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Research Paper

Dynamic modeling and simulation of tethered stratospheric satellite with thermal effects

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HIGHLIGHTS

- A model investigating the performance of stratospheric satellite with thermal effects is developed.
- An iterative method is built to predict equilibrium point of the system.
- The effect of TCS on the trajectory control of the stratospheric satellite is carried out.
- Launching location and launching time for the stratospheric satellite are suggested.

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ABSTRACT

The stratospheric satellite has attracted much attention due to its potential application in military and economy. In this paper, a novel dynamic model with thermal effects is addressed to describe thermodynamic and kinetic characteristics of the stratospheric satellite. By using the iterative calculation of multi-body dynamics system, the equilibrium point of the stratospheric satellite is received. The computational accuracy is improved and the computational quantity is reduced enormously by setting initial values of several parameters in advance. Based on the dynamic simulation, influences of the trajectory control system on meridional migration of the stratospheric satellite are analyzed. It improves the controllability and security of the stratospheric satellite effectively. Thermal effects on the system flight performance are simulated under given launch conditions. Simulation results show that choice of launch time should be made with reference to launch location for making best use of solar radiation. The best launch time is at sunset, because solar energy can be used to accelerate and at the end of ascent phase solar radiation basically disappears which will lead to lower differential pressure.

1. Introduction

Stratosphere is ideal environment for science research of earth because of its stable meteorological conditions and excellent electromagnetic characteristics. For the past few years, the application of the stratospheric platform in the environment observation, broadcasting and communication has been researched in lots of countries [1,2]. The stratospheric satellite (SS) travels along the east-west direction around the earth in 35 km height above, which is similar to the artificial satellite orbit [3]. In order to achieve this purpose, the SS adds height adjustment and the trajectory control system (TCS) on the basis of the traditional high altitude balloon, and joins them with a tether [4].

The TCS utilizes different wind speeds in different altitudes to control the trajectory of the overpressure stratospheric balloon [5]. Affected by the east-west prevailing winds, the SS trajectory presents zonal distribution. At the same time, the SS trajectory will skew along the latitudinal direction by the influence of north-south direction wind. During travelling, the lifting force is very sensitive to thermal effect. Both the balloon itself and the ambient environment affect trajectory control of the SS. Therefore, it is very important to consider the thermal design to obtain a better flight performance of the SS.

Nowadays, simulation on the stratospheric platform for high resolution earth observation has been made in many literatures. Aaron et al. [6] introduced the Trajectory Simulation and Prediction System (TSPS) which is used in NASA's Ultra Long Duration Balloon (ULDB) Project, and it was developed by Global Aerospace Corporation (GAC). Kreith and Kreider [7] developed a computer program to predict balloon ascent rates, ceiling, and behavior at cruise altitude which considered the thermal performances. The

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thermal performance of stratospheric platform during its ascent was studied by Shi et al. [8], but trajectory control of the stratospheric platform was not considered. A novel thermal dynamic model was developed by Liu et al. [9] which also took the balloon film temperature distribution into account.

Previous papers particularly stressed on the model considering thermal effect of a single balloon. However, the SS is a typical complex multi-body dynamics system unlike the single balloon. It is not accurate to ignore its aerodynamic force and weight because of the tether length [10]. At the same time, the temperature and pressure changes of the balloon will affect the satellite performance. In this work, stratospheric balloon thermodynamic models are used to calculate the temperature of the balloon film and the internal helium. After calculating the equilibrium point of the satellite, the system simulation is developed. Finally, effects of launch time and location are discussed based on the simulation results.

2. Characteristics of the SS system

A SS system consists of an overpressure balloon and a TCS. The balloon is made of composite fabric that is filled with helium and pressure inside it is maintained above the ambient pressure at all times to keep the balloon afloat at a constant altitude. In order to improve the efficiency of flight control surfaces, the TCS is designed in the low altitude which is tied by a 15 km rope underneath the balloon. The magnitude and direction of the aerodynamic lift can be controlled by changing the TCS work angle (incidence and roll), and the trajectory of the balloon can be controlled [6].

Based on the general model of fixed-wing aircraft, some specific features are introduced into the high altitude balloon model. The most difficult problem is how to build the tether model of this SS system which is used to connect the TCS and the balloon, and to restrain their relative motion. This flight system is a highly nonlinear and strong coupling system. In view of the above consideration, lump-mass-and-spring model is used for the tether. In this model, the tether is seen as more than one node and segment which are massless and elastic. At the same time, mass and external force is assumed to focus on the nodes. The overpressure balloon and TCS are regarded as nodes of this tether to facilitate the research. So if the tether is divided into n segments, there are $n+1$ nodes, which is shown in Fig. 1.

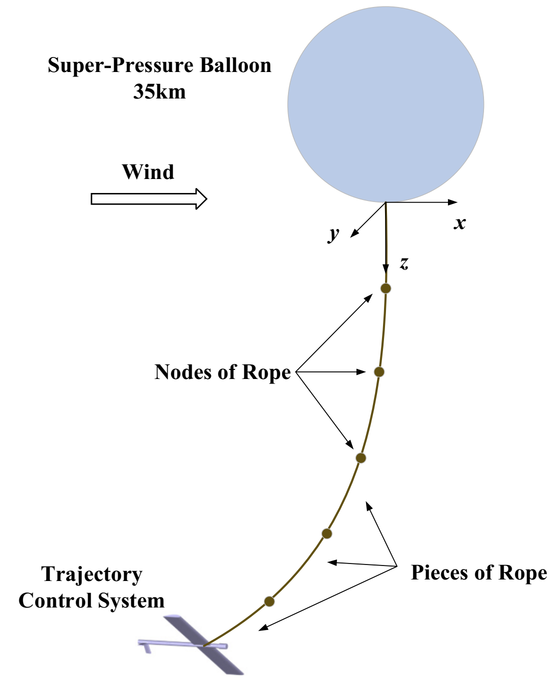

Fig. 1. The components of the SS system.

3. Atmospheric model

The atmosphere model in this paper implements the mathematical representation of the 1976 Committee on Extension to the Standard Atmosphere (COESA) United States standard lower atmospheric values for absolute temperature, pressure and density for the input geopotential altitude [11]. According to the fitted curve, the atmosphere model can be divided into three parts: troposphere (⩽11 km), lower stratosphere (11–25 km) and upper stratosphere (⩾25 km). The atmosphere temperature and pressure in upper stratosphere are shown as follows.

$$T = -131.21 + 0.00299h \tag{1}$$

$$p = 2.488 \times \left[\frac{T + 273.1}{216.6}\right]^{-11.388} \tag{2}$$

The values in lower stratosphere are shown as follows.

$$T = -56.46 \tag{3}$$

$$p = 22.65 \times e^{(1.73-0.000157h)} \tag{4}$$

And the atmospheric density is decided by temperature and pressure:

$$\rho = p/(0.2869 \times (T + 273.1)) \tag{5}$$

where p is the atmospheric pressure (kPa) and T is the temperature (°C).

The horizontal-wind model in this paper refers to HWM93 which is developed by Naval Research Laboratory (NRL) [12]. And the wind profile in the position of this paper is carried out by a program, which is shown as Fig. 2. From the curves conclusion can be drawn that the east and north wind velocity in summer and autumn is smaller than that in spring and winter. This phenomenon can influence the thermal effects, and produce an effect on the force convection between the balloon envelope film and the atmosphere around.

4. Mathematical model

4.1. Assumption

In the process of constructing the dynamic model, the following reasonable assumptions are made for simplification.

(1) The super-pressure balloon and TCS are treated as rigid bodies in kinetic equations.
(2) In the ascent phase, the shape of the balloon is always assumed to be spherical.
(3) The earth-fixed axis system is inertial coordinate.
(4) Ignoring the curvature of the earth, the ground is assumed as a flat.
(5) The gravitational acceleration does not change with altitude.
(6) The TCS is symmetrical in the geometric shape and quality distribution, so the product of inertia $I_{xy} = I_{zy} = 0$.

4.2. Thermal effects

The external thermal environment of super-pressure balloon includes atmosphere convection and external thermal radiation.