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Virtual-command-based model reference adaptive control for abrupt structurally damaged aircraft

Jing Zhang, Xiaoke Yang, Lingyu Yang*

School of Automation Science and Electrical Engineering, Beihang University, Beijing, 100191, China

A R T I C L E I N F O

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A B S T R A C T

Although a high-gain learning rate can offer ideal tracking performance in adaptive control in theory, it can also lead to high-frequency oscillations in practice due to the unmodeled dynamics of the system. In aircraft structural damage scenarios, the strong uncertainty and the safety-critical nature of the problem make this conflict critical. In this paper, a novel virtual-command-based model reference adaptive control (MRAC) scheme for flight control is proposed. In the new framework, the direct relationship between the learning law and the actual tracking error is broken; instead, a virtual command is introduced as the input to the standard MRAC controller. The key feature is that even when the virtual tracking error is large, the actual tracking error can be maintained within a small range; thus, the MRAC learning rate does not necessarily need to be large to suppress the virtual transient tracking error, which is greatly beneficial for the robustness of the MRAC controller. The proposed method is illustrated by the attitude control of the 6-DOF nonlinear Generic Transport Model in a scenario with a broken left wing tip.

1. Introduction

Structural damage to the airframe of a modern aircraft, such as structural failure in the wing tip, vertical tail or engine, is one of the most serious threats that pilots face. Such structural damage may lead to significant, abrupt and non-symmetric uncertainties in the aircraft aerodynamics, mass properties, and control efficiencies [1,2]. The control responses of such a damaged aircraft can be far different from those of normal aircraft [3–5]. Consequently, a fundamental problem arising in flight control theory is to ensure the recovery of stability and the level of desired performance when significant abrupt changes in uncertainties occur.

Compared with fixed-gain robust control design approaches, adaptive control methods more effectively address these sources of uncertainty and require less modeling information; thus, they have gradually gained popularity. A variety of adaptive control approaches have been proposed to address the strong uncertainty caused by structural damage [6–10]. These early studies mainly focused on large uncertainties and theoretical guarantees of asymptotic stability. However, little attention has been paid to the transient performance when abrupt variations occur. Unfortunately, due to the nonlinear and complex aerodynamics, poor transient performance can contribute to fatal accidents:

1) A poor transient response can excite unmodeled dynamics and/or place the aircraft under dangerous conditions, such as stall or spin [11,12].

2) The use of a high learning rate in adaptive control may result in high-frequency oscillations, which can violate actuator rate saturation constraints and excite unmodeled system dynamics [13].

Because the standard model reference adaptive control (MRAC) learning law directly relies on the tracking error, it usually has poor transient performance in the learning phase [14]. Before the stable region is reached, this undesired transient response can be far from the reference signal [15]. Improvement of the transient performance is thus a challenging practical topic in adaptive control.

A classic approach is to modify the reference model [16,11,17,18]. A closed-loop reference model (CRM) structure was proposed in [16,11], in which plant information was used to alter the reference trajectory to improve the transient properties. [17] introduced a new reference system to prevent the update law from attempting to learn from high-frequency system error content. Because the CRM approach does not introduce new information to the controller, i.e., the learning process is still driven by the tracking error, it can be treated as a nonlinear adjustment to the learning rate.

The transient performance can also be improved by adjusting the learning law. [19] and [20] modified the adaptive learning law in accordance with an upper bound or a prescribed performance bound on the desired transient performance. [21] and [22] used nonlinear generalized restricted potential functions to maintain

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* Corresponding author.
E-mail address: yanglingyu@buaa.edu.cn (L. Yang).

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Nomenclature

$\alpha_i(\boldsymbol{\lambda})$	scheduling coefficient for the ith vertex	
$\bar{\alpha}$	angle of attack	deg
$\bar{\beta}$	sideslip angle	deg
$\boldsymbol{\Gamma}_\delta \in \mathbb{R}_+^{m\times m}$	symmetric positive-definite learning matrix of $\boldsymbol{\delta}$	
$\boldsymbol{\Gamma}_\phi \in \mathbb{R}_+^{(l-1+m)\times(l-1+m)}$	symmetric positive-definite learning matrix of $\boldsymbol{\phi}$	
$\boldsymbol{\lambda} \in \mathbb{R}^{n_\lambda}$	vector of structural damage	
ω	bandwidth of the learning error observer	
ϕ	roll angle	deg
ψ	yaw angle	deg
$\sigma_{\max}(\cdot)$	maximum eigenvalues of the matrix	
$\sigma_{\min}(\cdot)$	minimum eigenvalues of the matrix	
θ	pitch angle	deg
$\boldsymbol{A}(\boldsymbol{\lambda}) \in \mathbb{R}^{n\times n}$	system matrix	
$\boldsymbol{A}_i \in \mathbb{R}^{n\times n}$	vertices of the convex hull	
$\boldsymbol{A}_m \in \mathbb{R}^{n\times n}$	system matrix of the reference model	
$\boldsymbol{B}(\boldsymbol{\lambda}) \in \mathbb{R}^{n\times m}$	control input matrix	
$\boldsymbol{B}_m \in \mathbb{R}^{n\times m}$	control input matrix of the reference model	
$\boldsymbol{d}(\boldsymbol{\lambda}) \in \mathbb{R}^{m}$	disturbance	
$\boldsymbol{D} \in \mathbb{R}^{n\times m}$	disturbance input matrix	
$\boldsymbol{e}_r \in \mathbb{R}^{n}$	actual tracking error	
$\boldsymbol{e}_v \in \mathbb{R}^{n}$	virtual tracking error	
$\boldsymbol{q} \in \mathbb{R}^{m}$	learning error of the adaptive control system	
$\boldsymbol{r} \in \mathbb{R}^{m}$	reference command/actual command	
$\boldsymbol{u} \in \mathbb{R}^{m}$	input vector	
$\boldsymbol{v} \in \mathbb{R}^{m}$	virtual command	
$\boldsymbol{x} \in \mathbb{R}^{n}$	state vector	
$\boldsymbol{x}_{m_r} \in \mathbb{R}^{n}$	actual reference state vector	
$\boldsymbol{x}_{m_v} \in \mathbb{R}^{n}$	virtual reference state vector	
$\boldsymbol{\Lambda}(\boldsymbol{\lambda}) \in \mathbb{R}^{m\times m}$	control effectiveness matrix	
H	altitude	m
p	roll rate	deg/s
q	pitch rate	deg/s
r	yaw rate	deg/s
t	time	s
t_d	time of the damage	s
u_e, u_a, u_r	deflections (deg) of the elevator, aileron and rudder	
v	airspeed	m/s
X	north position	m
Z	east position	m

the transient performance error below an a priori, user-defined worst-case closed-loop system performance bound. [23] developed a derivative-free adaptive control law and showed that its robustness against unmodeled dynamics is improved by increasing the adaptation gain. [14] added a mismatch estimation term to suppress high-frequency oscillations. [24] proposed a bi-objective optimal control modification method that establishes a tradeoff between performance and robustness through the suitable selection of the modification parameters. [25] introduced an artificial basis function to minimize the system tracking error during the learning phase of an adaptive controller. [26] presented a novel architecture that includes modification terms in the adaptive controller and the learning law; these modification terms vanish as the system reaches its steady state. In addition to the above approaches, [27–32] investigated the problem of improving the transient performance for specific systems.

In the existing methods, the transient performance is improved by modifying the reference model and/or the learning law; however, these methods still follow the basic MRAC scheme, i.e., the learning laws are driven by the tracking error. The tradeoff between a large transient tracking error and a high learning rate remains a problem. From a practical standpoint, a high learning rate may lead to control saturation, control oscillation or the excursion of control components outside of the linear regime, among other undesirable effects, and the learning rate cannot be increased to an unlimited extent. To solve this problem, this paper proposes a novel approach in which the direct relationship between the learning law and the closed-loop tracking error is broken; instead, a virtual command and a virtual tracking error are used to drive the learning law. The proposed control scheme has the following features: 1) The virtual command works on both the reference model and the controller but does not involve any modification of the reference model, the update law or the controller, especially the learning rate. Thus, the virtual command does not affect the stability, robustness or error convergence properties of the standard MRAC scheme, and it can be applied in combination with most MRAC methods. 2) The virtual tracking error can be large while the actual tracking error is maintained within a small range; thus, the MRAC learning rate does not necessarily need to be large to suppress the virtual transient tracking error, which is greatly beneficial for the robustness of the MRAC controller. 3) The virtual command is designed to compensate for the learning error instead of the MRAC tracking error. Note that the learning error is related to the time derivative of the tracking error; thus, compensating for the learning error is more efficient.

The remainder of this paper is organized as follows. Section 2 introduces the model of a damaged aircraft. Section 3 presents a standard linear-parameter-varying-model-based model reference adaptive control scheme (LPV-MRAC). Section 4 analyzes the transient performance of LPV-MRAC. A new approach, called virtual-command-based MRAC (VC-MRAC), is proposed in Section 5 to improve the transient performance. A simulation of the generic transport model (GTM) in a scenario in which the left wing tip has broken off is discussed in Section 6. Finally, conclusions are given in Section 7.

2. Plant models and problem formulation

In this paper, a linear parameter-varying (LPV) model is used to represent the dynamics of a structurally damaged aircraft as follows:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}(\boldsymbol{\lambda})\boldsymbol{x} + \boldsymbol{B}(\boldsymbol{\lambda})\boldsymbol{u} + \boldsymbol{D}\boldsymbol{d}(\boldsymbol{\lambda}), \tag{1}$$

where $\boldsymbol{D}$ is a known disturbance input matrix; and $\boldsymbol{A}(\boldsymbol{\lambda})$, $\boldsymbol{B}(\boldsymbol{\lambda})$ and $\boldsymbol{d}(\boldsymbol{\lambda})$ are functions of an unknown parameter vector $\boldsymbol{\lambda}$, which represents the severity of various types of damage, such as a broken-off wing tip, a broken-off vertical tail and a broken-off left stabilizer.

Considering that aircraft damage occurs instantaneously, $\boldsymbol{\lambda}$ is formulated as a function that shows switching behavior at a specific time, that is,

$$\boldsymbol{\lambda}(t) = \begin{cases} \boldsymbol{\lambda}_0, t < t_d \\ \boldsymbol{\lambda}_d, t \geq t_d \end{cases}. \tag{2}$$

Note that an aircraft is a physical system, and $\boldsymbol{\lambda}$ can be assumed to be bounded such that $\boldsymbol{\lambda} \in \Omega_{\boldsymbol{\lambda}}$. Therefore, $\boldsymbol{A}(\boldsymbol{\lambda})$ must lie in a compact set that can be embedded in a polytope, that is,

$$\boldsymbol{A}(\boldsymbol{\lambda}) = \sum_{i=1}^{l} \alpha_i(\boldsymbol{\lambda})\boldsymbol{A}_i, \tag{3}$$

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