MULTI-DISCIPLINARY DESIGN OPTIMIZATION OF HYPERSONIC AIR-BREATHING VEHICLE*

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A 2D hypersonic vehicle shape with an idealized scramjet is designed at a cruise regime: Mach number (Ma) = 8.0, Angle of attack (AOA) = 0 deg and altitude (H) = 30kms. Then a multi-objective design optimization of the 2D vehicle is carried out by using a Pareto Non-dominated Sorting Genetic Algorithm II (NSGA-II). In the optimization process, the flow around the air-breathing vehicle is simulated by inviscid Euler equations using FLUENT software and the combustion in the combustor is modeled by a methodology based on the well known combination effects of area-varying pipe flow and heat transfer pipe flow. Optimization results reveal tradeoffs among total pressure recovery coefficient of forebody, lift to drag ratio of vehicle, specific impulse of scramjet engine and the maximum temperature on the surface of vehicle.

Keywords: Hypersonic vehicle; multi-objective design optimization; Non-dominated Sorting Genetic Algorithm II, Euler equation.

1. Introduction

At present, hypersonic vehicle has been the hotspot of strategic and tactical competition of the world's major aviation and space powers for its high flight speed, good mobility, long-distance strike capacity, etc. Many significant studies have been carried out or carrying on in this area. Nowadays, it is uncovered that the aerodynamic integrated design of scramjet is one of the most challenging tasks because the hypersonic propulsion system is strongly coupled with the vehicle airframe, and the three basic components of a scramjet, i.e. inlet, combustor, and nozzle, interact and influence each other. More precisely, the coupling effects with the airframe and the engine are multi-disciplinary and therefore the integration of air-breathing hypersonic vehicle impose strong interactions among disciplines, especially between the propulsion system operational performances and the airframe basic aerodynamic characteristics. Therefore, the preliminary design of hypersonic vehicle requires an integrated design that includes some crucial target

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disciplines, i.e. aerodynamics, propulsion, thermodynamics and overall performance. Only by taking a full consideration of the strong coupling effect between airframe and engine, global optimal design concept can be obtained.

2. Hypersonic vehicle design integrated with scramjet

In this section, as presented in Fig.1, a two-dimensional hypersonic vehicle is designed at a specified cruise regime: Mach number (Ma) = 8.0, Angle of attack (AOA) = 0 deg and altitude (H) = 30kms.

Fig. 1. Full view configuration of the hypersonic vehicle

The vehicle consists of four basic components, i.e. forebody/inlet, isolator, combustor, and afterbody/nozzle, which interact and influence each other strongly. Taking a full consideration of the strong coupling effect between airframe and engine, the vehicle is designed with an integrated design methodology as follows:

Firstly, the forebody/inlet is designed to make the first three oblique shocks (blue dashed line in Fig.2) focus on the cowl tip (point E), and the fourth hit the lower point of forebody (point C), see Fig.2. Then a constant area passage, segment CD in Fig. 2, namely isolator, is last to the exit of the inlet. Then, for a given height of forebody H_0 which is determined by the thrust requirements, the configuration can be obtained by solving shock theory. In forebody/inlet design, three wedge angles α_i ($i=1,2,3$) is chosen to be the design variables of the optimization problem.

Fig. 2. Configuration of forebody/inlet

Secondly, a constant area passage is proposed in isolator design. Here, the length of isolator is calculated by Eq.(1), which is proposed by P.J.Waltrup¹ according to his research results. As we can see, the design of isolator is strongly coupled with three wedge angles.

$$L_{isolator} = 0.01(0.971875(H_0/h)^2 - 24.0875(H_0/h) + 162.3) \quad (1)$$

Next, the combustor is designed to be a slightly increasing area channel by considering the fuel reaction time and the gas velocity, with the combustor expanding angle of 2 degree. It will be introduced in section 3 in details.

Finally, a Single-Expansion-Ramp Nozzle² (SERN) is proposed in the design of afterbody/nozzle, which is usually adopted in the preliminary design. As presented in Fig.3, choosing deflection angle of the external nozzle θ_{aft} , length of internal nozzle L_{sp} and deflection angle of internal nozzle θ_{sp} as the design variables, the configuration can be easily determined.

Fig. 3. Configuration of afterbody/nozzle

Note that a cruise fuel/gas ratio should be obtained by iteration method to assure the vehicle be designed under the specified cruise regime. The iteration process for obtaining a cruise fuel/gas ratio is shown in Fig.4.

Fig. 4. Iteration process of cruise fuel/gas ratio

To sum up, under the specified cruise regime, given a constant height of vehicle H_0 , for a group vehicle shape design variables $\mathbf{x}=[\alpha_1, \alpha_2, \alpha_3, \theta_{sp}, L_{sp}, \theta_{aft}]^T$, the configuration of hypersonic vehicle can be determined with a cruise fuel/gas ratio f_{cruise} . The full view pressure contour of one sample is shown in Fig.5, the result reveals that the developed integrated design methodology can meet the design requirements well.

Fig. 5. Full view pressure contour of the hypersonic vehicle

3. Multi-disciplinary analysis model of the hypersonic vehicle

In this paper, four disciplines are taken into account, that is, aerodynamics, propulsion, thermodynamics and combustion. The analysis model of each discipline is present as follows.

3.1. Propulsion analysis model of engine

A quick propulsion evaluation methodology³ for preliminary design analysis of an idealized, integrated engine air-breathing vehicle is adopted. By regarding the combustion as the combination effect of area-varying pipe flow and heat transfer pipe flow, the propulsion can be simulated as:

$$a = \gamma(kc - 1) - kc \quad b = 2kc - 1$$

Let

$$fm = \frac{aMa_i^2 + b}{aMa_e^2 + b} \quad gm = \frac{Ma_i^2}{Ma_e^2} \quad hm = \frac{1 + \frac{\gamma-1}{2}Ma_e^2}{1 + \frac{\gamma-1}{2}Ma_i^2} \quad (2)$$

where, kc is a multiplying factor, subscript i means combustor inlet and e means outlet.

Then the inlet and outlet flow properties of combustor can be obtained:

$$\begin{aligned} \frac{A_e}{A_i} &= fm^{-kc(\frac{1}{a} + \frac{1}{b})} gm^{\frac{kc}{b}}; \quad \frac{V_e}{V_i} = [fm \cdot gm^{-1}]^{\frac{kc-1}{b}}; \quad \frac{P_e}{P_i} = fm^{\frac{\gamma(kc-1)}{a}} \\ \frac{T_e}{T_i} &= fm^{1-\frac{1}{b}} gm^{\frac{1}{b}}; \quad \frac{P_{te}}{P_{ti}} = \frac{P_e}{P_i} hm^{\frac{\gamma}{\gamma-1}}; \quad \frac{T_{te}}{T_{ti}} = \frac{T_e}{T_i} hm \end{aligned} \quad (3)$$

For engine control, the fuel-gas rate is more convenient to be specified as an independent parameter. With respect to the required heating value, thus

$$\dot{\eta} \dot{m}_f H_f = \dot{m}_a (h_{te} - h_{ti}) + \dot{m}_f h_{te} \quad (4)$$

For a calorically perfect gas, the following relationships exist:

$$f = \dot{m}_f / \dot{m}_a = \lambda \varphi \quad (5)$$

$$h_{te} = C_p T_{te} \quad h_{ti} = C_p T_{ti} \quad (6)$$

here, liquid hydrogen fuel (LH₂) is selected as the fuel and kc is assigned to be 1.2 in the sample calculation.

Then, from Eq.(4) to Eq.(6), T_{te}/T_{ti} can be obtained with a specified fuel/gas rate f . Moreover, according inlet flow properties obtained from the forebody/inlet flow calculation, the A_e and A_i , as well as the other flow properties of inlet and outlet can be obtained from Eq.(3). Then, with a combustor expanding angle of 2° , the length of combustor can be obtained as

$$L_{com} = (A_e - A_i) \cot 2^\circ \quad (7)$$

Finally, based on the momentum theorem, the thrust T_p and specific impulse of engine I_{sp} that acts in the centerline direction of the divergent channel combustor is defined as

$$T_p = \dot{m}_a (V_e - V_i) + \dot{m}_f V_e + (P_e A_e - P_i A_i) + \frac{1}{2} (P_e + P_i) (A_e - A_i) \quad (8)$$

$$I_{sp} = T_p / \dot{m}_f \quad (9)$$

For propulsion analysis model, the specific impulse of engine I_{sp} is chosen to be the design objective to evaluate the propulsion performance.

3.2. Aerodynamics and thermodynamics analysis model of vehicle

Aerodynamics and thermodynamics performance of hypersonic vehicle are obtained by the numerical simulation of inviscid Euler equations⁴. The 2D Euler equations can be expressed as

$$\frac{\partial}{\partial t} \int_{\Omega} W d\Omega + \int_s (F dy - G dx) = 0 \quad (10)$$

where, W is the vector of conserved variables and F, G are flux vectors:

$$W = \begin{bmatrix} \rho \\ \rho U \\ \rho V \\ \rho E \end{bmatrix} \quad F = \begin{bmatrix} \rho U \\ \rho U^2 + P \\ \rho UV \\ \rho UH \end{bmatrix} \quad G = \begin{bmatrix} \rho V \\ \rho UV \\ \rho V^2 + P \\ \rho VH \end{bmatrix} \quad (11)$$

and E is total energy per unit mass, H means total enthalpy per unit mass.

The numerical simulation is conducted by FLUENT software, in order to capture the shocks clearly, mesh refinement is adopt into the forebody and afterbody area, see Fig.6. The governing equations are solved by using implicit second-order upwind finite volume scheme. Then, the inlet of combustor is taken as pressure-outlet boundary condition, and

the outlet is considered as pressure-inlet, respectively. Then, lift to drag ratio of vehicle and maximum temperature on vehicle surface can be obtained.

Fig. 6. Mesh refinement of the hypersonic vehicle flow field

Finally, the lift to drag ratio of vehicle C_l/C_d is chosen to be the design objective to evaluate the aerodynamics performance and the maximum temperature on vehicle surface T_{max} is also established to be the another design objective to analysis thermodynamics performance.

3.3. Aerodynamics analysis model of forebody/inlet

In this paper, the pressure recovery σ is proposed to evaluate energy loss due to shocks, it can be easily obtained by using shock wave formulation.

4. Multi-Objective Optimization model of hypersonic vehicle

Based on the design variables proposed in section 2 and design objectives presented in section 3, a four-objective optimization problem is solved in this section.

4.1. Definition of Four-Objective Optimization Problem

The primary value and variation range of each design variable is given in table.1. For a set of design vector: $\mathbf{x}=[\alpha_1,\alpha_2,\alpha_3,\theta_{sp},L_{sp},\theta_{aft}]^T$, a four-objective optimization design is proposed as follows.

Table 1. Design variable details of four-objective optimization

Serial Number	Design Variables	Description	Primary Value	Variation Range
1	α_1	First wedge angle	5.5°	2.0°~10.0°
2	α_2	Second wedge angle	7.0°	2.0°~10.0°
3	α_3	Third wedge angle	5.3°	2.0°~10.0°
4	θ_{sp}	Deflection angle of internal nozzle	6.0°	2.0°~45.0°
5	θ_{aft}	Deflection angle of external nozzle	13.2°	5.0°~20.0°
6	L_{sp}	Length of internal nozzle	60mm	10~500mm

The vehicle configuration is constrained as $L_{forebody}/H_0 \in [4, 6.5]$, $L_{iso} + L_{com}/H_0 \in [1.0, 3.5]$ and $L_{afterbody}/H_0 \in [2.5, 4.5]$ for geometrical consistency with the primary vehicle shape⁵⁻⁶ of $L_{forebody}/H_0 = 5.0$, $L_{iso} + L_{com}/H_0 = 2.0$ and $L_{afterbody}/H_0 = 3.6$. The static pressure, Mach number and temperature at the inlet of combustor cross plane are constrained as $P_i \geq 0.5 \text{ atm}$, $Ma_i \geq 1.5$ and $1000 \text{ K} \leq T_i \leq 1470 \text{ K}$ for combustion considerations⁷, respectively. Finally, the optimization problem is defined as

$$\text{Obj.: } \max f(x) = \{\sigma(x), C_l/C_d(x), I_{sp}(x), -T_{max}(x)\}$$

S.t.:

$$P_i \geq 50662.5, 1000 \leq T_i \leq 1470, Ma_i \geq 1.5;$$

$$L_{forebody}/H_0 \in [4, 6.5];$$

$$L_{iso} + L_{com}/H_0 \in [1.0, 3.5];$$

$$L_{afterbody}/H_0 \in [2.5, 4.5];$$

$$2^\circ \leq \alpha_1 \leq 10^\circ, 2^\circ \leq \alpha_2 \leq 10^\circ, 2^\circ \leq \alpha_3 \leq 10^\circ;$$

$$2^\circ \leq \theta_{sp} \leq 45^\circ, 5^\circ \leq \theta_{aft} \leq 20^\circ;$$

$$10 \leq L_{sp} \leq 500;$$

$$\text{Thrust} = \text{Drag}$$

$$\text{Where: } \alpha_i (i=1, 2, 3), \theta_{sp}, L_{sp}, \theta_{aft}, f_{cruise}$$

where, f_{cruise} is a design variable to meet cruise status constraint: $\text{Thrust} = \text{Drag}$.

A Pareto Non-dominated Sorting Genetic Algorithm⁸, i.e. NSGA-II, is used to solve this problem. The control parameters are set as: population size is 100, probability of crossover is 0.9, and maximum evolution generation is 60. In order to decrease the design cost and improve the design efficiency, the optimization model is designed in parallel pattern, that is, the optimization process is finished in a high performance computing environment of 24 cores and executes in parallel of 6 runs at one time.

4.2. Result Analysis of Four-Objective Optimization Problem

The execution details are presented in table.2.

Table 2. Execution details of four-objective optimization

Failed designs	Infeasible designs	Feasible designs	CPU time	CPU time of one sample
41	1,647	4,312	90h20'40"	5'27"

Here, the Pareto front of this four-objective optimization problem is split into two 3-3 sub-fronts as shown in Fig.7, because it is not possible to display a 4-dimensional picture on paper. All of design points obtained on the Pareto front reveal the tradeoff information between four coupled disciplines.

Fig. 7. Two 3-3 objective Pareto sub-fronts of the four-objective optimization problem

5. Conclusions

In this paper, a 2D hypersonic air-breathing vehicle shape with an idealized scramjet is designed at cruise regime: $Ma=8.0$, $AOA=0$ deg and $H=30$ km. Then a multi-objectives optimization model is established by using Non-dominated Sorting Genetic Algorithm II. In the optimization, the flow around the air-breathing vehicle is simulated by Euler equations and the combustion in the combustor is modelled by well known combination of area-varying pipe flow and heat transfer pipe flow. Lastly, the Pareto front of the optimization problem is obtained and the obtained design points reveal the tradeoffs among different target disciplines involved in this paper.

Finally, it should be pointed out that several additional factors are still needed to conduct a further research in the future. These may include: 1) the real gas effect in the hypersonic engine flow; 2) the chemical dynamics effect in the nozzle⁹; 3) off-design performance of the optimal individuals obtained on Pareto front, etc.

References

1. P.J.Waltrup, F.S.Billig, M.C.Euans. Critical Considerations in the Design of Supersonic Combustion Ramjet (Scramjet) Engines. *Journal of Spacecraft and Rockets*.18(4):350-357(1981).
2. Edward C L W, Small W J, Weidner J P, et al. Studies of Scramjet/Airframe Integration Techniques for Hypersonic Aircraft. *AIAA*.20-25(1975).
3. Ikawa H. Rapid Methodology for Design and Performance Predication of Integrated Supersonic Combustion Ramjet Engine. *AIAA*.7(3):437-444(1991).
4. JAMESON, A Numerical solution of the Euler equations for compressible inviscid fluids, *Numerical Methods for the Euler Equations of Fluid Dynamics*, pp 199-245(1985).
5. C.R.McClinton, D.R.Ronald. Hyper-X Program Status. *AIAA*2001-1910(2001).
6. Charles E.Cockrell, Jr.,Walter C.Engelund, et al. Integrated Aero-Propulsion CFD Methodology for the Hyper-X Flight Experiment. *AIAA*2000-4010(2000).
7. Chen Bing,Xu Xu,Cai Guo Biao.Single- and Multi-objective Optimization of Scramjet Components Using Genetic Algorithms Based on a Parabolized Navier-Stokes Solver. *AIAA*2006-4686(2006).
8. Kalyanmoy Deb, Amrit Pratap, Sameer Agarwal, et al. A Fast and Elist Multi-objective Genetic Algorithm: NSGA-II. *IEEE. Transaction on Evolutionary Computation*, 5(2): 182~197(2002).
9. Lee, S.H., Mitani, T. Reactive Flow in Scramjet External Nozzle. *AIAA*99-0616(1999).