Chinese Journal of Aeronautics, (2018), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Adaptive sliding mode control for limit protection of aircraft engines

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Received 26 June 2017; revised 12 September 2017; accepted 14 September 2017

KEYWORDS

Adaptive control;
Aircraft engine;
Estimators;
Protection;
Sliding mode control

Abstract In practice, some sensors of aircraft engines naturally fail to obtain an acceptable measurement for control propose, which will severely degrade the system performance and even deactivate the limit protection function. This paper proposes an adaptive strategy for the limit protection task under unreliable measurement. With the help of a nominal system, an online estimator with gradient adaption law and low-pass filter is devised to evaluate output uncertainty. Based on the estimation result, a sliding mode controller is designed by defining a sliding surface and deriving a control law. Using Lyapunov theorem, the stability of the online estimator and the closed-loop system is detailedly proven. Simulations based on a reliable turbofan model are presented, which verify the stability and effectiveness of the proposed method. Simulation results show that the online estimator can operate against the measurement noise, and the sliding controller can keep relevant outputs within their limits despite slow-response sensors.

1. Introduction

This paper is concerned with the problem of limit protection under unreliable measurement, relevant to practical situations where system outputs are difficult to be measured but should be kept within safe boundary. This situation arises, for instance, in aircraft engine control, where outputs such as turbine temperature and compressor pressure must be regulated within limits, while the corresponding sensors suffer considerable uncertainties.

Limit protection, which frequently exists as an auxiliary part in control systems, is absolutely not the primary intention of control but is a necessary guarantee of safety. As in the case of aircraft engine control, the main objective is to provide the desired thrust based on the position of the throttle, nevertheless, limit protection is indispensable to keep the engine operating within the limits.[1,2] Fig. 1 shows the widely used architecture of a typical system in aircraft engine control field, which contains steady-state control (primary control), transient control and limit protection. Despite multi-regulator, only the selected control input is available to handle all those

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2018.05.011
1000-9361

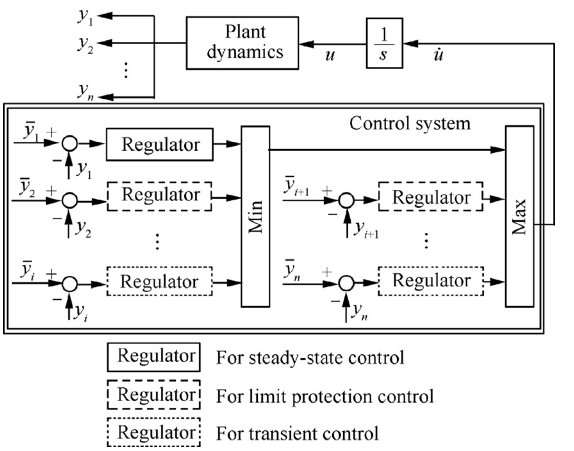

Fig. 1 Typical architecture in aircraft engine control field.3

three functions. The specific meanings of variables in Fig. 1 can be found in Ref. 3.

There are plenty of candidates that can be applied to design the regulators for limit protection. Proportional-Integral-Derivative (PID) control with gain-scheduling technique has been used for decades in the aerospace industry.[4–8] Sliding Mode Control (SMC) is well-known with mature theories and numerous successful applications.[9,10] With the one-sided convergence property, SMC is especially suitable for limit protection tasks. In the case of aircraft engine control, SMC regulators have been developed to supplant traditional linear regulators, where SMC can strictly keep relevant outputs within their limits and improve the control performance.[3,11,12,13]

In aircraft engine control field, various kinds of sensors are applied to measure rotor speed, temperature and pressure. Therefore, a universal assumption is made in most studies that the states and outputs of a turbo-plant are measurable. In practical situations, however, some sensors naturally failed to obtain the accurate parameters immediately. Because of the need to shield the thermocouples, for example, the temperature measurement has slow response time and is not particularly good for control proposes.[2] This motivates a reconsideration of the uncertainties in measurement.

For the control tasks with parameter uncertainty, adaptive control is useful to improve control performance online by an adaptation or estimation mechanism. Generally, there are two main approaches for adaptive control. One is the so-called Model-Reference Adaptive Control (MRAC), and the other is the so-called self-turning control. In the former approach, a reference model is introduced for the adaption of unknown parameters,[14–16] while in the latter approach, an estimator is designed to judge the unknown parameters. Unlike in MRAC design where the parameter adaption law is affected by the choice of the control law, the estimation law is independent of the choice of control law in self-turning control.[17]

In this article, we concentrate on the limit protection task, which is a sub-problem in the entire control system. Accordingly, an adaptive sliding mode regulator is proposed with system uncertainties considered, especially the ones in output measurement. The rest of this paper is organized as follows: First, a tracking problem with system uncertainties is described. Next, an online estimator and its adaptive law are devised to judge the output uncertainties and remedy their adverse effects on output measurements. Then, a sliding controller coupled with the estimator is designed by defining a sliding surface and deriving a SMC law. The system stability on sliding surface is detailedly proven and the reachability of sliding surface is guaranteed. And then, simulations based on a reliable nonlinear turbofan plant are presented, which verify the effectiveness of the proposed controller. Finally, we conclude the paper.

2. Problem formulation

Consider the uncertain dynamical system

$$\begin{aligned} \dot{\boldsymbol{x}}(t) &= (\boldsymbol{A}+\Delta\boldsymbol{A}(t))\boldsymbol{x}(t)+(\boldsymbol{B}+\Delta\boldsymbol{B}(t))\boldsymbol{u}(t) \\ \boldsymbol{y}(t) &= \boldsymbol{C}\boldsymbol{x}(t)+\boldsymbol{D}\boldsymbol{u}(t)+\boldsymbol{f}(t) \end{aligned} \tag{1}$$

where $\boldsymbol{x}(t)\in\mathbf{R}^n$ is the measurable state vector, $\boldsymbol{u}(t)\in\mathbf{R}^m$ is the control input and $\boldsymbol{y}(t)\in\mathbf{R}^m$ is the output vector; $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{D}$ are constant matrices of appropriate dimensions; $\Delta\boldsymbol{A}(t)$ and$\Delta\boldsymbol{B}(t)$ represent the state and the input uncertainty respectively; $\boldsymbol{f}(t)$ represent the output uncertainty. With a desired signal $\boldsymbol{r}(t)\in\mathbf{R}^m$ given, we intend to devise a feedback control so that the output $\boldsymbol{y}(t)$ tracks $\boldsymbol{r}(t)$ as time goes to infinity.

The following assumption of $\Delta\boldsymbol{A}(t)$ and $\Delta\boldsymbol{B}(t)$ is made.

Assumption 1. The uncertainty matrix $\Delta A(t)$ and $\Delta B(t)$ satisfy

$$[\,\Delta\boldsymbol{A}(t)\quad \Delta\boldsymbol{B}(t)\,] = \boldsymbol{E}\cdot[\,\boldsymbol{F}_{\rm a}(t)\boldsymbol{H}_{\rm a}\quad \boldsymbol{F}_{\rm b}(t)\boldsymbol{H}_{\rm b}\,] \tag{2}$$

where E, $H_{\rm a}$ and $H_{\rm b}$ are known constant matrices, while $F_{\rm a}(t)$ and $F_{\rm b}(t)$ are unknown time-varying matricessatisfying $F_{\rm a}^{\rm T}(t)F_{\rm a}(t)\leq I$ and $F_{\rm b}^{\rm T}(t)F_{\rm b}(t)\leq I$.

Due to an unknown $f(t)$, $y(t)$ cannot be acquired by the known states and inputs, which makes it elusive to achieve the tracking problem. However, the desire to obtain an available $y(t)$ motivates us to design an online estimator in the next section.

3. Online estimator design

To provide an accurate estimation of $\boldsymbol{f}(t)$, we utilize both output measurements and the nominal system of Eq. (1).

As mentioned before, sensors for output measurement $\boldsymbol{y}(t)$, temperature for instance, are unacceptable due to slow response time. We regard them as first-order dynamics for convenience with the following form:

$$\begin{cases} \boldsymbol{\Lambda}_{\rm s}\dot{\boldsymbol{y}}_{\rm s}(t) = -\boldsymbol{y}_{\rm s}(t)+\boldsymbol{y}(t) \\ \boldsymbol{\Lambda}_{\rm s} = \begin{bmatrix} \tau_1 & 0 & \cdots & 0 \\ 0 & \tau_2 & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & \tau_m \end{bmatrix} \end{cases} \tag{3}$$

where $\boldsymbol{y}_{\rm s}(t)\in\mathbf{R}^m$ is the output vector of sensors and τ_i is the time constant of the ith sensor.

The nominal system of Eq. (1) can be written as

$$\begin{aligned} \dot{\boldsymbol{x}}^*(t) &= \boldsymbol{A}\boldsymbol{x}^*(t)+\boldsymbol{B}\boldsymbol{u}(t) \\ \boldsymbol{y}^*(t) &= \boldsymbol{C}\boldsymbol{x}^*(t)+\boldsymbol{D}\boldsymbol{u}(t) \end{aligned} \tag{4}$$

Substituting Eq. (4) into Eq. (1) yields