Phase compensation design for prevention of PIO due to actuator rate saturation

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***Abstract*— This paper presents a simple and effective solution for type 2 pilot-induced oscillations due to rate limit in the control surface. The proposed method uses a nonlinear filter that compensates the phase of the control signal before feeding the actuator. The structure of this filter has advantages over previous realizations that allow tuning simplicity considering limit cycle prevention as control specification. Simulation results demonstrate the good performance of the proposed compensation.**

I. Introduction

All aircraft control surfaces have restrictions when the actuators are operating at their maximum capacity. One of these limitations is known as rate limit and it relates to the maximum speed at which an actuator can follow changes in the input signal (see figure 1). Furthermore, in fly-by-wire (FBW) the control signals are rate limited by software before feeding the control surface in order to avoid stress in the actuator.

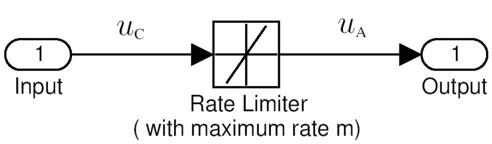

Fig. 1. Simulink block of the rate limiter nonlinearity

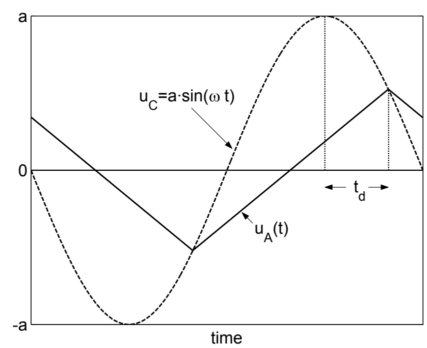

Fig. 2. Input signal to the actuator (dashed), output signal of the actuator with maximum rate denoted as m (solid) and time delay experienced t_d.

Fig. 3. JAS-39 PIO accident due to rate limit of the control surfaces

It is well known that the appearance of rate limitation leads to degradation in the performance of the vehicle. Consider the case of figure 2 with a pilot applying direct commands to an actuator with rate limit denoted as m. If the pilot applies very rapid changes in the input signal, for example an excessively rapid (or large) sinusoidal signal $u_c(t) = a\sin(\omega t)$, a phase lag occurs between the input and the output signals. This phase shift leads the pilot to experience a time delay (t_d) in relation to the commands given [10] and can cause the pilot to make a larger input than is necessary. Thus, rate limit of control surfaces causes a misadaptation between the pilot and the vehicle affecting its handling and leading to pilot-induced oscillations (PIO).

Diverse aircraft as the Space Shuttle, the C-17 and the Boeing 777 have recorded PIOs during its development phase. Indeed, in highly augmented fly-by-wire fighters these incidents have led to highly publicized crashes as the YF-22 raptor [5] and the JAS-39 Gripen [12].

Furthermore, prevention of PIO requires more than just high actuation rates, as evidenced by the early F/A-18 problems of rate saturated lateral PIO despite 100 degrees/sec aileron rates. In fact, an important research effort is being made on PIO prevention.

The paper is divided as follows. *Section II*, provides an overview of previous compensation techniques adopted. The compensator will be described in *Section III*. *Section IV* presents a simple case of application, and finally, *Section V* provides a set of remarks and conclusions to the paper.

II. Existing methods for prevention of category 2 PIO

As has been commented, prevention of type 2 PIO requires more than just high actuation rates, and actually

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there is a wide scope of compensation methods.

One of the first compensations used was to reduce gain in the stick commands [13] or gain in the feedback control, but this deteriorates the flying qualities of the aircraft and produces a delayed gain recovery (a highly augmented aircraft flying like a transport aircraft).

Another solution is related to the use of phase compensation when the rate limitation is active. In this more elaborated approach the behaviour must meet the following requirements:

1) Provide the same input and output signal when the input signals are average or sufficiently slow.
2) Reduce the phase retardation in the case of sinusoidal input signals of PIO frequency.
3) Do not provide less gain attenuation than a pure rate limiter.

In this context, there are two different tendencies for executing phase compensation in control systems with rate limitation:

- Methods that use logical conditions (if-then-else) to establish whether a phase compensation requires to be executed in the control system. These methods switch between different behaviours [7], [1].
- Methods that generate a continuous signal by feedback. These are methods inspired in anti-windup techniques [12], [4].

Actually, the best phase compensators seem to be the feedback type [11], [6], such as the Rundqwist's compensators for the Gripen [12] and that for the Tornado SPILS [11]. In any case, the parameters of the compensator need to be carefully chosen for the particular circumstances [14].

III. The Proposed Phase Compensator

In the diagram block of figure 4, the proposed compensator is shown. It is developed with a rate-limited feedback and a phase-lead network for compensating the phase lag .

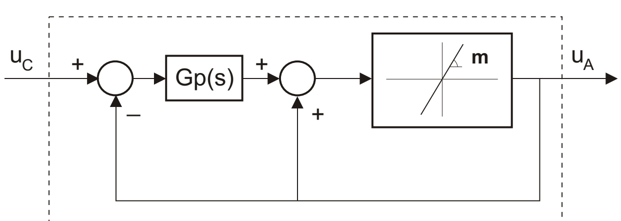

Fig. 4. Block diagram of the proposed rate-limited feedback

With this structure, the phase compensation is achieved by feeding back the output signal and obtaining an error signal. This error signal feeds a phase-lead network $G_p(s)$ that guarantees the minimum phase compensated. Finally, the result is summed up again to the output and passed through a rate limiter block in order to comply with the rate saturation. Actually, the proposed compensator has been filed for patent rights.

In figure 5, the frequency response of the phase appears for a given configuration of the compensator. Also in this figure, the frequency responses of the rate limiter without compensator as well as with Rundqwist's compensators are shown for comparative purposes.

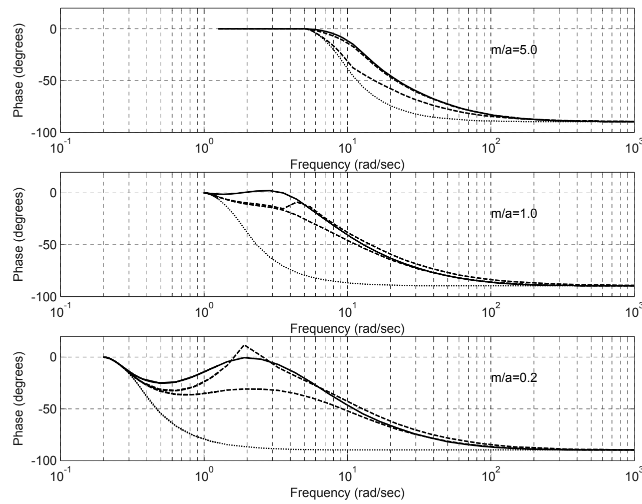

Fig. 5. Frequency responses with different values of amplitude (a) for a rate limiter without compensation (dotted), with the Rundqwist's compensators (dashed) and with the proposed compensator using $G_p(s) = (s+1)^2/(s+5)^2$ (solid)

As can be seen, the describing function of this compensator corresponds to the describing function of a rate limiter Ψ with at least the phase of the linear transfer function used $G_p(s)$. Furthermore, it must be remarked that the minimum phase shift does not depend on the amplitude of the signal as it happens with previous compensators.

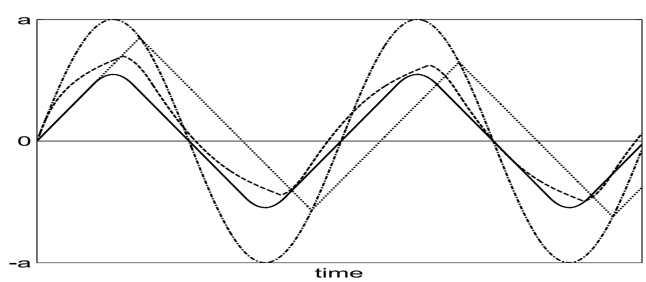

Fig. 6. Input signal to the actuator (dot dashed), temporal response of the rate limiter without compensation (dotted), with Rundqwist's compensator (dashed) and with the proposed compensator (solid)

In addition, figure 6 shows the time response of the proposed filter already compared with the pure rate limit behaviour and with the Rundqwist's compensator. It can be observed the phase compensation obtained for PIO frequencies.

IV. A Case of Study: The X-15 Landing Flare PIO

In the following, phase compensation is applied to a model of the X-15 research aircraft represented in figure 7. This test case is the nonlinear model of the longitudinal dynamics, for which a PIO occurred in the first flight, due to rate limiting of the horizontal stabilizers [9]. This incident is a classical platform for testing PIO prediction criteria and has been extensively studied [8], [3].

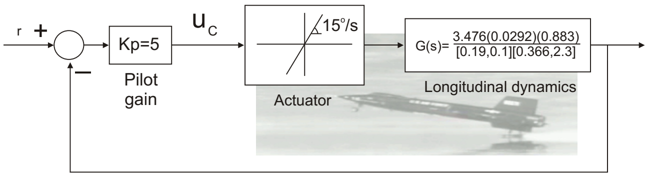

Fig. 7. Model of the original controlled longitudinal dynamics.

As can be seen in the model of figure 7, the block diagram of the longitudinal dynamics is given by the transfer function:

$$G(s) = \frac{\theta(s)}{\delta(s)} = \frac{3.476(0.0292)(0.883)}{[0.19, 0.1][0.366, 2.3]}$$

where (a) is equivalente to $(s + a)$ and $[\zeta, \omega_n]$ represents $(s^2 + 2\zeta\omega_n + \omega_n^2)$.

$$G(s) = \frac{\theta(s)}{\delta(s)} = \frac{3.476(s + 0.0292)(s + 0.883)}{(s^2 + 0.038s + 0.01)(s^2 + 1.6836s + 5.29)}$$

This transfer function will be used for analysis of PIO and tuning of the phase compensator.

1) PIO analysis of the original control loop: The existence of limit cycles in control loops with rate limiter can be investigated using the describing function method [2]. The limit cycles are solutions of the equation:

$$K_p G(j\omega) = -\frac{1}{\Psi\left(\frac{m}{wa}\right)} \tag{1}$$

This can be solved graphically finding intersections between the frequency responses of the negative inverse describing function of the rate limiter $-1/\Psi(\frac{m}{\omega a})$ and the linear part $G(s)$ in a Nyquist or Nichols chart. Any intersection of the two curves provides a candidate limit cycle with its frequency, amplitude and stability. Although the describing function method is an approximation and must be analyzed with simulations.

With this oscillations detection method, very good agreement was reached in the case of the X-15 (see figure 8). Thus, the minimum value predicted of K_p that arises pilot-induced oscillations ($K_p = 2.52$) is near to the value observed in simulations [1] ($K_p = 2.6$).

2) Filter design for PIO prevention: As has been noted, higher pilot gains have an unstable limit cycle and a stable one. So, for pilot gain $K_p = 5$ limit cycles existence is granted and represented in the Nichols chart of figure 9.

[1]It can be noted that for higher values of K_p two limit cycles are predicted (stable and unstable) and for lower K_p no interceptions are predicted. This behaviour with respect to K_p is described in qualitative theory of nonlinear systems as a saddle-node bifurcation of periodic orbits.

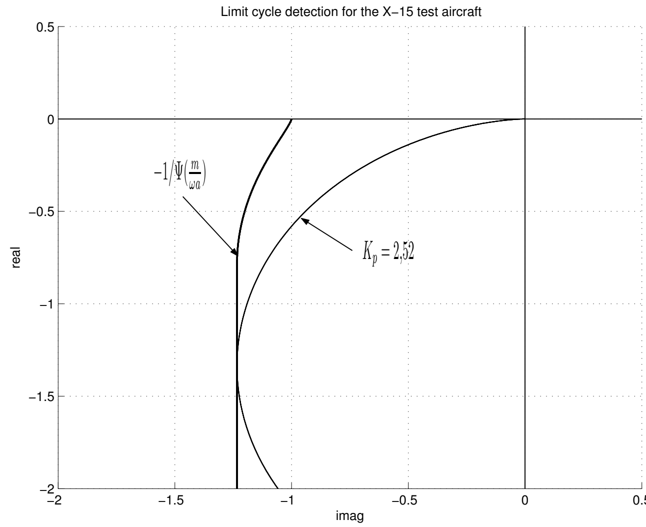

Fig. 8. Nyquist plot for the describing function method in order to obtain the minimum value of K_p that arises pilot-induced oscillations.

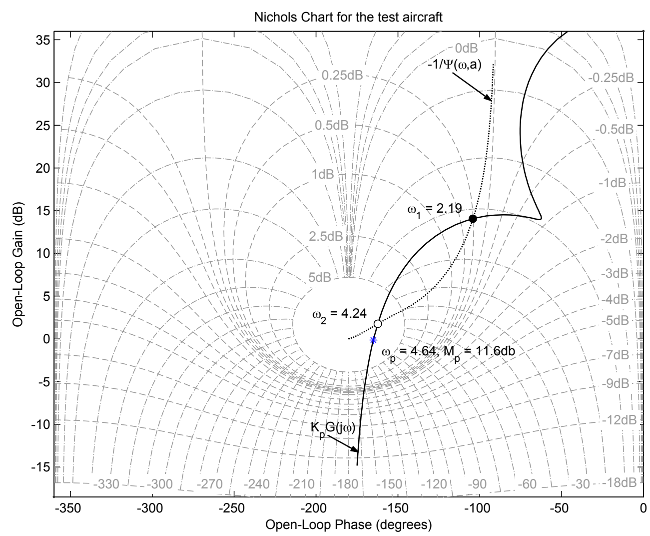

Fig. 9. Nichols chart with the longitudinal dynamics and the negative inverse describing function of the rate limiter.

In order to avoid the presence of limit cycles the proposed compensator has been included in the model and it filters the control signal before feeding the actuator (see figure 10).

The phase-lead network is designed in order to compensate and avoid intersections between the two curves knowing that its minimum phase shift corresponds to the phase of the linear transfer function $G_p(s)$. So, it can be easily tuned with the describing function method looking for $G_p(s)$ such that the following equation is never solved.

$$K_p G(j\omega) + \angle G_p(j\omega) = -\frac{1}{\Psi\left(\frac{m}{wa}\right)} \tag{2}$$

Then, $G_p(s)$ is such that at least it compensates the needed phase in the frequency range from $2.19\,rad/s$ to $4.24\,rad/s$

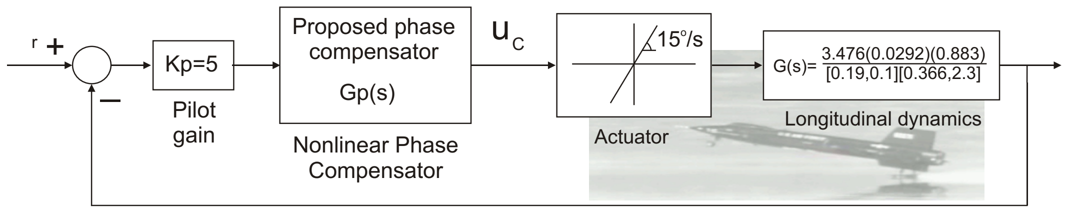

Fig. 10. Block diagram of the controlled longitudinal dynamics filtered with the phase compensator.

(see figure 9. The more compensation the more robust is the final system but worse time responses are obtained. Thus, the transfer function $G_p(s)$ has been chosen as:

$$G_p(s) = \frac{(s+2.4)^2}{(s+4.5)^2} \tag{3}$$

The phase of this transfer function is enough to avoid limit cycles existence without affecting the handling qualities as can be seen in figure 11.

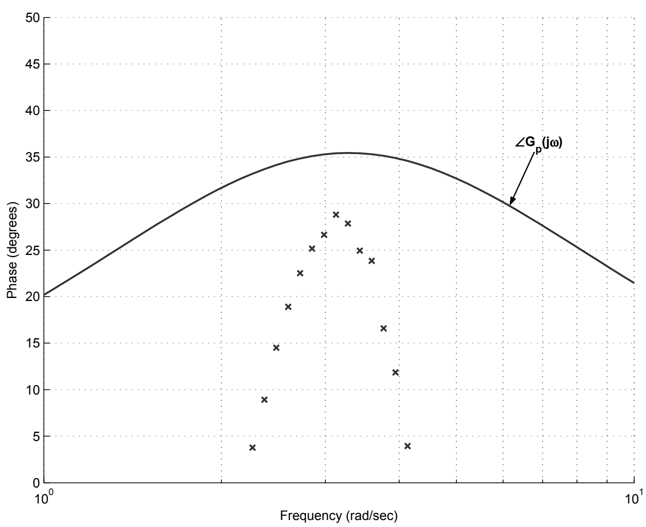

Fig. 11. Needed phase in order to avoid limit cycles in the control loop (x marks) and the phase of the chosen transfer function $G_p(s)$.

Thus, the Nichols chart of the compensated system is represented in figure 12 and is shown that PIO have been avoided. After that, the graphical results have been evaluated in simulation and comparative time responses are shown in figure 13. It can be seen the stable oscillations in the pitch angle for the original aircraft and the PIO supression obtained using the phase compensator. Furthermore, the phase compensation achieves good longitudinal performance and maintains the handling qualities of the system.

V. Conclusions

This paper presents a new nonlinear filter that executes phase compensation of rate saturation in an aircraft control system. The existence of limit cycles in the control loop have been investigated with the classical describing function

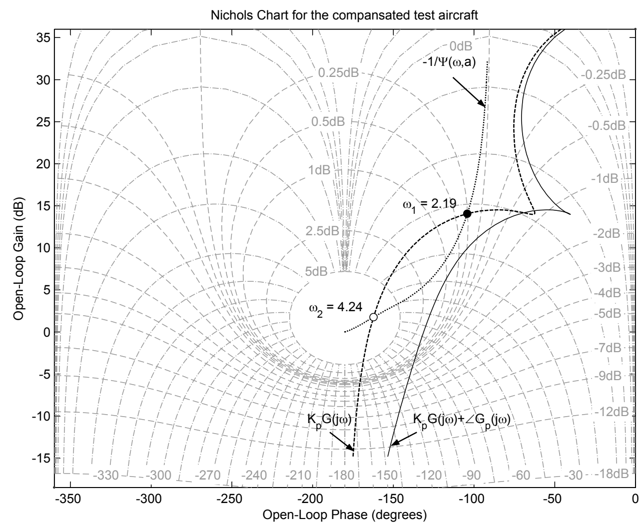

Fig. 12. Nichols chart of the compensated dynamics and the negative inverse describing function of the rate limiter.

method and using the properties of the proposed filter. Thus, the proposed compensator has been easily tuned avoiding pilot-induced oscillations due to the main advantages that it presents over previous realizations:

1) The minimum phase of the compensator does not depend on the amplitude of the signal.
2) Furthermore, this minimum phase compensated is the phase of the linear transfer function $G_p(s)$. So, it can be easily tuned with frequency design techniques.

This compensation has led to a dramatic increase in aircraft stability (effectively avoiding limit cycles), as shown by a case study. Furthermore, the local asymptotic stable system has been transformed into an asymptotic global stable system. The filter improves stability under PIO frequencies and maintains the handling qualities for usual frequencies.

Finally, this nonlinear compensator can be added as a software filter in control laws to prevent pilot-induced oscillations of future and present aircrafts minimizing the costs and impact of the change.

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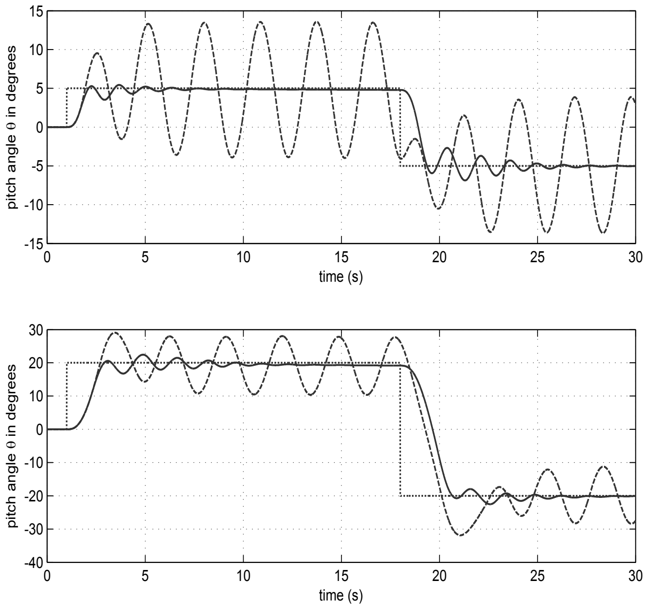

Fig. 13. Simulation time responses of the longitudinal behaviour for the uncompensated X-15 system (dashed) and with the phase compensator (solid)

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VI. ACKNOWLEDGMENTS

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