FLIGHT SIMULATION AND DIGITAL FLIGHT CONTROLS

D. Chatrenet
Handling Qualities Department
Aerospatiale
Toulouse, France

Abstract

The A320 is the first civil airliner to make extensive use of digital flight controls. Despite previous experience in this technological field, development of this system in a short time schedule has been a challenging issue. Simulation under its various forms, including simulators with a very high level of integration of actual aircraft components, have played a key role in the successfull achievement of the Flight Control development process. It has allowed a better overall system quality to be achieved by the extension and thoroughness of testing performed : some 18 000 hours of simulator testing were logged at the time of A320-200 certification. Simulation has also proved to be a perfect complement to flight testing which today still remains the definite way to validate a Flight Control System and associated Handling Qualities : by increasing the safety and effectiveness of flight testing, simulation has participated in the overall development cost and programme monitoring.

In the field of simulation used for airline training purposes, the introduction of digital flight controls has moved the representativity-critical areas from aerodynamic model accuracy to Flight Control System representation exactness. Aerospatiale is convinced that use of actual aircraft Flight Control computers is needed to guarantee fully the degree of fidelity consistent with the standard of training quality offered today. Simulator acceptance procedures had also to be adapted to address the case of closed loop controlled aircraft correctly.

1 . Introduction

European experience in fly-by-wire application to civil airliners is now some 20 years old. More recently, entry into service of the A320 has provided a major milestone in this technical challenge.

In the same period of time, simulation has benefitted from great improvements in computer power, model accuracy and environmental fidelity. It is now widely used in both training and development fields.

The objective of this lecture is to show how these two concepts : Digital Flight Controls and Simulation, have been intermixed in the case of both development and operation of a fly-by-wire civil airliner like the A320.

2 . Digital Flight Controls : A320 experience

2.1 . Previous experience

The decision to make extensive use of fly-by-wire was not taken without considering the experience acquired in this field :

- since 1969, Concorde has been flying with a three axis full authority analog flight control system with a mechanical back-up on each surface,
- in 1978, an experiment was conducted on Concorde 01 involving the use of a sidestick, a C* type of control law and a digital computer,
- in 1981, the concept of "Forward Facing Crew Cockpit" was introduced in the Airbus A300B4 programme ; this involves a digital dual-dual autopilot system (two computers, each with a Command and a Monitor channels),
- Airbus A310 and A300-600 have their spoilers, flaps and slats controlled by digital computers,
- in 1983 and 1985, extensive flight testing was performed on A300B S/N 3 modified to embody sidesticks and A320 type control laws.

2.2 . Brief survey of A320 Flight Control System

2.2.1 . Aerodynamics

The A320 is fairly conventional in this respect and early design did not take credit of fly-by-wire ; the tailplane and fin are therefore of usual size ; natural modes are damped throughout the flight envelope and CG range, and the maneuvering margin is still positive at the most rearward CG position.

Primary flight controls make use of the following control surfaces :

- a one piece rudder,
- a Trimmable Horizontal Stabilizer fitted with two mechanically independent elevators,
- two ailerons and ten upper wing surfaces.

2.2.2 . General architecture

All control surfaces are hydraulically activated through the three independent general supplies of the aircraft. All surfaces are electrically signalled. The roll axis and elevators have a purely electrical control. The THS and rudder have a mixed electrical/mechanical control so that the A320 can still be flown and kept under control in the case of a momentary complete electrical failure.

As the pilot's main pitch and roll controls are free of mechanical links, they are advantageously achieved by sidesticks. Their lack of mechanical synchronisation is replaced by a priority logic and announcement system.

The electrical Primary Flight Control System relies on the use of seven digital computers :

- two ELACs which provide Elevators, Ailerons and THS control. ELACs compute the normal control laws for all axes,
- three SECs which provide Spoiler, Elevators and THS control. The SECs are only capable of computing reconfigured control laws,
- two FACs which provide Rudder control through yaw damper actuators ; the FACs also compute the characteristic speeds, rudder travel limitation and rudder trim control.

The electrical supply to the Flight Control System comes from the two general AC and DC n° 1 and 2 systems fed by the two engine driven generators. In the case of failure or unserviceability, the two supplies can be taken over by the APU generator or the Ram Air Turbine. In addition, two batteries with a minimum endurance of 30 minutes provide a permanent back up supply.

2.2.3 . Flight Control Laws

One of the positive outcomes of Fly-By-Wire is to allow elaborate flight control laws to be introduced : conventional direct (linear) relationship between pilot's controls and surfaces is replaced by computations which interpret the pilot's input as a request for a given aircraft response and deflect the surfaces accordingly until the feedbacks indicate that the desired response has been obtained.

In pitch, the A320 makes use of the C* law which is basically a load factor demand type of control law : once the stick is released, the aircraft is forced to a one g flight, corrected for pitch and bank attitudes. As a consequence, the control law automatically provides the elevator deflection necessary to cope with turbulence, speed changes, CG effect, trim changes associated with thrust and high lift/airbrakes operation. From the pilot's point of view, corrective pulse inputs are just needed to correct attitude, and the aircraft benefits from auto-trim characteristics ; it displays neutral static stability and positive platform stability. When the stick is fully deflected, the load factor demand is automatically limited to an extent consistent with the structural design capability.

For the lateral axis, the sidestick deflection is treated as a roll rate demand and roll and yaw control surfaces are deflected in order to provide good turn coordination (sideslip minimization) and comfortable dutch roll damping. In the same way as on the pitch axis, the bank angle is corrected by pilot's pulse inputs ; the aircraft displays neutral spiral stability and positive bank stability with respects to turbulence. When the stick is fully deflected, the roll rate is limited to 15°/s which has been found to be good compromise between adequate maneuvering capability and margin relative to Pilot Induced Oscillation tendency (roll rate is not reduced when the aircraft is responding to turbulence). In the case of engine failure, even with no reaction from the pilot, the control law will stop the roll rate and stabilize the aircraft at a moderate bank attitude and slowly diverging heading.

Protections : while neutral static and spiral stabilities greatly improve the comfort of piloting in the usual operational envelope, they are inherently removing the cues that indicate the departure from these usual flight conditions on conventional aircraft. Therefore, protections have to be introduced when the aircraft reaches the boundary of the peripheral flight envelope :

- in pitch :

  - strong positive static stability is provided beyond VMO/MMO, reducing the maximum speed excursion in the case of diving upsets,
  - strong positive incidence stability is provided at low speed, reducing the maximum achievable angle of attack below the stalling incidence (Angle of Attack Protection),
  - pitch attitude is limited between the practical values of -15°/+ 30°.

- in roll :

  - strong positive spiral stability is provided beyond 33° bank angle ; maximum achievable bank angle is limited to ±67°,
  - maximum bank angle is further reduced when the aircraft is operating into either Angle of Attack Protection or High Speed Protection.

Reconfigurations : correct computation of the above control laws relies on the availability of consistent separate sources of feedback information as well as minimum number of control surfaces and computers. When these conditions are no longer satisfied, normal control laws are progressively reconfigured to downgraded modes according to the level of remaining available items. Reconfigurations only take place after double failures. The most downgraded level is achieved when the control laws have reverted to direct type.

2.2.4 . General precautions

Owing to the criticality of the flight control system, the following safety objectives have been set :

- definitive loss of roll control : Extremely Improbable,
- runaway of THS or elevators : Extremely Improbable,
- definitive loss of elevators : Extremely Remote.

In addition, the following maintenance objectives have been selected :

- take-off allowed with any one Flight Control computer failed,
- take-off allowed with one aileron or one spoiler or one THS motor failed,
- no special daily test or special test equipment,
- "Bite" system to identify the failed LRU.

These objectives have lead to the above mentioned system architecture. The following precautions and/or features also contribute to overall achievement of the objectives :

- Level 1 type software as defined by DO178,
- dissimilar redundancy between SECs and ELACs, between COM and MON channels,
- wire routing tolerant to mechanical failures of the structure,
- passive Electro-Magnetic Interference and Lightning protections,
- multimode electrically signalled hydraulic servojacks : active mode, damping mode, self centering mode.

3. Contribution of Simulation to Flight Controls System development

Now we reach the essential part of the presentation. In order to have a better understanding of the stakes involved, it is worth recalling the tight timescales that were put on the A320 programme:

programme launching	:	early 1984
first flight	:	February 1987
European certification	:	February 1988
Entry Into Service	:	March 1988
FAA certification	:	end of 1988

Despite previous experience relative to Fly-By-Wire, the extent of its application to the A320 coupled with the above timescales made the development phase a tough and challenging experience in which simulation played a key role.

3.1 . Simulation tools

3.1.1 . "Batch" type simulation codes

A modular system of codes and subroutines, called OSMA (for Outil de Simulation du Mouvement de l'Avion) has been extensively used for general Handling Quality studies as well as flight control laws tuning in non linear domains. It is worth noting that aerodynamic, propulsive, flight mechanics models and subroutines are the same as those used and supplied to the training simulators within the Data Packages.

3.1.2 . "Development" simulator

This simulator is fitted with a fixed faithfull replica of the A320 cockpit and controls and a visual system ; it was put into service as early as mid 1984, as soon as a set of previsional A320 aero data, based on wind tunnel tests, were made available. The

Flight Control System was at this stage fully simulated. The development simulator was used to develop and initially tune all flight control laws in a close loop cooperation process with Airbus Industry flight test pilots.

3.1.3."Integration" simulators

Three "Integration" simulators were put into service in 1986. They include the with fixed replica of the A320 cockpit, a visual system (for two of them), and a lot of actual aircraft equipment including computers, displays, control panels, warning and maintenance equipment ; one of them, called S1, is even coupled to the so called "Iron Bird" which is a full scale replica of hydraulic and electrical supplies and generation and is fitted with all the actual Flight Control System components including the servojacks. The main purpose of these simulators is to test the operation, integration and compatibility, and the process of interactive communication between the computers in an environment closely akin to that of an actual aircraft.

3.2 . Contribution of simulation to system quality

The quality and associated safety and reliability of operation, of a critical system like the Digital Flight Control, mainly relies on a two step process :

- quality of the specification,
- quality of software and complete consistency between software and specification.

The latest step is guaranteed through the use of the very stringent rules associated with "Level 1" software. These rules issued by the Certification Offices and supplemented by the own manufacturer's or vendor's rules (based on experience), theoritically ensure that the software embodied in the Flight Control System computers is strictly consistent with its specification.

Today the first step is still somewhat less formalized and more difficult to assess fully : how can it be guaranteed that the specification on which the software is based fullfills all the performance objectives and offers the adequate functioning in every forseeable configuration of the environment of the system ? In this area, simulation provides for an invaluable tool for analysis or checking of huge numbers of potential cases or combination of cases which are obviously out of the scope of flight testing ; for example, parameters like weight, center of gravity location, altitude, speed (inside and outside the normal flight envelope), aircraft configuration, wind, turbulence (including windshear) have been systematically covered by simulation at every major step of the Flight Control System design. We may even say that, owing to the considerable number of inputs to the system (several hundreds), checking all the combinations of these inputs, if they were considered to be independent, would be practically inaccessible even by simulation. In this respect, a good simulator providing faithful simulation of all these inputs to the system as well as overall aircraft behaviour, allows for a significant reduction of the number of potential cases to be analysed : all inputs are no longer fully independent parameters and combinations which are not possible are automatically eliminated.

Even if the nominal functioning and operation of a civil airliner already provides for a wide scope of various environmental conditions, the abnormal operation is still more complex. The A320 simulators have been extensively used to develop and check all the logics embodied in the Flight Control System specification which should malfunctions occur, either enable nominal operation of the system to be maintained or reconfigure the system to a level of performance geared to the resources resulting from the malfunction. Areas of particular interest in this respect include :

- runaway of inputs from other systems (ADCs, IRSs, ...)
- oscillatory failures
- mechanical failures (jamming, disconnection)
- electrical supply transients
- effects of lightning induced disturbances
- effects of Electro Magnetic Interference induced disturbances.

A thorough assessment of system behaviour in the case of the abovementioned abnormal conditions is clearly inaccessible by pure analysis or by flight testing.

3.3 . Contribution of simulation to safe and cost-effective flight testing

Flight Testing indoubtedly remains the ultimate and indispensable way of validating a flight control system. With the current state of the art in simulation, simulators cannot yet fully take the place of flight testing for Handling Quality assessment, especially for close to the ground phases of flight. On the other hand, A320 simulators have certainly made flight testing both safer and more productive. Anyway, safer flight testing also means a more cost effective development process when taking the short timescale and the cost of the machines into account, not to mention the detrimental advertizing arising from any incident.

Here are some examples which illustrate how simulators have proved to be perfect complements to flight testing in an overall cost-effective objective :

- flight crew training before first flight (self evident),
- reduction of the scale of test programme : prior selection on a simulator allows the most significant scenari to be selected,
- aircrew familiarisation in the case of tricky test successions (also self evident),
- systematic test on the integration simulators of any new version of software ; this test was mandatory before any new version of Flight Controls computer was allowed to be fitted on a development aircraft for flight testing,
- debugging in the case of unexpected failure during flight testing : by back playing the conditions of the incident, varying the suspected parameters or locally increasing the scale or sensitivity of the instrumentation, a detailed set of facts can rapidly be built up which allow the anomaly to be traced quickly and corrected with a minimum delay in the flight test programme,
- simulator use in place of flight testing for very severe or critical failures ; despite the introduction of this paragraph, some very severe failures have been tested on the simulators only ; this is the case when the probability of such failure or combination of failures allows hazardous or even catastrophic consequences according to the certification requirements ; this was also the case whenever the aircraft, volontarily forced in this failure state, became particularily vulnerable to an additional unexpected failure.

3.4 . Side contribution of simulators

Although far from their fundamental purpose, A320 simulators have also been something of a showcase for know-how. Many demonstrations have been performed on these simulators, to the benefit of customers (confirmed and potential), representatives of government agencies, various VIPs, etc ... Especially before the first flight or first roll out of production aircraft, simulators were one of the visible and tangible back ups to the confidence necessary to initiate or confirm the involved investments.

4 . Training Simulators of Digital Flight Controlled Aircraft

4.1 . Airbus worksharing

In the Airbus Industrie organization, the French partner, Aerospatiale, is in charge of the Flight Control System, cockpit design, general Handling Qualities assessment and certification, engine/airframe integration and aerodynamic data release.

This naturally leads to an additional task, for which

Aerospatiale is also responsible : gathering, formating, issuing and supporting all the information and equipment that are needed to build, check and certificate the training simulators of Airbus aircraft.

Over the past decades, the significant improvement in training simulator fidelity as well as their generalized use in the training cursus have played an unarguable role in the overall improvement of air travel safety. Good training is as important as well designed aircraft and good simulators are a must for achieving good training. What is the impact of digital flight controls on training simulators ? Here is Aerospatiale's experience-based opinion.

4.2 . Importance of Flight Control System representation

On a conventionally controlled aircraft, moving surface deflections are directly linked to pilot's control positions. Therefore, simulation of this part of the Flight Control System is straight forward and fidelity of simulator behaviour mainly relies on the accuracy of the aerodynamic model. But a good simulator must also provide whenever possible the most faithful cues. Control forces are among these cues ; in the case of mechanical control through cables and rods, hydraulically powered or boosted surfaces, including artificial feel and stall warning devices, the correct simulation of control forces is not an easy task. From an Handling Quality point of view, the two critical areas of a conventionnally controlled aircraft simulator are the aerodynamic model and the control force model ; acceptance tests of a training simulator, both for customer and certification, have a content in accordance with these areas of criticality.

On a digitally controlled aircraft, the behaviour of the aircraft, as felt by the pilot, is mostly affected by the Flight Control System ; the flight control laws, owing to their robustness and the feedbacks taken into account, make the behaviour even less sensitive to the aerodynamic model. Therefore, the critical area of a digitally flight controlled aircraft simulator is that of the Flight Control System representation ; criticality of the aerodynamic model only becomes significant for reconfigured modes, when these modes reproduce the direct type of control of todays' conventional designs.

4.3 . Simulation versus stimulation

All A320 training simulators are equipped with actual aircraft sidesticks ; this guarantees the fidelity of pitch and roll control forces without any further need for check or proof of match.

Early A320 training simulators were fitted with simulated Flight Control computers, because it was impossible to have the relevant aircraft computers available for training simulators in time and in sufficient number. In this case, the software embedded in the seven computers was carefully analysed and selectively compacted.

Now that the production run of ELACs, SECs and other computers does allow some sets of them to be allocated to training simulators, Aerospatiale is strongly in favour of the so-called "stimulation" option : in this option, training simulators are equipped with the actual aircraft computers, as opposed to a simulation of them. By the way, "stimulation" is already the only available option for Flight Management Systems of many current conventional aircraft.

Here are the reasons for Aerospatiale's position :

- criticality of Flight Control System representation for achieving effective training,
- difficulty to define criteria for simplified simulation of the Flight Control System : it is difficult to limit the actual use of a training simulator strictly to its validity domain ; risk of negative training in the case of uncontrolled use outside this validity domain,
- it is almost impossible to check the simulation of such a complex system thoroughly ; use of "Level 1" software rules to derive simulation software from the detailed specification of the computers is practically out of the reach of training simulators manufacturers or would be too costly. Validation of the simulation option relies on a sample set of test cases on which to base a general level of confidence in the overall simulation model,
- lengthy updating process leading to a simulator standard which is often beyond that of the airline fleet ; risk of a loose updating process monitoring,
- good compatibility of Flight Control computers with the specific operational use on a training simulator (repositioning, freeze...) and the injection of failures, without the need for computer modification.

For upcoming programs like the A340/A330 or the A321, Aerospatiale has decided to rationalize and improve its support to the training simulator community by only allowing the stimulation option.

4.4 . Training Simulator acceptance procedures

Acceptance of a training simulator is performed at two levels : by the customer (airline or training center) upon taking delivery and by the Airworthiness Authorities before allowing credit to be given for the training performed on the machine. The amount of testing needed for Certification is generally less extensive than (and included in) the list of tests used for customer acceptance.

In both cases, the list of tests used on simulators of conventionally controlled aircraft have been found inappropriate for a simulator of a digitally controlled aircraft :

- they were unnecessarily concentrating on control forces (useless when the sidestick is an actual aircraft component),
- they were not addressing specifically the case of a closed loop control aircraft.

Therefore, Aerospatiale has developed this opinion to the Airwothiness Authorities who were very receptive ; a working group has been set up including some airlines and simulators manufacturers as well. The outcome was a better alternative set of validation tests proposing a two step validation process :

- first step : validation of the aerodynamic model only (response of the aircraft to control surface position) ; once performed, conclusions remain valid whatever control law (normal or reconfigured) is active or after any modification/updating of the Flight Control system,
- second step : validation of the Flight Control system representation through complete, closed loop aircraft response ; the amount of these tests is intended to cover the most demanding simulation option and could be reduced in the event of the stimulation option being selected.

This acceptance procedure is now currently used to certificate all in service A320 simulators.

5 . Conclusion - A glimpse into the future

After relating the role played by simulation in the development process of the A320 Digital Flight Control System as well as the impact of this system technology on training simulators, this lecture can be concluded by a glimpse into the future :

Simulation will play an ever-increasing role in the development process in order to reduce cost and timescale by achieving the best definition at the earliest stage of development. Right now for the A340/A330 programmes, engineers in charge of flight control law design can test within minutes the control laws they have just specified on one of the design office simulators made of a console with main controls (joystick, thrust levers, controls for rudder, airbrakes, slats and flaps...), a video screen with a replica of the Primary Flight Display, Autopilot Command Unit and display of controls surface position, recording and plotting facilities, all linked to a host computer with full aerodynamic, engine, ground roll and Flight Control System modelizations. At the same time, engineers in charge of system architecture and computer logics benefit from a complete simulation of all software embedded in the five computers of the A340/A330 system ; this simulation is used to verify all reconfiguration logics as well as the dialogue between computers. Both simulation facilities are available well before any computer prototype is produced. They strongly rely on generalized digitalization methods that include computerized specification of both flight control laws and logics, followed by automatic generation of the associated simulation software.

In the training simulator area, sophistication and inter-relationship between digital systems including Flight Controls will lead to an increased use of actual aircraft equipment as a guarantee of simulator representativity : from the already stimulated FMS to Flight Control computers, Autopilot computers and even critical components in procedures training such as Flight Warning Computers. This tendency will only be reversed when the software embedded in these computers is made compatible and transportable without alteration onto simulator host computers sized to accept them all without truncation.