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Overshoot-free acceleration of aero-engines: An energy-based switching control method

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ABSTRACT

A switched controller is proposed for a two-spool turbofan engine to achieve overshoot-free speed control. Instead of a mathematical engine model, the real time data provided by the component level model and the equilibrium manifold are used in the design process. Controllers and a switching law are proposed to ensure that the system energy will not surpass the energy of the target working point so that no speed overshoot will arise. Meanwhile, the engine works at its safety limits as much as possible during the acceleration process, which shortens the regulation time. The asymptotic regulation, the overshoot-free performance as well as the safety issues are guaranteed theoretically. Simulations of a two-spool turbofan engine testify the correctness of the proposed method.

1. Introduction

Turbofan engines provide propulsion for many airplanes. Since the thrust is produced by the fan of the engine, the shaft speed (low-pressure shaft speed in the case of two-spool turbofan engines) is the main output to be manipulated in the propulsion control system. Much research has been done about the speed controller design of aero-engines (Richter, 2012). In the late 1990s, nonlinear programming method was used in designing optimal controllers for aero-engines to regulate their shaft speeds (Chipperfield, Bica, & Fleming, 2002; Kulkarni & KrishnaKumar, 2003; Teren, 1977), but the intensive calculation task of nonlinear programming blocked the way of application. The widely adopted method in reality is the max–min control method. In Yu, Liu, Bao, and Xu (2009), the stability of max–min control is ensured by the methods of switched systems (Branicky, 1998; Liberzon & Morse, 1999; Lin & Antsaklis, 2009; Long & Zhao, 2012; Ma, Liu, Zhao, Wang, & Zong, 2015; Sun & Wang, 2012). Recently, safety as well as stability issues of max–min control have been proved theoretically by Richter (2011). Linear models are used in Yu et al. (2009) and Richter (2011). In fact, the dynamics of the aero-engine are far more complicated, varying with the operating point and the working environment. This is why gain scheduling controllers usually have a better performance (Frederick, Garg, & Adibhatla, 2000; Wolodkin, Balas, & Garrard, 1999). Therefore, nonlinear models, including the linear parameter varying (LPV) model and the equilibrium manifold expansion (EME) model, have been proposed (Marcos & Balas, 2004; Sui, Yu, & Zhao, 2008), where a cluster of linear models are given along the equilibrium manifold (EM) and then a map is designed to correlate the current operating point to one of the linear models. Based on these models, Lyapunov theory has been applied to design gain scheduling controllers (Balas, 2002; Gilbert, Henrion, Bernussou, & Boyer, 2010; Pakmehr, Fitzgerald, Feron, Shamma, & Behbahani, 2012, 2013).

In the existing results, theoretical analyses are mostly about stability and safety. While the dynamic performance, which is very important in practice, is merely justified by simulations or experiments. Overshoot is a significant dynamic performance index. The overshoot of fan speed will lead to fluctuation in propulsion and hence jerking of the airplane, which is undesirable in consideration of comfort, let along the waste of fuel and the reduction of efficiency. Therefore, it is practically important to avoid speed overshoot of the fan. This is easy for a single-spool turbofan engine because the fan speed is directly determined by the fuel flow. For a two-spool turbofan engine like the Pratt & Whitney PW4084 turbofan engine (Spang & Brown, 1999) shown in Fig. 1, however, the overshoot-free regulation task becomes complicated, because the speed of the fan, i.e., the speed of the low-pressure shaft, is affected not only by the fuel flow but also by the speed of the high-pressure shaft. Traditionally, overshoot is avoided at the expense

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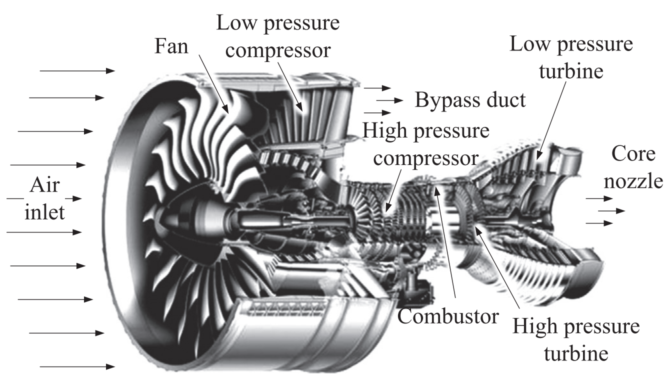

Fig. 1. Pratt & Whitney PW4084 turbofan engine.

of rapidity. How to ensure rapid as well as overshoot-free response theoretically is a meaningful yet difficult problem, and it is even harder in the absence of appropriate system model. To the best knowledge of the authors, no relevant results have been reported up to now.

It is noteworthy that although the linearization-based models, including the EME model and the LPV model, are relatively accurate on the EM, the accuracy of these models deteriorates while the system state moves far away from the EM. Unfortunately, in order to fully exploit the potential of the aero-engine and reduce the response time, we expect the aero-engine to operate at or near its safety limits in the acceleration process, i.e., far away from the EM. Therefore, the linearization-based models are not the best choice for high performance analysis. On the other hand, the component level (CL) model is pretty accurate within the whole flight envelope because it is developed according to the engines' aero thermodynamic principles and the components' thermodynamic characteristic (Liu, Yuan, Shi, & Zhao, 2014). However, the CL model contains charts of components' characteristic, which brings difficulty in controller design. This is why the CL model is mostly used in getting other types of models or simulation verification (Jaw & Mattingly, 2009; Meisner, Prasad, Chung, & Dhingra, 2014; Richter, 2012). Inspired by the idea in Chai, Hou, Lewis, Hussain, and Zhao (2011), we expect to design a high performance controller using the high accuracy data provided by the CL model.

Energy has been playing a significant role in control (Ortega, Van der Schaft, Mareels, & Maschke, 2001). For aero-engines, energy is especially important because the engine itself is an energy converting device. The energy stored in the two-spool aero-engine is mainly the total mechanical energy of the two shafts, and is reflected by the speeds of these shafts. Speed regulation needs to drive the system state from one equilibrium operating point to another, which amounts to changing the system energy from an initial level to a target level. Usually, we make the engine work at its safety limits in the early stage of a regulation process in order to gain a quicker energy storage rate (a greater acceleration). Since the high-pressure shaft responses faster than the low-pressure shaft, excessive energy is likely to be stored in the high-pressure shaft when the fan speed reaches its target value (Pakmehr et al., 2012, 2013). Part of this excessive energy will be passed on to the low-pressure shaft and lead to speed overshoot. Noticing that overshoot only arises when the system energy surpasses the target energy, we hope to guarantee an overshoot-free response by avoiding energy over-storage, which is the basic motivation of our work.

In this paper, a switching control strategy is proposed for the two-spool turbofan engine to ensure overshoot-free speed regulation. Controllers and an energy-based switching law are designed using the historical data from the EM and the real-time data provided by the CL model. Asymptotic speed regulation, safety and overshoot-free transient performance are all guaranteed theoretically. The simulation of a practical two-spool turbofan engine verifies the validity of the switched control strategy.

The result of this paper has four distinct features. First of all, no mathematical system model is used in the design and analysis process. Secondly, the overshoot-free performance is ensured theoretically rather than merely indicated by simulations or experiments. Thirdly, system energy is used in designing the switching law. Finally, the overshoot-free performance is totally independent of the regulation range and the initial system state.

The rest of this paper is arranged as follows. Preliminaries are given in Section 2. Then, the energy model and the speed regulation problem are presented in Section 3. Section 4 analyzes the EM of aero-engines and its relation with speed regulation. In Section 5, the overshoot-free switched controller is presented. Section 6 contains conclusions.

2. Preliminaries

Some useful preliminaries are given in this section. First, we introduce the concept of equilibrium manifold (EM). Consider a nonlinear system

$$\dot{x} = f(x, u), \tag{1}$$

where $x \in R^n$ is the state, $u \in R^m$ is the input.

The EM of System (1) is the set $\{(x, u) | f(x, u) = 0\}$ (Yu, Chang, & Bao, 2005). The dimension of the EM equals to the dimension of u provided that, for a specific constant input $u = u_e$, there is a unique equilibrium $x = x_e$ (Liu et al., 2014). In this case, the EM can be parameterized by an m dimensional variable α

$$x_e = x_e(\alpha), \quad u_e = u_e(\alpha). \tag{2}$$

Furthermore, a unique equilibrium point can be determined if m uncorrelated constrains are given in addition to (2).

Now, we give a lemma which will be used in the sequel.

Lemma 1. *Consider a nonlinear system*

$$\begin{cases} \dot{x}_1 = f(x_1, x_2), \\ \dot{x}_2 = -f(x_1, x_2), \end{cases} \tag{3}$$

where $f(x_1, x_2)$ is monotonically decreasing with respect to x_1 and monotonically increasing with respect to x_2. Suppose (x_{1e}, x_{2e}) is an equilibrium, i.e., $f(x_{1e}, x_{2e}) = 0$. If $x_1(t_0) \le x_{1e}$ and $x_1(t) + x_2(t) = x_{1e} + x_{2e}$ is satisfied for all $t \ge t_0$, then we have

(1) *$x_1(t)$ monotonically increases with t;*
(2) *$\lim_{t\to\infty} x_1(t) = x_{1e}$;*
(3) *$x_1(t) \le x_{1e}$ for all $t \ge t_0$.*

Proof. The proof can be easily completed by computing the time derivative of the positive definite function $V = (x_1 - x_{1e})^2$. □

3. Energy model and the speed regulation problem

In this section, we first review the thermodynamic principles of the engine, aiming at extracting an energy model that will be used in the following design and analysis. Then, the safety limits are introduced and the overshoot-free speed regulation problem is described.

As shown in Fig. 2, the two-spool turbofan engine is composed of several cascading modules (Meisner et al., 2014; Richter, 2012). The low-pressure rotor is composed of the fan, the low-pressure compressor (LPC) and the low-pressure turbine (LPT) which are