G E N E R A L   L E C T U R E S

FLIGHT CONTROL SYSTEM ON MODERN CIVIL AIRCRAFT

B. ZIEGLER AND M. DURANDEAU

Flight Test Pilot and
Senior Vice President
Flight & Support
Directorate
Airbus Industrie
B.P. N° 33
31700 BLAGNAC - FRANCE

Flying Controls Design
Engineer - Design Office
Aerospatiale
316, Route de Bayonne
31060 TOULOUSE CEDEX 03
FRANCE

I - General

For the majority of large civil aircraft flying today, control surface positioning is achieved by hydraulically powered servo-jacks mechanically signalled. To face the increase in aircraft performance and flight envelope, such systems have had to be highly sophisticated. As an example, a standard pitch control includes (fig. 1) :

- A variable artificial feel system to modulate pilot forces as a function of flight condition
- A servoed auto pilot input
- High lift protection devices like stick shaker and stick pusher
- Stability augmentation systems such as mach, speed and/or angle of attack trim
- A control wheel steering inputing the auto pilot from force detectors
- A dual path splitting system for jamming protection

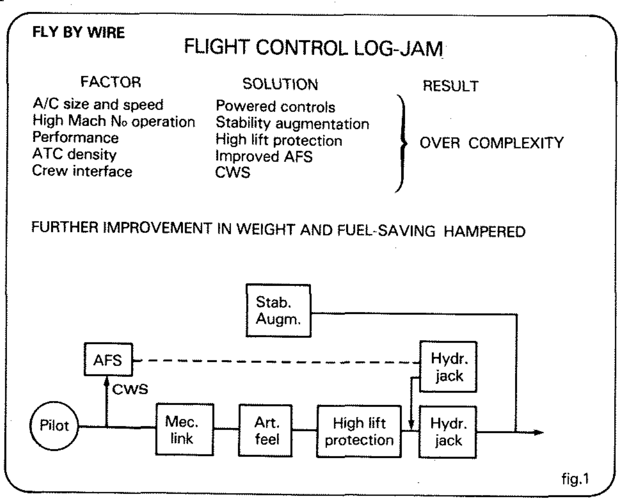

fig.1

Step by step were added jack, screw jack, dynamometric rod, bell crank, differential, position transmitter and microswitch to a point where a very heavy and expensive system is maintenance wise a nightmare and engineering wise does not offer any real flexibility for future developments. Such a log-jam situation has naturally driven the design office to completely reconsider the situation and to move to a new concept: the "Fly-by-Wire" (Fig. 2).

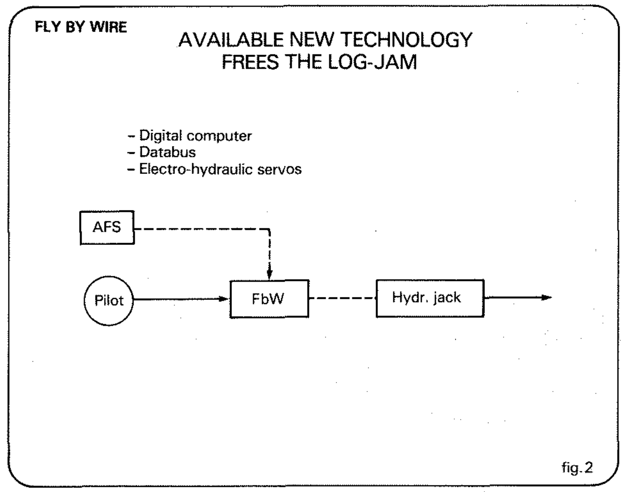

fig.2

Within Aerospatiale, the partner of Airbus Industrie in charge of flight control, the development of this new concept started 20 years ago.

II - First steps in electrically signalled flying controls

- The first application for civil aircraft was achieved to face the extension of the flight envelope with SST Concorde, which has been flying since 1969 with a full authority electrical control on the three axis.

The technology available at that time (analogue computer) and the lack of experience put a severe limitation on the system : a mechanical back-up was maintained (never used to our knowledge in revenue flight) and in this degraded mode the supersonic flight is no longer permitted.

- Another significant step has been achieved with the A310 and A300-600 upperwing control surfaces where there is no longer mechanical back-up.

There, the Fly-by-Wire concept has proven to be extremely efficient : with the same wing (A300-B4/A300-600) a weight saving of 300 kg was achieved plus some drastic simplification like the suppression of the low speed aileron and the roll control quality and efficiency was nevertheless improved. (Fig. 3).

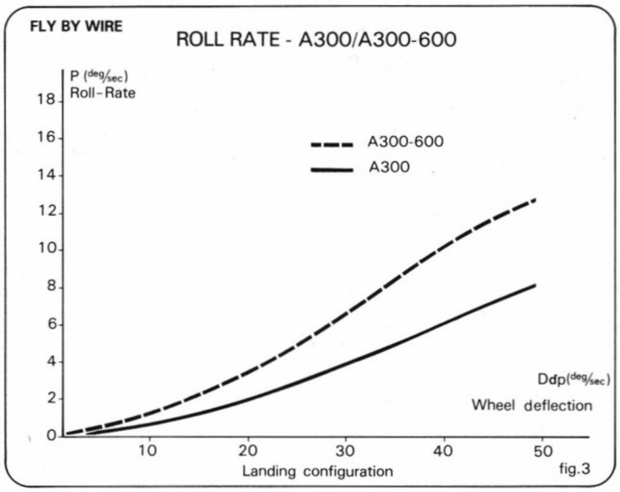

fig.3

Based on this experience it was reasonably obvious that the technology was now sufficiently mature to achieve a further step in simplification and weight saving and additional targets were settled like :

- Improve the protection at the border of the flight envelope
- Incorporate a load alleviation system
- Build up a new cockpit concept

Also, due to the novelty, some strong principles were laid down :

- Give priority to mature technology
- Use it only where most efficient
- Support as far as possible with flight experiments.

The first flight experiments were conducted during the second part of 1983 on our A300 test bird (A/C N° 3) which will be used for that purpose up to the end of 1985.

III - Electrical flying control tests achieved on an A300 A/C

3.1 System Definition (Fig. 4)

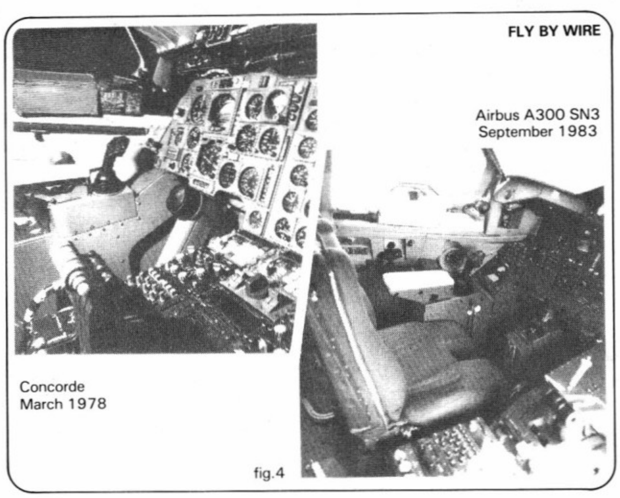

fig.4

- No change on F/O side
- Standard yaw control
- Electrical pitch and roll control input from a side-stick installed on the left hand console (Captain control column and wheel were removed)
- Electrical signalling achieved by the auto pilot with a specific software, which is further described. (Fig. 14 to 17).

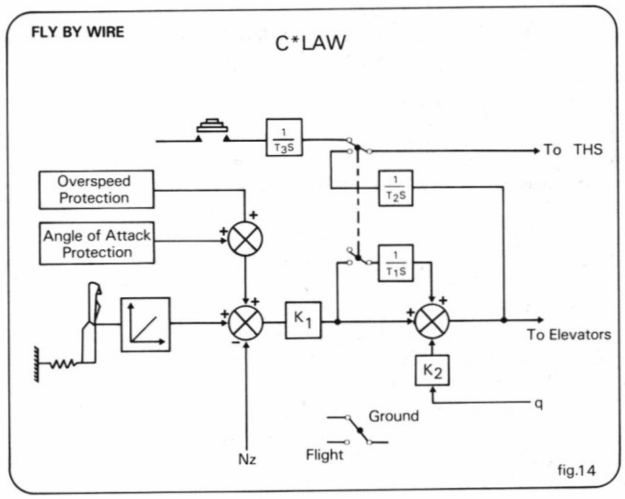

fig.14

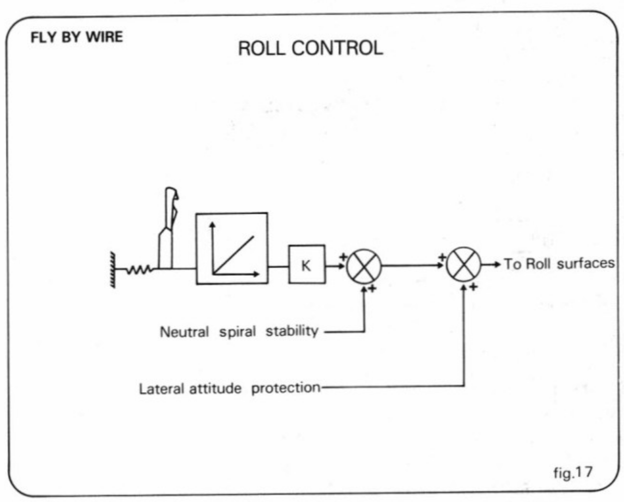

fig.17

3.2 Flight test achieved

- 75 flying hours were achieved. 48 pilots from 5 Airworthiness Authorities, 12 airlines, 3 aviation magazines and Airbus Industrie flew the aircraft.
- It is worth noting that before take off pilots have had a maximum of one hour flight simulator training.

3.3 Main results

- A qualitative assessment was made through a detailed questionnaire. The overall result was extremely positive (Fig. 5) and showed :
  . No difficulties of adaptation to side-stick
  . An unanimous approval of pitch law
  . An unanimous enthousiasm for the flight envelope protection, especially at low speed
  . An unexpected necessity to further develop lateral control.

A300 S/N3 — FLY BY WIRE AND SIDE STICK CONTROLLER EVALUATION — March 84

A questionnaires containing 42 questions was filled in by each team of visiting aircrew
25 such questionnaires were submitted

Summary of the results

Questionnaire answers

	Unacceptable					Excellent
RATING	1	2	3	4	5	6
No OF RESPONSES	17 1.6%	34 3.2%	92 8.8%	204 19.4%	352 33.8%	317 30.2%

Unanswered questions 34 or 3.2%
Total No of responses 1050 taken from 25 questionnaires
Note that 25 of the 51 responses in1&2 were related to roll characteristics

fig.5

- An attempt at quantitative assessment was made by manually flying 12 experimental circuits designed to pose a variety of flying problems. Three different combinations of aircraft and approach configuration were used, they are quoted FD (Flight Director and auto throttle system on), ILS (FD and AT off) and NDB (FD, AT and ILS off).

- These 12 circuits were flown twice by the same two pilots, once with the conventional control, once with the side-stick/FbW system. The results of this experiment documented several major performance benefits of the side-stick/FbW system :

  . All measurements of smoothness and stability favoured the FbW system. A typical example is the large reduction in transitions through zero of acceleration (Fig. 6), more, the absolute magnitude of acceleration is significantly reduced, for example in lateral from .004g to .001g.

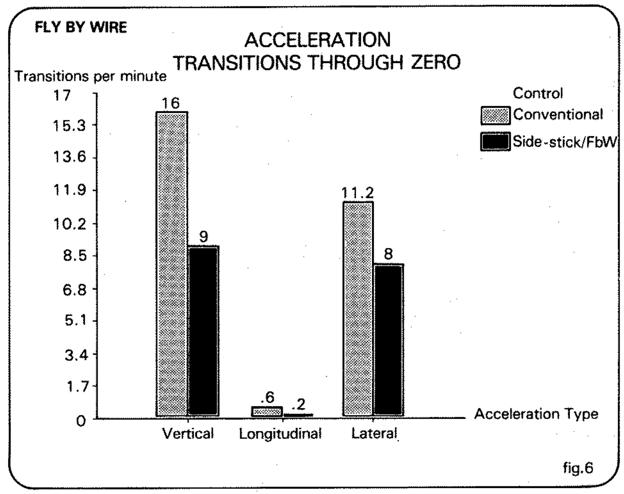

fig.6

  . The improvements in smoothness and stability noted above suggest that the aircraft/pilot system performs more efficiently when flown with side-stick/FbW control. This should yield reduced stress on the airframe and better fuel efficiency, which is confirmed by every recording of parameters related to drag/fuel burn. As an example the Fig. 7 shows the standard deviation of the N1 engine parameter achieved in both cases.

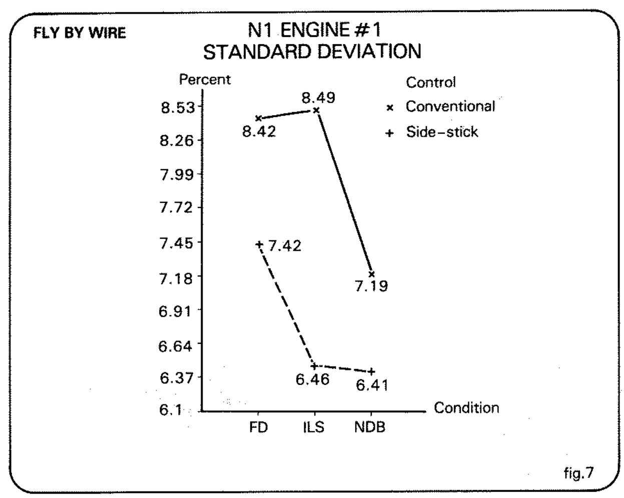

fig.7

  . A startling reduction of pilot task load is also obvious. (Fig. 8)

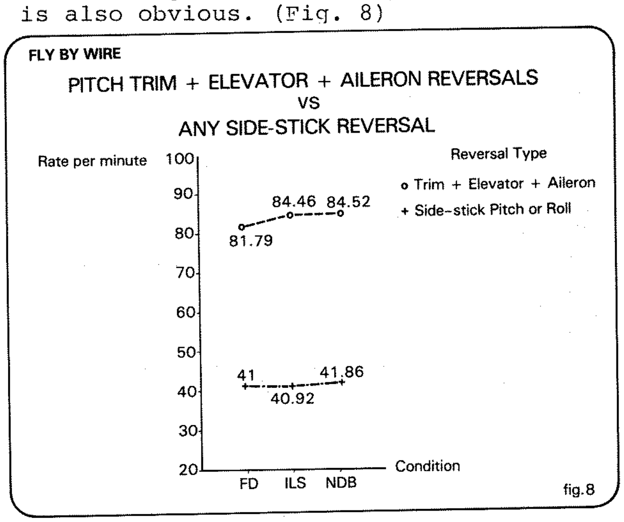

fig.8

IV - A320 Electric Flight Control System (EFCS) Architecture

4.1 Safety objectives

The target was to be able to dispatch the aircraft with one EFCS computer failed while still meeting the two following safety objectives :

- Complete loss of control : extremely improbable
- Any significant reduction of handling quality : remote

The difficulty to factually demonstrate that a momentary loss of all elctrical power is extremely improbable leads to the retention of a minimum mechanical back-up. Tests performed on A300 and A310 have shown that it was possible to keep a safe control in any configuration, over the whole flight envelope and in the whole range of CG by using only the rudder for yaw and roll and the trimable horizontal stabiliser (THS) for pitch. This leads us to the following architecture :

- a full EFCS will apply to roll and pitch control
- a minimum mechanical back-up will be ensured by a mechanically controlled rudder and standby THS control.

4.2 General architecture

- Pitch axis : 1 THS and two elevators (Fig. 9). Elevators are only electrically signalled, the THS is electrically signalled but incorporates a standby mechanical control.

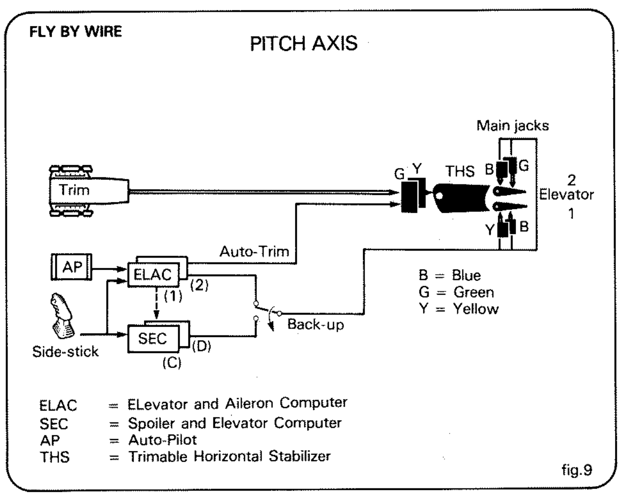

fig.9

- Roll axis : (Fig. 10)
  One aileron on each wing and four outer spoilers are all electrically signalled.

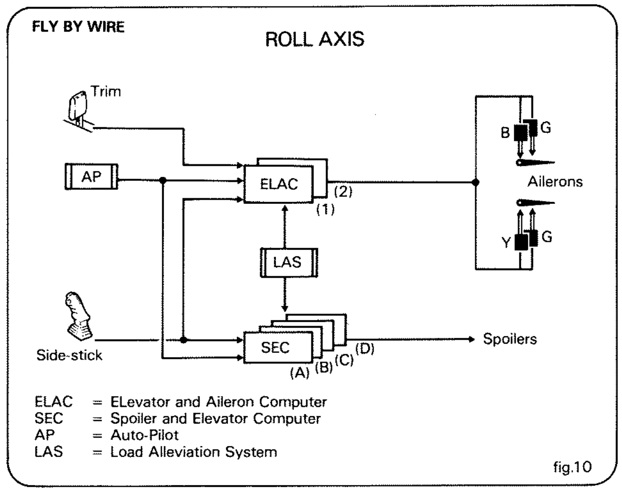

fig.10

- Yaw axis and ground steering : (Fig. 11)
  The rudder is mechanically controlled.

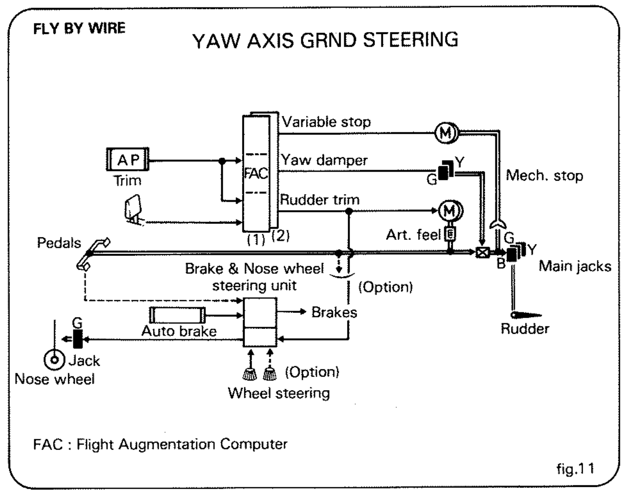

fig.11

4.3 EFCS system architecture (Fig. 12)

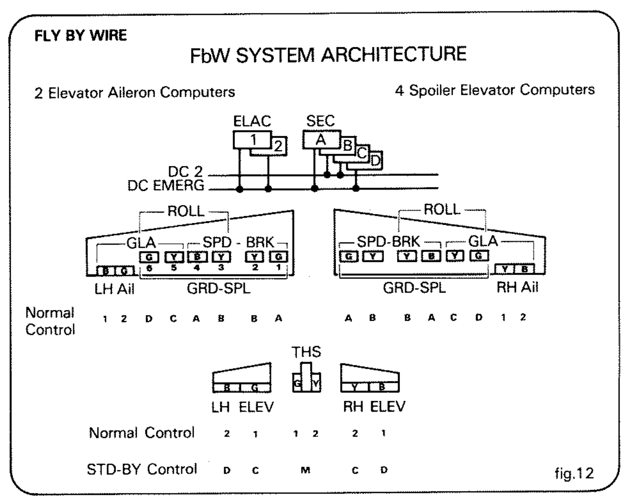

fig.12

Two types of computer achieve the electrical control : the Elevator and Aileron Computers (ELAC) and the Spoilers and Elevators Computers (SEC).

Surface controls are powered by hydraulic servo jacks electrically signalled and associated with analogue type position transducers (brushless inductive transducers in unpressurized area), servo valves (jet pipe type) and solenoid valves. Normally one servo jack per surface is ensuring the active control, the other one being in damping mode. In case of dual failure both are switched to a centering mode. (Fig. 13)

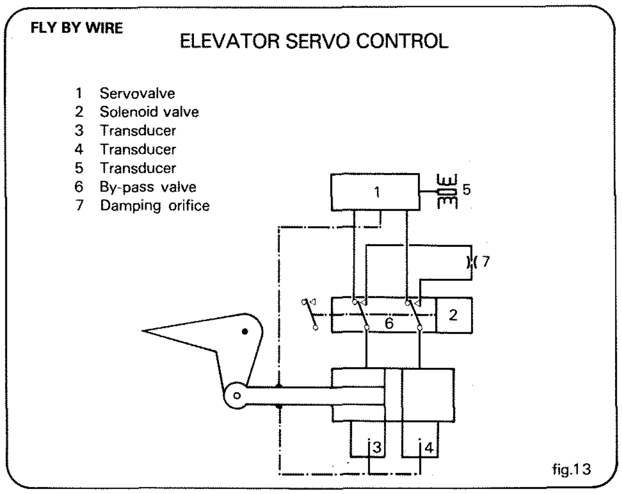

fig.13

A - Criteria for computer design

- Use of up to date matured technology
- Redundancies : two types of computer (dissimilar redundancy) are used to achieve roll control and elevator control. There are several computers of each type.
- Monitoring : one monitor channel is associated with each control channel. Dissimilar software and hardware are used for control and monitoring channels. An automatic test sequence is provided and a crosstalk is ensured between the two channels.
- A physical segregation is ensured between cable looms achieving controls separation.
- An outstanding effort has been made to protect against secondary effects of lightning strikes.

The emergency electrical power is delivered by a generator driven by an hydraulic motor on a circuit pressurized by a ram air turbine. So no limitation in time of this source exists in case of main generators failure.

B - Elevator, aileron computer (ELAC)

Two computers of this type are fed. Each of them achieves the control and monitoring of one jack on each aileron and each elevator and the control and monitoring of one of the electrical jacks driving THS screw jack control linkages.

C - Spoiler aileron computer (SEL)

Four computers of this type achieve the upperwing surfaces control, a standby elevator control and a standby control of the THS through the second electrical jack controlling the screw jack.

V - Control law

5.1 Pitch

Basically the said C* law (Fig. 14) is a short term direct flight path control by modulating the load factor (N_Z). At low speed a blend of pitch and load factor is used. Trim changes are automatically integrated. This auto-trim function is disabled below 200 ft to restore a standard flare feeling.

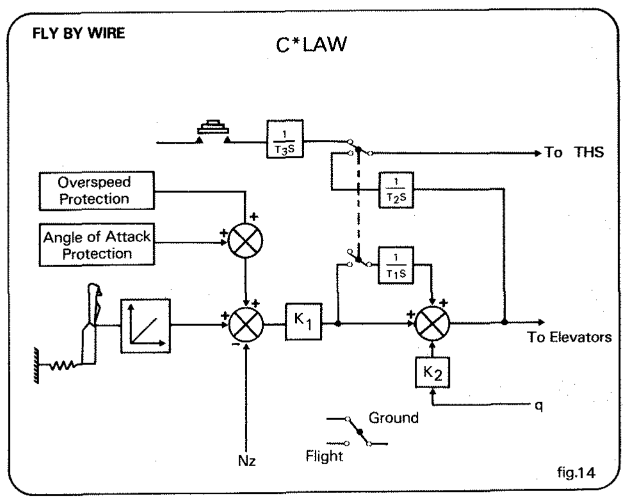

fig.14

This C* law includes several safety significant features and as such is a real revolution in aircraft handling :

- N_Z maximum driving value is limited where the stress office requires.
- A neutral stability is provided throughout the whole permitted flight envelope which is an old pilot's dream, BUT :
- An OVERSPEED PROTECTION (Fig. 15) provides a strong stability beyond V_{mo}/M_{mo} by introducing a positive load factor demand proportional to $\Delta V/\Delta M$, limited to 1.5g. The auto-trim is then stopped.

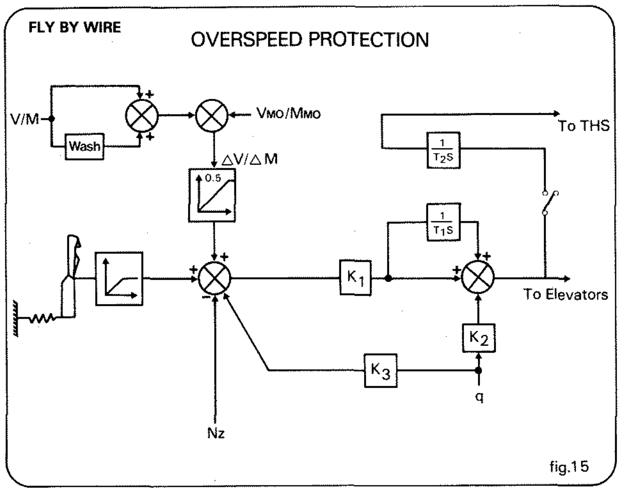

fig.15

- An unsurpassable ANGLE of ATTACK PROTECTION (Fig. 16) provides a deterrent stability preventing any excursion below stall speed. A nose down load factor input dependant on $\Delta\alpha$ is decreasing the pilot's input, the gain of which is also progressively decreased such that at maximum angle of attack, the maximum load factor achievable is 1. The value of maximum angle of attack is related to the configuration and the deceleration rate. The trim integrator is stopped as soon as the protection is acting.

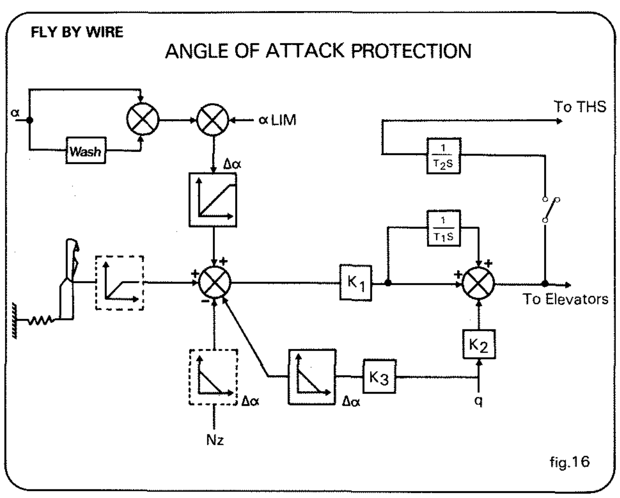

fig.16

A typical benefit of such a protection is its use to face a strong windshear situation : The autothrottle/α floor system already installed in every Airbus is automatically providing the full thrust in such a case, now by just pulling the stick fully back the full lift will also be made available : full thrust plus full lift is the best which can be provided to fly away.

5.2 Roll (Fig. 17)

A variable gear control is provided in roll offering an approximately constant roll rate to input ratio. Within the normal bank angle (± 30°) a neutral stability is offered, while beyond these limits a significant spiral stability will protect against lateral attitude upset.

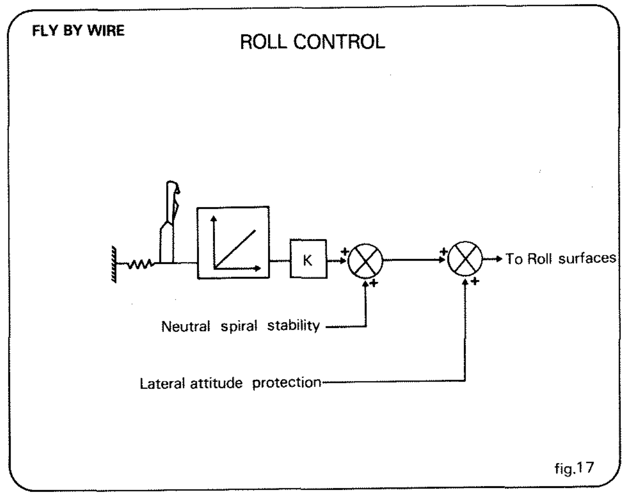

fig.17

VI - Pilot interface

6.1 Mini-stick

The central wheel was introduced in the car and the aircraft for two main reasons :

- The "horse" effect : having no more horse to keep the road, it became necessary for the pilot to continuously hold the track, thus a double-hand control was necessary. This is no longer the case when the system without any input is keeping the track. We have put a horse in our loop.
- Designed initially for a direct handling of the surface, the control had to transmit quite high forces. When the surfaces have been servoed, the natural friction and inertia of a lengthy mechanical linkage, still had to be handled but the pilot available forces were much too high and the necessary feel and protection had to be provided through an artificial feel system.

  With the EFCS there is no longer linkage to drive and the protection is directly provided from a computerized limit to the output.

  Therefore it was quite natural to consider the use of a "mini-stick", thus saving weight, volume and inertia.

6.2 Force or motion

- Several evaluations were performed worldwide. On simulator (no -g environment) the vote is 50/50, but as soon as the thing is flying there is an unanimous favouring of a significant motion.
- Displacement transducers are more simple and reliable than forces transducers. On A320 side-stick there are on each axis 10 such tranducers !

Our choice therefore was a centimetric motion mini-stick. Note that the law of effort per degree of displacement is asymmetric in roll.

6.3 Side-stick (Fig. 18)

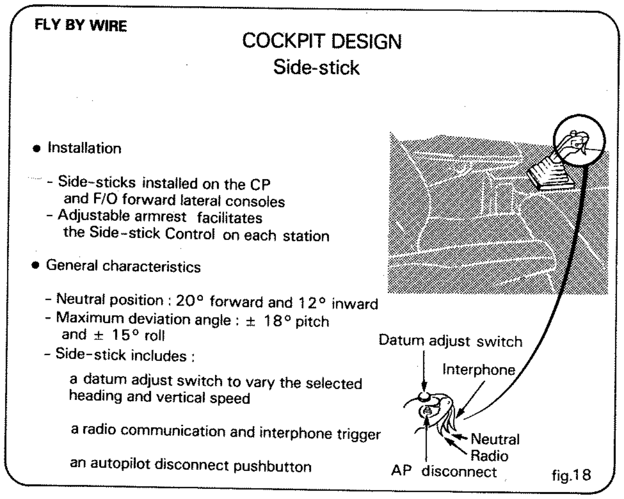

fig.18

Experience accumulated worldwide in simulator and flight test, higlights the difficulty to achieve a proper uncoupling between pitch and roll with a mini-stick in front of the pilot. This is no longer a problem with a side-stick.

It is also experimentally shown and confirmed by the airline experience with the standard wheel, that there is no difficulty to control from right or left hand or to transition from one to the other.

A side-stick provides the additional advantage to definitely clear the pilot view of the front panel instrumentation (Fig. 19 - cockpit view).

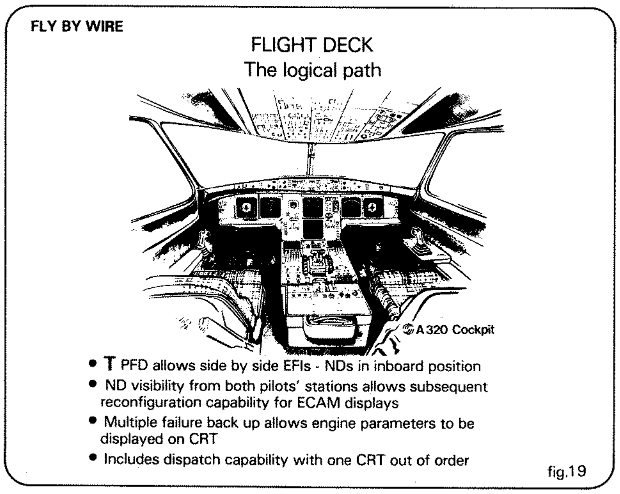

fig.19

The choice of a "side-stick" was definitely confirmed from the flight experiment in Concorde and Airbus.

The side-sticks are installed on the captain and F/O forward lateral consoles. An adjustable armrest to facilitate the side-stick control is fitted on each seat.

As there is no longer trim the side-stick includes a datum adjust switch to vary the selected heading and vertical speed.

A solenoid controlled by A/P computer freezes the stick in neutral position in A/P mode. Nevertheless if the pilot applies a force above a given threshold the stick becomes free and A/P disengages.

6.4 Interconnection

After careful reflection and tests on a flight simulator we have chosen not to have a mechanical linkage between the sticks but an electronic mixing between signals delivered by the two sticks with the following logic :

- Below a certain threshold (1/3 displacement) both orders are algebrically added. The resulting order is X + Y.
- Beyond this threshold the second stick to move through keeps the full authority, and the first one is limited to 1/3 (remaining displacement over 2/3 is ineffective).

In order to substantiate our proposal we have to review the operational reasons that could lead to the request for a linkage. There are four main reasons which are by order of importance :

1- To counter a "dead man" input (the "dead man" may well be a book or any reason to jam a stick).
With two hands and the full body it was possible to sustain a quite high break force, but this is no longer possible using one wrist. A rather low break force would therefore have to be considered to disconnect the coordination link with the recurrent risk of breaking through in normal counter operation (see 2).
With our proposal there is no longer a problem. In the worst case the remaining stick is left with two thirds of the full authority without additional effort.

2- To counter a dangerous manoeuver of the other pilot.
In case of a linkage such a counter action is braked by the opposite effort and considerably slowed down when not hampered. With the "mixing" the counter action is immediate and may be as efficient or smooth as desired.

3- To detect the use of the stick by the other pilot.
With standard flight control the aircraft may move significantly without flight control input and also a significant input of the flight control may have no apparent effect on aircraft (i.e. when countering the flaps or the engine trim change).
With the Fly-by-Wire system there is a consistant biunivocallity between aircraft movement and stick input at least in the normal flight envelope and out of minimized turbulence effect : no input, no motion.
Therefore the natural detection of roll or load factor gives an unmistakable warning that the other pilot (or the AP)

is inputing the flight control and the stick linkage is not necessary.

4- To lead a trainee in a tactile way
Although we have checked in the simulator that there is still a "feeling" of the other input, it is quite clear that the "mixing" does not give the same quality of back-up as a coordination.

But is it necessary ?
We are building a much better flying control system, which is much easier to fly, which is much easier to teach. And, indeed, we have released a lot of line pilots on our experimental aircraft left side-stick with a dead right stick, and we never had to disconnect.

This fourth reason is thus most probably of no significance and certainly not important enough to counter balance the obvious advantage shown in the first three points.

Therefore our conclusion is that on a pure operational point of view the proposed mixing is significantly better than any linkage.

VII - Certification Issue

For any new aircraft certification, Airbus Industrie is now bound to the Joint Airworthiness Requirement JAR 25 - Change 10, as required by the major European Airworthiness Authorities.

No difficulties are expected to meet the level of reliability required as per the objectives of JAR 25-1309 and the electrical redundancy requirements of JAR 25-1351. However it is obvious that not all the various requirements of sub part B (Flight) are appropriate. For example :

. Stall speeds definition and demonstration (JAR 25.103, 201, 203 and 205) :

The presence of the low speed protection function prevents demonstration of speeds lower than Vslg. Nevertheless the safety level provided by the protection must not result in performances penalties compared with conventional A/C and so a special condition has to be established defining a reference minimum speed lower than Vslg for performance calculations. This speed should be justified by maneouvrability criteria at the Reference Speed appropriate to the high lift device configuration.

. Stick force per g (JAR 25.143 f)

Control laws proposed are such that there is no stick force per g in stabilized turn up to 33° bank angle and therefore the system does not comply with the letter of the requirement.

However, we consider that the load factor limiting law and the artificial forces introduced in the side-stick for bank angles greater than 33° provide a safety level equivalent to that intended by the regulation.

. Maximum forces for temporary and prolonged application (JAR 25.143C and ACJ)

The values proposed by the requirement are only applicable to conventional controls operated by both hands.
Values applicable to a side-stick will be defined by simulator tests and included in a special condition.

. Static longitudinal stability (JAR 25. 171, 173, 175)

The positive static longitudinal stability requirement is to ensure that due to inadvertent control input or to atmospheric disturbances, the A/C will remain or return inside the normal flight envelope.
The EFCS and control laws provide a neutral stability inside the normal flight envelope, then the A/C does not literally comply with the requirement. However, due to the presence of low speed and high speed protections and the positive stability outside the normal flight envelope the level of safety obtained is equivalent to that intended by the regulation. A special condition has to be prepared to cover this aspect.

. Stall warning (JAR 25.207 and ACJ 207b)

A stick shaker is generally agreed as an acceptable mean of compliance with this requirement. The presence of a low speed protection function reduces the absolute importance of such a device and an alternative warning will be proposed.

. Out of trim characteristics (JAR 25.255 and ACJ)

With the control laws proposed in the EFCS, the aircraft is automatically trimmed inside the normal flight envelope. Out of trim becoming impossible, this requirement is not applicable.

. Rotation speed (JAR 25.107 e) IV)

Due to system design, the maximum practicable rotation rate is the normal rate : this requirement is therefore not applicable.

A joint task force grouping the four major European Airworthiness Authorities (DGAC, LBA, CAA and RLD), the three major European manufacturers (AS, MBB, BAe) and Airbus Industrie has been settled to identify all non-appropriate requirements, establish special conditions and interpretative material and proposed rule changes.
So far no significant difficulites to succeed in good time have been identified.

VIII - Conclusions (Fig. 20)

FLY BY WIRE

FROM A 300 TO A 3 XX

- 75 % fewer LRUs
- 600 kg weight saving
- 40 % maintenance cost reduction in chapter 22 and 27
- 30 % transition training cost reduction
- – 5 % fuel efficiency potential (relaxed stability)

fig.20

The EFCS as proposed is the result of a logical approach to take the maximum of benefit out of the available modern technology. Benefits are quoted in all significant areas :

- Safety : No more stall, overspeed or over-stress are the actual premiums of such a system.
  The optimum cockpit interface may at least be designed.
  In addition the possibility to achieve a standard behaviour of the aircraft round the flight envelope, although not quantifiable, will most probably further improve the adequacy of pilot response.

- Training : The possibility to offer the same handling characteristics whatever the aircraft type is expected to reduce the transition training cost by about 30 %.

- Maintenance cost : Four times less LRU, a much easier trouble shooting, a drastic reduction in line maintenance adjustment procedure will lead to a 40 % maintenance cost reduction as far as ATA chapters 22 (AFCS) and 27 (Flight Control) are concerned.

- Efficiency : Last but not least the aircraft efficiency will be significantly improved. Considering aircraft of the same size and aerodynamic standard, a 600 kg weight saving has been computed and a fuel saving of about 5 % is expected from a proper use of relaxed stability potential.

  There is no significant technical risk. The major difficulties are expected in the field of the natural and reasonable conservatism of Airworthiness Authorities and crews, but the necessary steps have been taken to overcome these difficulties in the natural way, that is rational logic and experiments.