Optimum design of the inlet port profile of a ramjet extended range projectile

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Abstract. The air-inlet is one of the important components of the stamped extended range engine. Its performance directly affects the thrust of the ramjet engine, which in turn affects the range of the projectile. Because the stamped extended range projectile has the characteristics of simple structure, light weight and small volume, the inlet profile of the stamped extended range projectile is generally unadjustable, and the air-inlet surface quality directly determines the performance of the air-inlet. And the resistance characteristics of the shells. Since the air-inlet is associated with the curved portion of the projectile, the curved portion is one of the main sources of resistance to the projectile, so it is necessary to optimize the design of the air-inlet profile. Firstly, based on the CFD flow field simulation, the optimal design method of the air-inlet profile is studied. The parametric modeling, flow field simulation and optimization strategy of the air-inlet are integrated on the platform to realize automatic optimization. The optimization of the nozzle is optimized by this optimized design method, which proves its feasibility. Then, the single-objective optimization and multi-objective optimization of the air-inlet profile are carried out, and the geometric model is established to more accurately describe the flow field characteristics and obtain a more accurate air-inlet profile. Finally, a supersonic wind tunnel test was carried out on the optimized air-inlet, and the wall static pressure and the total outlet pressure of the windward side and the leeward side were measured and compared with the simulated Mach number of 2.5 and 2.0. Comparative Results. The two are basically the same, indicating that the numerical simulation results can basically reflect the pressure change and the change of the total pressure in the air-inlet. Therefore, the reliability of simulation-based optimization results is high.

1. Introduction

With the long-range development of projectiles and arrows, the traditional range extension technology such as bottom concave and bottom row has gradually failed to meet the range requirements. Therefore, the use of stamping engines to achieve the range extension of shells has been increasingly studied and applied. The air inlet is one of the important components of the ram extended range engine. It’s performance directly affects the thrust of the ram engine and then affects the range of the shell. Because the ram range extended shell has a simple structure, light weight and small size, The inlet
profile of the extended range shell is generally not adjustable, so the quality of the inlet profile directly determines the performance of the inlet and the resistance characteristics of the shell. Because the inlet is associated with the arc of the shell, the arc shape is one of the main sources of shell resistance, so it is necessary to optimize the inlet profile.

Whether it is an aircraft inlet or a missile inlet can be roughly divided into two types: external inlet and integrated inlet. Traditional air inlets are externally mounted, and with the development of science and technology, the application of integrated air inlets on fighter aircraft has become more mature. Similarly, integrated air inlets are also suitable for shells powered by ram engines. At present, the main reasons that cause the intake port to not start are: one of the contraction ratio of the intake port is too large, and the throat area is too small, which will cause the intake port to be blocked; the other is that the required flow of the engine is reduced Small, causing the inlet back pressure at the outlet is too high, exceeding the capacity of the inlet itself, which is related to the matching of the inlet and the combustion chamber. When the pressure released by the combustion chamber exceeds the maximum anti-backpressure capability of the isolation section, the shock wave string will be pushed to the exit of the isolation section and even pushed out of the intake port, which will cause the engine to fail to start [1].

So far, domestic and foreign scholars have proposed many methods for the optimization of supersonic inlets. In foreign countries, Rodriguez used a simplex algorithm to optimize the intake port, and obtained the optimal optimization scheme among a variety of geometric constraints and optimization variables [2]. Za et al. Proposed a genetic algorithm to optimize the intake port, and under various optimization variables and geometric constraints, the optimal TPR intake port was obtained [3]. In China, Xiong et al. Used axisymmetric basic flow field to study, and finally came up with a parametric method to greatly improve the performance of hypersonic inversion inlets [4]. Wang et al. Proposed a multi-stage optimization method using the CFD method to optimize the hypersonic inversion inlet [5-7]. This method utilizes streamline tracking technology to optimize the inlet in a basic flow field. From these studies, it can be seen that the optimization design method may be a potential way to improve the performance of the inlet.

This paper uses the optimization design method of the inlet profile based on the CFD flow field simulation [8]. First, the inlet model is parametrically modeled, and the second is based on the CFD flow field simulation. Finally, analysis and verification with wind tunnel experiment results prove its feasibility.

2. Experimental / theoretical research
The subsonic expansion section has a small effect on the total pressure recovery coefficient of the inlet, but has a greater effect on the stability of the flow in the inlet and the distortion of the outlet flow field. In the design of the subsonic diffusive pressure section, the expansion law of the section, the calculation of the length of the expansion section and the loss situation should be considered in general.

There are four types of classic subsonic expansion rules:
   - Constant expansion angle: \( \frac{d \theta c q}{dx} = c \).
   - Equal area expansion: \( \frac{d A}{dx} = c \).
   - Isobaric pressure gradient: \( \frac{dp}{dx} = c \).
Constant Mach gradient expansion: \( \frac{dMa}{dx} = c \).
Among them, \( c \) is a constant, and \( x \) is the distance of the inlet axis.
There is no fixed and unified form for the subsonic diffused surface equations, but they must all meet certain expansion laws. In addition, the profile of the subsonic expansion section is greatly affected by the profile of the cover and the profile of the inlet outlet, so it is very difficult to express it with a unified profile equation.
Here is one of these equations.
Geometrical configuration of the subsurface of the subsonic expansion section:
The non-uniform rational B-spline curve is used to design the expansion section of the inlet. A \( k \)-order NURBS curve can be expressed as a piecewise rational polynomial vector function:

\[
p(u) = \frac{\sum_{i=0}^{n} \omega_i d_i N_{i,k} (u)}{\sum_{i=0}^{n} \omega_i N_{i,k} (u)}
\]  

(1)
In the above formula, \( \omega_i \) (\( i = 0,1,2, ..., n \)) is called weight or weight factor, which is respectively associated with the control vertex \( d_i \) (\( i = 0,1,2, ..., n \)). The first and last weighting factors \( \omega_0, \omega_n > 0 \), the rest \( \omega_i \geq 0 \), and the order \( k \) weighting factors are not 0 at the same time, in order to prevent the denominator from being 0, retaining the convex hull property, and the curve not being degraded to a point by the weighting factor.
In actual design, some points on the curve are roughly given, and the control vertices of the B-spline curve are calculated inversely as the initial control vertices of the curve design. In order for a \( k \)-degree spline curve to pass through a set of data points \( q_i \) (\( i = 0,1, ..., n \)), the inverse calculation process generally makes the first and last points of the curve consistent with the first and last data points, respectively, so that The segment connection points in turn correspond to the nodes in the B-spline curve definition domain, that is the \( q_i \) point has the node \( u_k + 1 \) (\( i = 0,1, ..., n \)). The B-spline curve defines \( n \) control vertices \( d_i \) and a node vector \( U = [u_0, u_1, ..., u_n + k = 1] \).
According to the characteristics of the inlet pressure expansion, the equivalent expansion angle in the subsonic pressure expansion section is generally between 3 ° ~ 8 °. According to the Mach number of the forward shock wave, an appropriate micro expansion section is selected, and the general micro expansion section is equivalently expanded. The angle does not exceed 1 °. When designing the subsonic expansion section, a series of data points are selected according to the expansion law, and then the rational B-spline curve is calculated. The design profile of the subsonic expansion section is shown in figure 1.

![Figure 1. Profile of the subsonic expansion section of the inlet.](image-url)
3. Results and discussion

3.1. Optimization of inlet profile based on CFD flow field simulation

3.1.1. Single-objective optimization of inlet profile. Figure 2 shows the model of the inlet optimization model. The curve ACD in the inlet profile is determined. According to the design method of the inlet expansion section profile, the AC expansion section of the inlet is subject to certain constraints. Take 10 data points: q1~q10, and use NURBS (non-uniform rational B-spline) curve to connect these data points in order to construct the curve EF. In order to conveniently express the coordinates of these data points, a cylindrical coordinate system with O as the center of the circle and OA as the x-axis is selected. The coordinates of any data point qi are (ri, θi), i = 1, 2, ..., 10. The data points of the CD expansion section of the intake duct are based on O as the origin, and the horizontal and plumb lines are the x-axis and y-axis coordinate systems, and data points q11 ~ q50 are taken within certain constraints. These data points are evenly distributed in the x-axis direction, and the data points are connected in sequence using the NURBS curve to construct the curve FG.

![Figure 2](image)

According to the analysis results, adjust the design parameters of the subsonic diffuser section of the inlet: 10 data points are still retained in the arc EF section, q1, q2, ..., q10, and 15 data points are selected in the arc FG section. q11, q12, ..., q25. The numerical simulation of the flow field was used to optimize the design parameters θ1, θ2, q1, q2, ..., q25 of the inlet profile with the maximum recovery coefficient of the inlet outlet pressure as the optimization objective function. Taking the maximum recovery coefficient of the inlet pressure as the optimization objective function, the combined optimization strategy was used to design the two half cone angles θ1 and θ2 of the double cone inlet with a Mach number of 2.5 and 25 data points in the subsonic pressure expansion section. Optimized design, the optimized historical curve is shown in figure 3, and the optimization results of each stage are shown in table 1. Due to the large number of data points in the subsonic diffusion section, it is inconvenient to list their values as figure 4.
Figure 3. Optimization history curve.

Figure 4. Comparison of profiles before and after optimization.

The design parameters of the optimization history curve are 27 in figure 5. It can be seen that the SA global optimization algorithm has a strong global optimization ability and can find the approximate range of the global optimal value in a short time. However, the number of optimization steps in sequential quadratic programming has increased significantly, because each gradient of the sequential quadratic programming algorithm needs to adjust 27 design parameters. Therefore, each adjustment takes about 27 steps, so optimization seems more laborious. It can be seen that it is necessary to reduce the number of design parameters through the DOE algorithm. Figure 6 is a comparison of the optimized profiles before and after optimization, where ini is the optimized profile and opt is the optimized profile. It can be seen from table 1 that the value of the objective function has been greatly improved in each optimization stage. A detailed comparison between the SA optimization results and the SQP optimization results. The cone angle combinations of the two are similar, but because the subsonic expansion section has different profiles, there is a certain gap in the total pressure recovery coefficient. Large impact, carefully designed subsonic expansion section can reduce the total pressure loss, the same cone angle combination of different subsonic expansion section profiles, the total pressure recovery coefficient is greatly different. Therefore, it is necessary to optimize the subsonic diffusion section.
Table 1. Optimization results of each stage.

| Parameter                      | θ₁ (°) | θ₂ (°) | rᵢ      | yⱼ      | σ          |
|--------------------------------|--------|--------|---------|---------|------------|
| Upper limit                    | 0      | 0      | 0.9 rc  | y_c     | —          |
| Lower limit                    | 30     | 28     | 1.1 rc  | y_g     | —          |
| The initial value              | 18.5   | 24     | —       | —       | 75.83%     |
| Orthogonal test results        | 21     | 12     | —       | —       | 81.09%     |
| S4P optimization results       | 22.06  | 15.06  | —       | —       | 83.48%     |
| S4P-optimization results       | 22.36  | 15.38  | —       | —       | 84.42%     |

Figure 5 is the contour map of the flow field before and after the optimization. The results of the orthogonal test before the optimization are shown. However, due to the increase of the turning angle of the airflow, the wave angle of the leading edge of the inlet shell increases, and the resistance increases; after optimization, the shock wave string of the expansion section of the inlet is elongated, and the flow field is more uniform. It can be seen from figure 6 that before the optimization, there is a small range of recirculation area near the center cone at the outlet of the intake port. Through the optimization of the profile, the recirculation area disappears and the flow field distortion is relatively reduced.

(a) Pressure contour map
(b) Pressure contour map

(a) Mach contour map
(b) Mach contour map

(a) Density contour plot
(b) Density contour plot

Figure 5. Contour plots of the flow field before and after optimization.
Figure 6. Comparison chart of inlet outlet speed vector.

Figure 7 to figure 9 show the static pressure distribution on each surface of the intake duct before and after optimization. Figure 8 and figure 9 show that the static pressure distribution of the inner wall surface and the central cone surface of the intake duct before and after optimization are basically the same. Therefore, the static pressure rise of the cone surface is larger than that before the optimization. After the positive shock wave, the pressure suddenly rises, and the pressure curve after the wave does not rise uniformly. A large fluctuation occurs near the throat of the inlet because the incoming flow passes through the shock. The wave is compressed, the direction is turned, and there is a certain angle between the inner wall surface of the air inlet cover and the tapered shoulder of the center cone, so the pressure expansion is uneven, and the static pressure rise of the air inlet outlet is slightly reduced and the fluctuation is slightly reduced after optimization. Small, indicating that flow loss can be reduced through profile optimization. Figure 7 is the static pressure curve of the inlet shell. Due to the increase of the total turning angle of the airflow after optimization, the shock intensity increases, and the pressure after the wave is greater. After the airflow passes through the convex expansion wave, the pressure is reduced. The convex angles of the waves are different, but the pressure is basically the same. It can be seen that the size of the resistance of the inlet shell is the wave resistance of the shock of the inlet shell, that is, the turning angle and the projected area of the front edge of the inlet shell. Figure 8 shows the distribution curve of the total pressure before and after the optimization of the inlet of the inlet. Due to the viscosity of the fluid, the velocity near the wall is almost 0, so the total pressure curve shows a trend of high in the middle and low in both sides, and the total pressure curve after optimization is completely before optimization. Above, it shows that the total pressure recovery coefficient can be effectively improved through optimization.
In addition, a three-dimensional model of the inlet is also established in this section. The three-dimensional flow field simulation of the inlet before and after optimization is performed at 0°, 2°, 4°, 6°, and 8° performance. Figure 11 is the curve of the total pressure recovery coefficient of the inlet with the angle of attack. The total pressure recovery coefficient of the three-dimensional simulation is slightly lower than the two-dimensional simulation result. It can be seen from the figure that the recovery coefficient of the total inlet pressure decreases with the increase of the angle of attack, and the larger the angle of attack, the faster the decrease. This is due to the asymmetry of the inlet flow field caused by the angle of attack. The increase of the positive shock wave on the leeward side is gradually pushed out of the throat, and the uniformity of the flow field after the wave becomes worse, while the forward shock wave on the windward side has multiple reflected shock waves, and the total pressure loss increases. Figure 12 is the change curve of the inlet resistance coefficient with the angle of attack. As the angle of attack increases, the intensity of the shock on the windward side increases and the leeward side decreases slightly. When the angle of attack increases from 0° to 4°, the intake air The resistance of the shell of the duct is slightly reduced, indicating that the average intensity of the shock wave system is slightly reduced. As the angle of attack further increases, the resistance of the intake duct shell gradually increases. At this time, the positive shock wave on the leeward side has been pushed out of the lip. Port, and the shock wave of the inlet shell interferes with each other, the
shock intensity increases, so the wave resistance increases faster. In summary, the recovery coefficient of the total pressure of the tapered inlet decreases with the increase of the angle of attack, and the angle of attack within $6^\circ$ has little effect on the resistance of the inlet shell.

![Figure 11. Total pressure recovery factor-angle of attack.](image1)

![Figure 12. Resistance coefficient-angle of attack.](image2)

3.1.2. Multi-objective optimization of inlet profile. Aiming at the maximum recovery coefficient of the total inlet pressure and the minimum resistance coefficient of the inlet shell, the genetic algorithm was used to perform multi-objective optimization of the double cone inlet with a design Mach number of 2.5. The optimization results are shown in figure 13 to figure 15. Figure 13 is the change curve of the total inlet pressure recovery coefficient $\sigma$ and the inlet shell resistance coefficient $C_d$ with the number of optimizations. It can be seen that the genetic algorithm can globally explore each optimization objective function to avoid falling into the local optimum. Figure 14 is the curve of the two half cone angles $\theta_1$ and $\theta_2$ with the number of optimizations. It can be seen that for multi-objective optimization, it is difficult to give an optimal advantage in the end, but through optimization, an optimal design curve can be obtained, and the points on this curve satisfy the total pressure recovery under the same inlet casing shell resistance coefficient. The highest coefficient is shown in figure 15. In the full range of stamping extended range projectiles, the engine operating time only accounts for about a quarter of the total flight time, and the flight range of the projectiles is affected by resistance. Therefore, various factors should be comprehensively evaluated to select appropriate design parameters.

![Figure 13. History curve of objective function optimization.](image3)

![Figure 14. History curve of design parameter optimization.](image4)
Figure 15. Optimal objective function curve.

In figure 15, a set of profile parameters with a total pressure recovery coefficient of 75.8% and a drag coefficient of 0.052 was selected to design the air inlet. The two half cone angles of the air inlet were 20.09° and 8.13° respectively. The numerical simulation of the flow field under the conditions of the incoming flow Mach number of 2.5 and the angle of attack of 0°, 2°, 4°, 6°, and 8° is compared with the single-objective optimization results in figure 14 to figure 16.

(a) Pressure contour map

(b) Mach contour map

(c) Density contour plot

Figure 16. Optimized pressure contour map.
The three dimensional inlet simulation total pressure recovery coefficient is 74.7\%, which is slightly lower than the two-dimensional simulation results. As can be seen from figure 17 and figure 18, although the multi-objective optimization results have reduced the total pressure recovery coefficient by approximately 0.1, the drag coefficient has decreased by 0.025. Reducing the resistance of the projectile effectively increased the range.

3.2. Experimental verification of wind tunnel in supersonic inlet

3.2.1. Analysis of wind tunnel test results. Figure 19 and figure 20 show the relationship between the recovery coefficient of the total pressure of the nozzle and the angle of attack at different incoming Mach numbers, with different throttle characteristics. At the same time, the experimental and simulation errors are also plotted in the figure. It can be seen from the figure that the error of the total pressure recovery coefficient $\sigma$ measured by simulation and experiment is about 5\%. Figure 19 (a) is the curve of the total pressure recovery coefficient with the angle of attack when the No. 1 throttle nozzle is used when the incoming Mach number is 2.5. In the figure, the solid triangle is the experimental value, the solid rectangle is the simulation value, and the hollow rectangle is The error between the two. In addition, the schematic diagram of the wave model of the test model is also drawn. The numbers 1, 2, ... 8 are the positions of the static pressure sensors. It can be seen that when the No. 1 throttle nozzle is used, the positive shock wave of the air inlet is located at the throat, which is in front of the No. 1 static pressure sensor, indicating that the air inlet is in a critical working state at this time. It can be seen from the figure that the total pressure recovery coefficient decreases as the angle of attack increases, and the larger the angle of attack, the faster the rate of decrease. This is because as the angle of attack increases, the shock from the leeward side is pushed out of the throat of the intake duct to form Overflow, the inlet mass flow is reduced, so the total pressure recovery coefficient is reduced. It can be seen that the performance of the range extender can guarantee the performance of the intake port within the range of small angle of attack, and the performance of the intake port deteriorates sharply when the angle of attack increases, and the angle of attack should generally be
kept within 6°. The error between the test value and the simulation value of the total pressure recovery coefficient is about 5%, and it decreases with the increase of the angle of attack. This is the test that the pressure tube is parallel to the inlet axis, and the angle of attack measured by the test is The change is achieved by changing the angle of the support rod (that is, the rod connected to the center cone tail in the intake duct in the figure), so when the angle of attack exists, the total pressure tube and the incoming flow have a certain angle, and the measured total pressure On the low side.

As the throat diameter of the throttling nozzle further increases, the total pressure recovery coefficient changes in a wave shape with the increase of the angle of attack, that is, first decreases and then increases. Figure 21 is a vector diagram of the speed of the throttle nozzle inlet at different angles of attack when the No. 5 throttle nozzle is used. The upper half of the figure is the leeward side and the lower half is the windward side. Due to the increase of the wavefront Mach number in the throat of the inlet, the shock loss is large, and a return flow is formed near the throttle nozzle inlet. The angle of attack affects the position of the return area, and the total pressure recovery coefficient also fluctuates.
Figure 19. Total pressure recovery system under different throttle nozzles when $Ma_H = 2.5$.

Figure 20. Relationship between the total pressure recovery coefficient under different throttle nozzles and the angle of attack when $Ma_H = 2.0$. 
Figure 21.  Vector diagram of nozzle inlet velocity at different angles of attack of $Ma_t = 2.5$.

Figure 22 is the throttle characteristic curve of the experimental inlet at $0^\circ$, $2^\circ$, $4^\circ$, $6^\circ$, and $8^\circ$ attack angles. It can be seen that at $0^\circ$ attack angle, the two shock waves of the inlet are sealed to the lips, and the end The shock wave is located between the throat and the outlet of the air inlet. At this time, the throttle curve is a smooth curve, and there are no sudden points, indicating that the air inlet can work stably during this throttle interval. Increased, the positive shock wave was pushed out of the throat of the inlet, part of the incoming flow overflowed at the inlet of the inlet, the flow coefficient decreased sharply, and the throttle curve appeared a sudden change. At this time, the working stability of the inlet was affected to some extent However, except for the throttle characteristic points of the No. 1 throttle nozzle, the other throttle section curves are still smooth, indicating that as long as the back pressure is appropriate, the intake port can still work stably in the presence of the angle of attack. Therefore, when designing the afterburner, a proper back pressure should be provided to the intake port to avoid sudden changes in its throttle characteristic curve.

In order to obtain the speed characteristic curve of the inlet, the experimental inlet model was simulated under different inflow Mach numbers at $0^\circ$ attack angle. The results are shown in figure 23. The simulation results of $Ma = 2.0$ and $Ma = 2.5$ are basically consistent with the experimental results. It can be seen that the speed characteristic curve is basically smooth, which indicates that the inlet can still work stably when the inlet is $Ma < Ma_d$. 
4. Conclusion
In this paper, single-objective optimization of the intake port of a ramjet engine is performed. Based on this, the objective is to optimize the 27 design parameters of the intake port with the minimum resistance of the casing of the intake port and the maximum recovery coefficient of the total pressure of the intake port. The optimal design curve is obtained. Concluded as follow:

(1) Based on the single-objective optimization of the intake port, using the combination optimization strategy to optimize the design parameters of the intake port profile, the total pressure recovery coefficient is $11.33\%$ higher than the initial result and $3\%$ higher than the orthogonal test. Compared with the single-objective optimization result, although the multi-objective optimization result reduces the total pressure recovery coefficient by about $0.1$, the drag coefficient decreases by $0.025$. The optimized intake port can sacrifice a smaller total pressure recovery coefficient. Greatly reduce the resistance of the shell and effectively increase the range;

(2) The flow field of the subsonic diffuser section of the inlet is complicated. The interference between the surface layer and the forward shock causes the complex post-wave flow field and the outlet distortion is serious. It also makes the geometric and pneumatic throats of the inlet Not coincident, so accurate flow fields must be obtained through simulation;

(3) Single-objective optimization of the inlet based on simulation can obtain the inlet profile with the highest total pressure recovery coefficient under the same design Mach number and wave system combination; multi-objective optimization of the inlet based on simulation can obtain the optimal design Curve. On this curve, the resistance coefficient of the intake port is the smallest under the same total pressure recovery coefficient. The combination optimization strategy can improve the optimization efficiency. The parameter sensitivity analysis can reduce the optimization design parameters and shorten the optimization time.

Acknowledgement
This work was supported by the Jiangsu Basic Research Project (Natural Science Fund; number BK20180982).
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