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FLIGHT SAFETY ASPECTS WITH MODERN FLIGHT CONTROL SYSTEMS

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1. Introduction

Air Transport Flight Safety is a concern which is naturally shared by everybody involved in this field of human activity. There are two main reasons for this : accidents are the only major shadows remaining in a picture of successes in terms of cost of travelling, punctuality, speed, comfort and enthusiasm about the materialization of Icare's dream, and the current power of media with their ability to magnify, to select and address directly our internal fears and distresses with shocking pictures. Many analyses concur to concede that the safety rate (in terms of accident rate per departure for instance), which has shown significant improvement in the sixties, is now no longer improving. If nothing is done, the traffic growth forecast might lead to an increase in the total number of accidents per year which the public is not prepared to accept.

Therefore, everything feasible or sensible must be done to improve the safety rate and nobody should feel exonerated from this quest. For this purpose, lessons from experience must be pragmatically collected and analysed ; additionally, the reasons for the safety rate curve flattening must be better understood and the new factors, threats and environmental conditions which are compensating for the overall aircraft reliability improvement must be identified.

This lecture proposes to analyse how the aircraft design, and more specifically how the Flight Control System design, can contribute to the drive towards better safety by providing efficient piloting aids improving the man-machine cooperation. For the sake of clarity, we will only address the flight control system and disregard other functions like the Autopilot or the Flight Management System which, because of the specificities of their functions and man-machine interface, could deserve a similar but adapted approach. In the light of the lessons learned from accidents analysis and of the growing influence of human factors in safety, more emphasis will be placed on :

- loss-of-control prevention,
- human error tolerance.

2. Short historical review of flight control involvement in flight safety improvement

Very basic flight dynamics principles which keep an aircraft airborne highlight the potential causes of loss of control :

- aerodynamic stall, with a sudden loss of lift (hence uncontrolled trajectory upset), loss of control surface efficiency and potential wing over,
- airframe overstressing with potential rupture of structural components critical for aircraft control,
- excessive speed with potential penetration into the diverging flutter domain,
- too low a speed which can either lead to the above mentioned stall or to insufficient control surface efficiency in face of lateral thrust asymetry or other upsets,
- pilot disorientation leaving unusual attitudes to develop unchecked, up to the point where one of the above causes leads to the loss of control, or up to the point where the trajectory will inevitably strike into terrain.

Across the years, modern flight control systems have progressively embodied features aimed at reducing the risks of encountering the above situations. These aids are adapted to the actual situation (time constraints, available human resources, risk) and range from improved situational awareness to warning with associated procedures and even to direct corrective action on the aircraft ; they have been backed up by associated airworthiness requirements to specify their mandatory nature and their performance. We can quote :

- Artificial feel, introduced in order to deter the pilot from overstressing the aircraft. At this point, it is nevertheless interesting to note that the level of force feedback deemed sufficient is highly influenced by subjective assessment. For instance, aircraft built in the former Eastern countries generally rely on higher forces than those built in the West. Military aircraft are often fitted with stepped force/displacement control characteristics the threshold of which is found adequate and unmistakable by an evaluating test pilot and completely unnoticed by a stressed combat pilot. And finally, despite high artificial feel forces, several airliners have been subjected to commanded excessive g during recoveries.
- Longitudinal static stability enhancement ; positive static stability has been an inherent aerodynamic characteristic of the transport

aircraft and thus provides a natural tendency of any aircraft to be speed stable ; therefore static stability is a protection against overspeed, underspeed and stall. A drive towards higher subsonic speeds and better fuel efficiency has lead to a decrease in the natural static stability: this has been compensated by the so called alpha trim/Vc trim/Mach trim features which, through artificial out-of-trim, restore an apparent positive static stability. It is to be noted that the effects of positive static stability can be altered if the pilot is so used to retrimming his aircraft that this action becomes unconscious and unnoticed. It is also a fact that an autothrust system, the use of which tends to become basic, provides a similar speed stability characteristic,

- Stall warning ; speed stability, as provided by static stability, has not proved to be sufficient to prevent stalls from occurring ; we can imagine several reasons for this : either the aircraft is permanently retrimmed by the pilot, or excessive nose-up forces are applied unnoticed on the controls, or a trajectory strategy (collision avoidance) prevails. Light aircraft generally provide strong cues when the aircraft enters a pre-stall domain : strong airframe buffeting, associated with controls shaking because of the reversibility of the flight control chain. On big transport aircraft, pre-stall buffet can be mild, and well balanced, unreversible controls would not vibrate. Therefore, artificial stall warning has been introduced with a might suited to the threat : tactile (stick-shaker), aural ("stall" called by synthetic voice, or cricket) and visual (red light flashing) cues are commonly used to compensate for the lack or weakness of natural stall warning. Pilots are trained to recover without hesitation following the activation of the artificial stall warning. The result of this is that undue activation of stall warning close to the ground must be absolutely avoided.

- Stick-pusher ; despite static stability, despite stall warning, experience has shown that stalls could still occur. Therefore, capability to recover from a stall had to be demonstrated. When this is not safely demonstrable, because of deep-stall characteristics for instance, a more powerful and deterrent system must be implemented : the stick-pusher. This system applies nose-down elevator with control forces likely to pull the controls out of the hands of the pilot ; this provides a kind of automatic recovery before critical angle-of-attack is reached. Obviously, undue stick-pusher activation must be strictly avoided and made extremely improbable close to the ground.

- Overspeed warning ; in exactly the same way as positive static stability alone was found insufficient to prevent stall occurrences, it also proved insufficient to prevent excessively high speed excursions. This is the reason why overspeed warning has been introduced, generally through the use of aural cues backed up by visual indications.

- Alpha-floor ; this function forces the autothrust system, once it is armed, to apply a fixed max thrust setting whenever an angle-of-attack threshold is exceeded. It has been introduced on the basis of two considerations :

  - lack of thrust, associated with the pilot or autopilot holding an incompatible trajectory, will inevitably lead to a speed decay and an increase in angle-of-attack which can be arrested or even reversed by the automatic application of high thrust,

  - when high manœuvrability is needed, going to high incidence must be accompanied with proper thrust, otherwise the trajectory will not be as expected in the long term.

As a conclusion of this brief review, the flight control system has already contributed in the past to an overall safety improvement by the introduction of features aimed at reducing the risk of loss of control. This introduction has resulted from a pragmatic analysis of the causes of reported incidents/accidents and the current accident rate would be undoubtedly higher without these features. Thousands of transport aircraft are currently flying with similar design and are providing, from a purely aircraft design point of view, an acceptable level of safety.

Nevertheless, if an improvement in safety is to be sought, then we have to analyse and address the cases when these features have been unable to prevent a loss of control. A careful look at accident reports reveals that :

- unusual attitudes, some in pitch and some in bank, a delayed recognition of this situation and the difficulty in applying the proper recovery strategy in due time are still causing accidents/incidents and are not directly addressed by the features listed before,

- deterrent force gradients on the controls are not efficient in stress situations, when pilots can develop very high forces without noticing it. Deterrent forces only work in "nominal" situations, when the pilot's perception is not obliterated by surprise, misunderstanding or overwhelming escape manœuver.

3 . Emergence of Fly-by-Wire

Although Fly-by-Wire has been controlling Concorde transport aircraft since 1969, its full development with digital technology in this field was achieved with the Airbus A320 in 1988 and more recently with the Boeing 777.

Fly-by-Wire gives the opportunity to offer the same safety enhancement features as those that were introduced on previous aircraft, with a much more integrated and simpler overall system. Fly-by-Wire also offers the opportunity to go further and to address those deficiencies which were highlighted when the current features were unable to stop an accident.

Fly-by-Wire control laws provide characteristics which can enhance safety through two distinct approaches, both clearly addressing the improvement in man-machine interface :

- they intend to be more error-tolerant ; which means they try to avoid a punishment in case of momentary lack of attention or even a loss of control in some of the cases when the pilot, for whatever reason, would not apply the standard operating procedures or even some of the basic airmanship rules,
- they intend to help the pilot to achieve, with the greatest efficiency the manœuvers which would be deemed necessary to escape from a threatening situation.

3.1 . Error-tolerant control laws

3.1.1 . Speed control

One of the most "popular" piloting inaccuracies when flying manually is to apply a loose speed control. Positive longitudinal static stability is the way non fly-by-wire aircraft offer tolerance to this behaviour, because a properly trimmed aircraft will keep a constant speed if no effort is applied to the controls. But relaxed stability and the habit (and the ease) of retrimming almost instinctively can alter this tolerance. The C* control law has been widely appraised as providing precise and confortable pitch control, mainly because the command resulting from the pilot input is of the same nature (load factor/pitch rate) as the most proeminent cues, which eases closing the loop by the pilot. Nevertheless C* by nature lacks static stability and compensating features must be allowed for. This can be done by adding to the C* an artificial speed stability term, which will add to the pilot input a load factor demand basically proportional to the difference between the actual speed and a target speed, this later being adjusted through the conventional trim switches. With such a modified C* law, the unattended aircraft behaves basically like a conventional aircraft, and the C* advantages are kept when manœuvering or for self-trimming of slats/flaps/thrust changes. Nevertheless, the same tendency to retrim inconsciously could, like on conventional aircraft, alter this speed stability. From an "unambiguous automation "point of view, this also presents an aspect open to criticism : when the autothrust is engaged, two systems can control the same speed parameter with different, non necessarily synchronized, targets. An alternative way has been used on Airbus : between allowable, safe min and max speeds, C* law is used unaltered and short term platform stability is offered at the expense of speed stability. This latter is left either to pilot vigilance or more simply to the autothrust which is almost as reliable as the flight control system ; C* and autothrust are fully compatible and their respective roles are clearly defined : C* (and associated stick pilot control) is in charge of the trajectory control while autothrust (and associated FCU speed knob pilot control) is in charge of the speed control. At both low speed and high speed ends of the normal flight envelope, very strong positive static stability is restored ; this means that an unattended aircraft, with autothrust disengaged, would in the end stabilize its speed at either Vmin or Vmax and would even recover these speeds when upset beyond ; because these speeds cannot be retrimmed, there is no chance of going through them unnoticed.

As Vmax is a fixed speed/mach value (set by load/flutter limits), the associated stability is triggered beyond a speed/mach threshold. As Vmin is a variable speed (according to weight) providing a fixed proportional margin to stalling speed, the associated stability is triggered beyond an angle-of-attack threshold (the so called Angle-of-Attack protection control law).

On Airbus A320 and A340 aircraft families, the strong positive static stability at low speed is also backed up by a dedicated aural warning of a low energy situation. This warning is given when the current thrust level is insufficient to allow for the recovery of level flight with only the help of the longitudinal controls. It clearly induces the pilot to add thrust before the alpha-floor function is triggered. This latter feature, already found on the former generation of aircraft, is kept on the A320-A340 families (with the additional advantage provided by the C* law characteristics which will automatically compensate for the induced pitching moment).

3.1.2 . Unusual attitudes

Experience has shown that unusual attitudes, either in pitch or bank, even if they are not dangerous at the time they are initiated (who said that acrobatic roll or loop manœuvers are dangerous, although they are quite uncommon on transport aircraft ?), quickly lead to potentially uncontrollable situations. Excessive nose-up attitude rapidly leads to too low a speed situation, while excessive nose-down attitude rapidly leads to excessive speed, potentially worsened by high transonic/supersonic effects, diverging flutter or high risk of overstressing during an insufficiently moderate recovery pull-up manœuver. Excessive bank angle, when left unchecked, systematically leads to an excessive nose-down attitude, associated with the above-mentioned risks and even worsened by the fact that :

- bank angle is more difficult to estimate, either by looking outside or through an ADI, with high nose down attitudes,
- if bank angle is not recovered first, any pitch recovery action will only lock the aircraft into a spiral dive. Unfortunately, experience has shown that excessive bank angle is less rare than excessive pitch attitude.

Attitude parameters are readily available inside Fly-by-Wire systems. These unusual attitudes can be detected and orders to the control surfaces can be generated, which are aimed at bringing these parameters back inside safe boundaries. By introducing strong positive spiral stability beyond a bank angle threshold, the aircraft will automatically recover a safe bank attitude if the pilot's controls are released, and any excursion beyond will require additional efforts. This is basically done on Boeing and Airbus Fly-by-Wire systems. On Airbus A320 and A340 families, this bank threshold is even reduced to zero in overspeed situations ; this helps to execute the recovery in the most effective way by bringing back the wings level before pulling-up.

In a similar way, positive pitch stability can be introduced beyond unusual pitch attitudes ; without pilot effort on the controls, the aircraft will have a natural tendency to recover the pitch threshold, while any stabilized flight beyond the threshold will need the application of permanent forces. This is also done on A320 and A340 aircraft. It is interesting to point out that this feeling of strong positive static stability at excessive pitch attitude is all the more efficient as neutral speed static stability is provided during nominal operation.

3.1.3 . Engine Asymmetry

Aircraft with wing-mounted engines are vulnerable to engine failure because the resulting yaw asymmetry leads to sideslip, which in turn causes significant sideslip-induced roll asymmetry. Therefore, an unchecked engine failure leads to a diverging rolling motion which could quickly bring the aircraft into an inverted attitude. The engine out situation can even be worsened when in IMC conditions or when the engine out situation progressively builds up without warning.

The flight control system can improve the survivability of an unnoticed engine-out situation in three ways :

- by providing protection against excessive bank attitude, as explained in the above paragraph ; this is only efficient if the positive spiral stability is given an authority which is effectively higher than the roll upset resulting from the engine out situation,
- by providing automatic detection of the engine out situation and by automatically deflecting the rudder accordingly ; this feature basically reproduces what a normally trained pilot would do in the same circumstances and provides the "reliability" (read the error-tolerant) of an automatic system. The design of such a system is nevertheless not easy because it must match the probable pilot response. If the rudder deflection is too high, then the engine failure might remain hidden whereas some engine-related cockpit actions should be performed quickly ; if it is too small, then the efficiency of the feature might be questioned in case of no pilot reaction (a diverging rolling motion would still occur) ; finally, a proper time sequence must be worked out for engine-out detection and compensation triggering, which must address all scenarios from slow asymmetry build-up to a sudden engine burst case,

- by tuning the lateral control law in order to provide self resistance to the asymmetry situation ; this option has been chosen on A320 and A340 Airbus families. With feet off the pedals and stick released, the lateral control law asks for zero sideslip and constant bank angle ; in case of thrust asymmetry, the control law will deflect ailerons and rudder in order to minimize the sideslip and bank angle deviations from their targets ; a steady state is quickly reached with a constant error between actual state and targets which is a function of the asymmetry upset : the aircraft is slightly banked on the side of the failed engine. Without pilot action, the overall behaviour is simultaneously pretty conventional and helps the pilot to recognize the engine failure, and pretty innocuous because bank angle is stabilized to a safe value ; this allows sufficient time for the pilot to apply conventional rudder to fully trim out the situation.

3.2 . Manœuvering Augmentation Control Laws

Circumstances in which pilots would benefit from the above "error-tolerant" features are fortunately rare and might only occur a few times in the life of any pilot. There are even rarer circumstances when exceptional manœuvering capability might be necessary : strong windshear near the ground or collision avoidance, with the ground or other aircraft. In those very exceptional circumstances, fly-by-wire can further help the pilot to successfully achieve a potentially critical manœuvre.

Fly-by-wire control laws, as they have been designed for the Airbus family, do address short falls or simply facts pragmatically gathered from the analysis of accidents or incidents when such extreme manœuvres have been involved :

- delayed or hesitating recovery action, generally too cautious and timorous at the start, then excessive,

- difficulty in flying exactly at the threshold of stall warning activation,

- difficulty in reacting properly in case of conflicting warnings (pull-up and stall warning for instance),

- difficulty in modulating control forces in a situation of high stress ; again, several events have shown that "supposed to be" deterrent forces have not deterred a pilot from pulling gs well in excess of the theoretical structural capability.

In answer to these findings, Airbus fly-by-wire control laws allow the sidestick to be deflected to its stop while keeping the aircraft at the border of the safe flight envelope :

- when fully deflected, in pitch, the sidestick will command load factor within the structural capability of the aircraft (- 1 g, + 2.5 g) ; note that, by nature, any C* law means that load factor is limited (by the actual max range of the demand variable),

- when flying at high angle-of-attack, a full back stick will command an angle-of-attack which is set a few degrees below stall ; in such a case, the control law actually allows the pilot to fly easily at the equivalent of a stall warning angle of attack, without the risks of either dangerous overshoot or non-optimum undershoot,

- when fully deflected in roll, the sidestick will command a bank angle limited to 67°, which is sufficient to offer adequate manœuvering capability and protects against loss of control by excessive bank attitude.

These Manœuvering Augmentation Features (sometimes referred to as "Hard Flight Envelope Protections") provide two significant advantages over "overridable protections" :

- they optimize the trajectory at its best practicable level,
- they allow the recovery to be prompted by removing the potential pilot hesitation (for instance, when recovering from a dive, a 2 s delayed pull up at 3.5 g leads to a worse trajectory than an immediate recovery at 2.5 g),

Two concerns have often been raised against this type of control laws and are worth commenting on :

- Some aircraft have been successfully landed, sometimes with buckled wings, after pulling gs well in excess of 2.5 (up to 5 g - 6 g range). True. But, none of them would have been lost if the recovery had been limited to 2.5 g, while some others have definitively broken up in the air. Moreover, who would claim that current derivative aircraft, where structural margins have been extensively used to increase operating weights, would still be capable of sustaining 5 g or 6 g at mid fatigue-life ?
- Non overridable protections might be dangerous if they are unduly activated. True ; that's why specific system precautions must be taken to make this event Extremely Improbable ; these precautions are readily available and were even pioneered by other systems like autopilots for All Weather Operation. But more fundamentally speaking, is this concern not already valid for a stick pusher ? Who would dare to say that a stick pusher hardover close to the ground is not dangerous, when a simple stall warning activation after lift-off has lead to a hull loss ?

3.3 . Full Authority Control Laws

Error-tolerant control laws keep an unattended aircraft inside the normal operating flight envelope. Manœuver Augmentation control laws keep a threat-escaping aircraft at the border of the safe flight envelope. And what happens if the aircraft, for whatever reason, is severely upset outside the safe envelope (imagine extreme vortex, mid-air collision, ...) ?

For this hopefully theoretical case to which no probability can be associated, Airbus fly-by-wire control laws revert to a basic full authority mode called "Abnormal Attitude Law" ; all protection features are deactivated (except overstressing) and only normal acceleration and pitch rate feedbacks are used ; lateral control is direct. This option has been preferred over keeping the normal law, for which thorough validation across the range of all possible situations (inverted flight, spin, very low speed, discontinuities of parameters) would have been difficult to perform. With this type of full authority control law, recovery from unusual attitude well outside the safe flight envelope is simply no more difficult than with a conventionally controlled aircraft.

4 . Conclusion

The design of modern flight control systems has already contributed to the improvement of the inherent safety characteristics of current airliners. Further improvements of these characteristics are deemed necessary to cope with more demanding environment and increasing traffic. The emergence of Fly-By-Wire technology offers new opportunities to improve overall air transportation safety even more, particularly in the field of loss-of-control prevention and better human error tolerance.

These objectives have been taken into account for the development of the current generation of electrical flight control systems. A pragmatic analysis of former incidents/accidents has provided the basis upon which the main principles have been based. As a consequence, the fly-by-wire system control laws provide in this respect :

- more error-tolerant characteristics which keep a momentarily unattended aircraft inside the normal flight envelope and indicate any excursion outside this envelope by resisting pilot control forces,
- manœuvering augmentation when exceptional manœuvrability is needed ; this allows a pilot to reach and maintain the optimum capability of the airframe/engine combination easily and quickly,
- full authority outside the safe flight envelope.

It is hoped that this deliberate use of available technology towards better safety will be merged into a largely wider stream of similar measures from all other fields of air transportation activities, and that flying will remain the most enjoyable and safest way to travel.