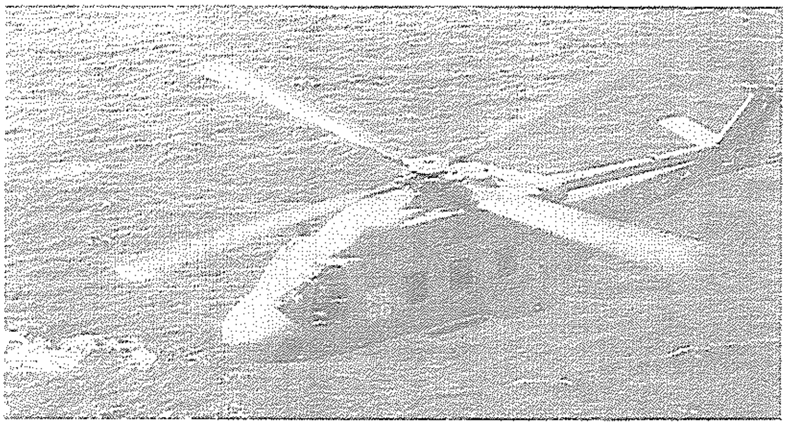
NH90 CONTROL LAWS SIMULATION AND FLIGHT VALIDATION ON THE DAUPHIN 6001 FBW DEMONSTRATOR



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Abstract

NHIndustries (NHI) joint venture among Agusta, Eurocopter, and Fokker Aerostructures is developing the NH90, first multirole naval and tactical transport helicopter in the 9 ton class fitted with a full Fly–By–Wire (FBW) system. Along with its helicopter airborne system experience, Eurocopter is responsible for the Flight Control System (FCS) and is in charge of Primary Flight Control System (PFCS) and associated control law development.

A definition of NH90 control law has been performed using all simulation tools of helicopter flight control law design (wind tunnel measurement, off–line simulation, piloted simulation).

After a first customer assessment of the industry choices on real time simulator, a flight evaluation was needed in order to:

- Confirm the general behavior of the NH90 control law architecture,
- Explore critical flight phases which are not fully representative in simulator such as takeoff, landing, taxiing.

The Eurocopter Fly–By–Wire demonstrator Dauphin 6001, provided with a proven FBW control system in whole flight envelope, has been used. General behavior of the control law has been proved to be satisfactory during flight tests and in particular during critical flight phases.

This evaluation concludes the flight control law preparation before first NH90 FBW prototype flight.

Acronyms

ACC	:Actuator Control Computer
ADS–33	:Aeronautical Design Standard
AFCS	:Automatic Flight Control System
ATT	:Nominal mode
CHR	:Cooper Harper Rating
DVE	:Degraded Visual Environment
FBW	:Fly By Wire
FCC	:Flight Control Computer
FCS	:Flight Control System
FTM	:Flight Test Maneuvers
IMC	:Instruments Meteorological Conditions
NFH	:Nato Frigate Helicopter
OFE	:Operational Flight Envelopes
PFCS	:Primary Flight Control System
SCAS	:first NOE mode
TAC	:second NOE mode
NOE	:Nap Of the Earth
TTH	:Tactical Transport Helicopter
WSDS	:Weapon System Development Specification

Introduction

In 1992, France, Germany, Italy and The Netherlands represented by the NATO Helicopter Management Agency (NAHEMA) launched the design and development phase of the NH90 program. The NH90 will be the first 9 ton class helicopter of the 21st. century fitted with FBW control system designed and qualified in accordance with the ADS–33 principles. It will open the way for a new generation of helicopters managed by a full authority FBW FCS.

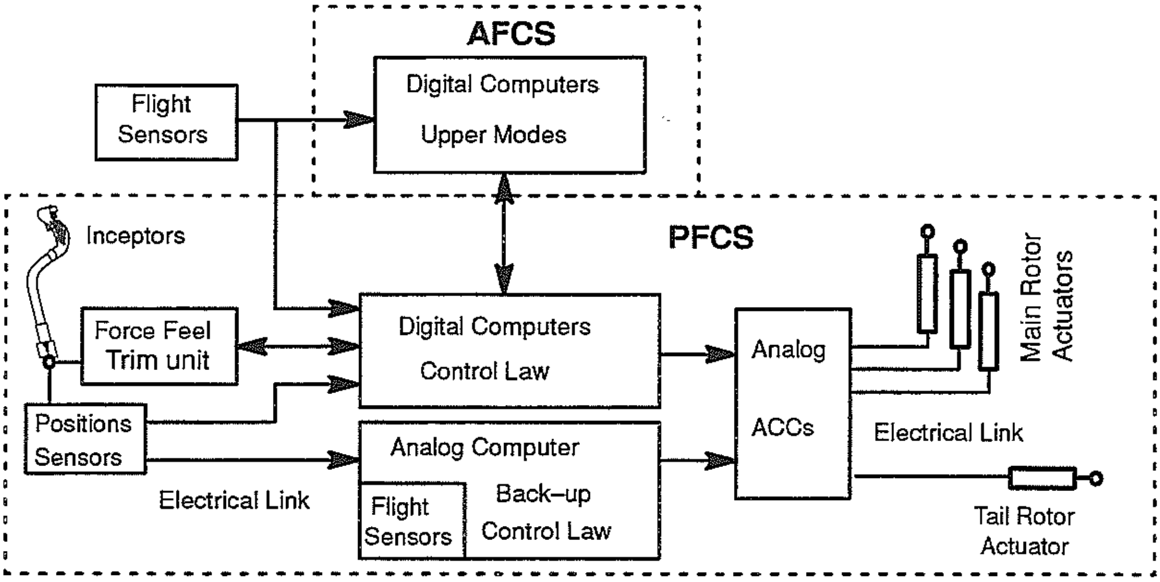


Figure 1 – NH90 Flight Control System layout

NHIndustries as prime contractor is in charge of design and development. In the work sharing Eurocopter is responsible for the FCS.

The first challenge was to define a control system which would fulfil large constraints as safety, mission reliability, survivability, cost, weight. NH90 FCS system design is now completed. Validation program is already in process. Digital control law will be evaluated in flight next year.

This document, starting with a description of FCS system, presents the control laws studies and the evaluations performed in order to prepare first digital FCS flight.

System design

The FCS is functionally divided into two main parts (see fig 1). The PFCS provides the basic control of the helicopter (Eurocopter responsibility). It elaborates the main and tail rotors actuators positions using pilot inputs and flight sensors information. It supports the control law and its degraded modes. The second part is composed of the Automatic Flight Control System (AFCS) which manages the upper–modes (Agusta responsibility).

Control processing

In order to meet the high level of safety, mission reliability and survivability required in the Weapon System Development Specification (WSDS), the NH90 FCS is based upon a quadruplex architecture using digital and analog technology. All control processings are integrated into two identical Flight Control Computers (FCCs). Each FCC is composed of one digital and one analog channel. Each channel is dual laned for an in–line monitoring (command/monitor) (see fig 2).

The digital channel of each FCC includes the AFCS part and the PFCS part, performed by different process located on separate boards in the FCCs. The architecture of each digital channel is built on the same principle : two lanes with in–line monitoring. Hardware and software of the digital lanes are identical but different compilers are used. A FCC digital channel is sufficient to achieve ADS–33 Level 1 of handling qualities.

The analog channels support the ultimate FCS back–up composed with a 1 by 1 direct link on the four axes between the pilot and the actuators. Moreover a SAS is implemented on the pitch and roll axes with dedicated gyrometers. The handling qualities performed by the analog PFCS are sufficient to ensure IMC and NOE safe return to base after a total loss of the digital part.

The two identical Actuator Control Computers (ACCs) house the four analog channels (2 by ACC) which ensure the control loop closure of the actuators. Each channel is composed of two dual lanes (control/monitor) using different hardware which feed and monitor the four force fighting motors located in each actuator.

Redundancy

A high level of redundancy has been chosen to meet the safety and the mission reliability target. The configuration management gives the priority to the digital channels in order to maintain as long as possible the best level of handling qualities. Moreover, the ballistic and fire aggressions are minimized by using four different wire routing.

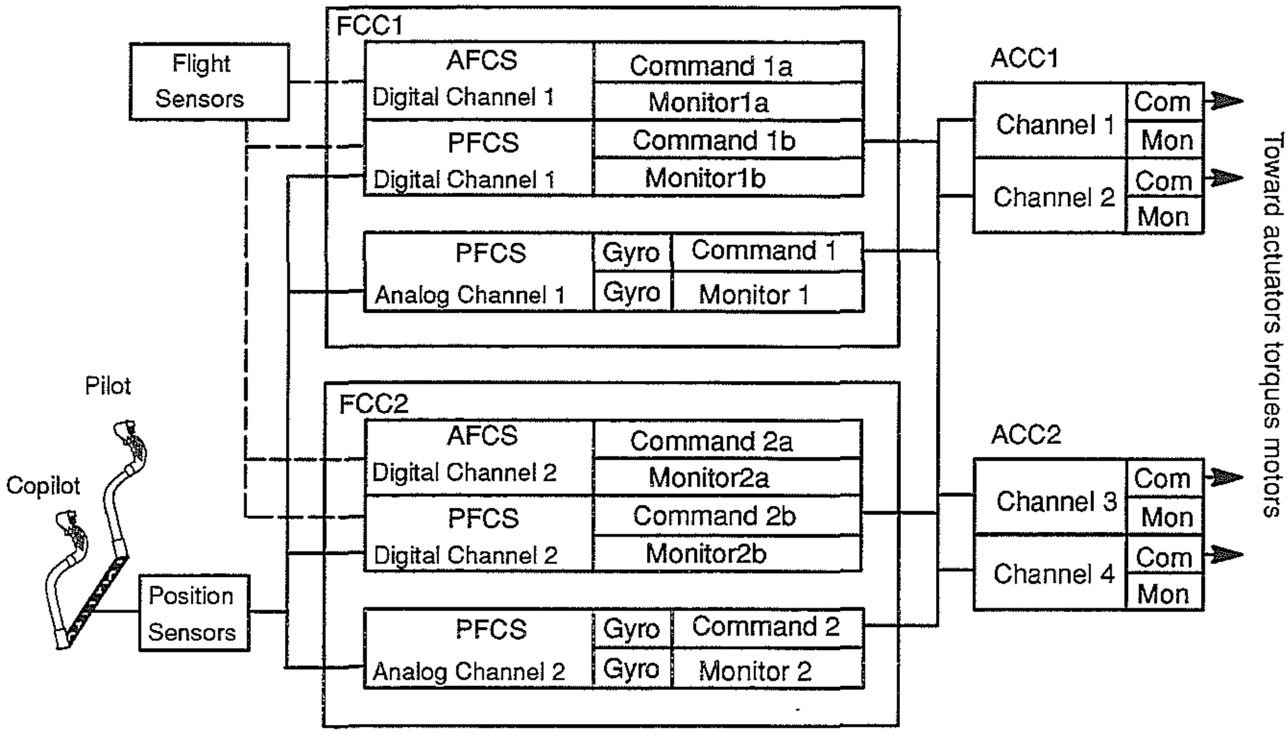


Figure 2 – NH90 Flight Control System architecture

Pilot inceptors

The pilot and copilot inceptors are mechanically coupled. Each of them is fitted with a trim unit (1 by axis) which provides :

–force feel
–stick trimming (displacement of neutral position by control laws or by beep trim)
–flight through detection
–adjustment of controls dynamics by internal friction and dampers

Methodology

The PFCS digital software is divided into two functional entities :

–the general management system which gathers monitoring, cross channel exchange, fault management, priority and validity management,
–the control law which ensure handling qualities level needed for the mission.

The methodology described hereafter regards the definition and validation principles of the control law, enhanced in the PFCS digital software.

The methodology can be introduced by the following steps (see fig 3).

–Definition of the law requirements. The gap between the bare aircraft behavior and the handling qualities level required for the NH90 missions, defines the aim of the control law in term of stabilization, decoupling, attitude hold function performance, response type.

–Definition of a general control law architecture. It includes all the functionalities identified as necessary to fulfil the aim defined in the first step.

–Definition of a detailed specification of the law architecture. For the NH90 a graphic specification tool dedicated to algorithmic description has been used.

–Simulation software production by an automatic generator using directly as input the graphic specification.

–Off–line simulation. This step allows to realize a first general behavior validation of the control law. A first setting of the law and a first comparison with regards to NH90 requirements is obtained.

–Real time simulation with "pilot in the loop". This step realized on the Eurocopter SPHERE simulator allows to analyze the behavior of the law during maneuvers. Handling qualities Level 1 has been achieved in this simulator.

–Flight demonstrator. After the simulations phases, Eurocopter used the Dauphin 6001, fitted with Fly–by–Wire system, to test the law during particular flight phases (slope landing, gusts, ...) usually difficult to achieve in a simulator.

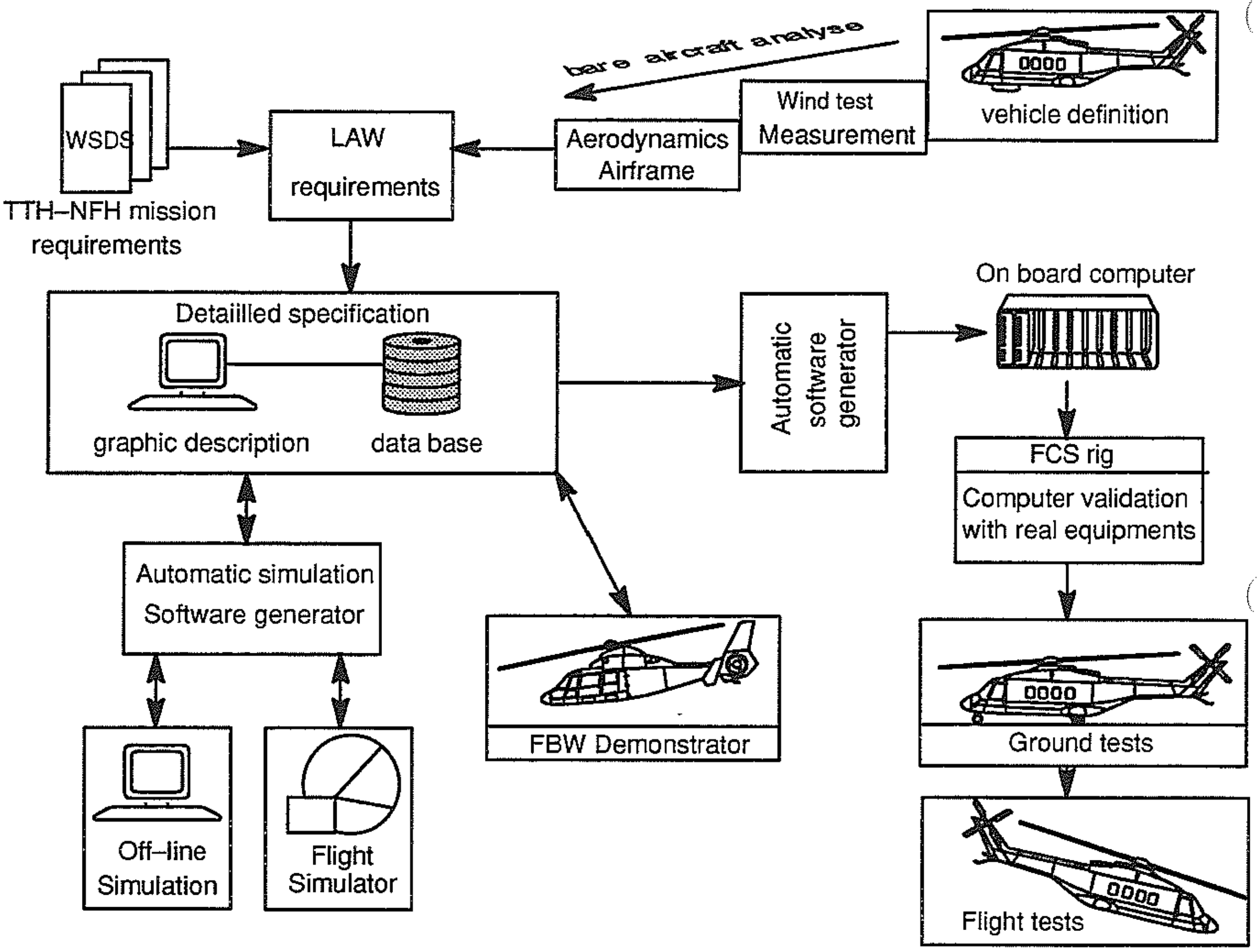


Figure 3 – Control law definition and validation methodology

–On–board software production by an automatic generator using directly as input the graphic specification validated by simulations.

–Control law integration in the PFCS digital software computer by coupling with the general management system.

–Validation of the on–board computers on the FCS rig. The rig allows to verify the behavior of the real equipments fitted on the helicopter (FCCs, ACCs, actuators, pilot displays, inceptors, trims, ...).

–Ground test. The trials are performed on the real helicopter with all the equipments, with stopped and turning rotors.

–Flight tests. Two aims are dedicated to this step, validation of the general system behavior in operational conditions and handling qualities evaluation.

The phases described hereafter regard the steps already achieved in control law's development. They start from the definition of law requirement up to the use of flight demonstrator.

Law requirements

A tailored version of the ADS–33, mutually agreed between the Customer and the Industry, is used as a design guideline.

The control law of the NH90 in nominal configuration must ensure Level 1 handling qualities for both Tactical Transport Helicopter (TTH) and Nato Frigate Helicopter (NFH) missions in Operational Flight Envelopes (OFEs). After failure, subsequent handling qualities levels are also specified. Level 1, 2 or 3 are required depending on failure types.

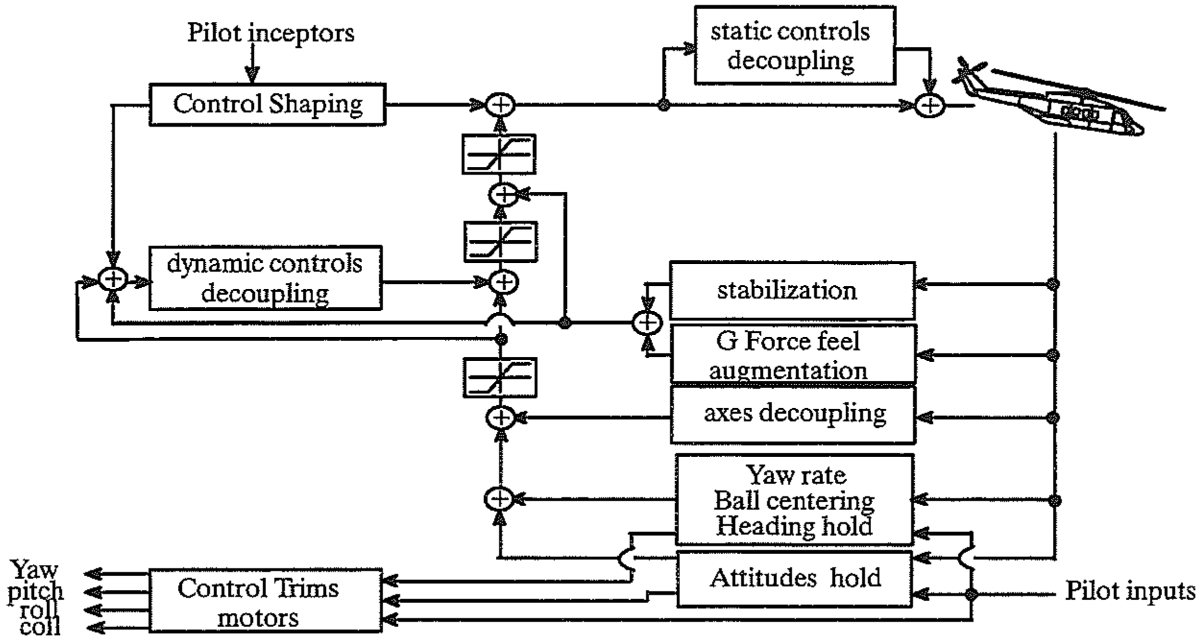


Figure 4 – NH90 nominal control law architecture

The tailored ADS–33 takes into account the specificity of the NH90 missions :

TTH
- –Tactical transport of material and personnel,
- –Heliborne operations,
- –Search and rescue missions,

NFH
- –Anti–submarine warfare,
- –Anti–surface unit warfare,
- –Search and rescue.

For NH90 qualification program based on WSDS and FAR 29, a limited selection of points resulting from this tailoring will be considered for handling qualities demonstration purposes. Referring to previous flight test experiences, Customers and Industry experts have defined measurable Flight Test Maneuvers (FTM's) including performance criteria requirements.

Specific constraints, such as knowledge of the rotor disk position, have been taken into account in control laws specification.

Control law design

For NH90 control law, extensive studies have been performed. Along with Eurocopter control laws experience, many points have been investigated. Aims were to improve stabilization, control shaping, decoupling, law architecture, flight setting in term of robustness and efficiency. New possibilities given by a full authority flight control system have been systematically investigated.

All these investigations lead to the detailed architecture of the NH90 control law (figure 4).

Full authority induces noticeable possibilities, mainly in piloted phases. First difference appears in the stability augmentation system. Feed back terms are not saturated. Consequences are:
- –a linear response whatever the amplitude of pilot inputs,
- –a non–saturated attitude feed back capability which can greatly improve the helicopter response in different flight configurations, as hover for instance.

Decoupling can be efficient for large command or helicopter status evolution.

New functions, which need important command in transient flight phases, are implemented.
- –G force augmentation introducing bias in the pitch law command during load factor excursions,
- –bias to re–center inceptors.

In non–piloted flight phases, full authority enables to realize smooth trim re–centering. For the pilot, this means a smooth stick motion and comfortable transition between piloted and non–piloted conditions.

Moreover the problems typically encountered with a full authority control law, as command margins or ground transition for example, have been solved.

The FCS landing function involving landing gear information in addition to other data already available in the computer, insures commands transitions. Main objectives achieved by this function are to ensure:
- –maximum help of the law during landing phase,

- –full availability and reliability taking into account all possible failures,
- –smooth and easy piloting transition.

Compared to a classical autopilot system, the use of electrical FCS configurations adds also, further advantages, such as :

- –capability to shape pilot inputs before sending them to actuators. Thus, it is possible to cancel frequencies or to filter inceptors signals,
- –deletion of phase delays introduced by mechanical serial actuators.

The NH90 PFCS provides three basic control law modes. The nominal mode is ATT and can be connected with the upper modes. It is designed to achieve Level 1 Handling Qualities in Instruments Meteorological Conditions (IMC) conditions and also in Degraded Visual Environment (DVE) in hover and at low speed when combined with some AFCS modes, depending on the FTM's. Two other modes SCAS and TAC are dedicated to Nap–of–the–Earth flight:

- –SCAS ensures stability and control augmentation, decoupling functions, a yaw rate hold in hover, and ball centering in cruise,
- –ATT includes SCAS functionalities with attitudes pitch/roll hold, and heading in hover,
- –TAC includes all ATT functionalities with automatical trim follow–up and specific references synchronization.

In addition, a limited number of degraded modes are provided to take into account sensors or trim failures.

Specification

The detailed specification is realized with a graphic language issued from AEROSPATIALE Group.

As shown on figure 3, several environments comprising off–line simulation, simulator, FBW demonstrator, have been used to validate the PFCS control law.

A constraint has been to guaranty that the software implemented on each environment describes the same specification. For this purpose, a data management system, specially developed by Eurocopter, references control law versions for each environment as well as for on–board software.

An other important point has been to ensure that on–board computer software and specification validated with simulations, are the same. Automatic generators, using as input the same graphic specification, generate both simulations software and on–board computer software.

This methodology reduces the software production cycle and minimize human treatments for on–board software realization in order to optimize the validation phase.

Off–line simulation

Off–line simulation is the first environment where the software, automatically generated from the graphic law specification, has been run. The control law validation using off–line simulation is divided in two main parts.

–A validation of the PFCS control law alone. It includes law simulation software, and modelizations of helicopter, ACCs, actuators, inceptors, computer and bus time delay, sensors. The real time sharing between the different functionalities realized in the on–board computer is also simulated.
Tests required in non–piloted conditions can be executed such as beep switch inputs. Nevertheless, without sufficient visual environment feedback, it is not possible to perform precise piloting tasks.
First step is dedicated to detection and corrections of design mistakes. A functional test is achieved in order to validate the specification phase.
Second step is dedicated to validate performance of each component of the law in closed loop with a non linear helicopter model. They are evaluated in terms of performance, robustness, simpleness and ability to be tuned.
Third step is dedicated to validate general behavior of the complete architecture control law. Components interconnections are validated.
At the end of this phase, a first setting of the gains is achieved.

–A validation of all PFCS software. A complete simulation of the PFCS is performed by linking together the control law and the management system. It includes modelization of two digital channels and their two dual lanes monitoring architecture. This kind of simulation is realized in order to verify that the functional control law behavior is always compliant with the first phase results.

After off–line simulation, pilot–in–the–loop evaluations have been necessary to confirm the improvements in handling qualities provided by the FCS control law.

Piloted simulation

Eurocopter SPHERE fixed base simulator performs a dome projection providing 180°H x 80°V field of view. Adjustable inceptors enable to define suitable characteristics in terms of force feel, damping, friction, travels. A representative cockpit allows to achieve precise piloting tasks. The representativity of the environment is well adapted for a realistic evaluation of the piloting workload. Software models used in the first part of the off-line simulation are implemented on SPHERE.

First objective is to check the consequences, in term of piloting workload, of :

- –flight phases transitions (cruise, hover, landing and so on),
- –state switchings (hands-on, hands-off),
- –modes switchings (ATT, SCAS, TAC, degraded modes).

Second objective is to improve and estimate handling qualities achieved with control law. This phase has involved a team of Eurocopter test pilots.

Third objective is to get, on simulator, a first agreement of law design by customers pilots.
For this purpose, used FTM's were: precision hover, hovering turn, side step, acceleration/deceleration, NOE flight/talweg following, pull-up/push-over, low altitude flight, VMC/IMC climb.
Pilots were tasked to achieve FTM's inside performance criteria requirements (including maximum excursions for attitude, heading, speed, height and position depending on the FTM) and asked to deliver a Cooper Harper Rating (CHR). Trials were recorded in order to check the achieved performance.

Figure 5 presents Cooper Harper ratings for some FTM's assessment. All mean CHR's are within the Level 1 range despite the penalizing effect of simulation environment (typically, 1 or 2 points in the CHR according to other experiments).

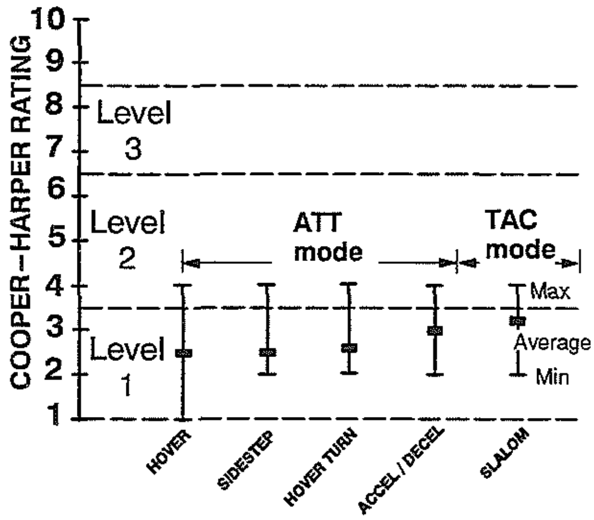


Figure 5 – Preliminary NH90 FTM's assessment

For the side step for example, the FTM is achieved in front of a bridge in order to have good visual cues on the simulator. The intent is to check roll response near hover conditions.

–The FTM description given to pilots before the trial is : establish a steady hover middle in front of left bridge arch at approximatively 25ft height. Translate laterally to the right arch and restabilize hover condition.

–The performance criteria required, in order to substantiate the Cooper–Harper rating, are given in the following table.

Side Step		
Performance parameters	Desired	Adequate
Height deviation (radar)	$< \pm 10$ ft	$< \pm 15$ ft
Heading deviation	$< \pm 5°$	$< \pm 10°$
Time to complete up to hover re–stabilization	< 20 s	< 30 s

–Appendix 1 presents a record of pilot trial in ATT mode. The performance achieved in terms of height ($\pm$5ft) and heading ($\pm$3°) are inside the desired performance. The hands–on/hands–off boolean for pitch, roll and yaw show a moderate activity on pitch and roll inceptors and no action on pedals. In accordance with the performance achieved and the pilot workload estimation, the Cooper Harper rating giving by this pilot is 2 (Level 1 range).

Degraded modes have also been evaluated with a reduced number of FTM's and judged easy to fly (at least Level 2 in most cases).

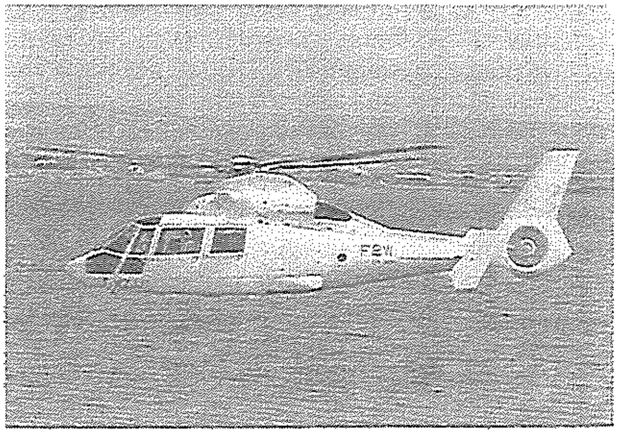
Others FTM's such as slope landing, ship deck landing have been performed successfully. These phases involve flight model with ground effect, a complete landing gear model, a moving ship model. All are implemented in Eurocopter simulator. But to perform a precise and smooth landing, pilot uses acceleration cues and must evaluate precisely its height. This two aspects are not easily perceived in simulator. Real flights were necessary to confirm control law design performance in such phases.

Control law evaluation in SPHERE took 1500 hours from January 1993 to January1996. Up to thirty four pilots, both from Industry and Customers side, have been invited to assess handling qualities.

After this phase, the control law has been judged ready for flight evaluation.

Flight demonstrator

Dauphin 6001 is the Eurocopter fly–by–wire demonstrator. Its control system has been validated in the whole flight envelope. It was used to assess in flight NH90 control law.



Dauphin 6001 FBW

First objective was to confirm nominal law design behavior.

Second objective was to test control laws where simulations models are not fully representative.

Demonstrator FBW architecture is presented in figure 6. The assessing pilot operates from the right–hand seat through two cross–monitored on–board computers. The safety pilot operates from the left–hand seat through a mechanical back up. In electrical operation mode, the linkage allows the safety pilot to follow the movement of the electrical actuators. Transition to mechanical control is automatic after a failure detection on the electrical channel or a pressure on mechanical linkage achieved by the safety pilot.

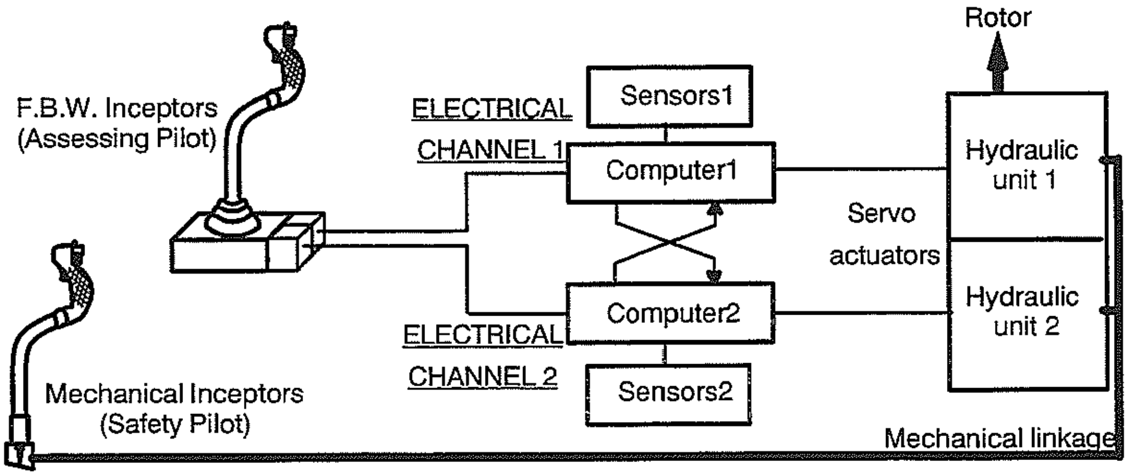


Figure 6 – Dauphin 6001 FBW architecture

Assessment flights have taken place between October 1995 and march 1996. The whole speed envelope was covered. All modes were engaged.

In hover, no modification was necessary. Piloting response, fly through logic, law commutations, attitude hold, command decoupling provided good results without any modifications. NH90 pedals have centering forces which take them back to their trim anchorage position when released. Hover helicopter response on the yaw axis confirmed results evidenced on simulator.

Many landing were performed. Various test conditions were :

–horizontal ground surfaces,
–cross–slope, down–slope, up–slope surfaces from 0° to 10°
–slope landings with wind (20–25kt)
–landing with longitudinal speed
–taxiing.

Smooth transitions between flight to ground law were confirmed and did not perturb the pilot during landing phases. Moreover, slope landing have been judged easy. A problem of oscillation appeared during one wheel contact but was solved by tuning the landing function. It handles the ground resonance phenomenon without degradation for the pilot during landing transition.

At the end of the experimentation, a complete flight from take–off to landing was achieved in FBW mode and nominal law.

Concluding remarks

The challenge imposed by the NH90 program was to develop a control law providing Level 1 Handling Qualities capability for two kinds of missions (TTH, NFH) and eight users (4 Navies, 3 Armies, 1 Air force), each of them having specific operational constraints. An extensive cooperation between the Official tests centers and Eurocopter was necessary to define control law requirements.

Definition and validation phase lead to a control law complying with this requirement. A piloted simulation assessment by the customer have evidenced that :

–the law is well adapted to the NH90 operational missions,
–Level 1 of handling qualities is achieved on the simulator without any specific pilot training.

The trials on the FBW demonstrator have confirmed the good results obtained in simulations, especially in the transitions phases (landing for example).

After the freeze of the vehicle definition, the next step is to use PT1 flight data to improve the tuning of the law. This phase is currently in progress.

First version of the PFCS digital software is available on the FCS rig and validation trials have started.

The PT2 started flights with the Analog PFCS section on 2nd of July 1997. Control law definition and validation phase in simulation is now achieved and Eurocopter is now preparing the flight test validation of the digital PFCS.

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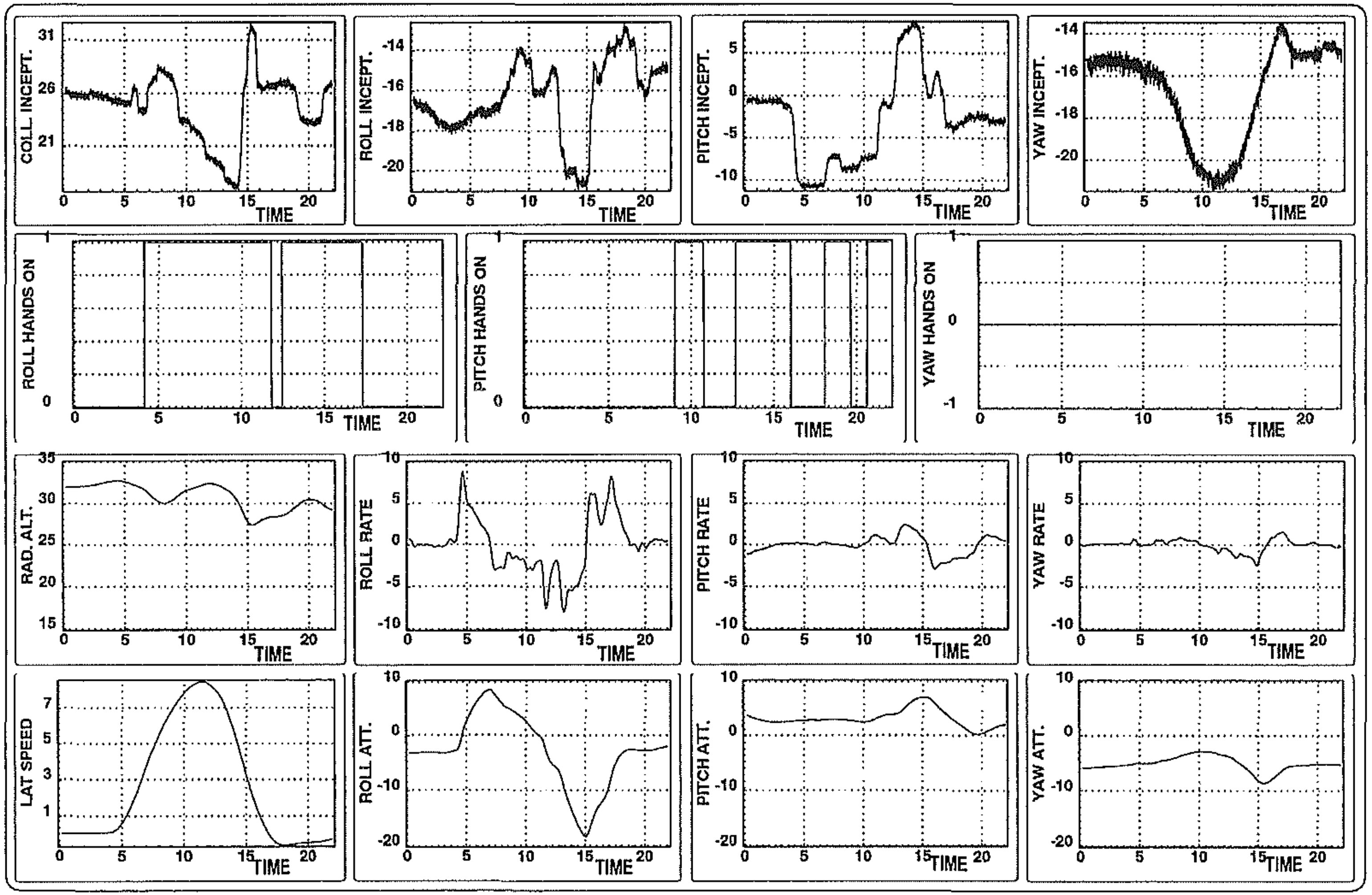

APPENDX 1 ATT MODE, Side Step