CEAS-GNC-2024-068

EuroGNC Bristol, UK June 11th-13th 2024

Improving Pitch Capture for Aircraft Take-Off Rotation Law

Victor GIBERT Flight Control Designer, Airbus, Toulouse, France.
victor.gibert@airbus.com

Stephane DELANNOY Flight Control Expert, Airbus, Toulouse, France.
stephane.delannoy@airbus.com

ABSTRACT

The paper describes the lastest improvements made within Airbus flight control laws for the rotation phase. It explains operational constraints such as delayed signals, non-linearities or limitations and proposes a way to answer to industrial needs. It proposes a way to gain in robustness and performance in case of weight on wheel signal delay by consolidating the ground to flight condition and robustify angle-of-attack signal. It changes anti-tail strike law structure to improve electronic tail bumper protection effectiveness. Non-linear effects are finally detailed and tackled. All the improvements allow a better pitch capture during rotation and therefore good aircraft performance.

Keywords: Aircraft Take-Off; Rotation Laws; Pitch capture; Non-linear compensations

Nomenclature

θ	=	aircraft pitch angle
ϕ	=	aircraft bank angle
β	=	aircraft side-slip angle
α	=	aircraft Angle-of-Attack (AoA)
q_1	=	aircraft pitch rate in body axis
p_1	=	aircraft roll rate in body axis
V	=	aircraft true airspeed
m	=	aircraft weight
g	=	gravity vector
S	=	aircraft reference surface
l_{ref}	=	aircraft mean aerodynamic chord
P_{dyn}	=	Dynamic pressure ($= \frac{1}{2}\rho V^2$)
δ_q	=	elevator deflection
δ_{q_T}	=	Trimmable Horizontal Stabilizer deflection

1 Introduction

Optimizing take-off performances (take-off distances, rotation speeds, rate of climb or weight limitations) is a key challenge during development of new aircraft. A rotation law needs to be designed in

order to perform calibrated and reproductible flight test and to provide an homogeneous airplane response for any take-off conditions (weight, center of gravity (CG) position, high lift configuration (i.e. slat/flap position), thrust or environmental conditions).
Based on the state of the art developed in Ref. [1], this paper describes novelties in rotation flight control law for Airbus commercial airplanes.
The paper show different improvements not necessarily linked together. It is organized as follows. The section 2 describes how to improve ground to flight transitions in presence of delay in weight on wheel signal. Section 3 explains the different flight control tail strike protections developed for the rotation phase. Before conclusion, the last section focuses on non-linear compensations linked with pitch increase during the rotation phase on ground.

2 Robust pitch rate capture with weight on wheel signal delay

During a take-off run, transition from ground to flight is a crucial phase. Flight control laws have to control a varying dynamic system with or without ground reaction on nose landing gear and on main landing gears. Airbus rotation law architecture described in Ref. [1] consists of two controllers respectively for ground and flight phase having different model equations.
To select which inner loop to use, flight control computers should have access to lift-off information. A measure of weight on wheel requires specific sensors that are not installed in commercial aircraft other than flight test aircraft. The only sensor available and monitored is a proximity sensor that provides boolean (named weight on wheel signal) information about gear extension. For an aircraft, due to the non-linear forces and reactions in the Landing Gear system, this information is not perfectly synchronized with real aircraft lift-off and it can deliver the lift-off information to computer few seconds later the real lift-off. In order to limit this delay and to be robust to unavailability of this weight on wheel information, aircraft pitch angle and radio altimeter measurements are also used in order to ensure transition to flight law. By leveraging airline data collected by Airbus, threshold on pitch angle and height have been reduced to ensure transition to flight mode quickly. Moreover, ground rotation law needs to be robust to this delay and ensure a good pitch rate capture. As explained in Ref. [1], as the airplane is performing a rotation but still in contact with the ground (no vertical acceleration assumption) the flight path angle is null, therefore angle-of-attack α is equal to pitch angle θ. In case of delay for the ground to flight information, aircraft is climbing so $\alpha = \theta$ is not valid anymore. To ensure good behaviour of ground rotation law, α needs to be used instead of θ. Indeed, this feedback generates too much pitch up elevator order when using θ. But to ensure a valid and robust angle of attack information in a domain where ground effects perturbate the AoA measurement, several monitorings need to be launched and require confirmation time and high speed so that the AoA probes provide reliable information (same principle as presented in Ref. [2] or Ref. [3]). For low speed, α is not available for control laws use. In this low speed case, aircraft should be on ground so $\alpha = \theta$ remains valid.

Once system monitoring allow angle of attack usage, α build as the median value (called triplex) of the 3 AoA probes is used instead of theta. In case of loss of one AoA probe, the used value is the average of the 2 remaining α. In order to reduce impact of one source running away, it has been decided to use the median value of the remaining α and the value of consolidated θ. When aircraft is climbing, θ is higher than α and the difference is the slope angle of the aircraft. This feature provides a non impact on a runaway of one source to lower values because the good α information will be the median one. In case of positive runaway of one of the two remaining AoA probes, θ will be the median one and will limit runaway effect on the feedback parameter. This limiation of the feedback will reduce its effect on law order hence giving a smooth behaviour of the aircraft in case of sensor value runaway.

In addition, AoA probes are external sensors and are prone to noisy measurement and are reflecting all aerodynamic perturbations such as gust or turbulence. In order to avoid having this phenomenon in control law order, an hybridization is performed by using inertial computation of $\dot{\alpha}_i$ and measured α_m. Based on Vertical load factor nz_1 expressed in body frame and with hypothesis of small angle on α and β, we obtain following equation

$$\dot{\alpha}_i = \frac{g(cos(\theta).cos(\phi) - nz_1)}{V} + q_1 - p_1.\beta \tag{1}$$

Hybridization is performed with simple complementary filter as follow

$$\alpha_{hyb} = \frac{\alpha_m + \tau\dot{\alpha}_i}{1 + \tau s} \tag{2}$$

Hybridization is also giving robustness to probes measure runaway. Indeed, in case of runaway of the measured α_m, the short term dynamic will be mainly coming from inertial α_i. Giving sufficient time for system monitoring to detect and limit the runaway and limiting impact in law feedback of this shoddy measurement.

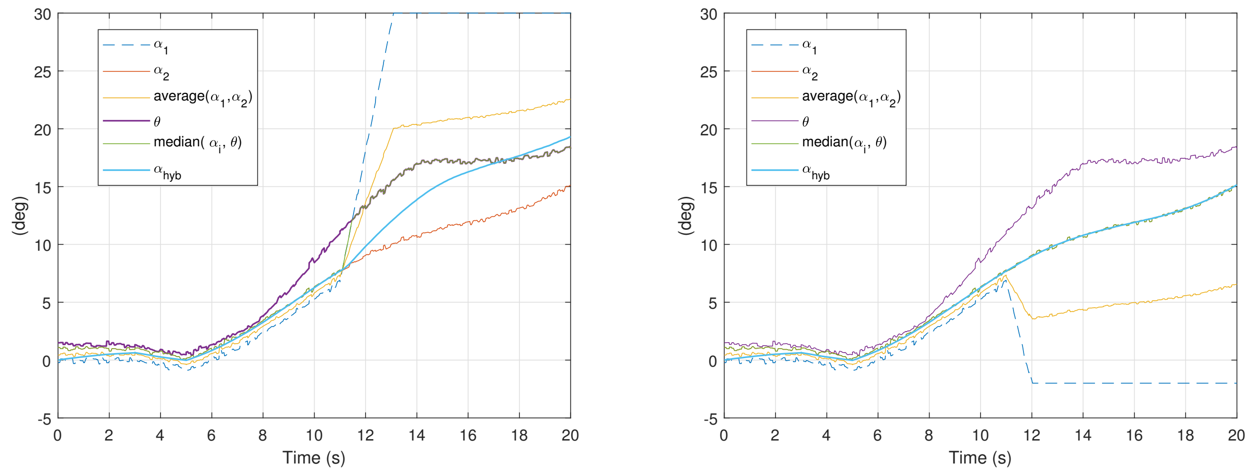

Fig. 1 Positive (left) or negative (right) runaway on α_1 in case of only two AoA sensor available.

As shown in Fig. 1, for two normal take-off during rotation phase initiated at 5 seconds, the aircraft is pitch up until reaching arround 18 deg of pitch angle. The figure shows a negative runaway of one of the two remaining AoA sensor is providing the good AoA feedback (here α_2) with noise reduction. In case of positive runaway, Fig. 1 show a limited variation of the final α_{hyb} compare with the simple mean value of α_1 and α_2. It is smoothing the runaway and finally goes to the θ value at long term. This smooth behaviour is totally acceptable because it gives the time to the integral term of the inner loop to correct the elevator command in order to converge to the commanded pitch rate.

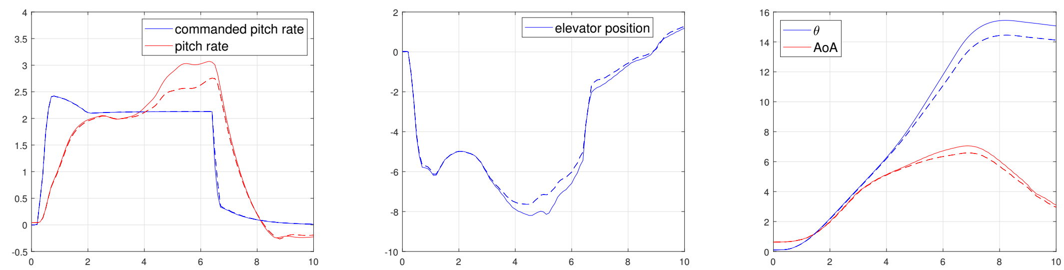

Fig. 2 A Take-off with θ feedback (solid line) vs a take-off with α_{hyb} (dashed line).

In Fig. 2, the left plot shows overshoot in pitch rate q_1 compared with the commanded pitch rate q_{com}. This overshoot is reduced by using α_{hyb} instead of θ in the inner loop and in compensations.

Indeed, looking for the right plot, the difference between α and θ become less and less negligible after lift-off (corresponding to vertical line 1). One can notice that the difference of pitch rate between the two take-offs is due to a command difference on elevator lower than 1.5 deg.

3 Electronic Tail bumper protections

Aircraft longitudinal control laws are different for ground or flight phase and based respectively on ground or flight model equations provided in Ref. [1]. It produces two inner-loop that have not the same behaviour. Ground law have to deal with landing gear reactions, rotate around the gear and need nose-wheel load compensation whereas flight inner loop have vertical motion by short period mode.
Thanks to efficient compensations of non-linear effects and robust inner-loop gain computation, closed loop composed by ground rotation law and aircraft can be associated to a first order system transfer function

$$q = \frac{1}{1+\tau s} q_{com} \tag{3}$$

whereas, due to short period mode, closed loop composed by flight rotation law and aircraft is behaving has a second order transfer function with poles and zeros.

$$\frac{(1-\frac{s}{p_\alpha})\omega^2}{\omega^2 + 2\xi\omega s + s^2} q_{com} \tag{4}$$

In order to protect against tail strike, pitch rate command from pilot can be limited by a protection called Electronic Tail Bumper (ETB). This protection is designed as a pitch angle protection where pitch target θ_T is computed using radio-altimeter measurements. A pitch protection means design of an outer loop with pitch angle objective, generating a pitch rate command for the inner-loop and looking for the transfer $\frac{\theta}{\theta_c}$ which can be seen as adding a pure integrator in the loop ($\dot{\theta} = q$ for wings-leveled aircraft).

Using ground equation Eq. (3) the pitch protection design in Ref. [1] with two feedback $K_\theta \Delta_\theta$ and $K_q q$ is sufficient to place all the dynamic of the system. However, with the flight inner loop Eq. (4), two gains are not sufficient to place the three modes (inner loop and pure integrator). In this case, the previous structure will produce a free mode that can be dominant over the desired dynamic. In order to ensure full placement of the mode, a pseudo derivative of pitch rate is added to the pitch protection law for flight phase.

$$q_{com_{ETB}} = \frac{1}{1-\frac{s}{p_\alpha}} (K_\theta(\theta_c - \theta) + K_q q + K_{\dot{q}} \frac{\tau_q s}{1+\tau_q s} q) \tag{5}$$

In most of aircraft, this protection is limited to positive value of pitch rate commanded to avoid a pitch down effect during rotation. But to ensure a good performance of the protection, gains are computed in order to obtain a second order dynamic with optimized damping (i.e. 0.7). This second order objective generates overshoot of the command by design. By limiting the pitch rate command only to positive value, it creates a non-homogenous response of the law, especially for sizing cases that ask for negative pitch rate command to protect against tail strike. In these sizing cases, pitch rate will have a lower reduction than expected reducing aircraft performance for all cases. By limiting the ETB protection to a negative value, it gives an homogeneous response of pitch rate, and improve aircraft performances. The value has been chosen in order to avoid having a negative pitch rate of the aircraft but only a temporary negative command. In case of failure of radio altimeter, the minimum negative limit will ensure good handling qualities to the pilot that can still override the protection with more than 3/4 full back stick.

4 Non-Linear compensations during rotation phase on ground

Once the aircraft reaches rotation speed, the pilot flying initiates the rotation. The stick input is converted to a commanded pitch rate and send to the ground inner loop which computes an elevator command to follow the pitch rate command. The ground inner loop is a PID controller with stick feedforward term with gain adapted to flight condition as in Ref. [4]. In order to ease the inner-loop workload and homogenize pitch rate response, compensations such as nose wheel unload or Anti-Non Linearity law (called ANL. It is a rejection law to provide short-term compensation for unmodelized pitch-momentum disturbance. See more in Ref. [5]) are added to the inner loop order. Thanks to the nose-wheel unloading feedforward, the ground inner-loop is working on an aircraft that is directly able to rotate. During the ground rotation phase (i.e. from nose-wheel unload to lift-off), the aircraft will increase its pitch angle leading to two non-linear phenomena.
The first is on the THS efficiency when coming closer to the ground. Indeed, when pitch angle increases, local angle-of-attack of THS is reduced by ground effect reaction (also called THS cushion). Thus THS efficiency for pitching up is reduced leading to a break in the rotation. The ground inner-loop will handle this non-linearity but with the time response of the integral term (around 2 seconds) thus the pitch rate response will have a temporary reduction compared with commanded pitch rate. To avoid this phenomenon and enhance the pitch capture, a compensation of this aerodynamic non-linearity $\delta_{q_{NLaero}}$ is added to the elevator order

$$\delta_{q_{NLaero}} = \frac{\Delta Cm_{NLaero}}{Cm_{\delta_q}} \tag{6}$$

with ΔCm_{NLaero} based on angle-of-attack α, CG and slat/flap configuration.

A second non-linear effect is geometrical. During the rotation and before lift-off, aircraft is still on ground and lift force is not sufficient yet to compensate the weight. There is a ground reaction on the gear that creates a pitch down moment which is non-linear function of pitch angle θ. The main lever-arm is between main landing gear and CG along the fuselage axis. It is physically roughly tackled thanks to THS setting δ_{q_T} and precisely balanced thanks to nose-wheel unloading feedforward. But during the pitch increase the lever-arm between main landing gear and CG along the vertical axis is not negligible. It reduces the pitching moment with an increase of θ. To compensate this phenomenon, a weight variation estimation is done using lift equation and its vertical part is creating a moment at CG. Finally, to compensate this phenomenon, elevator pitching moment efficiency is necessary to compute the right elevator deflection $\delta_{q_{NLgeo}}$ in order to avoid pitch variation.

$$\delta_{q_{NLgeo}} = \frac{\Delta Cm_{NLgeo}}{Sl_{ref}P_{dyn}Cm_{\delta_q}} = \frac{Z_{CG}sin(\theta).SP_{dyn}C_{L\alpha}\alpha}{Sl_{ref}P_{dyn}Cm_{\delta_q}} \tag{7}$$

Note that, as shown in first section, α used in Eq. (7) is actually the robust hybridized α_{hyb}, the only one we decided to used on ground phase.

5 Conclusion

The paper presents different improvements made upon Airbus aircraft state of the art rotation law already developed in [1]. The different features help giving robustness of the law or improving performances. The management of angle of attack signal used as feedback in ground rotation law allows improving pitch capture in case of ground to flight information delay. Structure of anti-tail strike protection has involved in order to match precisely with aircraft physics and with law architecture in computer. Compensations during take-off run for geometrical or aerodynamic effects caused by pitch increase allow good pitch capture all along the rotation phase.

Acknowledgments

For their full contribution to the modifications and improvements, many thanks to Airbus colleagues Clément FROT, Baptiste GATIER, Simon OUDIN and A321 XLR system team.

References

[1] Simon Oudin and Clement Frot. Optimizing take-off performances using a protected rotation law. In *AIAA SciTech Forum*, San Diego, CA, USA, Jan. 2022.

[2] Denis Berdjag, Jérôme Cieslak, and Ali Zolghadri. Fault diagnosis and monitoring of oscillatory failure case in aircraft inertial system. *Control Engineering Practice*, 2012.

[3] Daniel Ossmann, Hans-Dieter Joos, and Philippe Goupil. Enhanced sensor monitoring to maintain optimal aircraft handling in case of faults. *Journal of Guidance, Control, and Dynamics*, 2017.

[4] Simon Oudin, Stephane Delannoy, and Pierre Debusschere. Low speed protections for a commercial airliner : a practical approach. In *Scitech Guidance, Navigation, and Control Conference*, Grapevine, Texas, USA, Jan. 2017.

[5] Stephane Delannoy and Simon Oudin. Longitudinal control law for modern long range civil aircraft. In *Proceedings of the 2013 CEAS Specialist Conference on Guidance, Navigation and Control (EuroGNC)*, Delft, The Netherlands, Apr. 2013.