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Adaptive Control of Aircraft Lateral Movement in Landing Mode[1]

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Abstract: The paper describes the problem of adaptive control of the aircraft lateral movement in landing mode. The control system with a reference model based on the modified algorithm of high order tuner is proposed. The proposed algorithm tracks the output of the plant to the reference output with the required accuracy. Simulation results illustrate the efficiency of the synthesized algorithm.

1. INTRODUCTION

Modern highly maneuverable aircraft, such as fighters, operate over a wide range of flight conditions, which vary with altitude, Much number, angle of attack, and engine thrust. The mechanical characteristics of an airframe, such as the centre of gravity, change as well. The aircraft autopilot has to be able to produce a response that is accurate and fast despite sever variations in speed and altitude of the airframe or, in other words, in the face of large parametric uncertainty (Gurfil, 2001, Tsourdos and White, 2001, Belkharraz and Singh, Steinberg, and Page, 2003, Sobel, 2007) and external disturbances (Bukov, 2006). The adaptive and robust methods have to meet the conflicting requirements on the tuning rate and performance quality under conditions of lack of aircraft state measurements (Ben Yamin, Yaesh, and Shaked, 2007; Schumacher and Kumar, 2000; Singh et al., 2003).

Many different methods are used for control of aircraft movement (Miroshnik, Nikiforov, and Fradkov, 1999, Bobtsov et al., 2012, Bobtsov and Pyrkin, 2012). This problem is attributed to systems with unknown parameters and disturbances, therefore adaptive and robust control are the most effective algorithms for it. Passification-based adaptive control under assumption, that open-loop system is hyper-minimum-phase is used in Pogromsky, Andrievsky, Rooda, 2009. It should be note, that if there are significant perturbations in the system, some solutions cannot correspond to required plant behavior. This case is considered in Fradkov and Andrievsky, 2011, where the problem is solved using a speed-gradient and anti-windup methods. In Bukov, 2006 new method called imbedding systems is developed for building invariant control systems. These algorithms are used for control of the aircraft lateral movement in the landing mode under parametric uncertainties and external disturbances. Compensation of parametric and external disturbances method with application to the aircraft model is considered in Furtat and Putov, 2013, Furtat, Fradkov, and Peaucelle, 2014. This algorithm is compared to well-known methods such as H-∞ and speed-gradient control in Furtat, Fradkov, and Peaucelle, 2014. Shown that the proposed method is more robust to disturbances and real limit of control signal.

In this paper the new modified algorithm of high order tuner is used. This algorithm is proposed in Tsykunov, 2006 for control of linear plants under parametric uncertainties. In comparison with Miroshnik, Nikiforov, and Fradkov, 1999 it has low order and shows better results of transients. The simulation results illustrate the efficiency and robustness of the suggested control system.

2. PROBLEM STATEMENT

Consider the linearized model of the lateral motion of an aircraft in the landing mode (Letov, 1969, Bukov, 2006)

$$\dot{x}(t) = Ax(t) + Bu(t) + Df(t), \quad y(t) = Lx(t), \qquad (1)$$

where $x(t) = [\Delta z(t), \Delta\psi(t), \Delta\gamma(t), \Delta\omega_x(t)]^{\mathrm{T}}$, $u(t) = \delta(t)$ is a state vector and control of the linearized mathematical model of the aircraft movement without sliding, $\delta(t)$ is an aileron deviation of its balancing position, $\Delta z(t)$ is a value of the lateral deviation of the mass center of the aircraft relative to the longitudinal axis of the landing strip, $\Delta\psi(t)$ is an angle between a longitudinal axis of the landing strip and a horizontal projection of aircraft velocity vector, $\Delta\gamma(t)$ is a change the roll angle of the aircraft, $\Delta\omega_x(t)$ is a change the angular velocity of rotation of the aircraft around its longitudinal axis, A, B, D are numerical matrices with

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appropriate dimensions, $f(t)$ is a scalar bounded disturbance and $L = [1, 0, 0, 0]$.

Model (1) is simplified and we consider only lateral motion of the aircraft without taking into account full motion.

Assumptions

1. The following conditions hold: $A = A_N + B_N c_0^T$, $B = B_N + B_N \tau$, $D = B_N k$, where A_N, B_N are known nominal matrixes and A_N is Hurwitz, $c_0 \in R^4$, $\tau \in R$, $k \in R$ are unknown vector and numbers.

2. Unknown elements of vector c_0 and unknown numbers τ and k belong to known and bounded set Ξ.

3. The plant (1) is minimum phase.

4. Only signals $y(t)$ and $u(t)$ are available for measurement, but not its derivatives.

5. The pair of matrix (A, B) is controllable, the pair of matrix (A, L) is observable.

Reference model is defined by the following equation

$$\dot{x}_m(t) = A_N x_m(t) + B_N r(t), \quad y_m(t) = L x_m(t), \tag{2}$$

where $x_m(t) \in R^4$ is a state vector of reference model.

The goal is to design a continuous control law such that the following condition holds

$$\overline{\lim_{t\to\infty}} |y(t) - y_m(t)| < \Delta, \tag{3}$$

where $\Delta > 0$ is a control accuracy.

3. MAIN RESULT

According to Letov, 1969 and Bukov, 2006, state of the aircraft in the landing mode must be such that this integral performance index is minimized:

$$J = \int_0^\infty \left[x_m^T(t) Q x_m(t) + R r^2(t) \right] dt, \tag{4}$$

where Q and R are weight matrix and weight coefficient accordingly.

For minimizing (4) the optimal control law is defined as

$$r(t) = -K_0 x_N(t), \tag{5}$$

where $K_0 = R^{-1} B_N^{\mathrm{T}} H$, $H = H^{\mathrm{T}} > 0$ is a solution of the matrix Riccati equation

$$A_N^T H + H A_N - H B_N R^{-1} B_N^T H = -Q. \tag{6}$$

The required behavior of the aircraft in the landing mode is defined by the following reference equation

$$\dot{x}_m(t) = A_0 x_m(t), \quad y_m(t) = L x_m(t),$$

where $A_0 = A_N - B_N K_0$.

Taking into account Assumption 1, rewrite plant equation (1) as follows

$$\begin{aligned} \dot{x}(t) &= A_N x(t) + B_N u_0(t) + B_N u(t) + B_N c_0^T x(t) \\ &\quad + B_N \tau u(t) + B_N \big(kf(t) - u_0(t)\big), \\ y(t) &= L x(t), \end{aligned} \tag{7}$$

were

$$u_0(t) = -K_0 \hat{x}(t). \tag{8}$$

Equation (8) is optimal control law for the following nominal plant

$$\dot{x}(t) = A_N x(t) + B_N u_0(t), \quad y(t) = L x(t)$$

and performance index

$$J = \int_0^\infty \left[\hat{x}^T(t) Q \hat{x}(t) + R u_0^2(t) \right] dt.$$

Here $\hat{x}(t)$ is an estimate of the signal $x(t)$ and $\hat{x}(t)$ is the solution of the following observer equation

$$\dot{\hat{x}}(t) = A_N \hat{x}(t) + B_N u_0(t) + C\big(\hat{y}(t) - y(t)\big), \; \hat{y}(t) = L\hat{x}(t), \tag{9}$$

where C is chosen such that matrix $A_N + CL$ is Hurwitz.

Taking into account (8), rewrite (7) in the form

$$\begin{aligned} \dot{x}(t) &= \left(A_0 + B_N c_0^T\right) x(t) + B u(t) + B_N \varphi(t), \\ y(t) &= L x(t), \end{aligned} \tag{10}$$

where $\varphi(t) = kf(t) - u_0(t) + K_0\big(\hat{x}(t) - x(t)\big)$.

Transform model (10) to the form

$$Q(p) y(t) = R(p)\big(u(t) + \varphi(t)\big). \tag{11}$$

For synthesis of the control law let us use the modified algorithm of high order tuner (Tsykunov, 2006).

According to Tsykunov, 2006, introduce the control law

$$\begin{aligned} u(t) &= T(p)\hat{v}(t), \quad v(t) = c^T(t) w(t), \\ \dot{c}(t) &= -\alpha e(t) w(t) + \beta e^2(t) c(t), \end{aligned} \tag{12}$$

where $T(\lambda)$ is a stable polynomial of the third order such that the transfer function $\dfrac{R_m(\lambda)T(\lambda)}{Q_m(\lambda)}$ is a strictly positive real function, λ is a complex variable, $\hat{v}(t)$ is an estimate of auxiliary control signal $v(t)$, $c(t)$ is a vector of adjustable parameters, $w(t) = \left[V^T(t), e(t), \dfrac{r(t)}{T(p)} \right]^T$ is a regression vector, $V(t)$ is a solution of the following equation

$$\dot{V}(t) = F V(t) + b e(t), \tag{13}$$

where F is matrix in Frobenius form with characteristic polynomial $R_m(\lambda)T(\lambda)$, $b = [0, 0, 0, 1]^T$.

For implementation of control (12), consider the following observer (Atassi, Khalil, 1999)

$$\dot{\xi}(t) = G_0 \xi(t) + B\big(\hat{v}(t) - v(t)\big), \; \hat{v}(t) = L\xi(t), \tag{14}$$

where $G_0 = \begin{bmatrix} 0 & I_3 \\ 0 & 0 \end{bmatrix}$, $B = \left[\dfrac{d_1}{\mu}, \dfrac{d_2}{\mu^2}, \dfrac{d_3}{\mu^3}, \dfrac{d_4}{\mu^4} \right]^T$, $d_1, \ldots, d_4$ are chosen such that matrix $G_0 - [d_1, \ldots, d_4] L$ is Hurwitz, $\mu > 0$ is enough small number.

Theorem. Let Assumptions 1-5 hold. Then control system (8), (9), (12)-(14) provides implementation of goal (3).