Aerospace Science and Technology 50 (2016) 281–294

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Further investigation of the body torques on a square solar sail due to the displacement of the sail attachment points

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A R T I C L E I N F O

Article history:
Received 14 January 2015
Received in revised form 7 December 2015
Accepted 13 January 2016
Available online 21 January 2016

Keywords:
Solar sail
Attitude control
Developable surface
Incident radiation direction
Membrane billow

A B S T R A C T

This paper presents further investigation of the idea of performing orientation change and attitude control of solar sail spacecraft by moving one or more of the attachment points of the sail material. In its normal mode of operation, a rigid-type solar sail flies with its sail membrane flat and taut. Moving one of the attachment points of the sail will cause the sail material to sag under the action of solar radiation. Such a sag can lead to system asymmetry resulting in a body moment on the system; and such a moment can be exploited for orientation control. The focus of this study is on the determination of the shape that the sail membrane assumes when one of its attachment points is displaced a known amount. Comparisons are made between the exact shape of the sail membrane as determined in this study, and a simpler but approximated shape suggested in previous studies. Errors in the force and body moment predictions that would result from the use of a simpler model of the deformed sail are also assessed. Finally, the effect of the solar radiation incidence angle on the magnitude of the moment applied to the solar sail body is also investigated.

1. Introduction

The first successful solar sail in interplanetary flight is the spacecraft IKAROS [1]. This craft flew past Venus in December 2010 and continued to function for over two years beyond its designed mission lifetime. The remarkable achievement of IKAROS demonstrates the effectiveness of spacecraft propulsion by solar radiation and gives hope to the future of the solar sail mode of space transportation.

IKAROS is spin deployed, and uses centrifugal forces to maintain the deployed configuration. ‘Spin’ sails of this type must always have a non-zero angular velocity about their major spin axis. The advantage of spin type sailcraft is that they have few structural components and are easy to deploy. Another type of solar sail design that belongs to the ‘spin’ sailcraft category is the Heliogyro, whose sail membrane is in the form of blades connected to a central hub, with the combination operating in a manner similar to a helicopter rotor. However, spin type sailcraft is generally not well suited for carrying large payload. The reason is that the pressure applied on a sailcraft by solar radiation is generally quite low ($\sim\mu N/m^2$), thus to carry sufficient payload, the area of the reflective membrane would need to be large (in the order of kilometer squared for several metric ton payload) to achieve reasonable performance. In the case of the Heliogyro, each blade would then need to be over several kilometers long in order have the required effective area. Such a size would result in large centrifugal forces that could cause the thin and fragile sail membrane to disintegrate. Even if the spin speed is low enough to avoid sail disintegration, the angular momentum of the system would be quite large because of the large moment of inertia of each of the spinning strips of membrane. Effective attitude control would then become a challenge. The above problems impose a limit on the allowable size of spin type solar sails.

Solar sails that rely on some structural component to hold or support their sail material are referred to as ‘rigid’ type sails. This class of sailcraft need not spin at all. So they can avoid the disintegration problem discussed above, and can therefore take on much larger sizes than spin type sails. Rigid sails are thus more promising in becoming large payload carriers. The main challenge for this class of solar sails is in their deployment; and as sail size gets larger, successful deployment becomes even more challenging.

One of the simplest rigid type solar sails is the square solar sail (Fig. 1), which uses two orthogonal structural booms to support four triangular sail membranes. Each of these triangular membranes will be referred to in the remainder of this paper as a wing. Several methods have been proposed in the literature for effecting orientation change or attitude control for the square solar sail [2–4]. Almost all of these require additional hardware whose

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http://dx.doi.org/10.1016/j.ast.2016.01.007
1270-9638/

Nomenclature

dS	area differential element	m^2
u	arc length	m
C	integration constant	
K	integration constant	
L	boom length of flat wing	m
$M_{x,y,z}$	component of body torque of wing in the x-, y- or z-axis direction	Nm
R	radius of curvature of cylindrical wing	m
T	tension force	N
P_0	solar radiation pressure at the current sail-sun distance	N/m
α	angle between $\mathbf{n}_r$ and $\mathbf{n}$ (see Fig. 8)	rad
β	solar radiation pressure force on differential element	N
δ	wing tip displacement	m
$\zeta_{1,2}$	solar misalignment angles	degrees
η	efficiency factor	
ρ	density of the wing	$\mathrm{kg/m}^2$
$\rho_{a,d,s}$	portion of absorbed, diffuse reflected or specular reflected radiation	
ϕ	center angle	rad
$\mathbf{n}$	unit vector of differential surface element	
$\mathbf{n}_r$	unit vector of incident radiation	
$\mathbf{n}_t$	unit vector tangent to sail (see Fig. 8)	
$\mathbf{r}_s$	position vector from origin to dS	
$\mathbf{M}_o$	net SRP moment for a wing about the point O	Nm
$\mathbf{I}$	Inertia dyadic of a wing	
$\mathbf{U}$	Unit dyadic	

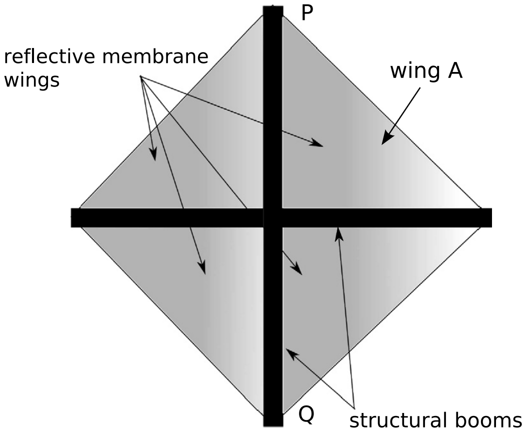

Fig. 1. Square solar sail.

mass and size increase as sail size is increased. For most of these methods, the amount of additional hardware required for effective control of a kilometer squared size sail is unreasonably large. Attitude control thus becomes a stumbling block to flying solar sails of very large size. Yet, as discussed above, very large solar sails are exactly what is needed to ferry large payload between planets or across interplanetary space.

In a recent paper, Fu and Eke [5] presented a method for sailcraft attitude reorientation that overcomes the shortcomings of previous methods and is applicable to any size solar sail, including very large ones. More detailed discussion of the various shortcomings of other existing methods of attitude control, as well as the major advantages of the tip displacement method can be found in reference [5]. This method requires that each of the four triangular wings of a square sailcraft be connected to the supporting booms at only three points — the triangle's vertices. For each wing, the vertex that is connected to the intersection of the booms is immovable, but the other two can be made to move along the booms to which they are attached. The normal operating configuration of the sailcraft is that in which all four wings are flat. If, for example, the vertex or tip P of wing A (see Fig. 1) is moved some distance inward, the wing sags or billows under the action of solar radiation pressure. Such a sag results in asymmetry of the system and causes the center of pressure to move away from the system center of mass, thus creating a body torque that can be used for attitude change or attitude control. It turns out (see reference [5]) that a moment can be created about any of the three principal body axes of the craft by judiciously selecting the wingtip(s) to be moved. The magnitude of the moment generated depends on the displacement of each movable wing vertex. This method of generating body torques for attitude control will be referred to in what follows as the tip displacement method (TDM) of attitude control.

In reference [5], a detailed model of a single wing of a square sail was developed for the purpose of assessing the feasibility of this method of attitude control. This model was used to determine expressions for the forces and moments that result from the effect of solar radiation pressure (SRP) on the wing. Naturally, a number of simplifying assumptions were made in this process; the main ones are listed below. (a) The sail material is inextensible. (b) The dynamics of the membrane material as one of its vertices is moved is negligible. In other words a sail wing attains its deformed shape in a quasi-static manner whenever one of its attachment points is moved. (c) All calculations, including moment calculations are based on the assumption that the direction of solar radiation remains perpendicular to the undeformed sail at all times. (d) When one tip of a wing is displaced inward, the deformed wing takes on the shape of a ruled surface with uniform curvature — specifically a portion of a right circular cylindrical shell.

Although the above assumptions are reasonable for an initial feasibility study, there are clearly limits at which some of these assumptions are likely to break down. This paper aims to re-evaluate and refine the assumptions and determine how the results obtained in [5] would change for a more realistic model.

The assumption of inextensible sail membrane makes sense because the forces acting on the membrane are small, and, for a typical sail material that is Kapton based, the resulting elastic deformation is small (see reference [5]). Therefore, assumption (a) will be retained in this study.

When an attachment point of a wing is moved, the dynamics of the sail membrane can only become significant if either the wing tip is moved rapidly, or the orientation of the sailcraft is changed rapidly. Now, in actual sailcraft operation, attitude maneuvers are inherently slow. For example, an attitude control experiment performed by IKAROS showed approximately one degree of sun-sail angle (angle between sail surface normal and solar incident direction) change per day [4]. Since time is never of the essence in sailcraft attitude control, wing tip displacements in the TDM of attitude control can occur slowly. Hence, the quasi-static assumption is valid to a great extent, and will not be discussed further in this paper.

For a solar sail, the magnitude and direction of sailcraft thrust vector is determined by sail orientation. During a mission, the direction of solar radiation relative to the sailcraft is not likely to remain constant and orthogonal to the sail, hence it is important to relax assumption (c) above and study how a change in the direction of incident radiation affects attitude moment.