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Research Note

A Control Method Based on the Dynamic Response of the Airplane for Compensation of Pilot-Induced Oscillations: Benefits and Flaws

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Pilot-Induced Oscillation (PIO) is an unwanted, inadvertent phenomenon that has the ability to damage the aircraft completely. This paper suggests a novel control method that can damp PIO after predicting its occurrence. The specific point of this control algorithm is that it contains a preprocessor that will not let the controller be activated unless in the case of probable PIOs, so pilot commands will not be disturbed in normal flight situations. Besides, with regard to the unconscious tendency of the pilot towards establishing PIO, this control algorithm decides on pilot and controller shares in the control signal. By implementing the suggested method, the control algorithm is able to prevent and suppress a general form of PIO. This paper focuses on those groups of phenomena which take place as a result of a sudden disturbance which perturbs one of the states of Pilot-Vehicle System (PVS). It is also shown that the method can block PIO in cases of complex tracking. As a case study, an airplane model based on F-4 derivatives is presented.

INTRODUCTION

Since the first flight of Wright brothers, PIO has created great challenges for most of the aerospace designers and engineers. A large number of accidents and incidents have been recorded as a result of PIO [1].

In general, the oscillations which occur while the pilot is intending to control the aircraft are named Pilot-Induced Oscillations. The main reason for this unwanted event is an imbalance between aircraft dynamics and pilot model. Pilots may perform inappropriately in cases of tiredness or environmental conversions such as night and disturbances. As can be seen, a pilot who is attempting to control and navigate the aircraft is a core element for PIO occurrence.

Since pilot has the most pivotal role in PIO formation, the easiest way for impeding PIO is "pilot stick release"; but, as the pilot is not usually aware of PIO or feels it too late (in most cases, PIO has the ability to cause failure in less than five seconds), finding suitable methods for PIO prevention is necessary.

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Based on the degree of nonlinearities in the event, PIOs can be classified into three categories [1],

Category I: Linear pilot-vehicle system oscillations.
Category II: Quasi-linear events with some nonlinear contributions, such as rate or position limiting. Usually, these PIOs can be modeled as linear events, with an identifiable nonlinear contribution that may be treated separately. The most common nonlinear contribution is rate limiting of a control effector actuator.
Category III: Nonlinear PIO with transients.

The second category of PIO is the most prevalent one; thus, almost all researchers work on this category. Models related to this group contain rate limiters in addition to Pilot-Vehicle System's lags.

During recent years, multifaceted investigations on this phenomenon have been implemented. Some of these investigations focused on dynamical aspects of PIO, and others surveyed control approaches.

The authors of [4] inspect airplane dynamics and then calculate PIO rating during preliminary design. As a result, some coefficients or, perhaps, a part of configuration can be changed to adjust the shortcoming and prevent PIO during actual flights.

In [5] which is one of the oldest references on this subject, it is suggested that by positioning specific filters in PVS's loop, the pilot force and its rate will be suppressed before being applied to control surfaces. The main logic of this idea is emanated from the undesirable role of the pilot in PIO shaping – that is, by lessening pilot effect, oscillations can be damped more easily.

The author in [6] compensates the harmful role of rate limiters by putting rate limit compensators in the closed-loop of PVS. This research focuses on those kinds of PIOs which occur when the pilot is tracking impulses.

In the current paper, we suggest a control algorithm based on dynamical behaviors and responses of PVS and our goal is to prevent PIO during cruise phase. We consider a general case in which PIO happens when a hard disturbance directly disturbs one of the states of the aircraft while the pilot is trying to hold that state in a specific value.

The mentioned algorithm, firstly, recognizes the probability of PIO and, then, decides on pilot and controller shares in controlling the aircraft. We, finally, evaluate our algorithm by applying it to the case of "pilot tracking impulses" [6].

Being motivated by the concept of adaptive automation [7], *i.e.* dynamic function allocation among different control components in the system, we could come up with the original idea of theoretically assigning shares to the input from the pilot and automation. In addition, we suggest a criterion whose satisfaction can be considered as a triger to activate the controller in the loop.

PROBLEM FORMULATION

Consider a continuous-time nonlinear dynamical system:

$$\dot{V}=\frac{1}{m}(-\bar{q}SCD+T\cos(\alpha)-mg(\cos(\alpha)\sin(\theta) -\sin(\alpha)\cos(\theta)))$$

$$\dot{\alpha}=\frac{1}{mV}$$

$$\dot{q}=\frac{\bar{q}S\bar{c}Cm}{I_{y'}}$$

$$\dot{\theta}=q \tag{1}$$

with state $x=[V,\alpha,q,\theta]$ consisting of total velocity V, angle of attack α, pitch rate q and pitch angle θ. Numerical values for stability derivatives are taken from data for the F-4 [8].

We draw on a work by Gately, *et.al.* [6] to define PIO as an event during which the angle of attack transgresses its allowable bounds while the pilot tries to control other states of the aircraft. We also choose the allowable values of angle attack to be between -10 and +30 degrees (Note that this value can be different for various classes of aircraft). It is assumed that by passing these angles, the dynamical behavior of the airplane will change unpredictably or the aircraft may stall.

In cases in which the pilot is involved in tracking tasks, the angle of attack may go beyond its allowable value without any oscillation. In some other cases, the airplane may start oscillating and continuously enters and exits the stall region; we should note that entering the stall region can result in harmful damages.

In this paper, we focus on designing a controller which can prevent PIO for the condition in which a severe disturbance disturbs the airplane's pitch angle while the pilot is trying to hold that state. Meanwhile, the effectiveness of the designed controller will be investigated on non-oscillatory PIOs. We model the pilot as a crossover form - that is:

$$Y_p(s)=K_p e^{-\tau_e s}\frac{T_L s+1}{T_I s+1} \tag{2}$$

with τ_e the time delay of pilot reaction, T_L the lead term, and T_I the lag term. We consider these parameters to have the values of 0.2 sec, 0.1 sec, and 0.2 sec respectively.

A non-linear PID which has very prompt responses and ignorable overshoots is used as a control unit [9]:

$$\dot{e}_\alpha(t)=\dot{\alpha}_d(t)-\dot{\alpha}(t)$$

$$I(t)=(I(t-\Delta t)+e_\alpha(t)\Delta t)\frac{n}{n+\dot{e}_\alpha^2(t)}$$

$$n=n_{\max}\left(\lambda+\frac{|\dot{\alpha}|}{\dot{\alpha}_{\max}}\right) \tag{3}$$

with $\dot{\alpha}_{max}$, $n_{max}=10000$, and $\lambda=0.1$.

A CONTROL STRUCTURE FOR PIO REMEDY

Now that the important role of the angle of attack in PIO occurrence is clarified, we consider the first step in perception and controlling PIO to be limiting airplane's angle of attack while the pilot is unconsciously making inappropriate changes in it.

In our method, we set a controller in PVS loop that bounds the angle of attack while the pilot is controlling pitch angle (If the angle of attack and its rate become limited simultaneously, this angle can be controlled more accurately).

The controller has a part that decides on a suitable set point for the angle of attack. The value of this set point depends on the predicted value of the angle of attack – that is, if the value of the subsequent angle of attack is close to the upper margin, the set

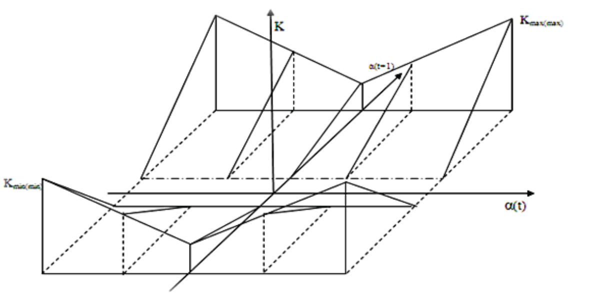

Figure 1. Gain management for controller with reference to current and proceeding angles of attacks.

point will be selected less than the average value, and vice versa.

The gains of our controller also depend on current and subsequent angles of attack. Figure 1 shows a schematic diagram of this gain management.

Finally, the final control law is the result of both pilot and controller commands, which can be formulated as:

$$u_{total} = (1 - PIOR)u_p + PIOR\, u_c \tag{4}$$

with u_p the pilot control input, u_c the automation control input, and PIOR representing aircraft inclination towards PIO or marginal angles of attack.

Equation (4) shows that the overall control law depends on the aircraft tendency toward PIO which is evaluated via the subsequent angle of attack. Hence, as the probability of PIO increases, pilot share in final command will decrease, and the controller share will increase. The following formula defines the changes in PIOR with regard to the value of α at the next instant:

$$PIOR = \max(0, \min\left(1, \left(\frac{\alpha - \alpha_m}{\alpha_{bound} - \alpha_m}\right)\right)) \tag{5}$$

with α the subsequent value of the angle of attack. For $\alpha > \alpha_{avg}$, α_ϵ is positive and $\alpha_{bound} = \alpha_{max}$ and for $\alpha_{avg} > \alpha$, α_ϵ is negative, and $\alpha_{bound} = \alpha_{min}$. In our case, $\alpha_{max} = 30\,\text{deg}$, $\alpha_{min} = -10\,\text{deg}$, and $|\alpha_\epsilon| = 5$ deg.

Overall, the pilot and the controller are exerting two commands to the system, one in order to preserve or track the pitch angle and the other to limit the angle of attack. The resultant force which is transmitted to the control surfaces depends on the airplane behavior in the next moment. In this case, a proper portion is allocated to both control structures in PVS and the final command is the consequence of these two commands.

PIO RECOGNITION FOR ACTIVATING THE CONTROLLER

Continual presence of the suggested controller in the loop can make some problems (For example, when a pilot decides to perform some maneuvers or even when he aims to hold both the pitch angle and the flight path angle in zero, the controller will disturb his commands because the angle of attack is not within the neutral bound). Another example concerns flight phases such as take-off in which the angle of attack needs to adopt higher than normal value and its repression has harmful effects. Therefore, the controller needs a system to decide on its entrance in and exit from the loop and not to let it disturb favorable pilot commands.

The fundamental issue when dealing with adaptive automation is to invoke the automation when necessary. One method of invoking the automation is by considering certain critical events. The critical event is not only defined by the dynamical behavior of the system but also by the performance and the physiological (and psychological) measurement of the user [9], [10].

Hence, to recognize the proper time for controller entrance in the loop, the most important parameter

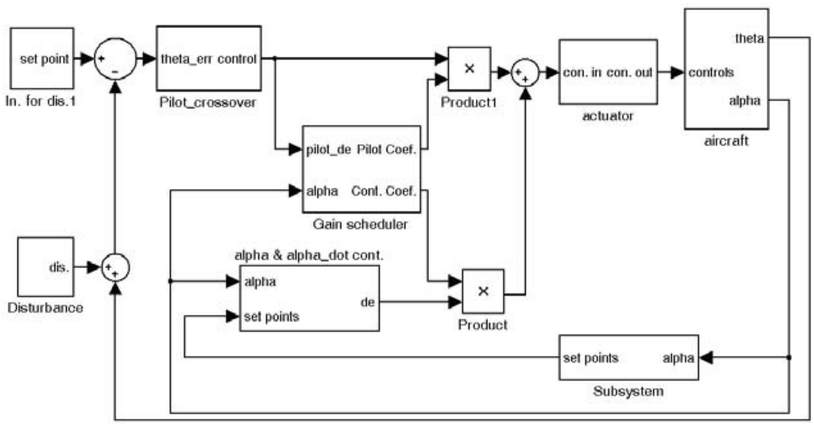

Figure 2. PVS Block Diagram.

is the one which is related to pilot stunning. We use pilot's workload as a tool to check whether the input from the pilot might be entirely impaired as a result of rate limiting. If so, the controller should be added to the loop.

As mentioned, one of the main reasons which leads to the second category of PIO is the presence of rate limiters in the loop which has unfavorable effects. It is obvious that if the pilot exerts high rate input, the rate limiter will not let the control surfaces achieve the desired value. It must also be noticed that this high rate input can show pilot disquietness. Thus, inspecting the rate of pilot command at each moment leads us to learn about the appropriate time for controller activation. If pilot rate reaches a specific value, which must be evaluated exactly, the above mentioned control method will start functioning and will modify pilot commands.

The controller switches off gradually in cases in which the angle of attack and pilot rate gain normal values for a reasonable period of time. Figure 2 shows a PVS together with this control algorithm.

SIMULATION RESULTS

This section contains some diagrams of PIO occurrence for an F-4 during its subsonic cruise. These diagrams are for cases in which a sudden disturbance disturbs aircraft pitch state for 15 seconds while the pilot is trying to hold the pitch angle.

To help the reader understand the period during which the disturbance is applied, the disturbance is also shown in the diagram, though this disturbance is just disturbing the state and has nothing to do with the set point. Figure 3 shows pilot performance when he decides to manage the case of 23 degrees pitch hold and 60 degrees disturbance. Figure 4 shows the effectiveness of using the suggested control method.

As can be seen in these two diagrams, when the pilot is trying to improve the condition solely,

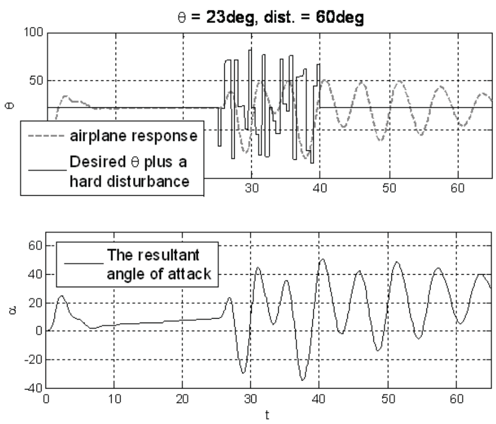

Figure 3. Pilot-alone in controlling the case of 23 degrees θ hold and 60 degrees disturbance.

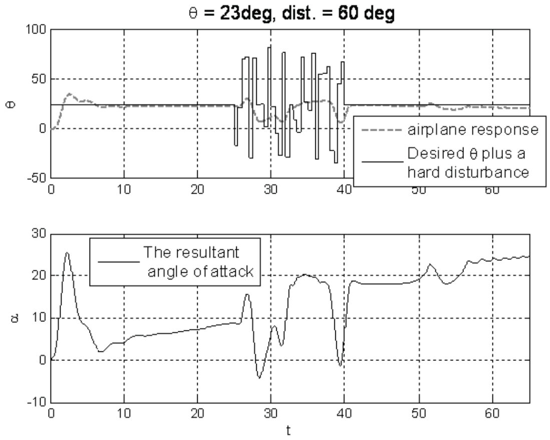

Figure 4. Pilot plus controller in controlling the case of 23 degrees θ hold and 60 degrees disturbance.

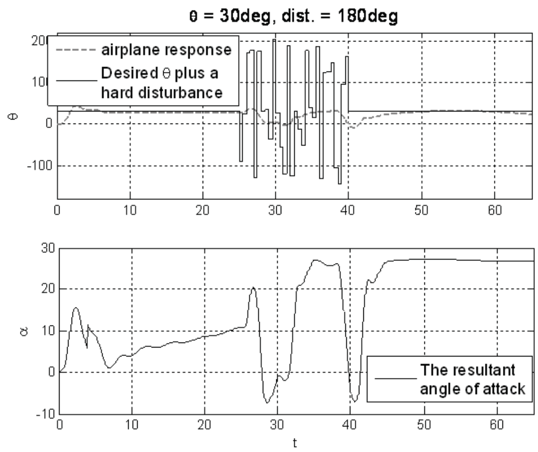

Figure 5. Pilot plus controller in controlling the case of 30 degrees θ hold and 180 degrees disturbance.

the unfavorable effects of disturbances remain in PVS dynamics and the pilot imposes harsh oscillations on the aircraft. On the other hand, it can be seen that the suggested controller has the ability to damp oscillations rapidly and does not let the angle of attack enter prohibited margins.

Figure 5 shows that this method can even solve the problem for a very severe condition of 30 degrees pitch hold and 180 degrees disturbance.

In Figure 6, the share of the pilot and controller in shaping the control signal can be seen.

THE TOLERABLE ASYMMETRY OF DISTURBANCES FOR THE PROPOSED CONTROLLER

Figure 7(a) and Figure 7(b) show that the proposed control method can handle PIO in cases in which ± 45 degree asymmetric disturbance is exerted on the pitch angle. In these two figures, the goal of the pilot is to keep the pitch angle at 30 degrees.

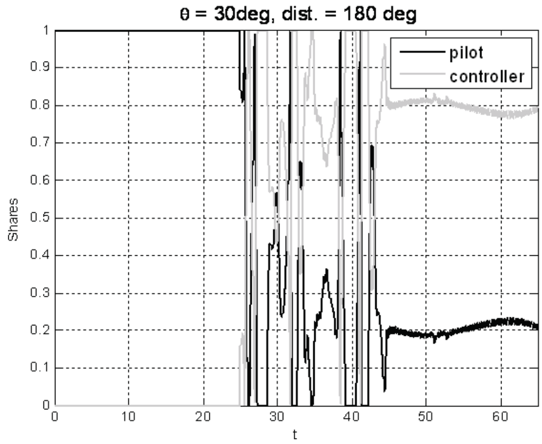

Figure 6. Pilot and Controller shares in control pattern.

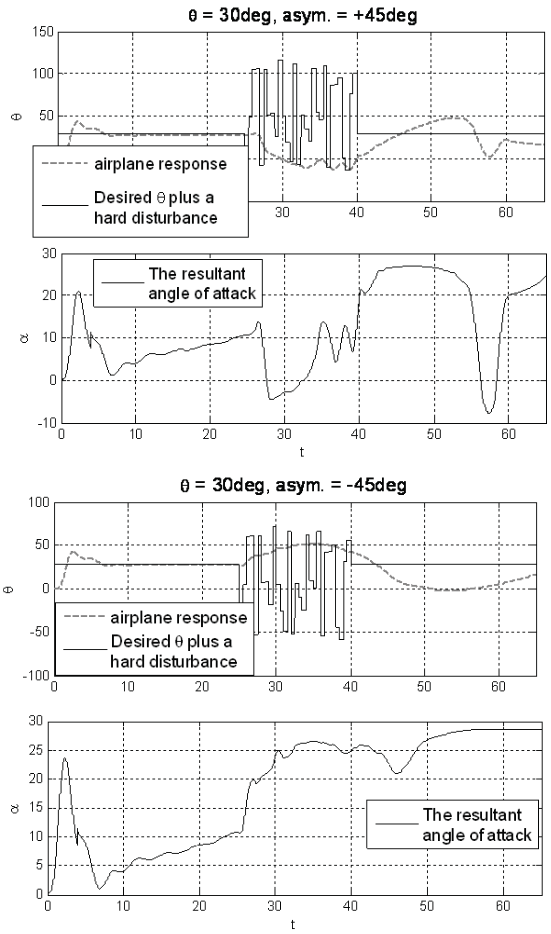

Figure 7. (a) +45 degrees asymmetry, (b)- 45 degrees asymmetry.

For lighter pitch holds, the tolerable level of asymmetry increases but for safety, $\pm 45^{\circ}$ is the value that can be certainly controlled by the proposed control algorithm.

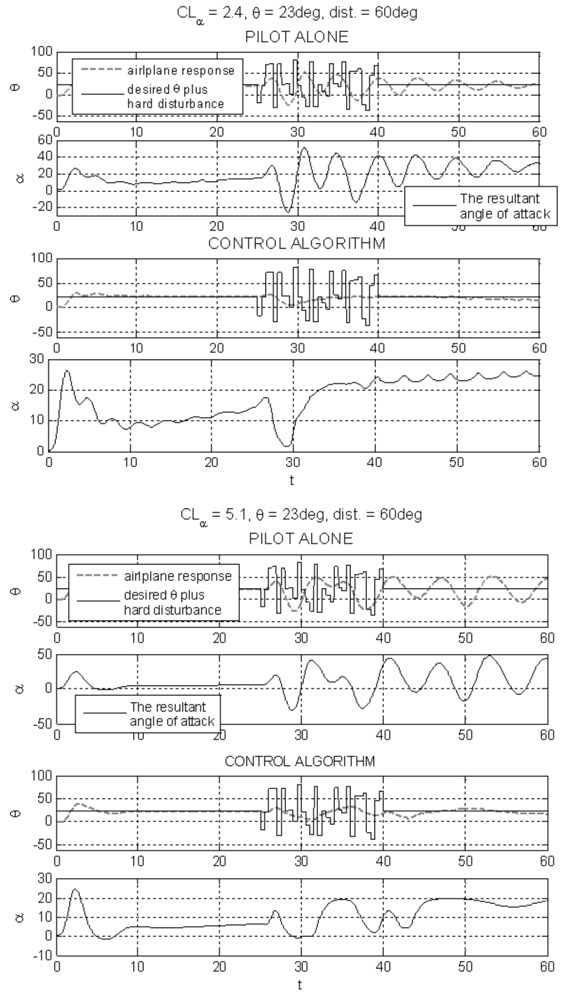

Figure 8. Pilot-alone and pilot plus controller in cases of (a) $CL_{\alpha} = 2.4$, (b) $CL_{\alpha} = 5.1$.

THE INFLUENCE OF DERIVATIVE CHANGES IN CONTROLLER PERFORMANCE

In this section, the effect of changing some most important longitudinal derivatives [8] in the performance of our controller will be evaluated.

Figure 8 shows the effect of changes in CL_{α} for cases of pilot alone and pilot plus controller.

The worst case appears for changes in Cm_{α}. Again, the controller can tolerate changes of this derivative in the allowable bound for fighters. In Figure 9, when Cm_{α} has the value of -0.3, which is the upper bound of this derivative for fighters, pilot effort puts the aircraft (angle of attack and pitch angle) in high amplitude oscillations. In such a critical and dangerous case, the controller can damp oscillations easily.

By condoning the unacceptable values of Cm_{α}, we can claim that the control algorithm can perform perfectly for various values of derivatives.

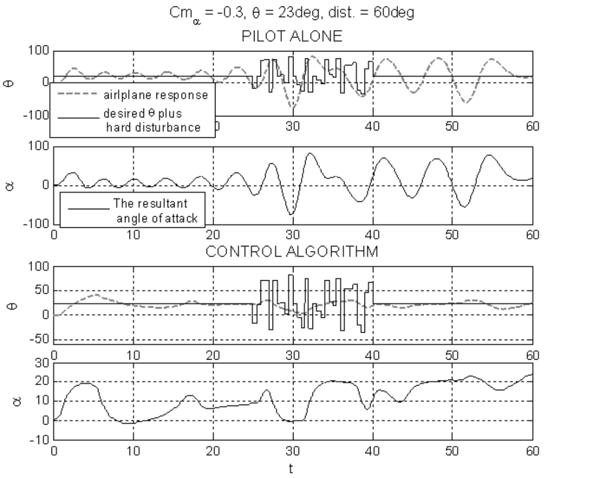

Figure 9. Pilot-alone and pilot plus controller in the case of $Cm_\alpha = -0.3$.

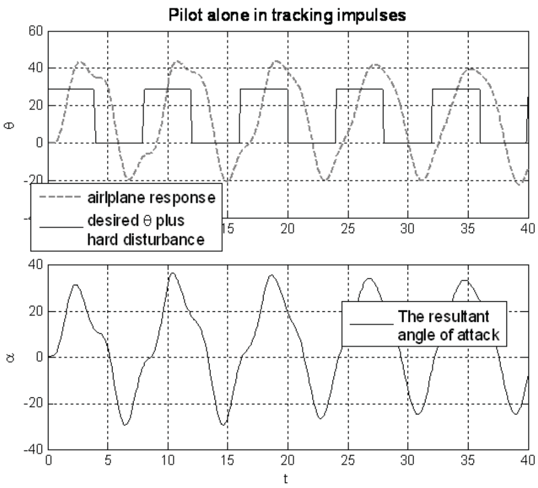

Figure 10. Pilot tracking high frequency impulses.

EFFECTIVENESS OF THE PRESENTED CONTROLLER FOR COMPLEX TRACKING

Figure 10 shows that during tracking a pitch angle which is made up of high frequency impulses, pilot effort will lead to inappropriate values of angle of attack. In Figure 11, it is shown that the controller can solve the mentioned problem.

Since the aim of our control algorithm is preventing PIO (not accurate tracking), the outcome is an infelicitous tracking.

CONCLUSION

This paper presents a control algorithm based on the dynamical behavior of an aircraft. The suggested method was shown to be able to solve oscillatory and non-oscillatory PIO problems within specific conditions.

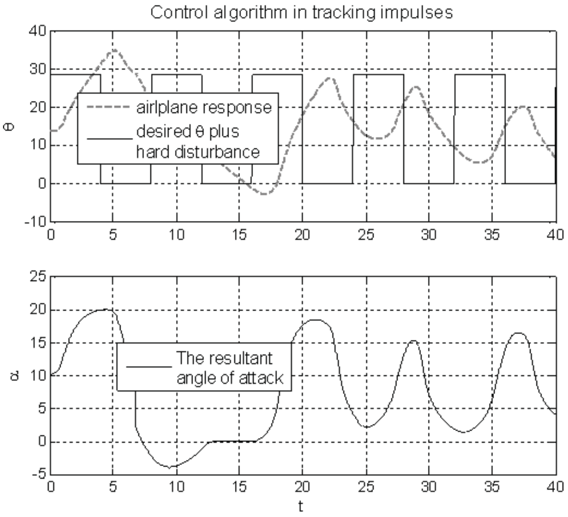

Figure 11. Control algorithm in tracking high frequency responses.

Since we used a simplified model of the system, there exists a broad field of research for improving our method. The crossover model of the pilot, the assumption of constant mass for the aircraft, and the consistency of derivatives with regard to changes in the angle of attack are some points that can be improved.

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