Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2014) xxx–xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Attitude stability criteria of axisymmetric solar sail

Xiaosai Hu*, Shengping Gong, Junfeng Li

School of Aerospace, Tsinghua University, Beijing 100084, China

Received 21 October 2013; received in revised form 27 February 2014; accepted 5 March 2014

Abstract

Passive attitude stability criteria of a solar sail whose membrane surface is axisymmetric are studied in this paper under a general SRP model. This paper proves that arbitrary attitude equilibrium position can be designed through adjusting the deviation between the pressure center and the mass center of the sail. The linearized method is applied to inspect analytically the stability of the equilibrium point from two different points of views. The results show that the attitude stability depends on the membrane surface shape and area. The results of simulation with full dynamic equations confirm that the two stability criteria are effective in judging the attitude stability for axisymmetric solar sail. Several possible applications of the study are also mentioned.

Keywords: Solar sail; Passive stability; Axisymmetric

---

1. Introduction

Attitude dynamics is a very important issue for solar sails. As is well known, the conventional thrust and reaction wheels usually cannot be implemented in attitude control of solar sail as they either consume too much fuel or increase the complexity of the sail. Fortunately, solar sail is originally propelled by the SRP (solar radiation pressure) force exerted on the sail membrane and the SRP torque itself can be employed for attitude control. This attitude control strategy may not be a new concept for ordinary spacecraft. Actually, attitude stabilization of a spacecraft by SRP has been proposed early by Sohn (1959) and since then many attitude stabilization researches of satellites have been conducted. The attitude control by SRP force for solar sail was studied later. The SRP torque is generated when the offset of the mass center with respect to the pressure center exists. The attitude control by SRP torque usually can be obtained by means of changing the distribution of the mass of the solar sail. Benjamin (2001) investigated the attitude dynamics and control of solar sails using a gimbaled control boom to shift the mass center with respect to the pressure center. After that, the gimbaled control boom and sail control vanes were discussed in detail by Bong (2004a,b). In Romagnoli and Oehlschlagel (2011) proposes a solar sail attitude controller using ballast masses moving inside the sail's boom and demonstrated its high performance. Passive control by SRP is one possible option to stabilize the attitude of solar sail in an effective way. Kirpichnikov et al. (1996)investigated the passive control of the two-folding shaped solar sail in interplanetary transfer problem. Passive control of a flat solar sail on the displaced solar orbit was investigated by McInnes (1998). The passive design of solar sail with a four-triangle form was discussed by Gong et al. (2007, 2008). After that, a spin-stabilized solar sail of cone configuration was proposed again by Gong et al. (2011). There are much focuses on the following two points in most published literatures. One point is that the ideal SRP model is chosen in calculating the SRP to simplify the attitude dynamics.

---

* Corresponding author.
E-mail addresses: huxs12@mails.tsinghua.edu.cn (X. Hu), gongsp@mail.tsinghua.edu.cn (S. Gong), lijunf@tsinghua.edu.cn (J. Li).

http://dx.doi.org/10.1016/j.asr.2014.03.008
0273-1177/

Please cite this article in press as: Hu, X., et al. Attitude stability criteria of axisymmetric solar sail. J. Adv. Space Res. (2014), http://dx.doi.org/10.1016/j.asr.2014.03.008

The other is that the criterion of attitude stability only applies to the solar sail with a certain specific configuration. This paper will make some contributions in the above two aspects.

The passive attitude stability in any attitude position with respect to the sun will be investigated in this paper. The axisymmetric (means no matter what angle the solar sail rotates about the axis of symmetry, there is a superposition with the initial position) solar sail (Fig. 1) is discussed, whose membrane is axisymmetric while a payload is located at the end of a boom stretched out from the apex of the membrane surface. First, attitude equations of motion under the general SRP model are established in the body frame. Then the attitude equilibrium point is designed by noting the relationship between the equilibrium point and the position of mass center. Next, linearization method is adopted to analyze the stability of the attitude equilibrium point from two different views. One point of view to analyze the stability is judging the stability of the sun angle using derivation method and the other one uses Lyapunov stability theory to investigate the stability of the attitude angles. It should be noted that the former method is an approximated way to verify the stability compared with the latter one. The results indicate that the attitude stability depends on the membrane surface shape and area. The attitude can be stabilized via designing the membrane shape and area based on the proposed stability criteria. Finally, several numerical examples are presented to validate the conclusions. The examples show that all simulation results conform to the analytical criteria and thus prove the validity of the attitude stability criteria to some degree. The simulation examples provide the proper configuration parameters to keep the passive stability for sail with a cone or paraboloid shape.

There are several possible applications for the paper's work. The missions demanding a fixed attitude with respect to the sun-sail line will benefit much from this passive attitude study, especially when the stability of the orbit is independent from the attitude, such as the passive attitude control in the displaced orbit (Gong et al., 2009a) or around artificial Lagrange points (Gong et al., 2009b), and or in the inclination cranking process of the Solar Polar Imager mission (Dachwald et al., 2006). Some qualitative conclusions about the attitude stability in this work can be applied directly to provide design criterion for the simulated axisymmetric solar sails, and the analytical method in this paper may be expanded to deal with some complex solar sail shapes in future work.

2. Dynamical attitude equations

In this section, the attitude dynamical model of an axisymmetric solar sail as shown in Fig. 1 is presented. Firstly, the coordinate systems used in this paper are elaborated. Then, the attitude dynamical equations of motion are established in the body frame (Fig. 2). In addition, the transformation matrices between the coordinate systems are also given in this section.

2.1. Coordinate frames

Four right-handed frames are used in this paper to describe the attitude dynamics of solar sail. The inertial frame $Ox^Iy^Iz^I$ is defined as: the origin O is at the Sun; the x^I axis points to the J2000 Equinox; z^I axis is perpendicular to the ecliptic plane. The body frame $o_cx^by^bz^b$ is the fixed principle axes system of the solar sail. Its origin o_c is the mass center of the solar sail. The relative frames translated to the origin o are presented in Fig. 2.

A frame (called light frame in this paper) $ox^*y^*z^*$ is defined to describe the SRP force and torque more visually. The origin is the apex in the center of the sail membrane;

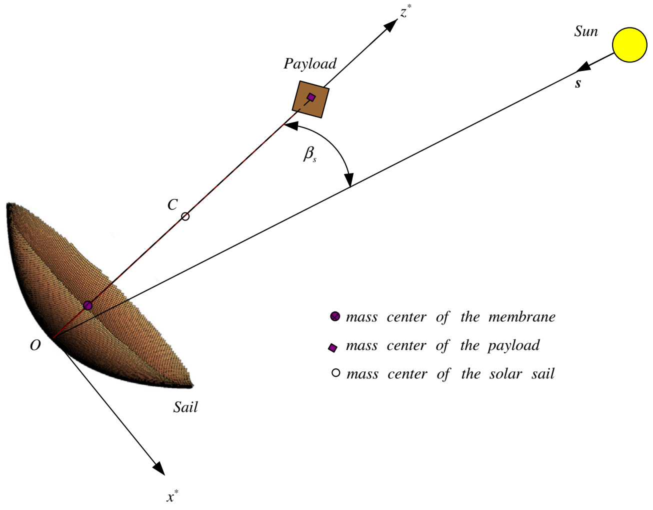

Fig. 1. Axisymmetric configuration of the solar sail.

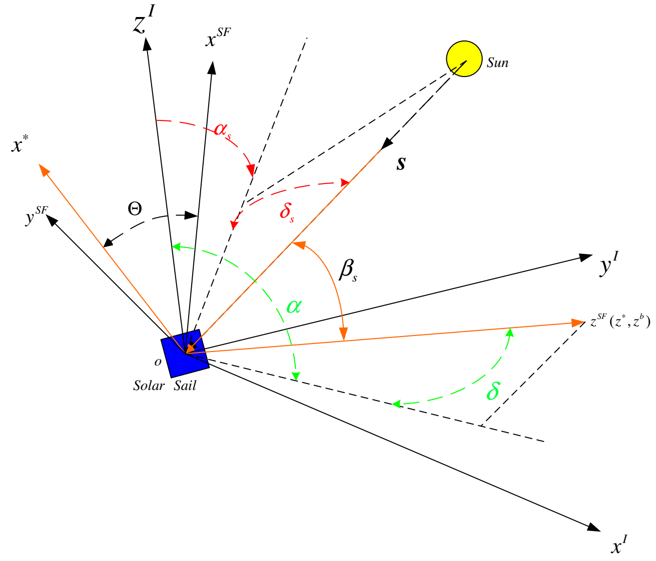

Fig. 2. The reference frames.

Please cite this article in press as: Hu, X., et al. Attitude stability criteria of axisymmetric solar sail. J. Adv. Space Res. (2014), http://dx.doi.org/10.1016/j.asr.2014.03.008