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Study of the unsteady mode transition process for an over-under TBCC exhaust system

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ABSTRACT

The present study focuses on the unsteady mode transition process of an over-under TBCC exhaust system. The method of characteristics is applied to design the over-under TBCC exhaust system according to the entrance parameters of the turbine nozzle and ramjet nozzle at the design point. The dynamic mesh is adopted to adjust to the update of the computational domain, and the unsteady numerical method is employed to simulate the dynamic flowfield of the exhaust system during the mode transition process. The results show that the flowfield structure and the performance vary greatly during the mode transition. Owing to the interaction between the turbine exhaust jet and ramjet plume, the flowfiled in the turbine nozzle is affected by the ramjet exhaust jet considerably. The axial thrust of the turbine nozzle decreases, while that of the ramjet nozzle increases gradually during the mode transition, but the total axial thrust of the entire exhaust system varies smoothly. Both the axial thrust coefficient and pitching moment of the exhaust system increase along with the open of the ramjet nozzle, while the result for the lift is contrary. However, the axial thrust coefficient, lift and pitching moment all decrease rapidly with the shutdown of the turbine nozzle, and the decreases in axial thrust coefficient, lift and pitching moment are 1.04%, 67.15% and 80.92%, respectively. Besides, two sudden change of the axial thrust coefficient exist at the beginning and end of the motion of the splitter plate.

1. Introduction

Compared to rockets, the air breathing propulsion systems can avoid carrying oxidizer by using oxygen in the atmosphere, which results in superior safety and higher specific impulse over the entire operating range of the flight Mach numbers. Therefore, the air breathing propulsion engine becomes a promising candidate for the vehicles which can take-off horizontally and speed up to Mach 5 and beyond depending on the mission. However, no single air breathing engine shows superior specific impulse performance over the wide operating range, so combined cycle engines such as turbine based combined cycle (TBCC) engines are being considered to exploit the performance benefits of multiple engines at different Mach numbers [1].

Unlike a pure turbine engine, the TBCC concept combines a gas turbine with a ramjet or scramjet, as shown in Fig. 1, the low-speed turbine flowpath is located parallel to and above the high-speed ramjet/scramjet flowpath in an over-under TBCC configuration [2]. Applying combined cycles engines instead of using separate engines for each cycle is expected to offer less weight with similar or improved performance levels. Consequently, the propulsion system should be highly integrated with the vehicle airframe, which requires that the common inlet and nozzle are employed for both low-speed turbine and high-speed cycle engine and then, two splitter plates are involved to close the low-speed flowpath as the high-speed engine takes over (Fig. 1) [3]. For takeoff, and through the low supersonic flight regime, the turbine flowpath provides thrust to accelerate the vehicle; however, continued acceleration through the supersonic regime, the propulsion system will be transitioned from the low-speed turbine flowpath to ramjet/scramjet flowpath.

During the mode transition process, the low-speed turbine engine and high-speed ramjet/scramjet operate simultaneously, and at the same time, both the close of the low-speed flowpath and open of the high-speed flowpath are conducted gradually along with the rotation of the splitters and cowls. In terms of the common inlet, the airflow is diverted from the low-speed flowpath to the other, and the unstart for both the low-speed and high-speed inlet may occur, causing the rapid reduction in mass flow and pressure to the engine, and thus a large thrust loss along with increased drag. While considering the common nozzle during the mode transition, the open and close of the nozzle doors control the mass flow rate of the two separate flowpaths, which

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Nomenclature

C_{fx}	axial thrust coefficient
C_P	pressure coefficient
C_m	pitching moment coefficient
C_n	lift coefficient
F_s	ideal thrust
F_x	axial thrust
H	flight altitude
H_e	nozzle exit height
$H_{e,r}$	exit height of ramjet nozzle
$H_{e,t}$	exit height of turbine nozzle
H_t	throat height
$H_{t,r}$	throat height of ramjet nozzle
$H_{t,t}$	throat height of turbine nozzle
L_N	nozzle length
L	lift
L_P	location of turbine nozzle
M	pitching moment
Ma	Mach number
P	pressure
P_{amb}	ambient pressure
P_t	total pressure
R	gas constant
T_t	total temperature
t_0	initial condition
u	velocity in x direction
v	velocity in y direction
x	X direction coordinate
y	Y direction coordinate
α	attack of angle
Δt	time step
θ	rotation angle
γ	the ratio of specific heat
ρ	density
μ	viscosity

Subscript

ram	ramjet engine
tur	turbine engine
∞	freestream

have a significant impact on the thrust, lift and pitching moment of the exhaust system [4]. Overall, the smooth and stable mode transition reflects directly the efficiency of the propulsion system, so it is very critical to design the TBCC propulsion system and it has been the subject of interest in aerospace engineering [5].

Over the last few decades, many efforts have been made to investigate the performance variances of the TBCC propulsion system [6]. Chen et al. [7,8] developed a component-based variable cycle turbo-ramjet engine model to simulate the mode transition process, and the results showed that smooth turbofan/ramjet mode transition could be guaranteed by the multi-variable control law derived by Newton-Raphson multi-goal programming algorithm. In Reference [9], Huang et al. established a mathematical model to compute performance and analyze the thermodynamic parameters variation of turbine/ramjet combined cycle engine during mode transition, and this study also provided the quantitative opening area of mode transition value to satisfy the criteria of thrust smoothing. Even though the investigations [7, 8 and 9] on overall performance of TBCC propulsion system during the mode transition process provided theoretical methods to obtain the smooth mode transition, the detailed flowfield and performance variations of the common inlet and nozzle are not taken into account, in particular the unsteady process during mode transition. Therefore, researchers have turned attentions to study the flowfield and performance variations of the components. Le et al. [10] applied a simulation scheme based on the Memory-Mapped-Files technique to study the complex interactions between the inlet-dynamics, variable-geometry actuation mechanisms and flow-controls in the transition from the supersonic to hypersonic conditions, and the results showed that inlet back-pressure dynamics was likely to be an important factor in mode transition control. In Reference [11,12], an

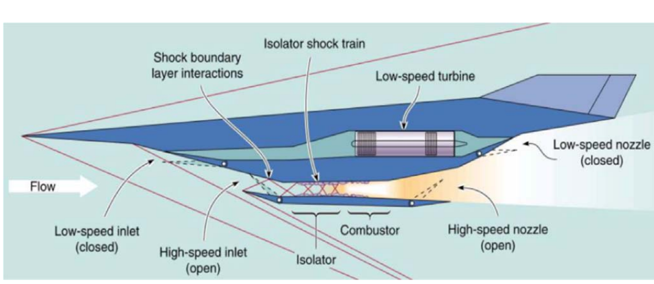

Fig. 1. Sketch of an over-under TBCC concept [2].

inlet mode transition experimental study was conducted in a 10- by 10-ft supersonic wind tunnel to identify any interactions between the low and high speed inlets during the mode transition phase, and the results indicated that the inlets did not interact with each other sufficiently to affect the inlet operability and a low speed inlet unstart did not cause the high speed inlet to unstart. Prior to carrying out the experiment in Reference [11,12], Csank and Stueber [5] employed the High Mach Transient Engine Cycle Code (HiTECC) simulation package to represent the NASA large-scale inlet model for combined cycle engine mode transition studies. To study the unsteady flowfield of the inlet during mode transition process, Xiang et al. [13] utilized dynamic overset grid technology to control and simulate the coupled rotation of both the flow splitter and ramjet cowl of TBCC inlet. The results showed that Mach number, time and rotating patterns of the splitter had great influence on the dual-flowpath inlet throat performance as well as the aerodynamic characteristic with similar hysteresis effects.

As state above, most previous studies focused on the flowfield and performance variations of an over-under TBCC inlet during mode transition process; however, the studies of the mode transition process for an over-under exhaust system were very few and only some studies examined the steady flowfield and performance for the over-under TBCC exhaust system [14–16]. Reference [14] studied the flowfield feature of a TBCC exhaust system at a steady condition, and the results indicated that the plumes from the turbojet and ramjet interacted with each other at the end of the splitter and the shock waves and a shear layer were formed at the confluence of the two jets. Mo et al. [15] investigated the fundamental physics of the complex flow in the TBCC exhaust system during mode transition and obtained the aerodynamic performance of the exhaust nozzle at steady state. The results denoted that the flow structure was complicated owing to the two exhaust jets interacted with each other and the exhaust system thrust coefficient varied from 0.9288 to 0.9657 during the mode transition process. In Reference [16], an integrated fluid-structure interaction simulation of the splitter plate at a specific operation in a TBCC exhaust system was conducted, and the results showed that the fluid-structure interaction had some effect on the performance of the exhaust system, and the thrust, lift and pitching moment were increased by 0.68%, 2.82% and 5.86%, respectively. Although the results [14–16] obtained by steady numerical method can reflect the operational state of a TBCC exhaust system at some crucial conditions, it can't embody the performance of the exhaust nozzle over the entire mode transition process. Moreover, the mode transition is a dynamic process and the performance of the