Nonlinear Oscillations Prevention in Unmanned Aerial Vehicle

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Abstract. The paper considers the prevention of nonlinear oscillations of a small unmanned aerial vehicle of a fixed wing (UAV) in a closed loop. This phenomenon is a rapidly developing aircraft oscillations accompanied by increasing amplitude in angular velocities and angles. The pilot can overcome the process of small amplitude oscillations by disconnecting from the control loop. However, since the oscillations begin suddenly and develop so quickly that the pilot does not have time to react. Often these events lead to loss of control and stability of the aircraft. In manned aircraft, this phenomenon has been known since the inception of large aviation. In literature it is called the pilot induced oscillations (PIO) or the aircraft pilot coupling (APC). Oscillations prevention is proposed to be implemented by introducing into the control loop a nonlinear corrective device that provides the control system in question with the desired phase stability margin. Simulation results of pitch angle are presented with active pilot control and the maximum possible time delay and amplitude of input signal.

Keywords: Nonlinear correction · UAV · Oscillations · PIO · Aircraft · Time delay· Phase shift· Saturation.

1 Introduction

Despite its prescription, the issue of PIO still exists and the last accident in commercial aviation dates from 2014 [7]. At the same time, UAVs became the successors of this problem. In recently years UAVs have become widely used in various fields of human activity. In this research we consider the UAV called "Phastball" which can operate both offline and/or remotely with the participation of a human operator. It was found from flight experiments that nonlinear oscillations occur when the UAV control modes switch from manual to control mode from a ground station [15]. After switching, the time delay of the transmitted input signal increases, and there is also the actuator rate limit, which affects the stability of the entire flight control system. Typical trigger of PIO are limit of control surface actuator, high pilot gain and time delay of signals. Its appear generally under conditions of demanding maneuvering, dramatically changing flight control modes and weather conditions. Oscillations can be severe irreversible, leading to loss of control of the aircraft. Thus, the task of oscillation prevention relates to the field of flight safety.

All existing methods are not suitable for all types of aircraft; any of them requires intensive modeling and testing. The emergence of PIO is not always associated with external factors, but in any case, the prevention of PIO is associated with ensuring the stability of the system. Currently, there are several approaches for prevention PIO. Inverse dynamics method [13,17]. The disadvantage of this method is the occurrence of errors in the transition to the original model, which is overcome in adaptive method [19] including neural network. In the paper [9] the authors propose to transfer full control to the electronic unit in dangerous moments of the flight. This method has the disadvantage that no fault tolerant avionics exist and the control system structure loses its mechanical reserve. The control allocation PIO method containing optimal control is proposed in [1]. In [8] H_∞ optimization and anti-windup compensator were designed for actuator loss in aircraft control system. Also such simplicity of implementation approaches are known as the phase compensation [3, 14, 18] using prefilters of various configurations. All of them are aimed at suppressing a high-frequency spectrum in the control loop and compensating for the phase lag between the input and output signal. Thus, in this work, a nonlinear prefilter easy to implement for preventing PIO in UAV is intended, characterized in that it expands the capabilities of the control system without loss of control accuracy at any level of the input signal compared to previously proposed ones.

The rest of the paper is organized as follows. The mathematical description of the system under study is given in Sec. 2. Representation of suggested nonlinear corrective device is given in Sec. 3. Simulation and concluding remarks are given in Sec. 4.

2 UAV-Pilot Model

Consider UAV-pilot model consisting of 3 components: pilot, nonlinear actuator and UAV as shown in Fig. 1. ϑ^* is the pitch reference signal, ϑ is the pitch output signal.

2.1 Pilot Model

One of the most important classes of piloting tasks is compensatory tracking tasks in which the pilot acts on the displayed error between a desired command input and the comparable vehicle output motion to produce a control action. The pilot model corresponding to the flight mission is taken in the form [16] with the parameters obtained in [15]:

$$W_p(s) = K_p \frac{T_L s + 1}{T_I s + 1} e^{-\tau s}, \tag{1}$$

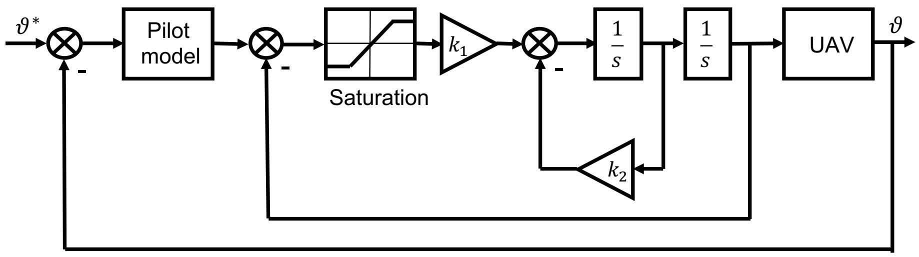

Fig. 1. Structure of UAV-pilot model

where K_p is the pilot static gain, which expresses the response to control error ratio. High level of K_p means that the pilot in active control. T_L and T_I is the lead and lag time constants respectively, τ is effective time delay, including transport delays and high frequency neuromuscular lags.

2.2 Actuator Model

A second-order nonlinear actuator model contained the rate limit component is described by the equations [4]:

$$\begin{aligned} \dot{\delta}(t) &= \begin{cases} 0, & \text{if} \quad (\delta \leq \bar{\delta}^{+}) \cup (v\delta > 0))|(\delta \leq \bar{\delta}^{-}) \cup (v\delta < 0) \\ v, & \text{other}, \end{cases} \\ \dot{v}(t) &= sat_{\bar{v}}(w(t)), \\ w(t) &= K_1(\delta^*(t) - \delta(t)) - K_2 v(t), \end{aligned} \tag{2}$$

where $\bar{\delta}^{+}$, $\bar{\delta}^{-}$ – the upper and lower boundary of the steering wheel deviation, $\bar{v}(\cdot)$ is the saturation function, $\bar{v}$ – rate limit, the coefficients K_1, K_2 set the characteristic frequency ω_a and the damping coefficient ξ_a: $\omega_a = \sqrt{K_1}$, $\xi = K_2/2\sqrt{K_1}$.

We take the characteristic of the rate limit nonlinearity as odd-symmetric and it is represented as describing function [12] depending on input amplitude A only:

$$J(A) = \frac{2B}{\pi b}\Big[\psi + \frac{\sin(2\psi)}{2}\Big], \tag{3}$$

where B/b – slope of the linear part of the saturation function characteristic, $\psi = \arcsin(b/A)$ is the phase shift between input and actuator signal. As shown in paper [6], if the magnitude of the phase shift exceeds the phase stability margin of the system, then the system loses stability. This can lead to both oscillations of unlimited amplitude and self-oscillations. Also in paper [2], it is argued that actuator rate limit does not always lead to PIO, from which it can be concluded that the PIO phenomenon only occurs under certain conditions and a wide range system parameters.

2.3 UAV Model

The UAV model is presented in the form of a transfer function from pitch angle to elevator deflection obtained in [15]:

$$W_{plant}(s) = \frac{29.11s^2 + 115.5s - 49.29}{s^4 + 7s^3 + 22.6s^2 - 10.64s + 0.3} \tag{4}$$

For simulation transfer function (4) was reduced through the same channels to the third order. Also due to its instability using the method of root-locus curve [5] the pitch rate feedback was introduced.

The simulation result of noncorrective flight control system with pulse generator reference signal is shown in Fig. 2.

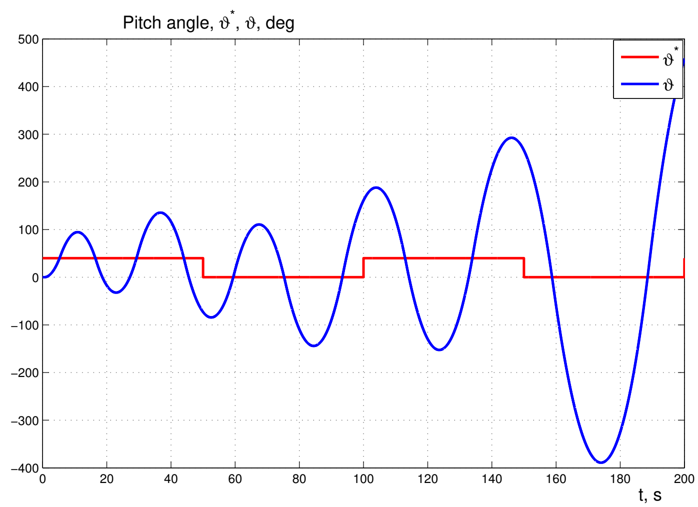

Fig. 2. Time history of pitch angle under $K_p = 1$, $\tau = 0.5$ s and $\theta^* = 40$ deg

Fig. 2 shows that that an increase in the amplitude of the input signal to 40 degrees leads to oscillatory processes, the system lose their stability.

3 Nonlinear Corrective Device

Based on results from Sec. 2, the most desirable corrective device should be such that its frequency characteristics have the properties of attenuation gain, accompanied by an increase in phase advance with increasing frequency. The inclusion of such a correction device improves the relative stability of the flight control system, i.e. increased of phase and modulus margin. Consider the corrective device in the form of a nonlinear filter containing separate amplitude and phase channels [10, 11]:

$$y = |x_1| sign(\sigma),$$
$$|x_1| = x \cdot W_A(s), \quad (5)$$
$$\sigma = x \cdot W_p(s),$$

where y is the vector of state output, x is the vector of state input, $W_A(s)$, $W_p(s)$ are the low-pass filters of amplitude and phase formation, respectively, are selected in the following form:

$$W_A(s) = \frac{k}{T_2 s + 1}, \quad (6)$$

$$W_p(s) = \frac{T_1}{T} \cdot \frac{Ts + 1}{T_1 s + 1}, \quad (7)$$

where $0 < T_1 < T_2$ are time constants. Coefficient k is chosen less than 1 to attenuate the amplitude. In this study, it became necessary to introduce an additional low-pass filter W_A compared with study [3]. It introduce the negative phase shift, but information about it is not saved using the module capture unit. The main positive phase shift is introduced by the filter (7):

$$\phi_p(\omega) = \arctan \frac{\omega T(1 - T_1/T)}{1 + \omega^2 T^2 T_1/T} > 0 \quad (8)$$

And the sign function isn't stored information about the amplitude of the signal passing through the filter (7). Thus, from one branch of the correction device, we get the value of the desired amplitude, from the other – the desired phase. A distinctive feature of the correction device is the independence of the frequency characteristics from the input amplitude, and an increase in phase margin with increasing frequency. This structure (5) is universal, but there is no general methodology for choosing its parameters due to the variety of nonlinear systems. Nyquist plot for (5) is shown at Figs. 3, 4.

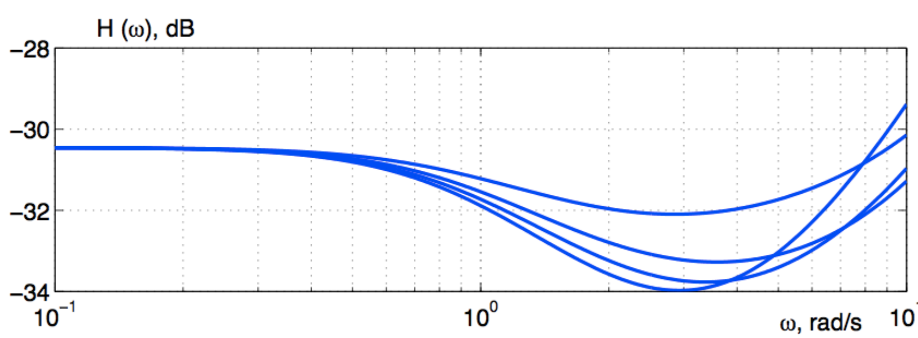

Fig. 3. Amplitude frequency response

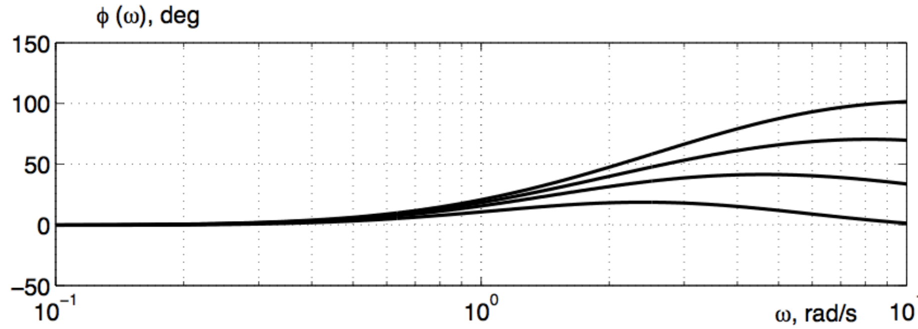

Fig. 4. Phase-frequency characteristic

Simulation results are carried out at a fixed value of $T = 0.01$ and several attitude ratio values of T_1/T. The maximum attenuation of the amplitude at Fig. 3 corresponds to the maximum positive phase shift at 4. To correct the system of interest, a filter configuration with a phase margin of 100 degrees was chosen.

4 The Results of Nonlinear Correction and Conclution

The corrective device described by (5) is embedded into the structure in Fig. 1 between pilot and actuator. The simulation results of corrective flight control system are shown in Fig. 5.

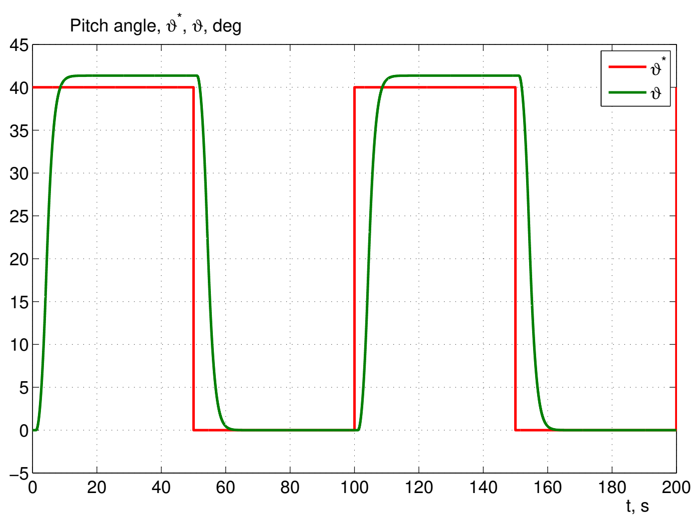

Fig. 5. Time history of pitch angle

The parameters of the corrected system are selected as follows: $K_p = 8$, $\tau = 1.5$ s and $\theta^* = 40$ deg. These are extremely valid parameters for the such kind of system. Thus the introduction of the nonlinear corrective device system allows to increase the amplitude of the input signal and to introduce the time delay, together with empowering pilot. Last-mentioned is an important property when fulfilling demanding flight conditions and maneuverability of UAV.

In conclusion, in this work, the UAV flight control system with the participation of a human operator was investigated. To prevent the nonlinear oscillations the nonlinear corrective device with set parameters was introduced, which allows to form independently of the amplitude of the input signal and separately desired phase and amplitude frequency characteristics of the system. Allowable numerical boundaries of the parameters of the adjusted system were established. An additional low-pass filter has been introduced to attenuate the amplitude of the control signal. Thus, the introduction of non-linear correction increases the maneuverability of the drone in conditions of vigorous control and actuator rate limit.

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