Two Dimensional Hypersonic Body-Intake Multi-Object Optimization with NSGA-II Algorithm

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Abstract. The forebody/inlet shape of the scramjet engine is significant to airplane performance. A multi-object optimization of hypersonic body-intake configuration is reported in the present work. The optimization system consists of geometry parameterization, mesh deformation, aerodynamic performance evaluation via computational fluid dynamics (CFD) and the top level driving optimization algorithm. In the present work, geometry parameterization is accomplished through B-Spline based free form deformation (FFD) method, volume mesh deformation is computed via inverse distance weight (IDW) method. Aerodynamic performance is evaluated with shear stress transportation model closed Reynolds averaged Navier-Stokes equations. At the top level, optimization is driven by the non-dominated sorting genetic algorithm II (NSGA-II) algorithm. Finally, the present optimization system is applied to a two dimensional hypersonic combined forebody-intake configuration. Numerical result shows that optimization gained improvement of 5% thrust, 9% pressure rise ratio and 7% total mass flow rate, which approved the effectiveness of the present optimization methodology.

1. Introduction

The history of human aviation was a history of pursuing “higher and faster” flight. For a long time in future, hypersonic vehicles will be at the forefront of aerospace technology development. Hypersonic vehicles share some inheritance continuity in technology with subsonic/supersonic aircrafts [1], but there are many techniques that limit the development of hypersonic vehicles, such as scramjet technology, heat insulation materials, thermal protection technology, aerodynamic optimization design technology, integrated technology, etc. The aerodynamic optimization design of the supersonic aircraft is a key technology. The traditional design methods can improve the performance of the aircraft, but it relies heavily on the experience of the designer. Computer Aided Optimization (CAO) can improve design efficiency and reduce time consumption of product development cycles. Compared with the traditional method, the CAO method can obtain the optimal value in the whole domain, and often can obtain the effect that the traditional method cannot obtain.

The forebody/inlet of the scramjet engine is expected to provide lift as well as a compressed airflow with a high total pressure recovery factor for the engine which is crucial to enlarge thrust of
the engine. Therefore, the forebody/inlet is a key component of the air-intake super-aircraft. Studying the optimized design of the forebody/inlet can improve the total pressure recovery coefficient of the inlet and improve the lift-to-drag ratio of the forebody. The layout design of the hypersonic vehicle has a higher pursuit of the lift-to-drag ratio. Studying the optimized design of the aerodynamic layout can improve the lift-to-drag ratio of the aircraft. At the same weight, an aircraft with a high lift-to-drag ratio layout can reduce the thrust requirements on the engine. In summary, the aerodynamic optimization design of hypersonic vehicles has great research value.

On integrated design of fuselage/propulsion system, the basic idea of the design of the hypersonic aircraft body/engine integration [2] is: the scramjet engine is placed in the lower abdomen of the high lift-to-drag ratio body. The lower wall of the forebody acts as the outer compression section of the inlet, and the lower wall of the rear body acts as the outer expansion section of the nozzle. The idea of integrated body/engine design stems from a combination of hypersonic flight test and scramjet technology. In the early 1960s, the US Langley Center attempted to use the X-15 as a test platform to verify the hypersonic vehicle configuration using a scramjet engine. In 1964, the X-15 achieved its first flight, when the flight speed record of 6.7 Mach was created. In the mid-1980s, the United States proposed the NSAP program (National Aero-Space Plane). In the more than ten years after the plan was proposed, a variety of aerodynamic/engine-integrated aerospace aircraft solutions have been proposed. In the later Hyper-X program, the X-43A, which is the core of the program, completed two flight tests of Mach numbers 7 and 10 in 2004, enabling the free flight of the aspirating hypersonic vehicle. In 2018, the advanced full-speed engine project of DARPA has completed the low Mach number mode transition test of the dual-mode ramjet engine. A large number of theoretical and experimental studies have been carried out on the foreign body/engine integration design.

Hypersonic body propulsion integration technology research started late in Asia, but also made a lot of meaningful work in the design of the body/propulsion system integration: Luo Shibin[3] established a hypersonic vehicle integrated design framework and integrated multidisciplinary design optimization model based on the overall multidisciplinary design optimization method. Li Xiaoyu [4] carried out research on the optimal design method of two-dimensional forebody/inlet and rear/tail nozzles, and proposed the idea of riding the side edges of hypersonic vehicles. Wu Xianyu [5] developed a progressive optimization method based on the surrogate model, and combined with large-scale direct-connect experiments, optimized the integrated flow path of the scramjet engine. Jin Liang[6] conducted a detailed analysis of the combustion flow field of the combustion chamber, and considered the effects of turbulence models and chemical reactions on combustion. Yi Jun [7] used the US X-43A and X-51 hypersonic vehicles as the research object, numerically simulated the aerodynamic performance of the two types of aircraft. Based on this, the two types of hypersonic vehicles were compared and analyzed. Zhang Hongying [8] conducted a wind tunnel test and numerical simulation study on a suction-type hypersonic integrated configuration of X-43A, and analyzed flow field structure and aerodynamic characteristics of the full channel in different flow Mach numbers, total pressure and angles of attack. Fan Xiaojian [9] designed the hypersonic integrated cold flow ventilation experimental model using the super-combustion ramjet engine as the propulsion system based on the coupling of the body propulsion system and the three-dimensional side pressure inlet. The aerodynamic force test of the aircraft was completed in the hypersonic wind tunnel.

2. Optimization methodology

2.1. Geometry parameterization
The parameterization approach is the basis for aircraft shape optimization design. A good parameterization method can accurately describe the geometric deformation, so that a better optimal configuration can be reached through optimization algorithm. The FFD method [10]-[11] (free form deformation) solves the geometric deformation problem with the idea of deformation of the elastic body under force load, and can smoothly describe the geometric shape of curves, surfaces and three-dimensional geometry with fewer design variables. The FFD method could be applied to the local
shape modification design, and has the characteristics that the flow field mesh is automatically adjusted according to the deformation of the object.

2.2. Mesh deformation
The mesh deformation is computed based on B-spline defined FFD method, which can be apply to general 2-D or 3-D volume mesh by mapping between a control point and a set of mesh nodes. With such a method, the deformed mesh can guarantee the quality of the 3rd-order surface continuous in flow sensitive area and boundary layer mesh.

The basic principle of the mesh deformation algorithm is: If the CFD volume calculation grid is $\tilde{G}_s$, its surface mesh is $\tilde{G}_i$, then $\tilde{G}_i \in \tilde{G}_s$. The surface mesh corresponds to the aerodynamic shape in the optimized design. When the aerodynamic shape changes, $\tilde{G}_i$ changes into $\tilde{G}_i'$, then space grid $\tilde{G}_s$ has to be changed into $\tilde{G}_s'$ respect to surface mesh changing. There is a map from surface mesh $\tilde{G}_i$ to the volume $\tilde{G}_s$:

$$\tilde{G}_s = V(\tilde{G}_i) \quad (1)$$

If only the variation of the displacement of each grid point is considered, the map from the variation of the surface mesh to change of the volume grid could be defined as $W$:

$$\tilde{G}_s' - \tilde{G}_s = W(\tilde{G}_i' - \tilde{G}_i) \quad (2)$$

About the selection of $W$, the inverse distance weight (IDW) interpolation algorithm [12] is a pure algebraic interpolation mesh deformation algorithm. The basic idea is to realize the spatial grid from the translation and rotation of the surface mesh by the function of inverse distance.

2.3. Optimization Algorithm
NSGA-II [13] is one of the most popular multi-objective evolutionary algorithms at present. It reduces the complexity of non-inferior sorting genetic algorithm, has the advantages of fast running speed and good convergence of solution set, and becomes a benchmark algorithm of multi-objective optimization of performance. The NSGA-II algorithm was proposed by Deb [14] on the basis of NSGA in 2000. It is superior to the NSGA algorithm: it uses a fast non-dominated sorting algorithm, which has a much lower computational complexity than NSGA; The comparison operator replaces the shared radius that needs to be specified to extend to the entire Pareto domain and is evenly distributed, maintaining the diversity of the population; introducing an elite strategy, expanding the sampling space, preventing the loss of the best individual, and improved operational speed and robustness of the algorithm.

3. Test Case
3.1. Design of baseline configuration
As shown in Fig 1, the two-dimensional forebody/inlet of the study has a 3-stage external compression surface and a 2-stage internal compression surface. At the same time, it also contains an isolation section.
The theoretical basis for the initial design of the 2D forebody/inlet is the oblique shock relationship [15]-[16]. The design criterion [17] is the shock wave convergence criterion. The shock wave of the outer compression surface meets at the lip F of the outer cover, and the shock wave of the inner compression surface meets at the shoulder point D. The design conditions for a given inlet/forebody are as follows:

- Design state flight angle of attack $a = 2.0^\circ$, height $H = 25$ km, Mach number $Ma = 6.0$;
- The theoretical design of the inlet passage of the unit width captures the flow rate $\dot{m}_0 = 25.0$ kg/s.
- The 3 wedge angles are $\theta_1 = 6.0^\circ$, $\theta_2 = 10.0^\circ$, $\theta_3 = 13.0^\circ$, and the outer casing inclination angle $\theta_{cowl} = 6.0^\circ$
- The expansion angle of the upper wall of the forebody is $\delta = 2.5^\circ$;
- Cover thickness $T_{cowl} = 0.02m$.

The calculation of the oblique shock wave parameters of the compression surfaces of each stage is performed.

3.2. Intake optimization

FFD parameterization is performed on the entire 2D forebody/inlet configuration, Single point multi-objective optimization is performed on the two-dimensional forebody/inlet, where the drag coefficient constraint in the constraint is related to the thrust gain. For every 1% increase in the total pressure recovery coefficient, the thrust is increased by more than 1.3%. So, whenever the increase in resistance per time is not greater than 1.3% of the original state, there is a positive gain and satisfies the constraint.

The NSGA-II algorithm is used for multi-objective optimization. There are fifty samples per generation. After 16 generations, the optimization has converged, as shown in Fig 2. The total pressure recovery coefficient is stable above 0.5, the pressure rise ratio is around 29, and the flow coefficient is stable at around 0.88. The total pressure recovery coefficient, the pressure rise ratio, and the flow coefficient exhibit the same convergence tendency, and their converged values are larger than the initial value. For most points, the total pressure recovery coefficient and the mass flow rate shows a positive correlation, the total pressure recovery coefficient increases, and the flow coefficient increases.
Since this optimization is multi-objective optimization, when selecting the optimal result, comprehensive performance evaluation is needed to define the comprehensive performance $P_i$ as:

$$P_i = \frac{w_1\sigma' + w_2\phi' - w_3C'_d + w_4R'_p}{w_1 + w_2 - w_3 + w_4} \quad (3)$$

Where $w_i (i = 1,2,3,4)$ are weight coefficients and their values are set to $w_1 = 0.3$, $w_2 = 0.2$, $w_3 = 0.35$, $w_4 = 0.15$, $\sigma'$, $\phi'$, $C'_d$ and $R'_p$ are the ratios of the individual variables to the initial values. Select the best of the overall performance in all the points where the performance parameters are improved. Table 1 gives a comparison of the performance parameters of the most advantageous and initial configurations. The most advantageous total pressure recovery factor, pressure rise ratio and flow coefficient are increased. The drag coefficient also increased slightly, but the thrust gain from the total pressure recovery factor was $5.324\%$ greater than the resistance increase of $4.02\%$, so the resistance increase was acceptable.

| Table 1 Performance comparison of the forebody/intake configuration |
|------------------------|------------------------|------------------------|------------------------|------------------------|
| Configure              | Total Pressure recovery | Pressure rise ratio    | Mass flux ratio        | Drag coefficient       |
| Origin                 | 0.49716                | 29.492                 | 0.86204                | 0.098269               |
| Opt                    | 0.51691                | 32.159                 | 0.92539                | 0.10222                |

As we can see in the comparison of the total pressure contour in Fig 3, the total pressure of the optimized configuration at the head of the forebody and the lip of the casing is greater than the total pressure of the initial configuration, which results in a higher air flow energy into the inlet. Comparing Fig. 3 with Fig. 4, the shock wave system of the outer compression surface of the optimized configuration is basically distributed at the lip of the outer cover, and the total pressure loss becomes small. In summary, the total pressure recovery coefficient has increased.

At the same time, since the shock wave system of the outer compression surface of the optimized configuration is distributed to the lip of the outer cover, the fluid after the shock flows into the air inlet, and the outlet flow rate is increased, so the flow flux coefficient is also larger than the initial configuration.
Figure 3. Total pressure contour comparison of the forebody/intake configuration through optimization

Finally, the internal flow field is compared in Fig 4. The optimal internal flow field shock wave is stronger than the initial configuration, causing the shock train to move backwards. The exit of the isolation channel is in the last shock wave, which causes the pressure at the exit to become larger, so the pressure rise ratio will also be increased.

Figure 4. Pressure contour of internal flow field of the hypersonic intake

4. Conclusion
In this paper, based on the FFD parameterization method and the of NSGA-II optimization algorithm, the aerodynamic shape optimization design of the hypersonic two-dimensional precursor/inlet is carried out. The initial configuration of the optimized design is designed according to the theory of oblique shock under the inviscid hypothesis; the setting of the optimal design problem is single-point multi-objective optimization, and the optimization objectives include the maximum total pressure recovery coefficient, the maximum pressure rise ratio and the largest mass flow rate coefficient; The optimization goal is integrated into the objective function through a set of weight coefficients and passed to the optimization algorithm. The optimization results show that under the condition of 4.02% drag increase, the total pressure recovery coefficient, pressure rise ratio and mass flow rate coefficient of the optimized configuration are improved, and the estimated thrust gain is 5.324%, which is greater than the resistance increment, indicating that the result obtained by the entire optimization system is successful.

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