DEVELOPMENT OF MANUAL FLIGHT CONTROL FUNCTIONS FOR A SMALL TRANSPORT AIRCRAFT

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Abstract

An advanced small transport aircraft currently under study at DASA is to be equipped with an electronic primary flight control system. This paper discusses the manual flight control functions that will be implemented in that system. Design objectives are reviewed, an overview of the flight control system is given, the function of flight control laws is explained and the development process is described. Finally, test results derived from high-fidelity, fixed-base ground simulator tests and from flight tests with the DLR's VFW614/ATTAS test bed are discussed.

Nomenclature

ACC	accelerometer
ADIRS	Air Data/Inertial Reference System
AOA	angle of attack
ATTAS	Advanced Technologies Testing Aircraft System
CASE	computer aided software engineering
DA	Deutsche Aerospace Airbus
DASA	Deutsche Aerospace
DLM	Direct Link Module
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt
EFCS	Electronic Flight Control System
F_1, F_2	thrust (left hand, right hand)
FBW	fly by wire
FCL	flight control law
h	altitude
IOM	Input/Output Module
M	Mach number
ND	Navigation Display
n_z	normal load factor
PFCU	Primary Flight Control Unit
PFD	Primary Flight Display
PFM	Primary Flight Control Module
RA	radio altimeter
S/W	software
t	time
V	airspeed
V_{CAS}	calibrated airspeed
V_{lim}	airspeed corresponding to α_{lim}
V_{MO}	maximum operational speed
V_{prot}	airspeed corresponding to α_{prot}
V_{SH}	stick shaker speed
V_{Stall}	stall speed
α	angle of attack
γ	flight path angle
η	elevator deflection
η_{Tr}	horizontal stabilizer deflection
θ	pitch attitude
ξ_R	aileron deflection (right hand)
ϕ	bank angle

Introduction

Today, the application of fly by wire (FBW) technology to civil transport aircraft can be considered as the state of the art. Airbus Industrie was the first aircraft manufacturer to make use of this technology:

- flight control laws (FCL) and side stick operation was demonstrated in flight tests with an A300 test bed (1983-1985);

- the A320 was the first civil transport to be equipped with an electronic flight control system (EFCS);
- five aircraft types using this technology (A319, A320, A321, A330, A340) are now under production, and more than 500 aircraft will be in service by late 1994.

Boeing's first transport with EFCS - the 777 - has still not flown at the time of this writing (May, 1994), though it will almost certainly have accomplished its first flight by the time you read this article.

The projection for the end of the century is that more than 1000 aircraft with EFCS will be flying - most of them AIRBUS - and more than 10,000 pilots will have been trained.

Since 1986, Deutsche Airbus has been working on a small transport aircraft in the 100-seater class that will enter service in 2002, and will operate far into the 21st century (Fig. 1). An early study has shown that for this aircraft, EFCS is more suitable than mechanical flight controls:
- it targets airlines that operate fleets with bigger aircraft, and increasingly, these will be equipped with EFCS;
- it will operate in a future air traffic environment that will require more complex functions and enhanced maneuvering capabilities.

The price of a commercial transport is related to the number of passenger seats, and can be given in terms of dollars per seat. As the price of avionic systems - such as EFCS - is virtually independent of aircraft capacity (assuming equivalent performance), the EFCS share in the specific cost of a 100-seater is nearly twice that of a 200-seater[1].

Therefore, design to cost is a major challenge in EFCS development for small transport aircraft.

Design Objectives

Minimum requirements for EFCS are defined by the certification regulations. Additional requirements come from market analysis and the perceptible progress of technology.

Generally, it can be said that an aircraft that will enter service fifteen years after the A320 will have to fullfill at least the same standards even though it may be smaller in size: that is, it must offer:
- a three-axis fly-by-wire control concept;
- control of aircraft state parameters by means of feedback;
- flight envelope protection.

Due to the unfavorably high share that EFCS contributes to the specific cost of a small transport aircraft, cost efficiency becomes the dominating factor in the EFCS design process. Flight control law design, as part of EFCS design, will influence the following cost factors:
- system development costs;
- aircraft qualification costs (stability and control);
- crew training costs;
- modification costs.

A cost-effective FCL approach must be simple, based on proven techniques that are accepted by the certification authorities, and should use familiar standard control functions in order to reduce crew training costs. Special attention has to be paid to the software design process, as modern design tools (CASE tools) may significantly reduce software design costs if properly applied.

System Overview

A block diagram of EFCS is shown in Fig. 2. All flight control surfaces are electrically controlled and hydraulically activated (Fig. 3). The stabilizer and the rudder have an additional mechanical link as a backup.

In the cockpit, we find:
- two side sticks for pitch and roll control (not mechanically coupled);
- two pair of pedals for yaw control (rigidly interconnected);
- a rudder trim switch;
- two handwheels for control of the trimmable horizontal stabilizer;
- two priority push buttons;
- a speed brake lever;
- a slat/flap lever;
- a thrust lever.

Sensors that measure feedback parameters include:
- three air data/inertial reference units (ADIRU);
- two radio altimeters (RA);
- accelerometers (ACC).

Additional sensors necessary e.g. for ground spoiler logic are
- wheel tachometer;
- landing gear switch;
- thrust lever position sensor.

For flight parameter indication, the primary flight display is used. Two lamps indicate priority if requested by one of the pilots. System status and failure conditions are displayed on the Engine Display and the System Display, respectively. The quadro-duplex computer architecture is realized by two identical Primary Flight Control Units (PFCU) (Fig. 4). Each PFCU has two I/O Modules (IOM) and each module has a dissimilar control and monitor lane. The FCLs are calculated in the Primary Flight Control Modules (PFM). A direct link function which directly connects control devices and control surfaces is provided as an additional dissimilar backup for the unlikely event of a generic fault.

Flight Control Functions

The FCLs provide both primary control functions (pitch, roll and yaw) and secondary control functions (airbrake and ground spoiler). In addition, they calculate operational and limiting speeds as well as parameters having to do with the flight envelope protections, and display these on the PFD. Generally, the functional design is aimed at crew commonality with AIRBUS aircraft; all functions and the man-machine interface are similar in order to reduce the cost of transition training. However, everything that is hidden to the pilot - i.e. systems and software - is realized differently.
For normal operation (that is, as long as no systems have been degraded due to failures) three modes are necessary:

- ground mode;
- inflight mode;
- flare mode.

The transition from one mode to the other has to be smooth, with no adverse effect on the pilot's ability to control the aircraft.
These normal laws provide complete flight envelope protection as follows (see Fig. 5):

- load factor limitation;
- high angle of attack protection;
- high speed protection;
- pitch attitude protection;
- bank angle protection.

Envelope protections are designed to prevent specified boundaries from being exceeded. They assist the pilot by initiating corrective action if necessary, but they do not assume the pilot's decision-making role or his responsibility for safe flight.
In the event of multiple system failures, the FCLs shed protection functions or degrade from the normal law to the direct law, according to the number and nature of the successive failures.

Inflight Mode

Pitch Normal Law. The pitch normal law is a load factor demand law with automatic trim function. At low speed, load factor is blended with pitch rate. With the side stick at neutral during level flight, this law provides short-term flight path stability and compensates for turbulence. Turn compensation is provided up to bank angles of 33°.

Load Factor Limitation. The load factor is limited to
-1.0g and +2.5g (slats in),
0.0g and +2.0g (slats out).
This still allows adequate maneuvering capability even in an abrupt avoidance maneuver without risk of structural overload.

High AOA Protection. If α_{prot} (equivalent to 1.13 V_{s1g}, 1.03 V_{s1g} for takeoff) is exceeded, an angle of attack demand law becomes active, protecting the aircraft against stall caused either by inadvertent pilot action or as a consequence of atmospheric turbulence.
Side stick command is interpreted as an angle of attack demand with:
α_{prot} when the side stick is at neutral, and
α_{lim} when the side stick is in the full back position (see Fig. 6).

High Speed Protection. If airspeed exceeds a threshold of V_{MO} + 6 kts (M_{MO} + 0.01) which is reduced in high forward acceleration or low pitch attitude cases, the pilot's nose down command authority is gently reduced to zero and a nose up command is automatically introduced. Thus the airspeed will never exceed V_{MO} + 30 kts (M_{MO} + 0.07), even if the pilot suddenly applies full forward side stick. For a long-term full nose down side stick command, the maximum airspeed is limited to V_{MO} + 16 kts (M_{MO} + 0.04).

Pitch Attitude Protection. Pitch attitude is limited to +30° nose up (+25° at low speed) and -15° nose down. The pitch attitude protection reduces pilot authority beginning some 5° before a limit is reached, in order to stop at the limit without overshoot.

Roll Normal Law. Roll normal law is a roll rate demand/bank angle hold law. The roll rate demand is proportional to side stick deflection and limited to $\pm 15°/s$. Bank angle hold is provided up to $\pm 33°$ bank with automatic turn coordination and turn compensation. This allows turns to be flown in normal airline operations without pitch input.

Bank Angle Protection. Above $\pm 33°$ bank angle, positive spiral stability is introduced (Fig. 7). Maximum bank angle is limited to $\pm$ 67° ($\pm 45°$ in High AOA Protection, $\pm 40°$ in High Speed Protection). Turn compensation is reduced in accordance with the bank angle so that it is necessary for the pilot to pull the side stick. Level flight can be maintained with a 67° bank at the load factor limit of 2.5 g.

Yaw Normal Law. The yaw normal law is a direct control-to-surface law (pedals to rudder) with maximum deflections limited by the rudder travel limitation function. Additionally,
- yaw damping,
- turn coordination, and
- automatic trim in case of engine failure

is provided.

Flare Mode

In order to provide a conventional flare (where the pilot has to pull the side stick back progressively to achieve a gently increasing pitch attitude during flare), the longitudinal control laws are switched at 50 ft from inflight to flare mode:
- automatic trim is deactivated;
- a modified normal law with load factor and pitch rate feedback is activated.

Ground Mode

On the ground, side stick deflections correspond directly to elevator, aileron and roll spoiler deflections. There is no automatic pitch trim. After takeoff, the flight mode is progressively blended in.

FCL Development Process

Development of the system is an iterative process, and several different models are used to describe it. In the V-Model, the analytical steps are listed on the left leg, and the steps towards a synthesis on the right leg. The links between them define verification and validation activities on different levels (see Fig. 8).

FCL development is part of the system development process, and a rational and methodical approach can reduce development costs significantly. Therefore substantial effort has been devoted to three key elements:

- a CASE Tool:	HOSTESS
- test facilities:	development flight simulator
- flight test:	VFW614/ATTAS flying test bed.

These are described separately below.

The CASE Tool HOSTESS

Based on experience (e.g. with the center of gravity control computer for A300 and A310), DASA has developed the CASE tool HOSTESS (high order structuring tool for embedded system software). Its goal is to standardize software specification, to automate the coding process, to provide automatic checks and testing, to improve software documentation, and to facilitate configuration management. HOSTESS provides:
- software specification using a graphical block diagram language in conjunction with a symbol library and assembly rules which are easily understood by electronics and automation engineers (Fig. 9);
- a consistency check of each module;
- automatic coding with different code generators (FORTRAN, ADA, etc.);
- a hierarchical software structure.

The benefits are:
- a reduction in coding errors;
- the automatization of routine activities during the software development cycle, especially for modifications;
- standard, unambiguous software specification.

Flight Simulator

Tests on the flight simulator are conducted in order to validate the FCL functions and their reconfiguration in a real-time environment. In particular, the transitions from one mode to another in combination with different pilot inputs and various flight states can only be investigated in real time.

The DA flight simulator facility has been continously upgraded over the past years and now features:
- high fidelity simulation models;
- generic 100-seater cockpit (sidestick, 6 displays, etc.);
- visual system;
- sound system;

- data acquisition and analysis.

DA has selected a fixed-base development flight simulator for cost effectiveness reasons: the additional capabilities that a motion system would provide do not justify the expenditure for its acquisition and maintenance, especially in the light of the inherent limitations that result from the limited travel that can be realized. However, a good quality visual system does provide a significant enhancement of simulation fidelity. More than 1000 simulator flight hours have been "flown" during the FCL development program, with engineers and various test pilots at the controls.

ATTAS Flight Tests

ATTAS System Overview

ATTAS (Advanced Technologies Testing Aircraft System) is a modified VFW614 aircraft which is operated by the DLR as an inflight simulator and demonstrator aircraft (Fig. 10). The aircraft is equipped with complete flight test instrumentation and an additional fly-by-wire flight control system.[2,3]

This experimental reduced-authority FBW system provides an "experimental and control computer" where user-defined software can be implemented.

For the FCL experiments, it was decided to adapt the FCLs to the VFW614's flight dynamics, and not to use its mimicry capabilities to match ATTAS dynamics to the expected dynamics of the future small transport aircraft.

ATTAS can be operated in three principal modes:

- basic mode: VFW614 standard mechanical flight control;
- FBW mode: FBW system active as a direct link;
- SIM mode: FBW system active with user-defined functions.

Flight tests are performed in the SIM mode by the experimental pilot, who occupies the left seat. His side of the cockpit is equipped with a side stick and two displays (PFD and ND) (Fig. 11). The safety pilot in the right seat monitors commands by means of the moving control column and aircraft response, and overrides the experimental pilot if specified limits are exceeded.

The flight control software under test is implemented in the "experimental and control computer" of the ATTAS FBW system.

For safety reasons, the VFW614 flight envelope is restricted in the FBW and SIM modes (Fig. 12), so that:

- the minimum airspeed is $V_{SH} + 2$ kts ($\triangleq 1.2\ V_{Stall}$);
- the minimum altitude is 500 ft (10,000 ft if $V < 1.5\ V_{Stall}$);
- the maximum operational airspeed/Mach number is 288 kts/0.63;
- the maximum bank angle is $\pm 45°$ ($\pm 30°$ if $V < 180$ kts).

The high angle of attack and high speed protection features are so designed that neither pilot commands nor external disturbances can cause the aircraft to exceed the above limits.

Flight Test Description

During the flight test program, six test flights, all about 2.5 hours long, were carried out by several test pilots with different flight experience.

Test procedures were specified both with a view to validating flight control functions over the whole flight envelope and to evaluating handling qualities. Before each flight, the flight program and test procedures were verified and trained in the flight simulator.

For investigations of handling quality, a special maneuver was defined by DLR, in which the pilot flew a lateral and vertical pattern in the normal inflight law, running into the bank angle protection during the 45° bank turn (Fig. 13).

Flight Test Results

The first two test flights were dedicated to adjusting the FCLs to the ATTAS FBW system as to:

- sensor calibration and filtering;
- fine tuning of gains (e.g. turn coordination at low speed);
- adaption to the reduced-authority FBW actuators.

Minor software modifications became necessary. As an important result, the FCL development methodology proved to be efficient. Software modifications could be performed within a short time, reliably and accurately, using HOSTESS. Simulator tests showed high fidelity with respect to the flight tests except for the well-known and accepted shortcomings: real-life/visual system disparity, motion, and pilot anxiety levels.

Two representative time histories are presented to illustrate FCL functions. Fig. 14 shows the results of a lateral maneuver where the pilot was to stabilize bank angles of 33°,

37.5° and 45° without rudder and thrust inputs. The roll rate command/bank angle hold law is active up to 33° bank angle. Thus, the pilot initiated the turn with a side stick roll input and released side stick to neutral on approaching the 33° bank angle. Note that no pitch input is required to hold altitude (turn compensation). At bank angles of over 33°, bank angle protection becomes active and the FCLs switch to the bank angle command mode. To stabilize at 37.5° bank, the pilot has to deflect the side stick. The maximum bank angle for the ATTAS SIM mode is 45°, and is achieved by maximum side stick deflection. As turn compensation is reduced beginning at 33°, the sink rate has to be compensated manually via the side stick pitch command.
Pitch normal law and high AOA protection are illustrated in Fig. 15. The pilot decelerates the aircraft by reducing thrust to idle without side stick input. At t = 33s, AOA reaches α_{prot} and the high AOA protection is activated, which stabilizes α_{prot} for stick to neutral. After α_{prot} is stabilized, the pilot commands α_{lim} by pulling the side stick full back.
As with these two examples, all other FCL functions have been tested successfully. Pilots judged the inflight results to be consistent with the simulator results despite transition processes due to mode switching, particularly from the n_z-command to the α-command. This transition, which is sensitive to pitch rate and load factor cues, could only be optimized by means of flight testing. The handling qualities for normal operations were classified as Level 1.

Conclusions

A comprehensive set of manual control functions is being developed for implementation in a small EFCS transport. High priority has been given to an economical approach, which will reduce system development and aircraft qualification costs. The resulting design is functionally similar to that of AIRBUS aircraft, in order to offer the same standard and reduce transition training costs.
The FCLs have been validated with flight simulator tests and have been favorably received by pilots. For inflight tests, they were adapted to the dynamics and operational constraints of the DLR's VFW614/ATTAS flying test bed. Flight tests also produced consistantly favorable evaluations of the FCLs.
Further development with emphasis on simplification of system-associated functions is now in progress, and is aimed at supporting the projected 2002 delivery date for the small transport aircraft.

Acknowledgements

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Fig. 1: Future Advanced Small Airliner

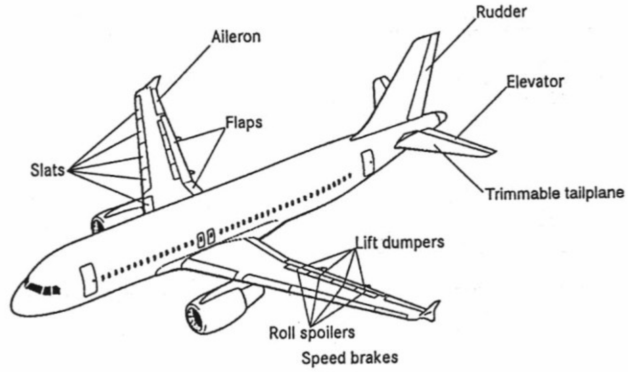


Fig. 3: Control Surfaces

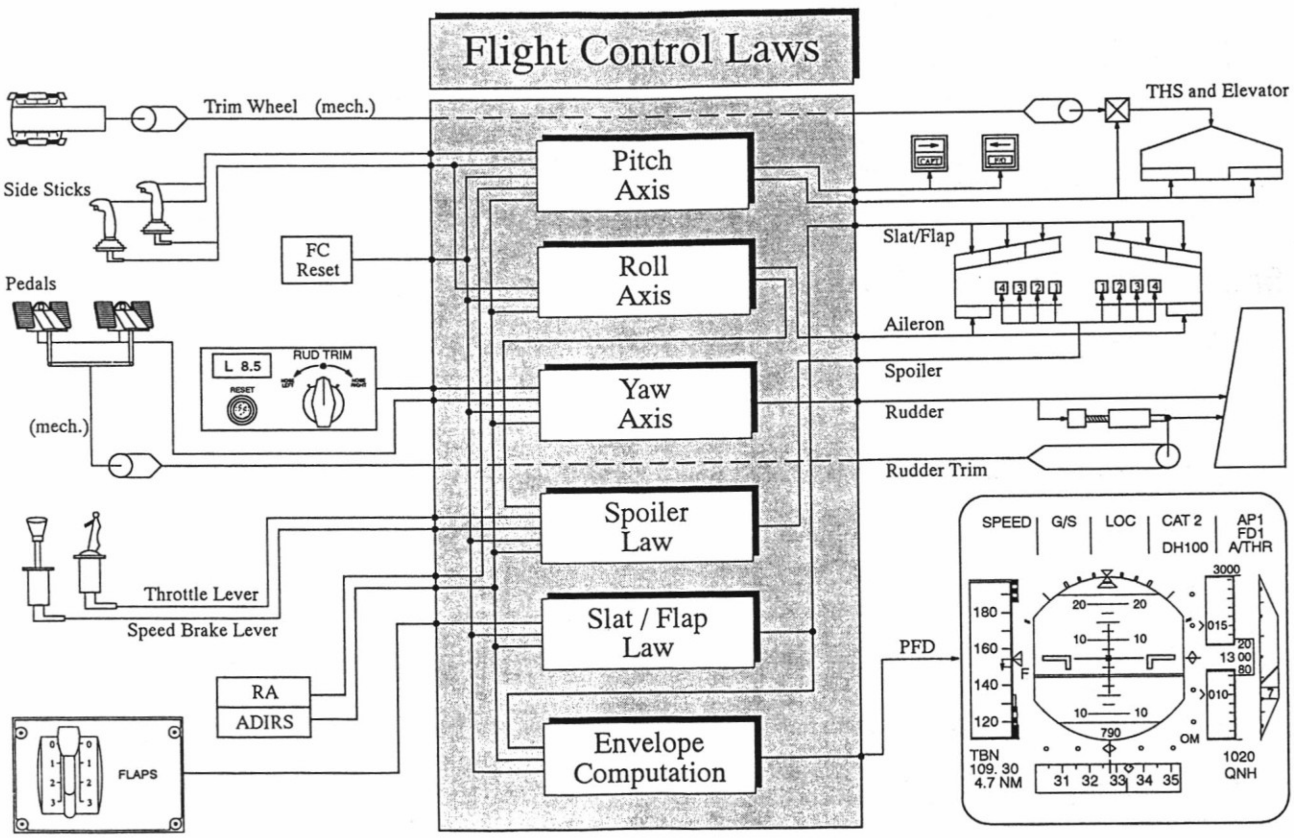
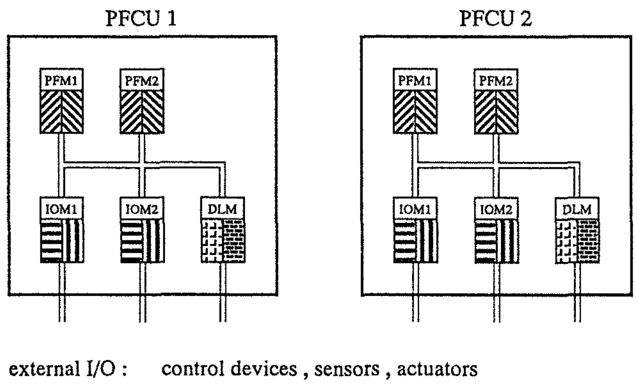


Fig. 2: EFCS Block Diagram



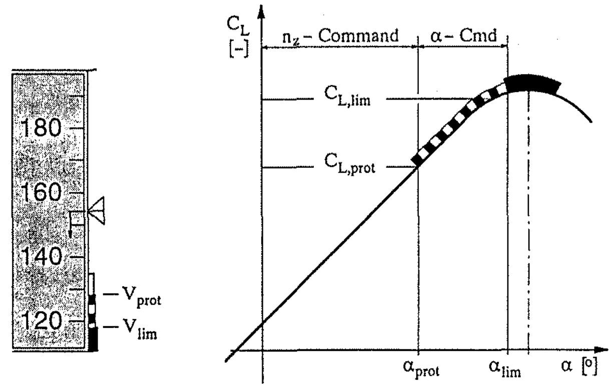
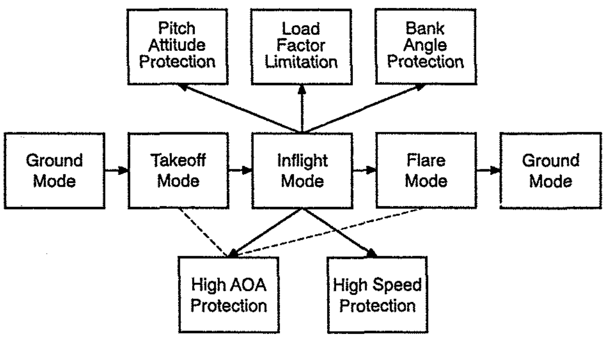


Fig. 4: Architecture of Flight Control Computer

Fig. 6: High AOA Protection



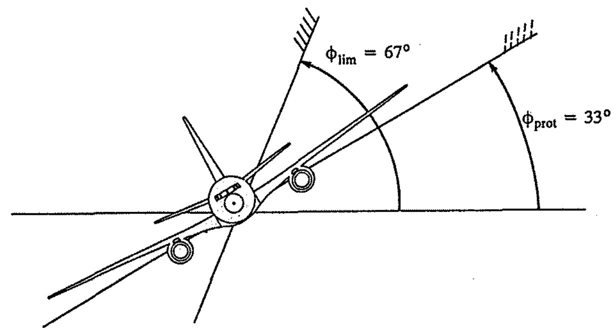


Fig. 5: Normal Flight Control Law Modes

Fig. 7: Bank Angle Protection

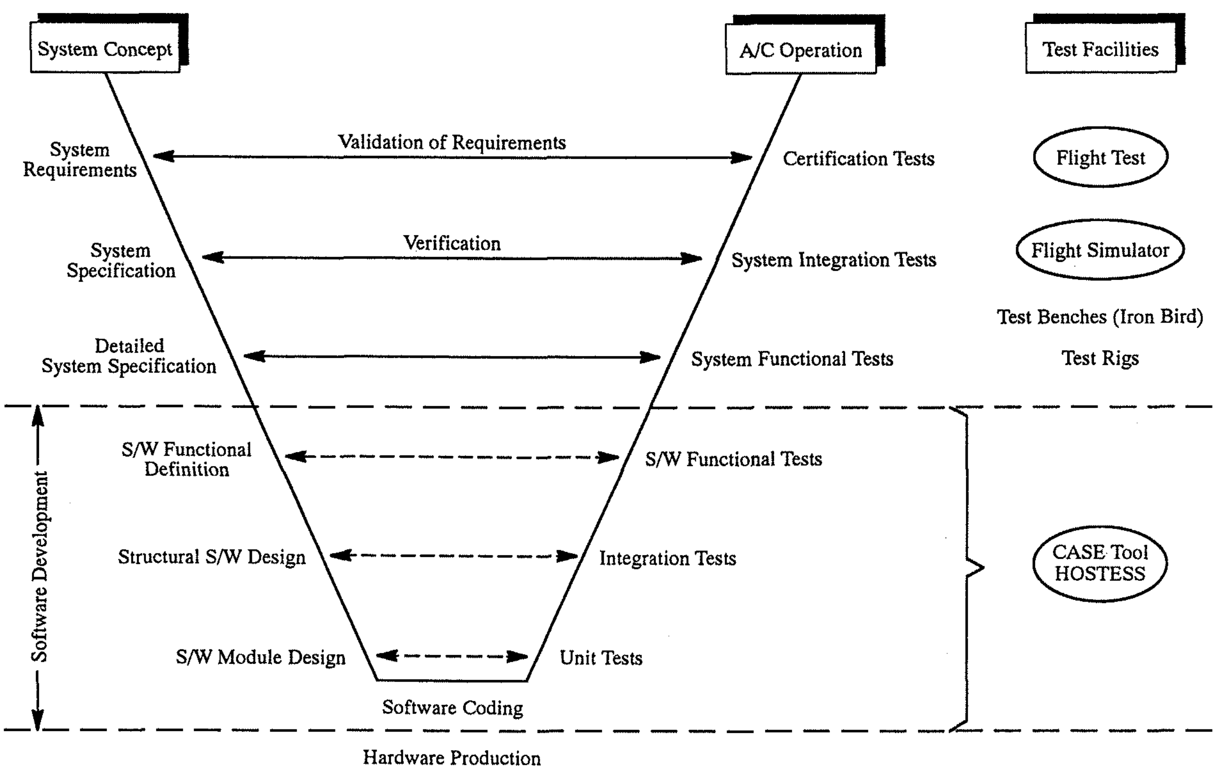
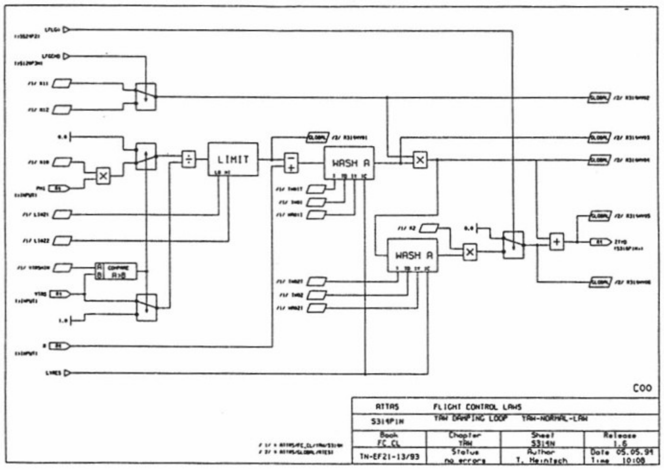
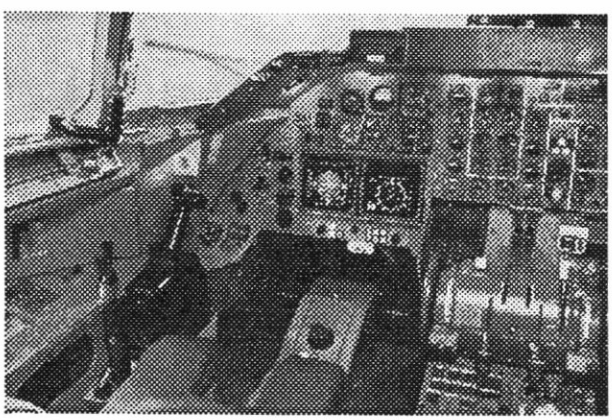


Fig. 8: V-Model for FCL Development Process

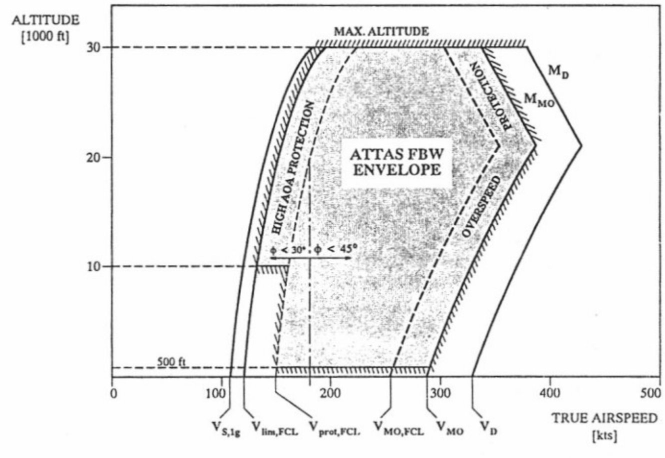


<u>Fig. 9:</u> HOSTESS FCL Block Diagram Specification

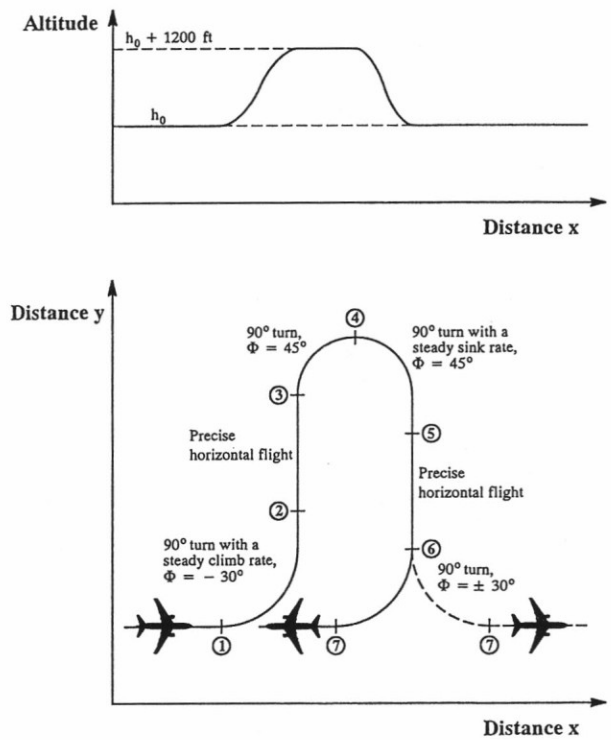
<u>Fig. 10:</u> VFW 614/ATTAS (photo by courtesy of DLR)



<u>Fig. 11:</u> VFW 614/ATTAS Experimental Cockpit (photo by courtesy of DLR)



<u>Fig. 12:</u> ATTAS Flight Envelope



<u>Fig. 13:</u> SAFIR-Maneuver

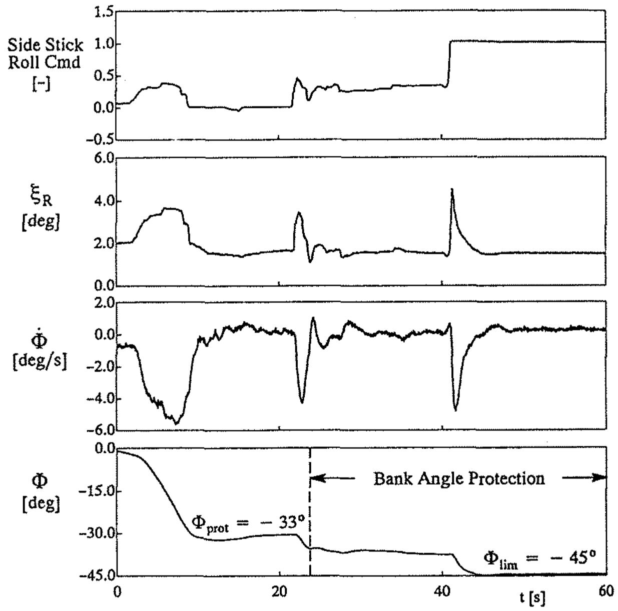


Fig. 14: Lateral Control with and without Bank Angle Protection (flight test result)

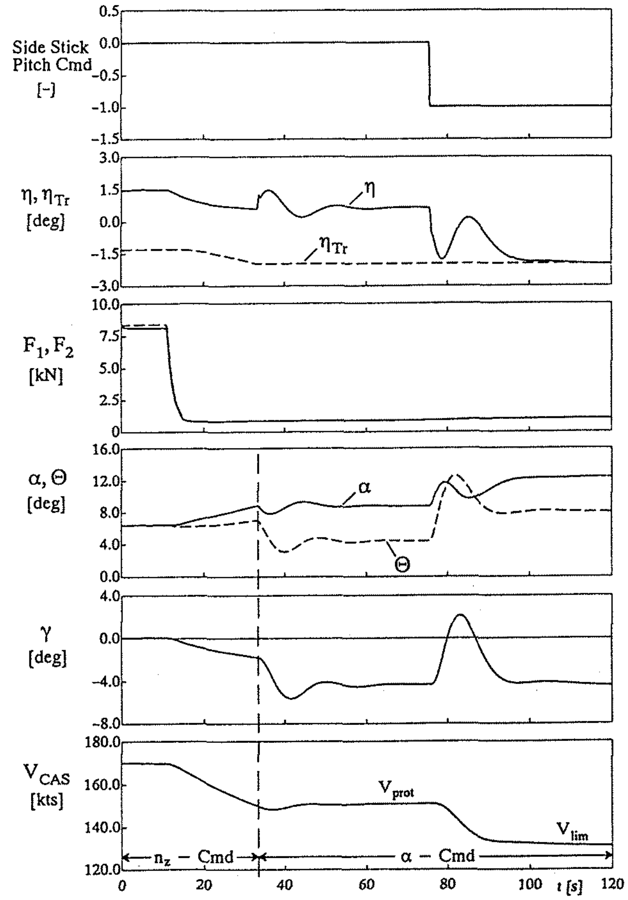


Fig. 15: Pitch Normal Law and High AOA Protection (simulator results)