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Research Article

Pilot-Induced Oscillation Suppression by Using L_1 Adaptive Control

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Despite significant technical advances, pilot-induced oscillation (PIO) continues to occur in both flight tests and operational aircrafts. Such a phenomenon has led to significant research activities that aim to alleviate this problem. In this paper, the L_1 adaptive controller has been introduced to suppress the PIO, which is caused by rate limiting and pure time delay. Due to its architecture, the L_1 adaptive controller will achieve a desired response with fast adaptation. The analysis of PIO and its suppression by L_1 adaptive controller are presented in detail in the paper. The simulation results indicate that the L_1 adaptive control is efficient in solving this kind of problem.

1. Introduction

The high performance demands of modern aircrafts, especially highly maneuverable military jets, require the implementation of advanced control systems. The use of a modern electronic flight control system could provide great potential for improvement in the aircraft's performance. In spite of all the improvements, a significant handling quality problem arose with the introduction of electronic flight control system: pilot-induced oscillation, also known as pilot in-the-loop oscillation.

Pilot-induced oscillations are described as pilot-aircraft dynamic couplings, which could lead to instability in the systems [1]. Both previous and current research has attempted to explain, predict, and avoid these oscillations. Almost every modern aircraft has experienced PIO, which is well known by the public for the catastrophic event it caused, such as the YF-22 [2] and Olympic Airways Falcon 900. The occurrence of such events has led to significant research activities that are intended to alleviate the negative effects due to PIO. Despite the research efforts made, PIOs continue to occur, and reports of PIOs on operational aircrafts are increasing.

The focus of this paper is to suppress the pilot-induced oscillation caused by both rate limiting and pure time delay by using the L_1 adaptive controller. The effects of rate limiting and other system nonlinearities are considered to be the main factors that result in the occurrence of PIOs [3–5]. Some of the existing methods, to some extent, could handle the PIO caused by rate limiting, but not necessarily work with the presence of pure time delay in the actuator model. The L_1 adaptive control is known for its fast adaptation and smooth control implementation due to its powerful control architecture [6, 7]. With proper design, the L_1 adaptive controller will make the system respond in the desired manner.

The objective of this paper is to design the L_1 adaptive controller to make the inner loop of the system respond according to a given first-order system, while suppressing the PIO phenomenon caused by both rate limiting and pure time delay in the pilot dynamic model. Section 2 gives a brief introduction of pilot-induced oscillation and pilot model. In Section 3, the design of an inner loop adaptive controller to suppress the PIO and to track desired response is given. The inner loop adaptive controller cannot handle the adversely high pilot command inputs because they are the commands to the inner closed loop system. The inner loop controlled by L_1 adaptive controller solely tracks the command inputs from the pilots.

2. Pilot-Induced Oscillation

Pilot-induced oscillations can be regarded as a closed-loop instability of the pilot-aircraft loop, and it often happens when the pilot proves to be unable to adapt himself to a sudden change of the vehicle dynamics during a high demanding flight task. PIOs are complex interactions between the pilot and the aircraft dynamics.

2.1. Types of PIOs. According to the report by National Research Council (NRC) Committee in 1997 [8], PIOs can be separated into three categories.

(i) Category I PIO: Linear pilot-vehicle system oscillation. These PIOs result from linear phenomena such as excessive time delay and excessive phase loss between the pilot's control input and the aircraft response. They are the simplest to model, understand, and prevent. Before the introduction of fly-by-wire technology, almost all PIOs were this type, and a large amount of research has been conducted on them. But they are currently the least common in operational flight. The main causes of Category I PIO are excessive lags due to time delays and various digital filter dynamics in the flight control system. These effects lead to a high frequency phase roll-off in the frequency response. There are roughly two groups of design criteria for preventing Category I PIO. One is according to the flight control stability, and the other is the handling quality requirements. In the first group of design criteria, the open loop aircraft frequency response needs to be checked as well as the phase and magnitude margin. If the phase rate of the system is too high, a small increase in frequency will result in a strong additional phase delay. This is usually related with time delay in the whole system.

(ii) Category II PIO: Quasi-linear events with some nonlinear contribution, such as rate or position limiting. For the most part, these PIOs can be modeled as linear events, with an identifiable nonlinear contribution that may be treated separately. Figure 1 shows two typical positions where rate-limiting blocks are installed in the flight control system. The block after the pilot model is installed to prevent the system from receiving a high input rate by the pilot. The other block after the controller is used to protect the actuator against overload. In the case of rate limiting, nonlinear system theory should be utilized for the analysis of the flight system, such as the Lyapunov theory and the phase plane method.

The majority of aircraft crashes due to PIOs are caused by Category II PIO through activating actuator rate limits. When the rate limiter is saturated, phase lag occurs and the aircraft dynamics change suddenly, which cause PIO and threaten the flight safety. Rate limiting adds additional phase lag, increasing the delay between the pilot input and the aircraft response. This tends to make the pilot compensate with faster responses, often worsening the situation. Rate limiting also reduces the gain, which the pilot interprets as a lack of control response and therefore makes larger command inputs, again making the situation worse.

(iii) Category III PIO: Nonlinear PIOs with transients. Such events are difficult to recognize and rarely occur but are always severe. Mode switching or rapid changes in effective vehicle characteristics could be reasons for this type of PIO. Fortunately, these events that result in nonoscillatory divergence and loss of control of the aircraft are rare.

2.2. Rate Limiting. Rate limiting of the actuator is one of main factors that lead to pilot-induced oscillation. Actuator rate limiting occurs when pilot input command error requires a higher rate than the actuator can actually provide. A simplified model of a rate-limited actuator is shown in Figure 2.

Rate limiting adds additional phase lag, increasing the delay between the pilot input and aircraft response. This tends to make the pilot compensate with faster responses, which will often worsen the situation.

2.3. Pilot Modeling. With rate limiting considered, another important factor that causes the PIO phenomenon is the pilot model, which is also regarded as the weakest point in the analysis due to its high nonlinearity and complexity. However, there are several specific pilot behavioral patterns [9] that could be used to analyze the cause of these PIOs. The pilot model is the source factor that distinguishes severe PIO problems from most aircraft feedback control design problems. The difference resides in unique human properties related to the adaptive characteristics of the human pilot.

Pilots exhibit peculiar transitions in the organizational structure of the pilot vehicle system. These transitions can involve both the pilot's compensation and effective architecture of the pilot's control strategy. The human pilot dynamics can be roughly separated into the following types.

(i) Compensatory behavior: essentially, the pilot has generated a lead to cancel out the lag in the aircraft model. However, the higher frequency lags of the pilot model can be approximated at the lower frequencies by the pure time delay.

(ii) Pursuit behavior: the introduction of the pursuit behavior permits an open-loop control in conjunction with the compensatory closed-loop error correcting action. The pilot model of both compensatory behavior and pursuit behavior will be superior to that where only compensatory operations are possible.

(iii) Precognitive behavior: this kind of pilot model gives a higher level of control performance. Based on the knowledge of the system dynamics, the pilot model will generate proper control signals at the right time so as to result in machine outputs that are almost as desired. This operation also appears in company with compensatory behavior as well as pursuit behavior. Most highly skilled movements will automatically fall into this category.

3. PIO Suppression by L_1 Adaptive Control

3.1. System Modeling. In most PIO cases that have happened in recent years, rate- and position-limiting phenomena appear. Hence, numerous research works have been conducted to analyze rate and position limiting [10–12]. In this situation, PIOs can be explained by limit cycles occurring in a nonlinear system where the nonlinearities cause a sustained,

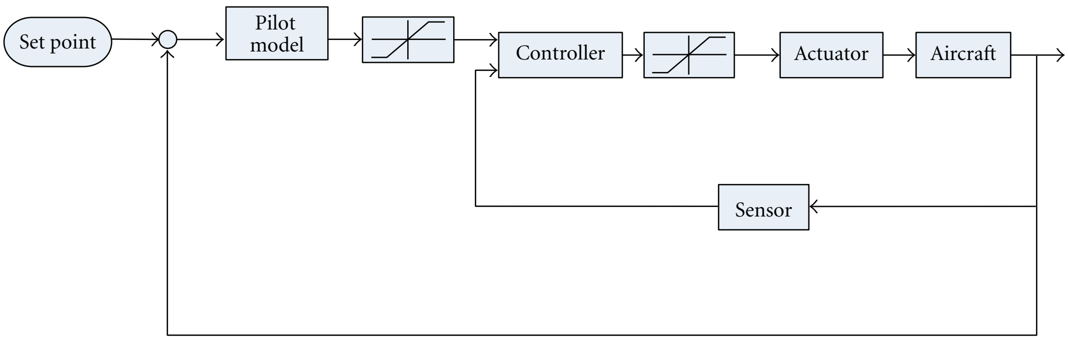


FIGURE 1: Rate limiting in flight control systems.

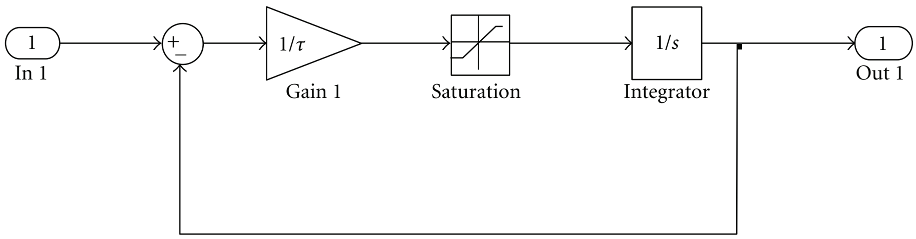


FIGURE 2: Rate limit actuator dynamic model.

constant amplitude oscillation. In those studies, rate limiting of the actuator is considered as one possible cause for PIOs. There are some other factors, such as relatively high pilot command gain and lag in the pilot model, contributing to the onset of PIOs. Rate limiting is commonly met in aviation practice. Hence, if an adaptive inner loop can compensate for the nonlinearities caused by rate limiting and eliminate the limit-cycle oscillations, it can be considered that the PIO is suppressed for such commonly seen situations. We apply the L_1 adaptive controller on the F-14 model taken from [10] in order to test this idea. A model of the Grumman Aircraft Company (GAC) F-14 was developed for this investigation. The approximated model in [10] is compared with data of a real F-14 that has severe PIOs during flight tests. The rate-limiting phenomenon we considered is due to sudden off-nominal conditions such as hydraulic pressure failure as in the F-14 example. Therefore, it is hard to estimate the nonlinearity caused by rate limiting in advance, like most other research work has done. Adaptive control is needed for such situations.

The control structure is shown in Figure 3. It is a longitudinal dynamic model. The system states are $[\alpha\,\theta\,q]$, and control input is the elevator. The L_1 adaptive inner loop controller is a pitch-rate augmentation system, which provides the desired dynamics for the $[\alpha\,q]$ subsystem. The outer loop takes the θ feedback signal and injects it into the pilot model. The pilot model outputs a pitch rate command for the inner loop to achieve the pitch attitude control (the θ angle). The pilot model is given by

$$p(s) = K(s+\beta)e^{-\tau s}, \tag{1}$$

which describes the compensatory behavior of the pilot.

3.2. Delay Margin Detection. Consider the Pilot model described by (1); we assume the desired response of the inner loop is given by

$$g_c(s) = \frac{1}{T_p s + 1}. \tag{2}$$

With the Pilot model, we could derive the transfer function of the closed-loop as

$$g(s) = \frac{p(s)g_c(s)}{p(s)g_c(s)+1} = \frac{K(s+\beta)e^{-\tau s}}{T_p s + 1 + K(s+\beta)e^{-\tau s}}. \tag{3}$$

In the PIO problem concerned, the pure time delay deviates between 0.2 and 0.3 second. The time delay term can be approximated by $e^{-\tau s} = (1-(\tau s/2))/(1+(\tau s/2))$ according to Pade approximation. Equation (3) can be further written as

$$\begin{aligned} g(s) &= \frac{K(s+\beta)1+\tau s/2}{\left(T_p s+1\right)(1+\tau s/2)+K(s+\beta)(1-\tau s/2)}e^{-\tau s} \\ &= \frac{(K\tau/2)s^2+(1+\tau\beta K/2)s+\beta K}{\left(\left(T_p-K\right)\tau/2\right)s^2+\left(T_p+K-\tau/2-\tau\beta K/2\right)s+1+K\beta}e^{-\tau s}, \end{aligned} \tag{4}$$

according to Routh stability criterion, we can get the following inequalities:

$$\begin{gathered} T_p > K, \\ 1+K\beta > 0, \\ T_p > K\tau\beta/2 - \tau/2 - K. \end{gathered} \tag{5}$$

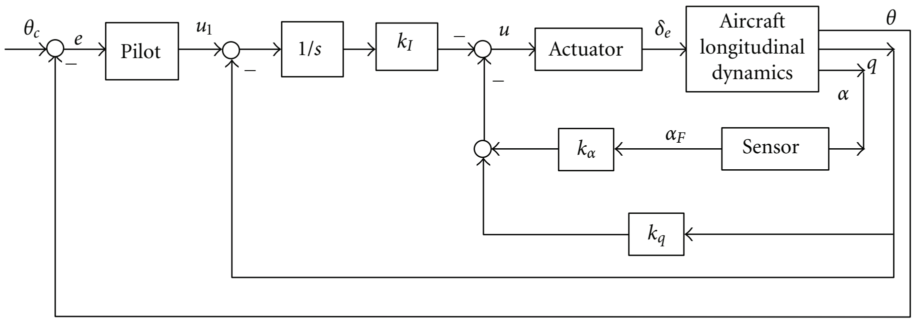


FIGURE 3: Control structure.

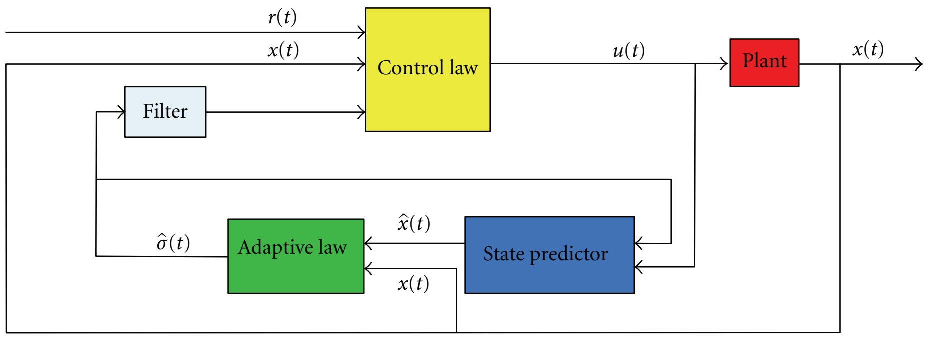


FIGURE 4: L_1 adaptive controller architecture.

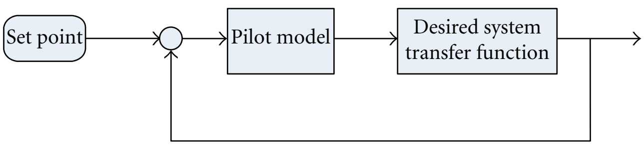


FIGURE 5: PIO delay margin detection architecture.

If the parameter T_p chosen is satisfied with unequal conditions in (5), the system will achieve the desired response with stability condition. From many PIO studies, the onset of PIO often was accompanied by high pilot command inputs. If some off-nominal conditions happen, such as hydraulic failure of the actuators in F-14 PIO accidents, the rate limiting comes into play. When the L_1 inner loop adaptive controller is applied to this model, it can compensate for the unknown effects caused by rate limiting and time delay, no matter whether they are linear or nonlinear. The design of the L_1 adaptive controller does not need a priori information for the rate limits of the actuator.

3.3. L_1 Adaptive Control Design to Achieve Desired Response. Consider the L_1 architecture given in Figure 4, the L_1 adaptive control [13] could be divided into three parts: the adaptive law, the state predictor, and the control law.

State Predictor Design. The state predictor of the aircraft longitudinal dynamic system in Figure 3 is designed as follows:

$$\dot{\hat{x}}(t) = A_m\hat{x}(t) + Bu(t) + \hat{\sigma}_x(t), \qquad \hat{x}(0) = x_0, \tag{6}$$

where $A_m \in R^{3\times3}$, $B \in R^{3\times1}$,

$$\hat{x}(t) = \begin{bmatrix} \hat{\theta}(t) \\ \hat{q}(t) \\ \hat{\alpha}(t) \end{bmatrix}, \qquad \hat{\sigma}_x(t) = \begin{bmatrix} \hat{\sigma}_1(t) \\ \hat{\sigma}_2(t) \\ \hat{\sigma}_3(t) \end{bmatrix}. \tag{7}$$

Matrix A should be Hurwitz to make sure of the stability of the model. $\hat{\sigma}$ can be divided into two parts, the model matched part and the model unmatched part

$$\hat{\sigma} = B\hat{\sigma}_m + \overline{B}\hat{\sigma}_{um}, \tag{8}$$

where $\overline{B}$ is the null space of B. $\hat{\sigma}_m$ is the matched part, and $\hat{\sigma}_{um}$ indicates the unmatched part. $\hat{\sigma}_m$ and $\hat{\sigma}_{um}$ can be calculated as follows:

$$\begin{bmatrix} \hat{\sigma}_m \\ \hat{\sigma}_{um} \end{bmatrix} = \begin{bmatrix} B & \overline{B} \end{bmatrix}^{-1} \hat{\sigma}. \tag{9}$$

Adaptive Law Design. Assume the system dynamics is as follows:

$$\dot{x}(t) = Ax(t) + Bu + \sigma(t). \tag{10}$$

Given any $T > 0$, we have

$$\Phi_x(T) = \int_0^T e^{A_m(T-\tau)} d\tau. \tag{11}$$

Letting $\tilde{x}(t) = \hat{x}(t) - x(t)$, the adaptive law for $\hat{\sigma}_x(t)$ is given by

$$\begin{aligned} \hat{\sigma}_x(t) &= \hat{\sigma}_x(iT), \quad t \in [iT, (i+1)T], \\ \hat{\sigma}_x(iT) &= -\Phi_x^{-1}(T)\mu_x(iT), \quad i = 0, 1, 2, \ldots, \end{aligned} \tag{12}$$

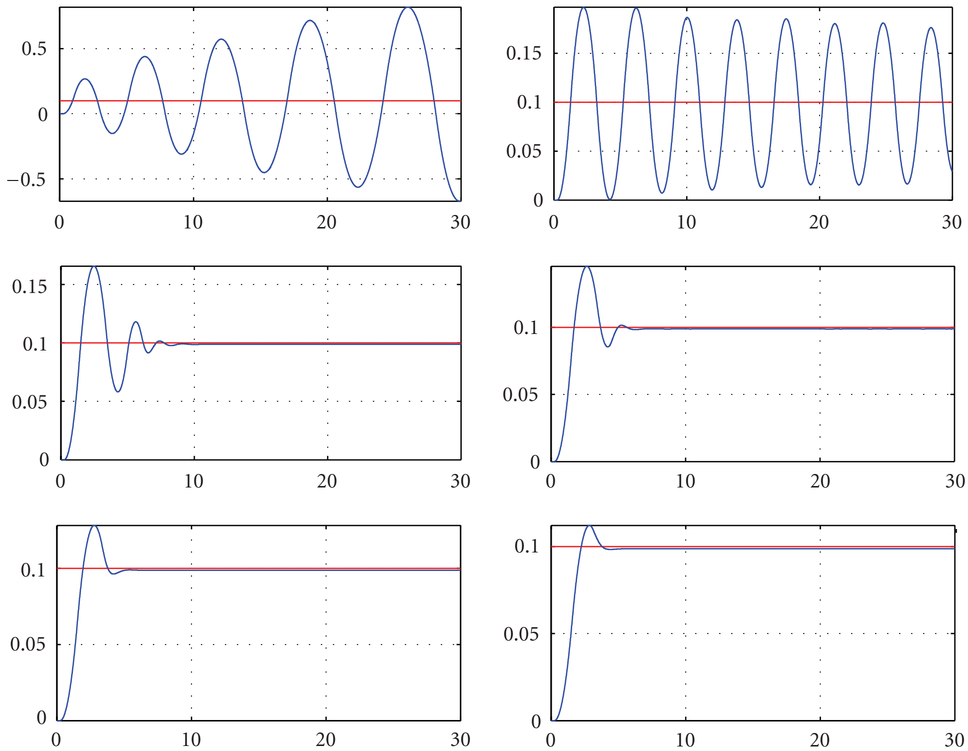


Figure 6: system responses with increasing T_p.

where $\Phi(T)$ is defined above, and

$$\begin{aligned} \mu_x(iT) &= e^{A_m T}\tilde{x}(iT), \quad i = 1, 2, \ldots \\ \hat{\sigma}_x(t) &= -\Phi_x^{-1}(T)e^{A_m T}\tilde{x}(t). \end{aligned} \tag{13}$$

Control Law Design. The output estimation of the system is given by

$$\hat{y} = C\hat{x}. \tag{14}$$

The control signal can be calculated by

$$\begin{aligned} u &= u_r + u_m + u_{um}, \\ u_r &= -\frac{r}{CA_m^{-1}B}, \\ u_m &= -\hat{\sigma}_m, \\ u_{um} &= \left[C(SI - A_m)^{-1}B\right]^{-1} C(SI - A_m)^{-1}\overline{B}\hat{\sigma}_{um}. \end{aligned} \tag{15}$$

u_r is the control signal used to track the reference signal with desired response designed aforementioned. u_m and u_{um} are control signals used to cancel the uncertainty part of the system, where u_m is the matched control signal and u_{um} is the unmatched one.

4. Simulation Study

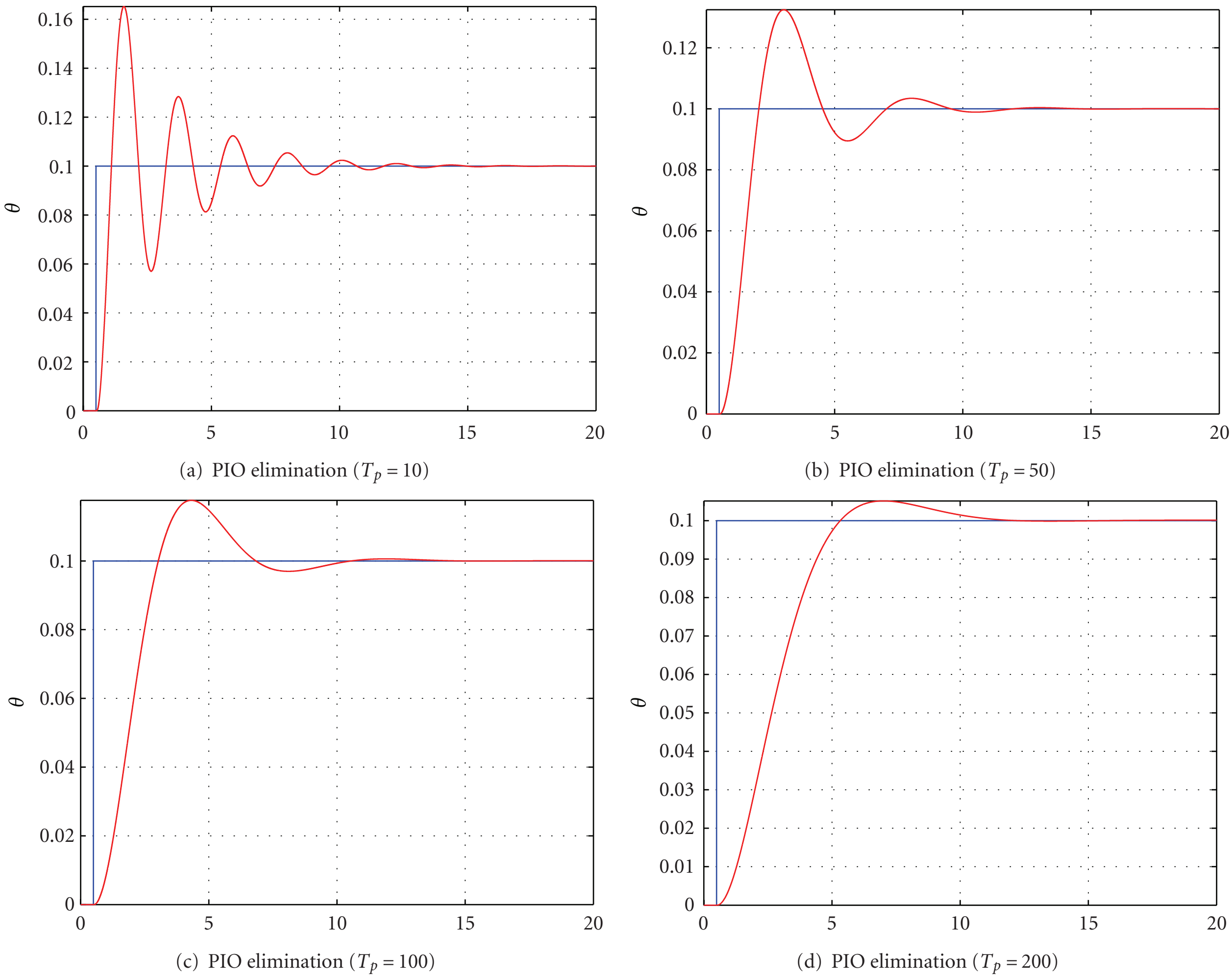
In general, rate limiting results in an amplitude reduction and a significant added phase lag. With the introduction of pure time delay into the pilot model, the closed-loop system could even become unstable.

Based on the delay margin detection architecture shown in Figure 5, the time variable in the desired system response model can be obtained from the result derived in the previous section. There is another alternative method that could be used for the detection of the delay margin by searching for the optimal value of T_p in (2). With an increase in T_p, the system response will change gradually in accordance. At some critical point, the oscillation will disappear and the system response will converge to the set-point value instead. If we further increase the time variable, the damping ratio of the closed-loop system will increase as well, which will affect the system's transient response including overshoot, rise time and so forth (Figure 6).

In Figure 7, the F-14 system responses of different time constants T_p are given. If the time variable T_p is small as shown in Figure 7(a), the system responds rapidly, but the overshoot is also very large. With increasing T_p, the overshoot decreases, but transient performance reduces as well. Thus, we need to build a balance between the overshoot and the rise time, which can be simply implemented by introducing an objective function as

$$\min J = \omega_1\delta + \omega_2 T_r, \tag{16}$$

where ω_1, ω_2 are weighting coefficients and δ, T_r represent the overshoot and rise time, respectively.



(a) PIO elimination ($T_p = 10$)

(b) PIO elimination ($T_p = 50$)

(c) PIO elimination ($T_p = 100$)

(d) PIO elimination ($T_p = 200$)

FIGURE 7: PIO elimination with different desired responses.

5. Conclusion and Future Research

This paper proposes an alternative method for suppressing the pilot-induced oscillation phenomenon caused by rate limiting and time delay in the pilot dynamic model. The delay margin is detected at the beginning, and the critical part of the method is design the L_1 adaptive controller to achieve the desired response of the system.

To further improve the performance of this method, we need to consider the following issues. First, certain criterion need to be built to determine the choice of T_p. The system response can be evaluated by stability, overshoot, and rise time, and so forth. For the robustness of this method, a time-varying pilot model should be considered.

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References

[1] I. Ashkenas, "Pilot-induced oscillations: their cause and analysis," Tech. Rep., 1964, DTIC Document.

[2] M. Dornheim, "Report pinpoints factors leading to yf-22 crash," *Aviation Week and Space Technology*, vol. 137, no. 19, pp. 53–54, 1992.

[3] D. G. Mitchell, B. A. Kish, and J. S. Seo, "A flight investigation of pilot-induced oscillation due to rate limiting," in *Proceedings of the IEEE Aerospace Conference*, vol. 3, pp. 59–74, March 1998.

[4] S. L. Gatley, M. C. Turner, I. Postlethwaite, and A. Kumar, "A comparison of rate-limit compensation schemes for pilot-induced- oscillation avoidance," *Aerospace Science and Technology*, vol. 10, no. 1, pp. 37–47, 2006.

[5] Y. Yildiz and I. V. Kolmanovsky, "A control allocation technique to recover from pilot-induced oscillations (capio) due to actuator rate limiting," in *Proceedinjgs of the American Control Conference (ACC '10)*, pp. 516–523, July 2010.

[6] C. Cao and N. Hovakimyan, "L_1 adaptive controller for a class of systems with unknown nonlinearities: part I," in *Proceedings*

of the American Control Conference (ACC '08), pp. 4093–4098, June 2008.

[7] C. Cao and N. Hovakimyan, "L_1 adaptive controller for nonlinear systems in the presence of unmodelled dynamics: part II," in *Proceedings of the American Control Conference (ACC '08)*, pp. 4099–4104, USA, June 2008.

[8] National Research Council (U.S.). Committee on the Effects of Aircraft-Pilot Coupling on Flight Safety, *Aviation Safety and Pilot Control: Understanding and Preventing Unfavorable Pilot-Vehicle Interactions*, National Academies Press, Washigton, DC, USA, 1997.

[9] D. McRuer, U. S. N. Aeronautics, S. A. Scientific, and T. I. Program, *Pilot-Induced Oscillations and Human Dynamic Behavior*, vol. 4683, NASA, 1995.

[10] A. Robbins, *Pilot variability during pilot-induced oscillation*, Ph.D. thesis, Virginia Polytechnic Institute and State University, 1999.

[11] M. R. Anderson, "Pilot-induced oscillations involving multiple nonlinearities," *Journal of Guidance, Control, and Dynamics*, vol. 21, no. 5, pp. 786–791, 1998.

[12] D. H. Klyde and D. G. Mitchell, "A pio case study—lessons learned through analysis," in *Proceedings of the AIAA Atmospheric Flight Mechanics Conference and Exhibit*, pp. 1–17, 2005.

[13] N. Hovakimyan and C. Cao, *L_1 Adaptive Control Theory: Guaranteed Robustness with Fast Adaptation*, SIAM, Philadelphia, Pa, USA, 2010.