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Time-delay compensation for networked hardware-in-the-loop simulation of a flight control system using polynomial prediction

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ABSTRACT: Hardware-in-the-loop simulation is an effective approach for testing the electronic controller of a closed-loop control system within a computer-based real-time simulation of the rest of the system. In this paper, the pitch attitude hold mode controller of an aircraft vehicle is tested using hardware-in-the-loop simulation. A computer is used for real-time simulation of flight, and an electronic board is employed for controller implementation. The controller and the simulator are connected using a network protocol. The hardware-in-the-loop simulation can achieve unstable behavior or inaccurate results due to the time-delay of network connection. The maximum allowable delay bound in networked connection is derived using the method of delayed differential equations. The sufficient conditions for the stability of linear time-delay systems are given. The proof makes use of Lyapunov–Krasovskii functional and the condition is expressed in term of linear matrix inequalities. Therefore, a polynomial-based predictor is designed for the time-delay compensation of network connection. The consistency of the experimental real-time simulation and off-line simulation shows the applicability of the presented method for mitigating the effect of time-delay in the networked hardware-in-the-loop simulation. Also, the uncertainty of the model due to stability and control derivatives are considered for analyzing the stability of the networked hardware-in-the-loop simulation.

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1. INTRODUCTION

Hardware-In-the-Loop (HIL) simulation is generally used to test the controller of a closed-loop control system through the simulation of the rest of the system in real-time. In a networked HIL simulation, the hardware is an electronic controller which connects to software models via a network connection. Several studies have reported the use of the HIL simulation approach for rapid prototyping of the flight control systems [1,2]. The performance and stability of the networked HIL simulation are usually affected by networked induced delays [2,3].

In this paper, a polynomial-based predictor is used for the time-delay compensation of network connection. The stability of networked HIL simulation is analyzed by consideration of uncertainties in the model.

2. NETWORKED HARDWARE-IN-THE-LOOP FRAMEWORK

The schematic of the networked HIL simulation framework for testing the flight control system is presented in Fig. 1. The aircraft is simulated numerically and the flight control system is implemented on a PC/104 hardware, as shown in Fig. 2.

3. MATHEMATICAL MODEL

A linear model of the aircraft is derived using aerodynamic and control derivatives as Eqs. (1) to (3).

$$\dot{X}(t) = AX(t) + Bu(t) \tag{1}$$

$$\mathrm{B} = \begin{bmatrix} X_{\delta e} & Z_{\delta e} & M_{\delta e} + M_{\dot{w}} Z_{\delta e} & 0 & 0 \end{bmatrix}^T \tag{2}$$

$$\mathrm{A} = \begin{bmatrix} X_u & X_w & X_q + w_0 & -g\cos\theta_0 & 0 \\ Z_u & Z_w & Z_q + w_0 & -g\sin\theta_0 & 0 \\ M_u + M_{\dot{w}} Z_u & M_w + M_{\dot{w}} Z_w & M_q + M_{\dot{w}} u_0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & U_0 & 0 \end{bmatrix} \tag{3}$$

4. POLYNOMIAL PREDICTION

Using a standard least-squares polynomial derivation, given n number of previous data *points (x0, y0), ... (xn-1, yn-1)*, number of P step-ahead prediction of y can be predicted as Eq. (4).

$$y' = t_p \left[\left(T^T T \right)^{-1} T^T \right] y \tag{4}$$

where y, t_p and T are as follows:

$$y = \begin{bmatrix} y_0 & y_1 & \dots & y_{n-1} \end{bmatrix}^T \tag{5}$$

$$t_p = \begin{bmatrix} 1 & P\Delta t & \dots & P^N \Delta t^N \end{bmatrix} \tag{6}$$

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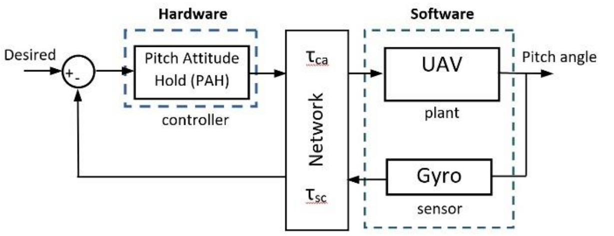

Fig. 1. Hardware-in-the-loop simulation of pitch attitude control system by networked connections

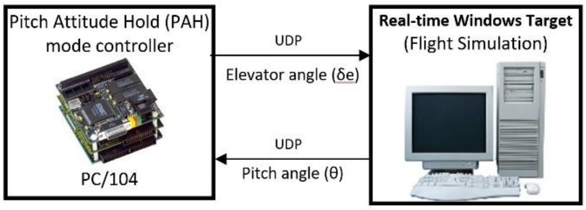

Fig.2. Framework of hardware-in-the-loop simulation of flight control system

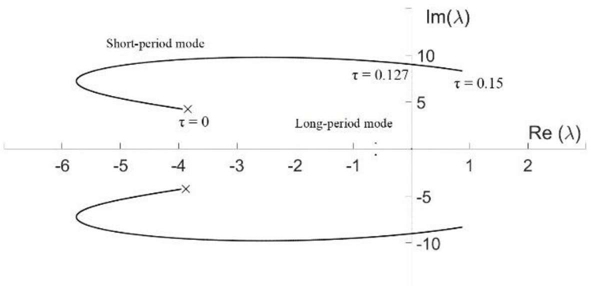

Fig. 3. Root locus of short and long period modes for time delay from $\tau = 0$ to $\tau = 0.15$ sec

$T =$

$$\begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 1 & -\Delta t & (-\Delta t)^2 & \cdots & (\Delta t)^N \\ 1 & -2\Delta t & (-2\Delta t)^2 & \cdots & (-2\Delta t)^N \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & -(n-1)\Delta t & [-(n-1)\Delta t]^2 & \cdots & [-(n-1)\Delta t]^N \end{bmatrix} \tag{7}$$

5. STABILITY ANALYSIS

The state-space model of a Linear Time-Invariant (LTI) system, with a fixed time-delay ($\tau = P\Delta t$) in control input, can be written as Eq. (8).

$$\dot{X}(t) = A_0 X(t) + Bu(t - \tau) \tag{8}$$

Using a state feedback controller, the control input is derived as Eq. (9).

$$u(t - \tau) = -K\, X(t - \tau) \tag{9}$$

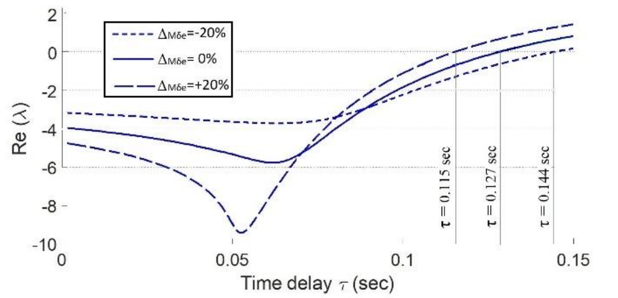

Fig. 4. Real part of short period roots for uncertainty $\Delta M_{\delta e} = \pm 20\%$

By substituting Eq. (9) into Eq. (8), a retarded type Delay Differential Equation (DDE) is derived as follows:

$$\dot{X}(t) = A_0 X(t) + A_1 X(t - \tau) \quad , \quad A_1 = -BK \tag{10}$$

where, K includes feedback gains as follows:

$$K = \begin{bmatrix} 0 & 0 & K_q & K_\theta & K_h \end{bmatrix} \tag{11}$$

The characteristic equation of Eq. (10) is derived as follows:

$$det\left(\lambda I - A_0 - A_1 e^{-\tau\lambda}\right) = 0 \tag{12}$$

The characteristic Eq. (12) is simplified to a polynomial equation of degree five. The coefficients of the characteristic equation include exponential terms such as $e^{-\tau s}$. The BIFTOOL toolbox is used to solve the characteristic equation [4]. Moreover, the stability of the delay differential Eq. (10) can be analyzed using Lyapunov-Krasovskii approach. The positive definite function $V(t,\mathbf{X})$ is defined as Eq. (13).

$$V(t,X) = X^T(t) P X(t) + \int_{t-\tau}^{t} X^T(s) Q X(s)\, ds \tag{13}$$

The time derivative of $V(t,X)$ is derived as follows.

$$\dot{V}(t,X) \le \begin{bmatrix} X^T(t) & X^T(t-\tau) \end{bmatrix} W \begin{bmatrix} X(t) \\ X(t-\tau) \end{bmatrix} \tag{14}$$

The feasibility condition is also derived using the LMI as follows.

$$W = \begin{bmatrix} A_0^T P + P A_0 + Q & P A_1 \\ A_1^T P & 0 \end{bmatrix} \le 0 \tag{15}$$

6. RESULTS AND DISCUSSION

The root locus, due to variation of the actuator time delay, is plotted in Fig.3. The short-period root branches cross the imaginary axis for $\tau = 0.127 sec$. The Real part of short period roots for uncertainty $\Delta M_{\delta e} = \pm 20\%$ is shown in Fig. 4. The increase of $M_{\delta e}$ results in a decrease in critical time delay. The

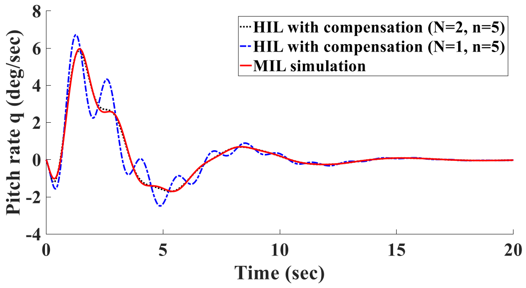

Fig. 5. Pitch rate trajectory in HIL simulation with first and second-order polynomial compensators versus Model-In-the-Loop (MIL) simulation

result of HIL simulation with polynomial prediction is shown in Fig. 5.

7. CONCLUSIONS

The networked hardware-in-the-loop simulation achieves unstable behavior due to the time-delay of network connection. The uncertainty ΔX_q, ΔZ_g and $\Delta Z_{\delta e}$ have more effects rather than others on the critical time delay of the networked HIL simulation. The prediction using five pervious points (*n=5*) and first/second-order polynomials have been used. The first-order polynomial (*N=1*) has 32% mean error while the mean error of the second-order polynomial (*N=2*) is 3%.

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