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A New Pitch Angle Adaptive Control Design

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***Abstract* - This paper presents a new pitch angle adaptive control design based on the pitch rate following of a desired trajectory that ensures closed loop satisfactory performance. The pitch rate is under adaptive predictive (AP) control, as previously seen in the literature, but its desired trajectory is produced by a guidance block within a global guidance system structure that ensures automatic pitch angle closed loop performance. Additionally, the guidance block presented in this paper allows satisfactory operation of the automatic pilot in a range of high control frequencies suitable for this kind of application, overcoming stability problems that may arise within these high frequencies by direct application of a pitch angle AP controller. Experimental results obtained by flying a simulated aircraft illustrate comparatively the guidance system performance, and show the robustness of the new design with aerodynamic disturbances.**

Index Terms – Pitch Angle Control; Optimized Adaptive Control; Adaptive Predictive Control; Derivative Control; Guidance System.

I. INTRODUCTION

The first real time application of adaptive predictive (AP) control was carried out in 1975 using the facilities of the Charles Stark Draper Laboratory in Cambridge, Massachusetts, USA [1, 2]. It consisted on the design and experimental evaluation of an automatic pilot for the pitch rate dynamic control of NASA´s F-8 supersonic aircraft.

The main difficulty in the application of control systems to the longitudinal dynamics (pitch control) of aircraft arises from the large variation in the plant parameters occurring during the course of normal flight operations. This variable nature of aircraft dynamics represented a challenge for the application of any control system, and particularly for the application of adaptive control systems. The difficulty of this problem was emphasized in a NASA research program for the adaptive control of the F-8, the results of which were published in 1977 [3 - 9]. In fact, the purpose of the program was not to develop new control methods, but, rather, to apply existing methods to the problem. The results of the program showed up the inability of the methodologies employed to solve this problem.

It is clear that, in this context, the application described in [1, 2] was a real challenge for AP control, which was implemented on the same F-8 aircraft utilized in the aforementioned NASA program. The excellent results obtained demonstrated the suitability of this technique for this kind of control problem.

Later on, many other methodological approaches have also been proposed for flight control systems. Amount others, non-adaptive feedback control algorithms such as linear quadratic regulator (LQR) theory [10, 11], eigenspace techniques [12, 13], optimal control algorithms [14], H∞ robust control synthesis technique [15]. All of them offer a high performance fixed-parameters control law when plant parameters are known under a linear formulation of the aircraft model. However, because of the time varying characteristics of the aircraft dynamics due to the varying configurations and operational parameters, such as fuel consumption, air density, velocity, it is difficult to synthesize a fixed-parameters control law to work effectively throughout the whole flight envelope. Therefore, adaptation appeared again as a need within the control scheme.

More recently, some studies [16] came back to the gain scheduling approach already introduced in [17]. PIDs with Gain Scheduling (GS-PID) were adjusted in different scenarios in the presence of actuator faults [18]. However, performance of gain scheduling depends on algorithms that switch from one PID to another, from accurate measures of health & flight conditions of the aircraft. Other adaptive techniques proposed include fuzzy control [19, 20], neural networks [21], genetic algorithms [22] and Lyapunov theory [23]. These techniques are generally complex and may be difficult to implement in practice with substantial flight performance improvement.

The original AP control methodology [2, 24-25] was extended in many ways to produce the body of optimized adaptive control techniques [26, 27], which has been successfully applied in many different industrial processes [28- 31]. This paper goes back to the first application in the aerospace field presented in [1] and includes its AP control scheme within a global guidance system, which from a set point produced by a guidance block controls the pitch rate evolution to achieve the desired performance of the pitch angle closed loop. In fact, pitch rate control was already used in [1], but pitch angle closed loop automatic performance was not considered.

Additionally, the guidance system presented in this paper allows satisfactory operation of the automatic control system in a range of high control frequencies suitable for this kind of application; while direct AP control of the pitch angle in these high frequencies can affect the sensitivity of a subset of parameters of the predictive model and deteriorate the control performance, introducing instability. The new guidance system, used in this application, is a particular case of a more general guidance system design [32], which has been the subject of an international patent [33].

Section II of this paper introduces the guidance system control strategy. Section III describes the guidance block, used in this particular implementation. Section IV presents the pitch angle control sequence of operations. Section V describes an aircraft simulation model. Section VI presents and analyses the experimental results obtained by flying said aircraft simulation, both with the guidance system and with a straight pitch angle AP controller in an ideal case. Section VII presents the effect of aerodynamics disturbances, both wind shear and turbulence, within the guidance system performance. Section VIII presents the conclusions.

II. GUIDANCE SYSTEM CONTROL STRATEGY

This section presents firstly the motivation to apply a guidance system to the pitch angle control and, secondly, a description of the guidance system structure considered here.

A. *Motivation of the Guidance System*

It is known that AP controllers, use a process cause-effect relationship or prediction model to predict the process output variables evolution. The reliability of said prediction depends on the value of the prediction model parameters, and on the other hand, the value of the predictive model parameters depends on the control period selected. Thus, the setting of the control period is important to ensure that the value of the predictive model parameters lie in a range appropriate to predict reliably the evolution of the aircraft dynamics. The choice of a control period below a certain threshold of time, that may be named *modelling threshold*, relatively small with respect to the natural time response of the aircraft, makes the values of a subset of the predictive model parameters to approach zero too closely. In fact, this makes that any small identification error in this parameters value may deteriorate the controller performance, due to the deterioration of the predicted output variable evolution and the corresponding control action computation.

However, the practical application of a flight control system may require the use of a reduced control period below. This requirement is to avoid, by means of a quick correction, undesirable deviations produced by disturbances acting on the aircraft, and can provide, in the context of AP control, the adaptation frequency necessary to track closely dynamic changes of the aircraft. But, as previously mentioned, the performance of the pitch angle controller may deteriorate if the control period have to be selected under said *modelling threshold*.

The guidance system used here is intended to allow the use of control periods below *modelling threshold*, improving for these control periods the control system performance obtained by direct application of AP controllers to the pitch angle control of an aircraft.

B. *Description of the Guidance System Structure*

The guidance system structure considered here for the pitch angle control design is represented in Fig.1, which shows two path to generate, at each control instant k, the elevator deflection control signal $\delta_e(k)$ to be applied to the aircraft.

When the pilot chooses the manual control path to set, at time k, $\delta_e(k)$, is directly applied to the process and also it inputs the AP controller, as shown in the figure. On the other hand, the pitch angle process output variable $\theta(k)$ inputs the guidance block, shown in the lower automatic control path of Fig. 1, and a computation block, which computes the increment of $\theta(k)$ between two successive control instants in order to generate the pitch rate variable $\dot{\theta}(k)$. The pitch rate inputs as well the AP controller. Thus, under manual control, the guidance strategy ensures that the AP controller can operate in the identification mode described in [25].

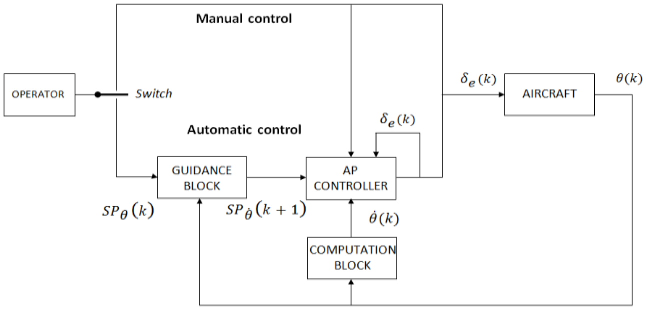


Fig. 1: Pitch angle control design based on Guidance System.

When the pilot chooses the automatic control path, he applies the pitch angle set point value $SP_\theta(k)$ to the Guidance Block of Fig. 1, which from the measured pitch angle generates a desired trajectory for the pitch angle to reach the applied set point. Taking into account the slope of the pitch angle desired trajectory, the guidance block computes a corresponding pitch rate set point $SP_{\dot{\theta}}(k+1)$ that is applied to the AP controller shown in the figure. $\delta_e(k)$ is then computed by AP controller. Under this design of the guidance system, a good performance of the AP pitch rate controller should ensure the pitch angle to approach satisfactorily the desired trajectory to reach its set point.

III. GUIDANCE BLOCK DESIGN

The Guidance Block design presented here is a particular case of the more general concept introduced in [32-33]. It computes periodically the pitch rate set point at updating instants t. The set of updating instants t is a subset of the set of control instants k characterized by the fact that two consecutive updating instants are separated by an updating period equal to q control periods, with $q\geq 1$. The guidance block computation of the pitch rate set point is performed at each updating instant t in accordance with the following two steps:

1. Selection at instant t of a desired output trajectory to guide the pitch angle $\theta(t)$ towards its set point, along the successive updating instants. This computation can be performed in many ways as described in [32-33], but the particular one considered here is illustrated in Fig. 2. In this figure can be seen the evolution of the pitch angle, under the operation of this particular design of the guidance block, assuming the performance of the AP controller of the guidance system is such that the pitch angle evolution follows, step by step without deviation, the desired process output trajectory generated at each updating instant by the guidance block. It can be observed that the future desired pitch angle trajectory is selected, at each updating time t, to be equal to a straight line that, in the plane of evolution of the pitch angle variable versus updating instants shown in Fig. 2, would link the current value of the pitch angle variable with the set point value. The slope of this straight line is determined by its increment approaching the set point value over an updating period of time, that is to say, the increment of the desired pitch angle trajectory between updating instants t and $t+1$. In this particular design of the guidance block, this increment, which is the slope of the considered straight line or the desired pitch rate per updating period, $SP_{\dot{\theta}}(t+1)$, between updating instants t and $t+1$, is computed as follows:

- $SP_{\dot{\theta}}(t+1)$ is equal to a maximum approaching speed value MAX, as long as the distance between the current value of the pitch angle variable $\theta(t)$, and the set point value $SP_{\theta}(t)$, is bigger than the product of MAX by a number of updating periods T_f. In this case the straight line, with slope equal to MAX per updating period would reach said set point value in more than T_f updating periods. Obviously, MAX and T_f are structure variables of the guidance block to be set by the designer.
- When the distance between $\theta(t)$, and $SP_{\theta}(t)$, is lower than the product $MAX * T_f$, the value of $SP_{\dot{\theta}}(t+1)$, defined as the slope of the straight line per updating period, is computed by:

  $$SP_{\dot{\theta}}(t+1) = [SP_{\theta}(t) - \theta(t)]/\, Ti \tag{1}$$

  Where T_i is a number of updating periods. T_i is another structure variable of the guidance block to be set by the designer. The computation of $SP_{\dot{\theta}}(t+1)$ by (1) means that the desired pitch angle trajectory at t will reach the set point $SP_{\theta}(t)$ in T_i updating periods being the desired pitch rate equal to $SP_{\dot{\theta}}(t+1)$.

The guidance block structure variables are chosen by the guidance block designer to make the evolution of $\theta(t)$ converge in a desired manner towards $SP_{\theta}(t)$.

2. Computation of $SP_{\dot{\theta}}(k+1)$, defined as the slope of the straight line per control period, by means of:

$$SP_{\dot{\theta}}(k+1) = SP_{\dot{\theta}}(t+1)/\, q \tag{2}$$

where q is the number of control periods by updating period, with $q \geq 1$.

IV. PITCH ANGLE CONTROL SEQUENCE

The specific operations that the guidance system will carry out at every control instant k, to automatically control the aircraft pitch angle, are described as follows:

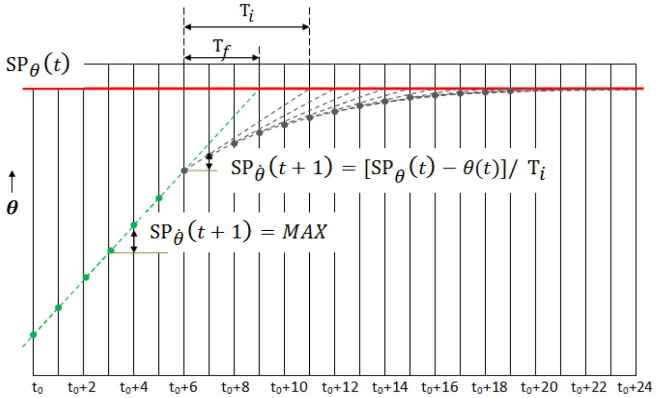


Fig. 2: Pitch angle evolution under a particular design of guidance block

1. Measurement of the pitch angle output process variable $\theta(k)$ to be controlled and computation of the pitch rate $\dot{\theta}(k)$ variable per control period in Computation Block by means of:

$$\dot{\theta}(k) = \theta(k) - \theta(k-1) \tag{3}$$

where $\dot{\theta}(k)$ is the increment of $\theta(k)$ between control instants $k-1$ and k. It should be noted that the pitch rate variable could be directly measured and modified per control period.

2. Computation by guidance block of the set point value $SP_{\dot{\theta}}(k+1)$ to be applied at instant k to the AP controller as previously described in Section III.

3. Computation of the elevator deflection $\delta_e(k)$ by the AP controller, from $\dot{\theta}(k)$ and $SP_{\dot{\theta}}(k+1)$ at $k+1$, computed by the guidance block. The sequence of operations of the AP controller used by the guidance system is described in [24-25] and is determined by the structure variables of the controller [2, 24-25], which were chosen as follows: (i) the control period was 40ms; (ii) the prediction horizon was equal to 1 control period; (iii) the driver block parameters were equal to those of a second order critically damped model with a time constant equal to a one control period, a gain and a damping ratio equal to 1, and (iv) the single-input single-output adaptive predictive model had two a_i parameters and three b_i parameters.

The updating period selected in order to carry out the experiments of this paper was 120 msec. and the values of the guidance block parameters, MAX, T_f and T_i, were chosen equal to 0.6 degrees per updating period, 2 and 3 updating periods, respectively. The increment of 0.6 degrees per updating period is the same as a slope of 5 degrees per second.

V. AIRCRAFT MODEL AND CONTROL OBJECTIVES

The application to the pitch angle control [34-36] of a simulated aircraft will be used to illustrate the guidance system operation. Also an AP controller will directly be applied to the same pitch angle control problem for a comparative evaluation of the guidance system performance. The *JSBSim Flight Dynamics Model*, a well-known flight simulator executed within the Flight Gear generic simulation environment [37], has been used to simulate the aircraft dynamics. The interest in accurate pitch angle control is basic as it allows excellent control of the aircraft's speed and altitude.

Fig. 3 shows a longitudinal aircraft diagram. As can be seen, the torque originated by the wing lift force, applied in the wing aerodynamic centre, and the weight, applied at the centre of mass, is compensated by the torque produced by elevator deflection. For each stable flight condition, a certain elevator deflection corresponds to a determined pitch angle, in the context of a highly non-linear process. If the elevator position deviates from equilibrium, the aforementioned torques will not be compensated for and the aircraft will begin to change its pitch angle. The elevator deflection of the simulated aircraft will be the control signal generated by the guidance system and also by the AP controller used for comparison purposes.

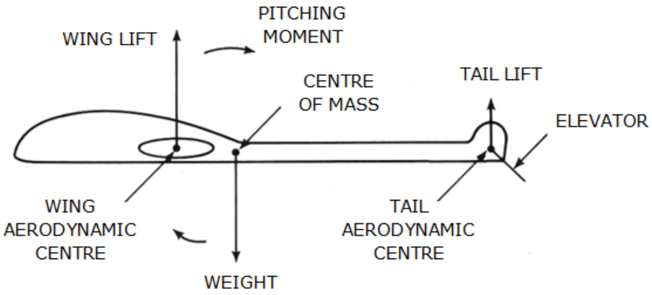


Fig. 3: Longitudinal aircraft diagram

The simulated aircraft chosen has a mass of 340 kg and 8 m of wingspan. It is powered by one propeller, and flies with a cruising speed of 125 km/h at 3000 m of altitude. Fig.4 shows, for these conditions, the effect on the pitch rate and pitch angle variables, for a 1 deg step change in the elevator deflection, with the autothrottle engaged.

Although there are many frequency and time domain objectives for the Flight Control System (FCS) design, in order to illustrate the guidance system concept, the following two time domain objectives have been selected in response to a step change in the pitch angle set point signal:

1. The overshoot peak of the pitch angle and oscillations decrease ratio *(D.R., which is derived by ratio between third and second oscillation peaks)*, characterizes the degree to which the response is well controlled. In this case, the overshoot must be less than 0.5 degrees and D.R. must be less than 25%.
2. The steady-state error and settling time of the pitch angle are indicators of how well the system tracks the desired command. In this case, the steady-state error must be less than ±0.3 degrees and the settling time is characterized by pitch rate demand which is established equal to 5 degrees/s.

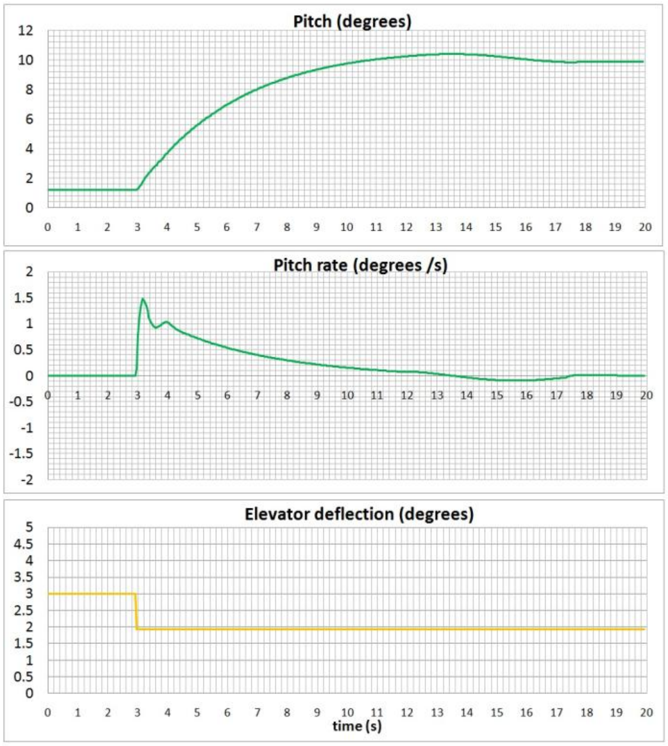


Fig. 4: Step in elevator deflection.

VI. EXPERIMENTAL AND COMPARATIVE RESULTS

This section presents the results obtained in an illustrative experiment where both systems, the guidance system described in the previous sections and an AP controller, were applied to pitch angle control of the simulated aircraft in the same control scenario. Fig. 5 shows the control schematics for the application of the AP controller.

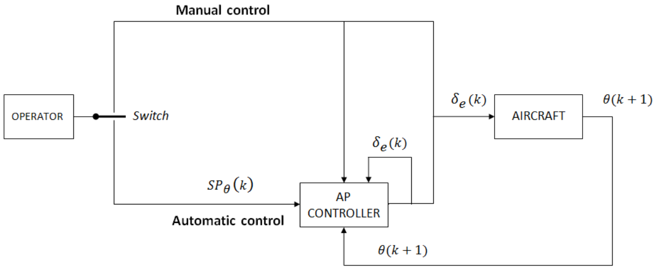
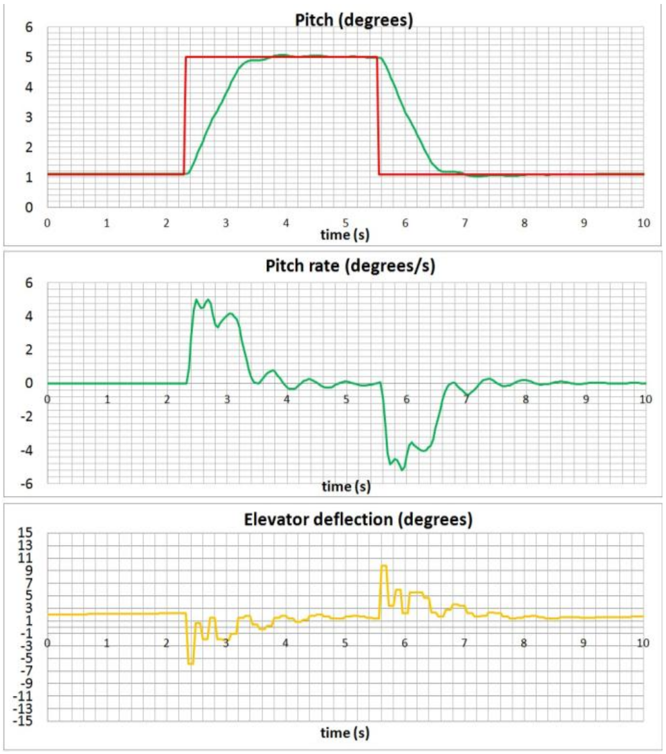


Fig. 5: Control Schematics using direct AP Controller.

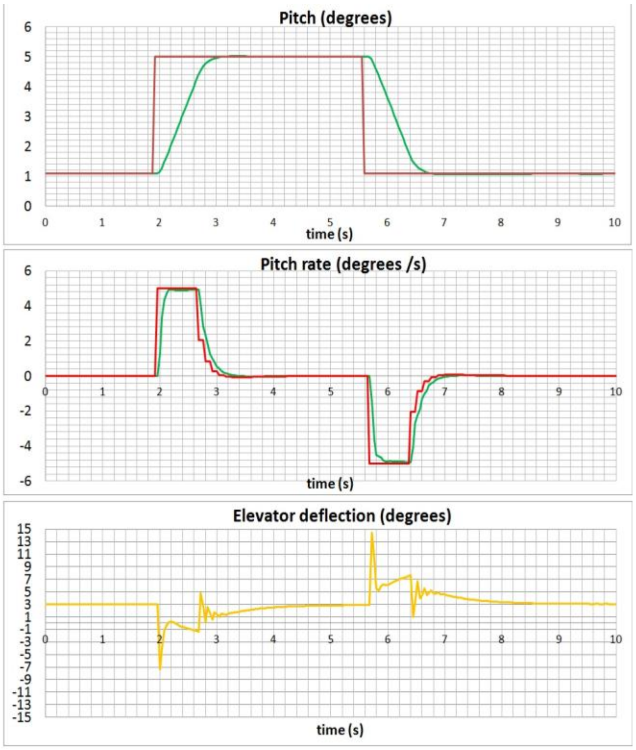
The AP controller was first applied with a control period of 120 ms, well under the *modeling threshold* frequency taking into account the aircraft dynamics. Later, a shorter control period of 40 ms, approaching to the *modeling threshold* frequency, was used in the implementation of the AP controller. The slope of the pitch


Pitch (degrees)

Pitch rate (degrees/s)

Elevator deflection (degrees)

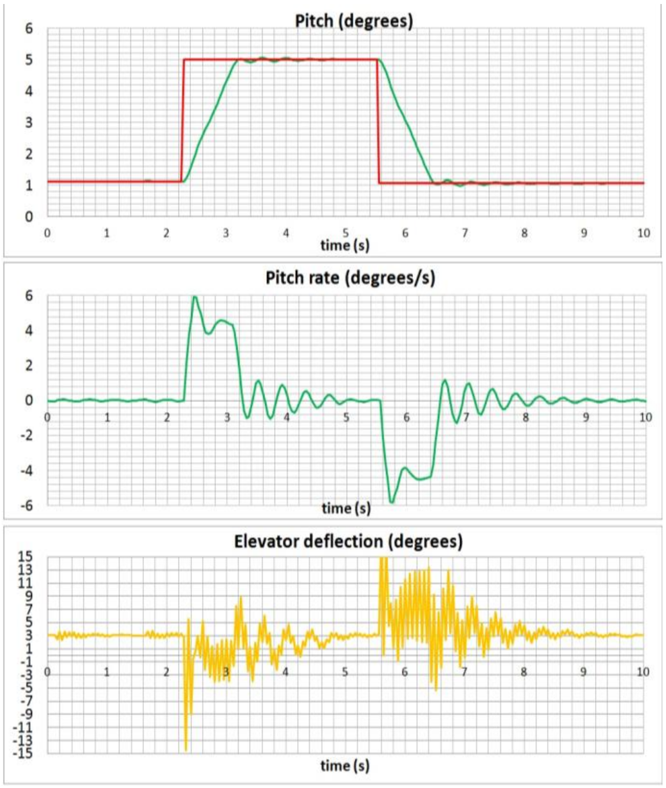
Fig. 6: Experimental Results obtained by the AP Controller (CP=120 ms)


Pitch (degrees)

Pitch rate (degrees /s)

Elevator deflection (degrees)

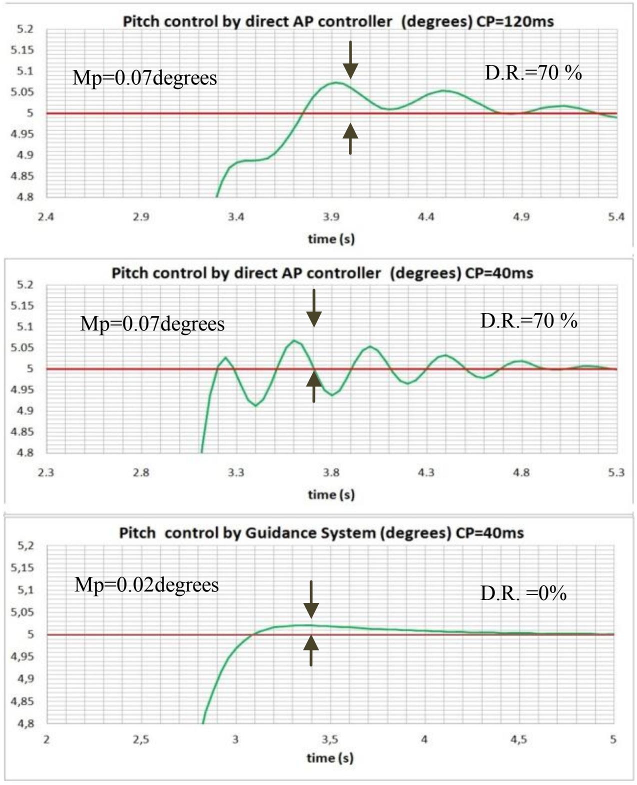
Fig. 8: Experimental Results by the guidance system (CP=40 ms)


Pitch (degrees)

Pitch rate (degrees/s)

Elevator deflection (degrees)

Fig. 7: Experimental Results obtained by the AP Controller (CP=40 ms)


Pitch control by direct AP controller (degrees) CP=120ms

Mp=0.07degrees

D.R.=70 %

Pitch control by direct AP controller (degrees) CP=40ms

Mp=0.07degrees

D.R.=70 %

Pitch control by Guidance System (degrees) CP=40ms

Mp=0.02degrees

D.R. =0%

Fig. 9: Detail of the Experim. Results upon the Set Point Change

angle desired trajectory generated in this case by the driver block was limited to the absolute value of 5 degrees per second in the implementation with both control periods. This limitation was equal to the maximum slope of the pitch angle desired trajectory generated by the guidance block. The other AP controller structure variables were set equal to those of the AP controller used in the implementation of the guidance system, already described in Section IV. The sequence of operations of the AP controller was in both cases that described in [24-25].

The initial steady state flight conditions for the selected control scenario were 3,048 meters of altitude and 128 km/h of airspeed. In these flight conditions, the pitch angle set point is increased to 5 degrees. The pitch angle set point is held at this last value for 3 seconds before it is returned to the initial value of 1 degree. The elevator range of actuation was limited to ±20 degrees of deflection.

The experimental results are shown in Figs. 6 to 9. The trend curves in these figures show, from top to bottom, the time evolution of pitch angle, pitch rate, and elevator deflection. Fig. 6 and 7 show the results when the AP controller was applied, with a control period of 120 ms and 40 ms, respectively, while Fig. 8 shows those corresponding to the guidance system. In order to better appreciate the quantitative improvement in the quality criteria previously considered in Section V, Fig. 9 shows the detail of the pitch angle approach to the set point in the upwards change shown in Figs. 6 to 8, enlarging 3sec. from the 10sec. of the global simulation.

In the following, the performance of both systems, the guidance system and the AP controller, is evaluated comparatively under the criteria established in Section V.

Fig. 6 shows a satisfactory pitch angle AP controller performance, although the pitch angle evolution presents oscillations that can be noticed by integration in the pitch angle. It could be interpreted that adaptation performance is limited by the large control period, and modeling errors result in control that produce oscillations. The pitch angle response under the AP controller operation with 120 ms of control period shows an overshoot (Mp) of 0.07 degrees and a decrease ratio (D.R.) of 70 %, as it can be observed in Fig. 9. Thus, the decrease ratio value is higher than the maximum specified value and the AP controller performance neither meets the control quality objectives.

Fig. 7 shows the pitch angle control performance obtained by the AP controller when the control period is decreased to 40 ms. In this case, although the frequency of adaptation is bigger, it approaches the *modeling threshold* limit. This implies that a subset of AP model parameters approach zero deteriorating the adaptation and control performance. The result is that control actions becomes abrupt and causes higher frequency oscillations in the pitch rate and pitch angle, as it can be observed in the middle and bottom graphs of Fig. 7.

The pitch angle response under the AP controller operation with 40 ms of control period shows an overshoot (Mp) of 0.07 degrees and a decrease ratio (D.R.) of 70 %, as it can be appreciated in Fig. 9. Thus, the decrease ratio value is higher than the maximum specified value and the AP controller performance does not meet the control quality objectives.

Fig. 8 shows the pitch angle control performance obtained by the guidance system with a control period of 40 ms. In this case, no angular accelerations that cause vibrations in the aircraft longitudinal axis are noticed in the pitch rate. Additionally, control actions over the elevator deflection are smooth, with a minimum wear for the elevator.

Thus, the experimental results show how the guidance system can overcome the AP controller performance, by avoiding oscillations in the pitch rate and angle, shown in Figs. 6 and 7, and abrupt control signals, shown in Fig. 7. On the other hand, the pitch angle response under the guidance system operation shows a reduced overshoot of 0.02 degrees, and convergence to the set point without further oscillation, as it can be observed in Fig. 9. Therefore, in this case the control quality criteria are verified.

VII. EFFECT OF AERODYNAMIC DISTURBANCES

Flight path control systems, such as an altitude hold or a glide slope hold, very often use an inner pitch angle control loop. Glide slope hold is used in landing phase, during which wind shear could occurs. The pitch angle controller should provide wind turbulence, shear or gust alleviation. This section illustrates the performance of the guidance system in the presence of aerodynamic disturbances. The same settling defined in Section V and the same flight conditions of Section VI are used in order to show the robustness of the design.

The first aerodynamic disturbance considered is wind shear. It affects pitch rate directly and pitch angle by integration. In order to model this effect, a 3deg step perturbation signal, shown in the first graph of Fig. 10, is added to the pitch rate in the simulator. Fig. 10 shows also the guidance system response in the second, third and fourth graphs. It may be observed how the guidance system deflects the elevator to maintain the desired pitch angle with a maximum error of 0.25deg. Five seconds later, the same steps in pitch angle performed in the previous section are repeated. Following the time domain objectives described in Section V, the pitch angle response shows a reduced overshoot of 0.02 degrees, and convergence to the set point without further oscillation. Also, Fig. 10 shows that when the3deg step perturbation is removed, after 21sec. from the starting of the simulation, the same performance is achieved by the guidance system.

The second aerodynamic disturbance considered is turbulence, including wind. Thus, Dryden model with moderate turbulence has been added to simulator. Experimental results of the guidance system response are showed in Fig.11a and Fig 11b. Fig.11a shows the linear and angular perturbations in the aircraft, while Fig.11b shows the guidance system response. It can be observed that in spite of the turbulence disturbances, the guidance system maintains the desired pitch angle with a maximum steady

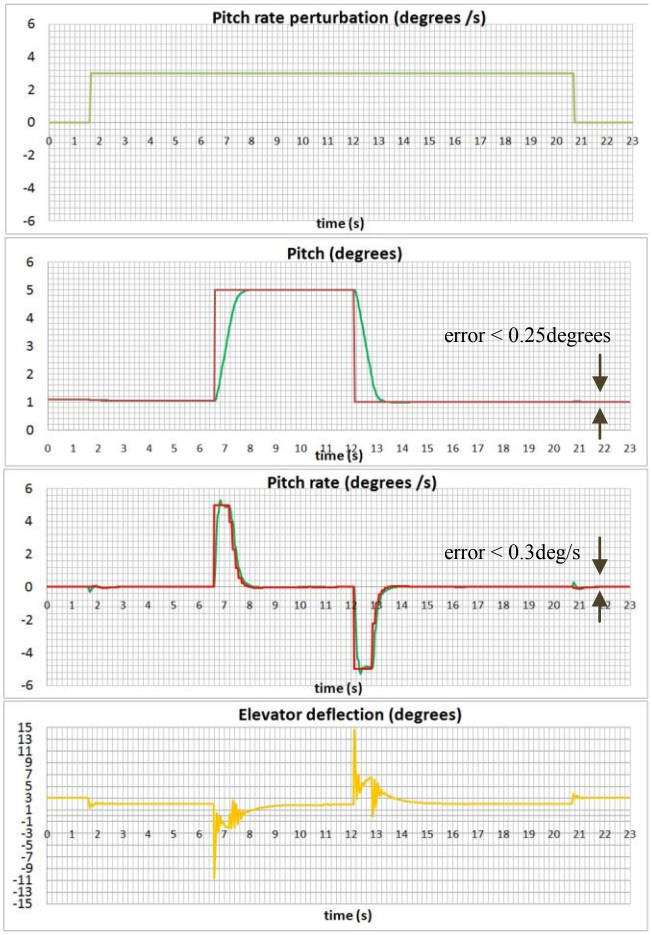


Fig. 10: Experimental Results with pitch rate disturbance.

state error of 0.02deg. The response to a change in pitch angle desired value is similar to the previous one, with a reduced overshoot of 0.03 degrees, and convergence to the set point without further oscillation, showing the robustness of the pitch angle adaptive control design described in this article.

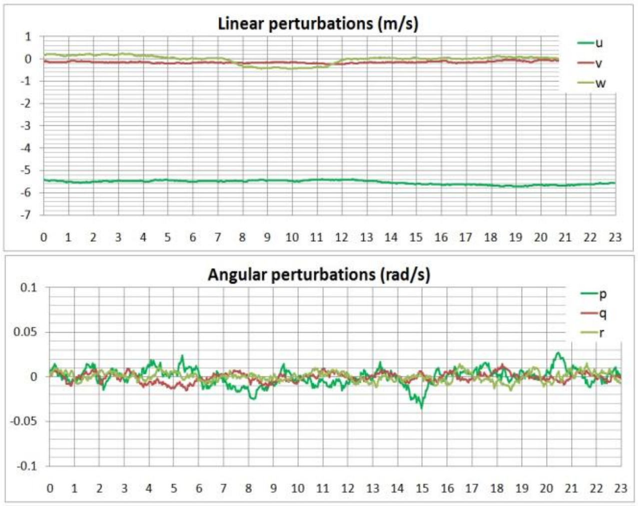


Fig. 11a: Experimental Results with turbulence (disturbances).

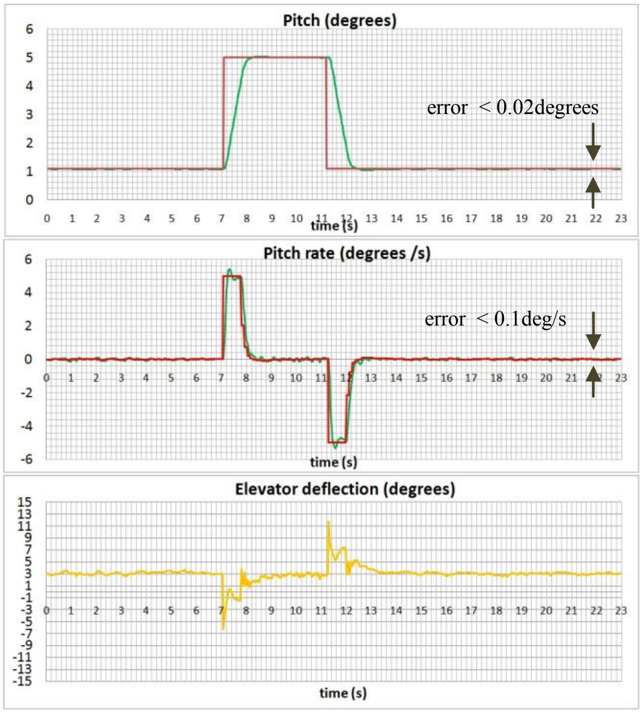


Fig. 11b: Experimental Results with turbulence (pitch response).

VIII. CONCLUSIONS

This paper has presented a new pitch angle adaptive control design based on a new guidance system concept, where the pitch rate follows a set point trajectory that ensures pitch angle closed loop satisfactory performance. This set point trajectory is produced by a guidance block and the control signal by a pitch rate AP controller.

The experimental results obtained by the guidance system, applied to a simulated aircraft, have been compared with those obtained by the direct application of an AP controller, using different control periods, in the same pitch angle control scenario. The guidance system improved the performance of the AP controller by verifying selected quality control criteria, avoiding pitch rate oscillations and abrupt control actions, particularly when the control period approached a certain *modeling threshold* value. Moreover, the robustness of this design has been successfully proven by including aerodynamic disturbances in the operation of the pitch angle adaptive control system.

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