"Had I not known this, understood that or paid attention to that, I wouldn't be here with you today" was a sentence Jacques often repeated when he referred to some of the thousands of flights he performed either as a fighter pilot or as an experimental test pilot. Sadly, Jacques is no longer with us today. He was a genius pilot, a humble man, a great man. Aviation was his passion, safety his quest. He was always ready to share his knowledge, experience and wisdom to improve safety, as he did with the following article.

HE WILL BE MISSED…

High-altitude manual flying

Flying an aircraft manually at high altitudes, and therefore necessarily at high Mach number, is a completely different discipline to what it may be like at low altitudes. As it turns out, opportunities to experience manual flying at high altitudes are rare in a pilot's career. Yet, regulations do require it in certain circumstances, such as when the Auto Pilot is unavailable.

JACQUES ROSAY
Experimental Test Pilot
Former Airbus Chief Test Pilot

Most of the time, commercial aircraft fly at high altitudes, above FL 290. In other words, they fly within the RVSM (Reduced Vertical Separation Minima) space that extends from FL 290 to 410 included, and which now covers a very large part of the world's airspace. As it turns out, use of the Auto Pilot (AP) within this airspace is mandatory, meaning that the regulations actually prevent the pilots from acquiring practical manual flying experience of their aircraft within the part of the envelope where they most often fly.

Pushing this paradox further, in certain cases, especially if the AP is unavailable, these same regulations require that the pilots manually fly the aircraft to rapidly leave this airspace in coordination with air traffic control. In other words, pilots are requested to do maneuvers for which practicing in flight is prohibited.

However, the behaviour of an aircraft at high altitude is significantly different from that of an aircraft at low and medium altitudes.

The aim of this article is to recall some qualitative aerodynamic, flight mechanics and handling qualities notions specific to the high Mach numbers and to high altitudes, to share practical experiences lived by Airbus test pilots in these domains and to make suggestions for training. Lastly, note that, apart from passages specifically dedicated to the normal and alternate electrical flight control laws, the whole of this article applies to all types of commercial aircraft whether equipped with electrical flight controls or not.

AERODYNAMIC ESSENTIALS

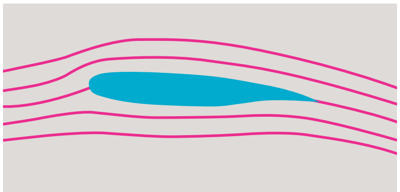
The effects of Mach number

The air flow around the wings accelerates on the upper surface creating a negative pressure and it is this negative pressure which mainly keeps the aircraft up **(fig.1)**.

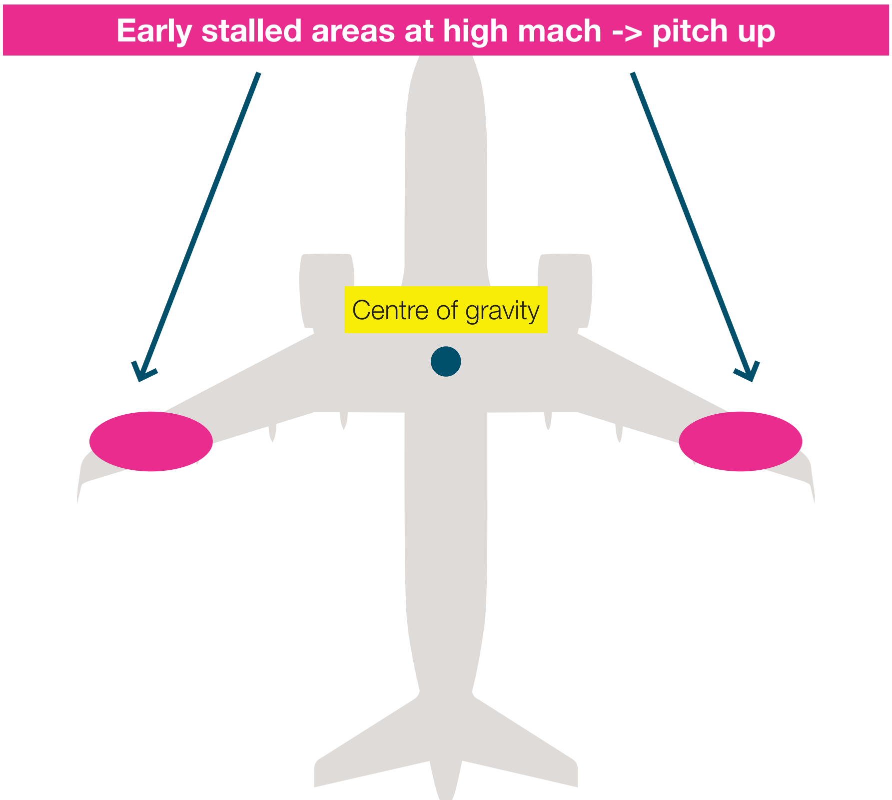
When the altitude increases and the air density falls, more aerodynamic speed is required to create the lift required for a given lift configuration. This reduction in the density and this increase in the aerodynamic speed is accompanied by an increase in the Mach number required for flight. We have seen that by passing over the wings, the air flow accelerates on the upper surface. Therefore, the local Mach number around the wings is much higher than the aircraft flight Mach number and in certain locations reaches transonic values. In high-altitude stabilised flight, shock waves can be seen at certain locations by looking at the upper surface through the cabin windows.

This sonic phenomenon around the wings leads to a degradation of their aerodynamic properties. This, in turn, leads mainly to a reduction in the maximum lift angle of attack as the

(fig.1)
Air flow around an airfoil



Mach number increases, which significantly reduces the stall margin. Thus, at a high-altitude normal cruise Mach number value, when the angle of attack is increased to produce the load factor required to make a turn or a pull-out, the angle-of-attack limit is more easily approached than when the same maneuver is done at low altitude and at a low Mach number.
Also, on most aircraft with sweepback wings, another well-known phenomenon is added to the previous one. As the local Mach numbers along the span are not identical, the distribution of the lift does not vary uniformly with the angle of attack. This creates non-linearities in the longitudinal balance of the aircraft most classically leading to spontaneous pitch-up tendencies or to self-tightening of the turn when the angle of attack increases **(fig.2)**.



(fig.2)
Early stalled areas along the wings

Clearly the aircraft has flight characteristics quite different at high altitude compared with its characteristics at low altitude. This means that if a Pilot has to fly manually at high altitude, he/she will not find the characteristics he/she is familiar with at low altitude. In addition, the aerodynamic speed, i.e. the speed in relation to the air molecules, therefore in relation to the earth coordinate system (excluding the wind), is much higher at high altitude. Consequently, the purely kinematic characteristics of the vehicle are radically different.
To get an idea of this, when flying in the initial approach zone at 3000 ft and 250 kt, which is often the case in manual flying, the aerodynamic speed is 260 kt. When flying at FL350 at M 0.85, at standard temperature, the aerodynamic speed is 490 kt. If the temperature is ISA + 12°, the aerodynamic speed is then 500 kt. That is practically twice as fast as the highest speeds usually seen at low altitude.
This difference is not without consequences on flying. For example, for a maneuver at identical load factor, the radius of curvature of an altitude capture is multiplied by four and therefore, starting from a given slope, anticipation for this maneuver must be multiplied by four in order not to exceed the target altitude.

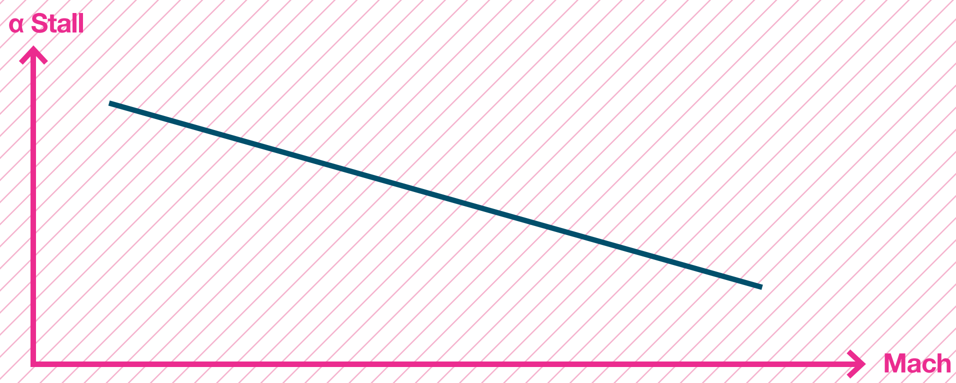
> " If a Pilot has to fly manually at high altitude, he/she will not find the characteristics he/she is familiar with at low altitude. "

Compressibility stall

We have seen that when the Mach number increases, the maximum lift angle-of-attack is reduced **(fig.3)**.

We can imagine that at a certain point in the increase of the Mach, the angle-of-attack can theoretically be so limited that the maximum lift the wings are capable of producing becomes insufficient to sustain the weight of the aircraft. In certain aerodynamic manuals, this theoretical point is called the "compressibility stall".
It depends on the evolution of the curve lift versus Mach. This change depends on many aerodynamic characteristics of the aircraft, such as the wing profile, the chord, the sweep, the span, etc. Remember that this phenomenon does not exist on an aircraft where the wings are designed for flight at supersonic speeds. Pilots who have flown on the T33 or the Alpha Jet may perhaps remember having reached subsonic Mach numbers beyond which the wings were incapable of providing a load factor of 1 g. Level flight could not be maintained: compressibility stall was reached. The Mach number had to be reduced to regain the load factor authority required for straight level flight. On the Alpha Jet in particular, with a little patience and a very small amount of fuel on-board, it is even possible to climb to an altitude where it was neither possible to decelerate due to low Mach number stall nor to accelerate due to compressibility stall. There was only one single practicable flight point: the aerodynamic ceiling was reached.

(fig.3)
General tendency in the evolution of the maximum angle-of-attack (α) versus the Mach number



Aerodynamic ceiling and buffeting margin

In practice, even if the compressibility stall and the aerodynamic ceiling can theoretically exist in aerodynamics in certain cases, they cannot be reached by a certified commercial aircraft and this for several reasons. Let us see why.

1) The certification regulations require that throughout the flight envelope, up to MMO, irrespective of the weight, the aircraft must have a buffeting margin of 0.3 g.
This means that a load factor of 1.3 g must be attainable before "buffet onset" is encountered. "Buffet onset" is defined such that when an accelerometer located under the pilot's seat measures peak-to-peak accelerations higher than 0.1 g. Therefore, the aircraft MMO value and the lift ceiling (which depends on the weight) are by definition such that there is always a buffeting margin of at least 0.3 g and therefore, a margin well above the compressibility stall is ensured.

2) The certification regulations also require that the flight tests check that the aircraft can fly above MMO up to MD.
MD is the highest Mach number at

which the aircraft must be able to fly without structural anomalies (this is the flutter margin) and without substantial degradation in the handling qualities allowing the aircraft to be always easily controlled. It is determined by calibrated maneuvers (FAA dive, JAA dive) defined by the certification regulations. In practice, typically MD = MMO + 0.06.

DETERMINING MD IN FLIGHT TESTS

During the flight test, MD must be reached fairly quickly by an accentuated dive before encountering another limit: the absolute speed limit VD (typically VD = VMO + 35 kt), which is approached as the altitude drops. For this, Airbus test pilots start from the aircraft ceiling, in direct law, at a Mach as close to MMO as possible. Then they accelerate by a dive with an attitude of around -15° at the start of the maneuver with engines at full throttle. When MD is reached, this Mach is maintained by adjusting the pitch attitude and then, the structure is excited by programmed impulses into the flight controls. The purpose of this is to check that there are no divergent structure oscillations (flutter). Then, test pilots do a positive pull-out, engines idling, to return to the normal flight envelope. This pull-out requires an important increase in the load factor and demonstrates that compressibility stall is still far from being reached. However, the buffeting margin of 0.3 g is no longer observed beyond MMO and approach of MD at n = 1 is in reality done with moderate buffeting, but the aircraft can still be controlled and maneuvered. Beyond MD, the structural integrity of the aircraft is no longer ensured! Based on the experience accumulated at Airbus and seeing how many aircraft still respond very well at MD load factor, very serious structural problems will be encountered before finding a possible compressibility stall which, if it exists, can be found only at Mach numbers well above MD, probably above Mach 1.

To conclude, the regulatory criteria related to the buffeting margin at MMO and to the flight characteristics up to MD imply that the "compressibility stall" and "aerodynamic ceiling" phenomena cannot be physically encountered due to the design of the aircraft. "Compressibility stall" does not exist on current commercial aircraft.

FLYING MANUALLY

Definition

It would be interesting to survey pilots as to what they understand by the terms "flying manually". Personally, I have often heard during test, demonstration, acceptance or airline flights, colleagues, young or older, airline pilots or test pilots, proudly say that they would do such or such a part of the flight - in general a complete approach followed by a landing - "in manual control mode". I would then observe how they performed and saw that all they did was actually disconnect the AP and servilely follow the Flight Director, leaving the Auto Thrust engaged. And this until start of the flare. This obviously allows an accurate trajectory to be followed, with correct captures, and good control of the speed. These functions are provided for this purpose.
However, within the scope of this article, which concerns manual flying, flying in this manner can in no way be considered as "flying manually". Indeed, the orders given to the flight controls by the pilot consist in setting the Flight Director (FD) bars to zero, which corresponds to the orders generated by the guidance function. These stick inputs are actions done mechanically by the pilot but are in no way elaborated by him/her. These

flight control orders are the same as those which the AP would give if it was engaged. Thus, the added value provided by the pilot is rather negative, as the cognitive resources that he/she uses to follow the FD bars are no longer available for the most elaborate flight monitoring and control functions. In other words, this exercise provides strictly nothing towards the manual flying training for the cases where the pilot would truly have to fly the aircraft manually.

The terms "flying manually" in this article imply that the guidance functions have become unavailable, possibly with the flight control laws in a degraded mode.
In this configuration, pilots must be able to correctly perform, at any altitude, all the maneuvers required to manually control the aircraft and land it under satisfactory safety conditions. These safety conditions would not be met if a pilot is not at ease when performing, under all flight control conditions which may be encountered following failures, manual flying without the FD, without the ATHR and without speed vector, from the cruise ceiling of the aircraft to instrument landing under CAT1 weather conditions.
The type certifications of all the commercial aircraft in the world are established by the Authorities on the fundamental hypothesis that any qualified pilot is capable of meeting this requirement.

"The pilot must anticipate to a greater extent the changes in the trajectories both vertically and horizontally."

Specificities of flight control laws

We have seen that the rules applicable for RVSM mean that the situations where the aircraft must be flown manually at high altitude are limited to degraded cases, especially cases where the AP is lost and, possibly, where the normal law is also lost. As the aim of this article is to get a better knowledge of these situations, let us look at the specificities of the high-altitude flight control laws.
As said earlier, compared to low altitude, the high aerodynamic speeds used at high altitude radically change the trajectories followed for given load factor applications. This means that the pilot must anticipate to a greater extent the changes in the trajectories both vertically and horizontally. This is valid whatever the flight control law used, including the normal law.
The behaviour of the normal law differs from its behaviour at low altitude by the effect of the speed on the trajectory. This is sufficient to make it worth the effort to become familiar with the situation in the simulator. For degraded laws, or for aircraft with conventional flight controls, the characteristics specific to high altitude are more affected and must be known.

Normal and alternate laws

The normal law and the alternate law - so-called C* laws, or load factor flight control laws - function practically identically on the longitudinal axis as long as we remain within the operational flight envelope and we do not perform dynamic maneuvers leading the angle-of-attack to approach maximum values (which depend on the Mach number). Beyond these limits, the alternate law no longer ensures the protections and this is recalled by the "protection lost" message on the ECAM. The pull-out and turn maneuvers, for a given longitudinal stick order, give the same load factor excursion. As the alternate law is not protected against excessive angles of attack, awareness of an approach to limiting angle-of-attack is ensured by the Stall Warning (SW) or, in certain cases, by the deterrent buffeting, to which the pilot must react immediately by releasing control. The SW directly alerts the crew of stall proximity but it also indirectly alerts it by indicating, during dynamic maneuvers, that it is approaching angles of attack where the pitch-up phenomenon may start to develop; this phenomenon itself can lead to stall if the pilot does not immediately counter it by reacting to the SW. In practice, maneuvers a little too dynamic can fairly easily lead to the SW, especially if they are done close to the maximum cruise altitude (REC MAX) calculated by the FMS. For this reason and to make flying more comfortable, even outside of the RVSM space, when flying in degraded laws, it is recommended to maintain some margin in altitude (around 4000 ft) below the REC MAX altitude.

According to the type of aircraft and type of failure, the alternate law may lead to lateral control being in direct law, i.e. a deflection of the ailerons according to the stick input and not according to a roll rate law, as is normally the case in normal law. This difference can be fairly significant, generally leading to roll responses a little more sharp than in normal law, but still easy to control.

Direct law

In direct law, as its name implies, the controls give direct orders to the control surfaces. In direct law, the aircraft becomes an “old aircraft” where no assistance is given to the pilot. The longitudinal trim must be used to zero forces on the stick and to balance the longitudinal effects of the engines. The ECAM and the Primary Flight Display (PFD) remind us of this by the “USE MAN PITCH TRIM” message. However, depending on the aircraft, very basic yaw or roll dynamic stabilisation functions may be included in the direct law. At high altitude, the trim law versus speed variations, and therefore the Mach number, is very “flat”. Pilots should therefore not be surprised that there is much less need to use the trim than at low altitude.

During flight tests, Airbus test pilots try to adjust the kinematics of the direct law to make it as “placid” as possible at high altitude in all the weight and CG ranges. The aim is to have enough authority to efficiently do the basic maneuvers in the vertical and horizontal planes, but without trying to do specifically dynamic maneuvers. Here also, as with alternate law, the deterrent buffeting and/or the SW warn against excess angles of attack taking into account, if applicable, a pitch-up tendency. The same recommendations also apply concerning the flight altitude.

“To make flying more comfortable, even outside of the RVSM space, when flying in degraded laws, it is recommended to maintain some margin in altitude (around 4000 ft) below the REC MAX altitude.”

TRAINING FOR HIGH-ALTITUDE MANUAL FLYING

Representativeness of simulators at high altitude

The flight mechanics models used on the training simulators are established based on specific tests conducted during real flights. They generate what is called the “data package. These tests are long and many to obtain a model very close to reality. As I have done several thousands of hours of tests of all sorts on simulators before doing them in flight, I can confidently say that the models supplied by the simulators are very close to reality. However, two important limits exist and must be known, which are the very high angles of attack and the representativeness of the cabin movements.

1) During flight tests, for each type of aircraft, hundreds of stalls are performed, beyond the SW and a little

> Over the normal operating domain of commercial flying, simulators are perfectly representative of reality and utmost confidence can be placed in them, for both low and high altitude manual flight.

beyond the maximum lift coefficient (Cl) to clearly identify the loss of lift. In practice, the maximum Cl is exceeded by several angle-of-attack degrees, let us say four or five, but not more. This means that all maneuvers on the simulator that go beyond these known values enter a domain where the representativeness of the model becomes erroneous. Therefore, the exercises on the simulator must not go further than the excursions leading to the reactions to the SW which, according to regulations, are expected by the pilot. In practice, not more than 3 seconds after the appearance of the SW during a dynamic maneuver in cruise. This obviously concerns only the unprotected laws.

2) The movements of mobile simulator cockpits are intended to trick the sensory channels of the pilots to make them believe that what they perceive corresponds to a real flight. This operates fairly well when the simulated movements remain low. Simply, let us say that the feelings are not too false whilst the movements of the aircraft are those that the Auto Pilot would command. Whenever significant dynamic movements are done, the feelings become very false and can clearly have counterproductive training effects as the pilots then perceive sensations contrary to what they would experience in reality. This can be asserted based on a comparison between the basic rotation speed and acceleration parameters on the three aircraft axis (i.e. p, q, r, nx, ny, nz of the flight mechanics) with the same parameters measured in the cockpit of a mobile simulator during somewhat dynamic maneuvers. For this reason, during the flight tests, cockpit movements are never used to fine tune the flight controls knowing that the sensations experienced are, essentially false, and can therefore seriously alter test pilots assessment of these.

Clearly these two limits can be considered as such only when certification flight tests maneuvers are performed very close to – if not beyond – the limits of the aircraft flight envelope. Over the normal operating domain of commercial flying, simulators are perfectly representative of reality and utmost confidence can be placed in them, for both low and high altitudes. For this reason, flying in a simulator is the best option for pilots to experience and train for manual flying at any altitude.

Some ideas for high-altitude manual flying training

Simulation training exercises must show pilots that at high altitudes and high Mach numbers, it is very important to adopt an especially calm, flexible flying attitude without aggressiveness. At the same time, the exercises suggested here will allow pilots to reinforce the necessary confidence in themselves. To gain this competence, it is important that they do maneuvers which go a little beyond those that they may have to do in flight. Here are several personal ideas of exercises to reach this objective. Within the same frame of mind, others can of course be proposed.

1) Normal law, AP engaged, weight = MLW + 2 hours of fuel consumption, REC MAX altitude and cruise Mach according to airline Cost Index. Loss of AP, FD and ATHR, return to alternate law. Keep level flight. Reduce Mach to alternate law limit (if applicable). Do a turn with a bank angle of 30° (that is 1.15 g) in level flight at constant Mach. Resume straight line flight. Descent with engines at idle to first level outside of the RVSM space, still at constant Mach. Temporarily stabilise at REC MAX – 4000 ft, maintaining the Mach. Observe the response of the aircraft, resume descent.

2) Normal law, AP engaged, weight = MLW + 2 hours of fuel consumption, REC MAX altitude. Loss of AP, FD and ATHR, return to direct law. Use the trim. Keep level flight. Reduce Mach to direct law limit (if applicable). Make a turn with a bank angle

of 25° (that is 1.1 g) in level flight at constant Mach. Resume straight line flight. Descent with engines at idle to first level outside RVSM space, still at constant Mach. Temporarily stabilise at REC MAX – 4000 ft, maintaining the Mach. Observe the response of the aircraft, resume descent.

As a passenger, I would be very happy to fly with an airline which gives its pilots the instruction to place themselves in the easiest situation at all times. Pilots should be instructed to use all the piloting aids placed at their disposal to facilitate their tasks as far as possible. In practice, this perfectly respectable policy leads the pilots to almost never manually fly the aircraft, except on take-off for a short period and for certain landings between the minima and the ground when automatic landing is impossible. This means that the pilots of such an airline acquire or maintain almost no manual flying training. But, again as a passenger, I at the same time require that these same pilots have all the manual flying skills that we have discussed and which they require to face up to failure cases where the piloting aids are no longer available, whether at high or low altitude.

These two requirements are contradictory only in appearance. Indeed, even as is the case in many airlines, the pilots are authorised to manually fly aircraft under certain conditions. During commercial flights, they could never fly manually at high altitude due to the RVSM rules, or under degraded flight control laws for obvious reasons, which deprives them of all knowledge of the reactions of their aircraft under these conditions.

The only solution to cover this need is therefore the intensive use of training simulators and this in perfect compliance with the limits of their representativeness. ■

" At high altitudes and high Mach numbers, it is very important to adopt an especially calm, flexible flying attitude without aggressiveness. "

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