Unsteady flow characteristic analysis of turbine based combined cycle (TBCC) inlet mode transition

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Abstract A turbine based combined cycle (TBCC) propulsion system uses a turbine-based engine to accelerate the vehicle from takeoff to the mode transition flight condition, at which point, the propulsion system performs a “mode transition” from the turbine to ramjet engine. Smooth inlet mode transition is accomplished when flow is diverted from one flowpath to the other, without experiencing unstart or buzz. The smooth inlet mode transition is a complex unsteady process and it is one of the enabling technologies for combined cycle engine to become a functional reality. In order to unveil the unsteady process of inlet mode transition, the research of over/under TBCC inlet mode transition was conducted through a numerical simulation. It shows that during the mode transition the terminal shock oscillates in the inlet. During the process of inlet mode transition mass flow rate and Mach number of turbojet flowpath reduce with oscillation. While in ramjet flowpath the flow field is non-uniform at the beginning of inlet mode transition. The speed of mode transition and the operation states of the turbojet and ramjet engines will affect the motion of terminal shock. The result obtained in present paper can help us realize the unsteady flow characteristic during the mode transition and provide some suggestions for TBCC inlet mode transition based on the smooth transition of thrust.

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1. Introduction

Airbreathing hypersonic vehicle is becoming one of the most prominent domain of the future vehicles. Many countries in the world are devoting themselves into the research of airbreathing hypersonic vehicle [1–4]. As the airbreathing hypersonic vehicle operates across a broad range of Mach numbers, inclusive of the subsonic, supersonic, and hypersonic flight regimes. So the propulsion system faces the giant challenges. At the same time it becomes the key technology of this airbreathing hypersonic vehicle. Nowadays, no matter what types of airbreathing engines could not be competent for this vehicle. Airbreathing engines can only work efficiently at narrow Mach number range, for instance turbojet engine can work properly at low Mach number and dual-mode scramjet engines are more suitable to work at high Mach number. So researchers in the world integrate different types of engines to form a combined cycle engine. There are two main combination of engines, one is rocket based combined cycle (RBCC) which is defined as the combination of rocket and dual-mode scramjet engine, the other is turbine based combined cycle (TBCC) which is defined as the combination of turbine and dual-mode scramjet engine. Turbine-based propulsion systems exhibit significant specific impulse improvements over rocket-based propulsion systems in the subsonic takeoff and return mission segments [5] and it can mitigate mission risk by providing operation flexibility for all weather launch, take-off and landing cross-range. So America, European countries and Japan as well as some universities in China are devoting themselves into the research of this TBCC airbreathing propulsion system [6–10].

The inlet of TBCC engine plays a vital role in airbreathing propulsion system. The performance of the TBCC inlet will affect the efficiency of the propulsion system directly [7]. The main role of TBCC inlet is to provide some airflow with proper pressure, temperature and velocity for turbine engine or dual-mode scramjet engine. Once the vehicle accelerated to the designed inlet mode transition point, the turbine engine would spool down and the low-speed flowpath would go from fully open to almost fully closed. From this point, the dual mode scramjet engine would provide the thrust beyond the mode transition condition. The process of TBCC inlet mode transition determine the performance of airbreathing propulsion system transferring from turbine mode to dual-mode scramjet mode. Inlet mode transition research is one of the most important parts of TBCC propulsion system programs in foreign countries. The demonstrator of Japanese HYPR program, HYPR90-C is the combination of turbofan and ramjet TBCC engine. In the HYPR90-C demonstrator tests they fulfill the smooth mode transition procedure from turbojet to ramjet mode [11]. And NASA have already done the over/under TBCC inlet mode transition experiment at Glenn research center. They demonstrate that smooth inlet mode transition procedure is realizable [12,13]. Besides researchers in Chinese universities, such as Chen Min and Wang Yongsheng, have already conducted the performance analysis of hypersonic airbreathing TBCC engine [14,15]. The research list above mainly focus on the steady process of inlet mode transition and performance analysis of combined cycle engine.

The present paper describes numerical studies of unsteady process of over/under TBCC inlet mode transition. The over/under TBCC inlet configuration is illustrate in Figure 2. This TBCC inlet shares a common compression ramps and the flowpath of turbojet and ramjet engine is separated by a splitter. The unsteady process of inlet mode transition is achieved by the rotation of the splitter that is the turbojet flowpath would go from fully open to almost fully closed. The process of over/under TBCC inlet mode transition has been partly clarified by one of the present author (Guo et al. 2012) [16]. They focused on the steady process of inlet mode transition. However, that was insufficient because the unsteady process of inlet mode transition has not been investigated. Some unsteady flow phenomenon would appear during the process, such as shock oscillation, which would change the flow total pressure and distortion into turbojet and that may cause the turbine engine stall. If that happens the TBCC mode transition failed. Therefore, the purpose of the present study is to investigate the unsteady flow characteristic during the over/under TBCC inlet mode transition and provide some suggestion for smooth mode transition.

2. Methodology

2.1. Numerical simulation method and validation

During the simulation of TBCC inlet mode transition the fluid domain is updating as the splitter rotates. The function of the splitter is to spill the flow into turbojet or ramjet/scramjet engine. As the splitter rotates, the flowpath to turbine closed while establishing design flowpath to ramjet, the inlet operation states transformed from turbojet to ramjet.

Dynamic mesh and unsteady numerical simulation method is used to fulfill the updating of fluid domain during the research of TBCC inlet mode transition. Firstly, the pitching of
NACA0012 airfoil experiment data is used to validate this simulation method. Because the shock oscillation phenomenon (as shown in Figure 1(a)) appear during the airfoil pitching is similar to that during the inlet mode transition (as shown in Figure 6). At the same time, the physical process of NACA0012 airfoil pitching is similar to the rotation of splitter during the TBCC inlet mode transition. According to the reference [17] NACA0012 airfoil pitches around the 1/4 chord length point away from the leading edge. During the process of NACA0012 airfoil pitching, the fluid domain updates according to time. When the splitter rotates around a specific point the fluid domain will update, too.

In the present paper, the FLUENT flow analysis software is used to simulate the process of over/under TBCC inlet mode transition. The unsteady Reynolds averaged Navier-Stokes equations (Eq. (1)) in two dimensions are solved by using a finite volume spatial discretization method.

\[
\frac{\partial u}{\partial t} + \frac{\partial f}{\partial x} + \frac{\partial g}{\partial y} = \frac{\partial a}{\partial x} + \frac{\partial b}{\partial y}
\]  

(1)

\( u \) denotes conservation vector, \( f \) and \( g \) are inviscid flux term and \( a \) and \( b \) are viscous flux term. In the computations, the inviscid flux scheme is Roe’s method and the monotonic upwind scheme for conservation laws (MUSCL) approach is used for variable extrapolation. And viscous flux scheme is discretized by second order central difference scheme [18]. Turbulence is modeled by the standard \( k - \varepsilon \) equations. The definition of turbulence viscosity of this model is:

\[
\mu_t = \rho C_{\mu} \frac{k}{\varepsilon}
\]

(2)

\( C_{\mu} \) is constant, \( k \) is turbulent kinetic energy defined as \( k = \frac{1}{2} u_i u_j \) and \( \varepsilon \) is rate of dissipation of turbulent kinetic energy defined as \( \varepsilon = \frac{\nu (\partial u_i / \partial x_j)^2}{C_{\varepsilon}} \). Dual-time stepping method is used in the unsteady simulation. The physical time step is chose based on the following formation:

\[
\Delta t < \frac{\text{shortest length of grids}}{\text{characteristic velocity}}
\]

(3)

the characteristic velocity above means the velocity of the characteristic wave through the flow field [19].

Figure 1 shows the result of NACA0012 airfoil Mach contour (Figure 1(a)) and moment coefficient (Figure 1(b)). The Mach number of inflow is 0.755, the static pressure is 101 kPa and the static temperature is 288 K. In Figure 1(b) continual line is the numerical solution of moment coefficient, discrete point is experiment data get from Ref. [17]. According to the result of Figure 1(b), the numerical solution data is close to the experiment data. So this dynamic mesh and unsteady simulation method can be used to simulate the process of over/under TBCC inlet mode transition.

2.2. Over/under TBCC inlet model

Figure 2 is the profile of over/under TBCC inlet model. This inlet consists of external compression, internal compression and subsonic diffuser. External compression consists of three different compression ramps, namely 6°, 2° and 3.5°. The internal contraction ratio is 1.2. The slot-coupled cavity designed in internal compression part aim to bleed the boundary layer grows from upstream and extend the operation range of Mach number of the over/under TBCC inlet. The subsonic diffuser part of this inlet consists of two flowpaths upper flowpath is for ramjet engine, lower flowpath is for turbojet engine. The inlet is designed to operate from \( Ma=0 \) to \( Ma=4 \), turbojet flowpath operates from takeoff to \( Ma=2.2 \) and ramjet flowpath operates from \( Ma=2 \) to \( Ma=4 \). Ramjet flowpath and turbojet flowpath are over and under parallel with each other. During the inlet mode transition, which happen at \( Ma=2.0 \), the splitter rotates from upper to lower (as shown in Figure 2) to divert...
2.3. Numerical approach of inlet mode transition

Structure and unstructured grids are used to discretize the over/under TBCC inlet geometry. Total elements of grids are about 120000 cells. And the $y^+$ of inlet wall is around 30, which is suitable for standard $k-\varepsilon$ turbulence model. As shown in Figure 3, near the splitter unstructured grids are used and other domain structure grids are adopted. Twenty eight static pressure gauging points are set in the inlet to measure the static pressure during the inlet mode transition, and the position of these points are shown in Figure 2. Additionally, free stream boundary condition including a free stream Mach number of 2.0, a static pressure of 11671 Pa, and a static temperature of 216 K is applied to the far field and a no-slip adiabatic boundary condition is imposed on the solid walls. As to the pressure outlet condition at the inlet exit, turbojet flowpath back pressure is 72360 Pa and ramjet flowpath back pressure is 11671 Pa during the inlet mode transition.

Before unsteady simulation of the inlet mode transition, the initial flow field at Mach number of 2.0 should be calculated first. During the inlet mode transition the splitter is set as a rigid body and rotates around a specific point. The angular velocity is equal to 2.44 rad/s, the total time of the inlet mode transition is 0.2 s. According to the Eq. (3), the time step for unsteady numerical simulation is $10^{-6}$ s. And the inner iteration for each time step is 100 times.

Because the unsteady calculation will take large amount of time, so if the number of grids can be reduced, it will save a lot of time. This paper adopt profile method to reduce grids [20]. First export the boundary profile file from the whole calculation domain result. Then import the boundary profile as the inflow condition of the part calculation domain. After the use of profile, total elements of grids reduce from 120000 to about 60000 cells. Figure 4 is figure of inlet Mach contour which shows the comparison between whole and part calculation domain. From Figure 4 the flow field of these pictures are almost the same and other parameters of these two kinds of results have been compared they stay close. The profile method can be used to reduce grids.

3. Analysis of TBCC inlet mode transition

Figure 5 shows the steady result of turbojet mode at specific back pressure before inlet mode transition. As shown in Figure 5, the Mach number in turbojet flowpath is subsonic while in ramjet flowpath there exits both supersonic and subsonic zone. And the mass flow rate of turbojet flowpath is 0.60, pressure recovery is 0.89, Mach number is 0.39. As for ramjet flowpath the mass flow rate is...
0.14, pressure recovery is 0.35. The terminal shock is right behind the slot-couple cavity.

Then unsteady inlet mode transition is simulated based on the above result. First of all, the flow phenomenon appear during TBCC inlet mode transition is analyzed. Then the influence of TBCC inlet mode transition speed is researched.

Figure 6 shows different time step Mach contour and streamline during the inlet mode transition. Figure 6(a) illustrates the process of terminal shock oscillation between rear edge of the slot-coupled cavity and the entrance of turbojet flowpath. From Figure 6(a) it can be seen clearly that when the terminal shock locates at the entrance of turbojet flowpath, terminal shock and boundary interaction induced boundary layer separation occur at the lower wall of turbojet flowpath. Then the terminal shock is pushed back until it reaches the rear edge of slot-couple cavity, at the same time the boundary separation disappear. Finally the terminal shock moves forward again and locates at the entrance of turbojet flowpath. That is a loop of terminal shock oscillation.

According to the analysis of Figure 6(b), during the inlet mode transition the terminal shock oscillates several times. Approximately, the inlet mode transition process can be divided into three phases. First phase is from \( t = 0 \) ms to \( t = 120 \) ms. The terminal shock oscillates between rear edge of the slot-coupled cavity and the entrance of turbojet flowpath, coupling with the separation bubble appear and disappear at the lower wall of turbojet flowpath. In this phase the flow field of ramjet flowpath change from non-uniform to uniform, that is the oblique shock system established when the splitter rotates down and builds the ramjet flowpath. At the beginning of the first phase the inlet area of ramjet flowpath is small and the expansion ratio of flow after splitter is large so sharp oblique shock formed during the meeting point of splitter and ramjet flowpath. As the splitter rotates down the inlet area of ramjet flowpath increase and the expansion ratio of flow decrease, the oblique shocks become weaker. And the flow field in ramjet flowpath become more uniform. Second phase is from \( t = 120 \) ms to \( t = 160 \) ms. This is a transition phase. In this phase the terminal shock become weaker than the first phase but the frequency increase. A big separation bubble stays in turbojet flowpath. Meanwhile the oblique shocks in ramjet flowpath become weaker. Third phase is from \( t = 160 \) ms to \( t = 200 \) ms. The terminal shock stays steadily at the rear edge of the slot-couple cavity, at the same time the flow into the turbojet flowpath is almost equal to zero except the boundary layer.

The results of Mach contour at different time of TBCC inlet mode transition show that terminal shock oscillation and separation bubble appear during inlet mode transition. Base on the qualitative results analyzed above, quantitative analysis of wall static pressure was presented following. Figure 7 illustrates time domain and frequency domain signals of lower wall pressure during the inlet mode transition. L5 and L6 static pressure probes are located between slot-coupled cavity and the turbojet flowpath entrance. The detail position of each probe is shown in Figure 2. Time domain pressure signal can be divided into three phases, which is consistent with the results presented.
above. In phase one, wall static pressure signal change sharply because terminal shock move past the measuring points. From L5 pressure signal we know that the interval between two pressure oscillation decrease, meanwhile the amplitude increase mildly as the splitter rotates down and closes the turbojet flowpath. Phase two is the transition stage of the movement of terminal shock. The interval between two pressure oscillation is tiny and the amplitude is smaller than phase one. In phase three the amplitude of pressure oscillation is even smaller. The terminal shock stay stable at the rear of slot-coupled cavity, meanwhile high pressure perturbation expelled from turbojet flowpath cause pressure oscillation.

From the analysis of time domain pressure signal, the characteristic of terminal shock oscillation is explained more detailedy. The following is the frequency domain signal of L6 pressure. Figure 7(b) shows the FFT transform of L6 pressure signal, x-coordinate denotes the frequency and y-coordinate denotes the number of power spectral density of L6 pressure signal. There are two high frequency peaks in power spectral density of L6 pressure in Figure 7(b). One peak is 128 Hz, which is the terminal shock oscillation frequency in phase one. The other peak is 358 Hz, which is the pressure oscillation frequency of phase three. The amplitude and frequency change at different phases because the behavior of separation bubble changes as the splitter rotates down. In first phase the separation bubble shed from turbojet flowpath in a loop of shock oscillation. While in third phase the separation bubble grows nearly the same as turbojet flowpath and stays at the flowpath. The pressure wave expelled from turbojet flowpath is mild but higher frequency which cause the change of amplitude and
frequency at this phase. According to the analysis of time domain and frequency domain signals of static pressure, the movement motion of terminal shock pressure oscillation phenomenon during the inlet mode transition have been explained.

The flow field and pressure signals during the inlet mode transition are analysed above. The performance parameters of turbojet/ramjet outlet are presented following. Figure 8 (a) is mass flow rate of turbojet and ramjet flowpath. From Figure 8(a) the turbojet flowpath mass flow rate decrease oscillatingly during the inlet mode transition, which is in accord with the motion of terminal shock. The behaviour of the mass flow rate in turbojet flowpath can be divided into three phases, which is the same as the terminal shock movement. From $t=0$ ms to $t=120$ ms, the oscillation amplitude is large and it increases as the splitter rotates down and close the turbojet flowpath. Then in transition phase two the oscillation amplitude decreases but the frequency increases. In the third phase mass flow rate nearly keep steadily but oscillationly. In ramjet flowpath the mass flow rate increases steadily as the splitter rotates.

![Figure 7](image1.png) Lowerwall static pressure signals during TBCC inlet mode transition.

![Figure 8](image2.png) Performance parameters of inlet during mode transition. (a) Mass flow rate and (b) Mach number.

![Figure 9](image3.png) Shock oscillation frequency at different splitter angular velocity.
and builds the ramjet flowpath. The Mach number of turbojet flowpath decreases mildly during inlet mode transition. While in ramjet flowpath the Mach number changes severely from \(t=0\) ms to \(t=60\) ms. Because during this period the flow field in ramjet flowpath is nonuniform. From then on the Mach number in ramjet decreases steadily and finally keep constant. The outlet Mach number of ramjet flowpath is always greater than 1.0, because no back pressure is added on it which simulate the ramjet is not power on. The present paper focus on the influence of turbojet flowpath backpressure.

**4. The effect of splitter angular velocity to TBCC inlet mode transition**

This paper have already analysed the flow field during the process of TBCC inlet mode transition when the angular velocity of splitter is 2.44 rad/s. What will happen if the angular velocity of splitter change? This section is going to explain the effect of splitter angular velocity to TBCC inlet mode transition.

The effect of angular velocity to TBCC inlet mode transition is researched at the same boundary conditions specified above. The angular velocity of splitter is the only one variable that is different. Four different angular velocity are simulated, they are 0.49 rad/s, 4.89 rad/s, 9.77 rad/s and 24.43 rad/s. After the analysis of static pressure of these four cases, the frequency of terminal shock oscillation increase when the angular velocity of splitter increase. Figure 9 shows the terminal shock oscillation frequency at different splitter angular velocity.

Table 1 lists the data of the inlet mode transition time and oscillation period at different splitter angular velocity. From Table 1 we can obtain that when the splitter angular velocity increases the gap between inlet mode transition time and oscillation period decrease. So the mode of terminal shock oscillation have the trend of changing from self sustained oscillation to force oscillation.

According to the analysis of above results, the reason for the change of shock oscillation is that when the angular velocity increase the pertuation of splitter at unit time increase so the movement of terminal shock become more violent and finally cause the increase of shock oscillation frequency.

**5. Conclusions**

According to the over/under TBCC inlet mode transition research, it indicates that:

1) The investigation of unsteady flow characteristic of TBCC inlet mode transition is important to the smooth mode transition. Not only the steady process but also the unsteady process of inlet mode transition is needed.
2) The dynamic mesh and unsteady numerical simulation method is validated by the experiment data of NACA0012 airfoil pitching. And it can be used to the simulation of over/under TBCC inlet mode transition.
3) During the process of inlet mode transition the terminal shock oscillation between rear edge of slot-coupled cavity and entrance of turbojet flowpath. Mass flow rate and Mach number of turbojet flowpath decrease with oscillation, as the splitter rotates down and closes the turbojet flowpath. In ramjet flowpath the Mach number changes severely at the beginning.
4) The terminal shock oscillation frequency is affected by the angular velocity of splitter. When the angular velocity increase from 0.49 rad/s to 24.43 rad/s, the terminal shock oscillation frequency increase from 126 Hz to 150 Hz.

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