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Drag derived altitude aided navigation method

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Abstract The navigation problem of the lifting reentry vehicles has attracted much research interest in the past decade. This paper researches the navigation in the blackout zone during the reentry phase of the aircraft, when the communication signals are attenuated and even interrupted by the blackout zone. However, when calculating altitude, a pure classic inertial navigation algorithm appears imprecise and divergent. In order to obtain a more precise aircraft altitude, this paper applies an integrated navigation method based on inertial navigation algorithms, which uses drag derived altitude to aid the inertial navigation during the blackout zone. This method can overcome the shortcomings of the inertial navigation system and improve the navigation accuracy. To further improve the navigation accuracy, the applicable condition and the main error factors, such as the atmospheric coefficient error and drag coefficient error are analyzed in detail. Then the damping circuit design of the navigation control system and the damping coefficients determination is introduced. The feasibility of the method is verified by the typical reentry trajectory simulation, and the influence of the iterative times on the accuracy is analyzed. Simulation results show that iterative three times achieves the best effect.

1. Introduction

Owing to the characteristics of the rocket, spacecraft, reentry vehicle and aircraft, the lifting reentry vehicle has been widely used in the field of space technology, and the navigation problem of the reentry vehicle has been getting more and more attention.[1,2] The reentry flight is characterized as high speed, large attack angle, large aerodynamic interference, and the existence of the phenomenon of blackout zone.[3,4] According to the characteristics of the reentry flight and autonomous navigation, the main reentry vehicle navigation is Inertial Navigation System (INS)/Global Positioning System (GPS)/Celestial Navigation System (CNS) integrated navigation at present.[5,6]

When the reentry vehicle returns to the atmosphere at a high speed, the ground communication will be interrupted in a certain altitude area, and the area is called blackout zone.[7,8]

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The blackout zone occurred between 35 km and 80 km over the Earth's atmosphere, and when the reentry vehicle is in the blackout zone, the temperature of the vehicle hulls will reach 2000 °C, hence the GPS, radio navigation and communication will be interrupted, and then the reentry vehicle losses external contact (high temperature ionizes the air around the aircraft into plasma, and then shields the electromagnetic wave). Thus the groundings cannot obtain the information of the shuttle's real-time condition.[9–12] At this point, the navigation of reentry vehicle can only rely on inertial navigation, a kind of independent navigation technology that does not rely on external signals. But due to the defect of INS, relying on pure inertial navigation will lead to large navigation errors. So when the vehicle returns, the blackout phenomenon makes real time communication and measurement rather hard.

In view of the problem of blackout phenomenon, Ref. [8] introduced several methods, such as changing the shape design of reentry vehicle, adding an external magnetic field to weaken the influence of the blackout zone. But with these methods, the aircraft structure or flight environment needs changing, the implementation is difficult and of high cost.[13] Some researches use only INS for the aircraft navigation during the blackout zone,[14,15] which employs inertial navigation system directly to calculate the altitude of the aircraft and proves to have a large error. In Refs. [5,6], the GPS's prediction information is used for the vehicle navigation during the blackout zone, but the uncertainty of the prediction information will affect the navigation accuracy. So in order to ensure the navigation accuracy when the aircraft is out of the blackout zone, it is necessary to use auxiliary method to restrain the divergence of INS. The Refs. [16,17] proposed a combined navigation method which uses Drag Derived Altitude (DDA) aided inertial navigation system to the reentry vehicle navigation in the blackout zone. The non-gravitational acceleration of the reentry vehicle, and the aerodynamic and atmospheric models are used to estimate the altitude of the craft in DDA. And using DDA is able to get a higher accuracy than a pure classic inertial navigation algorithm. But the main error factors of DDA and the damping circuit design of the integrated navigation control system has not been introduced in detail in the two articles.

This paper mainly discusses the navigation method during the blackout zone. Firstly it introduces the principle of DDA measurement and the solution of the parameters used, then a two order damping loop is established to combine the altitude of DDA with the inertial navigation information. Next, this paper analyses the applicable condition, the main error factors and the effect of the iterative times in detail. And at last, the integrated navigation method is applied to the navigation of the reentry vehicle during the blackout zone and the feasibility of this method is verified by simulation results.

2. Drag derived altitude

2.1. Definition of coordinate systems

(1) Earth-Centered Inertial (ECI) coordinate system

The inertial coordinate system of Earth defines a coordinate which is fixed with the rotating Earth and whose origin O_i is at Earth center. The principal direction x_i is through the equatorial at RAAN (Right Ascension of the plane Ascending Node of the orbit), z_i is through the Earth's rotation axis to north and y_i completes the right-handed system.

(2) Earth-Centered Earth-Fixed (ECEF) coordinate system

A coordinate system whose origin O_e is at the center of the Earth and axis x_e is through the equatorial at Greenwich, y_e is through the equatorial and is perpendicular to x_e, and z_e completes the right-handed system.

(3) Body coordinate system

A coordinate system whose origin O_b is at the aircraft center and axes move with the aircraft. The x_b is typically aligned with body spin axis and points to the head of the aircraft, and the y_b is perpendicular to x_b and points to the top of the aircraft, and z_b completes the right-handed system.

(4) Navigation coordinate system

Navigation coordinate system ($O_n x_n y_n z_n$) is the same as the Earth-centered inertial coordinate system in this paper.

(5) Speed coordinate system

A coordinate system whose origin O_b is at the aircraft center and whose axes move with the aircraft. The x_v is along the direction of the speed, the y_v is in the longitudinal symmetry plane of the aircraft and perpendicular to x_v and points to the top of the aircraft, and the z_v completes the right-handed system.

The transformation between different coordinate systems are usually defined as the form of $\boldsymbol{C}_1^2$, which means the transformation matrix from 1 coordinate system to 2 coordinate system. And the transformation between different coordinate systems are given as follows:

(A) Navigation coordinate system and body coordinate system

The transformation matrix can be acquired by rotating the navigation coordinate system three times to the body coordinate system $z(\theta) \rightarrow y(\psi) \rightarrow x(\gamma)$. The transformation matrix is

$$\boldsymbol{C}_n^b = \begin{bmatrix} \cos\theta\cos\psi & \sin\theta\cos\psi & -\sin\psi \\ -\sin\theta\cos\gamma + \cos\theta\sin\psi\sin\gamma & \cos\theta\cos\gamma + \sin\theta\sin\psi\sin\gamma & \cos\psi\sin\gamma \\ \sin\theta\sin\gamma + \cos\theta sin\psi\cos\gamma & -\cos\theta\sin\gamma + \sin\theta sin\psi\cos\gamma & \cos\psi\cos\gamma \end{bmatrix} \tag{1}$$