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Analysis of optimal initial glide conditions for hypersonic glide vehicles

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Abstract Hypersonic glide vehicles (HGVs) are launched by a solid booster and glide through the atmosphere at high speeds. HGVs will be important means for rapid long-range delivery in the future. Given that the glide is unpowered, the initial glide conditions (IGCs) are crucial for flight. This paper aims to find the optimal IGCs to improve the maneuverability and decrease the constraints of HGVs. By considering the IGCs as experiment factors, we design an orthogonal table with three factors that have five levels each by using the orthogonal experimental design method. Thereafter, we apply the Gauss pseudospectral method to perform glide trajectory optimization by using each test of the orthogonal table as the initial condition. Based on the analytic hierarchy process, an integrated indicator is established to evaluate the IGCs, which synthesizes the indexes of the maneuverability and constraints. The integrated indicator is calculated from the trajectory optimization results. Finally, optimal IGCs and valuable conclusions are obtained by using range analysis, variance analysis, and regression analysis on the integrated indicator.

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1. Introduction

Due to flexible maneuverability and time sensitivity, hypersonic glide vehicles (HGVs) for long-range delivery missions have obtained considerable attention in recent years. The US Department of Defense and Air Force launched the "Falcon" program in 2003. The proposed common aero vehicle (CAV) is a type of HGV that has a lifting body configuration and is launched by a solid booster rocket. The CAV is able to glide without power through the atmosphere by relying on aerodynamic control.[1,2] To demonstrate hypersonic technologies that will help achieve a prompt global-reach capability, the United States has conducted two experimental flight tests of the hypersonic technology vehicle 2 (HTV-2). The Minotaur Lite launch system successfully delivered the Falcon HTV-2 to the desired location. However, the HTV-2 failed to complete the whole flight. Although neither of the tests was fully successful, the future of HGV technology is promising.[3,4]

Considering that HGVs glide through the atmosphere unpowered, initial gliding conditions (IGCs) significantly influence the maneuverability and gliding trajectory constraints. Thus, analyzing the optimal glide conditions is necessary to enlarge delivery range while decreasing aerodynamic load and

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aerodynamic heating. The IGCs include initial height, speed, path angle, and azimuth. To determine the optimal IGC, we use the orthogonal experimental design method to arrange the experiment and generate an orthogonal table, which includes a number of experiment sets and the IGCs as experiment factors. By applying the Gauss pseudospectral method (GPM), optimal trajectories are accomplished by employing experiment sets as initial conditions. The evaluation indexes of optimal IGCs are established and acquired from the GPM optimization result. We achieve a synthetic indicator by adopting the analytic hierarchy process (AHP). The optimal IGCs and valuable conclusions are obtained by using range analysis, variance analysis, and regression analysis. Although the analysis conclusion is drawn for the CAV the conclusion is universally applicable for HGVs.

2. HGV model

The CAV is a type of HGV that can achieve high terminal accuracy, extended cross range, and high maneuverability. The CAV carries approximately 1000 lbs of munitions with a cross range of approximately 3000 NM. The CAV is widely used in research concerning glide trajectory optimization and re-entry guidance. The CAV-H is a high lift-to-drag scheme in the two CAV design. Fig. 1 shows the lift coefficient and drag coefficient of the CAV-H, respectively (AoA means angle of attack, C_L means lift coefficient, C_D means drag coefficient). The maximum lift-to-drag ratio of the CAV-H is 3.5 with a reference area of 0.48 m^2 and mass of 907 kg.[5]

3. Orthogonal experimental design (OED)

The OED is an analysis and optimization method for researching multiple factors and levels.[6] This method utilizes an orthogonal table to arrange the experiment scientifically and evaluate the effect of multiple factors. Based on orthogonality, some representative tests can be chosen from the overall tests. Results from the representative tests can be used to find optimal schemes, discover unanticipated important information, and achieve valuable conclusions through range analysis, variance analysis, and regression analysis method.[7]

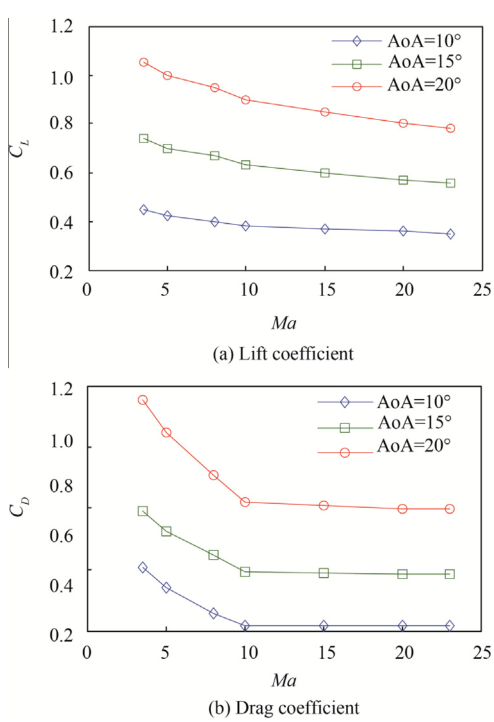

Fig. 1 Aero coefficient of CAV-H.

The IGCs include height, speed, path angle, and azimuth angle. We arrange four factors in the orthogonal design and use five levels for each factor to cover the factor value domain. The factors and their levels are shown in Table 1. In the table, V is the velocity, H is the altitude, γ is the flight path angle, ψ is the velocity azimuth angle, subscripts "0" and "f" indicate the initial and final values, respectively. The orthogonal table $L_{25}(5^6)$ is very suitable for the desired design and contains 25 tests. Without considering the interaction among the factors, four arbitrary columns from $L_{25}(5^6)$ are chosen to arrange four factors. The remaining columns can be used to represent the degree of experiment error. The orthogonal array is shown in Table 2.

4. Evaluation indexes of optimal IGCs

Table 2 shows 25 sets of IGCs. To analyze the optimal IGC, the evaluation indexes of optimality are required. Considering that the HGV is used to complete long-range missions, the maximum downrange and maximum cross range should first be considered. Second, the HGV glides through the atmosphere at high speeds for a long time. The HGV endures very serious aerodynamic load and aerodynamic heating, thus leading to hazardous conditions. Therefore, aerodynamic load and aerodynamic heating should be minimized and not exceed the maximum constraints. Considering the above requirements into account, the maximum downrange, maximum cross range, peak normal load, peak dynamic pressure, peak heat flux are chosen as evaluation indexes (see Fig. 2). By applying the AHP method, the evaluation indexes can be synthesized into a total indicator.

According to the characteristics of the evaluation indexes, the indexes can be divided into two types:

(1) Benefit index. A bigger index is preferable for maximum downrange and maximum cross range.
(2) Cost index. The index is as small as possible for peak normal load, peak dynamic pressure, peak heat flux. These four cost indexes can be synthesized into a total cost index by the AHP method.

Table 1 Factors and their OED levels.

Level	V_0 (m/s)	H_0 (km)	γ_0 (°)	ψ_0 (°)
1	5000	70	−2	60
2	5500	80	−1	75
3	6000	90	0	90
4	6500	100	1	105
5	7000	110	2	120

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