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Gust response stabilization for rigid aircraft with multi-control-effectors based on a novel integrated control scheme[☆]

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ABSTRACT

For the higher performance demand of aircraft, the active control techniques of flight control system become more attractive. Among these approaches, the gust response stabilization has been more significant for the consideration of safety and comfort. Due to the constraint of the traditional control law, the parameter tuning process in a large envelope is very time-consuming and some special maneuvers can't accomplish by these designs. In order to overcome these defects of the conventional flight control laws, a new integrated nonlinear control scheme with modified active disturbance rejection control and real-time direct lift compensation control allocation technology is proposed. Its switched extended state observer can bring the observers to their full talents to estimate the signals. Aiming at taking full potential of the multi-control-effectors aircraft, two real-time linear control allocation methods for the transition from virtual control variables to actual control variables are also introduced. The simulation showed that this structure has good tracking performance and wind resistance performance.

1. Introduction

By the modern aircrafts are becoming increasingly complicated, the design of the FCS be the same [1–7]. As a key technique of control configured vehicle design, GRS has been an attractive focus of many researchers. With the development of control theory, the design method of GRS control scheme is gradually transformed from optimal control to robust control [8,9]. In the last few years, many scholars have done research on it, including designing classical closed-loop controllers to complete gust mitigation, e.g. linear quadratic regulator (LQR) theory, linear quadratic Gaussian (LQG) theory [10], H_∞ control theory [11], μ synthesis theory [12], model reference adaptive control (MRAC) theory [13], L1 adaptive control theory [14], model predictive control (MPC) theory [15]. In any process of industrial control systems, the internal disturbances (unmodeled dynamics, model uncertainty, parameter perturbation, etc.) are very common in the controlled object. Moreover, during an actual flight, there will be many external disturbances, such as gust and turbulence, which makes the design of GRS more difficult. The system does not always converge completely when the nominal system parameters are uncertain and drifting. An improved H_∞ robust controller including parameter uncertainty or parameter error is established [16]. By describing the uncertainty of the object and setting the allowed range of perturbation, the structured singular value method is designed to keep the system stable and robust [17–19]. But the study only considered the wing bending (deformation between the wing root and wing tip) as a flexible variable, while the gust model only specified as the zero mean Gauss noises of unit intensity, the other gust models are not included.

An actual controlled object output is usually a dynamic part output, and it always has some extent of inertia. So, the output signal will not change too drastic. However, an input command is usually driven directly by an exogenous system. Hence, the input signal is likely to be hopping. Therefore, in the traditional feedback control theory, it is with restraint to eliminate the hopping input error signal by using the non-jumping output error signal. Normally, an error feedback control law consists of the proportional (P), integral (I) and derivative (D) of error signal. It is intuitive that the linear combination of these quantities is not the most appropriate combination. It is possible to find a more appropriate and efficient combination form in the nonlinear range. A large number of control engineering practices showed that the application of integral error feedback in the classical control plays a significant role in suppressing the constant disturbance [20]. But

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ACRONYMS

ADRC	Active disturbance rejection control
AOA	Angle of attack
(A/V)MV	(Actual/ virtual) manipulating variables
CA	Control allocation
(C/I)CV	(Command/intermediate) controlled variables
ESO	Extended state observer
FCS	Flight control system
GRS	Gust response stabilization
LADRC	Linear active disturbance rejection control
(L/N)SEF	(Linear/nonlinear) state error feedback
(L/N)ESO	(Linear/nonlinear) extended state observer
LQ(G/R)	Linear quadratic (Gaussian/ regulator)
MADRC	Modified active disturbance rejection control
MPC	Model predictive control
MRAC	Model reference adaptive control
NDI	Nonlinear dynamic inversion
RTDLC	Real-time direct lift compensation
RTLCA	Real-time linear control allocation
SEF	State error feedback
SESO	Switched extended state observer
SSEF	Switched state error feedback
TD	Tracking differentiator

this kind of method often brought some negative effects. It made the closed-loop system unresponsive, prone to oscillation and saturated to control variables. To remedy the inherent defect of classical model-based control theory, Jingqing Han proposed a newly active disturbance rejection control (ADRC) theory [21]. However, the nonlinear state error feedback control law and nonlinear extended state observer adopted in the basic ADRC make it difficult to tune the parameters, analyze the stability and analyze the performance. Zhiqiang Gao presented a Linear active disturbance rejection control (LADRC) [22]. The key breakthroughs of this paper are simmered down to:

(i) Heretofore, the GRS approaches mainly regarded an impact of gust on the rigid aircraft model as an effect of a disturbed AOA. The premise of this assumption is that the variation of true airspeed is not so drastic, which is not suitable for a nonlinear aircraft model due to the possible dramatic speed change. Another defect of this hypothesis is that the disturbed AOA is usually so small which can't depict an all-round gust impact on the aircraft precisely. In this paper, a more comprehensive longitudinal aircraft-gust generalized model is presented, which may restore the true environment of nonlinear rigid aircraft when the gust encountering.

(ii) The traditional ADRC is composed of a tracking differentiator (TD), an extended state observer (ESO) and an state error feedback (SEF) control law. The linear extended state observer (LESO) and linear state error feedback (LSEF) control law have clearer physical meaning and simpler parameter tuning. While, the nonlinear state error feedback (NSEF) control law and nonlinear extended state observer (NESO) have high parameter efficiency, good tracking accuracy and fast response speed. In order to give full ability to the above design methods, a modified active disturbance rejection control (MADRC) method has been put forward.

(iii) To effectively solve the control problem of multi-control-effectors aircraft, the intuitive idea is to apply the control allocation (CA) method to make the transition from virtual manipulating variables (VMV) to actual manipulating variables (AMV). However, the conventional CA methods generally treat the three axis angular rates/moments (or moment coefficients) as the VMV, and they often only solve the command tracking task. To broaden the traditional CA method to the GRS application, an idea of assigning the lift coefficient as the VMV has been introduced. In this paper, this CA technology is referred to as real-time direct lift compensation (RTDLC) control allocation technology.

(iv) Two methods to obtain the control effectiveness matrix have been proposed and have been applied successfully to the calculation of linear control allocation dynamically. The control effectiveness matrix contains both the lift coefficient and pitching moment coefficient corresponding to all effectors. The matrix is essentially a matrix-valued function of Mach number and AOA, which is solved in real-time by the current Mach number and AOA of the aircraft.

For clarity, the remaining parts of this paper are organized as follows. In Section 2, the longitudinal integrated model in a variable wind field is presented. The design of the controller is detailed in Section 3. The design of the allocator is illustrated in Section 4. The proposed scheme is verified and analyzed by the (Matlab/Simulink) simulation in Section 5. Finally, this method is summarized and showed some improvements in the future in Section 6.

2. The longitudinal integrated model in a variable wind field

Discarding the earth rotation and elastic deformation, the differential equation of the flight-path velocity vector $\{\vec{V}_K\}_r$ along to a moving reference frame S_r is defined as:

$$\begin{aligned} m\left(\left\{\begin{bmatrix}\dot{u}_K\\ \dot{v}_K\\ \dot{w}_K\end{bmatrix}\right\}_r+\left\{\begin{bmatrix}p\\ q\\ r\end{bmatrix}\right\}_r\times\left\{\begin{bmatrix}u_K\\ v_K\\ w_K\end{bmatrix}\right\}_r\right) \\ =\left\{\begin{bmatrix}F_x\\ F_y\\ F_z\end{bmatrix}\right\}_r \\ =\left\{\begin{bmatrix}T_x+A_x+G_x\\ T_y+A_y+G_y\\ T_z+A_z+G_z\end{bmatrix}\right\}_r \end{aligned} \tag{1}$$

where the subscript $\{*\}_r$ means a moving reference frame S_r. $\{[u_K \;\; v_K \;\; w_K]^T\}_r$ refers to the three components of the flight-path velocity vector $\{\vec{V}_K\}_r$ along to a moving reference frame S_r. $\{[p \;\; q \;\; r]^T\}_r$ refers to the three components of the flight-path angular velocity vector $\{\vec{\Omega}_K\}_r$ with respect to the inertial reference frame S_i along to the moving reference frame S_r. T, A, G refer to the thrust, the aerodynamic force and the gravity. In order to conveniently analyze the influence of the wind disturbance on the flight characteristic, it is necessary to establish the vector equation of the aircraft mass center motion along to the air-axes S_a. The air-axes to ground-axes rotational angular velocity vector is derived:

$$\{\vec{\Omega}_A\}_a=\begin{bmatrix}-\dot{\chi}_a\sin\gamma_a\\ \dot{\gamma}_a\\ \dot{\chi}_a\cos\gamma_a\end{bmatrix} \tag{2}$$

Then, defining the true airspeed vector $\{\vec{V}_A\}_a$ along to the air-axes S_a and the wind vector $\{\vec{V}_W\}_g$ along to the ground-axes S_g. According to these two vectors, the flight-path velocity vector $\{\vec{V}_K\}_a$ along to the air-axes S_a is defined: