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Effect of High-Altitude Airship's Attitude on Performance of its Energy System

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I. Introduction

IN ALMOST all the designs of the high-altitude airship (HAA), their energy system consists of flexible solar cells and regenerative fuel cells, and supplies electric power for direct current motors to drive the propellers of the HAA so that it can resist the horizontal laminar wind at the altitude of 20 km [1–3].

Generally, the flexible solar cells are installed on the back of the HAA, and its back is not a plane. The solar radiation on the solar cells of a curved surface with great curvature is very different from that on the horizontal projection plane. We present our computation method for solar radiation on solar cells of the curved surface of the HAA, and study the effect of the HAA's attitude on the performance of its energy system when the airship is flying in 40 deg north latitude region in winter and summer.

II. Computation Method for Solar Radiation on Solar Cells of Curved Surface

We calculate the solar radiation on an extraterrestrial plane perpendicular to the sunray using Eq. (1) without taking atmosphere absorption and scattering into account [4,5].

$$E_h = E_{sc}/(r/r_0)^2 \tag{1}$$

where E_{sc} is the solar constant (1367 W/m^2) and $(r_0/r)^2$ is the revised coefficient of the distance between the sun and the Earth. The coefficient can be expressed as

$$(r/r_0)^2 = 1.000423 + 0.032359\sin\theta + 0.000086\sin 2\theta - 0.008349\cos\theta + 0.000115\cos 2\theta \tag{2}$$

where θ is the day angle of the sun, and is given by

$$\theta = 2\pi(N - N_0)/365.2422 \tag{3}$$

where N is the day of a year, i.e., $N = 1$ when the date is January–1, $N = 366$ when the date is December 31 in a leap year, $N = 365$ when the date is December 31 in an ordinary year, and N_0 is given by

$$N_0 = 79.6764 + 0.2422 \cdot \{\text{year} - 1985 - \text{INT}[(\text{year} - 1985)/4]\} \tag{4}$$

The radiation on tilted surfaces can be expressed by [6–8]

$$E_t = E_h[\sin\delta(\sin\lambda\cos s - \cos\lambda\sin s\cos\gamma) + \cos\delta\cos\omega(\cos\lambda\cos s + \sin\lambda\sin s\cos\gamma) + \cos\delta\sin s\sin\gamma\sin\omega] \tag{5}$$

where δ is the declination of the sun, λ is latitude, γ is the azimuth angle (zero at true south, positive westward, negative eastward), s is tilt angle up from the horizontal plane toward the direction of the azimuth (zero at the horizontal plane), and ω is the hour angle of the sun (zero at noon, positive in the afternoon, negative in the morning); δ and ω are defined as

$$\delta = 0.3723 + 23.2567\sin\theta + 0.1149\sin 2\theta - 0.1712\sin 3\theta - 0.758\cos\theta + 0.3656\cos 2\theta + 0.0201\cos 3\theta \tag{6}$$

$$\omega = (\text{local time} - 12) \times 15 \tag{7}$$

The sunrise or sunset hour angle for a horizontal plane is defined as ω_s, and the sunrise hour angle and sunset hour angle for a tilted plane are defined as ω_{tr} and ω_{ts}, which can be described by [9–11]

$$\begin{aligned} \omega_s &= \arccos(-\tan\delta\tan\lambda) \\ \omega_{tr} &= -\min\left\{\omega_s, \arccos\left(-\frac{a}{D}\right) - \arcsin\left(\frac{c}{D}\right)\right\}, \\ \omega_{ts} &= \min\left\{\omega_s, \arccos\left(-\frac{a}{D}\right) + \arcsin\left(\frac{c}{D}\right)\right\} \end{aligned} \tag{8}$$

where a, b, c, and D are defined as

$$\begin{aligned} a &= \sin\delta(\sin\lambda\cos s - \cos\lambda\sin s\cos\gamma) \\ b &= \cos\delta(\cos\lambda\cos s + \sin\lambda\sin s\cos\gamma) \qquad c = \cos\delta\sin s\sin\gamma \\ D &= \sqrt{b^2 + c^2} \end{aligned} \tag{9}$$

The flexible solar cells of a curved surface on the back of the airship are partitioned into n(along with heading)$\times$ m(along with circumference) grids, and each grid can be seen as a tilted plane, as shown in Fig. 1. The tilt angle and azimuth angle on each grid are calculated, and the instantaneous radiation on each grid is obtained. The radiation on the whole solar cell of curved surface is the sum of that on each grid [11]. If each grid is small enough, the precision of calculation will satisfy engineering applications.

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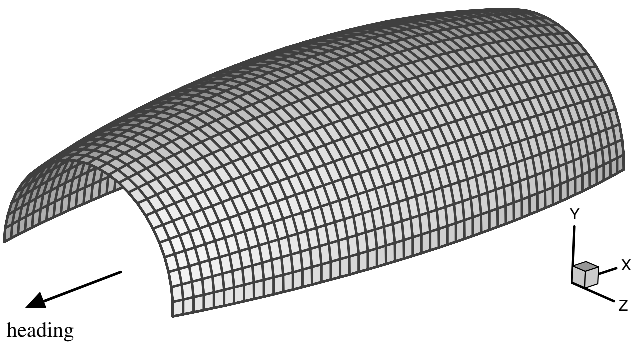

Fig. 1 Grids partition for solar cells of curved surface.

The radiation on a grid $D_{i,j}$ can be expressed by

$$E_{i,j} = \begin{cases} E'_{i,j} & [\omega_{\mathrm{tr}}(i,j) \le \omega \le \omega_{\mathrm{ts}}(i,j)] \\ 0 & [\omega \le \omega_{\mathrm{tr}}(i,j) \text{ or } \omega \ge \omega_{\mathrm{ts}}(i,j)] \end{cases} \tag{10}$$

where $\omega_{\mathrm{tr}}(i,j)$ is the hour angle of the grid $D_{i,j}$ at the sunrise, $\omega_{\mathrm{ts}}(i,j)$ is the hour angle of the grid $D_{i,j}$ at the sunset, and $E'_{i,j}$ is given by

$$\begin{aligned} E'_{i,j} = E_h[&\sin\delta(\sin\lambda\cos s_{i,j} - \cos\lambda\sin s_{i,j}\cos\gamma_{i,j}) \\ &+ \cos\delta\cos\omega(\cos\lambda\cos s_{i,j} + \sin\lambda\sin s_{i,j}\cos\gamma_{i,j}) \\ &+ \cos\delta\sin s_{i,j}\sin\gamma_{i,j}\sin\omega] \end{aligned}$$

where $s_{i,j}$ and $\gamma_{i,j}$ are tilt angle and azimuth angle of the grid $D_{i,j}$, and they are defined as

$$s_{i,j} = \begin{cases} \arcsin\left(\frac{|N_z|}{\sqrt{N_y^2+N_z^2}}\right) & N_z \ne 0 \\ 0 & N_y > 0 \quad \text{and} \quad N_z = 0 \\ \pi & N_y < 0 \quad \text{and} \quad N_z = 0 \end{cases} \tag{11}$$

$$\gamma_{i,j} = \begin{cases} -\arcsin\left(\frac{N_x}{\sqrt{N_x^2+N_z^2}}\right) & N_z \ge 0 \\ -\pi + \arcsin\left(\frac{N_x}{\sqrt{N_x^2+N_z^2}}\right) & N_z < 0 \quad \text{and} \quad N_x \ge 0 \\ \pi + \arcsin\left(\frac{N_x}{\sqrt{N_x^2+N_z^2}}\right) & N_z < 0 \quad \text{and} \quad N_x \le 0 \end{cases} \tag{12}$$

where $N(N_x, N_y, N_z)$ is normal of grid $D_{i,j}$.

The radiation on solar cells of a curved surface is calculated using Eq. (13), and is multiplied by the efficiency of flexible solar cells, thus obtaining the instantaneous power of the solar cells.

$$E_{\mathrm{cs}} = \sum_{i=1}^{n}\sum_{j=1}^{m} E_{i,j} \tag{13}$$

The solar cells of the curved surface shown in Fig. 1 are designed for our schemes of the HAA [12], with the surface area of the solar cells being 8200 m^2, and the area of their horizontal projection being 5190 m^2. The fineness ratio of the HAA is four, and the surface area of the solar cells is more than 30% of the hull surface area of the HAA. The HAA is assumed to fly in 40 deg north latitude region, and the power available of solar energy in winter solstice for the solar cells and their horizontal projection plane are shown in Fig. 2.

III. Effect of the HAA's Attitude on the Performance of an Energy System

To analyze the effect of the HAA's attitude on the performance of its energy system, we assume that the HAA flies in 40 deg north latitude region. The efficiency of solar cells is about 8% [13]. As shown in Figs. 3 and 4, the output power of solar cells changes obviously with the heading angle of the HAA in winter solstice and summer solstice.

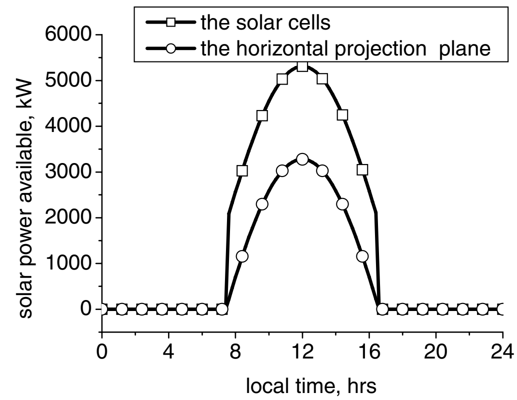

Fig. 2 Solar power available for the solar cells and their horizontal projection.

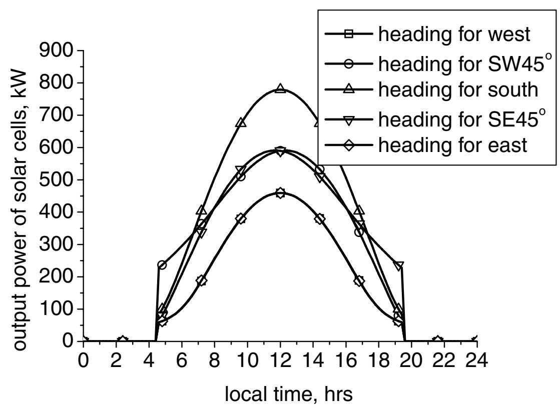

Fig. 3 Output power of solar cells in summer solstice.

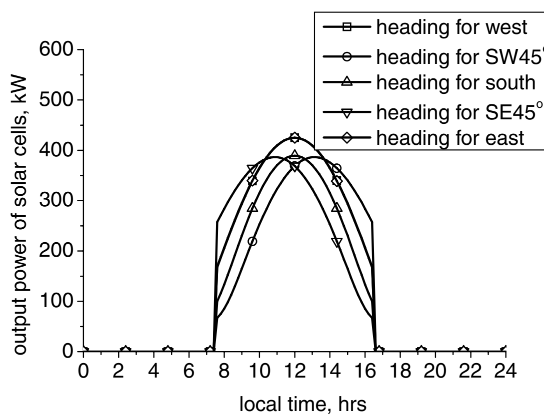

Fig. 4 Output power of solar cells in winter solstice.

In summer solstice, the output power of solar cells when the HAA is heading for the southwest is larger than that when heading for any other direction from 0430 to 1840 hrs. From 0640 to 1720 hrs, the output power when heading south is larger than that when heading for any other direction. From 1720 to 1930 hrs, the output power when heading southeast is larger than that when heading for any other direction. From 0430 to 1930 hrs, the output power when heading west or east is smaller than that when heading for any other direction.

In winter solstice, the output power of solar cells when the HAA is heading southeast is larger than that when heading for any other direction from 0730 to 1010 hrs. From 1010 to 1350 hrs, the output power when heading west or east is larger than that when heading for any other direction. From 1350 to 1630 hrs, the output power when heading southwest is larger than that when heading for any other direction.

IV. Conclusions

When the surface area of solar cells is more than 15% of the surface area of the HAA's hull, the effect of surface curvature should be taken into account in calculating the radiation on solar cells. To be a feasible design, the HAA is about 200 m long, and the surface area of solar cells is more than 25% of the hull surface of the HAA. Under these conditions, the effect can not be neglected.

When other researchers simulate the flight of the HAA, they pay much attention to flight dynamics, but the effect of the power available from its energy system on flight motion and the effect of the HAA's attitude on the power available often do not receive their attention. Our study presented in this Note is of reference value for the simulation and optimum control of the energy system of an HAA and its flight dynamics.

When the efficiency of flexible solar cells is about 8%, and the efficiency of regenerative fuel cells is around 25%, the output power available from the energy system of an HAA is very small. The change of its attitude may lead to decreasing of the output power of its solar cells. To increase its station-keeping ability, the HAA should keep the attitude at which its solar cells will absorb energy as much as possible.

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