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A model of mode transition logic in dual-mode scramjet engines

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ABSTRACT

Intricate process of mode transition exists in dual-mode scramjet engines, mainly amongst three typical operation modes (i.e., scramjet mode, ramjet mode and unstarted mode). Based on the analysis of an original analytical model, four transition boundaries are defined, and several corrections and considerations are carried out to clarify the way how to develop a model of mode transition logic. The complete mode transition logic is presented in a flowchart with a calculated case, and the corresponding implementation method for simulation is specified with programs in the paper. Combining the present mode transition logic unit with the original analytical parts, a dual-mode scramjet engine model for simulation, in which the inlet unstart issue is mainly caused by the interaction between thermodynamic effect and geometrical effect, could be acquired.

1. Introduction

Dual-mode scramjet (ramjet) engines are predominant propulsion systems of choice for an ascent trajectory from supersonic speed to hypersonic cruise. The key trait of the engine is that combustion could be done in both subsonic and supersonic flow within the same engine, respectively corresponding to the two operation modes of the engine, namely, the ramjet mode and the scramjet mode [1].

Under a wide range of Mach numbers within an ascent trajectory, the transition between ramjet mode and scramjet mode is inevitable, and meanwhile the operability limits exist. One striking dangerous working condition is the inlet unstart phenomenon which occurred more than once in the practical flight tests [2,3] and eventually led to the mission failures. As discussed further below, the inlet unstart phenomenon would also be regarded as an operation mode of the engine (named as unstarted mode), like the scramjet mode and the ramjet mode.

In the literature, there have been several papers devoting much work to developing the model of the scramjet-powered hypersonic vehicle. Aiming at presenting an integrated approach of capturing the strong couplings between propulsion system and airframe, the first comprehensive analytical model of the longitudinal dynamics was undertaken by Chavez and Schmidt [4]. And the scramjet model published in [4] was widely used by the following researches. Mirmirani et al. [5,6] developed a two-dimensional CFD-based model of a full-scale generic air-breathing hypersonic flight vehicle. Bolender and Doman [7] extended the work done by [4], and established a more completely first-principle physics-based model. Subsequently, Parker et al. [8] introduced the corresponding control-oriented model, in which the original (pure) scramjet model was greatly simplified by the polynomial expressions of thrust and pitch moment. Based on the model [8], Sigthorsson [9] developed a quasi-LPV model which is suitable for LMI-based robust control system design. These recent models reveal the substantial complexity of scramjet-powered hypersonic vehicle, and sequentially become more succinct that yields themselves better to flight control design. Despite obtaining the parameter-varying characteristic, compared with the true nature of a dual-mode scramjet engine, the above engine models cited widely are usually restricted in flight Mach 8 and above, and cannot represent the more complex attributes, such as the mode transition and the inlet unstart phenomenon.

Recently, Dalle et al. [10,11] and Torrez et al. [12,13] developed a first-principle reduced-order model based on the Bolender–Doman AFRL model [7]. A model called MASTrim code is improved to compute the boundaries of both engine unstart and ramjet-to-scramjet transition for a trimmed hypersonic vehicle. Several interesting vehicle results in ascent trajectories have been reported in [14]. It could be realized that when the mode transition from ramjet to scramjet is taken in account, the relevant optimal trajectory planning problems become complex [15].

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Nomenclature

A_{it}	area ratio of inlet throat
A_{ie}	area ratio of inlet exit
A_c	area ratio of combustor
A_{nt}	area ratio of nozzle throat
A_{ne}	area ratio of nozzle exit
c_p	specific heat
f_{st}	stoichiometric fuel–air ratio
P	pressure
Q	fuel lower heating value
q_m	mass flow rate
$\bar{q}$	dynamic pressure
T	temperature
Th	engine thrust
Ma	Mach number
x_b	body axis coordinate frame x direction
z_b	body axis coordinate frame z direction
α	angle of attack
γ	ratio of specific heats
δ	flow turn angle
δ_e	elevator deflection
η_c	combustor efficiency
θ	oblique shock angle
τ	overall total temperature rise ratio through combustor section
τ_a	aftbody vertex angle
τ_{fL}	lower forebody turn angle with respect to x_b axis
τ_{fU}	upper forebody turn angle with respect to x_b axis
φ	fuel–air equivalence ratio

Subscripts

d	design condition
f	fuel
rs	reflected shock
s	bow shock
sup	supersonic
t	stagnation value
0	freestream, flight condition
1	inlet entrance
2	inlet throat
3	inlet exit
5	combustor entrance
6	combustor exit
7	nozzle throat, thermal throat
8	nozzle exit

The process of mode transition is more complicated than that mentioned in [14], in our perspective, and it bears several nonlinear characteristics which require a model to present them for the further work in the perspective of system integration for airframe, propulsion and control. An original analytical model [16,17] is the base of our work, the previous description for the process of mode transition is presented by the topological rule, which cannot easily be developed in a simulation model. And a few considerations in the previous work, those that do not conform to the mode transition logic, need to be corrected. Then an unavoidable challenge appears, that is, how we can find a way to illustrate the intricate process of mode transition completely and implement it in a simulation model. The original intention of our work is to establish a dual-mode scramjet engine model which obtains three operation modes (i.e., scramjet mode, ramjet mode and unstarted mode) for simulation. Actually, most of this paper is for the description of mode transition logic, which, in our opinion, is the key aspect to enable the original analytical model to demonstrate the nonlinear characteristics of mode transition with several varying parameters from propulsion and vehicle system. Moreover, the disturbances which might induce the inlet to unstart can be the variation of flight conditions (i.e., angle of attack, flight Mach number, etc.), or the disturbance from the combustor. For an engine with a fixed geometric configuration, the inlet unstart issue, presented in the original analytical model and discussed in the paper, is primarily caused by high combustor backpressure.

2. Description of the analytical model and corrections

The analytical model includes two sub-models. One is the external compression system, which we name it as the entrance conditions of engine. The other segment is about the three modules of operation modes and the corrections we have done.

2.1. Entrance conditions of engine

Since an air-breathing hypersonic vehicle involves a tight airframe–propulsion integration design, when modeling, the first step of compression is freestream passing through the external

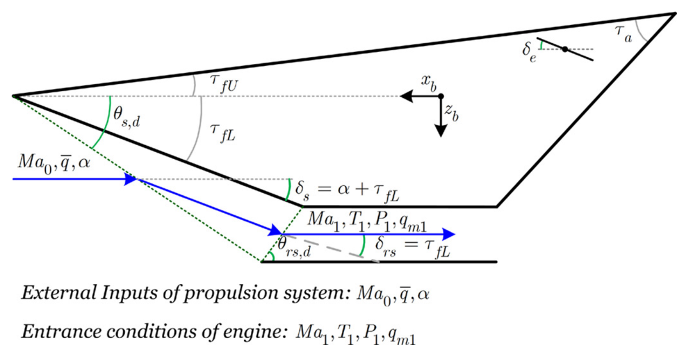

Fig. 1. External inputs and entrance conditions of engine.

oblique shock wave system, which generated by the lower forebody of vehicle and the inlet. The forebody geometry is shown in Fig. 1 and the model of the external compression system [7] is used to compute the entrance conditions of engine.

The flight parameters are inclusive of flight Mach number (or flight speed, alternatively), dynamic pressure (or flight altitude, alternatively) and angle of attack. The flight parameters are regard as the external inputs of propulsion system. The atmospheric parameters are determined by flight Mach number plus dynamic pressure. According to the oblique shock theory, the entrance conditions of engine, including Mach number, temperature, pressure and mass flow rate of air at station 1 (see Fig. 2), are calculated.

2.2. Modules of operation modes

The term "module of one mode" is used to refer to a unit which includes both a certain operation mode's thermodynamic equations and its corresponding critical conditions. The equations of three operation modes and four critical conditions quoted here were developed by Cui et al. [16,17] as an attempt to reveal the nonlinear hysteresis property of mode transition by topological rule. Yet, it should be noted that just having the prior analytical equations is insufficient to build a dual-mode scramjet engine model which contains the inlet unstart issue caused by the interaction between thermodynamic effect and geometrical effect. Hence,