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Technical Comment

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Comment on "Compound Solar Sail with Optical Properties: Models and Performance"

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COMPOUND solar sails recently became a subject of many studies because of the advantages they present when compared to flat sails. As the studies are based on a crude force model of the compound sail dynamics, a new contribution in this field would be important. A recent force model [1] for a dual reflector solar photon thrustor (DRSPT) is supposed to be more realistic. The model takes into account a nonideal light reflection on the sail surface. Unfortunately, there are several reasons to believe that the suggested model does not reflect basic optical properties of the DRSPT.

The DRSPT scheme is presented in Fig. 1 [1] (here we redraw its main features while adding some notations). Its modification studied in [1] consists of two spherical cofocal mirrors, collector C (intended to concentrate the sun radiation flow at focus F) and reflector R (presumably transforming the sun radiation flow to a parallel beam), completed by a flat mirror D that redirects the light beam out of the system. However, a number of important optical effects are neglected in [1]. It is easy to show that the light flux in the spherical version of DRSPT does not follow this idealized scheme because of shadowing, spherical aberration, limited size of the mirrors, and multiple reflections on the system elements.

Let us compare the force model developed in [1] to the results of numerical modeling that take into account all of the above optical effects with the accuracy of about 1%. We study the sailcraft from [1] with the collector and reflector aperture angles equal to $\xi_0 = 15$ deg. The effective area of the collector (i.e., the area of its projection onto the plane orthogonal to its symmetry axis) can be calculated as $A_p = 4\pi f^2 \sin^2\xi_0$, where f is the collector's focal distance. Following the suggestion of [1], the area of the director as well as the effective area of the reflector is chosen equal to $1/100\, A_p$. The focal distance of the reflector is then $f_r = 0.1f$. The distance $|FD|$ between director D and focus F is one of the variable parameters.

To focus on the main features, we first study the case when all the surfaces are ideal reflectors. Figure 2 shows the portion of the flux that leaves the system after consequent reflection on collector C, reflector R, and director D as a function of the control angle α for various locations of the director. Curves 1–6 correspond to the distances $|FD| = 0.1f$, $0.2f$, $0.3f$, $0.5f$, $0.7f$, and $0.9f$, respectively. One can see that the part of the light flux that can be described by the scheme of Fig. 1 never exceeds $2/3$ and depends on the director's location and inclination, that is, the control angle α. The best results are attained for $|FD| = 0.5f$, when this fraction varies between 60 and 65% for α from the interval $5 < \alpha < 63$ deg. For all other locations of the director the proportion of light that follows the scheme of [1] is significantly less. Each curve has a critical point $\alpha = \alpha_{cr}$ where it drops to zero meaning that the optical path changes completely.

Figure 3 shows, for five different locations of D, the ratio P/P_{max}, where P is the magnitude of the resultant force $\boldsymbol{P}$ produced by the light radiation, and P_{max} is its maximum value given by the "ideal sail" model [1]. The angle β between $\boldsymbol{P}$ and the sailcraft symmetry axis as a function of the control angle α is shown in Fig. 4. In both figures, curves 1–5 represent the results of the simulation and correspond to $|FD| = 0.1f, 0.3f, 0.5f, 0.7f$, and $0.9f$, respectively, while curve 6 shows the values calculated according to the ideal sail model. One can see that the magnitude of the resultant force fits the ideal sail model only for some curves and only for a limited range of α values. The closest similarity occurs again for $|FD| = 0.5f$ when the intensity of the resultant approximates the one predicted for $5 < \alpha < 65$ deg with the error up to 20%. But even in this case the direction of the propulsion force deviates widely from that of [1]: the angle β is about one-half of the predicted value. The error also increases as α grows. For any location of the director, as soon as α surpasses the critical value α_{cr} the predicted values of P have nothing to do with the results of simulation.

Figures 5 and 6 show the results of simulation of a sailcraft that has a nonideal collector while both reflector and director are ideal; in [1] this case is referred to as OC-IR-ID (optical behavior of the collector and ideal characteristics for both the reflector and the director). The propulsion force and the cone angle are represented as functions of α. In both figures, curves 1–5 correspond to $|FD| = 0.1f$, $0.2f$, $0.3f$, $0.7f$, and $0.9f$, respectively, and curve 6 indicates the values predicted by the "optical model" [1]. One can note a considerable discrepancy between the results of simulation and the values given by the optical model. Curves 1 and 2 do not resemble curve 6 at all. Curves 3, 4, and 5 from Fig. 5 can be to some extent approximated by curve 6 when α is smaller than critical value α_{cr}, but then the force directions differ considerably from those predicted by the optical model. And for all locations of the director, the force obtained from the numerical simulation has nothing in common with that predicted in [1] as soon as α surpasses the critical value α_{cr}.

This divergence is caused by the fact that the optical path shown in Fig. 1 and taken for granted in [1] contradicts the basic optical properties of the sailcraft. The first effect missed in [1] is related to the substitution of the parabolic mirrors, usually considered for a DRSPT, by the spherical ones. For reasonable values of the collector's aperture angle ξ_0, including the case $\xi_0 = 15$ deg, the light is not focused at F due to a considerable spherical aberration. The reflector increases the dispersion and does not form a parallel light beam on interval RD. To minimize the spherical aberration on the reflector, its focal distance has to be maximized. On the other hand, a reflector with a focal distance that is too large misses a part of

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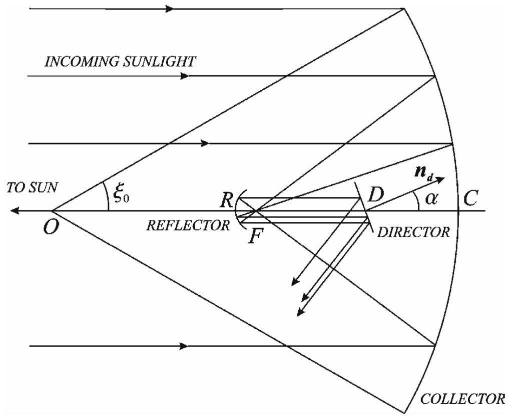

Fig. 1 General scheme of the compound solar sail.

the light flow. The maximum reflector focal distance f_r when R still catches all the light arriving from C can be found analyzing the light path. For the collector with $\xi_0 = 15$ deg, it is equal to $f_r = 0.065f$. For the sailcraft of [1] with $f_r = 0.1f$ about one-third of the flux specularly reflected on the collector misses the reflector, and the rest of it does not form a parallel beam. Consequently, the front side of director mirror D redirects only a part of the total flux, resulting in the force which is not described by the formulas from [1].

Another effect is shadowing. One can disregard the shadowing of the incoming sunlight by the director because its area is small as compared to the collector's area. However, after the reflection on C the light forms a converging beam, so the reflection of the flux on the backside of D can substantially change the resultant force. Because of the shadowing by the director mirror, an acceptable force model of the DRSPT should depend on the distance $|FD|$. The contributions of shadowing and spherical aberration depend on f_r, $|FD|$, and α but both result in energy loss that for the sailcraft of [1] varies from 34 to 100%. So, the energy balance (13) [1] is quite a rough approximation and even in the ideal case the forces acting on the collector and the reflector do not cancel.

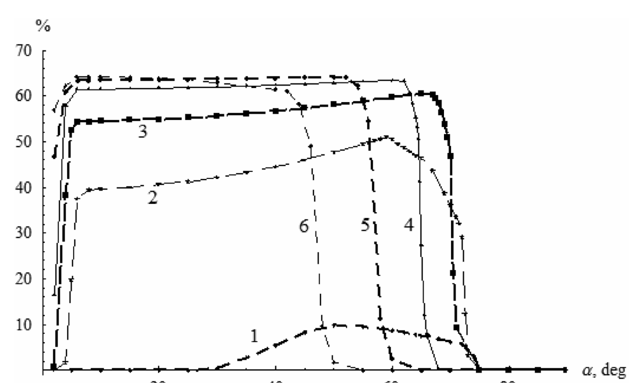

Fig. 2 Part of the light flux reflected in accordance with the scheme of Fig. 1.

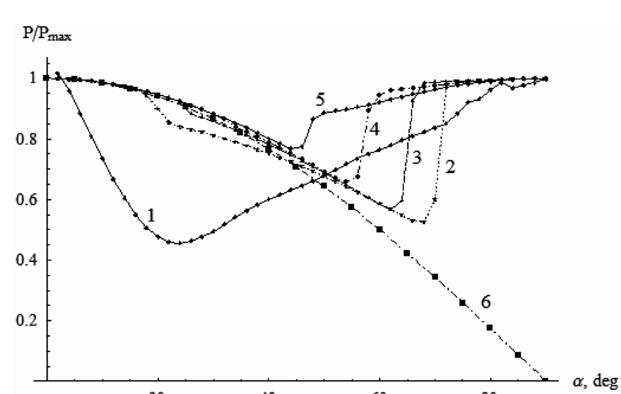

Fig. 3 Light pressure force applied to an ideal compound solar sail.

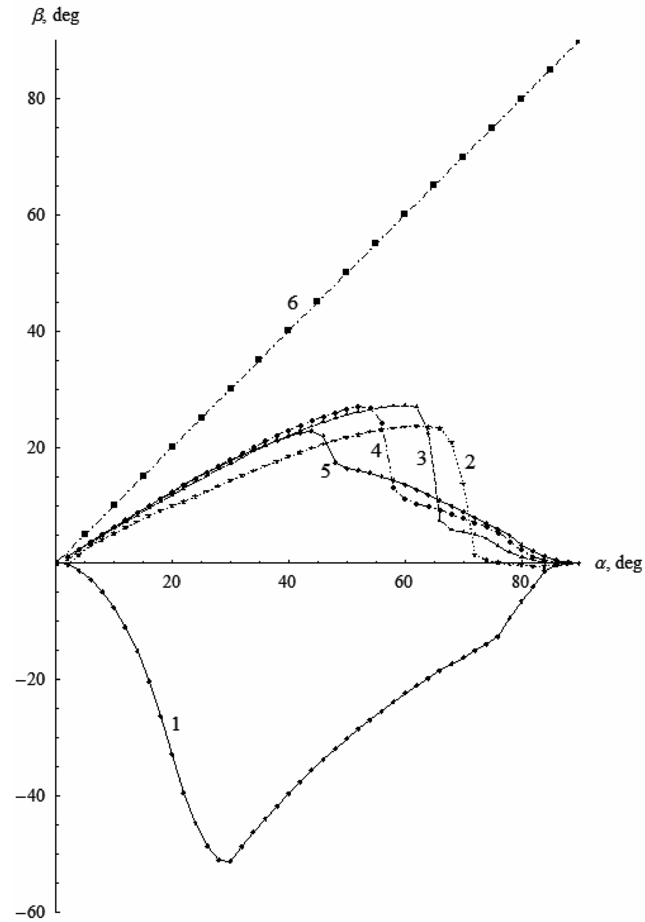

Fig. 4 Direction of the light pressure force applied to an ideal compound solar sail.

Finally, the optical path in the system changes qualitatively depending on the director's orientation. For small values of the control angle α, the light reflected on the director hits the reflector at least once more (sometimes multiple reflections on R and D occur) and the outgoing flux is not necessarily directed backward. With the increase of α, the director misses a greater part of the light beam which is then reflected on C. On the other hand, the director's inclination diminishes the shadowing effect, so the total outgoing light flux reflected by D changes slowly until α attains the critical value α_{cr}, when D starts to direct the light beam toward the collector. For the sailcraft in study, α_{cr} varies within the interval $41 < \alpha_{cr} < 76$ deg depending on the director location, and for $|FD| < 0.9319f$ it can be calculated as

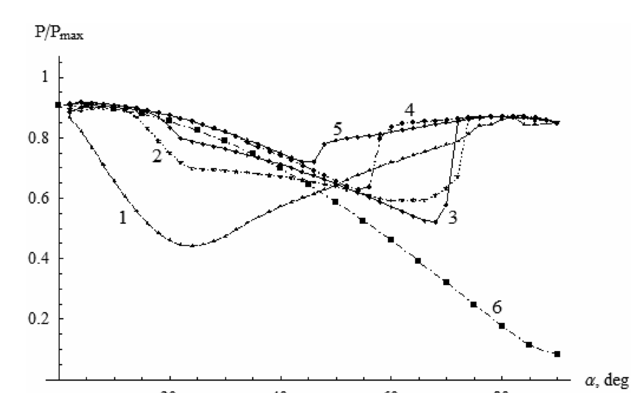

Fig. 5 Light pressure force applied to a compound solar sail with nonideal collector.

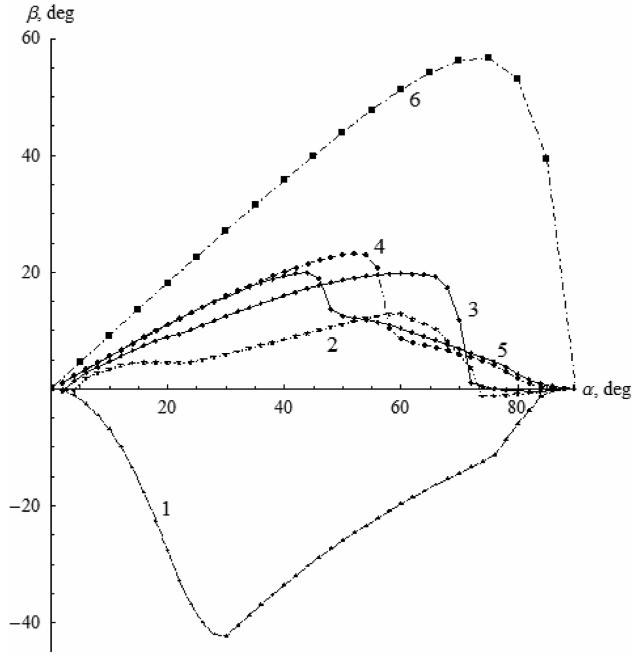

Fig. 6 Direction of the light pressure force applied to a compound solar sail with nonideal collector.

$$\alpha_{\mathrm{cr}} = \frac{1}{2}\left\{180\ \deg - \arctan\left[\frac{2f\sin\xi_0}{(2\cos\xi_0 - 1)f - |FD|}\right]\right\} = \frac{1}{2}\left[180\ \deg - \arctan\left(\frac{0.5176}{0.9319 - |FD|/f}\right)\right]$$

which is in perfect correspondence to the critical values of α from Figs. 2–6. The secondary reflection completely alters the direction and the magnitude of the propulsion force. Neglecting this effect, Mengali and Quarta [1] confirm the conclusion of the crude force model that for $\alpha = 90$ deg the total force applied to an ideally reflecting sailcraft vanishes. This would be possible only if the outgoing light flux had the same direction as the incoming one. It is obviously not the case: the outgoing light beam is always redirected either by D or by the reflection on the other system units. For $\alpha > \alpha_{\mathrm{cr}}$ the force model developed in [1] is not applicable. Therefore, both the data corresponding to $a \approx 80$–90 deg in Figs. 3 and 4 of [1] and the discussion in the cited article concerning the high values of the cone angle make no sense. Naturally, this raises serious doubts about the subsequent results of optimization and numerical simulations. All the conclusions concerning performance of a spherical DRSPT should be revised.

In conclusion, the mathematical model developed in [1] cannot be considered as an improvement as compared to the existent crude force model because neither describe some essential optical effects in the system in question. Nonideal light reflection is, no doubt, an important property of a compound solar sail, but it is hardly more relevant than the spherical aberration, the shadowing, the secondary reflection, and the real dimensions of the mirrors. Neglecting those causes an enormous error in the estimate of the light flux and the resulting forces. Hence, the advantages of the suggested force model seem exaggerated, and the idea of developing "a suitable model of a compound sailcraft, which takes the optical properties of the various components into account" [1] still awaits its implementation.

References

[1] Mengali, G., and Quarta, A. A., "Compound Solar Sail with Optical Properties: Models and Performance," *Journal of Spacecraft and Rockets*, Vol. 43, No. 1, 2006, pp. 239–245.

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