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Implementation of a pitch attitude protection for high vertical speed in go-around

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ABSTRACT

The paper describes the implementation made within Airbus Flight Control of a pitch attitude protection to avoid high vertical speed in case of tail strike during go-around manoeuvres. It explains the choice of the vertical speed as a key parameter for the protection target implementation. It proposes a way to enhance the performance of the protection as well as tackle intrusiveness, by having a dedicated control loop, based on pitch attitude command.

Keywords: Pitch Attitude protection law, Tail strike protection, Go around

Nomenclature

θ = Aircraft pitch angle
α = Angle of Attack angle
γ = Aircraft slope
q = Aircraft pitch rate in body axis
δ_q = Aircraft elevator deflection
V_z = Aircraft vertical speed in geographical axis
CG = Aircraft Centre of gravity
V = Aircraft true airspeed
S = Aircraft reference surface
l_{ref} = Aircraft mean aerodynamic chord
P_{dyn} = Dynamic pressure
I_{yy} = Aircraft Inertia in y body axis

1 Introduction

Landing phase is a critical phase of a flight journey of an aircraft, where occurring events (wind gust, failures, occupied track) can lead to go-around manoeuvers. The principle of the Go-around is to avoid the landing, and pragmatically to avoid the contact with the ground. In the majority of scenarios the go-around transient goes well, with a pull-up action of the pilot or the autopilot, simultaneously to a full thrust request on the throttle. In some late decision scenarios, a contact of the body landing gear with the ground may appear, and the gears are sized to cope with an important vertical speed at impact. But, in some extreme scenarios, a tail-strike may occur, due to possible combination of strong pilot inputs, failures or aerodynamic phenomenon leading to too strong pitch up moments. The tail structure is not sized to cope with high vertical speed impacts, unlike the train. When a strong impact is unavoidable, for the integrity of the aircraft it may become mandatory to contact the ground with the landing gear rather than the tail of the aircraft. At a moment a crucial challenge appears, opposing the need to generate some lift increase with a higher pitch angle to decrease the vertical speed, and the need to land on the landing gear rather than the tail. The proposed functionality aims at dealing with this challenge, to preserve the integrity of the structure, without jeopardizing the capability to generate lift when it is the more pertinent action.

1.1 Paper outline

The paper is organized as follows. After explaining the flight dynamics motion at stake, it uses the method developed in [1] and [2], based on a reference model-based controller whose gains are computed by an embedded algorithm. Starting with the model used, it introduces a new dedicated control inner-loop. This inner-loop, controlling the pitch attitude, aims at reducing the vertical speed at impact point on tail fuselage, to an acceptable level of structure loads, as well as ensuring non intrusiveness in nominal cases. It explains in the third section how the target in pitch attitude is built, and presents the simulation results in section four. Concluding remarks end the paper.

2 Dedicated control loop

2.1 Flight dynamics motion evolution

During the landing phase and the beginning of the go-around, the aircraft follows a negative slope. Therefore, it presents a negative vertical speed. Once go-around is initialized, the engine thrust produces a pitch up moment, combined with the ones created by the pilot pitch up input and/or any other aerodynamical effects (wind, failure etc). The first effect on motion is an increase of pitch attitude and angle of attack, before the increase of lift force and so the reduction of vertical speed.

The goal is then, taking into account the architecture of the flight control laws, to synthesise a controller which will slow down the pitch attitude increase to let the lift force increase and reduce the vertical speed.

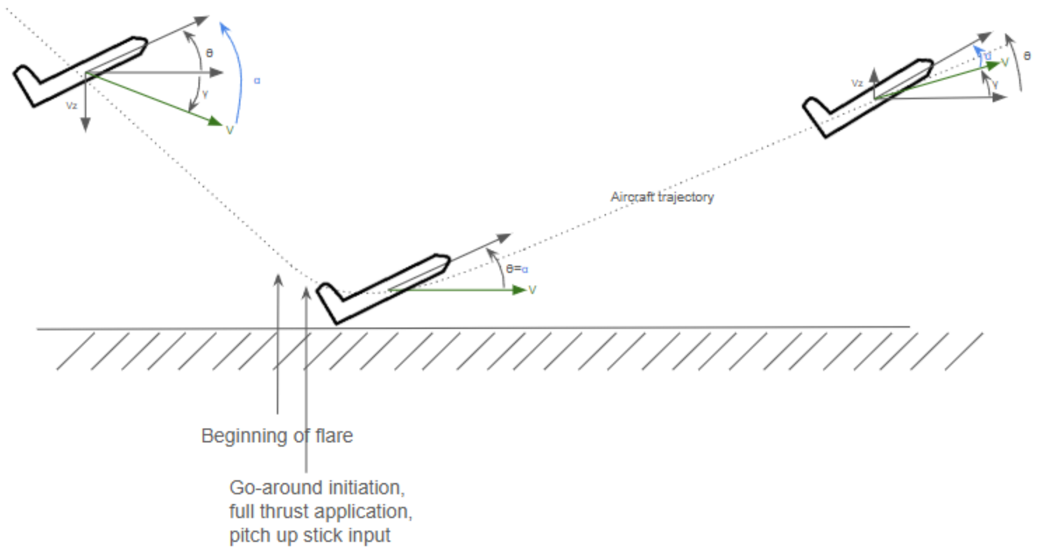

Fig. 1 **Aircraft trajectory during a go-around manoeuvre**

2.2 Flight Control architecture

The longitudinal architecture described in [2] is reminded below :

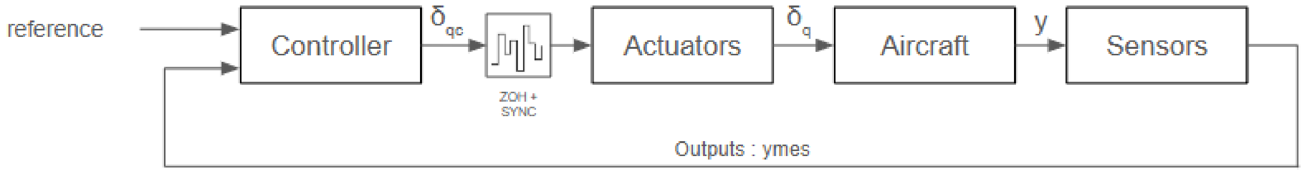

Fig. 2 **Aircraft longitudinal flight control loop**

This chain is detailed hereafter :

- The sensors comprise various equipments, such as Angle of Attack α probe, gyrolasers (for pitch rate q and pitch attitude θ, vertical accelerometers for load factor Nz, Inertial reference system unit (for vertical speed Vz), radio-altimeter (for Height).
- The controller is computing the longitudinal control order, at 25Hz
- The actuators driving the longitudinal elevator surfaces δq to the command deflection δq_c
- Delays of each treatment must of course be taken into account in the design of the control laws

Using the usual control loop described in [2], based on vertical load factor control with integrator (PI structure) would require tuning an outer loop converting a pitch attitude target into a load factor target. But most of all, as an outer loop is slower than the inner loop, it would limit the tuning of the dynamics required to follow this pitch attitude command. Indeed, the inner-loop in load factor is designed for optimizing comfort and performance, whereas the protection needs to be the least intrusive possible as well as very reactive, therefore we need to accelerate it more than the Nz inner-loop. Therefore, a dedicated control loop based on pitch attitude control is chosen.

The architecture is then updated from [2] in figure 3 :

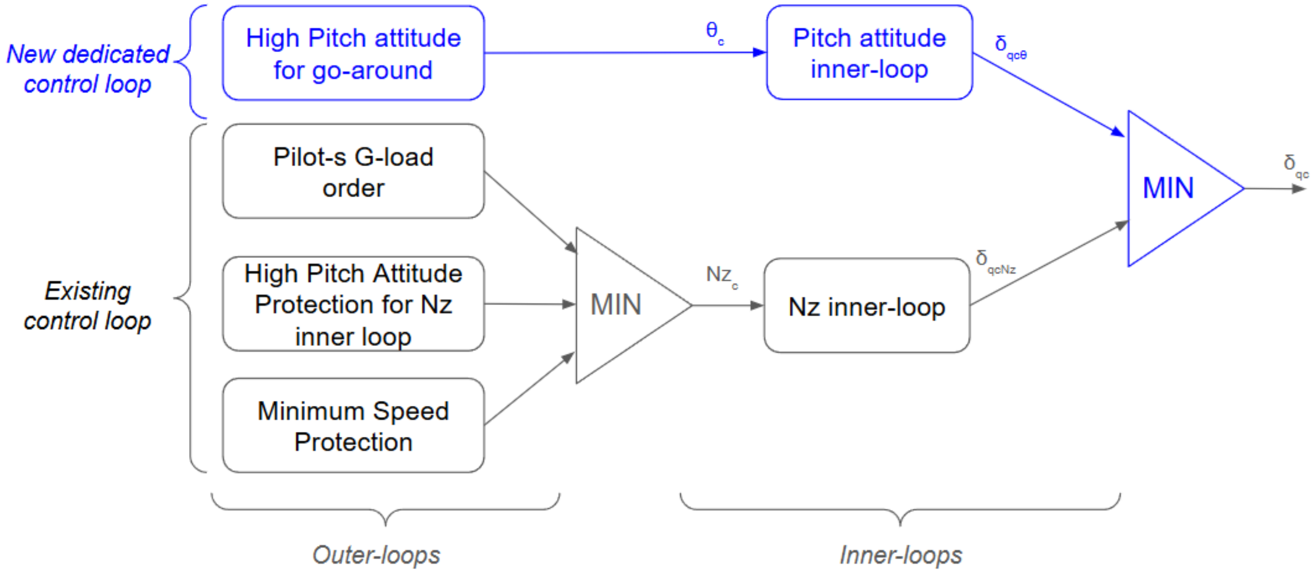

Fig. 3 Envelope protection with dedicated control loop architecture

The final elevator deflection order chosen is the minimum between the one from the Nz law and the one from the Pitch attitude protection law, ensuring a continuity of the final surface order. As mentioned earlier, the effect of this new dedicated is, when it is engaged, to slow down the pitch attitude increase to let the lift force increase and reduce the vertical speed, and therefore reduce the vertical speed in case of tail impact. Its design is developed in the next subsection.

2.3 Pitch attitude inner loop design

Let's develop the pitch attitude control inner loop design. First, we need to present the flight mechanics equation used as well as justify the dynamic mode we want to control. Considering the very dynamic phase of the go around, with pilot's short term action on the stick, only short period mode is used (the phugoid mode is much slower and not relevant for our motion at stake). The following short period model [3] is considered :

$$\begin{aligned} \dot{\alpha} &= p_\alpha \alpha + q \\ \dot{q} &= m_\alpha \alpha + m_q q + m_{\delta q} \delta_q \end{aligned} \tag{1}$$

With coefficients :

$$m_\alpha = \frac{SLP_{dyn}}{I_{yy}} Cm_\alpha \qquad m_q = \frac{SLP_{dyn}}{I_{yy}} Cm_q$$
$$m_{\delta q} = \frac{SLP_{dyn}}{I_{yy}} Cm_{\delta q} \qquad p_\alpha = \frac{SP_{dyn}}{mV} Cz_\alpha$$

Looking for transfer $\frac{\theta}{\theta_c}$ and considering $\dot{\theta} = q$ for leveled aircraft, the open loop dynamics gives in Laplace formalism :

$$
\begin{aligned}
\theta &= \frac{(s-p_\alpha)m_{\delta q}}{s(z_2 s^2 + z_1 s + z_0)}\delta_q \\
with & \\
z_0 &= m_q p_\alpha - m_\alpha \\
z_1 &= -(p_\alpha + m_q) \\
z_2 &= 1
\end{aligned}
\tag{2}
$$

The zero must be taken into account to master the transitory state, and to place all three modes, the following command structure is proposed :

$$
\delta_{q_c} = \frac{1}{m_{\delta q}}\left[\frac{1}{s-p_\alpha}\left(K_q q + K_\theta \theta + K_d \theta_c + \frac{K_i}{s}(\theta_c - \theta)\right) + K_{dq} q\right] \tag{3}
$$

The last term is essential to place the new mode introduced by the integrator term in the open loop equation; if not, the structure produces a free mode that can be dominant over the desired dynamics. As seen in [4], we can also use a pseudo derivative term, the command structure would become:

$$
\delta_{q_c} = \frac{1}{m_{\delta q}}\left[\frac{1}{s-p_\alpha}\left(K_q q + K_\theta \theta + K_d \theta_c + \frac{K_i}{s}(\theta_c - \theta) - p_\alpha K_{dq} s q\right)\right] \tag{4}
$$

These structures works well to place the desired dynamics, the first one avoids deriving the pitch rate term, adding robustness to pikes measurement.

The dynamics is placed, using Airbus embedded algorithm method (see [1]), to correctly manage the target overshoot, and minimize pitch rate long enough for the lift force to increase the vertical speed, as we will see in section four.

At last, as the reference model is linear, it does not include non-linear effects close to the ground. A model-based feedforward term to compensate ground effects, as well as a disturbance rejection law (ANL) can be added in the control law to tackle those phenomenon (see [1] and [5]).

3 Implementation of a pitch attitude target based on Vertical speed

Now we need to implement a pitch attitude target. The concept of the protection is to reduce the vertical speed at impact point on tail fuselage. It implies to minimize the pitch rate, to avoid overshooting the pitch attitude of tail strike. However it must not be to intrusive, which means it must not break the lift effect by stopping too early the pitch motion.

Due to aircraft trajectory before engaging go-around (negative slope), a command in pitch based only on radio-altimeter measurement [4] does not give satisfactory results. Vertical speed measurement is to take into account (or at least a phase advance in height).

Therefore the parametrization of the target in pitch attitude is proposed as follows :

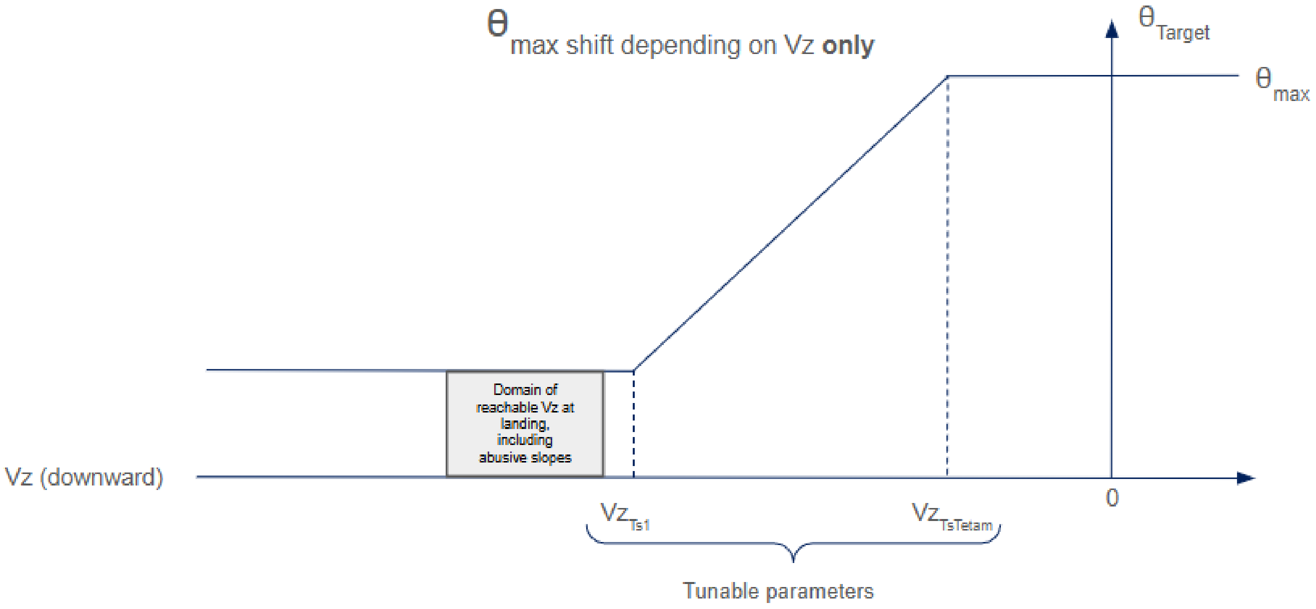

Fig. 4 Pitch attitude target depending on vertical speed

At the beginning of go-around, the vertical speed is downward. Therefore the target in pitch is rather low and prevents from developing a high pitch rate around the pitch attitude corresponding to tail strike. As soon as the vertical speed comes close to zero or higher, the target constraint is released to the usual high pitch attitude target. It avoids restraining the aircraft envelope.

The figure 5 below shows the evolution of vertical speed, and so the pitch attitude target during a go around. We will see later on that the target constraint is released before the minimal tail strike margin value is reached. This is a key parameter to tune between the constraint to avoid tail strike and the intrusiveness of the law.

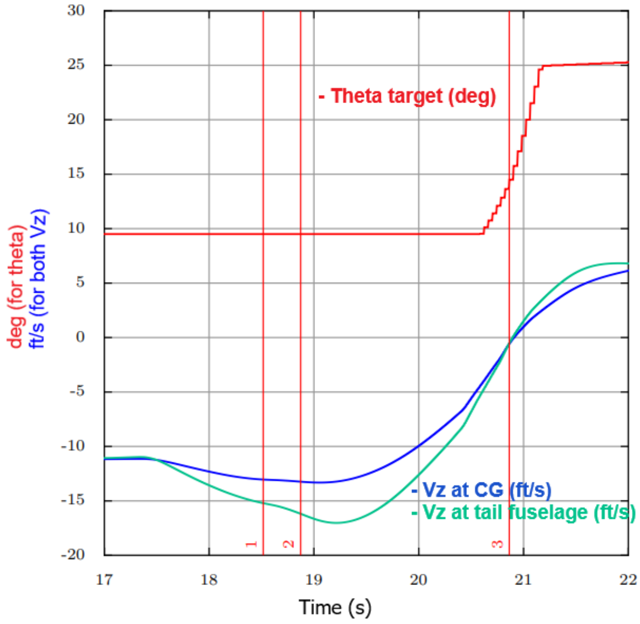

Fig. 5 Pitch attitude target and Vertical speed evolution during a go-around
Vertical lines correspond to 1 = go-around initiated (full engine thrust), 2 = back stick input, 3 = minimal tail strike margin

As illustrated in the figure 6 below, the minimum saturation of pitch attitude target, when Vz is increasing downward (in absolute), avoids limiting the angle of attack of the aircraft. Therefore, as the angle of attack is not constrained, it does not further constraint the lift force. Hence it helps recover a positive slope, thus a positive vertical speed.

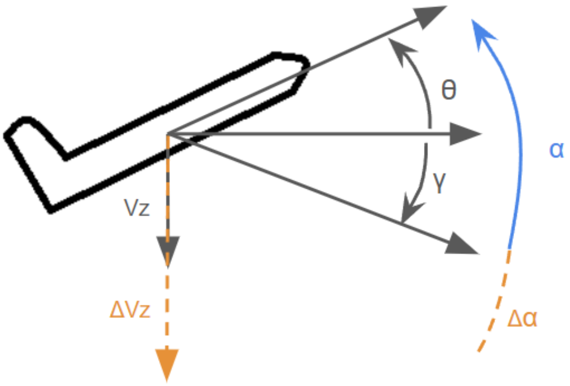

Fig. 6 Increase of V_z at constant θ implies an increase of α

The vertical speed used here can be roughly the one on the impact point of the tail fuselage, but the exact location of this point can vary depending on the height. An average point can be chosen in that case. However, taking the V_z at the center of gravity, gives already satisfactory results and avoids introducing two different sensors in the pitch attitude target computation.

4 Results

This design has been exposed to a validation and verification campaign in the latest Airbus representative simulation environment (non-linear 6-dof-simulation), including embedded calculator model.

The results are presented hereafter.

Figure 7 shows a go-around without the pitch protection, initiated in abusive condition at 25ft, with full engine thrust, and a full back stick input 0.5s later, we can see that the Vertical speed at impact point is indeed increasing downward due to pitch rate. The lift force establishment due to alpha increase happens in a second time, but too late to invert the vertical speed trend.

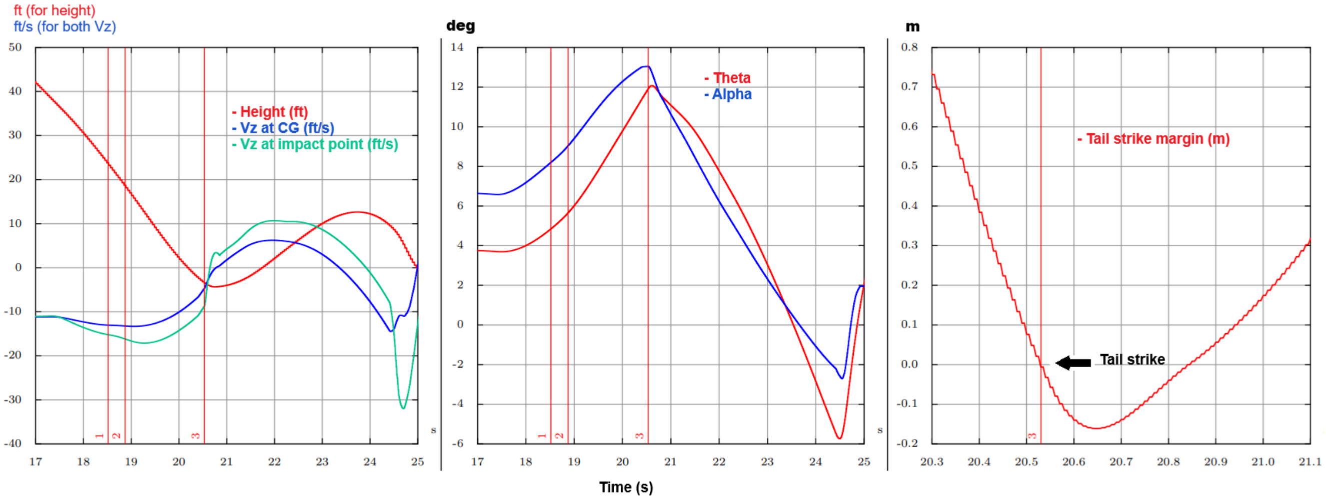

Fig. 7 Example of simulation of a go-around with tail strike.
Vertical lines correspond to 1 = go-around initiated (full engine thrust), 2 = back stick input, 3 = tail strike impact

Now in the same condition figure 8, the go-around with the pitch protection shows an improvement of the tail strike margin with no tail strike.

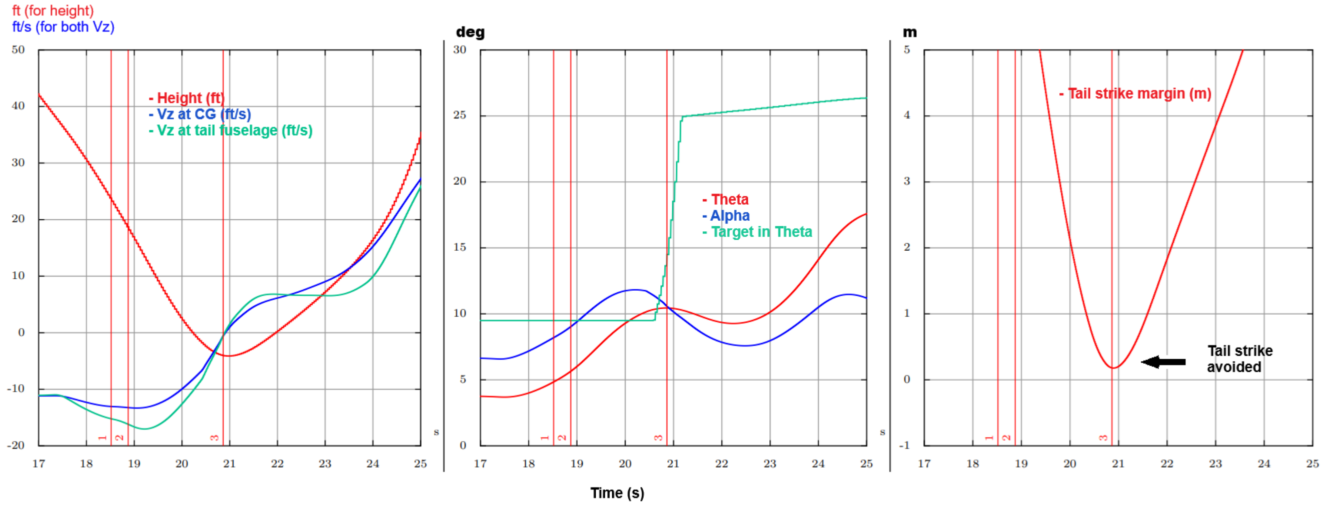

Fig. 8 Same simulation with protection activated
Vertical lines correspond to 1 = go-around initiated (full engine thrust), 2 = back stick input, 3 = positive tail strike margin

As we can see, it is a very dynamic phase, and once the Vz trend is reverted, meaning the Vertical speed gets closer to zero, the pitch attitude target value is released to let the aircraft have its full domain capacity.

This target is overshot briefly before releasing the constraint, to let the Nz inner-loop take over, as the goal is more to manage the transitory state by slowing down the pitch rate evolution before releasing the pitch target. We can tune the dynamics of the law to avoid such overshoot, but it would increase intrusiveness. Therefore, the optimum tuning of the pitch target and the dynamics of the law has to be found empirically (implying a good knowledge of the aerodynamic environment), between the constraint to avoid tail strike and the intrusiveness of the law.

Intrusiveness is indeed a key issue to avoid, when it is not necessary, to restrict the aircraft capacity to pitch up and reach a positive slope trajectory. Moreover, as the protection is always activated, the tuning has to take into account these constraints. We can see on figure 9, the delta between two trajectories with and without the protection, where there is no tail strike even without the protection. These deltas are judged satisfactory by pilots.

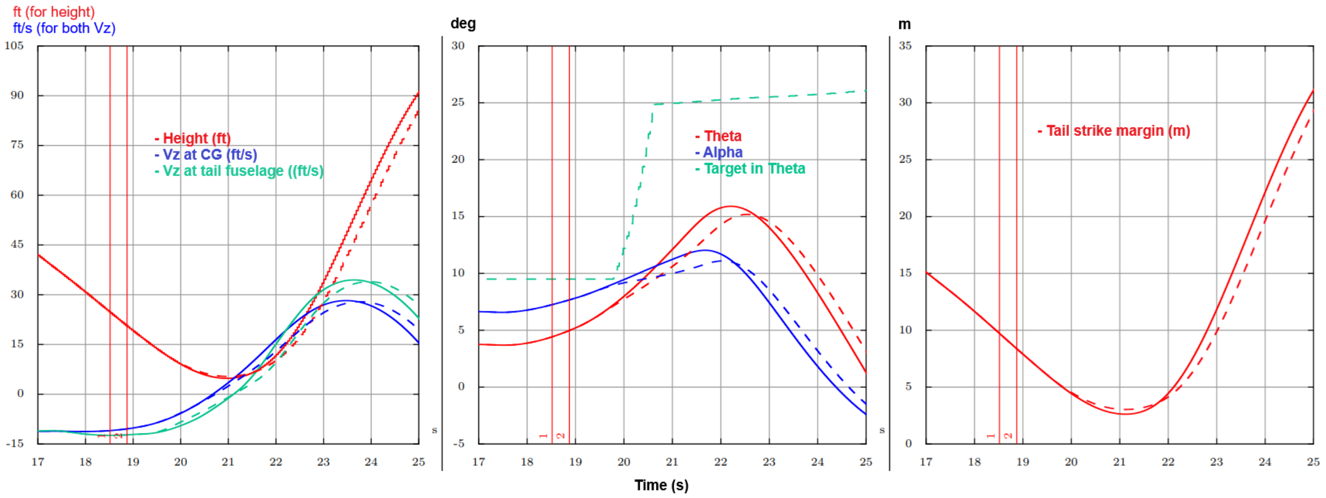

Fig. 9 Example of simulation of a go-around in full nominal conditions .
Vertical lines correspond to 1 = go-around initiated (full engine thrust), 2 = back stick input

5 Conclusion

The paper presents the implementation of a pitch attitude protection, used to reduce high vertical speed in case of tail strike during go-around. The embedded algorithm to compute control loop gains, based on a reference model, offers a rather efficient way to tune the dynamics and tackle the difficulty due to the very dynamic manoeuvre. The possible non linear-effects not taken into account in the reference model are not developed in this study but can be tackled by dedicated compensations or a disturbance rejection law (ANL, see [1] and [5]). The dynamics tuning depends on the acceptable structure constraint in case of impact, the pitch attitude overshoot as well as the intrusiveness acceptable. The rather simple pitch target implementation offers good visibility regarding its activation.
At last, the simulation sweeps made in the whole flight domain, using a representative environment simulator have given good results and proven the efficiency of this design.

Declaration of Use of Artificial Intelligence

"Artificial intelligence was not used in the work presented.".

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