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Research on Integrated Design and Optimization for Hypersonic-Glide Vehicle

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Abstract

The emergence of Hypersonic-Glide Vehicle (HGV) in the hypersonic regime brings a new series of technical challenges， such as strong system integration of parametric model, aerodynamics, thermal, trajectory, and problems about rapidly selecting acceptable conceptual designs.Traditionally, the subsystem of HGV models is designed and optimized separated without considering coupling, leading to losing the globally optimal solution. In this paper, the HGV Integrated Design Environment (HGVIDE) for HGV design and optimization will be presented, to improve the quality and efficiency of the traditional single solution optimization. First of all ,a parametric design method based on class function/shape function transformation (CST) and power function was established as the starting step on which the engineering estimation models for aerodynamic force and flux were executed. Secondly, it assesses the effect of vehicle design variables on the maximum lift-drag ratio boost-glide trajectory. Finally, the performance optimization problem is presented, which demonstrate the application of optimization techniques to the multi-disciplinary and multi-objective design of HGV. The investigation shows that the methods feature higher efficient and further complete, thus can give better optimal results for HGV integrated design and optimization problems.

Keywords: Hypersonic-Glide Vehicle, Parametric Modeling, Integrated Design, Multi-objective Optimization

Introduction

Hypersonic vehicles employing high L/D body offer affordable commercial and military applications. The emergence of Hypersonic-Glide Vehicle (HGV) in the hypersonic regime brings a new series of technical challenges, such as strong system integration of parametric modeling, aerodynamics, thermal, trajectory, and problems about rapidly selecting acceptable conceptual designs. To address these challenges, a HGV Integrated Design Environment (HGVIDE) which is based on Multi-disciplinary Design Optimization (MDO) method and multi-disciplinary integration technology is designed and applied to HGV multidisciplinary design optimization.

Many examples of MDO applications are presented in the literature[1-4]. The need to improve the engineering design process is an endless challenge[5]. For this purpose, system level optimization is needed to determine the most effective integrated concept. Whether the goals are to improve the quality of a design, or to reduce the amount of time required to do design, the desire to get better always exists . Traditionally, the subsystem of HGV models are designed and optimized separated without considering coupling. However the solution to the design problem does not reside within one discipline but will only be found by investigating the complex interactions between various disciplines. The objective of this paper was the development of integrated system approach to evaluate the best design to achieve overall performance. The HGVIDE is a tool used in research and development arena, focused on the design and optimization to improve the quality and efficiency of the traditional single solution optimization. The key idea is to use multi-disciplinary and multi-objective design and optimization aiming at aerodynamic performance and ballistic performance simultaneously to get more acceptable results.

The reference design point for HGV was as shown in figure 2-3 with the evaluation of the unpowered skipping trajectory. The major blocks of the simulation are geometry module, aerodynamics force module, aerodynamics thermal module, trajectory simulation module, and optimization module. Example capabilities of the process are demonstrated followed by conclusions and future plans.

1 HGVIDE Multi-Disciplinary Module

There are five main modules which make up the HGVIDE system, such as the Geometry Module, the Aerodynamics Force Module, the Aerodynamics Thermal Module, the Trajectory Simulation Module, and optimization module..The execution of the HGVIDE system is shown in Figure 1, as a design structure matrix. In this figure, the HGVIDE analysis modules are shown on the diagonal of a matrix in their execution order. The data generated by a module is shown on the module's row of the matrix (with the exception of the left column, which is input by the user or the optimization system). The data that a module needs from the HGVIDE system is shown in Figure 1. This is a useful tool for visualizing the overall process, as "feedforward" interactions are shown in the upper right triangle of the matrix, and "feedback" interactions are shown in the lower left. It helps to make module execution order decisions, as the desire is to minimize feedback interactions, which must be handled through iteration. Note that the HGVIDE system is far too complex to display in a single figure, so Figure 1 only shows the most significant interactions between modules. A system-level optimization layer is then added to the entire multidisciplinary analysis system .

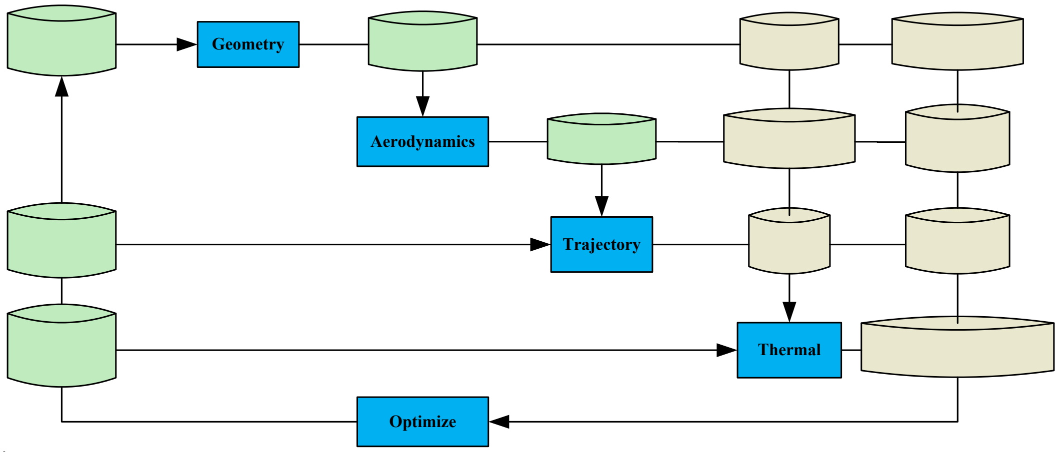


Figure 1: Main Modules of HGVIDE

1.1 Geometry Module

The HGVIDE Geometry Module is responsible for maintaining a geometric model of the configuration being analyzed, and for updating that model as system level design variables are being changed. This module based on class function/shape function transformation(CST)[6], dividing geometry configuration into top view outline parameter, side-looking outline parameter and bottom view outline parameter.

1.1.1 Top View Outline Parameter

As figure 2 shows, the top view outline parameter consists of six parameter, but total length L and bottom width W are separately assigned to 4000mm and 2400mm. In addition, the length of the dome L_1 and width of the dome bottom W_1 are nearly constant, so only two parameters are needed, the length of precentrum L_2 and width of the precentrum bottom W_2 to describe the top view outline.

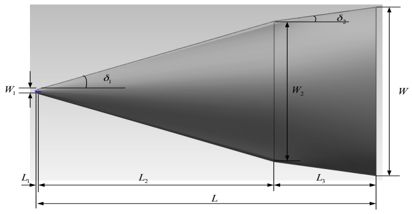


Figure 2: Top View Outline

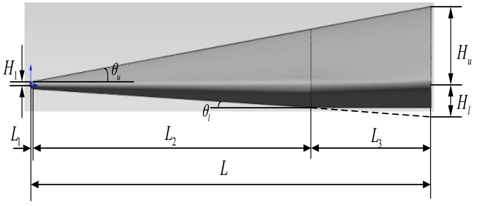


Figure 3: Side-looking Outline

1.1.2 Side-looking Outline Parameter

As figure 3 shows, the top view outline parameter consists of three parameters, but the thickness of the half dome H_1 are nearly constant, so only two parameters are needed, the thickness of back cone bottom H_u and H_l to describe the top view outline.

1.1.3 Bottom View Outline Parameter

Based on class function/ transformation (CST), the bottom view outline physical coordinate (x, y) is converted into parameterized coordinate (ψ,η) as Eq.(1), then the parameterized coordinate (ψ,η) can describe as multiply class function $C_{N_{c2}}^{N_{c1}}(\psi)$ by shape function $S_{N_{c2}}^{N_{c1}}(\psi)$ as follows:

$$\eta(\psi)=C(\psi)\cdot S(\psi)$$ (1

)

Shape function is $S=2^{2N_c}$ based on this mission. Class function is $C(\psi)=\psi^{N_{c1}}(1-\psi)^{N_{c2}}$ $,\psi\in(0,1)$. Where N_{c1}, N_{c2} are class function index numbers, we can get $N_{c1}=N_{c2}=N_c$ for plane symmetry aircraft.

In conclusion, the HGVIDE geometry module just need L_2, W_2, H_u, H_l, N_{cu} and N_{cl} all six parameters to express the Hypersonic-Glide Vehicle (HGV) appearance geometry feature. These parameters based on CST are separately but definitely, to confirm this module. examples are showed as follows.

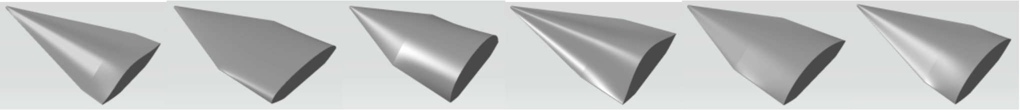


Figure 4: Examples based on CST method

The HGVIDE Geometry Module provides the structural subsystem data associated with the overall vehicle. The data includes a global surface mesh model and mass properties of the vehicle. A conceptual layout of the Geometry Module showing its three major components are shown graphically in Figure 5.

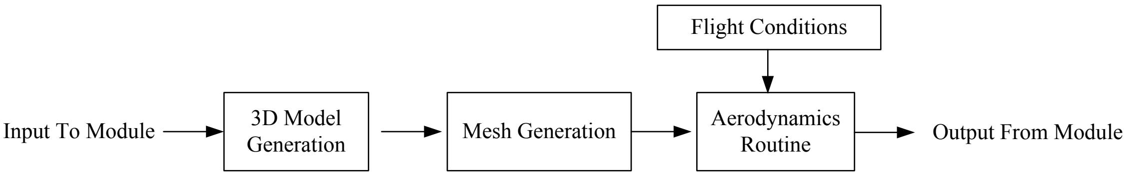


Figure 5: Architecture of the Aerodynamics Force Module

1.2 Aerodynamics Force Module

The HGVIDE Aerodynamics Force Module computes the aerodynamic performance of the vehicle over the expected flight envelope using a set of engineering estimation methods to aerodynamic analysis. This includes the modified Newton's formula as Eq.(2) based on Lees' contribution to complete pressure coefficient simulation of the windward side, and the Prandtl-Meyer's formula as Eq.(3) to complete the leeside. This approach combines the panel method code and the engineering estimation methods which described above to bias the low fidelity solution. This results in a good compromise between accuracy and solution time.

Modified Newton's formula:

$$C_p = C_{p\max} \sin^2 \theta, \quad C_{p\max} = \frac{2}{\gamma M_1^2} \left\{ \left[\frac{(\gamma+1)M_1^2}{4\gamma M_1^2 - 2(\gamma-1)} \right]^{\frac{\gamma}{\gamma-1}} \left(\frac{1-\gamma+2\gamma M_1^2}{\gamma+1} \right) - 1 \right\} \tag{2}$$

where C_P is the pressure coefficient, $C_{p\max}$ is the max pressure coefficient, θ is the inclination of the aircraft.

Prandtl-Meyer's formula:

$$C_p = -\frac{\gamma+1}{2} \delta^2 \left\{ \sqrt{1 + \left[\frac{4}{(\gamma+1)\ \mathrm{Ma}_\infty \delta} \right]^2} - 1 \right\} \tag{3}$$

in which, δ is the impact angle.

1.3 Aerodynamics Thermal Module

The HGVIDE Aerodynamics Thermal Module computes the stagnation point aerodynamic heating environment, and simulates the stagnation heat flux as the main index of the whole vehicle aerodynamic heating. Based on the flight conditions, height and temperature of the wall, this module introduces Scala formula as Eq.(4) to compute the density of stagnation heat flux.

$$q_{ws} = \frac{12.488}{\sqrt{R_N}} (10.0)^a (3.281 \times 10^{-3} v_\infty)_b, \quad \begin{aligned} a &= -(0.9689 + 6.9984 \times 10^5 T_w)(5.626 + 3.2285 \times 10^{-5} h) \\ b &= (0.9793 + 4.6715 \times 10^{-5} T_w)(2.838 + 9.843 \times 10^{-7} h) \end{aligned} \tag{4}$$

where q_{ws} is the density of stagnation heat flux, R_N is the radius of curvature of stagnation , v_∞ is the flight velocity, T_w is the temperature of the wall, and h is the flight height.1.4 Trajectory Simulation Module.

Based on boost – gliding trajectory, the trajectory simulation will consist of a three degree of freedom (3DOF) and a three section of process includes boost, free and reentry phase as Eq.(5~7), untrimmed analysis of the vehicle starting at time zero to the desired final statement.

Section 1: Boost Phase

$$\begin{cases} \dot{V} = \frac{P_e}{m} - \frac{1}{m} C_x q S_M + g \sin\theta \\ \theta = \frac{1}{mV}(P_e + CY^{\alpha})\alpha + \frac{g}{V}\cos\theta \\ y = V \sin\theta \\ x = V \cos\theta \\ \alpha = A_{\varphi}(\varphi_{pr} - \theta) \\ m = m_0 - mt \end{cases} \tag{5}$$

Section 2: Free Phase

$$\begin{cases} v_x = \frac{P}{m}\cos\varphi(t) - \frac{fM}{r^3}x \\ v_y = \frac{P}{m}\sin\varphi(t) - \frac{fM}{r^3}(y+R) \\ x = v_x \\ y = v_y \end{cases} \tag{6}$$

Section 3: Reentry Phase

$$\begin{cases} V = -\frac{D}{m} - \frac{fM}{r^2}\sin\theta_T \\ \theta_T = \frac{1}{V}\left[\frac{L\cos v}{m} - \left(\frac{fM}{r^2} - \frac{V^2}{r}\right)\cos\theta_T\right] \\ \sigma_T = \frac{-L\sin v}{mV\cos\theta_T} + \frac{V\cos\theta_T\sin\sigma_T\tan\phi}{r} \\ \phi = \frac{V\cos\theta_T\cos\sigma_T}{r} \\ \lambda = \frac{-V\cos\theta_T\sin\sigma_T}{r\cos\phi} \\ r = V\sin\theta_T \end{cases} \tag{7}$$

For the sake of analysis efficiency, the attitude dynamics and other less important equations are neglected.

1.5 Multi-disciplinary integration

Each of these component modules has a clearly description above. The HGV Integrated Design Environment (HGVIDE) which based on multi-disciplinary integration technology is designed and applied to HGV multidisciplinary design optimization.

2 HGV Trajectory Performance Multidisciplinary optimization

The fundamental approach employed in this work included construction of a parametric configuration geometry model; development of physics models for aerodynamics, heat flux, and mass properties as functions of geometric variables; then use of trajectory analysis to assess vehicle performance and a numerical optimization algorithm to search the set of geometric variables that maximize overall performance. To demonstrate the application of optimization techniques to the multi-disciplinary and multi-objective design of HGV, overall performances optimization problems are established. In this section, six geometry parameters and mass (M) are set as design parameters, the trajectory performance design function presents maximal range trajectory R_f and minimal total heat adsorption capacity of stationary point Q, and the corresponding Pareto fronts are used for describing results.

2.1 Optimization Model

Now, there are all seven design parameters, therein six geometry parameters are not facility to complete optimization, so we take Latin-Hypercube experiment design (DOE) to acquire the sensitivity of each parameter about the R_f and Q. In our research, N_{cl} has the minimal effect on range trajectory (1%) and total heat adsorption capacity of stationary point (2%), as a result, we select other six parameters M , L_2, N_{cu}, H_u, H_l, W_2 for optimization. On the other hand, during the parameters sensitivity analysis, it's easy to find that the tendency of maximal range trajectory R_f and minimal total heat adsorption capacity of stationary point Q response curve for six geometry parameters are opposite. In practice, the R_f and Q are important to HGV overall performance design, but the opposite tendency impose restrictions on the best optimization, so only aiming at R_f and Q meanwhile, can we realize multi-disciplinary trajectory optimization.

In order to endure the volume ratio and stability of the HGV, meanwhile considering the structural strength and thermal protection, it's reasonable to regard the volume V, the longitudinal pressure coefficient X_p, the dynamic pressure η and heat flux Q as constraint conditions. Optimization model as Eq.(8) follows:

$$F=\begin{cases}\max f_1(X)=R_f\\ \min f_2(X)=Q\end{cases}$$
$$X=(M,L_2,W_2,H_u,H_l,N_{cu})$$
$$s.t.\begin{cases}V\geq 1.6\\ V_e\geq 0.22\\ X_p\geq 0.6\\ \eta\leq 650kPa\\ Q\leq 1000kW/m^2\end{cases}\tag{8}$$

Where F is Optimization objective, X is design space, and $s.t.$ are constraint conditions.

2.2 Multi-disciplinary Optimization Result

Based on Multi-Disciplinary Integration platform we created before, by calling genetic algorithm optimizer Darwin, it's not difficult to establish the optimization model for Multi-disciplinary Optimization. In the end, the corresponding Pareto front is obtained as figure 6 shows.

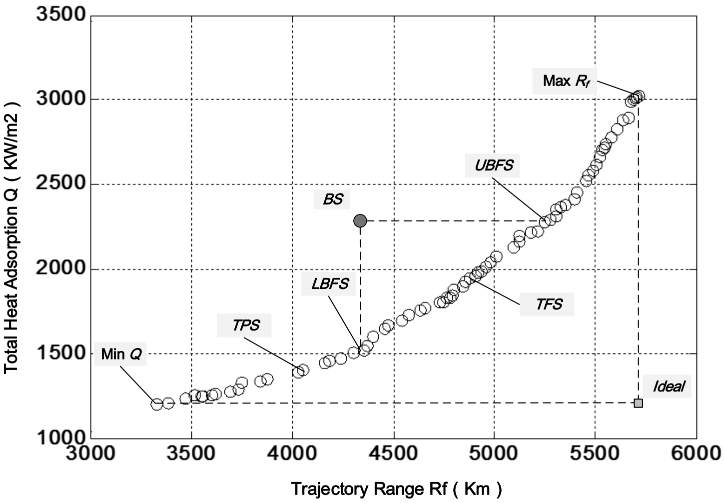
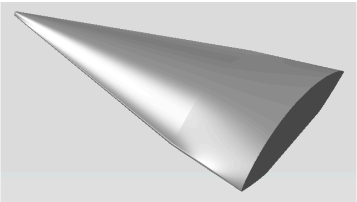
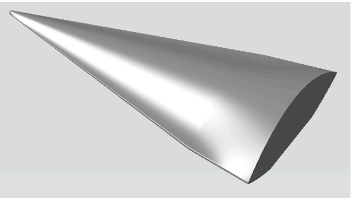


Figure 6: Multi-disciplinary optimization Pareto fronts

In figure 6, the based starting design (BS) and optimization Pareto fronts are separately marked as solid and hollow circles. More specifically, "Min Q" and "Max Rf" are maximal range trajectory R_f and minimal total heat adsorption capacity of stationary point Q, but the hollow-black ("Ideal"), which represents both maximal range trajectory and minimal total heat adsorption capacity of stationary point is conflicted, is impossible to reach. What's meaningful to feasible solution is Pareto fronts which within the range from "LBFS" to "UBFS", such as "TFS",can magnify trajectory range and decrease total heat adsorption capacity of stationary point. In addition, the Pareto fronts outside of this range, such as "TPS", can only change just one of two optimization performance.

In conclusion, the BS and TFS project appearance of HGV are showed in Figure 6, and the comparison between BS and TFS is also presented in Table 1. What's more, trajectory performance multi-disciplinary optimization based on HGVIDE in this article have achieved outstanding improvement. The maximal range trajectory R_f increases from 4332.6km to 4874.5km rising 12.51%, at the same time, the minimal total heat adsorption capacity of stationary point Q decreases from $2284.1kW/m^2$ to $1942.3kW/m^2$ decreasing 14.92%. In practice, we can select the finest corresponding Pareto front on the basis of design demands.





(a) BS project appearance (b) TFS project appearance

Figure 7: BS(a) and TFS(b) project appearance of HGV

Table1: Comparison between BS and TFS

Index	BS	TFS	Difference(%)
R_f(km)	4332.6	4874.5	12.51
Q(kW/m^2)	2284.1	1942.3	-14.92

3 CONCLUSIONS

In this article, a HGV Integrated Design Environment (HGVIDE) which based on Multidisciplinary Design Optimization (MDO) method and multi-disciplinary integration technology is designed and applied to HGV multidisciplinary design optimization. To develop a reasonable goal requirement in pre-concept design phase of HGV, a probabilistic analysis is presented. The procedure consists of probabilistic model based CST, aerodynamics force, thermal, trajectory simulation module, and multi-objective optimization. The most influential variables are selected by design of experiment method to make approximate model in the initial step. The objective is minimizing flux and maximizing range, the use of genetic algorithms to select from discrete component choices has been proven valuable in selecting the Pareto front. The HGV design capabilities presented in this paper will allow engineers to make quick changes to conceptual aero-shape design and get accurate, integrated results.

Results of the system level optimization showed the HGV tends to accelerate to the optimization efficient. And the presented methodology is satisfied to establish the acceptable solution requirement in pre-concept design phase. The HGVIDE system provides a design, analysis, and optimization tool with extensive capabilities, the environment can be used for on HGV integrated design and optimization, which has a good reference value for HGV overall design. The present approach provides many benefits to conceptual designers. The approach offers a better method for comparing the viability of candidate designs.Further work will focus on increasing the fidelity of the example models and incorporating more discrete system selection choices for construction of more complex systems.

4 Acknowledgments

The authors wish to acknowledge the rest member of HGVIDE System team, whose contribution work is the base of this research.

5 References

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