DEVELOPMENT OF THE TIGER AUTOPILOT

M. Obermayer — Eurocopter Deutschland GmbH, Ottobrunn Germany

M. Salesse-Lavergne — Eurocopter, Marignane France

Abstract

The development of the 4-axis Automatic Flight Control System (AFCS) of the Tiger combat helicopter has been successfully completed. This paper presents 3 important aspects of this development:

1. The operational needs of the Tiger AFCS:
   - tactical flight with aggressive maneuvers followed by attitude stabilization phases,
   - piloting help during weapon system use such as gun recoil compensation, precision hover for aiming or observation and aircraft alignment to a line-of-sight direction,
   - non combat low-attention flight phases such as ferry flights or return to base.
2. The main steps of control law development:
   - the in-flight identification of the aircraft dynamic responses,
   - the flight test preparation on bench,
   - the flight test analysis on-line and off-line.
3. The experiences learned for future projects:
   - AFCS definition with customers in the loop,
   - efficient software development procedures,
   - flight test support.

The fully digital AFCS has been designed to meet the operational environment commensurate with a highly maneuverable helicopter designed to operate at the front line of the battlefield. The digital flexibility permits control law gains and functional optimization to adapt the control laws to the full mission envelope. This paper will put particular emphasis on the lessons learned from flight testing and the tools used during the design (system identification and both off-line and pilot in the loop simulation).

Introduction

The development of the Tiger AFCS started from a detailed analysis of the piloting help it could bring in the various aspects of the Tiger mission. As a result a number of operational needs were identified. This is what the first part of this paper summarizes: why an AFCS or what should it do? Then the second part addresses how it has been developed, the day-to-day iterations. The last part shows the lessons learned in peripheral subjects to the control laws development.

1. Operational needs

1.1. Tactical flight

A key requirement about the Tiger helicopter was its ability to be flown with minimal pilot workload in Tactical flight conditions. Experience within Eurocopter in the field of aircraft design for Tactical flight goes back to the 60's and the Tiger fully benefitted of all these years of experience. The following review will give some insight about what the Tiger owes to previous developments.

A Tactical flight demonstration shows evolutions very near the ground, maximum attention paid to the outside world and potential threats, frequent changes of path to best use the protection of the terrain. It shows in fact a continuous succession of short but sometimes quick attitude changes followed by short stabilization phases. Here lie some important elements: maneuverability and ease of attitude stabilization.

Ease of attitude stabilization: whereas maneuverability is mainly a matter of the rotor system being able to induce fast aircraft motion, as will be seen later, the AFCS can play an essential role in reducing the stabilization effort. The Stability Augmentation Systems (SAS) with their angular rate or attitude derivative feedback and pseudo-attitude hold feature introduced some improvement in the 70's. A step further was made with the Fennec's Tactical mode. This basic AFCS mode synchronized the attitude's references during evolutions but then maintained steadily the new attitude reached upon stick release, avoiding the undesirable drifts observed with SAS. It allowed accurate attitudes setting and hold in particular for weapon delivery. The automatic changes between attitude follow-up and hold, based on override and angular rates conditions were completely transparent for the pilot for maximum simplicity and ease of use. Although carried-out some 20 years ago, the

Fennec development, which strongly involved customer operational test pilots, laid down the basis and was a reference for the Tiger development.

With hands-on control laws solely mechanized through a limited authority fast series actuator, it revealed also the potential of adding on a trim for the hands-off aircraft control. Tactical flight involves frequent transitions between hover and speeds of typically 40-60 kt. The static pitch and roll stick position changes requested by such maneuvers could then be performed by the trims without pilot intervention on cyclic resulting in lower workload.

Tactical flight involves also large collective inputs, to avoid obstacles or follow the terrain and fast aircraft banks to turn sharply. As a further result of the trim implementation it was decided to introduce on the Tiger large authority decoupling functions. They allow the pilot to perform the fastest collective and roll stick inputs without requiring his intervention on pitch or yaw because of saturated series actuators. More generally the trims allow the pilot to be never disturbed by series actuators authority limits or unpleasant recentering effects of wash-out filters introduced in control laws to prevent such saturations.

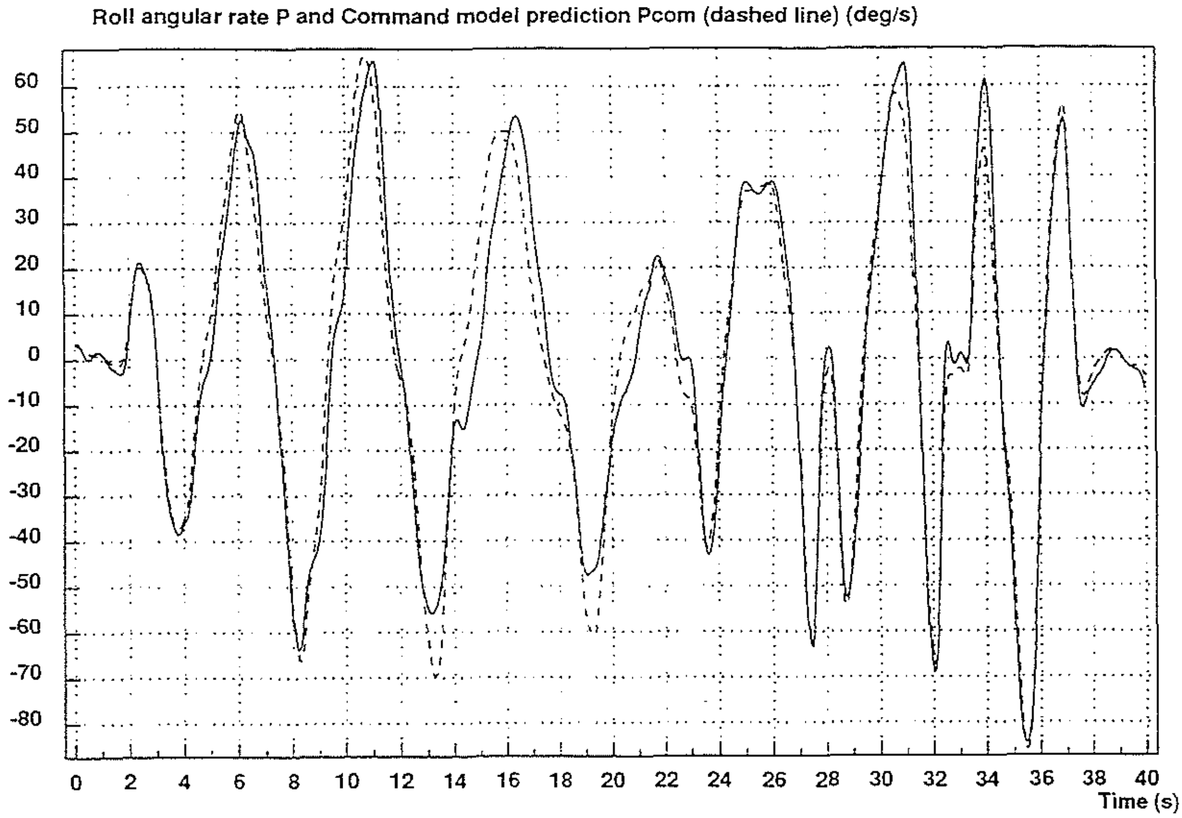
While hands-on the only solution for the pilot to cover cyclic stick static changes was to press the trim release button. Performing frequent trim release can be said to be common practise among pilots who often fly in Tactical conditions. However, because it requires to more or less dedicate the thumb to pressing this button, it comes in contradiction with this other requirement, widely adopted nowadays, to concentrate a number of key functions on the grips, like weapon selection, aiming and firing, radio frequencies selection, Identification of Friend-Foe, counter-measures ejection and so on. Another disadvantage of the trim release is that the efforts instantly vanish and a number of pilots acknowledge they feel less comfortable when having no effort in the stick and appreciate the help of the counteracting spring force during maneuvers or close to the aircraft limits.

This is why developments were carried out in the 80's about using trims whose anchoring point would stay still during maneuvers and join the stick position upon aircraft stabilization. The introduction of such trims with stick follow-up capability broadened up the possibilities offered to the Tiger. Not only does the cyclic trim follow any air speed changes but then also any attempt by the pilot to stabilize a new attitude is detected by the AFCS which activates attitude stabilization and then hold control laws and simultaneously drives the trim to the stick position within 1 or 2 s. Numerous iterations and flight tests were necessary to define the adequate conditions for control laws switching and the trims control philosophy. In particular specific attention was paid to the precision tasks useful for manual hovering or night patrol flights with several aircraft close to each others. On the contrary to usual Tactical flight maneuvers where the pilot inputs some controls displacement to move the aircraft and then try to stabilize it when it has reached a satisfactory attitude, here, in precision control tasks, the slightest stick displacement must be understood as a request to adjust the attitude to be held. Hence a small stick displacement will result in a small attitude change. The trim is then commanded to smoothly null the efforts and a new attitude reference is held without going through the destabilizing effect of a trim release.

Maneuverability: maneuverability requirements led to select for the Tiger a rotor of the hingeless family. Then with an aircraft which has very good natural handling qualities, the AFCS contribution to maneuverability consists at least in preserving the natural aircraft response thanks to a Command and Stability Augmentation System (CSAS). Now just this, on an aircraft which was dimensioned from its very beginning for air-to-air combat, turned-out to be more complex than expected.

Air-to-air engagement is likely to be the most demanding flight cases in terms of maximum load factors, angular accelerations and rates, and extreme attitudes. As a guideline or design objective, a number of aggressive maneuvers, called Mission Task Elements, were specified for the Tiger to comply with. These MTE proved very helpful because they set an ambitious reference for the designer. During the first MTE evaluations it turned out that the classical linear low-pass command models optimized for maneuvers up to 10 - 20 deg/s no longer suited at rates of 60 - 80 deg/s and more. They led in particular to over-control the aircraft when stopping the maneuver. Thanks to the flexibility of the digital implementation, significant adaptations in terms of non linearities, flight cases dependency or control laws switching allowed to use the AFCS in the entire flight envelope of the Tiger, even in aerobatics.

Example of Mission Task Element : Slalom



1.2. Piloting help during weapon system use

Precision hover: whereas every pilot is able to hover in clear daylight operation, controlling a precise hover at tree level while the gunner is aiming or observing the battlefield with the sight system becomes very difficult at night, with the limited sight angle and ground perception of Night Vision Goggles or even FLIR. In particular the lateral drifts are hardly perceivable by the pilot. Also maintaining an optimal observation height requires continuous pilot attention. For these reasons the Tiger AFCS was, from its early definition, specified to automatically control a 3D hover: hold the horizontal position (DOP mode) thanks to Doppler ground speeds while the height control (RHH mode) uses radar altimeter height. The engagement of these 2 modes is done via press buttons on the cyclic, respectively collective grips. Fast position's adjustments are made possible via cyclic beep inputs. Also the height can be accurately controlled via collective beep inputs. Finally on yaw axis, the aircraft heading can also be adjusted via lateral action on collective grip beep.

In all 4 axes these beep features proved to be quite convenient and well appreciated by the crews as a useful complement to the automatic 3D hover and heading control. In terms of development, a preliminary step was done during pilot in the loop simulation where the needs arose for a real horizontal position control on cyclic rather than just ground speed nulling, for a fast but limited in amplitude hover beep feature, reaching up to 10 kt in the beep direction, and finally for a vertical speed control upon collective beep action of 150ft/min in the beep direction with a permanently synchronized height reference.

During horizontal hover flight tests special efforts were made on reference position management, compensation of the perturbation effect generated by fast rotations and beep response optimization to combine crisp reaction and limited amplitude attitude changes.

During radar height flight tests some specific optimization was done for flight in high altitude area to automatically limit the upward power excursions to the maximum take-off power, maintain it to this upper level and signal any downward drift to the pilot.

Alignment on Line Of Sight: some symbols are presented in the head-down and head-up displays of the pilot to show him the direction of the gunner's sight. However, performing a fast and accurate control of the aircraft, solely with these symbols would retain full pilot attention and consequently a high workload. These considerations introduce the need for an AFCS feature that would perform an automatic accurate alignment of the helicopter on the target. In addition it should be sufficiently fast to compare with what the pilot would do and then free the pilot from the burden of continuously controlling a precise heading. Such AFCS Line Of Sight (LOS) mode had been already designed in the past on Gazelle and on the BO 105 PAH1. This last, particularly performing development, was used as a reference for the LOS mode design in the hover.

Flight test in the hover were mainly dedicated to defining a maximum acceptable initial acceleration and angular rate with which the crew would feel comfortable, even at night. In cruise flight tests were mainly performed to speed-up and improve the final alignment phase.

Gun recoil compensation: the ground support and escort version of the Tiger is equipped with a 30 mm turreted gun in the nose of the aircraft. The recoil force of this gun introduces a perturbation momentum destabilizing the aircraft. Early investigations and simulations had shown the benefit that could be expected from an AFCS feature that would anticipate this perturbation and counteract it.

During gun firing flight tests the first positive element came from the basic stabilization which demonstrated to hold the attitude/heading changes within 2 to 3 deg. without any additional precommand. Then the recoil precommand was tested and maintained the attitude/heading deviations between 0 and 1.5 deg. in the most severe firing conditions. Its effect is such that the crew only notices a shift of the entire aircraft but no rotational motion.

1.3. Non combat low attention ferry flights or return to base

Automatic cruise and help in approach: during day-to-day training, cases have been reported, in the French and German armies, of pilots being in trouble because caught inside clouds or fog, having to fly in Instrument Meteorological Conditions (IMC) without specific preparation during return to the base for example. An AFCS that could automatically control the flight path with all 4 axes, when necessary, would be of appreciable support in such condition. Also long cruise phases can be expected to transition to the combat area. Again the automatic flight path control could free completely pilot attention and allow him to concentrate on his mission and on the search for external threats. Finally long ferry flights are quite common also for combat aircraft and automatic cruise modes are very convenient in such cases.

For all these reasons automatic cruise modes were introduced in the AFCS:

- a navigation mode (NAV) automatically brings the aircraft from way-points to way-points following commands from the Autonomous Navigation subsystem,
- a heading acquire and hold mode (HDG) allows easy alignment on a VOR or Localizer signal. It can also be useful during Ground Control Approach,
- an indicated air speed hold mode (IAS) quite helpful in combination with
- a vertical speed mode (VS) for approach, for example on an ILS beam,
- an altitude hold mode (ALT) to maintain a flight level controlling either the pitch axis to allow maximum speed level flight or the collective axis in combination with the IAS mode and finally
- an altitude acquire mode (AAQ) for automatic level change.

These modes are identical to civilian aircraft cruise modes. As such the Tiger benefitted of all the refinements introduced during the previous commercial developments in terms of safe limitations (for example priority given to the altitude control versus air speed, torque and power control for the modes driving the collective axis), anti-turbulence features for comfort improvement and soft beep control.

Also it was decided during development that selecting either one of these cruise modes would disengage the TAC mode in order to best configure the AFCS for IMC operations: no more attitude synchronization upon override, modified hands-on control laws to soften the aircraft reactions and fix stick anchoring point.

All this was done to make sure the pilot can return safely whatever the weather conditions he encounters.

2. Control laws development

2.1. In flight identification

Control laws development requires a good knowledge of the dynamic behaviour of the aircraft to control. However, this necessary knowledge depends strongly on what is the aim of such aircraft dynamics identification. During the Tiger development typically 5 different aims were identified:

- aircraft response to small amplitude control inputs for first stage Command and Stability Augmentation System design,
- aircraft response to large amplitude inputs for complete CSAS design,
- gun recoil compensation,
- attitude control and associated decouplings,
- upper modes control.

The first aim is the simplest. Short steps, pulses or doublets on the controls are sufficient.

The next two aims require to deal directly with temporal responses: the aircraft response tends to become non-linear at high amplitudes and only aircraft responses are available for gun firing.

Then in terms of attitude control, it is necessary to know the behaviour of the aircraft response in its quasi-linear area over a broad frequency range. It is certainly the most demanding kind of identification in terms of precision. For this purpose essentially sinusoidal inputs were used either with sweeping or fixed frequency.

The last aim requires to identify very low frequency phenomenon but also deal with the sensors characteristics, in particular their noise spectrum and the effect of their position inside the aircraft.

All these identifications are conducted to then enable to designer to predict adequate AFCS transfer functions characteristics. However the control laws include a large number of features around the transfer functions which must be tested before going into flight test. The description of this preparation is the subject of the next section.

2.2. Flight test preparation on bench

The Tiger AFCS development demonstrated the need for specific test activities. The first level of test is the hardware interface test, mainly to the series actuators and trims. The second level is the control laws functional validation. The third level of test is the integration with the rest of the avionics.

For the control laws development, mainly the second level is of interest. Because of the large number of control laws (hands-on, hands-off, decouplings, upper modes ...) and their complexity, a closed loop bench, called ANSIR, was defined. It was able to run in real time, included a non-linear flight mechanics helicopter model with on-line data display, real trims and controls to easily simulate pilot intervention and real or simulated AFCS.

Access via a Digital Flight Test Unit (DFTU) to 475 internal AFCS parameters, for display or modification, and the possibility to prepare up to 10 gains sets, greatly contributed to the efficiency of the AFCS tests on bench and in flight.

A usual development iteration proceeded in the following way: every time a new control laws AFCS software was received, from the supplier Sextant Avionique, it was first tested on ANSIR. The proper performance of the modifications that originated the software change was first evaluated. If, at this stage, a default was identified a change was immediately specified and a new software was available 1 or 2 days later. Then once the new version was acceptable a check in flight of the correction was prepared. It consisted, for example, in presenting the modification to the test crew, or evaluating appropriate DFTU gains settings prepared from theoretical computation and selecting the ones to be tested in flight. The real-time closed loop nature of the bench enabled fast testing, detection of side effects and realistic simulation of override actions. Then the flight was performed. If a problem was identified in flight and not understood from telemetry room, it was then replayed on ANSIR and either a corrective action was possible by proper gains modifications or a software change was requested in which case one more iteration would take place.

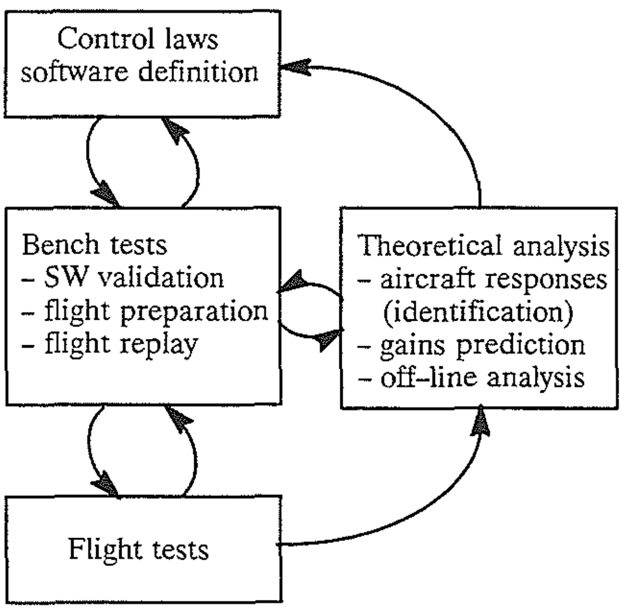
It can be understood from this description that ANSIR quickly became the key complement to the flight tests for control laws development.

2.3. Flight tests analysis

On-line analysis: probably the most interesting and challenging part of this development was when following the flights from telemetry room. More than 100 internal AFCS parameters and status words and all its inputs and outputs were recorded in flight and transmitted in real time from the aircraft to the telemetry reception. These data were then displayed in real time on several graphic screens hence permitting a very good view of the AFCS activity. This feature, together with the permanent radio contact with the crew, enabled immediate reaction every time a problem was found or a better gain setting was requested. It enabled efficient on-line control laws optimization with great efficiency. Finally, most of the flight analysis could be performed, in fact, during the flight.

Off-line analysis: in complement to the on-line analysis and bench replay activities mentioned above, some more detailed investigation also had to be performed like spectrum analysis, cross comparison between theoretical previsions and flight test results. Also to optimize upper modes filterings or prepare software evolutions, the corresponding algorithms were tested with real flight data.

The figure below gives an overview of the respective role of each activity.



3. Experience for future projects

3.1. Involvement of Customers

The French-German Tiger programme foresees several areas, where customer representatives are involved:

The Consulting Crew (CC) assesses and contributes to the definition of the man-machine interface (MMI). It consists of operational crews, flight test crews from the government test centres CEV and WTD61 and of industry flight test and engineering representatives. The assessments and definitions are split into 3 phases:

Status 0: MMI definition frozen on paper as basis for simulation

Status 1: MMI definition frozen in simulation as basis for rig and/or flight test

Status 2: MMI definition frozen in rig and/or flight test as basis for troop trials

These phases are further divided into assessments of "Functional Chains" (e.g. AFCS, navigation system, mission system) and in "Normal Modes" and "Degraded Modes". Final decisions are taken by the Cockpit Working Group with representatives from DFHB, national authorities, the CC and Eurocopter.

The Co-ordination Team consists of flight test crews from the government test centres CEV and WTD61. With the progress of the test programme it becomes more and more involved in development and qualification flight test and is mainly responsible for the assessment of airworthiness and performance.

This real involvement of customers since the very beginning of the definition phase and this good communication during all the development process avoids requirement conflicts and guaranties a final product fully consistant with customers expectations (i.e. CC for MMI aspects, Co-ordination team for airworthiness and performance, certification authorities for final qualification).

3.2. Software Development Procedures

In the Tiger programme, the AFCS Software (SW) design responsabilities are organized as follows:

The "Signal Management Processor" (SMP) is developed by NORD-MICRO (NM) and the Control Law Processor" (CLP) by SEXTANT Avionique.

Whereas the SMP SW has been specified by NM via a Software Requirement Specification (SRS) based on EC "paper specifications", the larger part of the CLP SW has been directly specified by EC using a graphic specification tool (HOSTESS/GALA), which allows a semi-automatic code generation.

Besides this specification and code generation tool, EC has applied a variety of further test tools for the development of the AFCS SW:

- Prior and parallel to flight testing, the control laws have been checked in closed loop on a simulation and integration rig (ANSIR) located in Marignane. This tool proved to be essential in the development process because necessary to the functional validation of control laws, to the preparation on ground of flight tests and to the verification of Intermediate Experimental Software versions (IESW) delivered by the supplier during development.

- Assessments of the man-machine interface (MMI) and of logics have been performed in the real-time Tiger simulation cockpit (SimCo) located in Ottobrunn.
- Interfaces to the hydraulic and flight control system and to the complete avionics system have been tested on a specific AFCS test bench and on the Primary Integration Rig (PIR) respectively. These tools allow only open-loop tests.

The classical "Level 1" (i.e. safety critical) software development procedures proved to be unnecessarily heavy and time consuming during flight test. In view of the good flying qualities of the Tiger without AFCS, Eurocopter, the authorities and the suppliers agreed to establish a simplified but safe method for rapid and easy software changes during flight test.

This simplified procedure has reduced the software turn-around time from several weeks or months to a few days or weeks by abandoning formal supplier test and QA activity. The idea is that EC continuously updates the SMP and CLP software specifications parallel to flight test and that the suppliers deliver "Intermediate Experimental Software" (IESW) at a development stage suitable for continuing flight tests. EC must demonstrate to EC QA and the Co-ordination Team that the software is correctly specified and implemented. This verification has mostly be done on ANSIR based on pre-defined test orders.

It can be said that only this procedure made it possible to successfully develop and test the quite complex and demanding 4-axes basic and upper modes control laws in about 50 SW releases during approx. 2 years. In more than 200 flight hours no critical incident has been reported, which could have been linked to this simplified procedure.

3.3. Flight Test Support

Besides a good co-operation with the official agencies and adequate software development procedures and tools there is a third element, which is important for an efficient AFCS flight test programme: a good support from the suppliers.

In the early development phases of the Tiger AFCS every specification change went through the usual change management process: a "Request for Alteration" (RFA) had to be issued by EC and was answered by the supplier with an "Engineering Change Proposal" (ECP) with cost quotation.

In order to make the technical development time schedule more independent from commercial issues, a contract was signed with the suppliers on a "General Support Agreement" (GSA) as a package covering all known and - up to a certain limit - unknown modifications within a limited time period.

The support agreement consisted of several parts: a software development support at SEXTANT Avionique in Paris and at NORD-MICRO in Frankfurt and an on-site support by SEXTANT at Eurocopter in Marignane, the place of the main AFCS flight test activities. Necessary changes of the control laws were specified by EC using HOSTESS and sent by E-mail to SEXTANT Paris, from where the ADA code was sent back by E-mail to Marignane, where the SEXTANT on-site support performed the retrofits using a specific AFCS programming station.

In connection with the IESW procedure mentioned above, the support agreement was extremely beneficial for the Tiger AFCS development. In particular, it was much easier, once the GSA had been settled, to create the spirit of an integrated team, where all the members aimed for a common success.

Conclusion

The development of the Tiger autopilot has shown to be a complex task in technical as well as organizational terms. However it enabled EC to improve its competence in setting up efficient development procedures and in specifying such a complex system.

With a joint effort of all partners from industry and from customer side, a high-performance and very competitive piloting help has been developed. Benefiting from a long experience, on both the french and german sides, and introducing a number of advanced new features for a combat helicopter, it enhances significantly the operational effectiveness of the Tiger.

References:

/1/ U. Butter, E. Meissirel: "Automatic Flight Control System Tiger", 20th European Rotorcraft Forum, Amsterdam, Netherlands, 1994