Technical Notes

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Solar Array Orientations for a Space Station in Low Earth Orbit

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Introduction

AN important parameter for selection of a solar array for a space station in low Earth orbit (LEO) is the aerodynamic drag. For orbits below about 700 km, the reboost propellant needed to offset drag is a major consideration in the operational requirements. A large portion of the drag is due to the solar array.[1] For a baseline 25-kW solar array in 334-km orbit, assuming H_2/O_2 thrusters (specific impulse 445 s), 1800 kg of reboost propellant per year is needed to counteract the drag of the array and associated radiator.

Ways of reducing the reboost propellant needed include higher orbital altitude, higher specific impulse propellant, or reduced drag. Drag can be reduced by increasing the array efficiency (e.g., by using higher efficiency solar cells) or by orienting the solar array to a minimum-drag position. In this paper we examine the effect of array orientation.

We use cumulative mass to orbit as a system figure of merit. While a better evaluation criterion is life-cycle cost, this depends on many parameters and is not always well defined or easily calculated. Thus, we use cumulative mass with the caveat that other factors are also important and must be considered in evaluation.

Options

We evaluated three options for orientation of the solar array:

1) *Sun pointing.* This is the baseline configuration for the solar array on the "Freedom" space station. Since the space station is Earth oriented, and the orbital period is approximately 90 min, this requires a gimbal rate (alpha gimbal) about 4 deg per min. The solar array gimbals[2] are defined in Fig. 1. The station maintains fixed orientation with respect to Earth. The alpha gimbal tracks the sun as the station rotates in its orbit; the beta gimbal compensates for variations in the angle of the sun to the orbital plane, or "solar inclination" angle.

2) *Hybrid (sun pointing during illuminated portion of orbit; edge on during eclipse).* Flying edge on significantly reduces the drag on the solar array. Since during eclipse (about 36 min of each orbit at 334-km altitude) the array need not be sun oriented; it can be gimbaled edge on to the orbital direction. This requires a rotation of 72 deg twice per orbit.

3) *Edge on during entire orbit.* Flying in the low-drag ("feathered") position will put the array at an oblique angle to the sun, and thus the array will have to be made larger. There are three suboptions: a) retaining both array gimbals, b) keeping only the beta gimbal, and c) eliminating both gimbals. In the edge-on position, the alpha gimbal is fixed. Keeping two gimbals allows the flexibility of sun tracking when temporarily higher power is desired at the expense of added drag. Alternatively, the alpha gimbal could be removed to lower the array weight. The array would still track the variation in solar inclination ("β-angle controlled" mode).

The beta gimbal could also be eliminated for an additional weight savings at the cost of an additional performance penalty because the array cannot track seasonal solar variations. This also allows two alternatives for the array to be fixed at $\gamma = 0$ deg (array normal in the orbital plane) or for it to be fixed at an optimum angle near 20 deg and the station periodically rotated when the sun vector crosses the orbital plane on the average once every 20 days.

It must be noted that if photovoltaic arrays are to be replaced by solar dynamic modules, which require high pointing accuracy, eliminating gimbals is not a viable option.

Baseline Parameters

The baseline orbit was 334-km altitude at 28.5-deg inclination with a worse case sun time:eclipse time of 54.76 min:36.38 min. We considered a baseline array with modular units of 25 kW. The solar cell efficiency is 12.2%[3] with an overall array efficiency about 7%. The total array area is 580 m^2. An additional 27 m^2 is required for the waste heat radiator. For the one-gimbal and no-gimbal cases, the heat radiator can be

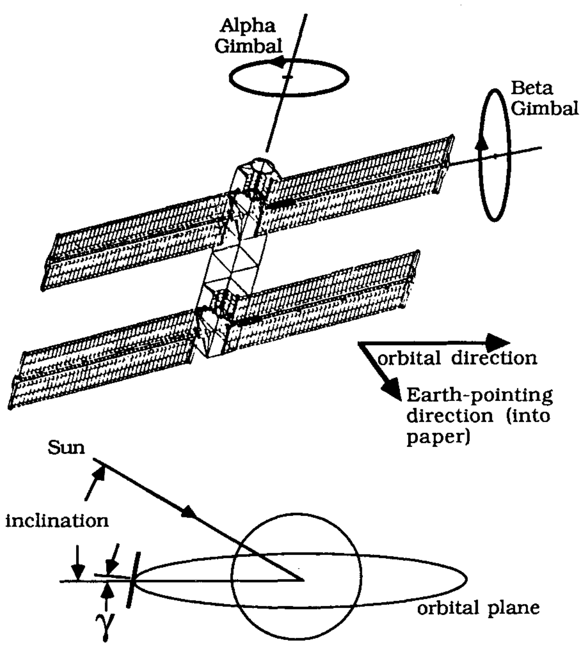

Fig. 1 Definition of alpha and beta gimbals and angles for solar array.

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chosen to be edge on to the orbit and, if desired, integrated into the main station radiator since it is no longer separated from the station by the rotating alpha gimbal. Battery storage is required for the period when the station is in eclipse or the array power is less than the operating power. We assume H_2/O_2 propellant for reboost with a specific impulse of 445 s. We also considered a higher orbit space station at 500-km altitude with sun time:eclipse time of 58.8 min:35.7 min. Details of the solar array assumptions appear elsewhere.[4]

Note that for the space station Freedom, the phase 1 solar array is 75 kW. Actual array wings supply 18.75 kW of user power but have a bulk power output at beginning of life of about 28 kW. Excess water produced by the Space Shuttle Space Transportation System (STS) fuel cells is designed to be transferred to the station for electrolysis and used for propulsion.[5] This provides up to 2950 kg/year of propellant at no additional required mass, assuming the maximum of five shuttle missions/year. Reboost propellant may also by provided by water scavanged from the life-support system. This will tend to reduce the importance of reboost propellant as a operational requirement. We also note that the solar arrays to be used on Freedom will have transparent back surfaces and thus convert some portion of the light incident on the back surface (e.g., albedo illumination)[6]—especially if the solar cells are optimized to take advantage of this. This effect was not included in our analysis.

Results

A first approximation for aerodymanic drag is that drag is proportional to the projected drag area in the direction of travel. Approximating the solar array as a thin sheet (plus an additional drag component independent of orientation, which will not be considered here), the drag area is proportional to the cosine of the array normal from the direction of travel. If we define $\theta = 0$ at mideclipse, then the ratio of average drag area to planform area in the sun-tracking mode is

$$\frac{A_d}{A_o} = \frac{1}{2\pi}\int_0^{2\pi} |\sin\theta|\ d\theta \qquad (1)$$

Hybrid (Edge on During Eclipse)

At 334-km orbital altitude, 40% of the orbit (144 deg) is in shadow. During this portion of the orbit, the array can be turned edge on with no loss of power. The average drag area is then $1.309/\pi$ or 0.417—an average area reduction to 68.7% of the baseline case. In the more exact calculation, we take into account the fact that the atmospheric density is higher in the sunlit portion of the orbit than that of the eclipsed portion by roughly a factor of two. The total effective drag is 81.5% of the baseline.

Edge on for Entire Orbit, Beta Gimbal Only

The array still tracks the sun in the direction normal to the orbital plane. The incident power is reduced by the cosine of the angle between the array normal and the sun. The worst case power occurs at solar inclination angle equal to zero. The ratio of average incident power to power incident in sun-pointing orientation is

$$\frac{P}{P_o} = \frac{1}{1.2\pi}\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} |\cos\theta|\ d\theta \qquad (2)$$

which equals 0.53. (The limits on the integral are $\pi/2$ to $3\pi/2$, since on the portion of the orbit on the eclipse side of the terminator, the back side of the array is illuminated. If the array is sensitive to back illumination or is rotated 180 deg as the orbit crosses the terminator, the limits are 0.4π–1.6π, which increases the power by about 5%.)

A second loss is due to increased reflection at nonnormal incidence; this contributes an additional 3% average loss to 0.515. This implies that the array area must be increased by a factor of 1.94 over the tracking array.

Average power generated by the array is 0.31 times the peak power. Because the time that power must be provided by the batteries is increased, the mass of the storage subsystem must be increased proportionately. Further, since the charging power now varies, the charging system must accommodate larger peak powers, which results in an additional mass increase. These factors together result in an increase in the storage subsystem mass by a factor of 1.72.

Fixed Angle

By going to a fully fixed array, the beta gimbal can also be eliminated. This results in an additional mass savings at some cost in efficiency. It would also have a possible additional advantage of eliminating possible vibrations due to array gimbaling; this could be important if the station runs extremely vibration sensitive experiments.

Incident power density will decrease with the solar inclination angle, which varies from +52 deg to −52 deg. If the array is fixed normal to the orbital plane ($\gamma = 0$ deg), the worst-case power comes at maximum solar inclination and equals 0.284 times the sun-tracking power, a reduction by a factor of 1.7 over the average available for the edge-on orientation if the beta gimbal tracks the sun. If the array is fixed at an optimum angle γ of slightly under 20 deg, the ratio of incident power to that of the sun pointing can be increased to 0.458. However this carries the penalty described earlier that the station must be rotated 180 deg roughly every 20 days.

Discussion

More exact calculations include the effects of decreased operating temperature and lower cell efficiency at a higher sun angle.[7] These two effects mostly cancel. The amount of propellant needed to offset the array drag varies with solar activity. An averaged atmospheric density over a solar cycle was estimated using a standard atmospheric model.[8]

Hardware replacement must also be considered. The solar array was assumed to be replaced every ten years[5] and the batteries (NiH_2 at 40% depth of discharge) replaced every six years.

Table 1 shows mass breakdown in the more exact calculation. Table 2 summarizes results.

Table 1 System mass breakdown in kg of 25-kW array for various orientation options, 334-km orbit

Orientation	Sun tracking	Hybrid	Edge on: β-controlled	Edge on: Fixed 0 deg
Gimbals	α,β	α,β	β	none
Solar array	1476	1476	3014	5191
Storage system	1804	1804	3108	3192
Gimbals	675	675	690	0
Radiator	371	371	371	371
Balance & structure	1790	1790	2036	2049
System total	6116	6116	9219	10,803

Table 2 Array area and propellant mass required to cancel drag

Orientation	Sun tracking	Hybrid	Edge on: β-controlled	Edge on: Fixed 0 deg
334-km orbit				
Array area (m²)	579	579	1182	2036
Radiator area (m²)	27	27	27	27
Propellant (kg/year)	1793	1462	0	0
500-km orbit				
Array area (m²)	555	555	1184	2039
Radiator area (m²)	27	27	27	27
Propellant (kg/year)	88	74	0	0

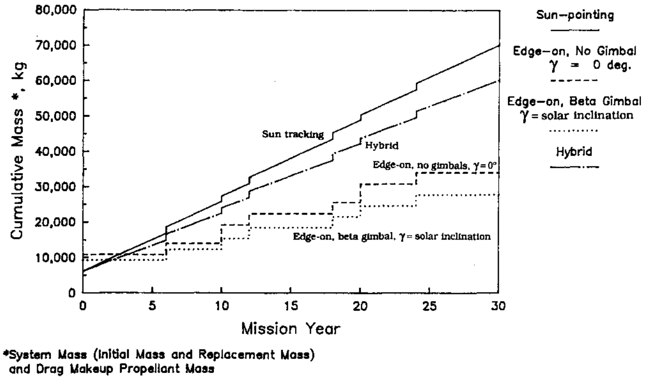

Fig. 2 Mass vs time for various array orientation options for station in 334-km orbit.

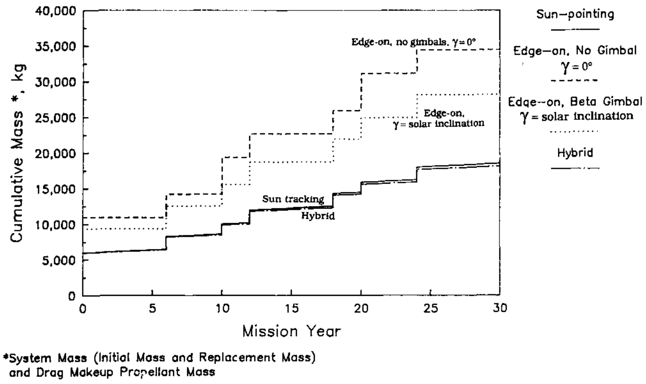

Fig. 3 Mass vs time for various array orientation options for station in 500-km orbit.

Figure 2 shows the cumulative mass to orbit needed for the solar array as a function of years of operation. This accounts for the system mass (including storage and structure) plus the mass of propellant used, assuming $I_{sp} = 445$ s, to cancel the array drag (i.e., not including the portion of the drag which is independent of orientation). The effect of hardware replacement is seen in the abrupt steps at the hardware replacement times. Cumulative mass without the assumption of hardware replacement can be seen by extrapolating the initial portion of the curve. Figure 3 shows the same plot for an assumed 500-km orbit.

Conclusions

The orientation strategy of rotating the array to the edge-on position during the 36-min eclipse period can result in a savings in the required drag makeup propellant of about 18.5% without increasing the array size or changing the configuration.

An array strategy of orienting the array to be always edge on to the flight direction requires the array area to be increased by a factor of two and the storage subsystem to be increased by 50%. This results in higher initial cost and mass but lower 30-year cumulative mass to orbit due to the decreased consumption of propellant. For the 334-km orbit, we calculate that the fully edge-on array orientation reaches a breakeven in mass-to-orbit at about one and a half years against the baseline orientation and at about two years against the edge on during eclipse orientation. For a space station in 500-km orbit, the edge-on configuration has no advantage.

A fully fixed array was examined, but the disadvantages apparently outweigh any advantages.

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Finite Element Analysis of Plasma Flows in Cusped Discharge Chambers

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Introduction

IN a cusped ion thruster, the configuration of the cusped magnetic field applied in the discharge chamber is a design parameter of primary importance because it has a great influence on discharge-chamber performance. A poor field configuration can lead not only to inefficient confinement of primary electrons, but also to a low fraction of the ions produced within the chamber that are extracted into the beam. Some research work to optimize field configurations has been conducted over the last decade, but most of this work has been done experimentally.[1-6] This procedure usually takes a lot of time and is costly because a large number of parameters are involved in chamber designs. Consequently, it is desirable to develop a theoretical model that can be used to suggest the field configuration that will yield optimum discharge-chamber performance.

The objective of this work, as a first step toward developing such a theoretical model, is to apply the finite element method to a simple two-dimensional model describing plasma flows within the discharge chamber for any magnetic field configuration.

Simple Plasma Flow Model

The governing equation for the particle balance within the discharge chamber is

$$-\nabla \cdot ([D]\{\nabla n\}) = Q \tag{1}$$

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