

ANALYSIS OF ELECTRONIC FLIGHT CONTROLS ENVELOPE PROTECTION  
FOR TRANSPORT CATEGORY AIRCRAFT

by

Brian Lewis Bixler

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This Graduate Research Project was prepared under the direction of the candidate's Research Committee Member, Professor Donald Metscher, Assistant Professor, Daytona Beach Campus, and the candidate's Research Committee Chair, Dr. Marvin Smith, Professor, Daytona Beach Campus, and has been approved by the Project Review Committee. It was submitted to the Extended Campus in partial fulfillment of the requirements for the degree of Master of Aeronautical Science

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## ABSTRACT

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Title: Analysis of Electronic Flight Controls Envelope Protection for Transport Category Aircraft

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The purpose of this project was to study the leading cause of transport category aircraft accidents--loss of control--and to determine what role electronic flight controls (“fly by wire”) with envelope protection might play in those accidents. Loss of aircraft control involves more than just the aircraft. The human interface and human actions play a large part in these accidents as well. This analysis deconstructed selected transport category aircraft accidents whose primary cause was loss of control, and discovered that the common thread among them is design and human factors. Modern fly by wire flight control systems were then analyzed to see if they properly addressed the common thread of design and human factors, and if so, which of them takes design and human factors into account holistically. The electronic flight controls design which appeared to account for the human factors element the best is the fly by wire system with flight envelope protection (“soft” limits, not flight envelope limitation (“hard” limits). This study recommends that air transport aircraft manufacturers use this feature in their latest designs for enhanced safety.

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## CHAPTER I

### INTRODUCTION

#### Background of the Problem

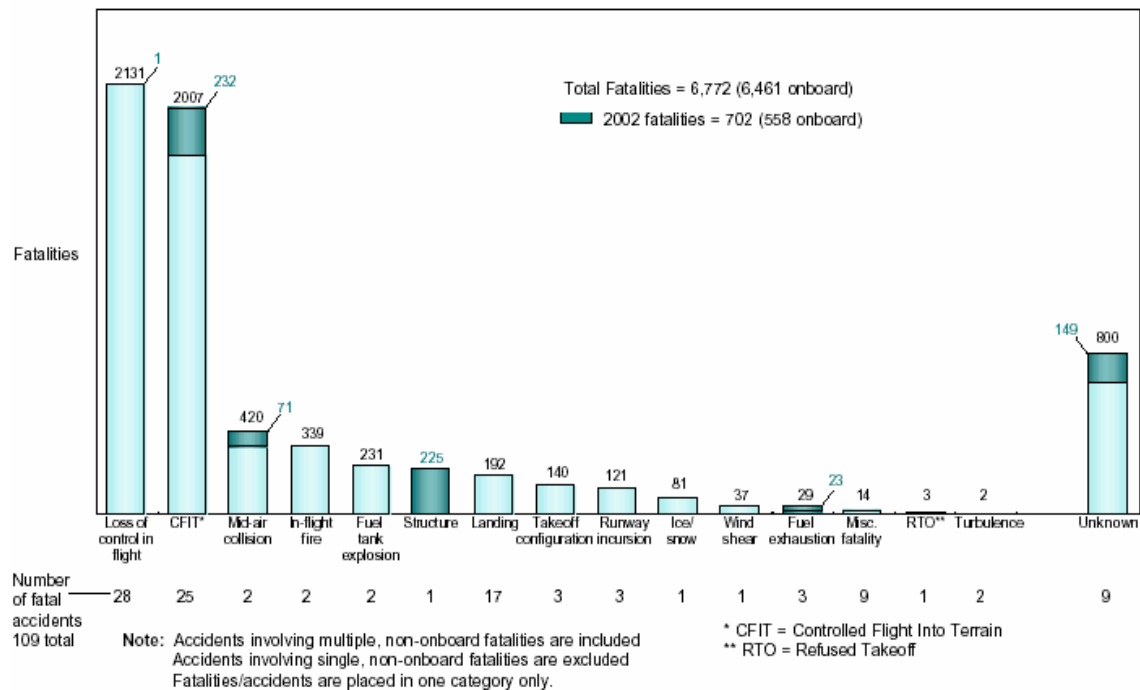
According to Boeing's *Statistical Summary of Aircraft Accidents, 1959-2002*, loss of aircraft control is the leading cause of fatal aircraft accidents, with 28 total accidents resulting in 2,131 fatalities during the above mentioned time period (Boeing, 2003).

As the jet age has progressed, jet transports have become increasingly more complex. Airplanes are flying farther, faster, and at a greater range than ever before. Aircraft designs are also becoming more inherently unstable as the design is aerodynamically optimized to achieve maximum performance. In addition, increased automation has multiplied the complexity of modern transport aircraft operation (Abbot et al., 1996). Overall, more demands are placed upon the airplane and the flight crew in order to complete the specified mission. Therefore, in order to deal with this trend towards more complexity and less inherent aerodynamic stability, flight controls have evolved from being solely mechanical into fully electronic "fly-by-wire" systems. Fly-by-wire (FBW) is defined for flight control systems where a computer processes the pilot's control movements and sends electric signals to the flight control surface actuators without any mechanical linkage (Stowe, 2000). As airplanes and flight controls increase in complexity, safety must be preserved through the proper design of the FBW system.



## Fatalities by Accident Category

Fatal Accidents - Worldwide Commercial Jet Fleet - 1993 Through 2002



*Figure 1 – Accident Summary 1959-2002*

### Statement of the Problem

The leading cause of fatal aircraft accidents overall since 1959 has been loss of control of the airplane. In an attempt to reduce pilot workload and enhance safety, today's complex jet transport aircraft, such as the Airbus A320/A330/A340 family and the Boeing 777, feature a fly-by-wire (FBW) flight control system (FCS). The purpose of the FCS is to operate the aircraft with maximum safety and efficiency. The question is- does FBW FCS actually enhance safety?

## Definition of Terms

*Aircraft–pilot coupling (APC)*—Inadvertent, unwanted flight path and attitude motions, usually oscillatory, caused by abnormal interactions between the aircraft FCS and the pilot. Also known as “PIO” for “pilot-induced oscillation,” with pilot-blaming implied. APC, or “pilot-involved oscillation,” implies the FCS may be at fault.

*Alpha feedback*—Feedback of angle-of-attack (denoted by the Greek letter  $\alpha$ , alpha). Because accurate alpha measurement at high angles of attack is difficult with airflow vane-type systems due to airframe buffeting and structural flexing, alpha values for feedback are often derived from inertial sensor data.

*Apparent neutral speed stability*—FBW feature such that the pilot doesn’t have to trim to maintain level flight during speed changes; e.g., autotrim.

*Augmentation*—Enhancing an aircraft’s natural aerodynamic response through the internal design characteristics of the flight control system. SAS, CAS, and FBW (see below) all provide augmentation.

*Augmented aircraft*—The combination of the aircraft’s natural aerodynamic response plus the additional dynamics and characteristics provided by the flight control system; augmentation systems turned on. Conversely, the “unaugmented aircraft” would have the augmentation systems turned off.

*Autotrim*—No pilot trim inputs required to maintain level flight when speed is changed. Autotrim can be a side-effect of a pitch rate command or g command FBW system, which is called “apparent neutral speed stability” (note: pitching moments due to the thrust changes that would effect the speed change are compensated for without the need for pilot trim inputs as well).

*Beta*—Sideslip angle,  $\beta$ , as measured with respect to the relative wind (often called the wind-axes, aerodynamic-axes, or stability-axes coordinate system). Sideslip angle is different from the yaw angle ( $\psi$ ), which is measured relative to the body axes coordinate system that is rigidly fixed in the airplane; the two are essentially numerically equivalent only at low angles of attack.

*Beta dot*—Rate of change of sideslip angle,  $\dot{\beta}$  with a dot over it (the dot means derivative or rate of change of the parameter). Beta dot and yaw rate are often used as feedback signals in the lateral–directional modes, depending on the application. For example, the B-777 yaw damper control law uses Beta dot feedback at low angles of attack and switches to yaw-rate feedback at high angles of attack.

*Block diagram*—A schematic diagram illustrating a basic control law, the signal flow, and associated sensors and feedbacks. As with electrical schematics, a block diagram may be represented by equations and analyzed mathematically for system stability characteristics.

*Body axes*—Set of three mutually perpendicular directions ( $x, y, z$ ), rigidly fixed to the body of an aircraft. Commonly, the axes originate at the cg and are defined as the longitudinal (roll) or  $x$  axis, measured positive forward and negative to rear; the lateral (UK= “transverse”) (pitch) or  $y$  axis, measured positive to the right and negative to the left; and the vertical (yaw) or  $z$  axis, measured positive downward and negative upward. The  $x$  axis may be parallel to the thrust line, the wing aerodynamic chord, or some other longitudinal reference line. The  $xz$  plane is the plane of symmetry for the aircraft.

*C\**—Pronounced “C Star,” a pitch-axis control law in which pitch-rate and load-factor (g) feedback are blended. Pitch rate dominates at low speed, load factor at higher speed. Used in the Airbus A320/330/340.

*C\*U*—Modified *C\** pitch-axis control law with forward velocity feedback included to give apparent speed stability. Used in the Boeing 777.

*CAS*—Control (or “command”) augmentation system; provides “power steering” and consistent aircraft response over a broad flight envelope. CAS functions originate in the forward path of the FCS block diagram. It essentially boosts the pilot’s initial control force and makes flying the airplane easier and more precise. Sensors in the CAS circuit provide feedback signals (typically load factor, pitch rate, or roll rate) to a computer, which compares the aircraft response to the pilot’s command signal to make the airplane respond as desired.

*Command path*—The portion of a control law, as shown on a block diagram, before summation with feedback. Here, the pilot’s command input may be shaped, filtered, or limited.

*Compensation*—FBW feature by which control laws automatically prevent unwanted flightpath excursions. Typically, compensation is provided to eliminate trim changes due to configuration changes (extending or retracting landing gear, flaps, and/or speed brake) or thrust changes, to automatically coordinate the rudder required during roll into a turn, to adjust pitch attitude to maintain level flight during a turn, and to provide gust alleviation. An example is the B-777 thrust asymmetry compensation system, which automatically adds rudder to minimize yaw due to engine failure.

*Direct mode*, aka direct link—A backup FBW mode in which analog electrical signals bypass the computers and go straight to the control actuators, producing deflection proportional to stick input. The ratio of control surface deflection to stick deflection/force is often fixed, called fixed gains, as a function of configuration, with more deflection provided with flaps down, for instance. Alternatively, gains may be optimized only for landing.

*Envelope protection*—FBW feature by which flight envelope limits are implemented through the flight control system's control laws. Protections provided might include g limiting (2.5 gs on A320), angle-of-attack limiting, overspeed protection, low-speed limiting, or bank-angle limiting.

*Feedback*—Motion output parameter such as pitch rate, angle of attack, or g that is measured, amplified (or attenuated), and then summed with the original input command. Named for the given parameter; for example, “pitch-rate feedback.”

*Feedback control system*—Flight control system circuit in which performance in maintaining a desired output parameter is substantially improved by feeding back the output for comparison with the input. If the output differs from the desired value, corrective signals are automatically sent to the flight control surface actuators without any pilot action required. Feedback circuits may consist of one or more “loops.”

*Feedback loop*—The portion of a block diagram that shows the path of the feedback signals that forms a “loop,” usually depicted as the lower part of a block diagram.

*Filter*- Modifies a feedback signal according to the frequency content of the parameter of interest to eliminate unwanted feedback effects. A “noise filter” can block nuisance variations in the feedback parameter; for example, pitch rate due to atmospheric

turbulence. A “notch filter” can block feedback of structural bending effects occurring at some specific frequency.

*Fly-by-wire (FBW)*—Flight control system in which a computer processes the pilot’s commands and sends them to the flight control surface actuators by electrical signals rather than mechanical linkage; backup modes may bypass the computer. FBW also includes “fly-by-light,” in which the same effects are accomplished through fiber-optic cables. “power-by-wire,” means the actuators themselves are electric.

*Forward path*—In a block diagram, the path for pilot inputs and their modification upstream of the flight control actuator.

*G command*—Pitch-axis control law by which the pilot gets the same “g” for a particular amount of stick force, regardless of speed (energy permitting).

*Gain*—Ratio of output to input, or amplification (or attenuation), of a feedback control system element. Pilot gain is often used to describe the magnitude and rapidity (frequency) of pilot control inputs. An urgent or high-effort task, such as flaring and touching down in a gusty crosswind, is often called a high-gain task.

*Gain margin*—Amount of additional gain that could be applied to a control law before the system becomes unstable, in the same manner as “static margin” affects static pitch stability. Note: FBW flight control laws are not stable for all values of gain that could be applied.

*Hard limits*—FBW envelope protection scheme by which the pilot cannot override the control law limits (in normal mode). Airbus designs use hard limits.

*Inertial Axes*—A set of axes used for analysis of inertial effects (that is, the effects of weight distribution) on an aircraft’s flightpath during maneuvering flight. In sustained

maneuvers, the aircraft would actually rotate about the inertial axes. The longitudinal inertial axis need not be the same as the body x axis or wind x axis; however, the y and z axes usually coincide for a symmetrically loaded aircraft.

*Integrator*—Circuit in an FBW flight control system that reduces response errors over time. It “remembers” the pilot’s command and continues to move the control surfaces until the desired response is achieved and no further “error signal” is present.

Represented by a “1/s” term in a block diagram. Important: integrator circuits often know only the pilot’s maneuver request and may have no clue as to what the aircraft’s physical capability to respond might be. Additionally, integrators remember the pilot’s request as of some time ago, which may differ significantly from the pilot’s instantaneous request during rapid control inputs. This may cause system lag and instability.

*Lag*—Delay between pilot inputs and the aircraft’s response. The severity of the lag is described by a parameter called phase lag or phase angle specified in angular degrees. Exactly opposite input and output would be a 180-degree phase lag/angle. Phase margin describes the additional amount of phase lag, measured in degrees, the system can have before it becomes unstable.

*Load factor (also g,  $N_z$ , or vertical-load factor)*—Ratio of lift generated to aircraft weight, which pilots call “gs.” Accelerometers that measure g for FBW feedback functions are not usually located at the cg, since it moves fore and aft during flight, but rather are located near the pilot’s station; g accelerometers located aft of the cg can induce feedback control system problems.

*Maneuver demand*—Because the pilot’s control input “demands” a certain maneuver response in a FBW flight control system, it is often referred to as a “maneuver demand” system.

*Multimode FCS*—FBW flight control system in which the effective dynamics change for different flight phases or tasks. The aircraft response is optimized, or “tailored,” for various events, such as in an approach mode or flare mode, for example. Each mode has a different control law; mode changes may be enabled through gear/flap/throttle position.

*Normal mode*—Normal control laws are in effect, all SAS and CAS functions working normally. Loss of certain sensors or components may cause automatic reversion to some degraded mode and control laws.

*Pitch attitude*—Pitch angle, represented in block diagrams by the Greek letter theta,  $q$ . Note: “Nose up” is usually positive, but the sign convention for corresponding elevator deflection varies. For instance, in NASA sign convention, a negative elevator deflection is trailing-edge-up, which produces a positive pitch motion.

*Pitch rate*—Rate of change of pitch attitude measured relative to the body “y” axis, represented in block diagrams by the letter “q.”

*Pitch-rate command*—Pitch-axis control law in which the pilot gets the same pitch rate for a particular amount of stick force (or deflection in some designs), regardless of speed.

*Proportional plus integral (PPI)*—Popular FBW arrangement that includes a “proportional” path to produce immediate control surface response to stick input while an “integrator” continues control surface commands until the feedback signal equals the pilot’s command signal, yielding precision over time. Used in the B-777 and A320 pitch-axis control laws.



*Rate limiting*—A phenomenon in FBW FCSs that causes handling difficulties ranging from unintended flightpath changes to loss of control. A flight control surface can be moved at some maximum rate, depending on the actuator's capability to reposition the surface (hardware limit) or on some lower rate limit imposed by the FBW flight control system (software limit). When the FCS commands exceed this limit, surface movement can significantly lag the pilot's inputs and go "stop-to-stop" trying to catch up with pilot commands. A data recorder time history would show the control surfaces moving back and forth in very unpilot-like straight lines, in a "sawtooth" fashion.

*Redundancy management*—Describes the level of backup capability. Quadraplex means four of all essential components and computers—common on military aircraft (because of battle damage potential). A "fail-operate" system can be produced with a triplex system (as on B-777 and A320/330/340). Duplex FBW provides a low level of redundancy and should probably require a full mechanical backup.

*Roll rate*—Rate of change of bank angle measured about the body "x" axis, represented by the letter "p." Usually, right roll and right stick are positive. Note: roll rate about the velocity vector (stability axis) may also be used.

*Soft limits*—FBW envelope protection scheme in which the pilot can override the control law limits. The Boeing 777 design philosophy uses soft limits.

*Stability augmentation system (SAS)*—Feedback control system that provides pitch, roll, or yaw damping; sometimes called a "damper." Older aircraft with an SAS use an electrical, single-loop feedback signal in parallel (stick moves) or series (stick doesn't move) with the mechanical flight control system.

*Summer*—In a block diagram, indicates the algebraic summation of the input quantities according to the arrows and the signs; represented by a circle or by a circle and an x.

*Time delay*—Delay from pilot input to FBW aircraft response. Caused by many factors including the effect of filters, computer processing time, task time-sharing by computers and signal processors, “higher order” effects of the feedback control system, digital sampling effects, and/or actuator rate limiting. Time delays of more than 0.25 second can cause enough lag to make the FBW aircraft unstable during certain tasks, especially in “high gain” situations.

*Yaw damper*—SAS system that damps unwanted yawing motions. A “body axis yaw damper” might use feedback from a yaw rate gyro or accelerometer and can be effective in eliminating “Dutch roll” tendency. However, these might be detrimental when roll about the velocity vector is desired (requires a “conical” motion with body axis roll and yaw rates) because it would oppose body axis yaw rate. Hence, Beta dot feedback might be used to provide damping about the velocity vector.

*Yaw rate*—Rate of change of yaw angle as measured about the airplane’s “z” body axis, denoted by “y.”

### Limitations and Assumptions

This study and analysis of aircraft accidents, flight control systems, and conclusions drawn therein are the views of the author only and do not reflect those of Embry-Riddle University, The Boeing Company, Airbus, or any other corporate or government entity. The author publicly acknowledges that he is an employee of The Boeing Company; however, this paper is strictly the authors' views and may not necessarily agree with those of Boeing.

## CHAPTER II

### REVIEW OF RELEVANT LITERATURE AND RESEARCH

#### Literature Review-Background

There are a variety of causes and contributing factors in a loss of control accident. The operational question is--“Did the aircraft’s flight control system play a role in the accident sequence at all?”. Secondly, “Would a fly by wire flight control system with envelope protection have helped the situation at all?”. Or, “If the aircraft was already equipped with a FBW FCS, did it contribute to the event, or did it save the day?”. Some of the most infamous crashes in recent history involving loss of control in flight include the following, in no particular order:

- 1) Air France Airbus A320, Habsheim, France, June 1988
- 2) USAir Boeing 737-300, Pittsburgh, PA, USA, September 1994
- 3) United Air Lines DC-10, Sioux City, Iowa, USA, July, 1989
- 4) ARIA Airbus A310, Russia, March 1994
- 5) China Airlines Airbus A300B4, Nagoya, Japan, April 1994
- 6) Egypt Air Boeing 767-300, Atlantic Ocean (60 mi. S of Nantucket), MA, USA, October 1999. (Job, 1998; NTSB, 2004)

#### Accident Reviews

These accidents were selected for study by the author because they represented a unique loss of control situation in which FBW FCS either exacerbated the situation or conversely, may have helped; or, they seemed indicative of a potential trend towards loss of control events in a certain aircraft type.

LOC accidents where a FBC FCS system with envelope protection may have helped include USAir Flight 427 Boeing 737-300 (along with an accident with a postulated similar probable cause, United Flight 585, Boeing 737-200, March 1991). (NTSB, 2004); and EgyptAir Boeing 767-300 (another accident with a similar probable cause- SilkAir Boeing 737-400, Palembang, Indonesia, December 1997) (NTSB, 2004) (FSF, 2001). In the USAir 427 737 accident, the probable cause as indicated by the NTSB is as follows:

The airplane crashed while maneuvering to land at Pittsburgh International Airport. The airplane entered an uncontrolled descent and impacted terrain about 6 miles east of the airport. The airplane struck the ground at an angle of descent of about 80 degrees, in a slight roll to the left, and the airspeed was about 260 knots at impact. The investigation revealed that during the accident sequence, the airplane rudder deflected rapidly to the left and reached its left aerodynamic blowdown limit shortly thereafter. Examination of the rudder system revealed that it is possible, in the main rudder power control unit (PCU) of the airplane (as a result of some combination of tight clearances within the servo valve, thermal effects, particulate matter in the hydraulic fluid, or other unknown factors), the servo valve secondary slide could jam to the servo valve housing at a position offset from its neutral position without leaving any obvious physical evidence and that, combined with rudder pedal input, could have caused the rudder to move opposite to the direction commanded by a rudder pedal input. This condition of the PCU was also consistent with analysis of the cockpit voice recorder, computer

simulation, and human performance data, including operational factors. (NTSB, p. 1,1999)

Other potential contributory factors were the penetration of a wake vortex left by a Boeing 727 approximately 4 nautical miles ahead of the 737, which may have contributed to the original upset, or exacerbated it (Job, 1998). For the time being, we shall set aside the NTSB findings with regards to the rudder PCU, seeing as they were dealing with no physical evidence and a series of hypotheses that may or may not be plausible. Instead, for our purposes, we will look at what followed immediately after the initial upset. The aircraft had enough altitude and control authority to recover from the initial upset- why did it not? The digital flight data recorder (DFDR) analysis showed that the 737 encountered the unexpected wake turbulence from the 727, then had a full deflection of left rudder, then full nose up control column that held the aircraft in a stalled condition all the way until impact (Job, 1998). Perhaps, a FBW FCS, if attuned properly, would not have allowed full deflection of the rudder to the blowdown limit, thereby limiting the amount of action (or reaction) of/to the initial upset. Also, a FBW FCS with proper stall protection or an alpha floor limiter would not have allowed the full aft deflection of the elevator, thereby allowing the wings to stay unstalled and aerodynamically unloaded, therefore perhaps allowing better roll control and a slower descent rate. Since the 737 was built well before FBW FCS were available, the author understands that this is nothing more than mere speculation- however, it is mentioned to stimulate thinking of using FBW FCS as a possible method for use in upset recovery. The Flight Safety Foundation also showed that through usage of differential thrust, unloading

the aircraft (pushover in the pitch axis so as not to stall), and full roll (column wheel) against the yaw upset made this a recoverable event (FSF, 2003).

As another possible addition to a FBW FCS system in the form of a “smart” autothrottle, the use of differential thrust in upset recovery or in maintaining controlled flight after the loss of all primary flight controls (United 232, DC-10, Sioux City, Iowa) has been the topic of studies by industry and government after that accident. To paraphrase the official NTSB findings of probable cause:

United Airline(s) Flt 232 was cruising at FL 370 [37,000 feet], when there was a catastrophic failure of the # 2 (tail mounted) eng[ine]. This was due to sep[eratio]n, fragmentation & forceful discharge of the stage 1 fan rotor assembly parts f[ro]m the #2 eng[ine] (uncontained failure), which led to loss of the 3 hyd[raulic] systems that powered the flt ctls [flight controls]. The flight crew experienced severe difficulties ctlg [controlling] the acft [aircraft], which subsequently crashed drg [during} an emerg lndg [emergency landing] at Sioux City. (NTSB, 1992, p. 1). (Note- the brackets [ ] around the previous words are simply expanding the jargon and abbreviations of the report into normal words).

After the UAL 232 accident, and also after taking into account other accidents (JAL 747, other DC-10 events involving loss of hydraulics) where the use of differential thrust would have enabled continued safe flight and landing, NASA performed a series of tests on a McDonnell Douglas/Boeing F-15 fighter and a MD-11 test aircraft of a Propulsion Controlled Aircraft (PCA) flight control system. The PCA FCS was developed by reprogramming the existing Flight Control Computers (FCCs), and engaged by the use of a separate switch to activate the PCA mode. These flight tests were

augmented with 747 and C-17 simulator studies. Together, these tests showed that an aircraft which has lost its primary control system by losing hydraulic control, is still capable of continued safe flight and landing through the proper application of differential thrust (Burcham et al., 1997).

On the other hand, there have been at least two commercial transport aircraft accidents that were not accidents, but in all probability, suicide. The two that interest us here are EgyptAir Flight 990, a Boeing 767, and SilkAir Boeing 737-400. Both were apparent suicides. Were they preventable with a FBW FCS with active envelope protection? (NTSB, 2004).

In both cases, commanded control inputs were used by the responsible crew in order to deliberately crash the airplane. EgyptAir Flight 990, for example, was placed into a dive from level flight at cruising altitude. The relief first officer placed the aircraft into a dive after the captain had gone to the lavatory. Even though the captain managed to make it back to the cockpit and fought the control inputs by the relief first officer, the energy state that the airplane was placed in was too much for a control input force fight to overcome. The captain's elevators were commanding nose up, and the relief first officer's elevators were commanded nose down. To seal the fate of the aircraft, during the dive, the engines were then shut down by fuel cutoff, presumably by the relief first officer. The Silk Air 737 crash was a similar event, as the airplane was intentionally dived into the ground from cruise altitude (NTSB, 2004).

Can a FBW FCS be designed with the proper level of envelope protection that would prevent such occurrences as EgyptAir and Silk Air, yet still give the pilot authority to perform an extreme maneuver such as applying full power and simultaneously



applying full aft control column or stick in order to avoid flying into terrain (the CFIT escape maneuver- described in more detail later) if required? Unfortunately, if someone is deliberately going to crash an airplane, it is probably going to be difficult to stop them.

The most critical aspect of designing the FBW FCS is designing the flight crew interface so that it is easily understood and interpreted by the crew. Two accidents prove this point convincingly--Aeroflot Airbus A310 in March of 1994, and that of an Air China Airbus A300B4-600 in April 1994.

The Aeroflot flight was something of an anomaly in that the captain permitted his children into the cockpit and allowed them to sit at his crew position and manipulate the flight controls. However, they did not attempt any radical maneuvers that would have caused the accident. The pilot's son commanded a 3-4 degree left turn on the yoke itself while the autopilot was still engaged. The captain selected a new heading via the autopilot that agreed with the commanded (by yoke) heading, then reselected the old intended heading and engaged the NAV mode. The son's overriding of the autopilot had the unintended (and unannounced to the flight crew) effect of causing the autopilot servo to disconnect from the aircraft control linkage. The important thing to note here is that there was no aural or visual warning to the flight crew to tell them that an autopilot servo had just been disconnected from the airplane's control linkage. Moreover, the autopilot continued to show that it was in its previously programmed mode, even though it no longer controlled roll. This led to a series of errors by both the captain and his son, who was unintentionally fighting the first officer for control of the aircraft by negating his inputs. The first officer was attempting to stop the increasing roll to the right that was being commanded by the son, and then, the son held firm to the control column. By the

time the captain and the first officer had figured out what was going on, the airplane had rolled and pitched its way into a series of stalls, and the autopilot was finally disengaged by the crew in an effort to regain control, the alpha floor protection feature kicked in. This only served to confuse matters further, and the end result of all of these wild crew and airplane gyrations was that the airplane crashed while in a spin. A perfectly good airplane had been mismanaged right into the ground. There are several causal factors at work here, including poor judgment and mass confusion amongst the flight crew and the captain's son, who initiated the event from left seat, and stayed there until finally removed by the captain just a few moments prior to impact. The captain tried some last minute attempts to save the airplane by "pumping" the controls and altering power settings, but seeing as it was night, and the airplane was in a violent upset condition, combined with lack of situational awareness- it was too little, too late. However, to us, the most serious of the many problems is when the aircraft performs a flight critical function change of state (partial disconnect of an autopilot function, engaging an alpha floor protection mode) without notifying the flight crew. In this case, it turned out to be a three way fight for control of the airplane at the most critical phase of this event- as it was initially evolving--the captain's son, the first officer, and the autopilot. Even after the autopilot was disengaged by the first officer, the alpha floor protection automatically pitching the nose down while steeply banked could not have helped this evolution much- in fact, it may have hurt (Job, 1998).

The Air China A300B4-600 accident on April 26, 1994, bears a few striking similarities to the above Aeroflot accident. The first officer inadvertently engaged a flight critical mode in the autopilot while the aircraft was on final approach to Nagoya, Japan,

leading to a series of pitch excursions that ended up in tragedy. The A300 was on final approach, during night VFR conditions. The approach seemed largely stabilized at three nautical miles (NM) from the runway, with landing gear and flaps down and properly configured for landing. It briefly leveled off, then began its descent on glide path again. However, this time the airspeed was decreasing and the nose was pitching up. This trend continued until about one NM from the runway, when the engines spooled up to high power, then back to low power again. A few seconds after that, the engines came up to high power again, pitched up, and the crew told ATC that they were going around. The pitchup continued to approximately 1500 feet AGL, then, the aircraft stalled. The stall seemed to break, the nose came down, and airspeed picked up. Then, the nose began another pitchup, but still with a high rate of descent. The aircraft struck the ground in a slightly nose-up and almost wings level attitude about 30 seconds after the crew's go-around radio transmission to ATC, with the landing gear still down.

The A300 Automatic Flight Control System has several modes of operation, and also incorporates an "alpha floor" protection as well. Evidently, the approach was proceeding normally, until the first officer inadvertently pushed the "Go Around" button on the thrust lever. The Go Around lever is actuated by moving it backwards- a counterintuitive method that could lead to entering the Go Around mode when actually commanding the thrust levers to retard thrust. When the Go Around lever is engaged, this immediately puts the AFCS in "Go Around" mode, in which the autopilot does NOT disconnect with manual control column forces applied by the flight crew. When the first officer triggered the "Go Around" mode, both engines immediately powered up for go-around thrust. This prompted the Flight Mode Annunciator to change to "Go Around",

and the captain immediately told the first officer to “Disengage it”. The short version of what ensued after that was a series of changing autopilot modes by the flight crew (while still remaining in Go Around mode, however- which does not disconnect with manual crew column inputs), coupled with thrust changes commanded and uncommanded by the crew, and an out of trim situation that rapidly became divergent as the crew combined manual column force inputs while the autopilot was still in Go Around mode. The crew had activated the “Command” mode to the autopilot, thinking that this would give them full control of the aircraft in an autoflight mode. This was not the case, however- the autopilot must be fully disconnected to “reset” it. Finally, as the crew was going through these control issues between the autopilot and their manual inputs, and with the out of trim between the horizontal stabilizer and the elevator situation at its worst, the alpha floor protection feature engaged when it sensed that the aircraft angle of attack was exceeding the prescribed limits for the flaps/slats configuration that the airplane was in. This automatically commanded the thrust to high power, giving the aircraft a large pitchup force. The captain finally called for a go around, and the flap lever was moved to the 0/0 position (fully retracted), then replaced to the proper setting of flaps 15. The flaps retraction would have only added to the nose pitch up moment. Couple these with the ongoing “fight” between the captain and the autopilot, which was still in “Go-Around” mode, inhibiting the crews attempts to retard thrust in an effort to bring the nose down, along with attempts to pitch the nose down with manual column force, which split the stabilizer and elevator because of discrepant autopilot and crew pitch commands, and the recipe for disaster was set (Job, 1998).

The primary interest is inherently in the pilot-airplane interface. If the aircraft goes out of control due to poor airmanship or even in an apparent successful suicide attempt, that is a matter beyond the scope of this research. The current research is focused on determining if the aircraft itself played a contributory role to the accident, or, could the accident have been alleviated by the addition of additional automation in the flight control system?

Wiener and Curry foreshadowed the issues regarding fly-by-wire flight control systems that would ensue with their seminal paper on flight deck automation (Wiener & Curry, 1980). Even though this paper dealt mainly with electronic Flight Management Systems (FMS) and associated automation, it also touched on the issue of who is in control of the airplane and at what time. This, in turn, prompted more research into flight deck automation and FBW FCS (e.g., Wiener et al.,) and an in depth review of the situation, including recommendations, by the FAA (Abott et al., 1996) In addition, several researchers have proposed sets of human centered guidelines and principles for the design of highly automated crewed systems (Rudisill, 2000). Subsequently, the controversy translating from the general topic of flight deck automation to the specific one of envelope protection in a transport aircraft equipped with a fly-by-wire flight control system gathered momentum after the 1988 Airbus A320 crash at Habsheim airport near Mulhouse, France. This accident occurred during a planned low altitude, low airspeed, high angle of attack flyby at an air show that was celebrating the introduction of the A320 into service with Air France. In this accident, the flight data recorder indicated that the airplane descended to 10 meters above the ground, at 118kts, with the engines at 29 percent N1, slats 22 degrees, flaps 20 degrees, landing gear down, and the flight

management system was in manual flight path and thrust control. The pilot applied go-around power, but the aircraft contacted the trees 5 seconds later. There was no indication of engine or flight control malfunction. The A320 is designed with hard flight envelope protection features that do not permit the pilot to exceed design limits or stall the aircraft. The 'alpha floor' envelope protection may have given the pilots false confidence that the aircraft would protect them from making mistakes. This protection, however, had the opposite effect and prevented the A320 from reaching maximum angle of attack which



may have been enough to keep the aircraft out of the trees as the engines spooled up.

Figure 2(a)– Airbus A319/A320/A321 family



Figure 2(b)- Boeing 777

After the A320 accident, the topic of cockpit automation and FBW FCS then broke out of the aerospace community and into the scientific community with (direct quote) Waldrip's article in Science in 1989: "We started out with cockpit automation backwards," says Northwest Airlines 747 pilot Kenneth Waldrip. In the 1970s and early 1980s, he says:

The idea was that the computers would fly the plane and the pilot would monitor them in case anything went wrong...." There was only one problem with that scenario, Waldrip says: humans are absolutely terrible at passive monitoring.... People get bored. Their attention flags. They start missing things. Worse, a passive pilot would often have to tackle an emergency cold.... (Waldrip, 1989, p. 36)

By the mid-1980s, aircraft designers, pilot trainers, and the aviation community generally had gone through a 180-degree turn in their concept of what automation should do. The new philosophy, which often goes under the name of "human-centered" automation, was illustrated in 1980 in a seminal paper by human factors researchers Earl Wiener (University of Miami) and Renwick Curry (NASA Ames Research Center). They used the image of an "Electric Cocoon" [similar to the Flight Envelope Protection System of today's A320].

### Statement of the Hypothesis

Transport category loss of control (LOC) accidents can be avoided with the proper use of fly by wire technology that contains a certain level of flight control envelope protection. However, it is imperative that the automation and its use be intuitive. Also, the flight crew must thoroughly understand the flight control system, exercise good airmanship procedures, and realize how the aircraft-pilot interface affects the dynamics of the potential LOC situation.



## CHAPTER III

### RESEARCH METHODOLOGY

The Research Design, Research Model, Data Gathering Device, Pilot Study, Instrument Pretest, Distribution Method, Instrument Reliability, and Instrument Validity sections do not apply to this GRP, since the primary source of quantitative data is aircraft statistical accident data that is available in the public domain. The author believes that any attempt to sample flight crew responses to flight control systems by setting up a double blind or similar study would be beyond the scope and budget of this project. Therefore, the emphasis of this paper is on readily available accident data that has been collected by worldwide authorities on the topic (e.g., NTSB, Boeing, Airbus, and other industry sources).

#### Survey Population

The survey population was comprised of two parts: (a) A selection of representative accidents over the past 20 years that represent the involvement of FBW FCS systems, or lack thereof, and (b) The entire airliner fleet from 1959-2003, to provide a method of normalizing the accident rate data by model, so that certain conclusions can be drawn.

#### Sources of Data

The author utilized the Boeing Statistical Accident Summary 1959-2003, the NTSB accident databases, the FAA accident databases, books and periodicals that deal with aviation safety and FBW FCS, and relevant Internet web sites that contain accident data that can be cross-referenced for accuracy. For FBW FCS systems, the author relied

upon engineering textbooks and appropriate publications for an in depth explanation on how FBW FCS work.

#### Treatment of Data and Procedures

The previously mentioned accident databases were searched for relevant accidents that involved loss of control as a causal factor. The author then tried to objectively apply those accident numbers against the causal factors, so that a reasonable conclusion could be drawn about causes of loss of control accidents. Then, papers and other works by acknowledged experts in the field were researched to see if a link could be established between FBW FCS complexity and accident rates in loss of control accidents.

## CHAPTER IV

### RESULTS

Table 1 depicts the absolute number of transport category aircraft accidents from 1985 to 2003, where loss of control was the cause of the accident. Looking at the raw data can be misleading, though. The aircraft type with the highest absolute number of LOC accidents (16) is the Boeing 737, according to these numbers, with the McDonnell Douglas DC-9 running a close second with 14 LOC accidents.

Table 1

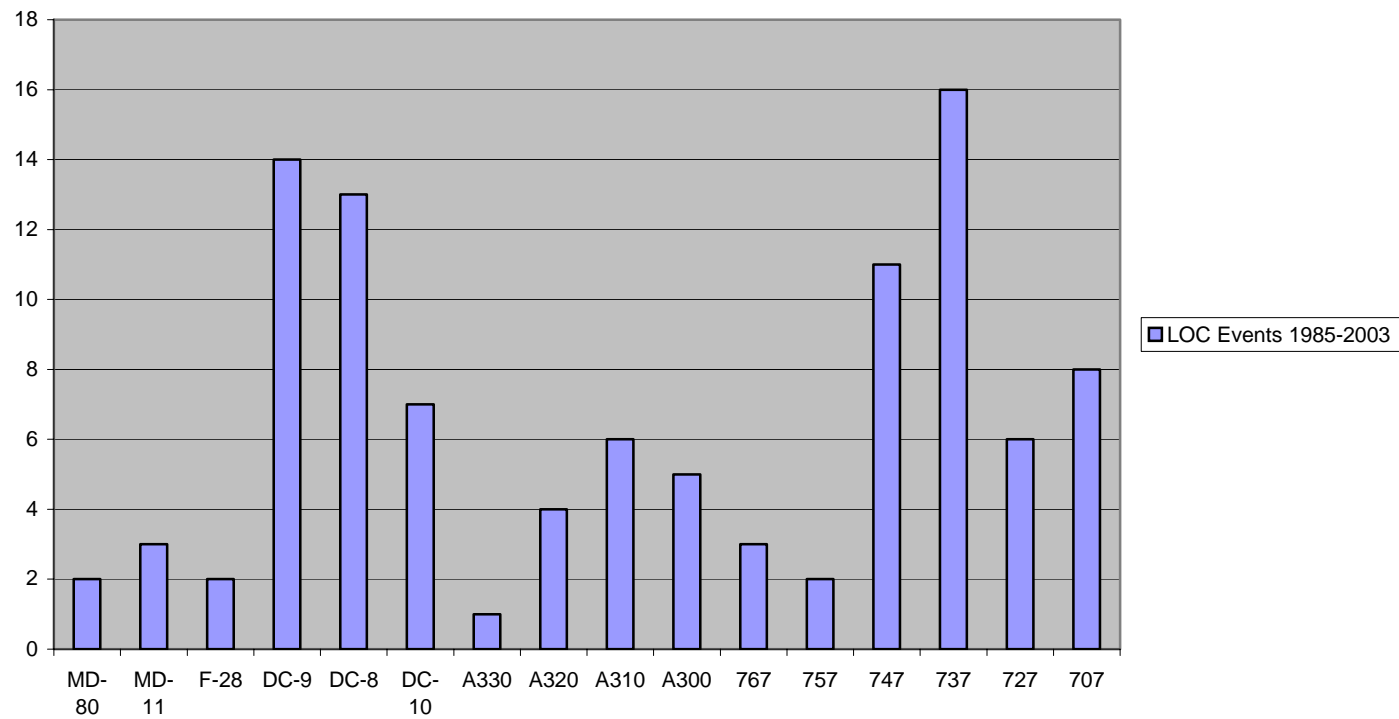
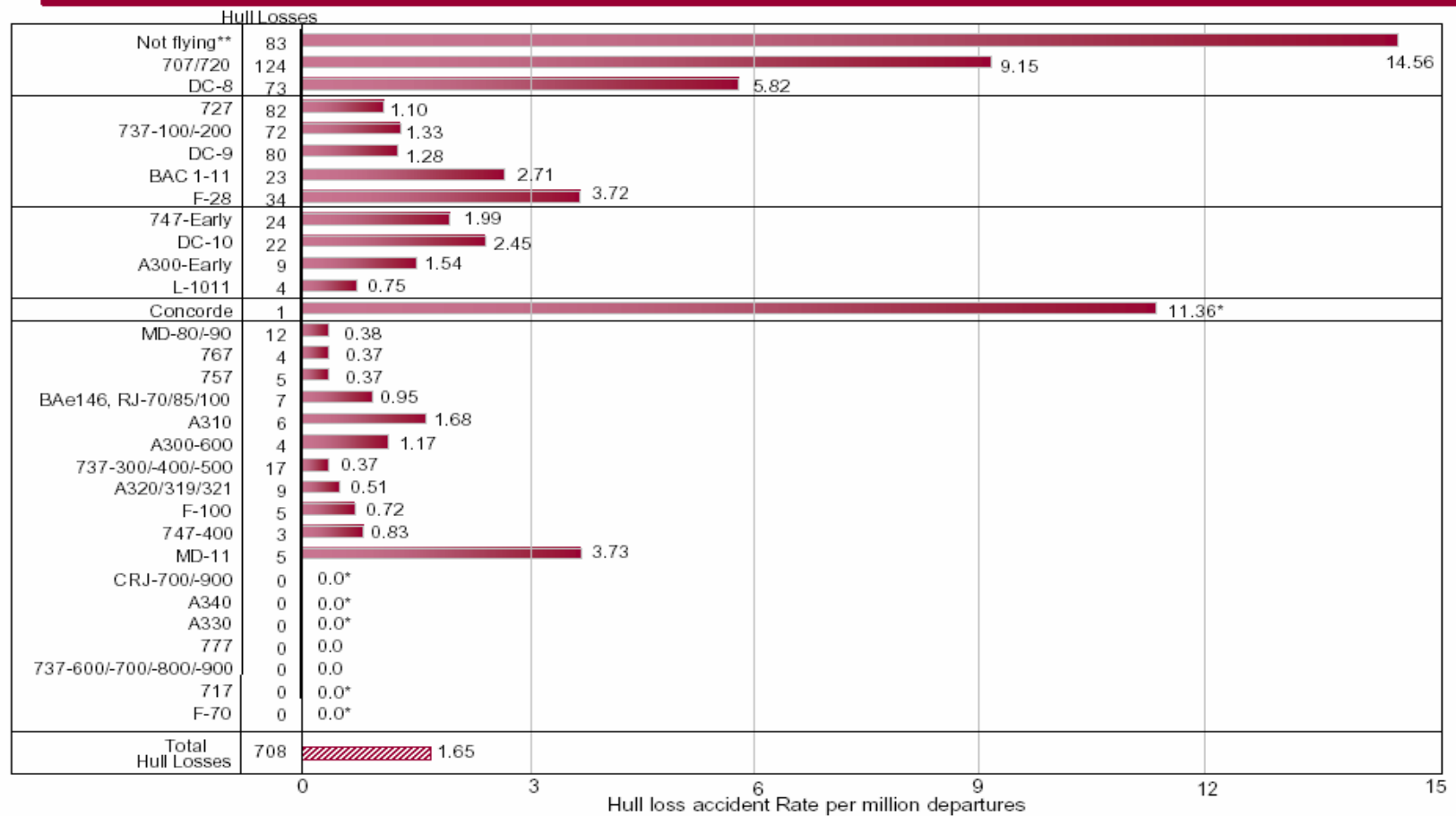
Loss Of Control Accidents By Aircraft Type 1985-2003

Table 2

Hull Loss Accident Rate Per Million Departures**Accident Rates by Airplane Type****Hull Loss Accidents - Worldwide Commercial Jet Fleet - 1959 through 2003**

However, raw numbers as seen in Table 1 above can be misleading. To get a truer representation of the LOC data, we must normalize it by taking into account fleet size and flight hours in addition to absolute number of accidents. For example, there have been over 5,200 737s of all 737 models (737-100/-200/-300/-400/-500/-600/-700/-800/-900 Boeing Business Jet (BBJ) ordered to date (2004) (Boeing). The 737 has been in service since 1967, and the fleet of this type flies hundreds of thousands of flight hours per year. The same line of reasoning may be applied to each aircraft type in the evaluation of the LOC data- the number of LOC events must be normalized by taking the number of accidents involving the aircraft type and dividing by fleet size times hours flown per year in order to get an accurate accident rate.

Table 2 provides accident rates for transport category aircraft from 1959-2003, per million departures (Boeing, 2004). Assuming a constant rate of LOC accidents per aircraft type (obviously a broad assumption) in order to break down the data further would be very difficult in this study due to unavailability of pre-1992 accident reports from the NTSB, and from many foreign countries. It would seem that flight control envelope protection did not help the first aircraft to have that feature, such as the Airbus A300-600, A310 and A320, with a respective accident rate of 1.17, 1.68 and .51 per million flight hours. The Boeing 757 and 767, with no active electronic flight control envelope protection, of .37 per million flight hours each. The 737, which is comparable to the A320 family, and also has no active electronic flight control envelope protection like the 757/767, shows a rate for the latest of the type (737NG, -600 through -900) of zero. The 737 “Classics” (-100 through -500) has an accident rate of 1.33 (-100, -200) and .37 (-300, -400, -500) per million flight hours. In contrast, the latest aircraft with active

electronic flight control envelope protection (Airbus A330/ A340, Boeing 777) all have an accident rate of 0.0 per thousands so far (none of them has yet achieved a million flying hours yet, due to fairly recent introduction (<20 years) into service). (Note: The A330 has had one accident classified as LOC, but since this was during a flight test by Airbus, it was excluded by Boeing's accident summary, which excludes flight testing, military action, etc.). A review of the FBW FCS technology will provide a possible explanation for this.

## CHAPTER V

### DISCUSSION

The common theme with the Aeroflot and the Air China accidents would appear to be AFCS and autopilot modes that might seem to be counterintuitive. Perhaps one could even characterize these modes as being “stealthy”, since it is not intuitively obvious to the flight crew what the airplane will do in a particular mode. Of course, the proper crew training and understanding of how the aircraft functions is imperative, and both crew appear to have fallen short in complete awareness of what their aircraft was capable of doing in whatever mode it was in. For example, the majority of the Air China captains’ recent flight experience was in the Boeing 747-200 and 747-400. In these aircraft, the pilot can override the autopilot manually with column commands, and the autopilot will adjust itself accordingly. However, with the Air China and Aeroflot accidents, it would seem that the human-airplane interface via the flight control system and autopilot was not intuitively obvious, as evidence by both crews exclamations of surprise and dismay directed towards the aircraft as they struggled to figure out what was going on. This is not a new phenomenon- when the Ground Proximity Warning System was mandated for use on all commercial transport category aircraft, there were a lot of false alarms. As more service history was accumulated, the GPWS systems gained reliability. However, many flight crews were still suspicious of it- to the point of one captain yelling at the GPWS to “shut up!” while it was telling him to “pull up, pull up” immediately prior to striking the ground in a “classic” controlled flight into terrain (CFIT) accident (Aviation Safety, 2004).



FBW technology can make an aerodynamically unstable aircraft stable, however, it can also destabilize an otherwise stable airframe. FBW flight control laws may not be stable for all values of gain or phase angle in the system. Playing an equal part alongside static margin as stability factors are "gain margin" and "phase margin"-a metric of how much additional gain or phase-angle lag are available until the system becomes unstable. These margins are set by the manufacturer. Highly augmented FBW aircraft, in which fly-by-wire transforms the basic aircraft aerodynamics, can exhibit handling qualities with little margin for error. One reason for this characteristic is that fly-by-wire systems are susceptible to time delay, due to any number of causes, which can seriously degrade the pilot's ability to control the aircraft. Another factor seen in a number of FBW aircraft accidents involving loss of control is actuator rate limiting, which occurs when the control actuator is commanded to move faster than it is physically capable of moving. Large or rapid control inputs, causing the actuator to lag or not respond to commands, can induce rate limiting in FBW airplanes. Rate limiting can also occur when multiple functions are trying to control the same surface; for example, during rapid pilot pitch commands while the pitch damping function is working hard during turbulence.

Some FBW designs may have a software rate limit placed on the pilot's inputs in the command path. In this case, commands faster than the software limit cause a delay between control movement and resulting aircraft response (Knotts et al., 1993).

With some FBW systems, pilots can move control surfaces opposite to their direction of motion due to a lack of control surface cueing. Furthermore, time delay and rate limiting can occur with all equipment components operating normally. There is no FCS failure required to obtain these undesirable effects. Added up improperly, these

factors can lead to an inadvertent or unwanted flight path motion, otherwise known as aircraft-pilot coupling (APC) (McRuer, 2003).

Two differing approaches have become the industry norm for the design of FBW systems. One design philosophy is that of “hard” limits of flight envelope protection, and is used by Airbus in their A320/A330/A340/A380 series of aircraft. Hard limits envelope protection, simply stated, puts the flight control computers (FCC) in charge of the airplane. The pilot is merely one input into the overall system, and can be out-voted by other considerations that the FCCs find to be more important at the time of the input. The other design philosophy, of “soft” limits of envelope protection, is employed by Boeing on the 777 series. With soft limits of envelope protection, the pilot has the final authority with the airplane. The FCCs may resist pilot input that the computers don’t “like”, however, it will tell the pilot so, via control feedback and other methods, while allowing the pilot to exceed the FCCs commands. The strongest argument for manual over-ride is that all possible contingencies can never be totally predicted (Rogers, 1999).

This difference in FBW systems has even driven a major difference in design of the flight deck. Figures 2 & 3 below show that the Airbus flight deck features an all-new sidestick controller as the primary flight control input, whereas Boeing has retained the control column and yoke arrangement.



*Figure 3 – Boeing 777 flight deck*



*Figure 4 – Airbus Flight Deck*

Figure 5 below shows a simplified schematic of one way how the pilot/computer FBW flight control system interface works. In an FBW schematic diagram of this process, called a block diagram, the upper line is called the forward path while the lower loop is called the feedback loop or path. Gain is the amplification (or attenuation) that is applied to the signal to adjust the aircraft response as desired. A filter may be used to block feedback of signals or motion of an undesired frequency. The diagram's circle, or summer, indicates algebraic summation according to the arrows and signs (Stowe, 2000).

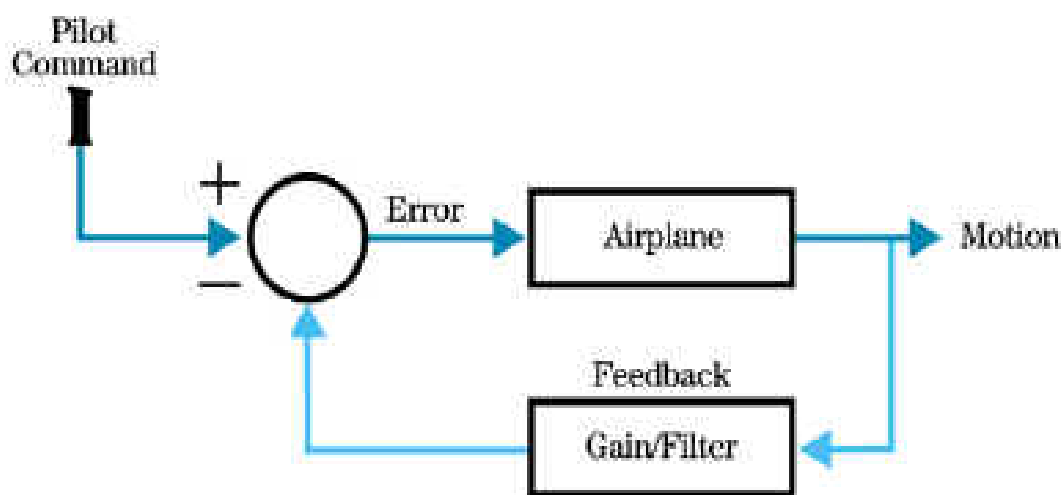


Figure 5 – Block Diagram Of Simple FBW System

A brief overview of how the A319/A320/A330 flight control system works should help understand the philosophy behind its design. Airbus uses three modes, or “laws” to describe the mode in which the ECS is operating- normal, alternate (a sub-mode of this is abnormal-alternate, explained in more detail below), and direct.

The Normal flight control law is the Normal operating configuration of the system. Failure of any single computer does not affect normal law. The ECS covers 3-axis control, flight envelope protection, and load alleviation. The Normal flight control law has 3 modes according to phase of flight.

## Ground Mode

The Ground mode is active when aircraft is on the ground. There is a direct proportional relationship between the sidestick deflection and deflection of the flight controls. Is active until shortly after liftoff. After touchdown, ground mode is reactivated and resets the stabilizer trim to zero.

## Flight Mode

Becomes active shortly after takeoff and remains active until shortly before touchdown. Sidestick deflection and load factor imposed on the aircraft are directly proportional, regardless of airspeed. With sidestick neutral and wings level, system maintains a 1 g load in pitch. No requirement to change pitch trim for changes in airspeed, configuration, or bank up to 33 degrees. At full aft/fwd sidestick deflection system maintains maximum load factor for flap position. Sidestick roll input commands a roll rate request.

- Roll rate is independent of airspeed. A given sidestick deflection always results in the same roll rate response.
- Flare Mode- transition to flare mode occurs at 50' RA during landing. System memorizes pitch attitude at 50' and begins to progressively reduce pitch, forcing pilot to flare the aircraft. In the event of a go-around, transition to flight mode occurs again at 50' RA.

## Protections and Load factor Limitation

These prevent the pilot from overstressing the aircraft even if full sidestick deflections are applied.

## Attitude Protection

- Pitch limited to 30 deg up, 15 deg down, and 67 deg of bank.
- These limits are indicated by green = signs on the PFD.
- Bank angles in excess of 33 deg require constant sidestick input.
- If input is released the aircraft returns to and maintains 33 deg of bank.

#### High Angle of Attack Protection (alpha):

- When alpha exceeds alpha protection, elevator control switches to alpha protection mode in which angle of attack is proportional to sidestick deflection.  
Alpha max will not be exceeded even if the pilot applies full aft deflection

#### High Speed Protection:

- Prevents exceeding  $V_{MO}$  or  $M_{MO}$  by introducing a pitch up load factor demand.  
The pilot can NOT override the pitch up command.

#### Low Energy Warning:

- Available in CONF 2,3, or FULL between 100' and 2,000' RA when TOGA not selected. Produces aural "SPEED SPEED SPEED" when change in flight path alone is insufficient to regain a positive flight path (Thrust must be increased).

#### Alternate Law

If multiple failures of redundant systems occur, the flight controls revert to Alternate Law.

#### Ground Mode:

The ground mode is identical to Normal Law.

#### Flight Mode:

In pitch alternate law the flight mode is a load factor demand law similar to the Normal Law flight mode, with reduced protections.

All protections in alternate law, except for load factor maneuvering protection are lost.

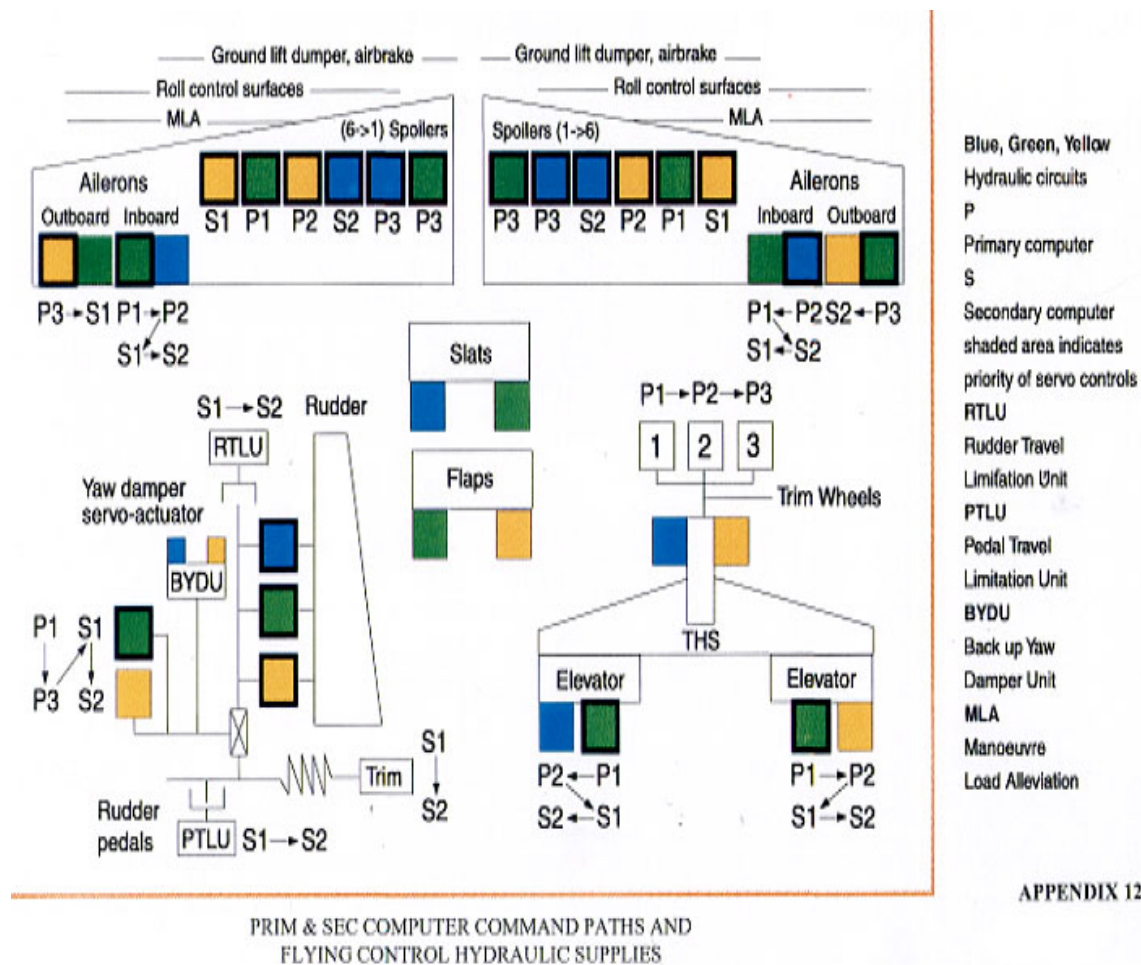
The airplane can be stalled in alternate law, and bank angle protection is lost.

#### Abnormal Alternate Law

Abnormal Alternate Law is activated if the airplane enters an unusual attitude, allowing recovery from the unusual attitude. Pitch law becomes Alternate (without autotrim or protection other than Load Factor protection). Roll law becomes direct law with mechanical yaw control. After recovery from the unusual attitude, the following laws are active for the remainder of the flight: Pitch: Alternate law without protections and with autotrim. There is no reversion to direct law when the landing gear is extended.

#### Direct Law

Direct law is the lowest level of computer flight control and occurs with certain multiple failures. Pilot control inputs are transmitted unmodified to the control surfaces, providing a direct relationship between sidestick and control surface. Control sensitivity depends on airspeed and no autotrimming is available. If the flight controls degrade to alternate law, direct law automatically becomes active when the landing gear is extended if no autopilots are engaged. If an autopilot is engaged, the airplane will remain in alternate law until the autopilot is disconnected. There are no protections provided in direct law, however overspeed and stall aural warnings are provided. (Parks, 2003) (Sanford, 2003)



*Figure 6- Airbus Flight Control Architecture*

In the Boeing 777 PFCS, there are three (3) Primary Flight Control Modes:

#### Normal Control Mode

When the PFCS is in the Normal mode, pilot commands are input through control columns, wheels, rudder pedals and a speedbrake lever. The transducers sense the pilot commands for the Actuator Control Electronics. The ACEs then convert the analog command signals into digital form and transmit to the Primary Flight Computers via the



ARINC Busses. The PFCs receive the airplane inertial and air data from the ADIRU / SAARU. Flight control surface commands are transmitted to the ACEs via the ARINC Busses. Then, ACEs convert the digital commands to analog commands to electrically control the actuators. In normal mode, all control laws and envelope protection functions are active. The control laws calculate commands for roll, yaw, and pitch control. The protection functions include stall warning, overspeed, overyaw, and bank angle. Note that the autopilot operates only with the PFCS in Normal mode.

### Secondary Control Mode

The Secondary control mode operation is similar to Normal, except for some of the envelope protection features are not available. All flight control surfaces remain operational- although airplane handling qualities are affected. Secondary mode is entered under two conditions:

- Insufficient availability of inertial or air data, or irreconcilable differences in same
- When the ACEs are in the Direct Mode.
- The following functions are unavailable in Secondary mode:
  - autopilot
  - auto speed brakes
  - envelope protection
  - gust suppression
  - thrust asymmetry compensation (TAC)
  - yaw damping may be degraded, or inoperative
- Direct Control Mode- is entered into under two conditions:

Flight Deck Switch

- ACEs detecting Invalid commands from the PFCs. The PFCs do not operate in Direct mode. The ACEs use the Analog Pilot Controller transducer signals to generate surface commands. In Direct mode, the following functions are unavailable:
  - autopilot
  - auto speedbrakes
  - envelope protection
  - gust suppression
  - manual rudder trim cancel switch
  - thrust asymmetry compensation (TAC)
  - yaw damping (Boeing, 1994 & 2003)

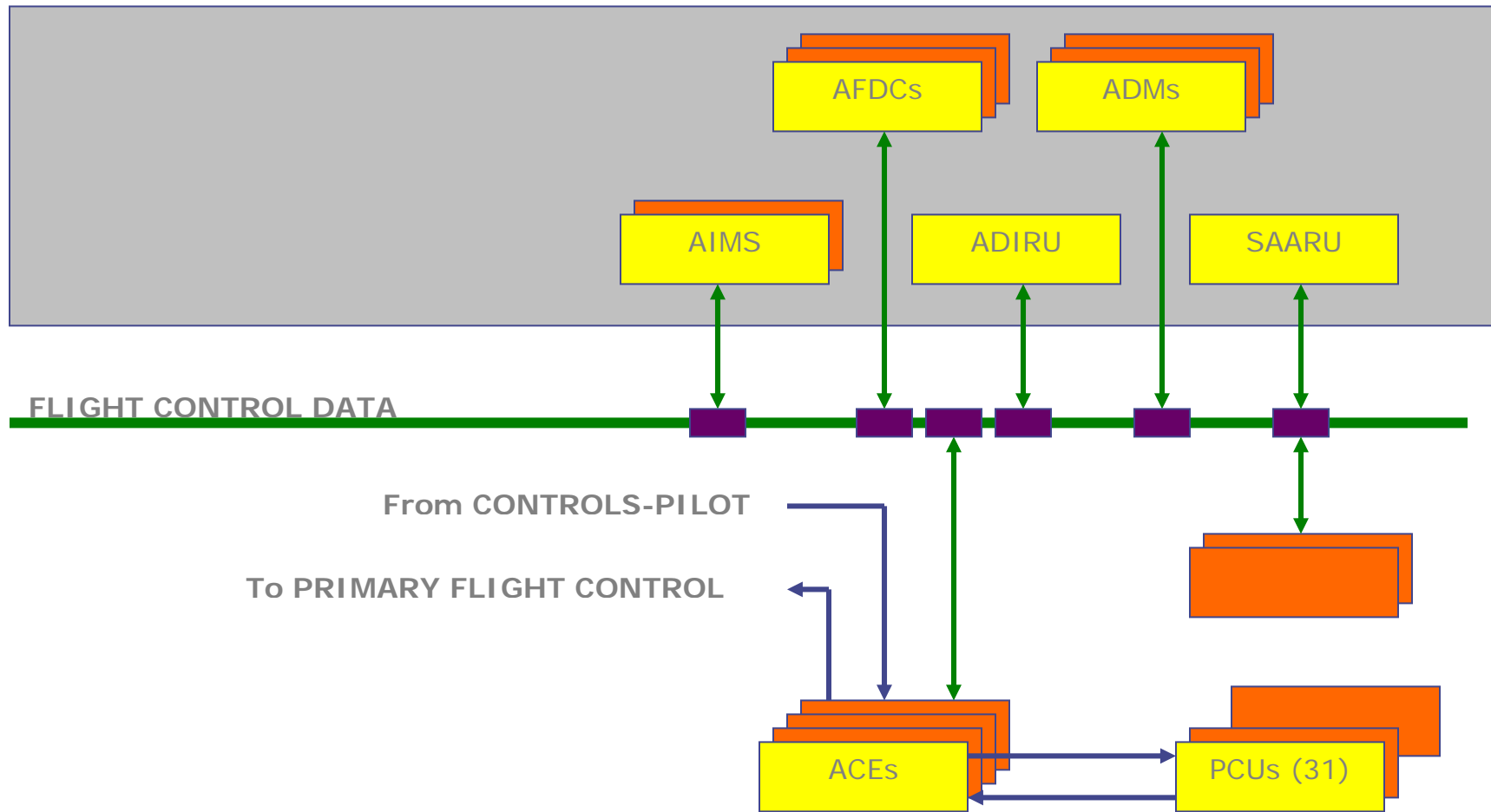


Figure 7- Boeing 777 Primary Flight Control System

**Figure Legend:**

AIMS: Aircraft Information Management System

AFDC : AutoPilot Flight Direction Computer

ADIRU: Air Data Inertial Reference Unit

SAARU: Secondary Altitude & Air Data Reference

ACE : Actuator Control Electronics

PFC : Primary Flight Computer

PCU : Power Control Units, Actuators

There are certain similarities between the two different FCS. They both have degrading levels of function, e.g. Normal, Secondary, or Alternate, and Direct modes. Each mode has its own specific operational parameters for mode degradation, and also for what control features will be available in each mode. For example, Boeing does not allow autopilot use in any mode other than Normal, whereas Airbus does allow some autopilot use below Normal mode, however, in very specific applications only.

After the A320 accident mentioned above, the interest and controversy surrounding hard vs. soft envelope protection has intensified dramatically. Even though there have been other incidents and accidents on Airbus aircraft where accident investigation findings have pointed at the flight control system (aviationsafetyonline.com, ATSB, NTSB, et al.), Airbus has stood by its method of hard envelope protection, and continues to utilize it in the A330 and A340 series of aircraft, as well as on its new A380 super-jumbo jet, which will debut in 2006. Obviously, the most interested parties to this controversy include the operators (the pilots), the aircraft manufacturers, and the flying public, in addition to the already mentioned academic and scientific communities.

Specifically, the Air Line Pilots Association (ALPA) has taken a very keen interest in the hard vs. soft FCS envelope protection debate, in part by forming an evaluation committee, which has filed a 54 page report with its findings and conclusions (Rogers, 1999).

In addition, even though the Boeing 777 has not yet had any flight control related accidents, ALPA wanted to gather even more data. They test flew an A330 and a 777, with particular emphasis on the Controlled Flight Into Terrain (CFIT) emergency escape maneuver (Rogers, 1999). Simply put, the CFIT emergency escape maneuver that was flown on both aircraft by ALPA pilots was simulating the airplane approaching flying accidentally into terrain, and escaping ground impact by pushing the engines up to full power while simultaneously applying a full back (climb) pitch command into the stick (A330)/yoke (777). ALPA's findings, in very high level summary, are presented below.

For the A330:

The procedure for the CFIT escape maneuver in the Airbus aircraft as recommended by Airbus, is for the pilot to pull full back on the stick and apply TOGA thrust. Speed brakes if extended, will automatically retract. Control laws either stabilize the AOA at an optimum value or adjust pitch rate to obtain maximum allowed g. With the Airbus CFIT escape maneuver pilots can quickly, easily, and repeatably achieve the maximum level of performance allowed by the envelope limiting system. This ease of handling might, in certain cases, result in optimum CFIT escape performance, even though full aerodynamic performance may not be achieved. (Rogers, 1999, p. 15)

For the 777:

On the 777, the pilot directly controls pitch attitude and pitch rate. High pitch rates can be attained by the pilot to quickly and precisely place the aircraft at optimum AOA. Although easier than for conventional aircraft, accurately maintaining the PLI still requires a reasonable degree of pilot technique. If ground contact is imminent the pilot can obtain the full aerodynamic performance of the aircraft. High stick forces are required to pull the aircraft into a stall; but the pilot receives numerous warnings and indications of the stall condition. Other than a ramp up of stick force there is not indication that the aircraft's g limit has been reached or exceeded. The authority to obtain maximum g is only limited by the feel system and control power. With this design the pilot is allowed to obtain the maximum aerodynamic capability of the aircraft (Rogers, 1999, p. 1).

Note that the design philosophy of soft envelope protection as embodied on the Boeing 777 with soft envelope protection gives the pilot full authority over the aircraft, while the design philosophy of hard envelope protection as featured on Airbus A320/330/340 series aircraft does not.

## CHAPTER VI

### CONCLUSIONS

If designed with the human interface in mind, FBW FCS enhances safety. As we have seen above, however, some aspects of FBW may be counter-intuitive, or may limit the pilot's ability to control the aircraft. Therefore, FBW FCS designers have put a feature into their designs known as envelope protection, which is intended to prevent loss of aircraft control. The Airbus flight control system features full flight envelope protection, otherwise noted as "hard" flight control limits. The Boeing 777 has an electronic flight control system that is designed with limited, or "soft" flight envelope protection. Hard envelope protection places an absolute limit on the control inputs that the pilot may make during aircraft operation. Soft envelope protection allows the pilot to override the FCS if necessary, and direct the airplane to the full capabilities of the airplane's aerodynamic design. So, does the above data actually tell us anything? I think that it does, if one compares it with the accident reports that we do have access to. The conclusion that this author draws from all of the above data, including both statistical and actual events as reported, would seem to indicate that the first generation of active electronic flight control envelope protection did not enhance safety, due to both design and lack of flight crew experience with FBW FCS. An analogy perhaps may be drawn to the early days of the Boeing 727, with crashes occurring with alarming regularity the first year or so after introduction into service. It is well known in the aviation industry that this was largely due to the brand new features of the 727 such as higher approach speeds and handling characteristics when compared to its' propeller driven brethren such as the DC-7, Convair 580, and the Lockheed Electra. Once the crews adjusted to the new (for the



time) technology of the 727, the accident rate quickly dropped below that of the piston engine powered airliners. The A330, A340 and the 777 seem to be benefiting from the lessons learned from previous accidents, with zero accidents so far (with the exception of one flight test accident in the A330). However, it seems that having “invisible” or “stealth” features to the FBW FCS, and an autopilot with counterintuitive modes that does not instantly disconnect in a simple fashion, can jeopardize safety. Granted, there is a “learning curve” for all new products, but since human beings operate these products, their operation must be in line with human actions and thought processes that are accepted as normal by the aviation safety and human factors professionals.

## CHAPTER VII

### RECOMMENDATIONS

After reviewing the data in the above accidents and flight tests, this author concluded that the safest method of electronic flight controls fly by wire envelope protection is the “soft” method such as employed on the Boeing 777. However, Airbus, in all probability, will continue with its current design of “hard” envelope protection.

Therefore, two things are recommended:

- 1) All transport category aircraft that feature FBW FCS should be designed with “soft” envelope protection. This form of envelope protection offers the maximum safety benefit and ease of use combined into one package.
- 2) Regardless of the type envelope protection that is designed into a of FBW FCS, proper crew training and crew procedures, coupled with correct execution of same, are a must to ensure safe operation of the aircraft.

## REFERENCES

- Abott, Kathy; Stimson, Don; Slotte, Stephen M, use all author's names here, (1996), *The interfaces between flight crews and modern flight deck systems*, Federal Aviation Administration Human Factors Team Report, <http://www.faa.gov>
- Australian Transportation Safety Board, (2003), *Accident & incident reports – detail -final report, occurrence number 200104399*,  
[http://www.atsb.gov.au/aviation/occurs/occurs\\_detail.cfm?ID=474](http://www.atsb.gov.au/aviation/occurs/occurs_detail.cfm?ID=474)
- Boeing Company, The (1994), *777 General familiarization manual*, The Boeing Company, P.O. Box 3707, Seattle, WA, <http://www.boeing.com>
- Boeing Company, The (1994), *Statistical summary of commercial jet aircraft accidents*, The Boeing Company, P.O. Box 3707, Seattle, WA, <http://www.boeing.com>
- Boeing Company, The (2003), *777 Operations Manual*, The Boeing Company, P.O. Box 3707, Seattle, WA, <http://www.boeing.com>
- Burcham, Frank W., Burken, John J, Main, Trindel A., Fullerto, C. Gordon, (1997), *Development and flight test of an emergency flight control system using only engine thrust on an md-11 transport airplane*, NASA/TP-97-206217, NASA Dryden Center, Edwards AFB, CA, USA,  
<http://www.dfrc.nasa.gov/DTRS/1997/PDF/H-2170.pdf>
- Federal Aviation Administration (2004), *The National Aviation Safety Data Analysis Center*, Washington, CD, USA, <https://www.nasdac.faa.gov/>
- Flight Safety Foundation, (2004), Alexandria, VA, USA,  
<http://www.flightsafety.org/home.html>,  
[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_aug01.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_aug01.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_mar01.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_mar01.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_oct99.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_oct99.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_jul\\_aug97.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_jul_aug97.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_oct94.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_oct94.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_jan92.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_jan92.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_jul91.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_jul91.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_jun91.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_jun91.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_apr89.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_apr89.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=ap/ap\\_july04.pdf](http://www.flightsafety.org/members/serveme.cfm?path=ap/ap_july04.pdf)

[http://www.flightsafety.org/members/serveme.cfm?path=fsd/fsd\\_jul-aug03.pdf](http://www.flightsafety.org/members/serveme.cfm?path=fsd/fsd_jul-aug03.pdf)

Job, Macarthur, (1998), *Air disaster, vol. 3*, Aerospace Publications Pty Ltd., Fyshwick, ACT, Australia

L. Knotts, M. Parrag, E. Ohmit, (1993), *Aircraft control system rate limiting*, Calspan Corp., USA

McRuer, Duane T., et al., (2003), *Aviation safety and pilot control: understanding and preventing unfavorable pilot-vehicle interactions*, Committee on the Effects of Aircraft-Pilot Coupling on Flight Safety, National Research Council,

<http://www.nap.edu/books/0309056888/html/index.html>

National Transportation Safety Board (2004), Washington, D.C. , *accident synopsis(s), accident database(s)*, <http://www.nts.gov>,

<http://www.nts.gov/nts/GenPDF.asp?id=DCA94MA076&rpt=fi>,

<http://www.nts.gov/nts/GenPDF.asp?id=DCA89MA063&rpt=fi>,

<http://www.nts.gov/publictn/2002/AAB0201.htm>

Parks, Eric (2003), *Airbus A319/A320/A321 notes-training notes*,

<http://www.chipsplace.com/>

Rogers, Ron, (1999), *CFIT Avoidance and fly-by-wire*, Air Line Pilot, September 1999  
issue, page 10, <http://cf.alpa.org/internet/alp/1999/septcfi.htm>

Rogers, Ron, (1999), *Pilot authority and aircraft protections*,

[http://www.bluecoat.org/reports/Rogers\\_99\\_Acft\\_Protect.pdf](http://www.bluecoat.org/reports/Rogers_99_Acft_Protect.pdf)

Rogers, Ron (1999), *Flight test results of the controlled flight into terrain avoidance  
maneuver in fly-by-wire transports*, Air Lines Pilots Association report,  
Airworthiness Performance Evaluation and Certification Committee,

[http://www.bluecoat.org/reports/Rogers\\_99\\_CFIT\\_FBW.pdf](http://www.bluecoat.org/reports/Rogers_99_CFIT_FBW.pdf)

Rudisill, Marianne (2000), *Crew/automation interaction in space transportation systems:  
lessons learned from the glass cockpit*,

<http://techreports.larc.nasa.gov/ltrs/PDF/2000/mtg/NASA-2000-hstew-mr.pdf>

Sanford, Bob (2003), *Airbus flight control laws*,

[http://www.airbusdriver.net/airbus\\_ftlaws.htm](http://www.airbusdriver.net/airbus_ftlaws.htm)

Sarter, N. B. and Woods, D. D. (1991) *Pilot Interaction with Cockpit Automation I:*

*Operational Experiences with the Flight Management System (FMS)*. Cognitive  
Systems Engineering Laboratory, Department of Industrial and Systems  
Engineering, The Ohio State University.

- Sarter, N. B., & Woods, D. D (2003), *An experimental simulation study of mode awareness and pilot-automation coordination on the flight deck of the A-320*,  
<http://www.flightdeckautomation.com>
- Stowe, Steve, (2000), *Fly-by-wire: a primer for aviation accident investigators*, Air Line Pilot, February 2000, page 18, Air Line Pilot's Association,  
<http://cf.alpa.org/internet/alp/2000/febfbw.htm>
- Waldrop, M. M., (1989), *Flying the electric skies*, Science 30 June 1989, p.1532ff, v.244, <http://catless.ncl.ac.uk/Risks/9.04.html#subj2>
- Wallace, James, (2000), *Unlike Airbus, Boeing lets aviator override fly-by-wire technology*, Seattle Post-Intelligencer article, 3-20-2000,  
<http://www.seattlepi.com>
- Wiener, E. L. & Curry, R. E. (1980), *Flight-deck automation: promises and problems*, NASA TM 81206. Moffett Field, CA: Ames Research Center.

## APPENDIX A

## BIBLIOGRAPHY

- Abott, Kathy; Stimson, Don; Slotte, Stephen M, all names (1996), *The interfaces between flightcrews and modern flight deck systems*, Federal Aviation Administration Human Factors Team Report, <http://www.faa.gov>
- American Psychological Association, (2001), *Publication manual of the American Psychological Association* (5<sup>th</sup> ed.), Washington, D.C.
- Australian Transportation Safety Board, (2003), *Accident & incident reports – detail-final report, occurrence number 200104399*,  
[http://www.atsb.gov.au/aviation/occurs/occurs\\_detail.cfm?ID=474](http://www.atsb.gov.au/aviation/occurs/occurs_detail.cfm?ID=474)
- Beringer, Dennis B (2002), *Applying performance-controlled systems, fuzzy logic, and fly-by-wire controls to general aviation*, Office of Aerospace Medicine, Washington, DC 20591
- Boeing Company, The (1994), *777 general familiarization manual*, The Boeing Company, P.O. Box 3707, Seattle, WA, <http://www.boeing.com>
- Boeing Company, The (1994), *Statistical summary of commercial jet aircraft accidents*, The Boeing Company, P.O. Box 3707, Seattle, WA, <http://www.boeing.com>
- Boeing Company, The (2003), *777 operations manual*, The Boeing Company, P.O. Box 3707, Seattle, WA, <http://www.boeing.com>

Bragg, Michael B.; Voulgaris, Petros G.; Hossain, Kishwar N, Sharma, Vikrant, (2003),

*Envelope protection and control adaptation in icing encounters,*

American Institute of Aeronautics and Astronautics Paper No. AIAA2003-25

Federal Register, (1997), Aviation Rulemaking Advisory Committee; *Transport airplane*

*and engine issues-new task*, August 28, 1997, Volume 62, Number 167,

<http://www.wais.access.gpo.gov>

Fielding, Chris, (unknown), *The design of fly-by-wire flight control systems*, article, BAE

Systems, Aerodynamics (W427D), Warton Aerodrome, Preston PR4 1AX

Garland, D., Wise, J., Hopkin, V. (1999), *Handbook of aviation human factors*, Embry-

Riddle Aeronautical University, published by Lawrence Erlbaum Associates, New

Jersey, London

Lambregts, Anthony A., (2003), *Flight mechanics and control, aeronautics & aviation*

*technologies workshop presentation*, [tonylambregts@faa.gov](mailto:tonylambregts@faa.gov)

Naidu, Amit Kumar (2002), *Case study: Airbus A340 flight control system: an analysis of*

*a highly dependable, fault tolerant architecture*, Department Of Computer

Science, University of Virginia

National Transportation Safety Board (2003), Washington, D.C. ,*Accident synopsis(s),*

*accident database(s)*, <http://www.nts.gov>

McRuer, Duane T., et al, (2003), *Aviation safety and pilot control: understanding and*

*preventing unfavorable pilot-vehicle interactions* , Committee on the Effects of

Aircraft-Pilot Coupling on Flight Safety, National Research Council,

<http://www.nap.edu/books/0309056888/html/index.html>



North, David, (2002), *Commonality enhances new airbus offering*, Aviation Week and Space Technology, McGraw-Hill, New York, NY, March 2002,

<http://www.aviationnow.com/content/publication/awst/20020325/aw56.htm>

Oosterom, Marcel; Bergsten Pontus; Babujska, Robert, (2002), *Fuzzy gain-scheduled  $h^\infty$  flight control law design*, American Institute of Aeronautics and Astronautics Paper No. AIAA 2002-4748

Parks, Eric (2003), *Airbus A319/A320/A321 notes-training notes*,

<http://www.chipsplace.com/>

Rogers, Ron, (1999), *CFIT Avoidance and fly-by-wire*, *Air Line Pilot*, September 1999 issue, page 10, <http://cf.alpa.org/internet/alp/1999/septcfi.htm>

Rogers, Ron, (1999), *Pilot authority and aircraft protections*,

[http://www.bluecoat.org/reports/Rogers\\_99\\_Acft\\_Protect.pdf](http://www.bluecoat.org/reports/Rogers_99_Acft_Protect.pdf)

Rogers, Ron (1999), *Flight test results of the controlled flight into terrain avoidance maneuver in fly-by-wire transports*, Air Lines Pilots Association report,

Airworthiness Performance Evaluation and Certification Committee,

[http://www.bluecoat.org/reports/Rogers\\_99\\_CFIT\\_FBW.pdf](http://www.bluecoat.org/reports/Rogers_99_CFIT_FBW.pdf)

Unknown author, (2003), *Airbus Industrie A320 Single Aisle Medium Range Airliner*,

Europe, retrieved 8-2003, Aerospace Technology, [http://www.aerospace-](http://www.aerospace-technology.com/projects/a320/)

[technology.com/projects/a320/](http://www.aerospace-technology.com/projects/a320/)

Unknown author, (2003), *Airbus Industrie A330 Wide-Bodied Medium/Long Range*

*Twin Engine Airliner*, Europe, Aerospace Technology, [http://www.aerospace-](http://www.aerospace-technology.com/projects/a330/)

[technology.com/projects/a330/](http://www.aerospace-technology.com/projects/a330/)

Unknown author, (2003), Our Advantages, Airbus Media Library, <http://www.airbus.com>

Unknown author (2003), 777-300ER Flight Testing Update- April 30, 2003,

<http://www.boeing.com>

Vakil, Sanjay S.; Hansman, R. John, (1998), Functional Models Of Flight Automation

Systems To Support Design, Certification And Operation, American Institute of  
Aeronautics and Astronautics Paper No. AIAA 98-1035

Sanford, Bob (2003), Airbus Flight Control Laws,

[http://www.airbusdriver.net/airbus\\_ftlaws.htm](http://www.airbusdriver.net/airbus_ftlaws.htm)