Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

Solar sail technology—A state of the art review

Bo Fu*, Evan Sperber, Fidelis Eke

University of California, Davis, One Shields Avenue, Davis, CA 95616, United States

ARTICLE INFO

Article history:
Received 26 February 2016
Received in revised form
5 July 2016
Accepted 6 July 2016

Keywords:
Solar sail
Solar radiation pressure
Attitude dynamics
Design and deployment

ABSTRACT

In this paper, the current state of the art of solar sail technology is reviewed. Solar sail research is quite broad and multi-disciplinary; this paper focuses mainly on areas such as solar sail dynamics, attitude control, design and deployment, and mission and trajectory analysis. Special attention is given to solar radiation pressure force modeling and attitude dynamics. Some basics of solar sailing which would be very useful for a new investigator in the area are also presented. Technological difficulties and current challenges in solar sail system design are identified, and possible ideas for future research in the field are also discussed.

Contents

* Corresponding author.
E-mail address: bofu@ucdavis.edu (B. Fu).

http://dx.doi.org/10.1016/j.paerosci.2016.07.001
0376-0421/

1. Introduction

The notion that solar radiation carries with it some form of pressure dates back to Johannes Kepler, who observed that the sun may be causing comet tails to point away from it. In 1610 he wrote in a correspondence with Galileo: "…provide ships or sails adapted to the heavenly breezes, and there will be some who will brave that void." [1]. In the 1860s, James Clerk Maxwell's theory of electromagnetism would yield that electromagnetic fields not only carry energy, but momentum as well. The transferred momentum conveys an effective force, and so radiation pressure is the average force per unit area of all incident and reflected radiation. Early pioneers of solar sailing include Konstantin Tsiolkovsky [2] and Friedrich Tsander [3], who realized that it is possible to attain cosmic velocities using the pressure of solar radiation. Early attempts to construct a functional sailcraft that uses solar radiation exclusively for its propulsion began at the Jet Propulsion Laboratory (JPL) in the seventies. At the time, the development of a solar sail Halley Rendezvous mission was on-going at JPL, and significant effort was expended in designing a practical solar sail for this mission. Although the mission was later dropped by NASA, the lessons learned from this effort laid a solid foundation for solar sailing technology. Much of the work done then is documented by Wright [4]; later work on solar sailing, which focuses on sail trajectory and mission design, is very well summarized by McInnes [5].

Solar radiation pressure (SRP) has been used as a secondary propulsion system in interplanetary space with Mariner 10 and the Messenger spacecraft [6,7]. In this paper, a solar sail (or sailcraft) is considered to be a spacecraft that is propelled mainly or exclusively by solar radiation, and not one where SRP only serves as a secondary means of propulsion. Under such a definition, a typical solar sail would utilize thin sheet(s) of reflective membrane material to harness sun's radiation for propulsion purposes.

The world's first interplanetary solar sail spacecraft called "Interplanetary Kite-craft Accelerated by Radiation Of the Sun" (abbreviated "IKAROS"), was launched by Japan Aerospace Exploration Agency (JAXA) in May 2010. IKAROS's mission demonstrated solar sail propulsion in interplanetary space, and is regarded as a milestone in solar sail technology. Following the IKAROS, the solar sail "LightSail A" from The Planetary Society successfully completed an in-orbit deployment test in June 2015. Three international symposia dedicated to solar sailing were held in 2007, 2010 and 2013. A wide range of research topics was covered including sail design, deployment mechanism, mission analysis, trajectory design, sail material, and sail dynamics. Research interest in solar sails continues to grow even today, as the technology gradually matures.

In order to understand what makes solar sails unique compared to other types of spacecraft, one must take a step back and look at the nature of space flight: a momentum exchange process. Through this momentum exchange process, a spacecraft's linear momentum is altered, and this enables the spacecraft to travel towards its destination. There are two ways in general to achieve linear momentum change for a spacecraft. One is by using propellants, where a portion of craft mass—the propellant mass—is sacrificed. Due to conservation of linear momentum, the craft gains momentum equivalent to that of the lost propellant. Both traditional chemical rockets and the more advanced electric propulsion engines use this method. The difference is that in chemical rockets the velocity of the ejected propellant is much smaller (few thousand meters per second) compared to what occurs in electric propulsion engines (over 10,000 meters per second). Therefore compared to chemical rockets, electric propulsion devices have a higher specific impulse.

The second way to change linear momentum of a spacecraft is through spacecraft–environment interaction, even if the craft mass remains unchanged. Although environmental forces are present regardless of the spacecraft type, most of the time they are treated simply as disturbance forces for spacecraft that rely on propellants. This is because these spacecraft lack the means to make use of the space environmental forces, and the forces themselves are orders of magnitude smaller than the thrust force provided by onboard propellant. A spacecraft that can harvest momentum from the surrounding environment may not need onboard fuel or propellant. Examples of spacecraft capable of environmental momentum exchange include solar sails, electric solar wind sails and magnetic sails. Although these concepts all have the word 'sail' in their names, the momentum exchange mechanism is different in each case. Solar sail in general refers to a type of spacecraft whose main source of thrust is solar radiation. Electric solar wind sails and magnetic sails are spacecraft whose thrust comes mainly from reflecting charged solar wind particles using electric or magnetic fields, thus harvesting momentum from particles in the solar wind.

The term 'sail' naturally evokes an analogy of sailing at sea. A sailship at sea exchanges momentum with its environment – wind, seawater, etc., in order to travel. In the space environment however, the situation is more complex. "Sailing" in space occurs amidst gravitational wells around massive bodies like the planets and the sun. In addition to gravity, there are many other different kinds of environmental forces that can act on a spacecraft. For example, Longuski and Todd [8] found that the space environmental forces on the Galileo spacecraft are estimated to be as shown in Table 1 . This table indicates that at various locations between the earth and Jupiter, forces on the Galileo spacecraft due to solar radiation pressure are order(s) of magnitude higher than other space environmental forces such as those from solar wind, meteoroids, Newtonian drag and magnetic field. Obviously, larger environmental forces indicate greater momentum exchange capabilities with the surrounding environment for a constant mass spacecraft. Thus, in the regions of the solar system visited by the

Table 1
Environmental forces on the Galileo spacecraft in Newtons (N).

Source	Near Venus (0.7 au, $10R_V$)	Near Earth (1 au, $10R_E$)	Interplanetary (3 au)	Near Jupiter (5 au, $10R_J$)
Solar radiation	1.7×10^{-4}	9×10^{-5}	1.1×10^{-5}	3.3×10^{-6}
Solar wind	5.9×10^{-8}	3.1×10^{-8}	3.6×10^{-9}	1.1×10^{-9}
Meteoroids	1.6×10^{-10}	1.1×10^{-10}	9.4×10^{-9}	4.2×10^{-9}
Newtonian drag	3.4×10^{-9}	7.9×10^{-11}	5.3×10^{-11}	5.7×10^{-7}
Magnetic field	5.4×10^{-14}	1.9×10^{-13}	2.1×10^{-11}	1.6×10^{-9}

Please cite this article as: B. Fu, et al., Solar sail technology—A state of the art review, Progress in Aerospace Sciences (2016), http://dx.doi.org/10.1016/j.paerosci.2016.07.001