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The Analysis and Design of Control System for Unpowered Skipping-glide Air Vehicle in Near Space

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Abstract: In allusion to the skipping-glide trajectory of the near space unpowered vehicle, one control system for the skipping-glide trajectory is presented. Firstly, the aerodynamic characteristic of the near space unpowered vehicle is analyzed. Secondly, the impacts of different flight altitudes and flight-path angles on the velocity variation rate are studied. Thirdly, the control system is designed based on the approach of combination of theoretical analysis and engineering trial and error. Finally, the effectiveness of the control system is verified by the computer simulation. The comparison of traditional cruise trajectory and the skipping-glide trajectory verifies that reasonable skipping-glide trajectory is superior to the traditional cruise trajectory in increasing the flying range and maintaining the velocity for the near space unpowered vehicle.

Key Words: Near space vehicle, skipping-glide trajectory, velocity maintaining, flying range, control system

1 Introduction

The near space vehicle is one kind of aircraft which is able to perform specific tasks in near space. Near space, generally refers to the airspace that is 20km to 100km from the ground. It is between the highest flying height of the existing aircrafts to the minimum flying height of the satellites [1]. In order to maintain the flying velocity and ensure a large landing Mach number, the near space unpowered vehicle mainly adopts the skipping-glide trajectory and only relies on aerodynamic lift and lateral force in the near space for maneuver so as to reach the purpose of avoiding interference and improving the penetration probability.

Skipping-glide trajectory is put forward by German scientist Saenger in the late 1930s. It means that the air vehicle firstly flies following a ballistic trajectory, and glides into the atmosphere, under the effect of a brief boost acceleration and lift, restores the ballistic flight, and repeats this action, which presents an undulate flight [2]. Saenger, Preston H and Eggers show that the cruising ability of skipping-glide trajectory is superior to the traditional parabolic trajectory [2-4]. Literature [5] designs and optimizes the hypersonic skipping-glide trajectory for increasing the flying range and reducing the aerodynamic heating. Literature [6] analyzes the minimum energy trajectory and the maximum lift-drag ratio trajectory of the unpowered skipping-glide transatmospheric vehicle and illustrates that adopting the maximum lift-drag ratio trajectory is the best control mode to get the largest flying range of the skipping-glide trajectory.

This paper is about the model analysis, the control system design and trajectory design of the near space unpowered skipping-glide vehicle. The work focuses on the effects of different trajectory parameters such as the skipping heights, skipping times, flight path angles on the flying parameters such as the flying range and the launching Mach number of near space unpowered vehicle. On this basis, complete the design of control system and trajectory of near space unpowered skipping-glide vehicle.

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2 Model Analysis of Near Space Unpowered Vehicle

This section firstly analyzes the characteristics of lift-drag ratio of the near space unpowered vehicle, and then studies the velocity variation rate under different heights and flight path angles of the vehicle during the skipping-glide trajectory, and finally concludes general principles of flying height selection for this kind of vehicle in skipping-glide flight.

2.1 Analysis of Lift-drag Ratio

In allusion to the skipping-glide maneuver flight for the unpowered vehicle in near space, in order to get a large flying range and a large launching Mach number, it is not difficult to draw the conclusion that the unpowered near space vehicle should have aerodynamic characteristics of a large lift-drag ratio. A certain type of near space skipping-glide vehicle adopts the axisymmetric pneumatic layout, and the range of angle of attack, sideslip angle and rudder angle are -30°~30°. The lift coefficient curve, drag coefficient curve and lift-drag ratio curve are as shown in Fig 1~3.

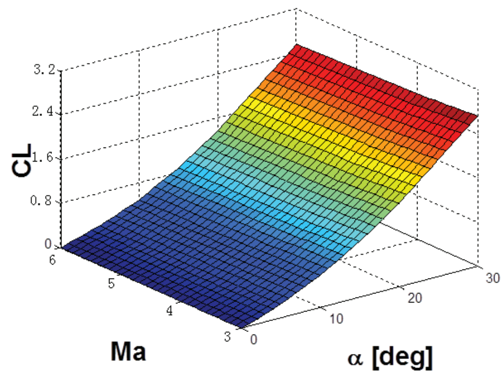

Fig. 1: The lift coefficient curve

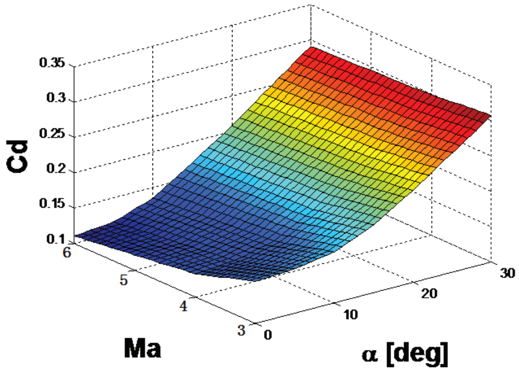

Fig. 2: The drag coefficient curve

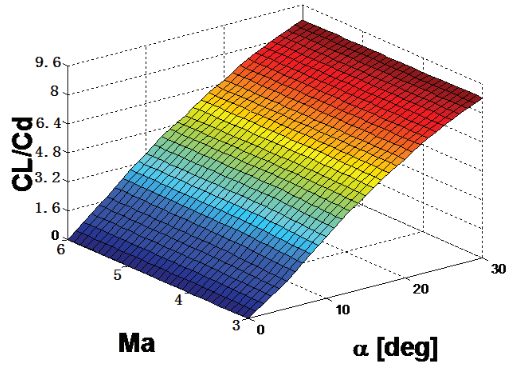

Fig. 3: The lift-drag ratio curve

Fig 1, Fig 2 and Fig 3 respectively show the curves of lift coefficient, drag coefficient and lift-drag ratio with the changes of Mach number and angle of attack. The range of Mach number is 3Ma~6Ma and the range of angle of attack is 0^{o}~30^{o}. From the three curves, it can be concluded that the lift-drag ratio of model is relatively large and increases with the increase of angle of attack, so the aircraft is suitable for skipping-glide maneuver flight.

2.2 Analysis of Velocity Variation Rate

The following is the specific analysis of the impact of the skipping-glide trajectory on velocity. Consider the longitudinal motion of the unpowered vehicle (no roll or sideslip), velocity equation is as follows:

$$m\frac{dV}{dt} = -X - mg\sin\theta \tag{1}$$

When the vehicle skips, the flight path angle θ is positive, so the aircraft is always in a state of deceleration. When the vehicle glides, the flight path angle θ is negative. If the gravity component is greater than the drag, the vehicle is in a state of acceleration. If gravity component is lesser than the drag, the aircraft is in a state of deceleration. Drag depends on not only the size of angle of attack at this time, but also the size of the dynamic pressure. When the vehicle skips, the velocity decreases, and the flying height increases, leading to the decrease of the dynamic pressure. The decrease of dynamic pressure is proportional to the amplitude of skipping. As a result, the reasonable design of skipping-glide trajectory is important to maintain the velocity.

Select two feature points on the skipping-glide trajectory for quantitative analysis of velocity rate (dV/dt). The first feature point is H=24km, V=6Ma. Choose three different flight attitudes: horizontal flight, skip and dive. The velocity variation rate curves change with the angle of attack and the elevator angle are as shown in Fig 4~6. From the three curves, the vehicle in three attitudes is in a state of deceleration. The range of the velocity variation rate is between -5m/s to -40m/s. When the vehicle dives (θ=-10°), the absolute value of velocity variation rate is minimum. When the vehicle skips (θ=10°), the absolute value of velocity variation rate is maximum. It also illustrates that on this feature point, weight component is not enough to offset the drag. The main reason is that the dynamic pressure is not small enough. When the elevator angle and the angle of attack are greater than 20^{o} or lesser than -20^{o}, the velocity decreases fastest and the drag is maximum. It is determined by the inherent aerodynamic characteristics of the vehicle. Similarly, in the middle area of the graphics, the velocity decreases slowest and the drag is minimum.

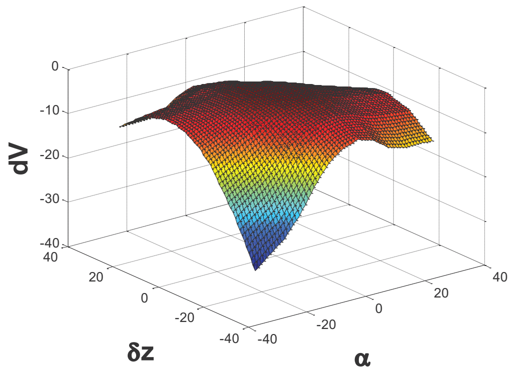

Fig 4: Velocity variation rate (H=24km,V=6Ma,θ=0^{o})

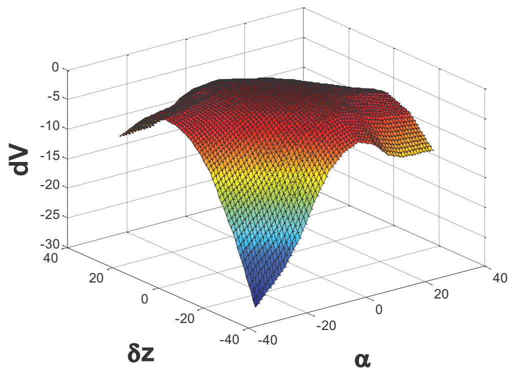

Fig 5: Velocity variation rate (H=24km,V=6Ma,θ=-10^{o})

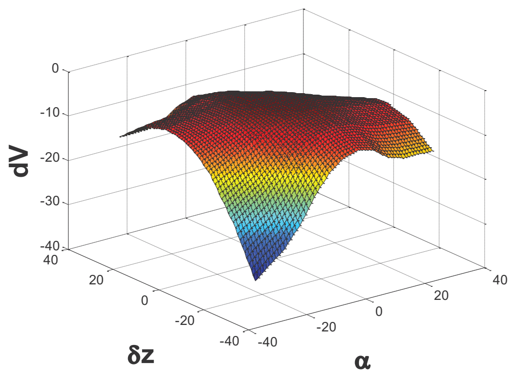

Fig 6: Velocity variation rate (H=24km,V=6Ma,θ=10^{o})

The second feature point is H=40km, V=5Ma. Select three attitudes: horizontal flight, skip and dive. The velocity variation rate curves change with the angle of attack and the elevator angle are as shown in Fig 7~9.

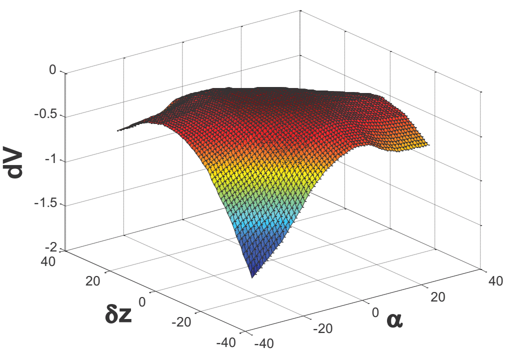

Fig 7: Velocity variation rate (H=40km,V=5Ma,θ=0°)

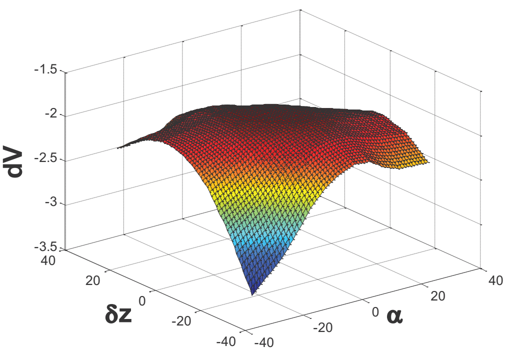

Fig 8: Velocity variation rate (H=40km,V=5Ma,θ=10°)

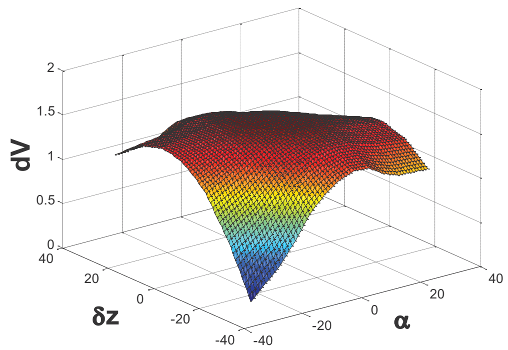

Fig 9: Velocity variation rate (H=40km,V=5Ma,θ=-10°)

From the three curves above, when the vehicle dives (θ=-10°), the velocity variation rate is positive, and the vehicle is in a state of acceleration. It indicates that the weight component is bigger than the drag. The range of velocity variation rate is between -3m/s to -2m/s. Compared with the first feature point, the overall change of the velocity variation rate is smaller. The reason is that the dynamic pressure of the second feature point is smaller and the drag is smaller. The general principles of skipping-glide trajectory for air vehicles can be drawn through the comparison of two feature points: The skipping amplitude range should be as large as possible under the permission of maneuver performance for the air vehicle. The air vehicle should fly in the airspace of small dynamic pressure.

2.3 Control System Design of Near Space Unpowered Vehicle

Select H=24km, V=6Ma as the design point. Select the no-sideslip horizontal flight as the baseline motion (ϕ=0°, β=0°). Select the trajectory inclination angle θ, pitching angle velocity component ω_z in missile body coordinate system, pitching angle ϑ, and elevator angle δ_z as the longitudinal motion state variables. The motion vector is $x^T=[\theta,\omega_z,\vartheta,\delta_z]$, and the control vector is $u^T=[\delta_{zc}]$.The vehicle longitudinal motion equation is as follows:

$$\left.\begin{aligned} mV\frac{d\theta}{dt} &= -X - mg\cos\theta \\ J_z\frac{d\omega_z}{dt} &= M_z \\ \frac{d\vartheta}{dt} &= \omega_z \\ \dot{\delta}_z &= -\frac{1}{T_{\delta_z}}\delta_z + \frac{K_{\delta_z}}{T_{\delta_z}}\delta_{zc} \end{aligned}\right\} \tag{2}$$

The linear state equation is obtained by the small disturbance linearization:

$$\dot{x} = Ax + Bu \tag{3}$$

In which

$$A=\begin{bmatrix} -0.04 & 0 & 0.04 & 0.0001 \\ 10.9 & 0 & -10.9 & -0.26 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -50 \end{bmatrix} \quad B=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 100 \end{bmatrix} \tag{4}$$

The inherent pole of the system is:

$$\lambda_{open}=\left[-1.65\times10^{-18}\ \ -0.022+3.3i\ \ -0.022+3.3i\ \ -50\right] \tag{5}$$

A conclusion can be drawn from the inherent poles that the system is static stable, the short cycle frequency is small, and the damping is small.

Therefore, the feedback coefficient designed using the method of pole assignment should increase the system damping and inherent frequency. The closed loop pole in the system is assigned to $\lambda_{close}=\left[-0.8\ \ -0.6+0.2i\ \ -0.6+0.2i\ \ -50\right]$by trial and error. The feedback matrix is

$$K=\left[-34.79\ \ -3.39\ \ 19.23\ \ 0.02\right] \tag{6}$$

The control law for the linear closed-loop system is u=-$K(x-v)$, υ is the control command, and the system response of the command of trajectory inclination angle 5° is as shown in Fig 10.

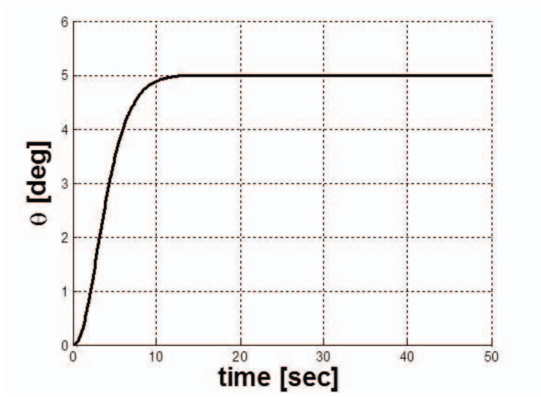

Fig 10: Response curve of trajectory inclination angle

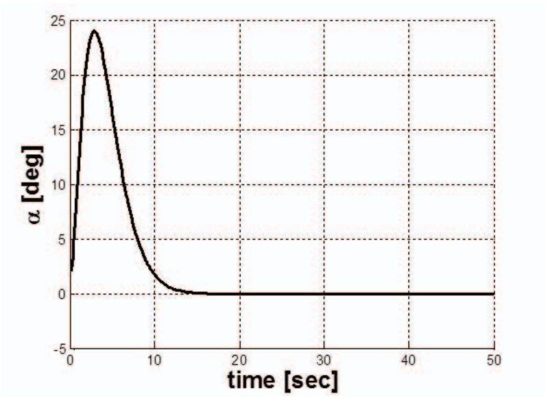

Fig 11: Response curve of angle of attack

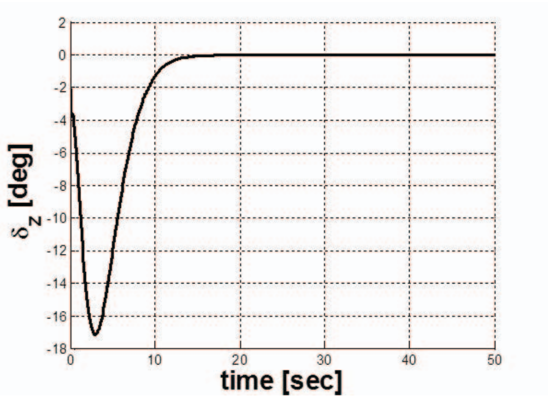

Fig 12: Response curve of elevator angle

The three curves above show that the control system is stable. The response performs well, and the characteristics of small inherent frequency and small damping of the system are improved.

The designed control law is applied into the nonlinear model. Combined the model analysis method with engineering trial and error, the simulation curves of the skipping-glide trajectory for near space unpowered vehicle are as shown in the Fig 13~17. The initial condition is that $H = 24km$, $Ma = 6$.

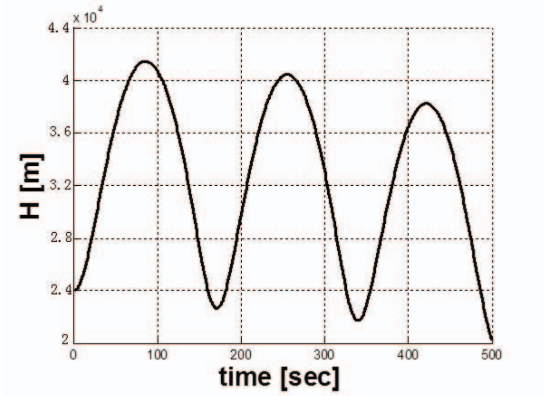

Fig 13: Response curve of height

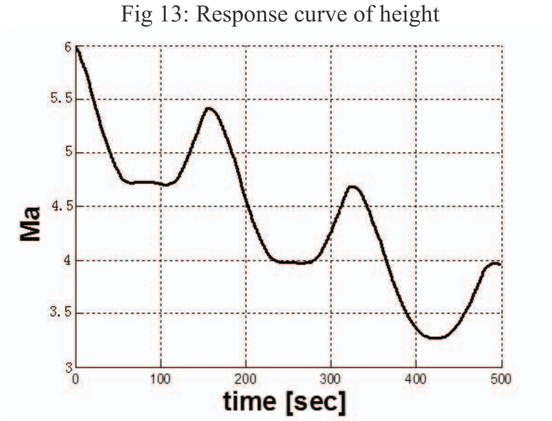

Fig 14: Response curve of Mach number

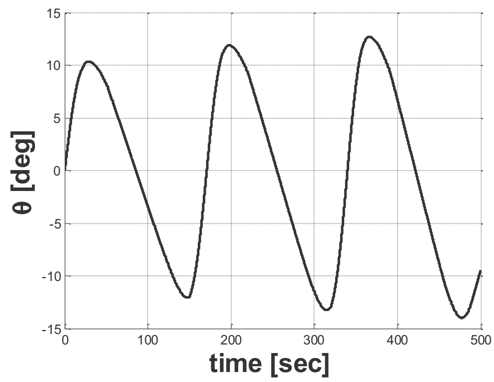

Fig 15 : Response curve of trajectory inclination angle

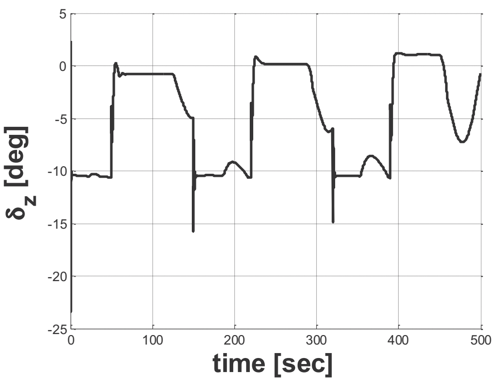

Fig 16: Response curve of elevator angle

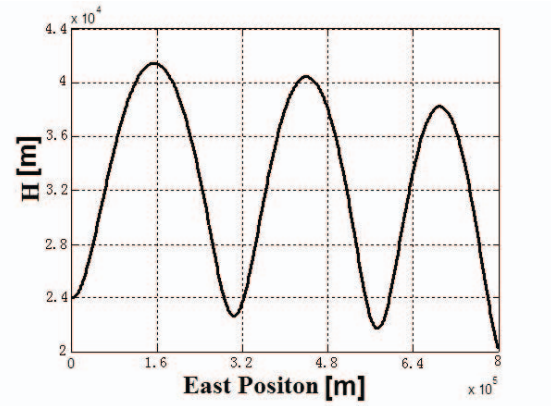

Fig 17: Longitudinal vertical plane trajectory

It can be concluded from the simulation curves that the control system is stable and performs well. The designed skipping-glide trajectory indicates the aerodynamic characteristic of big lift-drag ratio of the air vehicle and the Mach number maintains well. The average altitude for the air vehicle is 30km. The air vehicle skips for three times, and the skipping amplitude is around 20km. The Mach number drops from 6Ma to 4Ma. The flying process takes 500 seconds and the flying range is 800km. The simulation result is identical to the preceding aerodynamic analysis and trajectory analysis.

3 Comparative Analysis of Skipping-glide Trajectory and Cruise Trajectory

In order to adequately illustrate the impact of different trajectories on Mach number, the following simulation curves of another trajectory are given. The trajectory is described as follows: the air vehicle skips for one time and then makes a cruise flight. The simulation curves are as shown in Fig 18~22. The initial condition is same as that in Chapter 2.3.

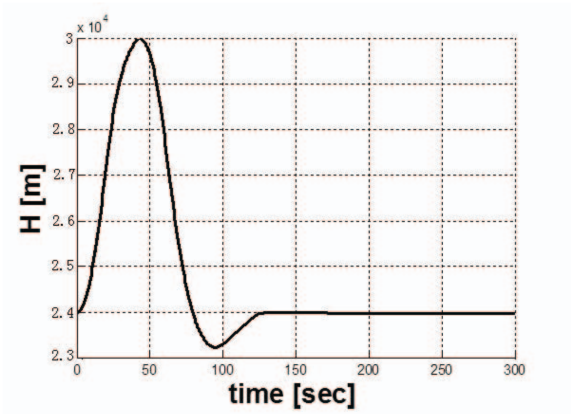

Fig 18: Response curve of cruise height

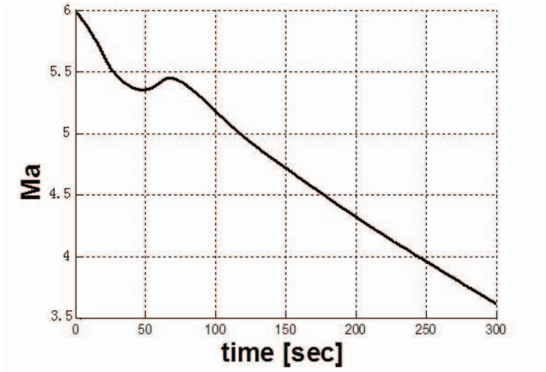

Fig 19: Response curve of cruise Mach number

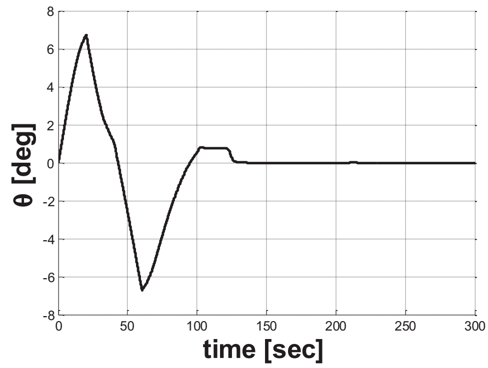

Fig 20: Response curve of trajectory inclination angle

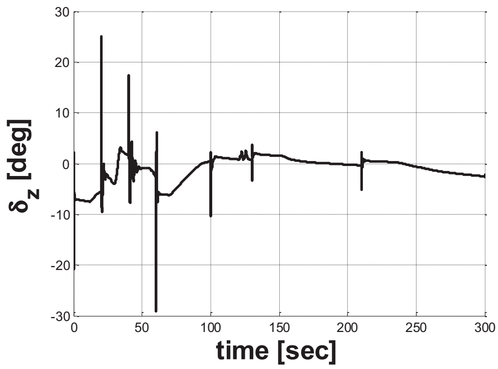

Fig 21: Response curve of elevator angle

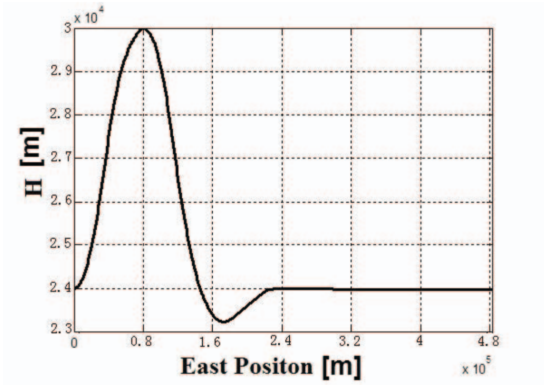

Fig 22: Longitudinal vertical plane trajectory

It can be concluded from the simulation curves that the average altitude for the air vehicle is 24km. The air vehicle skips around 6km for one time and Mach number drops from 6Ma to 3.6Ma. This process takes 300 seconds and the flying range is 480km. The comparison of flight parameters between skipping-glide trajectory and the cruise trajectory is as shown in Table 1.

Table 1: Trajectory Contrast

Trajectory	Skipping-glide	Cruise
Skipping Times	3	1
Average Altitude	30km	24km
Skipping Amplitude	20km	6km
Time of Flight	500s	300s
Velocity Change	6Ma to 4Ma	6Ma to 3.6Ma
Flying Range	800km	480km

It can be concluded from the table that compared with the skipping-glide trajectory of 3 times skipping, the flight time of the cruise trajectory is shorter, the skipping amplitude is smaller, the Mach number drops larger and the flying range is shorter. It means that the cruise trajectory of small skipping amplitude and then cruising flight is not conducive to the maintaining of Mach number. Namely, the cruising trajectory is not suitable for near space unpowered vehicle, and the skipping-glide trajectory is suitable.

4 Conclusion

The analysis and simulation above show that in order to increase the flying range and maintain the velocity of the near space unpowered vehicle, not only the air vehicle itself should have the aerodynamic characteristic of a large lift-drag ratio, but also the controller and the skipping-glide trajectory should be designed appropriately. The skipping amplitude range should be as large as possible under the permission of maneuver performance for the air vehicle. The air vehicle should fly in the airspace of small dynamic pressure. Select the appropriate control method combined with practical engineering to design control law and trajectory parameters. The selection of skipping times should be synthetically considered combined with the flight mission.

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