Longitudinal Automatic Landing in Adaptive PID Control Law Under Wind Shear Turbulence

Cheolkeun Ha* and Sangwon Ahn**
School of Transportation Systems Engineering, University of Ulsan, Ulsan, Korea
(Tel : +82-52-259-2590; E-mail: cha@mail.ulsan.ac.kr)

Abstract

This paper deals with a problem of automatic landing guidance and control of the longitudinal airplane motion under the wind shear turbulence. Adaptive gain scheduled PID control law is proposed in this paper. Fuzzy logic is the main part of the adaptive PID controller as gain scheduler. To illustrate the successful application of the proposed control law to the automatic landing control problem, numerical simulation is carried out based on the longitudinal nonlinear airplane model excited by the wind shear turbulence. The simulation results show that the automatic landing maneuver is successfully achieved with the satisfactory performance and the gain adaptation of the control law is made adequately within the limited gains.

Key Word : automatic landing, adaptive gain scheduled controller, fuzzy logic

Introduction

In aircraft flight, the final approach and landing is critical and requires constant monitoring and control. Because of increase of pilot's work load in the final approach and landing phase, the aircraft accidents are apt to happen in this flight phase. In order to guide approaching aircraft to the runway safely, some devices are invented and installed at airports such as ILS(Instrument Landing System)[1,2], MLS(Microwave Landing System)[3] and IBLS(Integrated Beacon Landing System)[4]. Among them, ILS is still popularly adopted in most airports as shown in Fig.1. It is assumed in this paper that the aircraft to be considered takes the final approach and landing under guidance of ILS. The ILS transmits two separate orthogonal radio beams whose intersection forms a signal that the aircraft follows all the way to the airport. At far end of the airport runway, the localizer transmitter emits a beam along a plane vertical to the runway. Near the opposite end of the runway, the glide slope transmitter emits a beam along a plane approximately 2.5 to 3.0 degrees from the horizontal. The path formed by the intersection of these two beams, referred to as the glide path, provides the optimum landing trajectory. During the final approach and landing, aircraft may come across a special wind turbulence at airports, called as wind shear. Wind shear is a change in the wind vector in a relatively small amount space. One of its consequences is a rapid change in the airflow over the aerodynamic surfaces of an aircraft. Such rapid changes of airflow can be hazardous, particularly to aircraft flying at low altitudes and at low speeds. It is a particularly difficult phenomenon to detect since the effects of wind shear are transitory, and its nature and occurrence are random[5]. In recent years techniques for the gain scheduled control law design have been of great attention in many industrial applications to uncertain nonlinear systems[6,7]. Capability of the gain adaptation is known to be able to improve sensitivity of control systems to uncertain environment under which the control system is

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* Professor
E-mail : cha@mail.ulsan.ac.kr, Tel : 052-259-2590, Fax : 052-259-2677
** Graduate Student

operating. Auto-landing maneuver of airplane is one of the most challenging flights under the uncertain environment that airplane flies at near stall speed around which aerodynamic characteristics may change abruptly and is vulnerable to the abrupt change of weather condition near the ground during the landing approach (e.g. "wind shear"). In this paper the guidance and control algorithm using an adaptive gain scheduled PID control law in fuzzy logic for auto-landing maneuver is proposed. Also this algorithm is illustrated in the longitudinal motion under the environment of wind shear.

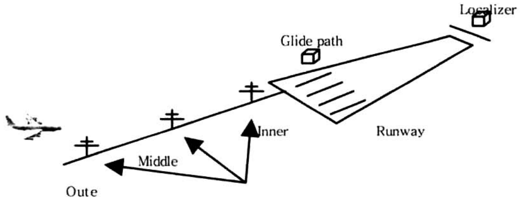

Fig. 1. Schematic Diagram of Instrument Landing System (ILS)

General Statements

In this paper only the longitudinal motion of the airplane, given in the appendix of Ref.[8], is considered for the auto-landing control law design. Also it is supposed that the associated airplane has the center of gravity at 35% MAC. This means that the airplane has the relaxed static stability in the final approach and landing flight condition. The airplane has an elevator with ±25deg maximum deflection and a throttle (%) for the longitudinal control. The elevator actuator model is a 1st-order system with 0.05sec time constant, and the engine dynamics with time-delay is considered for nonlinear simulation even though it is not included in the auto-landing control law deign. Aerodynamics due to flap surfaces are not considered. It is assumed that the airplane is trimmed at 1,500ft altitude with 250ft/sec airspeed and the wing level, and then is about to take the final approach. Available measurements for feedback are assumed to be rate gyro, altimeter, and IMU(Inertial Measurement Unit). In this design the angle of attack sensor is not used for noise sensitivity. According to MIL-8785C[9], the associated airplane belongs to Class-IV, Flight Phase Category 'C' and is required to satisfy the flying quality of Level '1' for the longitudinal motion. For the auto-landing maneuver in this paper, it is assumed that the path angle of glide slope beam is 3.0 deg set up by ILS at airport runway. The flight paths for the glide slope capture and the flare are depicted in Fig. 2.

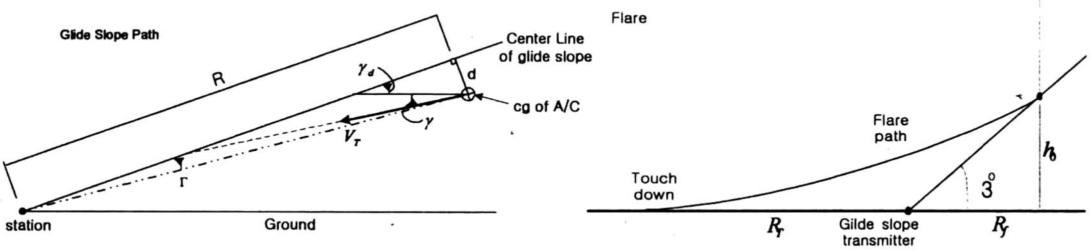

Fig. 2. Glide slope and Flare Path

Table 1. Design requirements

contents	specifications
ΔV_T	$\pm 10 ft/sec$
$\Delta\theta$	± 5 deg
$\Delta\alpha$	± 5 deg
Sink rate during the flare	≤ 1 deg

where γ is flight path angle, R the distance from ILS station to airplane, and h_0 the flare altitude. Moreover, the guidance and control law for auto-landing is designed to satisfy the requirements given in Table 1. Here these data in Table 1 are obtained from Ref.[8,10].

Guidance and Control Law Design

In this section the longitudinal airplane dynamics obtained from linearization about the trim mentioned previously is briefly explained. And adaptive gain scheduled control law based on PID (Proportional Derivative Integral) structure is proposed. The gain adaptation scheme is realized in fuzzy logic. So the PID controller gains are adapted online to change in the pefromance of the auto-landing flight control system of the associated airplane.

The Associated Airplane Dynamics

The linearized model of the airplane obtained from the trim (1,500ft altitude with 250ft/sec airspeed and the wing level) is expressed in state space:

$$\dot{x} = Ax + Bu \tag{1}$$

where the actuator model mentioned in the previous is included in Eq.(1) and the state (x) and input variables (u) in Eq.(1) are given as follows: airspeed V_T, angle of attack α, pitch rate q, pitch angle θ, and elevator actuator state δ_e. Also δ_{ec} is the elevator actuator input and δ_T is throttle input.

$$x^T = \{ V_T, \alpha, q, \theta, \delta_e \} \tag{2}$$

$$u^T = (\delta_{ec}, \delta_T) \tag{3}$$

It is noted that the nonlinear airplane model for this design problem is composed of the atmosphere model and the aerodynamic coefficients and propulsive coefficients, which are functions of the angle of attack α, the elevator deflection δ_e, Power Level, Mach number M and altitude H, given in the lookup table.

Gain Scheduled PID Control Law Design

In general, the transfer function of PID controller is defined in the following form:

$$K(s) = K_p + K_d\, s + K_i \frac{1}{s} \equiv \frac{u(s)}{e(s)} \tag{4}$$

where $u(s)$ and $e(s)$ means the input to the plant to be controlled and the error signal between a reference and a feedback output, respectively. And K_p, K_i and K_d are the proportional, integral, and derivative gains, respectively. As another useful expression of PID controller, a slightly different equivalent form is defined by

$$K(s) = K_p\left(1 + \frac{1}{T_i\, s} + T_d\, s\right) \tag{5}$$

where $T_i = \frac{K_p}{K_i}$ and $T_d = \frac{K_d}{K_p}$. T_i and T_d are known as the integral and derivative time constants, respectively. The parameters of the PID controller K_p, K_i and K_d (or K_p, T_i and T_d) can be manipulated to produce satisfactory responses from a given process to be controlled. Finding optimum adjustments of the PID controller for a given process is not trivial. So in this paper a gain scheduled PID controller is proposed. The controller gains are properly adapted online to change of the system performance to satisfy the requirements specified in Table 1. As a promising means for the adaptation of the controller gains, fuzzy logic[11,12] is introduced in this paper. The fuzzy rule and reasoning scheme in fuzzy logic is utilized to determine the controller gains, and the PID controller generates the control signal. The block diagram of the proposed control system is depicted in Fig. 3.

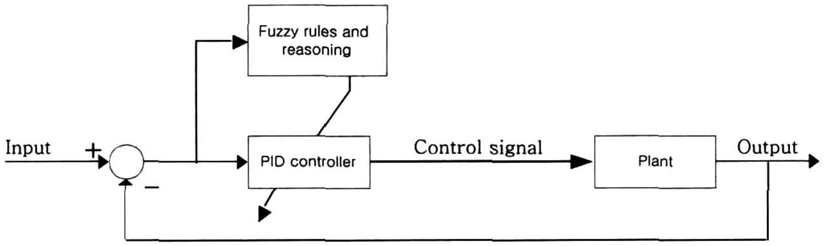

Fig. 3. PID control system with a fuzzy gain scheduler

For the PID controller given in Eq.(4) it is assumed that the gains K_p and K_d satisfy the following conditions:

$$K_{p_{\min}} \leq K_p \leq K_{p_{\max}}, \quad K_{d_{\min}} \leq K_d \leq K_{d_{\max}} \tag{6}$$

where $\{K_{p_{\min}}, K_{p_{\max}}\}$ and $\{K_{d_{\min}}, K_{d_{\max}}\}$ imply maximum and minimum gains, selected experimentally or analytically. It is noted that the parameter limits usually keep on the satisfactory performances within the stability limits. For convenience, K_p and K_d are normalized by the following linear transformation:

$$K_j^n = \frac{K_j - K_{j_{\min}}}{K_{j_{\max}} - K_{j_{\min}}}, \quad (j = p, d) \tag{7}$$

Note that K_j^n is in the range between zero and one. In the proposed PID controller, the integral gain is obtained from the integral time constant, T_i, determined with reference to the derivative time constant. T_d .

$$T_i = x\ T_d \tag{8}$$

Thus the integral gain K_i is obtained by

$$K_i = \frac{K_p^2}{x\ K_d} \tag{9}$$

Now, the parameters $\{K_p^n, K_d^n, x\}$ are determined by a set of fuzzy rules of the form :

$$\textit{If } e(t) \textit{ is } A_i \text{ and } \dot{e}(t) \textit{ is } B_i, \textit{ then } K_p^n \textit{ is } D_i, \text{ and } x = x_i, \text{ for } i = 1, 2, \ldots, N \tag{10}$$

Here, the values of A_i , B_i are fuzzy sets to be defined in the common triangular membership functions. The membership functions of these fuzzy sets for $e(t)$, $\dot{e}(t)$ are shown in Fig. 4. Also x_i is a constant defined in the singleton membership functions, shown in Fig. 5.

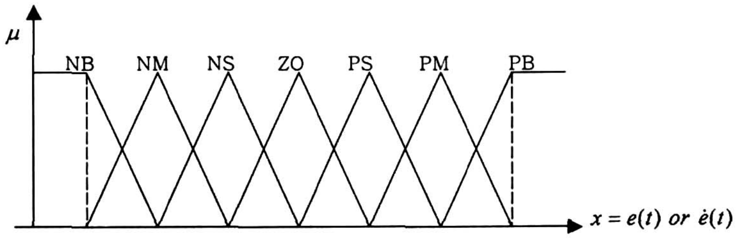

Fig. 4. Membership functions for $e(t)$ **and** $\dot{e}(t)$

In this figure, N represents negative, P positive, ZO nearly zero, S small, M medium, B big. For example, NM implies negative-medium, PB for positive big, and so on. The fuzzy sets of C_i, D_i may be defined as either B or S, and are specified by

$$\mu_S(\phi) = -\frac{1}{4}\log(\phi) \quad , \quad \mu_B(\phi) = -\frac{1}{4}\log(1-\phi) \tag{11}$$

where ϕ means $\{K_p^n, K_d^n\}$, respectively. The fuzzy rules of C_i, D_i in Eq.(10) in this paper are determined from the designer's experiences obtained from the classical design of the automatic landing maneuver [1,13]. Especially, whether the integral action should be strongly activated or weakly activated is determined by the well-known Ziegler-Nichols PID tuning rule [14]. In this design, x is the parameter related with the tendency of integral action. It is noted that the parameter x from Fig. 5 may be properly tuned in the control loop of the automatic landing system to be designed.

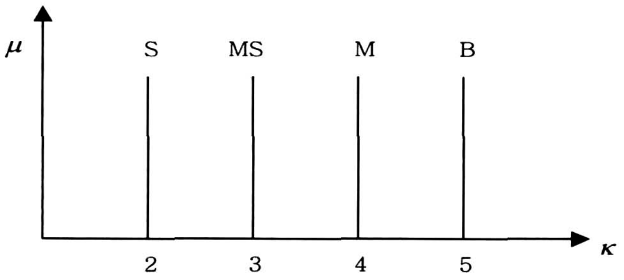

Fig. 5. Singleton Membership Function

The truth value (μ_i) of the i-th rule in Eq.(10) is obtained by the product of the membership function values in the antecedent part of the rule :

$$\mu_i = \mu_{A_i}(e(t)) \cdot \mu_{B_i}(\dot{e}(t)) \tag{12}$$

where μ_{A_i} is the membership function value of the fuzzy set A_i for a value of $e(t)$, and μ_{B_i} the membership value of the fuzzy set B_i for a value of $\dot{e}(t)$. The implication process of a fuzzy rule along with Eq.(11)-(12) determines the values of $\{K_p^n, K_d^n\}$ for each rule from their corresponding membership functions. By using the membership functions in Fig. 4, the following condition should be satisfied:

$$\sum_{i=1}^{N} \mu_i = 1 \tag{13}$$

Then, the defuzzification process yields the following conditions :

$$K_p^n = \sum_{i=1}^{N} \mu_i K^n_{p_i}, \quad K_d^n = \sum_{i=1}^{N} \mu_i K^n_{d_i}, \quad x = \sum_{i=1}^{N} \mu_i x_i \tag{14}$$

Once $\{K_p^n, K_d^n, x\}$ are obtained, the PID controller gains to be implemented for auto-landing control system are calculated from the inverse relation in Eq.(7) and in Eq.(8) and (9) :

$$K_j = (K_{j_{\max}} - K_{j_{\min}})K_j^n + K_{j_{\min}}, \quad j = p, d \tag{15}$$

Stability Analysis

In a control system design, first of all, the closed-loop system stability should be guaranteed. When the fuzzy logic is a part of the control system, it seems hard to prove the system stability, in particular, in linear analysis method because the overall closed-loop system is a nonlinear system. Gain scheduled controller in general is a class of nonlinear time-varying system because the controller properly adapts their gains online to variation of the performances. In this proposed approach, fuzzy logic as a gain scheduler is embedded in the feedforward loop of the system for the controller gain adaptation, shown in Fig.3. All the controller gains are limitedly varied within maximum and minimum of the gains in accordance with the fuzzy rule proposed in this paper. Limits of the controller gain variation are obtained in the successive loop closure from the root-locus in which the closed-loop system should always be stable and its performance is satisfactory. This means that the 'reasonable' start-up transients in this control system is tolerable. If the 'wild' start-up transients happen and the control system becomes unstable, then the system performance might be monitored in advance and then the gain scheduler might be turned off. Thereby the closed-loop system become stable because the system is operated only in the fixed gain PID control law designed to be stable. It is noted that this monitoring system is not yet involved in this system.

Simulation and Evaluation

In this section, the automatic landing guidance and control system in the gain scheduled PID controller is illustrated in the longitudinal nonlinear simulation model given in Ref.[8]. In the glide slope capture logic, PID type is determined, and in the flare logic, PD type is selected. The overall block diagram for simulation in SIMULINK^{TM} is shown in Fig. 6. Note that the throttle input(%) coming out of the linear feedback controller is transformed into the thrust(lb) that enters into one of the nonlinear simulation model inputs. The airplane is trimmed at 1,500 ft altitude with 250ft/sec airspeed and the wing level. From the trim, the airplane is about to take the final approach and landing under the effect of wind shear turbulence, shown in Fig. 7. Wind shear turbulence excites this nonlinear simulation model. The turbulence has characteristics that the airplane is influenced mainly by the head wind during about the first 30 sec and then strongly by the downdraft. After 60 sec, the tail wind mostly influences on the airplane motion until the flare starts. Strength level of the turbulence considered here belongs to 'class 1', reported by NSSL[13]. Moreover, the fuzzy rules, given in Table 2 and 3, are determined for this situation according to designer's experiences of classical auto-landing control law[1,14-16].

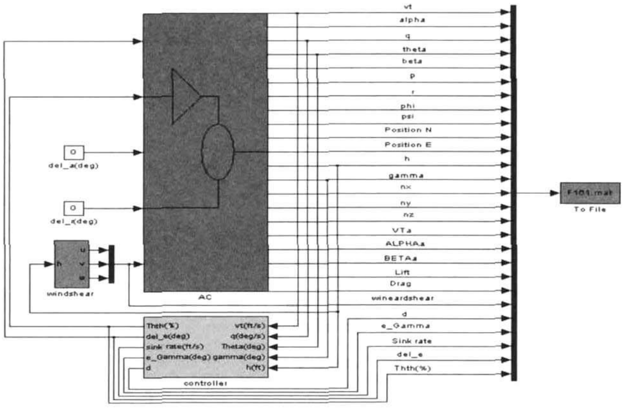

Fig. 6. Simulation block diagram

Table 2. Rule table for K_p

		$\dot{e}(t)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(t)$	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 3. Rule table for K_d

		$\dot{e}(t)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(t)$	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

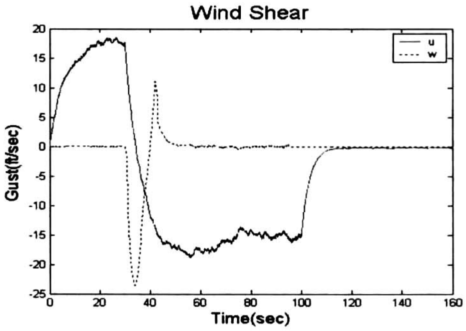

Fig. 7. Wind shear turbulence

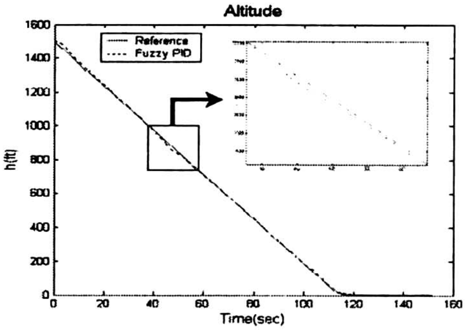

Fig. 8. Altitude response

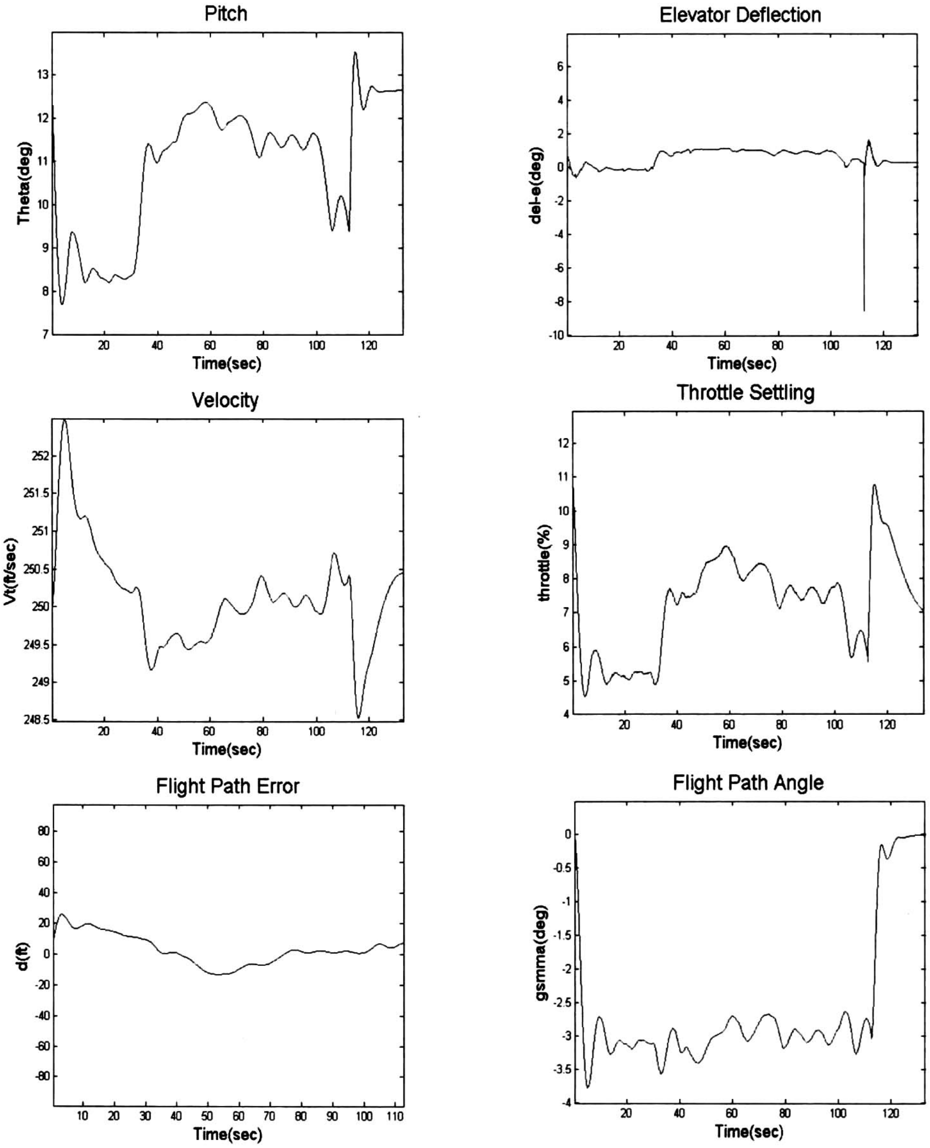

Fig. 9. Time responses to wind shear turbulence

The time responses of the control law to the wind shear turbulence excitation are given in Fig. 8 and 9 where 'solid' line means the reference trajectory to be followed by aircraft and 'dotted' line implies the actual flight path. From the time responses, it is observed that during the downdraft excitation from 30 sec to 50 sec the glide slope capture logic works well even though most of state variables show abrupt change in magnitude of the responses. Especially the throttle control mainly contributes to keeping satisfactory performance of the airplane during the downdraft excitation in spite of loss of the altitude. The flare starts at about 110 sec and the smooth touchdown takes place within 20 sec. During the approach and landing maneuver, the design results almost satisfy the design requirements. From the flight mechanics point of view, it is noted that the flare needs to increase the pitch angle to lead the airplane to smooth touchdown, causing reduction of airspeed. But airspeed must keep constant until touchdown and the flight path angle becomes zero. So the throttle control must be increased at the flare start. It is noted from the overall results that during the approach and landing maneuver under the turbulence excitation, the throttle control rather than the elevator control is dominantly contributed to satisfaction of the stability and performance during this flight.

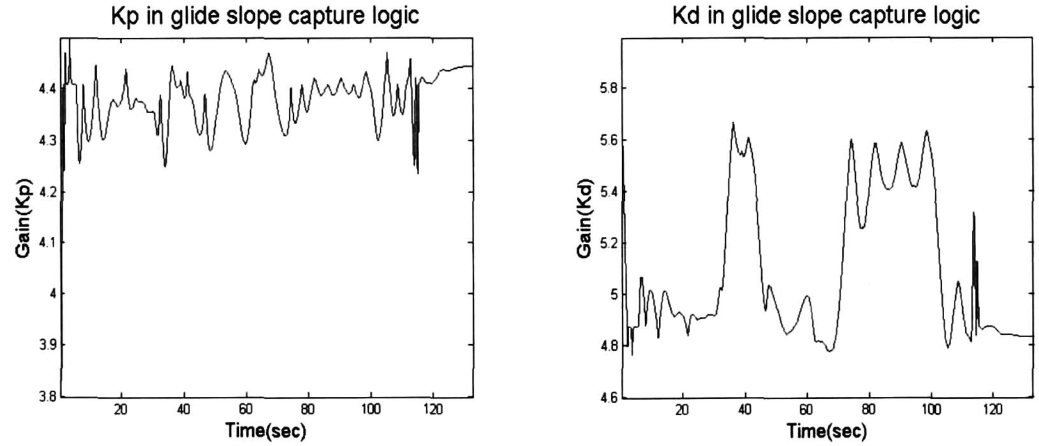

Fig. 10. Variation of controller gains for glide slope capture

Also, adaptation of the PID gains for the glide slope capture and flare maneuver is shown in Fig. 10 and 11. From the results, it is shown that the gains of PID controller are being properly adapted online within the limited gains selected. The gain change of the PID controller in Fig.10 takes place abruptly at the beginning of the simulation because of the sudden change of the airplane states from trim values. Because of the velocity control loop on for all times, it is shown that the PID controller gains shown in Fig. 10 during flare adapt their gains properly. From these results, it is noted that the controller gain adaptation proposed in this paper has advantage for the system that may be operated under unpredictable environments such as turbulence and for the system with uncertain parameters of the system that might affect the performance degradation unless properly controlled.

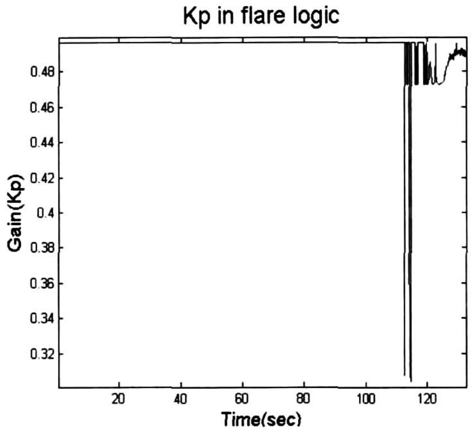

Fig. 11. Variation of controller gains for flare

Conclusions

So far the adaptive PID control law is proposed to apply to the design problem of the automatic landing under the effect of wind shear turbulence. For adaptation of the PID gains, fuzzy logic is utilized as gain scheduler. So the PID controller gains are adapted online to change to the performance variation caused by the wind shear turbulence. To illustrate the successful automatic landing maneuver in this gain scheduled control law, numerical simulation in the longitudinal nonlinear airplane model is carried out. Simulation results show the satisfactory performance during the maneuver of glide slope capture and flare. As results, the proposed control law in this paper is successfully applied to control of the automatic landing maneuver under the wind shear turbulence.

Acknowledgement

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