ARTICLE IN PRESS
Chinese Journal of Aeronautics, (2017), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University
Chinese Journal of Aeronautics
cja@buaa.edu.cn
www.sciencedirect.com

A study on optimal control of the aero-propulsion system acceleration process under the supersonic state

Sun Fengyong, Du Yao, Zhang Haibo *

College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
Jiangsu Province Key Laboratory of Aerospace Power System, Nanjing 210016, China

Received 21 February 2016; revised 4 August 2016; accepted 7 September 2016

KEYWORDS

Acceleration control;
Inlet control design;
Inlet and engine cooperative working;
Optimal control

Abstract In order to solve the aero-propulsion system acceleration optimal problem, the necessity of inlet control is discussed, and a fully new aero-propulsion system acceleration process control design including the inlet, engine, and nozzle is proposed in this paper. In the proposed propulsion system control scheme, the inlet, engine, and nozzle are simultaneously adjusted through the FSQP method. In order to implement the control scheme design, an aero-propulsion system component-level model is built to simulate the inlet working performance and the matching problems between the inlet and engine. Meanwhile, a stabilizing inlet control scheme is designed to solve the inlet control problems. In optimal control of the aero-propulsion system acceleration process, the inlet is an emphasized control unit in the optimal acceleration control system. Two inlet control patterns are discussed in the simulation. The simulation results prove that by taking the inlet ramp angle as an active control variable instead of being modulated passively, acceleration performance could be obviously enhanced. Acceleration objectives could be obtained with a faster acceleration time by 5%.

1. Introduction

Acceleration performance is one of the most important aircraft operation qualities.[1,2] During the acceleration process, the integral aero-propulsion system including the inlet, engine, and nozzle is the primary power unit to provide an aircraft with sufficient thrust to implement the acceleration process. Especially under the supersonic state, the inlet and engine are both crucial components of the acceleration parts, accompanying seriously coupling dynamics. As is well known, compressor surge prevention is the mainly focused factor in the

* Corresponding author at: College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China.
E-mail address: zh_zhhb@126.com (H. Zhang).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2017.02.002
1000-9361

engine acceleration design. Meanwhile, engine inlet distortion could shrink the surge margin.[3] Usually, engine inlet distortion is generated under the inlet supercritical state, and the engine acceleration process is always accompanied with inlet distortion. Therefore, it is meaningful to take the whole aero-propulsion system including the inlet and engine into consideration in the acceleration process control.

The inlet shows a big different performance under the supersonic state compared to that under the subsonic state. Under the supersonic state, a mismatched inlet could badly affect the engine installed performance. Moreover, a fixed-geometry inlet is restricted in the flight of a wide-range Mach number. On the inlet off-design point, air mass flows that the inlet provides and the engine demands might not couple with each other. Consequently, the inlet working state would depart from the critical state. Furthermore, inlet spillage airflow or inlet outlet distortion comes into being under the subcritical or supercritical state. Variety of airflow in the engine acceleration process requests the inlet to provide balanced airflow. However, a variable-geometry inlet could relieve that damage to the cooperative working conditions between the inlet and engine. Modulation of the inlet throat area by an inlet ramp angle could keep the inlet working near the critical state and prevent inlet outlet distortion and inlet surge.[4–7]

Engine acceleration design always focuses on the safety and response time when referring to the acceleration performance index. The compressor surge margin, turbine inlet temperature, and fuel-air ratio are also key factors to engine accelerating safety. Engine inlet distortion is the main external disturbance to the compressor surge margin, which could lessen the surge margin and even induce an engine surge.[8,9] On the other hand, varieties of engine working states might bring the inlet into an unsteady working state, in which the distortion comes into being at the inlet outlet. Therefore, the coupling working conditions between the engine and inlet could guarantee the safety of the inlet working state and the engine compressor surge margin.

Currently available propulsion system acceleration process control schemes could be classified into two categories, passive control and active control. The present work on the aero-propulsion system acceleration process control focuses on the engine accelerating road and its optimization. This would easily neglect the inlet impacts to the engine. Especially under the supersonic state, the engine is greatly influenced by the inlet air mass flow quality. However, in this paper, the matching problems between the inlet and engine are fully considered and analyzed. The inlet and engine cooperative working principals are analyzed in both the fluent and pressure fields. Furthermore, in the acceleration process control design, an inlet modulated variable is added to the fuel flow rate and nozzle throttle area as one of the main control variables.

In order to study the optimal control of the aero-propulsion system acceleration process, an integral component-level model including the inlet and engine is built. Based on the model, a new inlet control scheme accompanying the initial acceleration schedule is proposed. In addition, this paper always advances a new propulsion system optimal acceleration schedule by regulating the inlet, engine, and nozzle at the same time, which means that a corrected inlet ramp angle is added to the fuel mass flow and nozzle throat area as control variables in the acceleration process. All the acceleration optimal control designs and simulations are conducted on an aero-propulsion system including a supersonic inlet which is designed at a 2.5 Mach number and a turbofan engine.

2. Inlet regulation necessity in engine acceleration process

As is illustrated in Fig. 1, a special acceleration schedule is settled in the passive control management, and particular control logics are used in the engine active control.[10] Neither of the two control managements has taken the inlet coupling impacts into account. However, the inlet plays a non-ignorable role in the acceleration process which would be fully discussed in the second part.[11]

While the coupling factors between the inlet and engine involve the airflow field, pressure field, temperature field, and other physical aspects, the stress here is on the air mass flow and total pressure equilibrium in the integral propulsion system component-level modeling. More modeling technical details are described in Ref.[12]

Apparently, the purpose of the inlet is intended to support the engine steady and sufficient airflow. Under the supersonic state, the inlet outlet pressure is determined by the engine air stream. Meanwhile, the inlet terminal shock is also affected by the inlet outlet pressure. With the inlet and engine cooperative working principals, the inlet air mass flow should be equal to the engine mass flow. On the assumption that the inlet has a fixed geometry, the equal air mass flow equilibrium could be described as

$$\frac{\sigma}{\varphi} = \text{const} \cdot \frac{q(\lambda_0)}{q(\lambda_2)} \quad (1)$$

where σ is the inlet total pressure recovery, φ is the inlet mass flow ratio, $q(\lambda_0)$ is the inlet mass flow coefficient, and $q(\lambda_2)$ is the engine mass flow coefficient. As is illustrated from Fig. 2, the inlet and engine cooperative working conditions could be superimposed on the inlet characteristic map. The variations of "inlet and engine co-operating line" reflect the propulsion system cooperative working equation and the inlet ramp angle $\delta_1 > \delta_2 > \delta_3 > \delta_4$.

On the assumption that the engine and inlet are in a good cooperative working state and matched well to each other, then the co-working point "I" is in the critical region. In the engine acceleration process, the requirement for airflow increases would be beyond what is required for critical operation, and the inlet co-working point moves into the supercrit-

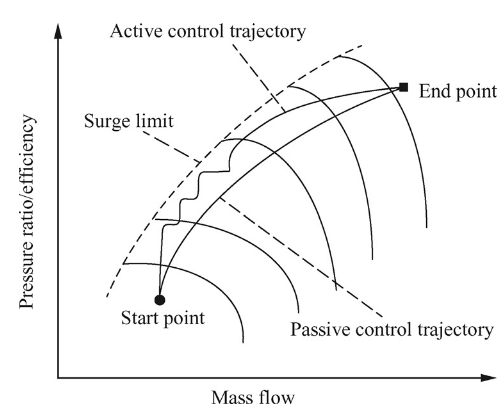

Fig. 1 Trajectory of the acceleration process in passive control and active control.

Please cite this article in press as: Sun F et al. A study on optimal control of the aero-propulsion system acceleration process under the supersonic state, *Chin J Aeronaut* (2017), http://dx.doi.org/10.1016/j.cja.2017.02.002