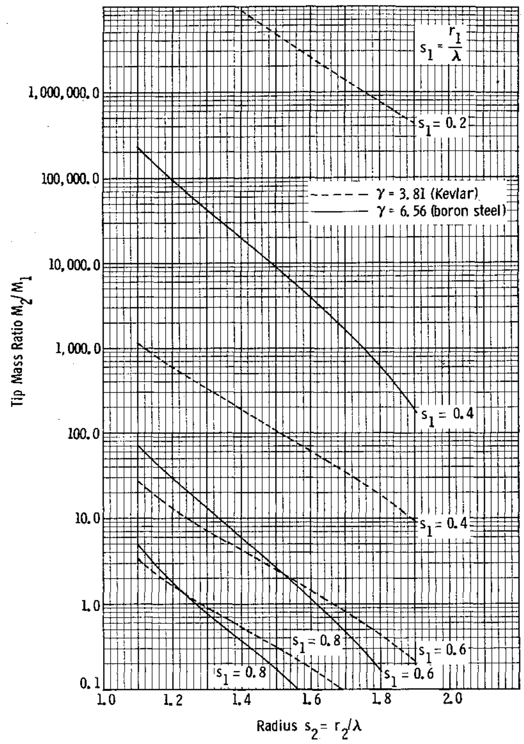

Fig. 3 Tip mass ratio vs radius s_2.

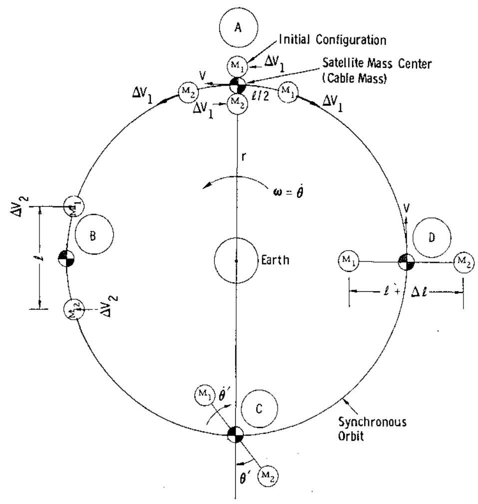

Fig. 4 Satellite deployment sequence.

equatorial orbit can be performed impulsively or by application of controlled thrusting as was suggested in Ref. 3. The impulsive deployment is simpler and is therefore preferable. It can be accomplished as follows.

1) With the cable and masses M_1, M_2 in the synchronous equatorial orbit apply a velocity impulse ΔV_1 to each end mass along and opposite to the satellite velocity vector V, respectively. This maneuver will initiate a separation of the masses and the unwinding of the cable. It is assumed that the end masses are stabilized in attitude relative to the local vertical.

2) After one or more orbital revolutions, the masses M_1 and M_2 will separate an in-track distance ℓ. Apply a ΔV_1 impulse to each mass in the direction opposite to that in Step 1 in the preceding to terminate further relative motion of the masses. The satellite mass center and the two end masses will now be in synchronous equatorial orbit with a relative separation of $\ell/2$ from the mass center (cable mass) as is shown schematically in Fig. 4 at A. For example, a $\Delta V_1 = 10$ fps will result in $\ell = 854$ n. mi after one orbital revolution. The value of ℓ will increase linearly each additional revolution as a result of the initial ΔV_1 application.

3) After a desired in-track separation is obtained, a velocity impulse ΔV_2 is applied normal to the velocity vector to each mass as shown at B in Fig. 4. This maneuver produces a torque about the satellite mass center and a relative angular velocity increment $\dot{\theta}'$. The latter is on the order of 10^{-3} deg/sec for a 4270 lb-sec impulse per mass. The resultant centrifugal acceleration is $a_c \approx 0.070$ rad/sec^2 which can be used to further extend the cable an increment $\Delta\ell$ and thus achieve gravitational capture as is shown at points C and D in Fig. 4.

4) Following gravitational capture, this process can be repeated for further extension of the cable.

The stabilization of the fully deployed system would require either an active, passive, or a combined method of damping to limit the oscillations (librations) of the masses about the local vertical. An entirely passive approach could be employed by taking advantage of the nonlinear resonance effects.[4,5] In this approach, the roll natural frequency is made equal to twice the orbital angular velocity by providing the appropriate flexibility and damping in the extensional mode of the cable. Energy dissipation occurs in all modes and an equilibrium (Earth pointing) configuration is eventually achieved. The cable tapering (for constant stress and weight reduction), material viscoelasticity, and the gravitationally induced tension are the controlling design parameters in such a scheme.

V. Concluding Remarks

The use of a viscoelastic material (Kevlar) can result in a significant weight reduction for the cable of a cable-connected two-body satellite. For example, the mass of the cable and counterweight is on the order of 25 times the mass of the Earth pointing satellite at one-half the synchronous altitude compared with about 80 times for the boron steel fiber. An efficient and simple impulsive deployment method was described which should provide initial gravitational stabilization of the system. Further studies of the deployment and stabilization methods by passive or more active approaches are necessary, however, to fully establish the feasibility of the system.

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