Aerodynamic Design and Numerical Simulation of Over-Under Turbine-Based Combined-Cycle (TBCC) Inlet Mode Transition

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Abstract

A parameterized design method is established for mode transition of over-under TBCC inlet and the design variables are optimized by Multi-Island Gene Algorithm using auto-CFD solution. Dynamic overset grid technology is utilized to control and simulate the coupled rotation of both the flow splitter and ramjet cowl of TBCC inlet. Mach number effects, time effects and rotating patterns of the splitter during TBCC mode transition are studied systematically by unsteady simulation in contrast to quasi-steady numerical result, and which shows that all these factors have great influence on the dual-flowpath inlet throat performance as well as the aerodynamic characteristics with similar hysteresis effects.

Keywords: TBCC inlet; Mode transition; Aerodynamic design; Unsteady numerical simulation; Overset grids

1. Introduction

As the most important and indispensable operating part of Turbine-Based Combined-Cycle (TBCC) engine, mode transition process between turbofan engine and ramjet/scramjet engine not only determine whether the thrust of TBCC engine can transit stably and effectively, but also have great influence on the external flowfiled of vehicle. Since inlet is a crucial component of propulsion system and TBCC mode transition will also start form inlet
primarily, the aerodynamic design and performance investigation of TBCC inlet mode transition have great value for both TBCC engine and high Mach number cruise vehicle development. But there is rare research work related to TBCC inlet mode transition in open literatures\cite{1-4} that no systematical methods of design and optimization have been established, and the adopted numerical simulation technique is also only limited to quasi-steady method which presents a striking contrast to the actual condition that both the high-speed cowl with a rotating lip, and the rotating low-speed cowl that serves as a splitter to divide the flow between the low-speed duct (turbojet inlet) and the high-speed duct (ramjet/scramjet inlet), have rather fiercely unsteady aerodynamic characteristics.

In the present paper, an over-under TBCC inlet for hypersonic Vehicle with cruise Mach number 5.0 and transition Mach number 2.5 has been investigated. Firstly, a type of parameterized method with mix-compression inlet and large setover diffuser is established to design both high- and low-speed ducts. Then, all the design variables of both high- and low-speed inlets are optimized respectively by Multi-Island Gene Algorithm using auto-CFD solution with optimizing targets such as maximum total pressure recovery, minimum length and drag and so forth. Finally, the unsteady numerical simulation method with dynamic overset grids technology is adopted to control the coupled rotation of both splitter and ramjet cowl, and the typical problems such as Mach number effects, time effects and rotating patterns of splitter during TBCC mode transition of two dimensional (2D) model are studied systematically in contrast to steady method. The numerical result shows the discrepancies between unsteady and steady cases are obvious, and the selection of transiting Mach number, duration and manner of splitter rotating all have great influence on TBCC mode transition with complicated hysteresis effects.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Nomenclature} & \\
\hline
$\Phi$ & flow capture coefficient \\
$\sigma$ & throat total pressure recovery coefficient \\
$\Pi$ & throat static pressure ratio \\
$\Theta$ & throat total pressure distortion \\
$Cl$ & lift coefficient of TBCC dual-flowpath inlet \\
$Cd$ & drag coefficient of TBCC dual-flowpath inlet \\
$Cm$ & pitch moment coefficient of TBCC dual-flowpath inlet \\
\hline
\end{tabular}
\caption{Nomenclature}
\end{table}

2. TBCC Inlet Mode Transition Aerodynamic Design

For the TBCC dual-flowpath inlet design, a high-speed flowpath with good aerodynamic performance should be designed by considering the vehicle cruise states firstly. And then, under the profile constraint of this obtained high speed intake system, the low-speed flowpath can be designed to integrate with the external surface of high-speed flowpath both geometrically and aerodynamically. Considering the compression effects of vehicle forebody, high speed-inlet design point is selected to decline at Mach number 4.0 and that of the low-speed inlet is at around Mach number 2.25 to compare with the transition Mach number 2.5 of vehicle flight.

2.1. High/Low-Speed Inlets

In the present work, high-speed inlet is matched to ramjet, and the mix-compression inlet design method is adopted with two external compression shocks that the related two wedge angles can be obtained by Oswatisch shock theory with equal shock strength, or optimized directly with the internal compression parameters under the consideration of total length limitation and so on. For the internal compression surface, cubic curve is used with parameterized control and also the cubic coefficients need to be confirmed with optimization method. Besides, the throat height is estimated by one dimensional flow theory with the internal compression parameters and then be enlarged by 5% to correct the boundary layer effects. The diffuser design is mainly refereed to X-43A and the capture height of ramjet inlet at design point is defined as 1000 mm in this work.

Low-speed inlet also adopts mix-compression inlet design method by using the same first wedge angle of the high-speed inlet as the only one external compression shocks, which means that the start point of second...
compression wedge is the start position of internal compression surface. Besides, the design method of internal compression surface is as same as that in high-speed inlet design. The lip position of turbo inlet, which is also the position of splitter after rotating by designed angle, will be used to design the lip profile from this point. The throat height of low-speed inlet can be obtained by the same method as high-speed inlet just with the different internal compression ratio (ICR) which can be estimated under the defined pressure ratio after cowl shock.

2.2. TBCC Inlet and Mode Transition Scheme

For the TBCC inlet mode transition design, the exact position of splitter hinge is ascertained on the ramjet internal compression surface after combining the geometry scale limitation and mechanical design problems. And then, the splitter surface is created with the wall compression surface of ramjet inlet and the lip-sided compression surface of turbojet inlet. Finally, aerodynamic design of TBCC mode transition can be completed by modifying partial geometry profiles with the rotating effects of both splitter and ramjet cowl during mode transition. The dual-flowpath design scheme of TBCC mode transition is presented in Figure 1.

3. Design Parameters Optimization

The design parameter selection of TBCC inlet is rather difficult not only because of its large amount of variables, but also with the complicated viscous effect in the internal flowfiled. Furthermore, we should also make compromise to finalize the parameters which are strongly coupled with each other, thus optimization is necessary.

3.1. Optimization Method

The traditional optimization method of inlet is mainly based on the inlet performance with shock theory and inviscid solution[5], and then the boundary layer correction is added to obtain the ultimate inlet profile. But actually, this method is rather limited as the real inlet flowfield is extremely complicated which may contain shock/shock and shock/boundary layer interactions and so on. Therefore, with the much higher requirement on both the efficiency and accuracy of inlet parameter optimization than before, the method based on auto-CFD viscous solution is expected under the balance of the above requirement, although it will spend much more computational time and resource to solve the real viscous flowfiled directly. Besides, Multi-Island Gene Algorithm (MIGA) is adopted for its good efficiency and robustness. The optimal process is illustrated in Figure 2.
Optimization variables and objectives are as follow.

Ramjet Inlet Optimization Variables:
1) Cowl compression angle, delta4, range: 6°~10°;
2) Internal compression length coefficient, L1coeff, range: 0.7~0.95;
3) Cowl heighten coefficient, Coeffh1cowl, range: 0.05~0.3.

Turbo Inlet Optimization Variables:
4) Splitter compression angle, delta2turbo, range: 6°~10°;
5) Splitter hinge position control coefficient, PointZcoeff, range: 0.5~0.95;
6) Initial constraint Z value of splitter base point at the other side, ROZ, range: 200~300.

Optimization Objectives:
1) Throat total pressure recovery coefficient (σ), as maximum as possible;
2) Throat static pressure ratio (Π), as maximum as possible;
3) Throat flow distortion (Θ), as minimum as possible;
4) Total inlet drag coefficient (Cd), as minimum as possible;

3.2. Optimized Result

The parameters of MIGA is specified as initial sub-population size 100 with number of islands 10, cross factor 0.99, mutation rate 0.05, and then reproduces 30 generations. For the strong interactive relationships among the optimization objectives, the excellent sub-individual generations are compared and compromised to get final generation based on which kind of performance is more required. The selected parameters of the optimized subgroup results in this work are illustrated in table 1, and the related performance results are in section 4.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coeffh1cowl</th>
<th>Delta4</th>
<th>L1coeff</th>
<th>Delta2turbo</th>
<th>PointZcoeff</th>
<th>ROZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized Result</td>
<td>0.239311</td>
<td>6.010559</td>
<td>0.950635</td>
<td>4.068666</td>
<td>0.928879</td>
<td>117.4113</td>
</tr>
</tbody>
</table>

4. Numerical Simulation

In present work, the investigation is only focused on simulating the transition mode from Turbojet to Ramjet in climbing. In order to combine with actual flight state, the equal dynamic pressure trajectory is adopted that the ramjet inlet design point is specified as local Mach number 4.0 at altitude 24km (dynamic pressure 33097.9 Pa).
4.1. CFD Method and Simulation Cases

Unsteady calculations with overset grids technique are performed to study the coupled effects of the rotating of the splitter and the ramjet cowl. The rotating manner, computational domain and meshes are showed in Figure. 3. Numerical solution is performed by using Reynolds-Averaged N-S equations solver on structured meshes with total point number approximately 0.1 million nodes, and the first layer height of grid near the wall satisfies the requirement of turbulence model (K-W SST). Viscosity is computed by Sutherland equation and also the $C_p$ is defined by variable specific heat. Besides, The Roe flux difference scheme is employed for the inviscid fluxes, while a standard central scheme is employed for the viscous fluxes and both schemes are second-order[6].

Eight cases summarized in table 2 have been simulated to investigate the aerodynamic characteristics of TBCC inlet during mode transition with different transition Mach numbers, rotating patterns and rotating durations of splitter. The simulation of Case 0 is used to obtain the steady numerical result under different fixed rotating position of splitter that can be compared with the following unsteady results. Cases 1 to Case 3 are mainly about the time effects investigation with different splitter rotating duration from 1second(s) to 4s, while Cases 4 and Case 5 focus on the different transition Mach numbers. Similarly, the splitter rotating patterns with three types of velocity function such as Sine (from acceleration to deceleration), Linear (equal speed) and Cosine (from deceleration to acceleration) which can represent three typical control methods of splitter movement approximately, are studied in both Cases 4 and Case 5, while the rotating pattern of ramjet cowl is fixed to Sine in all the eight cases and the rotating angels of splitter ($\delta_s$) and cowl ($\delta_c$) are respectively $9^\circ$ to close turbo flowpath incompletely for boundary layer control and $5.2^\circ$ to move the cowl to ramjet design position. The relative time when splitter closes is defined as symbol “T” in the table and it can be found that the movement of splitter and ramjet cowl are coupled during the first 0.5s of cowl rotating. Besides, it needs to illuminate that the diffuser backpressure and leading edge bluntness of inlet cowl and splitter are not considered for the moment in this work.

Table 2. Simulation cases of TBCC inlet mode transition.

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Splitter Rotating Time Range (s)</th>
<th>Ramjet Cowl Rotating Time Range (s)</th>
<th>Transition Mach Number</th>
<th>Splitter Rotating Velocity Pattern (function)</th>
<th>Numerical Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 0</td>
<td></td>
<td></td>
<td>2.25</td>
<td>-</td>
<td>Steady</td>
</tr>
<tr>
<td>Case 1</td>
<td>$0 \sim 2.0 (0 \sim T)$</td>
<td>$1.5 \sim 2.5 (0.75T \sim 1.25T)$</td>
<td>2.25</td>
<td>Sine</td>
<td>Unsteady</td>
</tr>
<tr>
<td>Case 2</td>
<td>$0 \sim 1.0 (0 \sim T)$</td>
<td>$0.5 \sim 1.5 (0.5T \sim 1.5T)$</td>
<td>2.0</td>
<td>Sine</td>
<td>Unsteady</td>
</tr>
<tr>
<td>Case 3</td>
<td>$0 \sim 4.0 (0 \sim T)$</td>
<td>$3.5 \sim 4.5 (0.875T \sim 1.125T)$</td>
<td>2.25</td>
<td>Linear</td>
<td>Unsteady</td>
</tr>
<tr>
<td>Case 4</td>
<td>$0 \sim 2.0 (0 \sim T)$</td>
<td>$1.5 \sim 2.5 (0.75T \sim 1.25T)$</td>
<td>2.0</td>
<td>Cosine</td>
<td>Unsteady</td>
</tr>
<tr>
<td>Case 6</td>
<td>$0 \sim 2.0 (0 \sim T)$</td>
<td>$1.5 \sim 2.5 (0.75T \sim 1.25T)$</td>
<td>2.25</td>
<td>Cosine</td>
<td>Unsteady</td>
</tr>
</tbody>
</table>

4.2. Analysis of CFD Result

Figure. 4 shows some screenshots of Mach number isoline during mode transition process in Case 5. With the coupled rotation of splitter and ramjet cowl, the structures of oblique shocks and expansion waves are varied dramatically that the compression strength of low-speed flowpath becomes weaker and then the flow expands to...
very large Mach number with extreme low static pressure which can be used for boundary layer bleeding and so on. The high-speed inlet still starts\cite{7,8} in time T with splitter rotating 9° to nearly close the low speed flowpath and also with 2.6° rotation of ramjet cowl (Figure. 4(e)), in contrast to the unstarted state in time 1.125T with 5.2° rotation of ramjet cowl (Figure. 4(f)), and which indicates the TBCC inlet can work in a wide range by a suitable control of the coupled rotation of splitter and ramjet cowl.

![Fig. 4. Typical flowfiled structures of TBCC inlet during mode transition process (Case 5).](image)

The CFD results reveal the obvious discrepancies between the steady and unsteady method, and also show the different hysteresis characteristics existed in the unsteady calculations. Flowfield structure comparisons of different cases but with same rotation angles of both splitter and ramjet cowl (δₛ=9.0°, δₑ=2.6°) are shown in figure 5 (including figure 4e). It can be found that the flow structure in Case 0 (steady result) is most noticeable not only for its large separation region but also with the strong bow shock upstream the ramjet cowl. By contrast, there are only normal shocks on the lip or in the internal flowpath of ramjet inlet which represents the inlet in these cases under transition Mach number 2.25 are unstart and also have a relative lower performance to the inlet of Case 5 in figure 4e. Besides, both the comparison of Case 1 to Case 3 which are used to investigate the splitter rotating time effects, and the comparison of Case1, Case 6 and Case 7 which are used to study the rotating pattern during mode transition, show the rotating speed of splitter when it is about to close the turbo inlet plays an important role in the hysteresis effects, and greater rotating speed will bring more serious hysteresis which can be confirmed in Figure. 5(f).

![Fig. 5. Hysteresis investigation with flowfield comparison of different Cases (δₛ=9.0°, δₑ=2.6°).](image)

Four parameters including mass flow capture coefficient Φ, throat total pressure recovery coefficient σ, static pressure ratio Π and Mach number, which are utilized to assess the TBCC dual-flowpath performance, are illustrated in Figure. 6. Φ is referred to the shock on lip condition of ramjet design point (about 41.178kg/s), while Π and σ are all referenced to the free stream values. All the results are calculated by mass weighted average method.
It can be seen that the variation rule of above performances are all similar under the hysteresis effects that the discrepancies become much greater when the splitter nearing closes low-speed inlet. Besides, it is confirmable that the differences caused by transition Mach number effects which can directly impact the inlet flow structures (start or unstart), are similar with that caused by hysteresis effects. Moreover, $\Phi$ is mainly changed linearly with the rotating angle of splitter and ramjet cowl which is correlated to the relative capture area after external oblique shocks. And it is found that the total $\Phi$ values of both high- and low-speed inlet during the mode transition process decrease from 1.48 of turbo mode to 1.14 of ramjet mode in the present designed case, and this may be not conducive to the stability of TBCC power transition and should be paid more attention in TBCC inlet design.

![Diagram](image-url)

**Fig. 6.** Performance of TBCC dual-flowpath during mode transition.

Considering integrative design with vehicle body and the relative scale of TBCC inlet is large enough to affect the aerodynamic characteristic of the whole vehicle significantly, the aerodynamic coefficients such as lift ($C_l$), drag ($C_d$), pitching moment ($C_m$) calculated at the inlet leading point, which are non-dimensionalized respectively with equal dynamic pressure, the reference area 10.0 (length for 2D inlet), are analyzed in Figure. 7. Similarly, it also shows that the discrepancies between the steady and unsteady result which are mostly caused by hysteresis effects, are existed especially when the splitter nearly close turbojet inlet. Beside, the selection of mode transition Mach number also has a great influence on these aerodynamic coefficients above, and all the coefficients increase gradually along with the rotation of splitter and ramjet cowl except for a special decrease by probably 8% with the splitter rotating angle 9 degrees and cowl rotating angle 2.6 degrees in Case 5 (transition Mach number 2.5), and which are mainly caused by that the inlet only starts in this case in contrast to the other unstart cases.
5. Conclusion

A parameterized design method has been established for mode transition of over-under TBCC inlet and the design variables are optimized by the Multi-Island Gene Algorithm using auto-CFD solution. The unsteady numerical simulation method with dynamic overset grids technology has been utilized to control and simulate the coupled rotation of both splitter and ramjet cowl. The studies of some typical problems such as Mach number effects, time effects and rotating patterns of splitter during TBCC mode transition show that the TBCC inlet can work efficiently in a wide range by a suitable control of coupled rotation of splitter and ramjet cowl, and the rotating speed of splitter when it is about to close the turbo inlet plays an important role in hysteresis effects that greater rotating speed will bring more serious hysteresis. Besides, total mass flow capture coefficients decline from 1.48 of turbo mode to 1.14 of ramjet mode that may be not conducive to the stability of TBCC power transition and should be paid more attention in TBCC inlet design. Moreover, all the aerodynamic coefficients of TBCC inlet increase gradually along with the rotation of splitter and ramjet cowl except for a special case when the inlet starts in contrast to the other unstart cases, and which also means the selection of transiting Mach number, duration and manner of splitter rotating all have great influence on TBCC mode transition.

Acknowledgements

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References