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Nonlinear gain-scheduled flight controller design via stable manifold method

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ABSTRACT

This research presents a nonlinear gain-scheduled flight controller design method via a stable manifold theory in order to handle the nonlinearities of the F-18 High Alpha Research Vehicle due to the change in the aerodynamic characteristics at different angles of attack and the airspeed variation. The designed longitudinal flight control system consists of a nonlinear gain-scheduled stabilization augmentation system which is designed using the stable manifold method, and a linear gain-scheduled control augmentation system which consists of proportional and integral gains. The nonlinear longitudinal flight controller is verified in a 6 degree-of-freedom simulator.

1. Introduction

One of the desired characteristics of modern fighter or acrobatic aircraft is the capability to fly at high angles of attack or post-stall conditions. However, the aerodynamic characteristics become extremely complex and highly nonlinear when the angle of attack exceeds a stall angle. At that moment, many aerodynamic coefficients of the aircraft dramatically change their values even with a small increment of the angle of attack, i.e., the aircraft experiences adverse phenomena, such as significant lift and pitching control losses, asymmetric stall, and auto-rotation, which generally cause linear controllers to be inadequate and inefficient [1,2].

A traditional approach to take into account the nonlinearities of the aircraft in the flight controller design process is to use gain-scheduling technique. In this approach, a number of operating points for specified flight conditions are defined, and then the mathematical model of the aircraft is linearized at each flight condition. A family of linear controller candidates for those flight conditions is constructed, then a gain-scheduled controller is obtained by blending controller candidates to cover the entire flight envelope [3–9]. The advantage of this approach is that it is simple and practical. However, it requires many operating points to capture the nonlinearity of the aircraft, especially in the post-stall region.

There are also other approaches which can consider the changes of aerodynamic characteristics in order to enable the aircraft to fly at high angles of attack or to perform super-maneuvers. It appears that nonlinear dynamic inversion and sliding mode control are two of the most applied methods to design nonlinear flight controllers recently. The nonlinear dynamic inversion approach [10–14] directly takes into account the nonlinearities within the entire flight envelope. Therefore, it can control the aircraft in the linear and post-stall regions by using a single controller. However, this method requires a precise knowledge of the aircraft model and is sensitive to modeling errors and parameter uncertainties. This sensitivity may be critical since it is not easy to obtain the exact model of the aircraft in practice. The sliding mode control approach [15–18] can also handle post-stall flights as well as perform super-maneuvers like Herbst and Cobra maneuvers. It is a robust nonlinear control design approach which can deal with modeling errors and parameter uncertainties efficiently. However, it experiences an undesirable oscillation phenomenon, called chattering, in implementation due to the discontinuous control action of the method. Some alternative approaches which can handle nonlinearities of the aircraft are, for instance, nonlinear optimal control [19–21], back-stepping [22–25], and neural networks [26–29].

This paper presents a flight controller design method for the longitudinal motion control of the F-18 High Alpha Research Vehicle (HARV) [30,31]. Although the HARV is equipped with thrust

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vectoring mechanism, only aerodynamic control surfaces are used to control the aircraft in this research. The flight controller structure considered in this research is similar to the conventional one which consists of a stabilization augmentation system (SAS) that uses proportional gains to feedback attitude rates, and a control augmentation system (CAS) that uses proportional and integral gains to feedback attitude angle errors. However, in this research, we take the angle of attack of the aircraft as a state variable in the SAS design to deal with the changes in the aerodynamic characteristics at high alpha angles. Moreover, since the variation of the aerodynamic characteristics is highly nonlinear, a nonlinear SAS is designed via the stable manifold method [32–36]. Additionally, since the dynamics of the aircraft also depend on the airspeed, the gain-scheduling technique is applied to deal with the change of airspeed in flight. The traditional gain-scheduling technique usually requires many operating points corresponding to specified flight conditions in order to capture the nonlinearities of the aircraft. Then, a linear controller candidate is designed for each flight condition. In this research, a set of sparse operating points is considered. For that reason, the nonlinearities of the aerodynamic characteristics between adjacent operating points are strong, which corrupt the control performance of the linear controller. The proposed nonlinear controller, on the other hand, does take into account those nonlinearities in the controller design process. Therefore, it can achieve better control performance compared with the linear one. A partial result of this research is briefly discussed in [37]. In this paper, the controller design method, result and discussion will be given in details.

The outline of this paper is as follows: In Section 2, a nonlinear mathematical model of the longitudinal motion of the aircraft is presented. Section 3 describes the structure of the gain-scheduled controller considered in this research. In Sections 4 and 5, the gain-scheduled SAS and CAS are designed. The simulation results and discussions are shown in Section 6. Section 7 concludes this paper.

2. Mathematical model

This section describes the nonlinear equations of motion (EOMs) of the HARV. In this research, we focus on the motion control in the longitudinal direction. The perturbations in the lateral–directional motion are kept at small values via a feedback controller. Therefore, the lateral–directional motion is omitted due to its weak impact on the longitudinal variables. For that reason, this paper only consider the longitudinal motion model of the aircraft. Since the purpose is to control the aircraft using only aerodynamic control surfaces, the thrust vectoring mechanism is unused. Hence, the direction of the thrust is fixed along the body x-axis. The general nonlinear EOMs for the longitudinal motion are reported in [38] (page 115) and are summarized as below

$$\begin{aligned}
\dot{\alpha} &= q + \frac{1}{mV_T}(-L - F_T\sin\alpha + mg_D\cos(\theta-\alpha)), \\
\dot{q} &= \frac{M}{I_{yy}}, \qquad (1)\\
\dot{\theta} &= q,
\end{aligned}$$

where α is the angle of attack, q is the pitch angular velocity, m is the mass of aircraft, V_T is the total velocity, L is the lift force, F_T is the thrust, g_D is the gravitational constant, I_{yy} is the pitching moment of inertia, and M is the pitch moment. In these equations, the definitions of the lift force L and the pitch moment M are

$$L = \frac{1}{2}\rho V_T^2 S C_L, \quad M = \frac{1}{2}\rho V_T^2 S\bar{c} C_M, \qquad (2)$$

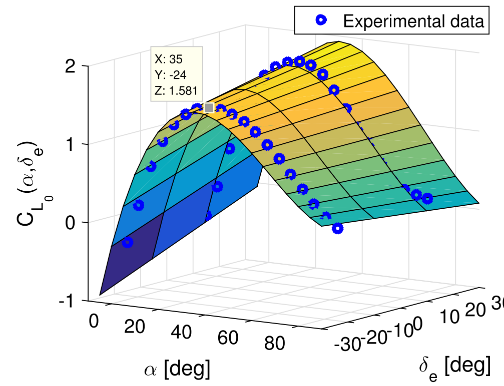

Fig. 1. Experimental data of $C_{L_0}(\alpha, \delta_e)$ at Mach 0.6 and its approximation which is expressed in (3).

where ρ is the air density, S is the reference area, $\bar{c}$ is the mean aerodynamic chord. C_L and C_M are the total lift and moment coefficients. In general, those coefficients depend on numerous parameters such as the altitude h, aircraft velocity V_T, angle of attack α, etc. In this research, we assume that around an operating point, the changes of the aerodynamic coefficients with respect to the altitude and velocity are small and can be neglected. Therefore, they can be expressed as functions of the angle of attack α and elevator deflection δ_e as below

$$\begin{aligned}
C_L &= C_{L_0}(\alpha,\delta_e) + \frac{\bar{c}}{2V_T}\left(C_{L_q}(\alpha)q + C_{L_{\dot{\alpha}}}(\alpha)\dot{\alpha}\right), \\
C_M &= C_{M_0}(\alpha,\delta_e) + \frac{\bar{c}}{2V_T}\left(C_{M_q}(\alpha)q + C_{M_{\dot{\alpha}}}(\alpha)\dot{\alpha}\right).
\end{aligned}$$

In the above equations, C_{*_*} denotes the aerodynamics derivative coefficients which are reported in [30]. Fig. 1 illustrates the values of $C_{L_0}(\alpha, \delta_e)$ at the altitude $h = 15000$ ft and Mach 0.6. It can be seen from this figure that the stall angle is around 35 deg. When the angle of attack exceeds the stall angle, the aerodynamic coefficients dramatically change, and the aircraft is beyond the linear region.

In order to design the flight controller for the HARV, the aerodynamic data of the aircraft are expressed in high order polynomials which are constructed by using a polynomial fitting method [33]. For example, the approximated polynomial function of $C_{L_0}(\alpha, \delta_e)$ is shown below

$$\begin{aligned}
C_{L_0}(\alpha,\delta_e) = {} & 0.1262 + 0.1094\alpha - 0.0022\alpha^2 \\
& + 1.0893\text{E}-05\alpha^3 + 0.0131\delta_e - 0.0002\alpha\delta_e \\
& + 4.6787\text{E}-07\alpha^2\delta_e. \qquad (3)
\end{aligned}$$

Note that only two sets of data corresponding to two positions of the elevator are provided in [30]. Therefore, the aerodynamic data of $C_{L_0}(\alpha, \delta_e)$ at the other elevator angles are estimated using (3). Fig. 1 shows that the approximated data of $C_{L_0}(\alpha, \delta_e)$, which are calculated from (3), and the experimental data, which are described in [30], are matching.

Substituting the approximated functions of the aerodynamic derivative coefficients into (1), eliminating the high order terms of δ_e (δ_e^k, $k = 2, 3, \dots$) since they are small, and assuming that $\theta - \alpha$ is insignificant, which makes $\cos(\theta - \alpha) \approx 1$, ones obtain

$$\begin{aligned}
\dot{\alpha} &= f_1(\alpha,q) + g_1(\alpha,q)\delta_e, \\
\dot{q} &= f_2(\alpha,q) + g_2(\alpha,q)\delta_e, \qquad (4)\\
\dot{\theta} &= q,
\end{aligned}$$