FLY-BY-WIRE AUGMENTED MANUAL CONTROL - BASIC DESIGN CONSIDERATIONS

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Abstract

After the introduction of Fly-by-Wire (FBW) flight control in the late eighties, several thousands of commercial FBW aircraft are in service today. Looking back, it can be concluded that FBW has brought an impressive improvement to handling qualities and flight safety. However, after the long time of experience with the first generations of FBW aircraft, open questions and issues with respect to the design and the operation of FBW have been revealed. The main objective of this paper is to discuss those issues and to point out further research needs in this field. The characteristics of manual augmented pitch control algorithms implemented in commercial FBW aircraft are discussed in detail. Subsequently the paper describes particular features of Airbus and Boeing FBW control systems that are not directly related to the chosen control algorithm. Open questions and resulting research needs with special focus on recent incidents and accidents are discussed.

1 Introduction

Over 20 years after the introduction of the first digital FBW control system in commercial aircraft by Airbus in the late eighties, the trend to replace mechanical controls by electrical connections has become irreversible. Today commercial FBW aircraft from six different manufacturers, being Airbus, Boeing, Embraer, Iljuschin, Tupolev, Suchoi and Antonov, are in service. The vast majority of them has been delivered by Boeing, Airbus and Embraer (see Table 1).
The main benefits of FBW control leading to its wide application include:

- Standardization of control handling qualities between different airplane models of the same manufacturer allowing reduced training requirements
- Weight and maintenance effort reduction by replacing mechanical components (e.g. pulleys, cables)
- Introduction of flight envelope protection functions for enhanced safety
- Introduction of maneuver/gust load alleviation functions
- Optimization of aerodynamic performance (e.g. drag reduction by aft-shifted center of gravity)

Manufacturer	Current Models	No. of deliveries
Boeing	B777	1003
	B787	8
Airbus	A318/319/320/321	5022
	A330/340	1225
	A380	71
Embraer	E-170/190	802
Antonov	An-148	16
Iljushin	IL-96	26
Tupolev	TU-204/214	74
Suchoi	SSJ 100	7
Total		8106

Table 1 Commercial FBW aircraft: No. of Deliveries

Looking back, it can be concluded that FBW designs have been very successful and have accumulated a flight safety record as good as, or better than the mechanical flight control systems of the previous aircraft generation. Especially with respect to aerodynamic stall accidents the introduction of FBW control and the related envelope protection functions have saved a lot of lives. According to [14] there have been 27 stall accidents in transport operations with 848 fatalities between 1993-2008. None of those accidents involved a FBW aircraft. However, shortly after the publication of this statistics two stall accidents with FBW aircraft occurred, but in both cases the envelope protection function was not working properly due to sensor malfunctions.

Although FBW design has reduced the mechanical system complexity and maintenance effort, the application of FBW control has increased the functional complexity of the Flight Guidance and Control System due to additional control features, necessary monitoring functions and reversionary modes to provide continuity of essential control functions under various failure conditions. Each reversionary mode tends to have its own characteristics putting a higher level of demand on flight crew proficiency, compared to previous airplane generations, to correctly handle the operating scenarios for all possible failure conditions.

Every aircraft manufacturer has developed its own distinct design solution. Two general types of FBW flight control system design approaches are being used today:

1. Simple FBW designs with little or no stability augmentation: The traditional mechanical signaling from the pilot's control inceptor to the control surfaces is replaced with electrical signaling, possibly including gain scheduling and feedback of sensor output variables that have associated stability derivatives. Classical airplane dynamic modes and stability characteristics are maintained so that the airplane can be certified under existing airworthiness regulations.
   This type of FBW control is implemented in the Embraer E-170/190.

2. Complex FBW controller designs using non-classical stability/command augmentation: Typically, such designs include elements of the type 1 design, as well as other design features, possibly including feedbacks of sensor output variables that have no associated stability derivatives (e.g. attitudes or accelerations). This type of design may also include dynamic elements (filters) in the feedforward and feedback signal paths that result in an "higher order controller", which typically alters the fundamental airplane dynamic modes and airplane response to pilot control input. Such designs may not meet the basic certification requirement for stability and long term (trim) behavior and therefore may need "equivalent safety" features, e.g. envelope protection.
   This type of control is implemented in Airbus and Boeing FBW aircraft.

To reduce perceived program risks, development costs and maintain continuity of the product characteristics, an evolutionary design approach has generally been used - punctuated by radical exceptions often at the time of first product offering. Airbus chose a FBW design approach that creates an unconventional aircraft behavior by providing a pseudo trajectory hold feature when the pilot leaves the control loop. The resulting loss of classical speed stability led to the introduction of envelope protection functions to achieve equivalent safety required for certification [7]. In contrast, when Boeing introduced FBW control, it was decided to maintain operational consistency with the previous mechanically controlled airplanes.

The different design concepts introduced by Airbus and Boeing for their first time on the Airbus A320 and the Boeing B777, respectively, were maintained on their subsequent FBW aircraft types until today. Generally aircraft manufacturers tend to keep the design choices made for their first FBW airplane model in order to maintain commonality of the handling characteristics of the subsequent FBW aircraft types. As a result, many FBW design issues continue to be the subject of intense debates, including

- Control inceptor types: column wheel versus sidesticks; active versus passive inceptor feel
- Manual augmented control algorithm types and the resulting aircraft handling characteristics
- Application of envelope protection functions to regain equivalent safety to compensate for the loss of classical speed stability and to reduce the probability of exceeding the envelope boundaries and of Loss of Control (LOC)

No consensus between the different aircraft manufacturers has emerged on these design issues. Additionally, although FBW aircraft are extremely safe, incidents and accidents involving FBW aircraft from different manufacturers have revealed further issues related to the design and the operation of FBW control. Many of the issues result from the specific characteristics of FBW aircraft and, except of Pilot Induced Oscillations (PIO), they do not have a counterpart in non FBW airplanes [20].

This paper describes different manual augmented control design approaches of commercial aircraft in detail and discusses open questions related to the particular design. The main focus will be put on the FBW control system design of type 2 which are implemented in Boeing and Airbus aircraft. Questions such as

- How is the piloting task affected by a particular manual augmented control algorithm?
- What is the impact of particular features of existing FBW systems on the pilot-aircraft-interaction?

are discussed with respect to particular design characteristics. Furthermore, relevant incidents or accidents are presented.

2 Characteristics of Current Control Algorithms

Often the characteristics of a specific control algorithm are classified by their "response type". The algorithm's "response type" and the variable commanded by the control inceptor are named after the main feedback variable in the control algorithm, e.g. angle of attack (AOA), vertical load factor (n_z), pitch rate or vertical flight path angle (FPA). In the context of manual augmented control it is a popular notion that a specific "control algorithm response type" produces distinct short-term maneuvering characteristics providing an inherent advantage over other algorithm types. As a result, the characteristics of pitch rate, pitch attitude, angle of attack and vertical load factor short-term responses at constant airspeed of a particular pitch control algorithm are discussed in terms of its "response type".

However, this is not very meaningful, since the response characteristics at constant speed, i.e. the short-term response or the response with activated autothrust, can be made to look identical for control algorithms with different "response types" [13]. Furthermore, naming an algorithm by its "response type" does not adequately describe the feedforward and feedback signal processing that determines the control inceptor to control effector command relationship including the very important distinction, whether the control algorithm uses only proportional feedback or, in addition, also integral feedback. Therefore control algorithm response labels can be misleading.

Instead, the characterization of current control algorithms as used in this paper focuses on the long-term behavior of each algorithm, because its effect on the long-term response of key airplane state variables, e.g. such as pitch attitude, airspeed or flight path angle, at constant thrust with the control inceptor at neutral is at least equally important. This behavior is mainly influenced by the design of the integral signal path. Depending on the control algorithm the aircraft may return to its trimmed airspeed, maintain pitch attitude, vertical speed or flight path angle.

This behavior significantly affects the pilot's control technique and monitoring task. Consequently, in this paper the distinction between existing control algorithms is made with respect to their long-term responses at constant thrust without any pilot control input. The objective of this section is to describe the general characteristics of the control algorithm rather than dealing with the specific design chosen by the corresponding aircraft manufacturer.

2.1 The C^* Control Algorithm

In the 1960's a C^* handling qualities criterion was formulated by H.Tobie, H.Elliott and L.Malcom [22]. It is defined by the linear combination of pitch rate and vertical load factor signals. According to [22] the original definition is:

$$C^* = (\Delta n_z)_{pilot} + \frac{V_{co}}{g} \cdot q \qquad (1)$$

where $(\Delta n_z)_{pilot}$ is the vertical load factor at the pilot's location, q is the pitch rate , V_{co} is the so-called "crossover" airspeed and g being the gravity constant. The "crossover" airspeed is the airspeed at which the signals $\frac{V_{co}}{g} \cdot q$ and $(\Delta n_z)_{pilot}$ are equally weighted ($V_{co} \approx 240kt$). The criterion asserts that pilots use the pitch rate in the low speed regime and the vertical load factor in the high speed regime as main control cues. The airplane's handling qualities are satisfactory when the C^* quantity falls within certain boundaries.

The validity of the C^* handling quality criterion has long been repudiated [19], because the pilot cannot control pitch rate independently from normal acceleration or vice versa. Pilots generally maneuver the airplane with approximately the same relatively low vertical acceleration levels for all flight conditions to achieve a given incremental load factor. As a result the natural airplane dynamics dictate a higher pitch rate at low speed than at high speed.

However, the use of the C^* variable as a command/feedback quantity has been adopted in several manual augmented control systems denoted as C^* control algorithms. According to [7, 16] all Airbus FBW aircraft use a C^* command/feedback control algorithm as primary pitch axis control law in all flight phases except of take off and landing flare, but the corresponding feedback quantity does not exactly correspond to the original C^* quantity that uses a fixed pitch rate gain (see Equation 1). In the Airbus flight control algorithms the gain for the integral pitch rate feedback path is a function of calibrated airspeed [6]. Further information on the detailed design of the pitch rate gain of the C^* quantity is scarce. A simplified structure of the C^* algorithm is shown in Figure 1.

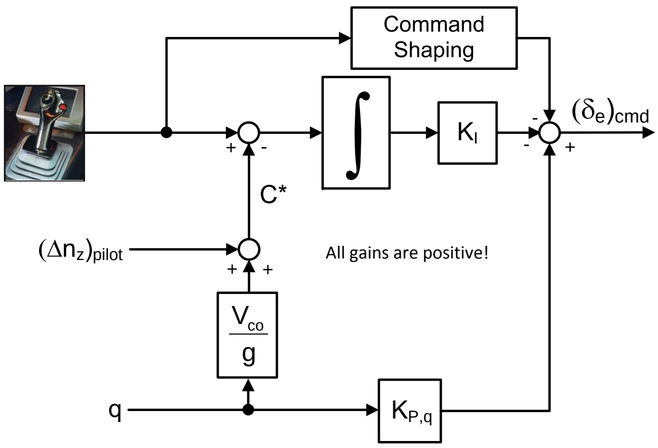

Fig. 1 Simplified structure of C^* algorithm

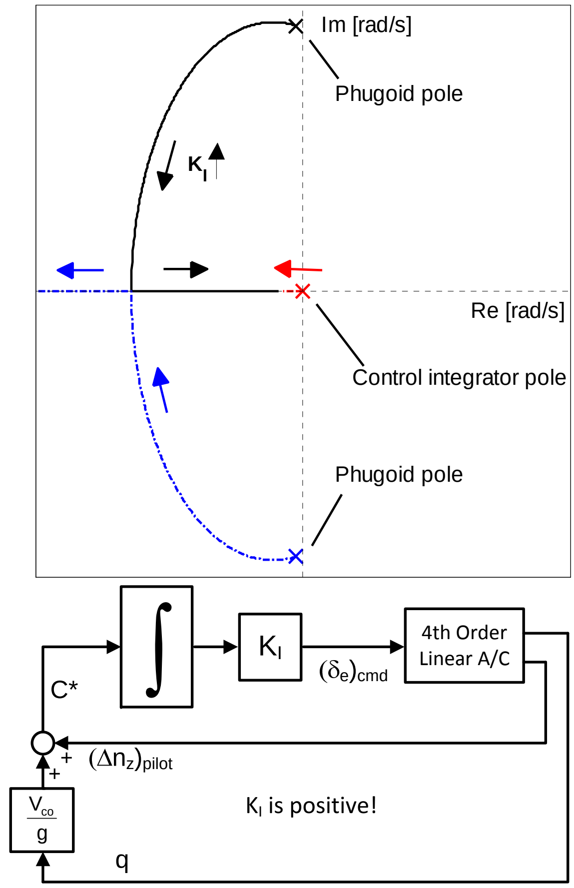

Fig. 2 Root locus plot for C^* integral feedback (Short-period poles are not shown)

The proportional pitch rate feedback increases the damping of the short-period motion. The algorithm might include other proportional feedback paths for the modification of the short-period motion. For a basic understanding of the shaping of the control response the feedback of pitch rate and incremental load factor through an integral path can be approximated as proportional feedbacks of pitch attitude and vertical speed resulting in an increase of short-period frequency and phugoid damping. Typically the phugoid conjugate-complex pole pair breaks up into two real poles [10]. One pole is located close to the origin of the complex plane dominating the long-term speed response (see black solid line in Figure 2). The second pole affects the short-term angle of attack and n_z-response (see blue dash-dotted line in Figure 2). Another pole that is generally located closer to the origin of the complex plane than the former phugoid pole results from the shift of the former controller pole (see red dashed line in Figure 2).

It is often stated that the C^* algorithm provides flight path stability. This is based on the fact that, without any pilot stick input the controller tends to stabilize the aircraft at a constant vertical speed or flight path angle assuming that airspeed is kept constant by thrust control. However, the algorithm is not capable of guaranteeing a zero steady-state flight path angle deviation, because it does not include integral control of the flight path angle resulting in flight path deviations due to external disturbances and configuration or thrust changes. As a result, the pilot must periodically re-enter the control loop to keep the airplane on the desired earth referenced flight path.
Since the C^* algorithm basically tends to hold vertical speed as a consequence of the integral control of the vertical load factor, any pilot input changes the vertical speed reference and causes the airspeed to drift away without bounds, unless the thrust is re-trimmed by the automatic thrust control or by the pilot. Thus the C^* control algorithm destroys the natural speed stability of the aircraft. There is no "trim speed" in

the classical sense of trimming out the stick force to stabilize at and hold a desired speed. The change in speed due to a constant stick displacement (or stick force) is infinite, because the pilot must get out of the control loop to stop the pitch rate.
As a result, the C^* algorithm does not meet the Federal Aviation Regulations Part 25 for static longitudinal stability, which requires a pull force to achieve and maintain a steady state speed decrease relative to the trim speed and vice versa [9]. Additionally, after having released the stick, the speed has to return to the trim speed [9]. To comply with the intent of the speed stability requirement and guarantee an equivalent safety level, speed stability has to be restored at the edge of the aircraft envelope, which is provided by envelope protection functions [7].
In practice, pilots resort to use the automatic thrust control to hold the speed and prevent it from diverging, when the pilot generates pitch inputs. As the C^* algorithm integrator commands the elevator deflection necessary to maintain the flight path, irrespective of the airspeed, the steady-state elevator deflection could become large reducing the maneuver control authority in one direction and increasing trim drag. Therefore an automatic stabilizer trim function is used in combination with the C^* algorithm in order to offload the long-term elevator trim deflection onto the horizontal stabilizer.

2.2 The C^*U Control Algorithm

The C^*U control algorithm is build around a core C^* algorithm including an additional airspeed feedback loop to the controller integrator reintroducing an artificial speed stability. It was invented by Boeing and is applied to both Boeing FBW aircraft types, being the B777 and B787. The controlled variable is a combination of the C^*-parameter (see Equation 1) and a speed stability term. The resulting variable is denoted as C^*U and is defined as follows:

$$C^*U = C^* - K_V U_{err} \tag{2}$$

with U_{err} being the error between the airplane calibrated airspeed V_{CAS} (or equivalent airspeed) and the C^*U reference speed and K_V being the speed stability gain [18]. The simplified structure of the C^*U algorithm is presented in Figure 3.

The reference speed used for the computation of U_{err} is derived from the trim switches on the left side of the control wheel. That means that the pilot com-

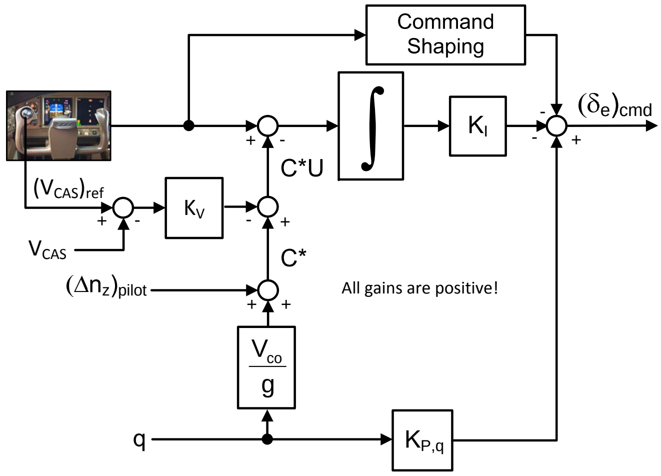

Fig. 3 Simplified structure of C^*U algorithm

mands a trim speed instead of a stabilizer position by using the trim control devices. Conventional aircraft are trimmed at a particular angle of attack by generating a horizontal stabilizer position that guarantees an equilibrium of moments. A statically stable aircraft will return to the trimmed angle of attack after an external disturbance. This conventional behavior is replaced by an artificial airspeed trimming in the C^*U algorithm. Since airspeed (error) is fed back to the integrator, the C^*U algorithm causes the aircraft to return to the commanded trim speed in the long-term response. The column input basically commands an incremental load factor (or pitch rate) in the short-term and a change of airspeed in the long-term response.
The feedback of the airspeed error re-establishes in principle the conventional lowly damped phugoid behavior. Figure 4 shows the root locus plot for a variation of the speed stability gain K_V assuming that the calibrated airspeed loop is closed around the linear aircraft model and the integral C^* feedback path which uses a fixed integrator gain K_I (see Figure 2). The two real poles close to the origin of the complex plane resulting from the C^* feedback form an oscillatory mode that dominates the long-term speed response (see red and black lines in Figure 4). The speed error feedback gain must be kept low, because a too high frequency of the airspeed control would interfere with the vertical load factor control. Consequently, flight path angle changes would be quickly compensated by the airspeed error feedback leading to adverse effects on the flight path control handling characteristics.
The resulting responses look "conventional" depend-

ing on the phugoid damping provided allowing the C^*U algorithm to be certified under the existing Federal Aviation Regulations. As a result, the C^*U algorithm still requires manual trim inputs to trim the aircraft at a new reference speed.

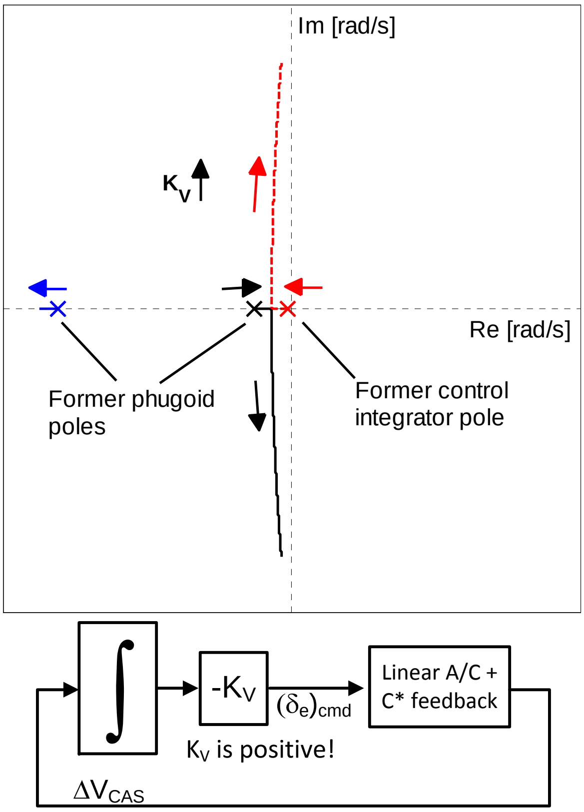

Fig. 4 Root locus plot for ΔV_{CAS} integral feedback (A/C incl. fixed C^* integral feedback)

3 Specific Design Features of Existing FBW Systems

3.1 Automatic Stabilizer Trim Function

When flying an aircraft using the C^* control algorithm, the pilot is not required to trim manually, because the controller generates the elevator deflection necessary to maintain a desired flight path. In Airbus aircraft an automatic stabilizer trim function, denoted as *Autotrim*, moves the horizontal stabilizer to offload the elevator deflection commanded by the C^* algorithm by feeding the slowly integrated elevator command as a trim command to horizontal stabilizer actuators [6]. This function is only available, when the flight control system operates in the normal mode, denoted as *Normal Law*, or in the backup mode *Alternate Law*.

The cockpits of the first two generations of Airbus FBW aircraft (A320, A330/A340) still feature conventional trim wheels for manual trimming in case of the *Autotrim* function is lost. As the motion of the trim wheels directly reflects stabilizer motion, the crew can monitor the *Autotrim* function operation. In the Airbus A380 flight deck the trim wheels are replaced by trim switches located in the rear part of the center pedestal. An additional display below the Primary Flight Display (PFD) informs the crew of the current horizontal stabilizer position. In addition, all Airbus FBW aircraft display the current stabilizer position on the flight control page of the Electronic Centralized Aircraft Monitor (ECAM). In case of loss of the automatic stabilizer trim function, e.g. when the control algorithm reverts to the backup mode *Direct Law*, the crew is informed by a message on the PFD ("USE MAN PITCH TRIM"), indicating that trimming to bring the elevator back to neutral must be done manually.

In Boeing FBW aircraft the pitch trim switches on the control wheels are used to set the reference airspeed and the airspeed error is used by the C^*U pitch algorithm as a feedback to the integral control signal path, when the aircraft is operated in the *Normal Mode* (see Figure 3). In contrast to conventionally controlled airplanes, on the Boeing FBW airplanes the pilot does not control the horizontal stabilizer directly, when he uses the primary trim switches on the control wheel in *Normal Mode*. The horizontal stabilizer is automatically driven by the automatic stabilizer trim function to offload the elevator and allow it return to its neutral position [8], in a manner similar to Airbus aircraft.

In addition to the trim switches on the control wheel, the *Alternate Pitch Trim Levers* in the center pedestal are available providing a backup horizontal stabilizer control function. The *Alternate Pitch Trim Levers* move the horizontal stabilizer directly and at the same time the reference airspeed for the C^*U control algorithm is adapted accordingly (only in *Normal Mode*). The *Alternate Pitch Trim Lever* commands have priority over the control wheel trim switch commands in all flight control modes [8].

The automatic horizontal stabilizer trim function is not active, when the flight control system operates in one of the backup modes. In the backup flight control modes, denoted as *Secondary Mode* and *Direct Mode*, the pilot can still use the trim switches on the control wheel, but in the case they directly move the stabilizer

instead of commanding a reference speed to the flight control algorithm. Manual trimming of the horizontal stabilizer in the backup modes causes a change in the column trim forces, so that the pilot can trim the elevator to the neutral position by trimming out the control forces.
In the B777 the horizontal stabilizer position is indicated by the Stabilizer Position Indicator located left to the Alternate Pitch Trim levers on the center pedestal and on the flight control synoptics page of the multifunction display.

3.2 Envelope Protection Functions

Generally Airbus FBW aircraft provide envelope protection functions that prevent the pilot from maneuvering the airplane beyond the airplane safety limits. The following protections are available in the *Normal Law* [1]:

- *High AOA Protection*:
  Prevents the pilot from commanding an AOA in excess of a defined limit
- *High-Speed Protection*:
  Prevents the pilot from controlling the aircraft to a speed in excess of a selected limit
- *Load Factor Limitation*:
  Prevents the pilot from commanding a vertical load factor in excess of selected upper and lower limits
- *Pitch Attitude Protection*:
  Prevents the pilot from commanding a pitch attitude in excess of selected upper and limits
- *Bank Angle Protection*:
  Prevents the pilot from commanding a bank angle in excess of a selected limit

The loss of speed stability due to the C^* control algorithm requires speed envelope protection functions that reintroduce speed stability at the edge of the envelope (see Section 2.1). For the high speed protection the flight control algorithm generates a nose-up command within the C^* algorithm and overrides the nose-down authority of the sidestick as the speed increases above the maximum operating speed [1]. The automatic stabilizer trim function is deactivated, when the *High-Speed Protection* is active. In *Normal Law* speed stability at low speeds is provided by the High AOA protection function by switching the control algorithm from a C^* command algorithm to an AOA command algorithm, in which the commanded AOA is proportional to stick deflection. With the stick in neutral position the command corresponds to the AOA at which the protection function is activated [1]. With full aft deflection the stick commands the maximum AOA allowed by the system (generally smaller than AOA at maximum lift coefficient).
As the C^*U control algorithm used in Boeing FBW aircraft exhibits "conventional" behavior including speed stability over the entire envelope and provides artificial force feedback on the control column, the design approach of the protection functions within the Boeing flight control system is different to that in Airbus aircraft. When *Normal Mode* is active, the B777 provides the following protection functions [8]:

- *Stall Protection*:
  Reduces the likelihood of inadvertently exceeding the stall AOA by providing enhanced crew awareness of the approach to a stall or to a stalled condition
- *Overspeed Protection*:
  Limits the maximum (C^*U reference) speed to which the aircraft can be trimmed
- *Roll Envelope Bank Angle Protection*:
  Reduces the likelihood of exceeding the bank angle boundary by providing counteracting roll control wheel inputs

The *Stall Protection* function of the B777 incorporates different features that increase the pilot's awareness of approaching the stall speed. Firstly, this function limits the minimum speed to which the aircraft can be trimmed. This is performed by limiting the reference speed of the C^*U control algorithm to a predefined minimum maneuvering speed. Consequently, the pilot must continuously apply an aft control force that cannot be compensated by trimming in order to maintain speeds below the minimum maneuvering speed. Secondly, the *Stall Protection* function further increases the column force gradient when the aircraft is close to stall speed. Further the automatic stabilizer trim function is inhibited when the stall protection force gradient is activated.
Similar to the *Stall Protection* the *Overspeed Protection* function limits the maximum trim speed used as reference speed for the C^*U control algorithm.

Hence, the pilot must apply higher continuous forward column force to maintain airspeed above the maximum operating airspeed or Mach number [8].

4 FBW Control Design Considerations

The objective of this section is to discuss design considerations and open questions that are related to the implementation and the operation of FBW systems. Additionally, the impact of specific FBW design features on the interaction between pilot and aircraft are highlighted for each issue mentioned in this section.

Incidents or accidents are described in order to clarify the issues. It has to be noted that each issue mentioned with respect to a particular incident or accident might not be the main cause for the event but only a contributor to its occurrence.

4.1 Impact of Speed Stability

Certainly both, the C^* algorithm as well as the C^*U algorithms, provide good handling qualities, but the debate on the need of speed stability is still going on. The motivation of choosing a control algorithm that prioritizes control of the flight path and maintenance of the established flight path when the pilot leaves the control loop, is a possible ease of flight path control and a reduction in workload. On the other hand the motivation of choosing an algorithm that preserves speed stability is a possible increase in speed control performance and speed awareness. A lot of research work has been performed on the impact of speed stability on handling qualities and control performance of the pilot. However, there is still no clear consensus on the superiority of control algorithms that preserve the natural speed stability over algorithms that lack natural speed stability and provide "flight path stability" instead, or vice versa:

From a flight path control handling qualities point of view, Mooij [17] found a small advantage for a Pitch Rate Command/Pitch Attitude Hold (PRC/PAH) control algorithm that has no speed stability thus exhibiting similar responses to the C^* algorithm in this regard.

Field [11] evaluated several control algorithms during approach and landing using a ground-based simulator. He could not identify a clear preference of the pilots for algorithms with or without speed stability. Although the workload may have been reduced with respect to flight path control using a control algorithm that lacks speed stability, it resulted in poorer airspeed control [11].

Gautrey [12] performed a similar simulator study testing different control algorithms with and without speed stability. These studies demonstrated the advantages of control algorithms without speed stability such as the normal acceleration control algorithm during the approach. In the summary of his work he points out that the normal acceleration algorithm reduces the pilot's workload significantly as it enables the pilot to adopt an open loop strategy for flight path control situations as it is the case for the approach task [12]. The opinion on the absence of the manual trimming task, when using control algorithms without speed stability, was very ambiguous. Whereas most pilots stated that they preferred the lower workload due to removing the requirement to trim, some pilots commented that an airspeed trimming strategy, as used in the C^*U algorithm, was very desirable and helped to keep them in the loop. The pilot comments did not reflect a clear opinion on the increase of speed awareness due to the requirement to trim either [12].

The results of the studies presented in this section cannot provide a definite answer on the necessity of speed stability as part of the manual augmented control algorithm. Although, in contrast to the studies of Mooij and Field, Gautrey states that after some acclimatisation the pilots became more and more in favor of the control algorithms without speed stability, one important further open questions arose with respect to a reversion to a backup mode providing natural speed stability. Comments from the evaluation pilots in [12] indicated that pilots used to control algorithms without speed stability, such as the C^* algorithm, would experience a higher workload due to the mode reversion than pilots used to speed stable aircraft. According to the evaluation pilots' opinion this increase mainly results from the requirement to relearn to trim [12].

4.2 Piloting Technique for Disturbance Compensation

The influence of manual augmented control on the optimal piloting technique is significant. For conventionally controlled aircraft the task of stabilizing the aircraft on the desired flight path after an external disturbance is left to the pilot, but the pilot has no suitable indication of flight path deviation on his PFD. For that reason pilots are still used to react to a change of attitude angles. As the attitude angles are easy to derive either from the outside view or from the PFD that puts the main focus on the aircraft attitude control, the main control references for manual control are still the pitch angle for longitudinal control and the bank angle for lateral control.

However, the application of manual augmented control in modern FBW aircraft has influenced the distribution of tasks between the pilot and the flight control system with respect to the compensation for external disturbances.

For lateral motion control, Airbus uses a roll rate command and bank angle hold system which actively tries to keep the bank angle at zero after a lateral disturbance. The B777 FBW lateral control is basically a Direct Control mode without feedbacks and a roll attitude hold feature, so the airplane responds to a lateral disturbance like a conventionally controlled airplane. The B787 has an integrated lateral/directional control algorithm that provides basically roll rate command/ roll attitude hold control, similar to the Airbus design. The latter type of designs provide more roll attitude stiffness and thus require less pilot compensation for external disturbances. For those control algorithms a strong reaction of the pilot in response to rotational rates or attitude angle changes might lead to adverse effects due to a significant interaction between pilot and the flight control algorithm.

In 2010 DLR performed a study on a Airbus A330 Full Flight Simulator, where the aircraft was disturbed by a simulated wake vortex encounter while the pilots were manually flying an ILS approach. The study revealed that numerous pilots aggravated the impact of the wake vortex on the aircraft response by generating to strong and to abrupt inputs on the stick, although they were informed that a wake encounter could occur [23]. This was especially observed for pilots with little experience on FBW aircraft. The final report recommends that the pilots should react to the lateral and vertical flight path deviation with extremely smooth inputs on the stick rather than trying to overcompensate for the change in attitude angles [23]. These recommendations are similar to those given by Airbus for manual control during wake-vortex encounters [21].

Hence, the piloting technique should change from a continuous compensatory control to an intermittent control strategy, because the short-term control task of continuous pitch and roll attitude stabilization is performed by the control algorithm. In many current airline training programs no emphasis is put on the adaptation of the piloting technique that is needed to safely operate a FBW aircraft with manual augmented control in case of external disturbances. It seems that in most cases the pilot still uses pitch angle as his primary control variable. During the simulator study performed by Gautrey several pilots commented on the desirability of a flight path vector display, especially for the unconventional systems without speed stability, because this is the parameter which they are ultimately trying to control [12]. For the majority of existing Airbus FBW aircraft the flight path vector symbol is only available in the PFD, if certain autopilot modes are triggered. However, flight path information is displayed in the head-up display which can be optionally ordered for every Airbus FBW aircraft.

Further research activities should analyze the impact of the availability of the flight path vector symbol on the piloting technique. The availability of a suitable display might change the pilot's focus, driving him to close the control loop rather on flight path angle than on pitch attitude. It has to be noted though that, in contrast to a real flight path angle hold algorithm, the C^* algorithm does not provide a true flight path angle hold function. Therefore, it is reasonable to expect that future designs will utilize true FPA rate command / FPA hold control (FPARC/FPAH) algorithms. A considerable amount research was accomplished toward that goal in the late seventies under the NASA TCV program [15] and more research on this subject is under way at DLR and the FAA. Also the new Dassault Falcon 7X and the Embraer Legacy 450/500 feature FPARC/FPAH control algorithms.

4.3 Trim Position Awareness

The absence of the manual trimming task for control algorithms without speed stability reduces the pilot workload during normal operation. On the other hand, the pilot might get unused to continuously trim the aircraft (see Section 4.1). An additional issue related to the inherent pitch trim of an algorithm without speed stability is the crew's awareness of the horizontal stabilizer position during normal operation.

In Airbus aircraft the horizontal stabilizer is continually moved by the *Autotrim* function in order to keep the elevator in a neutral position. The crew is able to discern the operation of the automatic stabilizer trim function either from the PFD or from the motion of the trim wheels as well as from the ECAM (see Section 3.1). The pilot's awareness of the horizontal stabilizer position is of crucial importance to flight safety, especially when the automatic stabilizer function is suddenly lost in flight conditions close to the edge of the envelope.

In 2008 an A320 crashed during an acceptance flight before returning the aircraft back to the owner at the end of a leasing transfer. The acceptance test flight was conducted from Perpignan, France, without a rigorous and well prepared test plan. Various system functions were checked and a final test was conducted to check the functionality of the AOA protection system, while descending over the Mediterranean Sea for an approach to Perpignan. From FL320 until the impact with the surface two of the three AOA vanes remained frozen in place due to icing [5]. The voting algorithm rejected the measurement of the third valid vane signal and used the two measurements from the jammed vanes as valid signals for the flight control laws. With the throttles at idle, the flaps were moved to the final approach setting, and the airspeed was allowed to bleed down in order to demonstrate and check the AOA based low speed protection. As the airplane decelerated, the automatic horizontal stabilizer trim system continued to trim nose-up until the stabilizer reached its stop position. The AOA protection failed to activate and the airplane stalled and rolled to a bank angle of 45 degrees causing the Air Data to go invalid and the control mode to revert to the backup mode *Alternate Law*, which corresponded to the *Direct Law* in this case, because the landing gear was extracted [1]. Consequently, the system provided a direct stick-to-elevator relationship and the automatic stabilizer trim function was deactivated. At this point, with the horizontal stabilizer at the nose-up limit, the pilot applied take-off thrust and moved the stick full nose-down, but it took an additional five seconds for the elevator to reach the full nose-down position. Although the stick and the elevator remained in the nose-down stop position for 25 seconds, the pitch attitude increased from 8 to 58 degrees. The accident report findings state that the combination of full pitch-up horizontal stabilizer position and take-off thrust made pitch down control impossible [5]. The nose-down authority of the elevator was inadequate to overcome the nose-up pitching moment generated by the horizontal stabilizer.

Until the end of the flight the crew never generated any manual trim input. This seems to indicate that both pilots were not aware that the automatic trim system was no longer available [5], although the manual pitch trim advisory was displayed in the PFD. The final accident report states that "in the absence of preparation and anticipation of the phenomenon, the habit of having the automatic trim system available made it difficult to return to flying with manual trimming of the aeroplane" [5].

The report thus picks up an issue that is related to control algorithms without speed stability and the resulting absence of the manual trimming task during normal operation. Especially in a situation with high workload it might be hard to remind the crew that they have to take over the pitch trim task from the automation. Additionally, the crew did not seem to be aware of the full nose-up position of the horizontal stabilizer, although the pilots could monitor the commands of the automatic stabilizer trim function by the movement of the trim wheels. It is therefore essential to find adequate means to draw the crew's attention to the current stabilizer position and the need for manual trimming, when the automatic stabilizer trim function is lost. The integration of a horizontal stabilizer position indication below the PFD of the Airbus A380 is a important modification, as it is expected to enhance the crew' awareness of the stabilizer position.

4.4 Stall Impact

In 2009 an A330 crashed over the Atlantic Ocean. The triggering event in this crash was the failure of the flight-critical air data functions due to icing of the pitot tubes. The loss of valid air data precipitated the disengagement of the autopilot and a reversion to *Alternate Law*. The *Alternate Law* still uses a C^* algorithm, but in case of speed information loss it does not provide AOA or *Low Speed Stability* envelope protection functions. The multiplicity of warning confused the flight crew. The copilot commanded nose-up for considerable periods of time causing the airplane to decelerate and climb initially. The aural stall warning was activated, but it was ignored. The airplane stalled and started to develop a negative (downward) vertical speed. The copilot continued a nose-up command causing the elevator and the automatic horizontal stabilizer trim system to reach their nose-up stops. Pitch control was lost. The airplane entered a "deep stall", which was probably not recognized by the crew. The copilot continued to apply erratic, mostly nose-up control. Twice the elevator came out of the nose-up stop, but never changed to a nose-down position. As a result, the stabilizer remained at the nose-up stops until the impact on the sea.

Both accidents discussed above point to a serious concern about entry into and recovery from a stall for algorithms such as the C^* and C^*U algorithms that use an integral control signal path. When the airplane enters a stall, the Δnz and q feedback responses tend to fall off, due to lift loss and nose-down pitching moment. Consequently, the elevator is more and more driven nose-up, due to integration of the increasingly large C^* error, in particular, if a nose-up stick input is maintained. Operation of the automatic stabilizer trim function will exacerbate this condition to the point where both the elevator and the horizontal stabilizer can end up on the nose-up stop (as was the case for the mid Atlantic A330 crash), unless the pilot reverses his stick input early enough to overpower the adverse C^* feedback error and drive the elevator to a nose-down position.

Existing algorithms include a logic to prevent windup of the control algorithm integrator during times, when the elevator is at the stop. Still, if the pilot starts the recovery too late and the elevator command has reached the nose-up stop, a stick reversal to a nose-down command may not be enough to immediately command sufficient elevator to start bringing the airplane nose-down. To generate a net nose-down pitching moment, the elevator command must be large enough to overcome the nose-up pitching moments due to the adverse stabilizer position, thrust and possibly AOA if the pitching moment due to AOA derivative has adverse post-stall pitch-up characteristics. Furthermore, the recovery capability also depends on the gain of the proportional stick-to-elevator command signal path. An adverse command built up on the integrator, can partially or fully offset the elevator command resulting from the direct stick-to-elevator signal path, initially after stick reversal. In addition, the automatic stabilizer trim function will only start moving nose-down after the elevator has moved from a nose-up to a nose-down position. Furthermore, in a deep stall the stabilizer and elevator effectiveness may be reduced sharply. Some or all of these characteristics may have played a role in the accidents discussed above, making recovery from any full blown stall for a C^* or C^*U based FBW design difficult, even for experienced test pilots.

4.5 Sensor Failure Management

Modern FBW systems with manual augmented control algorithms like C^* or C^*U algorithms require numerous sensor feedback signals (see Section 2). Generally the aircraft are equipped with a multiplicity of redundant sensors in order to reduce the probability of the activation of backup modes in case of one or more sensor failures. The flight control system includes a failure management algorithm that is designed to prevent faulty sensors from being used by the flight control computers. This task is very complex due to the variety of sensor failure types. A number of incidents involving current FBW aircraft show that failures can arise that were not considered during the development and certification of the failure management algorithm. In those cases the faulty sensor was not identified by the system and its signal was fed back to the control algorithm causing a malfunction of the flight control system. Due to the high complexity of the control algorithm and its reliance on several feedback signals it is very difficult for the pilots to attribute a specific behavior of the control system to a particular sensor signal.

In 2005 a B777 experienced a serious pitch upset up to nearly 20° of pitch attitude, while climbing through FL380 northwest of Perth, Australia. The pitch-up and the resulting high normal acceleration levels occurred, when a backup accelerometer used in the C^*U algorithm failed causing an accelerometer that had failed earlier to be reinstated in the control algorithm [3]. The source of the problem was a design error in the *Fault Detection and Redundancy Management* software of the *Air Data Inertial Reference Unit* (ADIRU) [3].

In 2008 close to Learmonth, Australia, a serious pitch upset occurred on an A330 causing vertical acceleration spikes of -0.8g. The flight control system twice commanded the aircraft to pitch down sharply in response to spikes in the AOA signal that were not flagged as invalid and therefore used by the AOA protection function, while the aircraft was cruising at FL370. The design of the AOA signal processing algorithm and the *Failure Detection and Redundancy Management* function was found to be deficient, as the possibility of recurring spikes in the data from an ADIRU was not fully considered during the development of the flight control system [4].

The large number of sensors used and the complex processing required make these algorithms susceptible to failures, which may increase the requirement for reversionary modes to provide "continued safe flight and landing" capability for all possible failure modes. The more complex the overall design, the more difficult it is to assure design integrity for all possible failure conditions. The report of the discussed B777 incident points out that due to high design complexity of modern FBW systems the human error might be moved from the pilots to the engineers, because it is impossible to cover every failure case in such complex systems. Furthermore, it is nearly impossible for the pilots to understand the source of the problems during incidents such as the discussed B777 event [3].
However, it must be noted that due to the high reliability of the fault detection algorithms developed by the aircraft manufacturers such incidents are very improbable. In case of the A330 incident discussed above, the occurrence was the only known case of a design limitation in the *Failure Detection and Redundancy Management* function affecting the aircraft's flight path in over 28 million flight hours on A330/A340. This is within the acceptable probability range defined in certification requirements for a hazardous event [4].

4.6 Unnoticed Law Switching

It is very difficult for airline pilots to quickly adapt to a sudden change in the flight control laws. Often the pilot has not only to get used to the different handling characteristics, but at the same time he also has to remember the change in operational procedures due to the deactivation of functions such as envelope protection or automatic stabilizer trim. In order to ease this task during stressful situations the pilot has to become clearly aware of the mode change and the resulting implications.
In 2000 over the North Atlantic an A340 unintentionally climbed from its cruise flight level FL360 to FL384 thereby coming precariously close to an A330 that was flying at FL370. After the A340 had experienced moderate Clear Air Turbulence which triggered the engagement and latching of the *High AOA Protection* function and activated the *Alpha Floor* mode commanding go-around thrust. The pilots did not generate any sidestick input for 18 seconds. Consequently, the *High AOA Protection* function held the AOA constant at the value where it was activated. During that time the aircraft climbed rapidly with a maximum climb rate of about 6000 feet per minute [2].
The incident report reveals that the crew of the A340 did not realize that the *High AOA Protection* function was activated. The switching was hard to detect because the aircraft was flying in turbulence resulting in speed oscillations and possibly pitch oscillations on the PFD. Furthermore, no aural warning or text message informed the pilot that the *High AOA Protection* was engaged. The crew could have unlatched the AOA protection mode and re-established the C^* algorithm, simply by a slight nose-down stick input.
The A320 accident at Perpignan and the Mid-Atlantic A330 accident discussed above also indicate that the pilots being under stress were not able to respond as required to maintain safe operation, following the switching from *Normal Law* to the *Alternate* or *Direct Law*, although the switching event was presented on the ECAM. Consequently, the pilots were not fully aware of the deactivation of the envelope protection function and the automatic stabilizer trim function and the need for immediate manual nose-down trim.
This shows how essential it is to provide adequate means to draw the crew's attention to the modification of the flight control mode and the immediate actions required, especially during high workload situations.

4.7 Certification Issues

To deal with the changes in the aircraft dynamics and the pilot-aircraft interaction resulting from the application of the FBW design strategies discussed in this paper a number of "Special Conditions" have been issued for the certification of specific FBW flight control designs. However, the mentioned incidents and accidents raise further questions about the adequacy of current FBW certification requirements to assure:

- the flight crew's ability to assess and understand the airplane state and how to maintain/regain control over the airplane.

- the continuity/integrity of the flight-critical control functions and required pilot actions in case of specific failures (e.g. sensor failures). Ideally, the system design should include sufficient component redundancy to minimize the need to resort to alternate control modes with vastly different characteristics and required piloting procedures

- the operational suitability and safety of backup modes in terms of the flight crews ability to correctly apply the required alternate piloting strategies under stress. The accident record suggests line pilots do not perform well when faced with sudden changes in required operation procedures.

- safe algorithm operation during entry into and recovery from a stall condition, in particular for complex algorithms using integral control functions.

- safe automatic stabilizer trim operation. Stabilizer trim should be inhibited in the nose-up direction at a position that assures adequate stick/elevator control authority for stall recovery, even at full thrust. The automatic stabilizer trim operation should be inhibited well before stall (e.g. based on AOA or speed margin above 1g-stall speed).

5 Future Fly-by-Wire Design Considerations

Since most of the discussed issues can be attributed to design and operational complexities, it is worthwhile to explore whether unnecessary design and operational complexity can be avoided. In past FBW design has been approached as a problem almost entirely separate from automatic flight guidance and control design. Future FBW design strategies should generally be approached as part of the overall automatic flight guidance and control design. Whether acknowledged or not, FBW design is to a large extend an automation problem with the added difficulty that the design must accommodate the pilot to seamlessly interact with the automatic control functions by using control inceptor inputs to smoothly establish the desired airplane trajectory. Therefore, it is extremely important to avoid unnecessary complexity and the need for the pilot to use multiple mental models for correctly controlling the airplane depending on the mode of operation. Future FBW designs should therefore use the same generalized control strategy for the automatic and the augmented manual control modes. For example, all automatic vertical path modes can use FPA control as the lowest level core controller, which can serve as the basis for the FBW augmented manual mode. It has been demonstrated that the needed control response augmentation to achieve the desired handling qualities can then simply be provided by processing the pilot's pitch control inceptor signal to produce the necessary feedforward signal for the core FPA controller [13].
Then, during periods without inceptor inputs, the FBW algorithm should maintain the established trajectory. In this way the control reverts to the lowest level automatic mode, when the pilot is out of the control loop. As a result, FBW augmented manual control design can evolve to less complex and more pilot-friendly design solutions that provide a lower number of modes of operation and an increased consistency between autopilot and FBW control modes.

6 Conclusion

After Fly-by-Wire (FBW) control has been in service on commercial transport airplanes for nearly 25 years, FBW control and the accompanying introduction of envelope protection functions has increased flight safety significantly. The development of the Airbus A320 as the first commercial aircraft with digital FBW, caused a revolutionary change in the flight control system design and the resulting control handling characteristics. In 1995 the B777 was delivered being the first Boeing FBW aircraft. In spite of the complete new flight control system designs both aircraft manufacturers managed to develop highly reliable systems that substantially increased the overall aircraft efficiency. However, after the long time of experience with the first generations of FBW aircraft, open questions with respect to the design and the operation of FBW have been revealed in this paper. Especially

- the optimal piloting technique for FBW manual augmented control and

- the awareness of the crew with respect to the stabilizer position

will have to be further investigated in future research activities. These activities should include the development of new training methods specifically dedicated to the manual operation of FBW aircraft.
In addition to that, within the scope of a cooperation DLR and FAA will further investigate the feasibility and the pros and cons of future FBW design approaches with reduced complexity to mitigate current FBW safety issues.

References

[1] Airbus, *A320 Flight Crew Operating Manual*. Issue 01-Dec-2008, Airbus, Toulouse, France, 2008.

[2] Aircraft Accident Investigation Board, *AIRPROX, Airbus A330 C-GGWD, Airbus A340 TC-JDN*. AAIB Bulletin No: 6/2001, Aircraft Accident Investigation Board, Aldershot, UK, 2001.

[3] Australian Transport Safety Bureau, *In-flight upset event 240 km north-west of Perth, WA, Boeing Company 777-200, 9M-MRG, 1 August 2005*. Final Aviation Occurrence Report Ű 200503722, Australian Transport Safety Bureau, Canberra, Australia, 2007.

[4] Australian Transport Safety Bureau, *In-flight Upset 154 km West of Learmonth, WA, 7 October 2008, VH-QPA, Airbus A330-303*. Final Report AO-2008-070, Australian Transport Safety Bureau, Canberra, Australia, 2011.

[5] Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA), *Report - Accident on 27 November 2008 of the coast of Canet-Plage to the Airbus A320-232 rergistered D-AXLA operated by XL Airways Germany*. BEA, Le Bourget, France, 2010.

[6] Brockhaus R., Alles, W., Luckner, R., *Flugregelung*. Springer Verlag, Berlin, Germany, 2010.

[7] Chatrenet, D., *Les qualités de vol des avions de transport civil à commandes de vol électriques*. In Active Control Technology: Applications and Lesson Learned, AGARD, Neuilly-Sur-Seine, France, 1995.

[8] Continental Airlines, *B777 Flight Manual*. Revision #17 Dated 08/09/02, Continental Airlines, Denver (CO), USA, 2002.

[9] Federal Aviation Administration, *Federal Aviation Regulations - Title 14 Part 25*. Electronic Code of Federal Regulations, Retrieved June 26, 2012, From http://www.faa.gov/regulations_policies/faa_regulations/

[10] Favre, C., *Fly-by-Wire for Commercial Aircraft: The Airbus Experience*. International Journal of Control, Vol. 59, No.1, PP. 139-157, Taylor & Francis Group, London, UK, 1994.

[11] Field, E., *A Piloted Simulation Investigation of Several Command Concepts for Transport Aircraft in the Approach and Landing*. COA report No. 9401, College of Aeronautics, Cranfield University, Cranfield, UK, 1994.

[12] Gautrey, J.E., *Flying Qualities and Flight Control System Design for a Fly-by-Wire Transport Aircraft*. Doctorate Thesis, Cranfield University, Cranfield, United Kingdom, 1998.

[13] Lambregts, A.A., *Fundamentals of FBW Manual Augmented Control*. SAE International, Warrendale (PA), USA, 2005.

[14] Lambregts et al., *Airplane Upsets: Old Problems, New Issues*. In AIAA Guidance, Navigation and Control Conference Online Proceedings, Honolulu (HI), USA, 2008.

[15] Lambregts, A.A., Cannon, D.G. *Development of a Control Wheel Steering Mode and Suitable Displays That Reduce Pilot Workload and Improve Efficiency and Safety of Operation in the Terminal Area and in Windshear*. In AIAA Guidance and Control Conference Collection of Technical Papers, Boulder (CO), USA, August 6-8 1979, pp. 609-620, AIAA-1979-1887, American Institute of Aeronautics and Astronautics, New York, USA, 1979.

[16] Lelaie, C., *Airbus A320 - Flight Controls and Flight Envelope Protection*. In Proceedings of the 21st European Symposium, Society of Experimental Test Pilots , Lancaster (CA), USA, 1989.

[17] Mooij, H.A., *Criteria for Low-Speed Handling Qualities of Transport Aircraft with Closed-Loop Flight Control Systems*. Martinus Nijhoff Publishers for Nationaal Lucht- en Ruimtevaartlaboratorium (NLR), Dordrecht, The Netherlands, 1985.

[18] Najmabadi et al., *Aircraft Pitch-Axis Stability and Command Augmentation*. U.S. Patent 5 722 620, 1998.

[19] Neal, T.P., Smith, Rogers E., *An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes*. AFFDL-TR-70-74, 1970

[20] Newman, Richard L., *Fly-by-Wire Incidents and Accidents: Memo to Robert C. Jones*. Federal Aviation Administration, Washington D.C., USA, 2008.

[21] Rouzeval, M., *Lessons Learned from the Airbus Wake Vortex Flight Test Campaign: Some Resulting Operational Recommendations*. RAEs VORTEX Training Considerations, June 2009.

[22] Tobie, H.N., Elliott, E.M., Malcolm, L.M., *A New Longitudinal Handling Qualities Criterion*. In Proceedings of the Annual National Aerospace Electronics Conference, Dayton (OH), USA, 16-18 May 1966, pp. 93-99., 1966.

[23] Vechtel, D., Fezans, N., *Full Flight Simulator Study for Evaluation of Aircraft Dynamics while Encountering Curved Wake Vortices (Part II Result Evaluation)*. Institute Report IB 111-2010/18, Deutsches Zentrum für Luft- und Raumfahrt e.V., Braunschweig, 2010.