THE DEVELOPMENT OF A CIVILIAN FLY BY WIRE FLIGHT CONTROL SYSTEM

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Abstract

Within a national research and development program funded by the german ministry of education and research (BMBF) new fly by wire flight control system has been developed and is in the process of certification according to JAR 25. Technology readiness was demonstrated for those technologies which are potential candidates for a new aircraft. New equipment was developed and demonstrated in several flights of the ATD (Aerospace Technologies Demonstrator) aircraft. The following new technologies have been demonstrated: cabinets for the computing system, smart actuator, electromechanical actuator, full fly by wire rudder and a hydraulic power package. For the first time the modular avionic approach was applied to a flight control system. As a result of this program each technology which is now approved by flight can be selected within future systems as building blocks and composed to systems (not only flight control) adequate for any aircraft type.

1. Introduction

The design philosophy of Airbus A320 was studied in order to have a reference for designing the ATD flight control system.

The prime requirement for primary flight control is safety. Acceptable handling qualities for the pilot must be achieved with high reliability and all single and multiple failures of sensors, computing resources, actuators and also hydraulic and electric systems must be tolerated. A wide spread of failure scenarios must be mastered and the goal is to achieve minimal effects in case of failures. The solution for this is automatic extensive fault detection and isolation of all devices and system redundancies to be multiple fail operational. The new system allows minimised degradation of handling qualities especially in case of multiple failures. Experienced failure detecting principles like command/ monitor and dissimilarity which are state of the art have been adopted.

2. Evolution of Fly by Wire Systems

The first fly by wire flight control system on commercial transport aircraft was operationally introduced in 1988 by the Airbus A320. Approved versions followed with A330/A340 and in 1995 Boeing introduced its first fly by wire aircraft with the 777 aircraft. Up to now Airbus Industries has delivered more than 1300 fly by wire aircraft of different types with more than 15 million flight hours operating time. Today Fly by Wire is a proven technology and there is no more discussion about its safety and usefulness.

3. Advantages of Fly by Wire

There are benefits from fly by wire in the design phase as well as during aircraft operation. Following advantages of Fly by Wire can be identified:

- ease of pilot workload through support of automatic control features (i.e. turn coordination, auto trim)
- improvement of safety (i.e. envelope protection)
- reduction of weight and parts
- common handling qualities on different aircraft types (decrease of crew training cost)

- features of autopilot are in manual control mode available (i.e. attitude control)
- minimizing of structural loads by control law design or active load control
- common control surfaces for different types
- possibility to implement new control laws functions (i.e. adaptive wing)

4. The challenge of a Fly by Wire System

For the development of a fly by wire aircraft precaution must be taken also on the connected systems like electric, hydraulic and energy sources to achieve the minimal failure probability of 10 E-9 per flight hours for flight control.

The certification level for the flight control system of ATD was JAR 25 change 14. This regulations imposes requirements to the system itself but also to the development process and to the verification /validation process.

The functionality of flight control is shown on figure 1: the cockpit control inputs, the sensors (ADIRS), the flight control laws and the actuation system. Primary pilot inputs are two sidesticks and pedals.

Good handling quality of an aircraft is achieved through the features of the control laws which are implemented as software within the control computers. But the handling qualities decline in case of functional degradation of the control law. These are degraded if either computing resources fail or sensor information (like attitude, airspeed, angle of attack, pilot's command) or actuation performance is lost. Within the control system different control modes exist, beginning at failure free mode with all redundancies available. The first failure in the system doesn't impact handling qualities but with accumulating failures of the system more and more awareness is requested from the pilot. It is task of the system designer to assure the decline of handling qualities at an acceptable probability.

This probability gives the requested availability of each sensor information or actuation commands and thus the redundancies of each system device. These redundancies cover hardware failures, but there must be taken provisions to be fault tolerant also in respect to a software design failure.

Further challenge by the control system is managing the different system redundancies. Items which can have different operating states must be switched in the adequate state or isolated in order to have a consistent system behaviour: force fight of actuators or

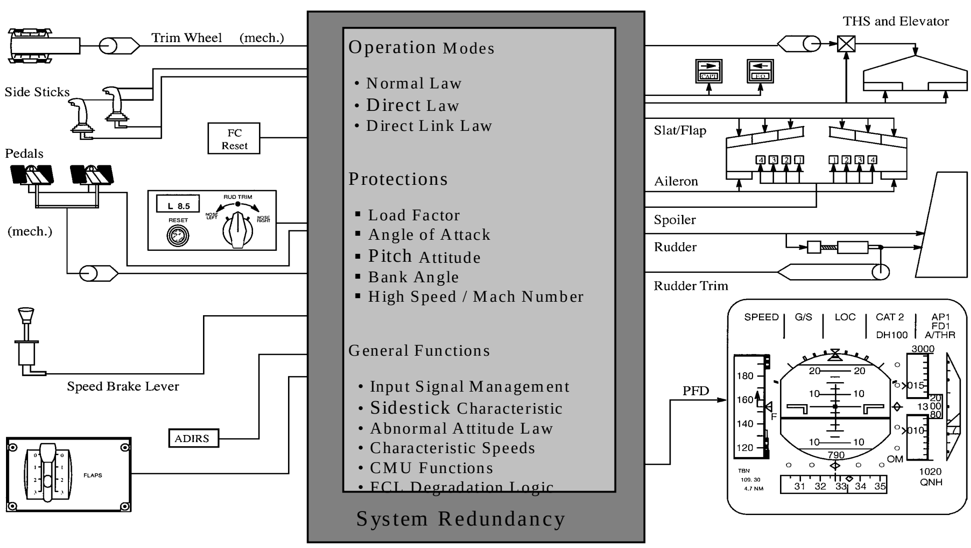

Figure 1: Flight Control Functions

contradicting control orders must be prevented.

To identify faulty items from the system effective fault detection mechanisms are required. State of the art mechanisms comparing two or three redundant data sources and identifying the erroneous data are used. The computing system is built of multiple pairs of computing resources. The results are exchanged and compared and if they are different the whole pair is isolated. For correct working of this mechanisms a common failure on both sources must be excluded. One common failure is a design error within both sources. To exclude this they are built from dissimilar soft- and hardware.

To master system complexity tools and environment must be established to ensure system and function consistencies at an early state of the program. For the validation of the control laws a tool for automatic software code generation (HOSTESS) was used. The control law code from this tool together with a flight simulator was tested in parallel to the general system development. By this means highly tested control laws have been implemented into the control computers. During tests test vectors were produced which were used also for system validation with real hardware.

Regarding at system aspects complex system scenarios were simulated with the tool Matrix X.

5. Flight control program of DA

The following steps are taken for the ATD program:

1. Start of EFCS development for ATD in mid of 1994
2. First flight of the demonstrator in August 1999
3. Flight test period of the demonstrator until mid of 2000

In the technology program of DA several supplier companies participated. Following technologies are implemented within the architecture:

- two cabinets for the computing system (supplier: Bodenseewerk Gerätetechnik)
- Flight Control Laws (DA)
- smart hydraulic actuator at the wing for aileron (supplier: Liebherr)
- smart electromechanical actuators at the spoilers (supplier: Liebherr)
- fly by wire rudder actuation (supplier: Liebherr)
- hydraulic power package in the rear as third hydraulic system (supplier: Liebherr)

After demonstration of these technologies possible risk by application in future programs is minimised. Only adaptation to the new objectives is necessary.

5.1 Flight Control System of the ATD

Within the ATD flight control system all primary surfaces are powered hydraulically. At elevators and ailerons two actuators are installed which work in active/ standby modes. The rudder also is driven by three actuators where only one actuator is active. The two outer spoilers are used for roll control and speed brake.

A mechanical backup is at the horizontal trim stabiliser and the rudder. All actuators at the wing are smart type actuators, which means they are equipped with actuator control electronic. The actuators are controlled by the Primary Flight Control Units (PFCU) and are connected to the IO-modules (IOM) of the associated cabinet. Principally each cabinet is linked to a set of actuators. This means that each cabinet can control all surfaces independently. The actuators at the elevators, spoilers and rudder are connected on two IO-modules of the cabinet to achieve the availability requirements (explanation: 2/1 means IOM 1 of PFCU 2, see figure 4).

Similar to Airbus or Boeing the control laws have different modes: Normal mode, Alternate or Degraded mode, Direct mode and Direct Link mode.

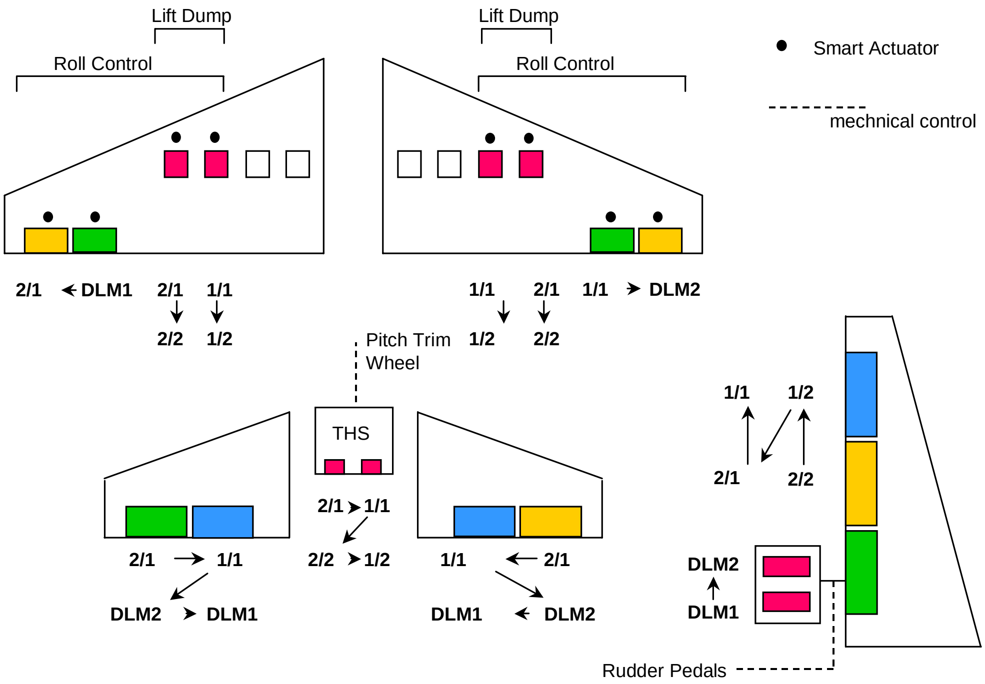

Figure 2: Actuation System and connected computing modules

Within normal flight control law vertical acceleration combined with pitch rate is commanded from the sidestick in the pitch axis. Within roll axis a roll rate is commanded. Protections are implemented i.e. speed, attitude, and vertical acceleration (see figure 1) In Alternate mode the normal law is adapted at failures. In Direct Link and Direct Law mode the control principle is changed: only surface positions are commanded from the sidestick. They are the most degraded modes

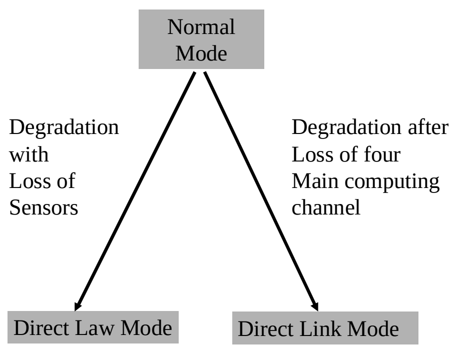

Figure 3: Degradation Principles

Control Laws modes are switched depending on the flight phase and in case of failures. Failures can be divided into loss of sensors (like speed, attitude) or loss of computing resources. The system reaction is different in each case. If a computing channel is lost another channel is activated and there can be activated up to four channels without degradation of handling qualities. After four failures the Direct Link Mode becomes active. This mode is dual redundant. For differentiation from the Direct Link Mode the described normal mode is called Main mode, incorporating four computing channels.

In case of loosing sensor information on all main computing channels no other computing channel is activated but the flight control law itself is reconfigured from the normal - failure free – mode to a degraded mode. At multiple sensor failures the Direct Law mode becomes active.

If sensor information is different on the main computing channels then this channel with the highest capability is activated.

As mentioned the flight control system also shall be fault tolerant to a software design error. A software design error in the Main channel affects all main channels and is detected by the Command/Monitor failure detection. If a design error occurs all Main channels switch passive and the Direct Link mode becomes active

The Main mode and Direct Link mode are principally two functional dissimilar operation modes. The Main mode is principally similar to the Airbus A340 Flight Control Primary computer (FCPC) and the Direct Link mode to the Flight Control Secondary Computer (FCSC).

5.2 Computing System of the ATD

The flight control computer system is built up by two similar cabinets (see figure 4) each containing line replaceable modules (LRM). Module types are the PFM (Primary Flight Module), the IOM (Input Output Module), the DLM (Direct Link Module). Further modules are the MAM (Maintenance Module) and PSM (Power Supply Module), which are not shown in the figure.

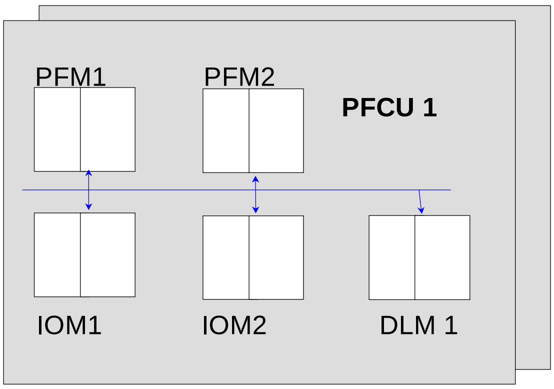

Figure 4 : Primary Flight Control Units

The PFM is calculating the Flight Control Laws and performs the management of the system redundancies. The IOM contain the actuator control loops and voting and monitoring of the data. The DLM works normally like an IOM but at loss of the four PFM (= loss of main computing channels) the DLM switches into the Direct Link mode. In this mode each DLM is able to control the aircraft. The MAM is used for flight test data acquisition in the ATD but in later airlines operations this module will be the interface to the maintenance computer.

All computing modules, except the MAM are built up by two HW and SW dissimilar lanes. The modules are communicating via internal dedicated point to point serial high speed links (20 Mbit/sec).

Through the extensive communication within the cabinet and also through the exchange of surface position commands between the cabinets it is possible to separate the selection of the active main computing channel from the choice of the active actuator at the surfaces.

This feature allows to select that PFM for control (out of four PFM) which offers the highest level of handling qualities. The commands of the selected PFM are routed to all IOMs/DLMs on both cabinets. The decision which actuator is active or in standby can be taken independently from the PFM selection.

As the FCL level is based on the sensor information (i.e. air data, angle of attack, speed) the ATD system allows a decoupling of sensor failures and actuator failures.

The independence of FCL computation and actuation configuration allows at multiple and mixed failures (actuation and sensors) a higher level of aircraft handling quality. Switching of PFM is only necessary with loss of sensor information in one cabinet.

Within commercial airline operation the Flight Control Computer system tolerates two electrical failures prior to dispatch.

5.3 Smart actuator technologies

The smart actuator technology extracts the actuator related functions from the central control computer and moves it into an electronic module on the actuator, the actuator control electronic (ACE). The functional partitioning allows development and test of actuator and electronic module as one package under the responsibility of one supplier. An other advantage is the reduction of wiring between the flight control cabinet and the actuator. Disadvantage is the additional hardware and its maintenance which will be the consequence.

In the EFCS demonstrator the actuators at the wing (two spoilers and one aileron at each wing) are equipped with electronic modules. The modules, which are line replaceable units are similar and are built up by two dissimilar computer lanes.

To investigate the optimal failure management two principles for powering the module are applied. The smart module of the spoiler is powered directly by the electric power supply of the aircraft but the ailerons power sources are switched by the PFCU. Thus different redundancy management principles in the PFCU and in the smart modules are proved.

5.4 Electromechanical actuators

At the flight spoilers of the demonstrator electromechanical actuators are installed. System improvement results primarily from the higher availability of the electrical supply by using the redundancy of the electrical system and from the exclusion of the third hydraulic power supply from the wing. Advantages are reduced weight and reduced maintenance problems. The third hydraulic system is restricted to the rear part of the demonstrator. This gives an advantage for systems segregation which is necessary for mastering engine burst. For the third system a special hydraulic pump with integrated electric motor was developed (Hydraulic Power Package).

5.5 Fly by wire rudder

The actuation concept of the rudder consists of three hydraulic actuators. Two electro hydraulic actuators are controlled by the fly by wire system and the third actuator, which is mechanically signaled, is part of the mechanical backup. It is controlled by cables from the pedals. Only one actuator is active at a time. The mechanical path becomes active if the computer modules have lost the rudder control. Advantages are cost and weight reduction by minimizing the mechanical path.

5.6 System implementation into the ATD

For the implementation of the flight control system the connected systems of the ATD had to be modified in order to fulfil the safety requirements.

Major modification have been:

- Complete extraction of the basic flight control system of the VFW 614 and integration of all system parts of the EFCS flight control system.
- Upgrade of the Electric and Hydraulic Power System from two systems to three independent redundant systems
- Usage of the Auxiliary Power Unit as third energy source in flight
- Implementation of EFCS specific displays and pilot inputs and rearrangement of the basic instruments in the cockpit
- Segregation of wiring to avoid common failures
- Development and integration of a flight test environment and integration of an emergency exit

For demonstration of the flight worthiness of the above described technologies a VFW 614 aircraft was reactivated through a D-check and following flight tests.

After the aircraft has regained its basic flight worthiness the aircraft modifications on basic systems and the integration of all flight control items were carried out.

5.7 Validation

As yet mentioned the certification of the ATD imposed restrictive processes for validating the systems and the aircraft. For this purpose tools have been used: a system test rig containing the critical actuators, the computers, the sidesticks, pedals and cockpit instruments as original parts. Additionally all IO to the computers can be simulated. The Iron Bird incorporates the actuation system hardware, four elevator, rudder, one aileron and one spoiler.

The flight control system was validated at the system testrig and at the ATD itself by performing a test program. Each test step was referenced by the appropriate system or component requirement to insure complete test coverage. Also a failure tree analysis was performed to show the coverage.

The control law software was developed by means of HOSTESS with graphic input and automatic SW coding. This software was validated by simulation on a generic flight simulator.

After implementation of the control law software into the computers again test have been carried out: automatic tests to verify the correct implementation of the software and also manual flight test on the simulator. For this purpose a simplified ATD cockpit but with original instruments was used.

The modifications of basic systems of the ATD have been verified and validated by tests within the aircraft itself.

During development and tests there was imposed a strict fault tracing and change management for the aircraft and test facilities.

For transmitting and recording of data a powerful flight test installation was built on ground and in the ATD.

Certification of the ATD is monitored by the german institute, the Luftfahrt Bundesamt (LBA) First flight took place in August 99.
Since then flight tests are going on.

6. Conclusion

For the first time a cabinet system was applied within a flight control system and proved by flight tests. The timing requirements have been high as the control system of the ATD is highly dynamic. The program has fulfilled the highest level of regulations and so it will be possible to adapt the system also to other aircrafts.

The modular concept allows to increase the redundancy by one additional redundant control path. This allows to dispatch with two electrical failures.

At ATD the secondary flight control system was not changed but an integration should be cost effective and should be evaluated in future design.

Maintenance cost reduction result from the low number of spare parts (four spare parts for 16 LRU).

By integration of further functions (autopilot and secondary flight control) volume and number of spare parts again become better and a potential cost reduction also for maintenance cost is achievable.