Chinese Journal of Aeronautics, (2014),27(5): 1097–1110

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Design for aircraft engine multi-objective controllers with switching characteristics

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Received 24 July 2013; revised 14 April 2014; accepted 7 May 2014
Available online 20 August 2014

KEYWORDS

Aircraft engine;
Compensatory controller;
Min/Max switching;
Multi-objectives control;
Smooth switching;
Switching scheme

Abstract The aircraft engine multi-loop control system is described and the switching control theory is introduced to solve the regulating and protecting control problems in this paper. The aircraft engine multi-loop control system is firstly described and the control problems are formulated. Secondly, the theory of the smooth switching control is devoted and a new extended scheme for the smooth switching of a switched control system is introduced. Then, for the key technologies of aero-engines switching control, a design algorithm is presented which can determine which candidate controller should be put in feedback with the plant to achieve a desired performance and the procedure to design the aircraft engine multi-loop control system is detailed. The switching performance objectives and the switching scheme are given and a family of PID controllers and compensators is designed. The simulation shows that using the switching control design method can not only improve the dynamic performance of the aircraft engine control system and reduce the switching times, but also guarantee the stability in some peculiar occasions.

1. Introduction

With the development of advanced aircraft engine technology, the control technology plays an increasingly important role. Because the aircraft engines have become more complex, with more control signals and higher demands on performance and functionality, electronic control systems have been introduced.[1,2] The experience of development of the aircraft engines in the world shows that the performance parameters of aircraft engines, such as thrust, specific fuel consumption, surge margin, etc., can be changed to a certain extent in order to increase aircraft engines function, adaptation and reliability to meet the requirements of different potential users and can be implemented only by using advanced control modes and control laws, causing little change on the aircraft engines' hardware.

The aircraft engine is a complex nonlinear system operated in an uncertain environment of limits: limits in temperature, air pressure and physical acceleration, etc. Aircraft engine

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2014.08.002

control systems can be designed by using linearized engine models under the multiple trimmed flight conditions throughout the flight envelope. For each of these operating points a corresponding linear controller is derived using the well-established linear-based control design methods.[3–5] However, a problem of this approach is that good performance and robustness properties cannot be guaranteed for a highly nonlinear aircraft engine. Nonlinear control methods have been developed to overcome the shortcomings of linear design approaches.

Several nonlinear control system design methods have emerged over the past two decades.[6–9] The theoretically established feedback linearization approach is the best known and most widely used among these methods. Feedback linearization is a nonlinear design method that can explicitly handle systems with known nonlinearities. By using nonlinear feedback and exact state transformations rather than linear approximations the nonlinear system is transformed into a constant linear system. This linear system can in principle be controlled by just a single linear controller.[10,11]

During the past decade, switched systems have attracted significant attention, because they can model several practical control problems that involve the integration of supervisory logic-based control schemes and feedback control algorithms. And the results have been developed for linear[12] and nonlinear systems.[13–15] Concerning output feedback control of switched systems, the results are as follows. In Ref.[16], by checking the existence of a switched Lyapunov function, linear matrix inequality-based sufficient conditions are derived to deal with the switched static output feedback control of discrete-time switched systems under arbitrary switching. Since there exist linear time-invariant systems, which cannot be stabilized via a single static output feedback, research has been dedicated to the study of hybrid static output feedback stabilization of linear time-invariant systems.[17–21] In Ref.[22], the output feedback robust stabilizability problem for uncertain dynamic systems is also considered.

The outline of this paper is as follows. First, the aircraft engine multi-loop control system is described in Section 2 and the control problems are formulated. Section 3 is devoted to the theory of the smooth switching control; a new extended scheme for the smooth switching of a switched control system and an algorithm is also presented in this section. Section 4 shows the procedure to design the aircraft engine multi-loop control system and the simulation results and comparisons. Finally, the conclusion can be obtained in Section 5.

2. Description of aircraft engine multi-loop control system

2.1. Aircraft engine descriptions

No matter for the linear or nonlinear control system design methods, the aircraft engine will encounter limits on some occasions. So the aircraft engine control system consists of a family of continuous-time subsystems and switches from one to another depending on various environmental factors (see Fig. 1). When the aircraft engine switches from one sub-control loop to another, the stability of the system is the basic performance that must be considered. Therefore, there is much space to improve the dynamic performance of the control system.

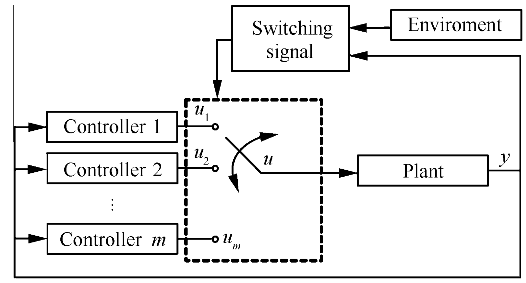

Fig. 1 Architecture of multi-controllers.

In this section, the aircraft engine of two-spool turbofan engine model was developed by the MATLAB simulation environment and its Simulink toolbox. The schematic configuration of the turbofan engine that was simulated is shown in Fig. 2. The high pressure compressor (HPC) and high pressure turbine (HPT) are on one shaft (driven by the high speed rotor), while the fan, booster and low pressure turbine (LPT) are on the other shaft (driven by the low speed rotor). Bleed effects (for air bleed from the booster and the compressor) are not currently considered in the model.

The engine simulation model, which is called nonlinear component level (NCL) model, consists of the static elements: inlet, fan (single stage), booster (four stages), high pressure compressor (nine stages), combustor, high pressure turbine (single stage), low pressure turbine (four stages) and main nozzle which are modeled as lumped parameter thermodynamic systems, represented by performance maps, constant coefficients, and thermo and aero-dynamic relationships and the dynamic elements which include low speed rotor and high speed rotor. In the model, the rotor dynamics (for the high speed and low speed rotors) is represented by the equation of conservation of angular momentum. Components, including the fan, the compressor and the turbines, are described in the form of maps and look-up tables based on their individual experimental data. The combustion efficiency and pressure losses are simply fitted by curves. Fig. 3 shows the characteristics of the turbofan engine typical components. In Fig. 3, π_F, η_F, $w_{a,cor,F}$ are fan pressure ratio, fan efficiency, and fan corrected air mass flow; π_B, η_B, $w_{a,cor,B}$ are booster pressure ratio, booster efficiency, and booster corrected air mass flow; π_C, η_C, $w_{a,cor,C}$ are compressor pressure ratio, compressor efficiency, and compressor corrected air mass flow.

2.2. Multi-objective with aircraft engine

As a modern aircraft, in order to achieve high performance flights, a high performance aircraft engine control system is essentially indispensable. But there are also many limits during the aircraft engine working process. For example, when the aircraft engine accelerates from one stable condition to another, the compressor surge imposes limits on the aircraft engine operation.

Fig. 4 shows the limit represented by the surge line. The surge line demarcates the regions between stable and unstable operation of the compressor. If the accelerating line goes through the surge line, the stability of the aircraft engine working condition is destroyed. Therefore, the aircraft engine