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THE EUROPEAN ACT PROGRAMME:

COMPLEMENTARY USE OF GROUND BASED SIMULATION FACILITIES AND EXPERIMENTAL "FLY BY WIRE/LIGHT" HELICOPTERS

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The European ACT programme: Complementary use of ground based simulation facilities and experimental "fly by wire/light" helicopters

by

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Abstract

A European collaborative programme in Active Control Technology is underway to define a common approach to certain aspects of ACT helicopter flight control systems.

To accomplish the activities of the programme, two working teams have been set-up; Working Team 1 dealing with Handling Qualities and Control Laws, and Working Team 2, dealing with Inceptors. This paper concentrates on the work performed within Working Team 1.

The facilities available in France, Italy, UK and Germany and used in this programme are described. This comprise experimental FBW/L helicopters BO105 S3 at DLR and Dauphin 6001 at ECF, the moving-base simulation facility at DRA and the fixed based dome projection simulation facilities at ECD and ECF. The common use of the facilities includes the whole evaluation procedure; planning and preparation of trials, execution of the trials by 4 pilots from the participating nations and the analysis work.

The preparation and execution of the simulation and flight trials is described. The overall trials programme is divided into three phases, of which phase 1 is nearly finished. During the first year a detailled preparation was performed which included a review of literature and a comparison of existing handling qualities requirements. A mission analysis study was performed, and a commonly defined reference mission and mission task elements were defined together with a common procedure for pilot questionnaires. The ground based simulation activities of the first phase included a comparison of the simulation facilities at DRA/Bedford, ECD/Ottobrunn and ECF/Marignane and an investigation of handling qualities at DRA/Bedford only; for both activities the DRA Conceptual Simulation model was used. In parallel nonlinear simulations are performed, including the specific helicopter model and the control law design, which is used during the flight tests. The flight trials were performed according to the objectives of phase 1, testing the two helicopters in a direct and a rate command control mode. The flight and simulation tasks are essentially the same.

Results are shown from the trials, which were performed during Phase 1, concentrating on the comparison of facilities, the investigation of handling qualities and some results from the flight tests.

1. Introduction

This programme was originally undertaken by Eurocopter France (formerly Aerospatiale), Agusta, in the U.K. by Westland Helicopters and DRA Bedford (formerly RAE), and in Germany by Eurocopter Deutschland (formerly MBB), supported throughout by the DLR. ONERA provided technical assistance for Eurocopter France and will contribute during phase 2. The programme is sponsored by the Ministries of Defence of the participating nations, whose officials also work together at a european level.

The general organisation is shown in figure 1.

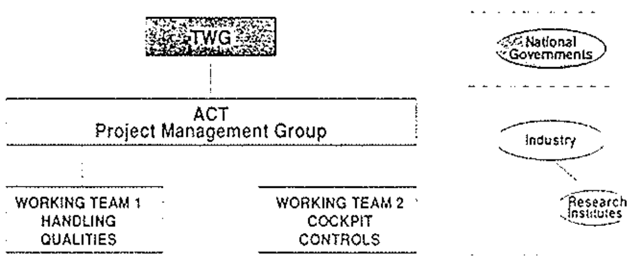

Figure 1: Organization of the ACT Programme

In accordance with the long-term objectives of the programme, common main activities were defined:

- Development of European handling qualities requirements for ACT helicopters
- Development of European inceptor requirements for ACT helicopters
- Development of methods of evaluating handling qualities
- Increased confidence in the ability to implement ACT and in the benefits which ACT should provide

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Additionally, the partners have defined individual topics of main emphasis; Eurocopter France and Deutschland concentrating on the development of control laws for inflight evaluations, the UK concentrating more on handling qualities investigations specifically, the analysis of response types and carefree handling aspects. Agusta focused its activity on inceptor requirement's preparation. These main items both reflect the agreed phase 1 workshare and result from the facilities, available in the different nations. In France and Germany experimental FBW/L helicopters are used for the evaluation of control laws, whereas the contribution of the UK is more concentrated on simulation using the Advanced Flight Simulator (AFS) at DRA/Bedford. Simulation is also performed at ECD and ECF in support of the flight trials.

The common approach for all the activities is fundamental to this programme, and the majority of simulation and flight trials have included the participation of pilots and engineers from each nation.

2. Description of the facilities

2.1 DRA's Advanced Flight Simulation Facility

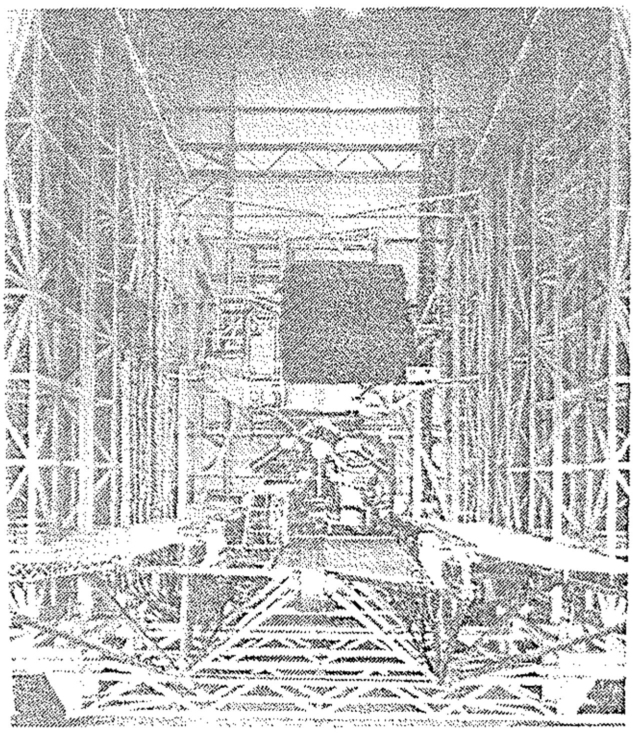

Figure 2: General View of the AFS

Figure 2 shows a general view of the Advanced Flight Simulator (AFS) facility used to support ACT trials at DRA Bedford. The AFS provides a key research tool for the DRA to investigate advanced flight control concepts and handling qualities aspects for future flight vehicles through piloted simulation. The facility was recently enhanced by the addition of the Large Motion System (LMS). Platform motion in 5 axes is provided, with roll, pitch, yaw, heave and sway or surge, depending on the orientation of the cockpit when mounted into the motion system, and unlike conventional 6-leg motion systems, maximum performance can be achieved simultaneously in all axes. So far, the LMS has only been used in sway mode during ACT trials, although the plan is to use the surge configuration in a later trial during the programme.

Motion system	max disp.	max vel.	max acc.
Sway/Surge	± 4.0 m	2.5 m/s	5.0 m/s2
Heave	± 5.0 m	3.0 m/s	10. m/s2
Roll	± 0.5 rad	0.7 rad/s	3.0 rad/s2
Pitch	± 0.5 rad	0.5 rad/s	2.0 rad/s2
Yaw	± 0.5 rad	0.5 rad/s	1.5 rad/s2

Table 1: LMS performance characteristics

Table 1 summarises the LMS performance characteristics and from the data shown, the LMS is noteworthy for the large linear displacements and high velocity and acceleration capabilities in all axes. Motion cues are generated by a combination of software and hardware, through motion "drive laws" as discussed in Ref. 1. Prior to the ACT trials, an exercise was carried out to optimise the drive laws for the tasks to be flown, based on pilot subjective opinion. Ref. 1 also reports on simulation validation work recently carried at the AFS using the LMS.

The cockpit used for the trials during phase 1 is a hybrid helicopter/fast jet facility and while some of its features are representative of those found in rotary wing aircraft, eg rudder pedals and collective control, others are not. For example, a Head-up-display (HUD) is available and was used in ACT trials to provide a continous display of flight information, eg. roll/pitch attitudes, heading, airspeed and height etc. The centre-stick probably represents the most significant departure however; this is a conventional fixed-wing stick taken from a BAe Hawk aircraft, and although the spring gradients for a Westland Lynx helicopter were used, the maximum control displacements, pivot locations and dynamic characteristics could not be matched.

The pilot's seat and seating position are also more typical of fixed-wing aircraft, although it does provide both normal, 'g' onset cueing and vibration cueing and has provision for the installation of sidearm controllers. For general interest, Refs 2 and 3 discuss the utility and benefits of using a dynamic seat for normal 'g' onset cueing. Sound cueing includes rotor, gearbox and engine effects and an 'active' noise suppression system is available for masking motion system sounds.

It should be noted that a new cockpit will be available for the next round of trials, which has been designed expressly for helicopter trials. Its layout is largely based on the Lynx insofar as the seat and primary flight instrument layout are concerned, and the pilot's controls (conventional centre-stick, collective and rudder pedals) and their mechanical characteristics (damping and inertias and spring gradients) are also modelled on those of the Lynx.

Visual cueing is provided by a 3-channel Link-Miles CGI Image IV graphics system through collimated CRT monitors mounted symmetrically in the cockpit to give a centre window and two side windows. Figure 3 shows an example of the general view from the cockpit; the approximate total field-of-view (FOV) in azimuth is ± 63 deg, while in the vertical plane it is ± 18 deg and ± 24 deg for the centre and side windows respectively. A number of general data bases are available including both landscape scenarios and seascape scenarios and the system has the flexibility to allow user defined features/objects to be "overlayed" onto the scene content. With CGI, which has an inherent computing time delay of around 80 ms, the AFS's computing hierarchy has been optimised to give a mean total through put time delay, from pilot control input to visual system response, of 125 ms.

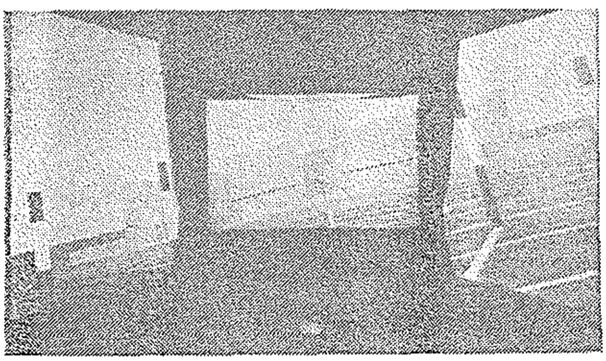

Figure 3: General view from the cockpit (Sidestep task)

2.2 ECF's Simulation Centre

This is a new research and development facility specifically for helicopter piloted simulation. The ACT trials were the first use of this facility, the characteristics of which are still being improved. (eg. improved field of view and equipment)

The visual system consists of a 8 m diameter dome screen on which is projected a computer generated imagery. The global field of view presently available is 120 deg in azimuth (60 deg only was available for phase 1 ACT tests), and 80 deg in the vertical plane. Different types of imagery are available: day, night, dusk, infra-red. Two databases are available: the first one, used for ACT, has been specially developed for helicopter piloted simulations to allow a better realism of NOE flight (different surface types: meadows, forests, cultivated lands, roads tracks, a whole village...).

Specific obstacles have been implemented for the MTE realization (lateral jinking, sidestep, quickhop and hurdle task).

The cockpit has been designed for Man Machine Interface studies for 7/9 tonne helicopters. It has side by side seating and is equipped with conventional collective and pedal controls, and a two axis sidestick controller. Head down , there are two CRT displays. A HUD will be available later but was not installed for the ACT trials.

The main computer comprises several standard microprocessors linked on a VME bus.

Figure 4 and 5 present a general view of the simitation center. The inset gives an example of the arrangement of visual cueing for the lateral jinking task.

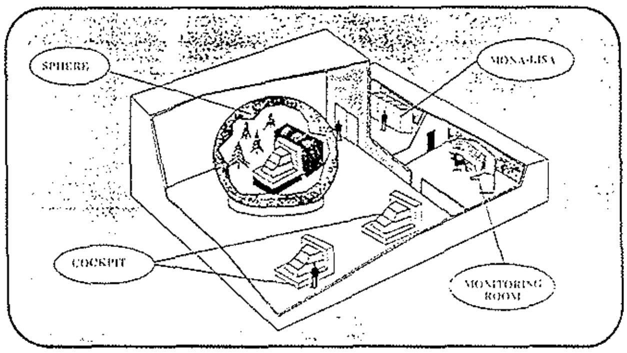

Figure 4: General overview of the simulation center

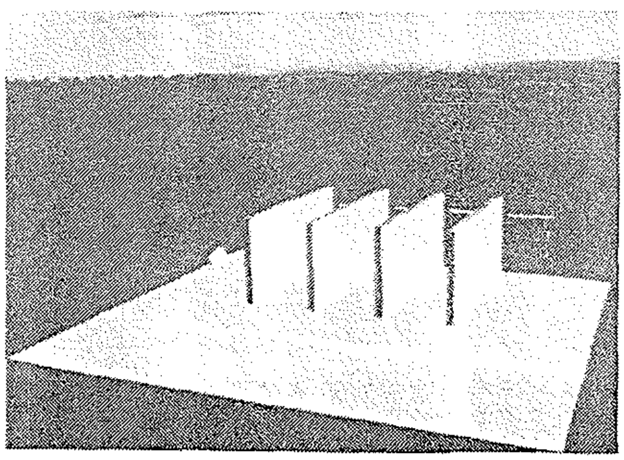

Figure 5: Visual cues for the sidestep task

2.3 ECD's Simulation Centre

This facility is located at and operated by the military aircraft division, with helicopter and military aircraft division sharing the utilization of the simulator. It was laid out and purchased according to the requirements of the two users and has the following features:

- interchangeable cockpits
- large field-of-view computer generated imagery
- fixed base with provisions for buffeting and g-seat
- vibration and noise generation.

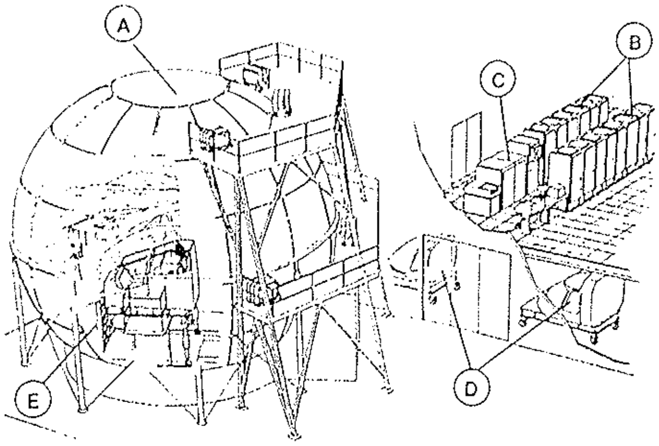

Figure 6: General architecture of the ECD simulation center

The general architecture of the ECD simulation facility is shown in Figure 6. The heart of the facility is the General Electric COMPU-SCENE IV visual system. This consists of a 10 metre spherical dome, a six channel projection system (A), a computer image generator using the photomapping method (B), a powerful HARRIS Nighthawk simulation computer (C), three easy to exchange helicopter simulation cockpits (D), and an interface computer as a link between cockpit and simulation computer for I/O operations and signal converting (E).

The field of view of the projection system is adapted to the requirements of helicopter simulation; ± 70° in azimuth and + 70°/- 40° in evaluation.

Figure 7: The research simulation cockpit, used for the ACT trials

The cockpit shown in figure 7 is derived from the BO108 and used at ECD for research simulation.

For ACT simulation, the cockpit is equipped with conventional controls for left hand seat, with an adjustable mounting on the right hand seat. This enables the pilot to adjust the position of sidestick controllers to an optimum ergonomic position.

Presently, only ECD-developed sidesticks have been mounted in the cockpit, but no problems are envisaged when sidestick controllers developed under this programme are installed.

Several data bases for the visual system are available. A 15 x 15 nautical miles more detailed area is mainly used particularly for helicopter trials. Figure 8 gives an impression of the field of view and the so-called enhanced area looking through the windows of the ACT simulation cockpit as it was used during the international simulation trials. A more detailed description of this facility is given in several papers, e.g. Ref. 4.

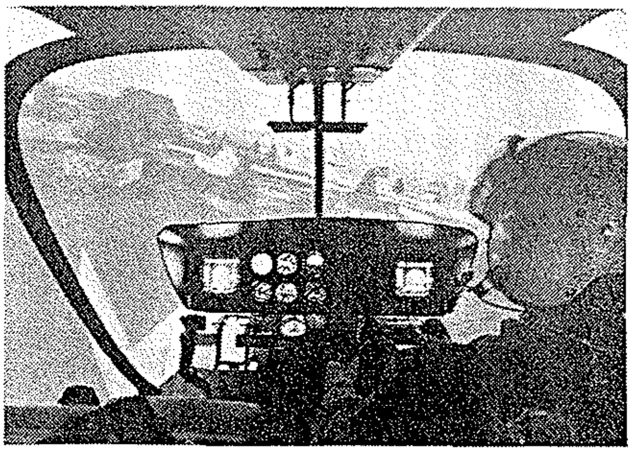

Figure 8: Pilot's view through the windows of the research simulation cockpit

2.4 FBW/L helicopter BO105 S3

This test vehicle is equipped with a full authority nonredundant fly-by-wire (FBW) control system for the main rotor and a fly-by light (FBL) control system for the tail rotor. It requires a two-men crew, consisting of a simulation pilot and a safety pilot. The safety pilot is provided with the standard mechanical link to the rotor controls whereas the simulation pilot's controllers are linked electrically/optically to the rotor controls. The FBW/L actuator inputs, which are commanded by the simulation pilot and/or the flight control system, are mechanically fed back to the safety pilot's controllers. With this function, the safety pilot is able to monitor the rotor control inputs. The safety pilot can disengage the FBW/L control system by switching off the FBW/L system or by overriding the control actuators. In addition, an automatic safety system is installed, monitoring the hub and lag bending moments of the main rotor. The vehicle can be flown in three modes:

- the FBW/L disengaged mode, where the safety pilot has exclusive control,
- the 1:1 FBW/L mode, where the simulation pilot has full authority to fly the basic helicopter, and
- the control law mode, where the simulation pilot is flying a control law with full authority.

In the 1:1 and the control law mode the flight envelope is restricted to 50 ft above ground in hover and 100 ft above ground in forward flight.

To incorporate the digital control system for in-flight simulation purposes an onboard computer and a data acquisition system have been developed. In the specifications for the design the following system conditions and requirements have been considered:

- Limited space is available in the helicopter.
- Software modifications in the control system must be accomplished in a host computer on the ground.
- A system simulation facility, which is compatible to the onboard system, is needed to check any software modifications before going into flight.
- The onboard system tasks, control system and data recording have to be clearly separated.
- The flight tests have to be observed and managed from a ground station.

Figure 9 shows a block diagram of the onboard system. Two computers, ruggedized for operation in the airborne environment, are installed. The data recording task and the control system task are assigned to the computers which allows a largely autonomous treatment of the data streams needed for the control laws and needed for the data recording for the control system performance evaluation.

The simulation pilot's inputs and the state variables, which are used in the control laws, are obtained directly from the preconditioned sensor signals with an installed 16 channel A/D converter. In the present state a sampling cycle of 25 Hz is realized. After the initialization, the control system is held in the trim position. The control system starts, when the simulation pilot switches on the control status and the computer generates a subcycle (8 msec at present) of 1/5 of the frame time. The subcycle allows a refresh at the FBW/L actuators in a shorter time frame that the sampling frame. More detailed information on the FBW/L helicopter BO105 S3 is provided in Ref 5.

2.5 <u>FBW helicopter Dauphin 6001</u>

The architecture of the system chosen for the Dauphin 6001 is a duplex electrical architecture with a mechanical back-up system in order to comply with the level of safety required for this type of flying demonstrator. The FBW evaluation pilot has the right-hand modified controls, while the safety pilot keeps the conventional mechanical controls. This architecture is shown in Figure 10.

The constraint of mechanical back-up required the development and installation of servo controls with two electrical and one mechanical input instead of the standard servo controls used on production Dauphin aircraft. Switching to the stand-by mode (or mechanical back-up mode) can be initiated at any time, since the safety pilot's sticks are backdriven when the electrical mode is engaged. This is guaranteed by the mechanical link between the stand-by control linkage and the FBW servo control values.

Return to mechanical mode can be performed manually either by deliberate safety pilot action with his disengagement switches located for that purpose on his cyclic and collective pitch sticks, by safety pilot load override on these controls or by the FBW system disconnecting lever located within both pilots reach on the central console. Return to the mechanical model is also ensured automatically on detection of a FBW system failure by means of operating parameters monitoring.

Electrical control commands are generated by the two synchronous FBW computers that monitor one another. This monitoring is performed by exchanging data between the two computers to check the consistency of the data they receive and the data they transmit to the control equipment.

The input data consists of various FBW system sensor detections (stick positions, helicopter movement state sensors and servo control positions) and is processed internally according to the computer's control laws. The sensors used in the FBW system are duplicated, each set of sensors keeping its corresponding computer informed. The sensors used in the experimental system are totally conventional and use gyroscopic, accelerometer and barometric data.

The FBW laws generate the control commands, which are consolidated on output before being transmitted to the servo control input stages. An ARINC frame allows the exchange of the required information between the two computers. The aircraft computers are programmed in two different languages (Pascal and LTR), thus reducing the sources of error in the programming of the onboard software. This constraint was imposed by considerations of maximum safety, handled here by dissimilar software (command monitor philosophy).

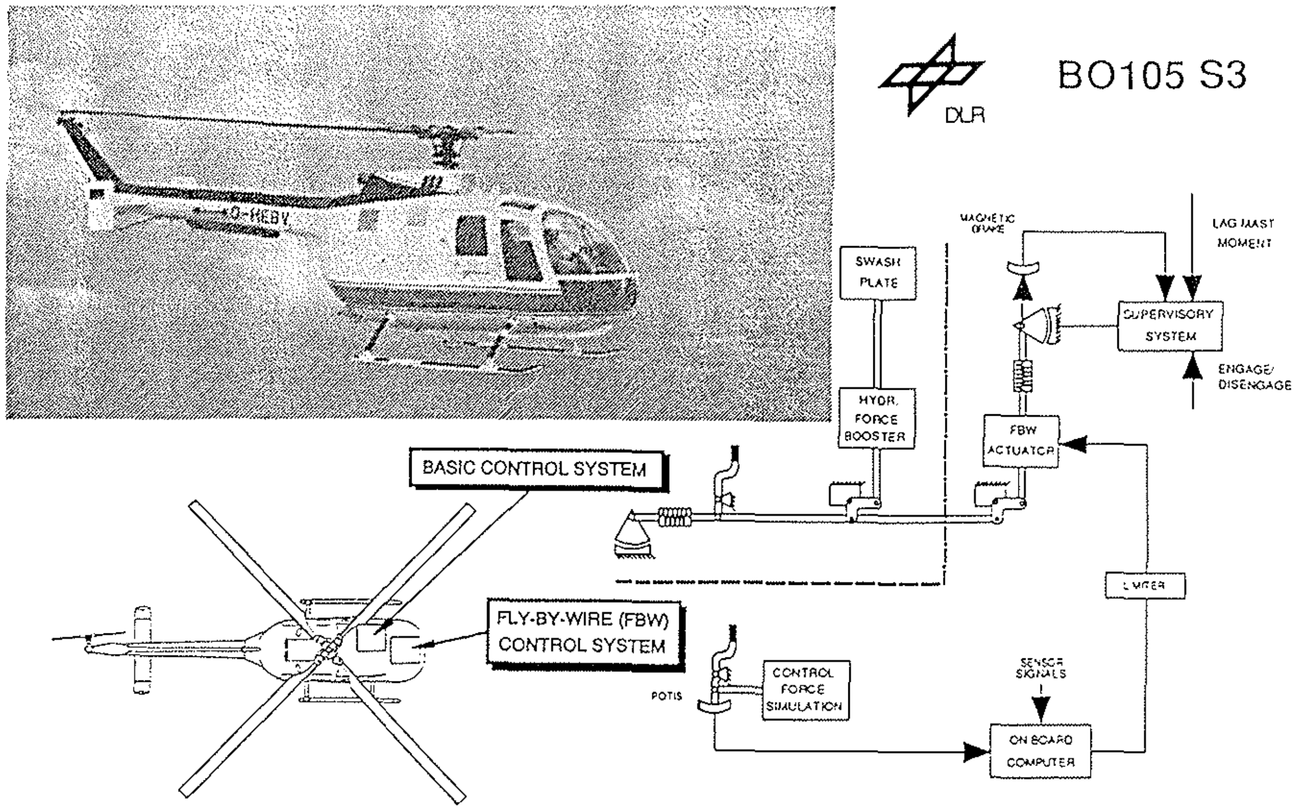

Figure 9: Experimental FBW/L helicopter BO 105 S3

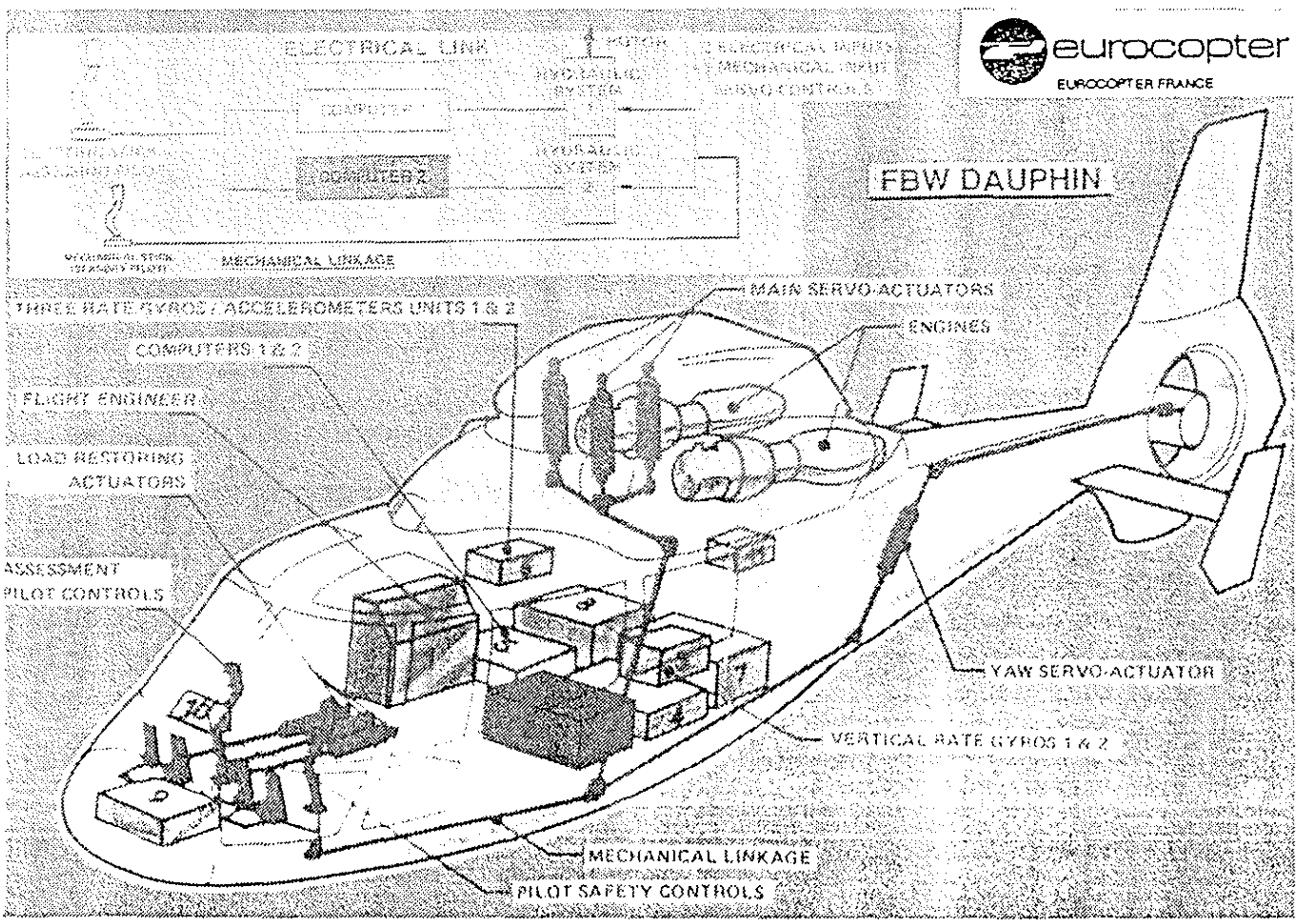

Figure 10:Experimental FBW helicopter Dauphin 6001

The commands transmitted by the computers are duplex and are delivered to both input stages of each servo control. These two commands are monitored on entry into each servo control to check the consistency of the information received from each computer. This monitoring is performed by an electronic system installed inside each servo control. The input stages have the task of slaving the commands from the two control valves which feed the two servo control bodies. The performance of the servo controls have been increased with respect to the ones installed on production Dauphin aircraft. They have a 12 Hz bandwidth, and their maximum travel speed reaches 150 mm/s, allowing full travel in 1 s.

3. Trials Preparation and Execution

In accordance with the different activities, a procedure was agreed which proved very effective. Figure 11 explains this procedure. The single elements of the preparation and execution phase are described in the following chapters.

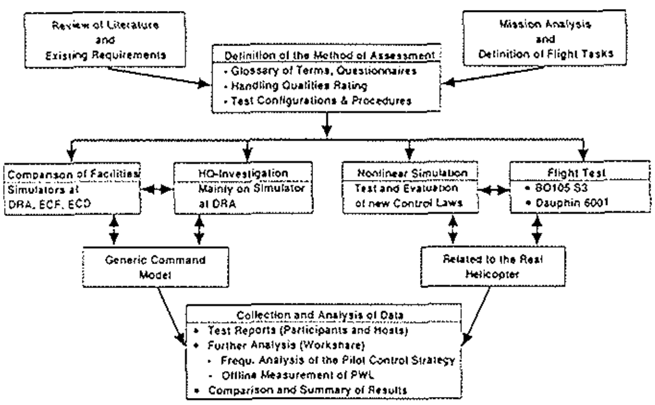

Figure 11: Procedure for the preparation and execution of the trials

3.1 Preparation Work

3.1.1 Review of Literature and existing Requirements

This topic started with a review of existing literature and a comparison of current and proposed Handling Qualities Requirements (ADS-33C). The objective of this was to indicate some areas of particular interest for the ACT programme. The relevence of the requirements to ACT-equipped helicopters have been identified and gaps in the existing data bases used for their establishment have been pointed out.

Five different specifications have been studied and compared with ADS-33C.

- MIL-H-8501
- FAR part 29
- MIL-F-83300
- MIL-STD-1797
- DEF STAN 00-970

The areas of interest for the ACT programme have been derived from this review and have been agreed by all partners.

The first topic undertaken was the definition of a set of common Mission Task Elements (MTE) and from these to derive a set of flight test manoeuvres. These manoeuvres have been designed to be reproducable and reflect the demands of the missions from which they have been derived (see 3.1.2). Following this, the response types most applicable to these MTE's were identified. It was decided to concentrate on selected response types, starting with Rate Command, Rate Command Attitude Hold and Attitude Command Attitude Hold systems.

As well as the investigations of the different response types themselves, the blending and transfer between response types was of high interest, particularly as it was not very well covered in the reviewed specifications. These investigations would include both switching between response types and the degradation in response types due to failures.

The review of the current Handling Qualities Data bases has established a priority for the investigations.

The small-amplitude/short term criteria are of essential importance for ACT. Some data gaps have been identified which need filling to verify the bandwidth/phase delay criteria.

The criteria for moderate amplitude manoeuvres shall also be considered, especially the transfer between small and moderate amplitude criteria.

The formulation of the coupling criteria shall also be studied.

Large amplitude criteria should be taken into consideration with the definition of desired/required task performance in the flight test manoeuvres.

3.1.2 Mission Analysis

The objective of this work package was the definition of mission oriented flight tasks, which later on were used in flight or on ground based simulators. Three main steps were identified, for this work:

- Relationship to the real mission through a mission analysis including piloting aspects;
- Selection of important mission phases using an handling qualities oriented criterion like the pilot workload;
- Reduction of mission phases to well defined and reproducible mission tasks.

Reproducible mission task elements are also defined in Ref. 6 . Recent evaluations for these mission task elements are presented in Ref. 7 . The analysis performed within this programme started with a European review of this topic.

Correlation to real missions was achieved by analysing all possible helicopter missions, civil and military ones, and describing the characteristic phases in terms of the mission profile (Height, Speed, time, distance), the typical visibility conditions and vision aids used, the primary control activity and secondary activities (Navigation, communication, weapon operation etc.), the pilot workload and the actual and desired control laws.

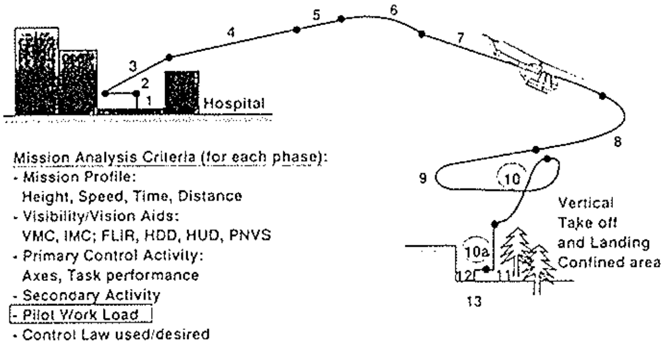

Figure 12: Sample analysis of an emergency medical service (EMS) mission

Figure 12 shows an example of this mission analysis for the emergency medical service mission (EMS). The EMS mission was derived from the national air rescue system founded by the German ADAC. The mission results mainly from ADAC pilots, experienced in EMS and SAR missions.

About 30 different mission types were identified, but due to different national strategies within one mission type, more than 30 missions were collected and described.

The next step was the selection of important phases. The decisive criterium for this selection was the pilot workload. As expected most of the civil missions had only few phases with high pilot workload. For the EMS-mission, the discussion and the analysis with pilots showed that above all, the vertical take-off and landing in a confined area is the most attentive phase and a typical demand for this mission. This identification of phases with high pilot workload in a realistic environment was the basis for the definition of the misson task elements.

The last step of this mission analysis was the reduction of the selected phases to well defined and reproducible mission tasks.

This definition includes a task description, the environmental conditions, the adequate and desired precision values and three different levels of aggression. The two precision values are related to the Cooper Harper rating scale and should support the pilot's assessment. The three levels of aggression proved useful, allowing a feedback about the influence on task performance. The result of the mission analysis were lists of mission task elements categorised under headings of "take off", "hover and low speed", "transition", "forward flight", and "landing". Response types relating to typical speed ranges or flight phases were included. A large database was created by this mission analysis which included wealth of international pilot experience. It enabled critical mission task elements to be identified where the use of ACT would essential.

The pitch and roll axis tasks were of main interest for phase 1 of this programme. Therefore the pitch and roll axis tasks sidestep, quickstop, lateral jinking and pitch tracking were selected for the first evaluations. In addition to the mission task elements, which are very demanding but cover only a limited flight profile, a so-called reference mission was defined. This mission is derived from a low level flight/VMC transport mission, which includes the whole spectrum of normal maneuvering, arranged with increasing demands: Low level flight, climb, descent, acceleration, deceleration, turns, turning quickstop, air taxiing. These well defined mission phases proved useful for the familiarization of the pilots as well as for an additional evaluation during the flight tests.

3.1.3 Method of Assessment

The results from the mission analysis exercise were used as a basis for defining a method of assessment to support the programme's handling qualities objectives. More specifically, the aim was to develop a flight test technique for the planned in-flight and ground based simulation trials activities. From Ref. 6, MTEs may be regarded as "..an element of a mission that can be treated as a handling qualities task". Accordingly, the MTEs were used to create flight tasks with well defined control strategies and task performance objectives, suitable for piloted evaluations using the Cooper-Harper rating scale for handling qualities (Ref. 8).

The MTE descriptions include a set of initial manoeuvre conditions as regards height and speed for example, together with set task performance requirements for the different control axes in terms of the levels of height, speed, heading and flight path accuracy that the pilot should endeavour to achieve. Suitable task cues, eg posts, markers, lines etc., were developed both to help the pilot judge the progress of the manoeuvre and to support assessment of task performance. While there were inevitably differences between 'real' world and CGI task cue arrangements, the aim was to produce tasks that required essentially the same pilot control strategy. Figure 3 shows an example for the sidestep task as implemented on the CGI visual system at the DRA's AFS facility. The diamond and square arrangement are intended to provide positional cues for the repositioning and hover elements of the task, while the red and white posts are designed to give both height and longitudinal displacement cues, in relation to the specified desired/adequate performance margins.

Aggression was introduced as a task parameter to provide a means of evaluating the handling characteristics of different test configurations across a range of available agility. Moreover, since ACT promises to provide levels of augmentation that aleviate handling deficiencies normally present as task time pressures increase, it was considered important that task aggression was covered by the test conditions. Required levels of task aggression were expressed in terms of an "aggression" parameter, which might be either the primary control variable associated with a given task, eg. roll or pitch attitude, or a minimum task time. Pilots were then briefed to fly tasks within the constraints of predetermined values for low, moderate and high aggression.

Retrieval of both qualitative and quantitative data, regarding for example vehicle responses, achieved levels of task performance and task aggression and pilot workload, was an essential ingredient of the assessment methodology. As noted above, all of the airborne and ground based trials facilites have some form of provision for objective data logging and a number of questionaires were developed for recording subjective pilot comment and opinion. The so-called "in-cockpit" questionaire was used to record pilots handling qualities ratings and supporting comments during ground based simulation trials. The questionnaire's format was designed around the Cooper-Harper scale and is intended to assist the pilot in deciding on a final rating. Key sections include task cues, perceived level of aggression (as opposed to "designed level of aggression"), task performance and task workload; the pilot is also asked give individual ratings for each element using specified five point rating scales. In the final section, the pilot is asked to note the main factors that influenced their choice of Cooper-Harper rating. "Post-sortie" and "post-trial" questionnaires were also used to record more detailed comments regarding handling qualities issues and overall impressions of the trials facilities.

In recognition of the different nationalities and varying background experience of the evaluation pilots engaged in the trials, a "glossary of terms" was researched and compiled. The glossary was intended to provide a set of standard definitions for rotary wing biased handling qualities terminology generally accepted within the international community, and which might be used in questionnaires and pilot de-briefings. Figure 13 shows a diagrammatical description to describe control sensitivity, damping, precision and control power for a vehicle's primary control response characteristics. Additionally this figure shows the definition of the most important handling qualities parameters, which were evaluated with the Conceptual Model during the Comparison of the facilities and the investigation of handling qualities at DRA.

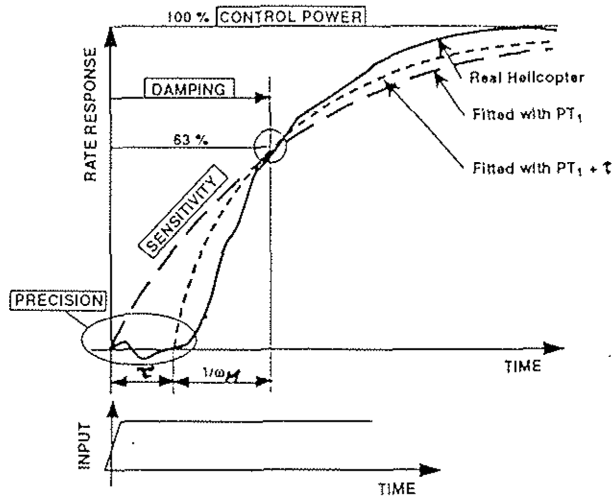

Figure 13: Definition of important handling qualities parameters

3.2 Execution of the Trials

According to Figure 11, the execution of trials can be devided into four types of investigations. For the comparison trials and handling qualities trials a generic command model (conceptual model) was used. The nonlinear simulation and the flight test are related to the real helicopter model (Lynx, BO105, Dauphin). In the following, the execution of these trials is described in detail.

3.2.1 Comparison Trials at DRA, ECF and ECD

Dedicated trials have been performed on the available ground based simulators at DRA, ECF and ECD, with the aim of comparing the different facilities and assessing those aspects that are most important for handling qualities evaluations on ground based simulators.

As already described in Section 2, the investigated simulators offer very different solutions to the problem of providing the pilot with effective sensory cues, ranging from a facility with large amplitude motion system and CRT monitor displays to a fixed based cockpit installed in a dome with very wide field of view. In order to highlight the influence of the characteristics of each simulator, the trials were planned to minimize any differences that were not related to the facilities. Therefore WT1 agreed to perform the trials with the same pilots and engineers, using the same test procedures and flying the same MTE's with similar scenarios in each simulator. Furthermore, the same CSM helicopter mathematical model was implemented on the three facilities. The model is described in Section 3.2.2 and was developed and supplied to other partners by DRA.

The test pilots and engineers from the four participating nations were divided into two teams for the comparison trials. Each Team spent two days at each facility during which the two pilots flew alternate sorties. Due to the limited time available for simulation, WT1 agreed to evaluate on each simulator a subset of four MTE's and three model response configurations among those selected in the trial preparation work. Each MTE was flown at three levels of aggression. The MTE's and configurations used are listed below:

4 Mission Task Elements:

SIDESTEP: primary axis roll, low speed task;
QUICKHOP: primary axis pitch, low speed task;
LATERAL JINKING: primary axis roll, forward flight task;
HURDLES: primary axis pitch, forward flight task;

3 Configurations:

C1: baseline values of damping and sensitivity;
C2: decreased damping and sensitivity (relative to C1);
C3: increased damping and sensitivity (relative to C1).

The control power of the three configurations was the same.

3.2.2 Handling qualities trials at the AFS facility

In accordance with the objectives outlined in the introduction, a series of handling qualities investigations were proposed, which were to be centred on the AFS simulation facility. The primary objective of the work was to explore handling qualities criteria and evaluation techniques, through piloted simulation trials, using the evaluation methods discussed in Section 3.1.3. As noted in the previous section, a secondary objective was that the trials would also serve as DRA's contribution to the comparison exercise.

A conceptual simulation model that the DRA had previously developed expressly for handling qualities investigations was adopted for the AFS trials. DRA's experience with this model (Ref. 1), referred to as the "Conceptual Simulation Model" (CSM), has shown that such an approach would offer an effective means to explore and validate handling criteria without the constraints normally associated with a full nonlinear solution. A modified form of the model with fully decoupled first order responses and rate demand response types in the pitch and roll axes, has been initially adopted for the trials. For the yaw axis, the response type is rate demand below 40 kts blending to sideslip demand/sideslip suppression above 50 kn. In heave, rotor thrust response is modelled by momentum/blade element theory, giving a short term acceleration response to collective control, and thrust also responds to changes to disc incidence. Turn coordination is also provided for turns at up to 70 deg angle of bank and above a blend speed range of between 40-50 kn.

Following the review of handling criteria for rotary wing aircraft, (section 3.1.1) it was decided that the Ref. 6 small amplitude bandwidth and phase delay criteria, in combination with the more classical damping and control sensitivity criteria, would form an appropriate focus for the first phase of the investigations. A matrix of roll, pitch and yaw axis test cases was devised, based on different damping versus control sensitivity and bandwidth versus phase delay configurations. To illustrate the case, figure 13 shows a typical rate time history response to a step input for the CSM, showing the effect of w_M and τ and how they relate to controllability criteria derived from flight data, such as that given by Edenborough/Wernicke (Ref. 9). The following low order equivalent system transfer functions define the main parameters of these criteria. They are related to rate command systems:

$$\frac{\text{RATE}}{\text{INPUT}} = \frac{K}{T_1 S+1} \qquad T_1 = T_1' + \tau \qquad (1)$$

$$\frac{\text{RATE}}{\text{INPUT}} = \frac{K'}{T_1' S+1} * e^{-\tau S} \qquad T_1' = \frac{1}{w_M} \qquad (2)$$

$$\frac{\text{RATE}}{\text{INPUT}} = \frac{K''}{(1/w_M S+1)(1/w_A S+1)} * e^{-\tau S} \qquad w_A = \text{const.},\quad w_A \gg w_M \qquad (3)$$

Equation (2) includes all the parameters, which were varied during the handling qualities trials:

- Damping parameter: w_M
- Time delay: τ (Minimum at the AFS: 125 ms)
- Sensitivity parameter: $K' \cdot w_M$

Equation (1) was used to compare with the controllability diagram:

- *Damping* : $1/T_1$
- Sensitivity : K/T_1
- Control Power : K

An additional constant lag term, w_A, was incorporated in the model to attenuate the initial acceleration (Equation 3).

The CSM was restructured to implement the test matrix, so that the described parameter could be selected for each axis. A complete configuration for a specific flight task was determined firstly for the primary control axis eg. lateral sidestep - roll axis, and then "harmonised" values set for the other control axes.

To date, two handling qualities trials have taken place at the AFS and for the first of these, the test matrix was based on the three baseline configurations used for the comparison exercise, C1, C2 and C3. In that trial, handling evaluations of two roll axis (lateral sidestep and lateral jinking) and two pitch axis tasks (quickhop and hurdles) were completed by the ACT pilots. An expanded test matrix, including additional time delays of up to 200 ms and different control sensitivity, was subsequently explored in a follow on trial and a further trial is planned for later in 1992 for investigating heave and yaw axis tasks. Some results from the two trials to date are discussed further in Section 4.2 below.

3.2.3 Flight Tests on BO105 S3 and Dauphin 6001

The first ACT flight tests were performed with the BO105 S3 test helicopter at DLR in Braunschweig. Within four test days, from November 4th to 7 th, 1991, the international test programme was completed. Two partners were divided into a team. The partners for team 1 were ECF/ECD, for team 2 WHL/GA. Each team had two test days available to execute the flight test programme (reference mission and mission task elements, see section 3.1.2 and 3.1.3). The flight tests were carried out in the direct FBW/L 1:1 mode on the first day, and on the second test day abstracts out of the test programme were flown in the FBW/L rate command control law mode.

The first ACT flight tests on the Dolphin 6001 have been partially performed: ECD and ECF have flown and WHL will do it soon. As for the BO105 flights, the reference mission and the Mission Task Elements were flown both in the direct FBW 1:1 mode and with a Rate Command Control Law.

3.2.4 Non Linear Simulation

As described earlier, the CSM was used to ensure the consistency of helicopter characteristics when making handling parameters investigations and when comparing simulators. For the development of control laws for flight evaluation, it is necessary to use non-linear simulation. These simulation models are necessarily helicopter specific and include detailed modelling of such items as the aerodynamic forces and moments, the flight control and actuation system, together with sensors and any structural filtering. Within the European GARTEUR group, these models were described and the results compared. In general, the constraint to operate in real-time restricts the complexity of the rotor models and some non-linear effects may be excluded.

The requirement to investigate different response types led to a sharing of the work, with each company developing the control laws for the response type which had the highest priority within their company. ECD chose to start with rate control, and ECF with attitude control. Due to the intention of ECD and ECF to test their control laws inflight, they did not select very advanced response types. WHL was more interested in pursuing a more advanced response type; they had previously looked at rate control in some detail and as there would be little chance of a flight evaluation of their control laws under the current programme, preferred to investigate Translational Rate Control (TRC).

Prior to the flight testing of the control laws, ECD/DLR and ECF perform non-linear simulation of their control laws using their own facilities and simulation models. In the case of WHL, the TRC control laws have been developed in-house, but against the DRA-supplied non-linear helicopter model 'HELISIM'. These laws have been designed for evaluation on the AFS at DRA Bedford. In the future it is hoped to fly these control laws on a suitable test vehicle.

In later phases, prior to flight evaluation, non-linear simulation will be used at all facilities to evaluate the new control laws using the ACT inceptors designed and manufactured under this programme.

4. Results

4.1 Comparison of Facilities

This section addresses the first outcome of the ground based simulator comparison exercise, reflecting pilots' comments regarding the different features of the investigated facilities. The results mainly reflect subjective pilot impressions; further work is currently in progress, with the aim of validating pilot comments by correlating them against objective analyses of task performance, and pilot control activity.
Important data for the three facilities are summarized in table 2, while figure 14 shows average Cooper-Harper ratings for each MTE at three levels of aggression, averaged for the three configurations. Therefore HQR represent a large number of single assessments. Due to this very concentrated presentation the absolute differences are rather small. Because the task definition and helicopter model response were the same for each facility the differences in the ratings are related to the specific facility characteristics and the implementation of task scenarios. As will be discussed below.
Regarding the results from the trials, it should be noted that comments about the ECF facility relate only to its configuration at the time of the trials. As already described in section 2.2, this facility is still in the build up phase and many of the negative features of the visual system will be improved by impending upgrades.

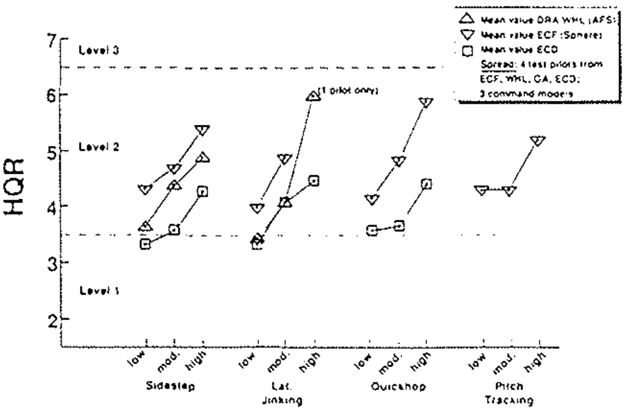

Figure 14: Average HQR vs MTE for 3 facilities at 3 Levels of aggression

Facility	DRA			ECF	ECD
Motion system	max disp.	max vel.	max acc.	Fixed base.	Fixed base.
Sway/Surge	±4.0 m	2.5 m/s	5.0 m/s2		
Heave	±5.0 m	3.0 m/s	10. m/s2		
Roll	±0.5 rad	0.7 rad/s	3.0 rad/s2		
Pitch	±0.5 rad	0.5 rad/s	2.0 rad/s2		
Yaw	±0.5 rad	0.5 rad/s	1.5 rad/s2		
Vibration/"g" cues	Normal "g" and vibration cueing at 4R frequency via "g" seat			Not available. (planned in 1993)	Not available. (planned)
Sound	Rotor, gearbox, engine noise simulation.			Not available. (planned in 1993)	Noise simulation available but not used in the trials.
Vision system	Link-Miles CGI image IV graphic system.			SOGITEC CGI system	General Electric Compu Scene IV
Display system	3 CRT (central CRT positioned horizontal; lateral CRT's vertical)			8 m diameter dome with 1 projector (3 channels planned in 1993)	9 m diameter dome with 6 projectors
Field of View	Azimuth: ±63 deg; Vertical: ±18/24 deg. (±18 deg in the central CRT) (±24 deg in the lateral CRT's)			Azimuth: ±30 deg; Vertical: +30/-50 deg. (180 deg in azimuth planned in 1993) Vertical FOV limited by the cockpit to about -20 deg	Azimuth: ±70 deg; Vertical: +70/-40 deg.
Update frequency	50 Hz			25 Hz	33 Hz
Cockpit layout	1 seat, hybrid helicopter/fighter type			2 seats, 7-9 tons class helicopter cockpit	2 seats, medium class helicopter cockpit
Controls	Cyclic: Hawk (fixed wing) centre-stick. Conventional collective and pedals (Lynx-like). (2 axis sidestick available)			Cyclic: 2 axis sidestick (non-linear control shaping). Conventional collective and pedals.	Cyclic: conventional helicopter centre-stick. Conventional collective and pedals.
Instruments	Conventional analog instruments + HUD			CRT display (no conventional analog instruments). (simulated HUD planned in 1992)	CRT display (EFIS) + conventional analog backup instruments.
Overall time delay	125 ms			200 ms	120 ms

Table 2: Data of the compared facilities

4.1.1 Motion cues

The comments about the cues provided by the Large Motion System (LMS) in the AFS at DRA have been generally positive. Pilot's comments have shown, the motion to be harmonized with the visual cues and no disorientation perceived.

However, some misleading cues were experienced in the pitch axis tasks which were probably due to the lack of surge motion. Note that the AFS cockpit can be mounted to give surge movement as opposed to sway if pitching manoeuvres are of particular interest. During aggressive roll tasks some jerkiness was noticed. This effect was improved for the main ACT handling qualities evaluation trial by modification of the motion drive laws. Any remaining jerkiness was probably due to the sharp acceleration response of the CSM model.

It is clear from pilot's comments that motion cues contribute significantly to the adoption of a more "natural" control strategy. A particular comment was that the motion cues inhibited pilots from making unrealistically large control inputs. Where not present, the lack of acceleration cues was commented as having a negative effect on both task performance and pilot behaviour particularly in the heave axis where there was a greater tendency to overcontrol.

In addition the ACT trials supported previous DRA research results (Ref. 11) regarding the importance of motion cues for the investigation of short term response characteristics such as PIO and time delay effects. Tests at the DRA confirmed that pilots found it difficult to recognise additional pure time delays introduced in the system response with motion switched off.

Normal "G" onset cues generated through the seat at the DRA simulator gave rise to conflicting pilot comments. Some pilots appreciated the effectiveness of the "G" seat in reducing any tendency to overcontrol in the heave axis. Other pilots were less convinced of the value of the seat because of a perception of the cue being in the opposite direction to that expected and also because of the unnatural localised sensation caused by the seat available at DRA. However dedicated trials performed at DRA have indicated that the "G" seat does enhance the realism of the simulator enabling the pilot to control height more realistically and effectively in the absence of platform motion (Ref. 2 and 3).

4.1.2 Visual Cues and Task Realization

The visual systems available in the three tested facilities have significant differences in terms of their primary characteristics, for example field of view (FOV). The AFS at the DRA offers a reasonably wide horizontal FOV but is limited vertically. The ECD dome surrounds the pilot with a large FOV both horizontally and vertically, whilst the ECF facility with the current single channel configuration gives a large vertical FOV but lacks significant lateral vision.

In addition to FOV, the differences between the visual systems in term of factors such as brightness, focus, resolution, scene content and texture were emphasised by the characteristics of the tasks performed during the ACT trials. Any deficiencies in the visual cues were highlighted by the high precision demands of the tasks flown close to the ground.

The trials confirmed that non-optimum distribution of field of view, coupled with lack of near-field details compromise the terrain. Considering the importance of a wide FOV in hover and low speed flight, it is not surprising that the pilots appreciated the ECD dome display. Even during aggressive manoeuvres the pilot was able to keep some outside references in the field of view which was sometimes not possible in the other facilities, thus reducing the requirement to look at instruments.

Also the good quality of the display image on the dome contributed to the favourable assessment of the facility at ECD. The number, variety and detailed nature of the objects in the scene increased the perceived realism and enhanced pilots' perception of both attitude/position and rates. It was possible to fly NOE using only outside visual references quite easily. General NOE flight and hover were more difficult in the other facilities especially in the ECF SPHERE due to the lack of lateral vision. Pilots commented that there was some difficulty in estimating height and vertical rate when flying NOE and in the hover. Instrumentation partially compensated for this deficiency. In particular pilots pointed out the importance of the head-up-display which had been used at DRA in order to improve the level of cues and to reduce workload.

The FOV of both the DRA and ECF facility was criticised. The former is insufficient in the vertical plane, particularly downwards, whilst the latter currently has a limited lateral vision. Therefore problems with single axis tasks related mainly to pitch axis tasks for the DRA facility and to the sidestep for the ECF simulator.

The quality of the displayed images on the DRA cockpit were commented by the pilots as being good especially in terms of brightness and focus. The images projected in the domes exhibit lower resolution compared to the bright and sharp images of the DRA CRT screens.

The current intermediate configuration of the ECF vision system drew some criticisms as expected. Focusing of the image was not good and some flickering was disturbing to pilots. According to ECF engineers these problems will be removed in a future release of software. However these factors plus insufficient resolution negatively affected both workload and task execution precision and thus degraded handling qualities ratings.

The ECF trials confirmed the importance of lateral FOV in helicopter simulation. Even in forward flight when pilot attention is focused on the frontal view, peripheral cues are of great help for height and speed perception as well as for attitude and angular rate estimation.

The different definitions of task scenarios was also a significant factor in the comparison of the facilities. DRA and ECF, as agreed by WT1, introduced into CGI databases a set of geometric elements such as sights, posts, walls together with reference lines on the ground. These rather stylized cues aimed to give immediate visual feedback of task execution errors with the intention of forcing the pilot to perform the task with the necessary aggression and precision. However, this type of task scenario results in a rather "artificial" environment.

ECD on the contrary, because of a limited ability to modify existing CGI databases, implemented the task scenarios using more "real world" objects such as helicopters, houses, streets and trees in addition to some artificial objects like discs, squares and bars. The resulting environment appears more "natural". Pilot comments confirmed this impression and expressed a preference for that type of realistic environment.

However when examining the trial results, it is not clear whether the ECD scenarios were sufficiently effective in providing immediate indications of the magnitude of task performance errors. The lower workload and the relatively good subjective ratings could be related to a more "relaxed" pilot behaviour due to less effective cues of task errors.

4.1.3 Concluding Remarks

Further analysis work is currently outstanding aiming at objectively evaluation the relative importance of visual and motion cueing on task performance and workload. However the results from subjective pilot comments can be summarized as follows:

- the large amplitude motion system at DRA provides acceleration cues which enable a more natural control strategy to be adopted. In particular pilots are prevented from applying unrepresentatively large control inputs and short term response characteristics such as time delay effects and PIO tendency are well represented.
- although not fully accepted by all pilots in this study, the DRA 'G' seat provided normal acceleration onset cues which reduced the tendency to overcontrol in the heave axis.
- lack of field of view can significantly increase workload so much that it can prevent the execution of aggressive manoeuvres.
- the visual perception of translational cues relative to nearby terrain are closely related to the availability of both a large field of view (especially downward) and rich, sharp near-field details in the displayed images.
- a natural environment in task scenarios as realized at ECD is better accepted by pilots compared with highly stylised visual cues, but its effectiveness in providing immediate task error cues has yet to be substantiated.

4.2 Handling qualities investigations

As noted in Section 3.2.2 above, this section addresses results achieved during the two handling qualities trials at the AFS. Some preliminary results from a summary of subjective pilot comments and ratings are presented and discussed, although it must be emphasised that further analysis of the objective test data is still needed to substantiate the findings. For brevity, and because the roll axis data are more extensive than for the pitch axis tasks, only results for the roll axis are presented here. Figure 15 summarises the maximum, mean and minimum Cooper-Harper ratings for the sidestep task for different test configurations with either the basic or the additional time delay element, flown at low, moderate or high aggression; note that for comparison purposes, a selection of cases were flown without the motion system engaged. Single points indicate a result for only one pilot.

Figures 16 illustrates the influence of bandwidth and damping on pilot ratings for a subset of test cases, while Figures 17 and 18 compare these cases against the controllability and bandwidth criteria and highlight some preliminary recommendations based on the results. The following sections discuss the results in more detail.

4.2.1 Effect of task aggression

Referring to Figure 15, as expected the results show a clear trend for a deterioration in ratings with increasing task aggression. The general trend indicates a reduction of some 3-4 rating points, from marginal Level 1 to the upper Level 2 range, across the range of aggression. Similar results were obtained from the lateral jinking task, which are not presented here. Poorer ratings were attributed to increased pilot workload, through the need for increased anticipation and control demand, and/or a reduction in task performance. Regarding the latter, a problem was noted during the trial as to the "correct" application of the Cooper-Harper scale. As discussed in Section 3.1.3 above, visual cues were provided to support pilot judgement of task performance, which, from the objective data, generally achieved this aim. On occassions, pilots were able to achieve the desired performance levels even at high aggression, and thus awarded a rating of 4. However, their supporting comments indicated that the aircraft exhibited "moderate to very objectionable deficiencies" with the need for "considerable-extensive pilot compensation", ie. attributes for ratings 5-6. More stringent task performance requirements might resolve the dilemma, but probably at the expense of reducing the range of aggression over which the task performance could be achieved (ratings < 7). During the trial, pilots were encouraged to "weight" ratings towards values more in keeping with the vehicle's characteristics and degree of pilot compensation required.

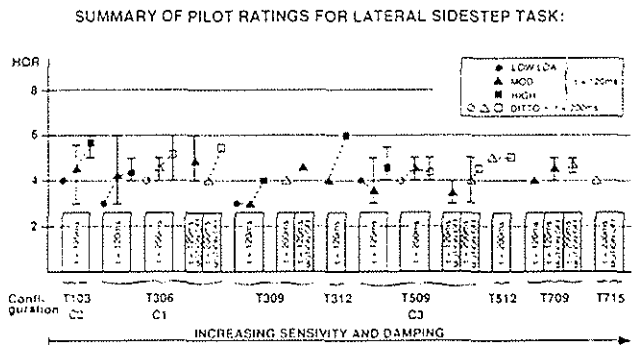

Figure 15: Effect of task aggression on HQR

From pilot comment, another noteworthy point is that motion cues gave an enhanced perception of aggression, more in keeping with "real" flight, than was the case for the fixed-base evaluations. From Figure 15, the limited results are inconclusive as regards the effect on pilot ratings, where some motion off cases have poorer ratings when compared to motion on cases, while others show improved ratings. However, subjectively, pilots considered that motion cues helped to remove the "video game" effect and gave rise to a greater conviction in the level of aggression applied in the pilot's control strategy. The objective data recorded during the trials will provide the opportunity to generate quantitative results to underpin such comments, and to make a more rigorous investigation of the influence of motion cueing, or its absence, on pilot control strategy and workload.

4.2.2 Influence of bandwidth and control damping

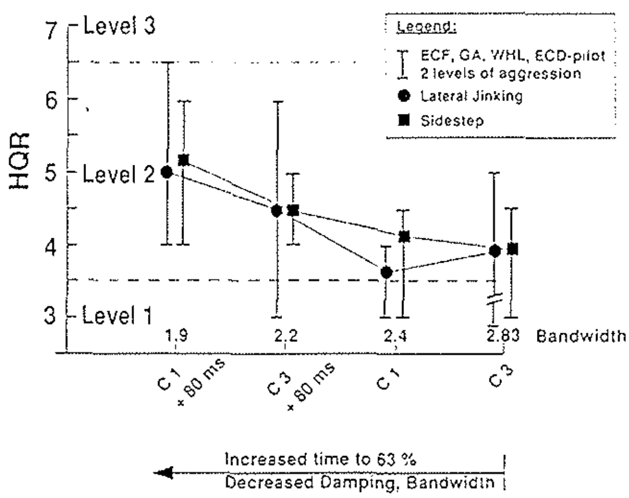

Figure 16: Influence of bandwidth and control damping on HQR

For the roll axis tasks, Figure 16 summarises the variations in pilot ratings for the two configurations that were most widely tested and accepted as giving the best handling characteristics, T306 (C1) and T509 (C3). Results for the additional time delay cases are also shown. The results are plotted in order of increasing bandwidth and as can be seen, the trend shows improved pilot ratings across the range, for both the sidestep and lateral jinking results. For the latter, there is some evidence that the lower bandwidth case C1 was marginally preferred and that some pilots found C3 "too crisp" at moderate to high task aggression, giving rise to a tendency for over-controlling during the acquisition phase of the manoeuvres. Reduced sensitivity relative to these configurations drew comments of "too sluggish" while increased sensitivity was considered to be "too crisp". The effect of additional time delay promoted comments that the configuration was "unpredictable" and ratings awarded were at least one point poorer, with motion on. However, the effect of the additional time delay with motion switched off was more difficult for pilots to detect, and this was reflected in the similarity of ratings given for the basic and additional time delay cases.

4.2.3 Handling qualities criteria

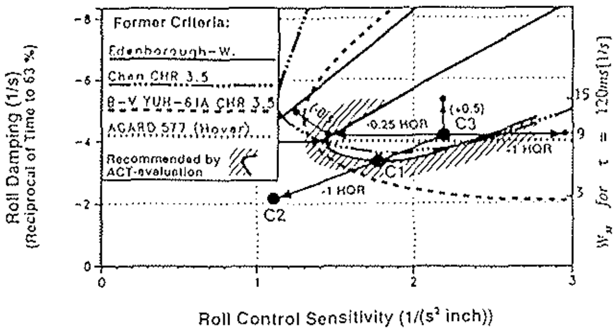

Figure 17: Recommended controllability criteria from previous studies and the ACT-investigation.

Figure 17 compares the roll axis results for several configurations for τ = 120 ms, against various controllability criteria recommended in previous studies, including Ref. 9. The shaded area is drawn from the ACT results and represents a preliminary recommendation. Compared to the existing criteria, it is in good agreement to most of them in terms of damping. For the optimum sensitivity a rather wide range was accepted by the pilots. Nevertheless a higher sensitivity was prefered compared to former recommendations (e.g. Ref. 9). These results may be caused by different controller characteristics such as different mechanical freeplay: With a high free play the pilot does not accept high control sensitivity. At DRA this freeplay was as low as can be expected for advanced sticks. Configuration C3 seemed to be optimum in terms of sensitivity and damping.

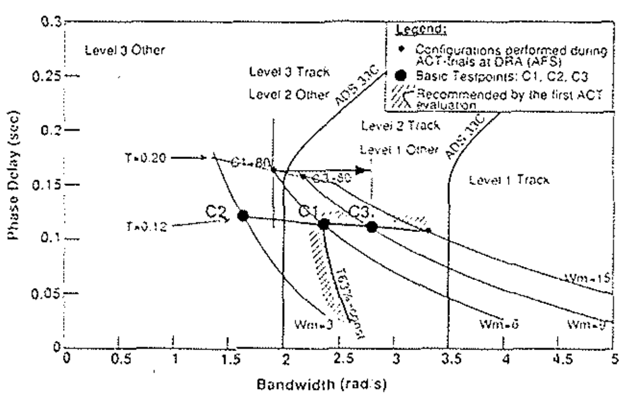

Figure 18: Recommended bandwidth criteria from Ref. 6 and the ACT-investigation

Referring to Figure 18, compared to the Ref. 6 bandwidth criteria, the ratings for C1 and C3 do not conform to the stipulated Level 1 HQR ≤ 3.5 criteria. Pilot comments indicate that simulation related factors, ie. visual system deficiencies (poor textural cues, limited FOV) and controller characteristics, contributed to this (see section 3.1.3)

Generally speaking however, the results do confirm the general trend of the bandwidth criterium (Figure 18). The particular impact of increased time delay seems to deteriorate the rating more than suggested by the Ref. 6 criteria. Ref. 10 confirms, that increased time delay influences the handling qualities more than proposed by Ref. 6. The shaded area, defined by the test configurations for τ = 120 ms and the time constant constraint, compares the optimum area of the ACT test matrix, against the Ref. 6 criteria.

4.3 Analysis of Flight Tests

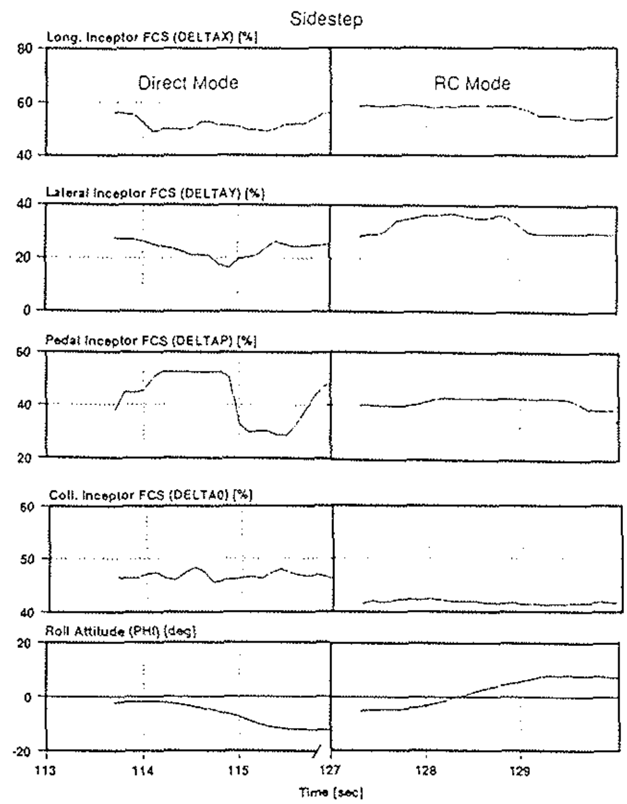

Figure 19: Sidestep, FBW/L direct and RC mode

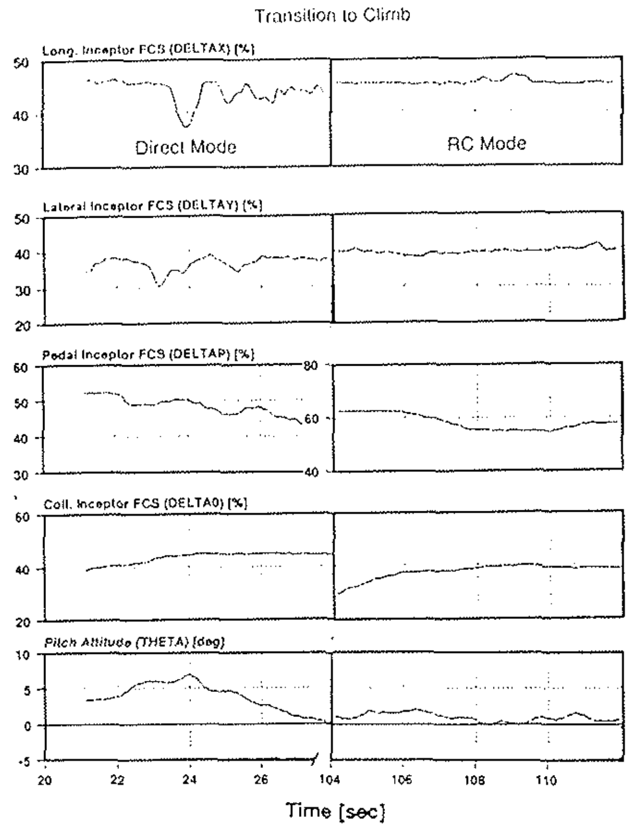

Figure 20: Transition to Climb, FBW/L direct and RC mode

Figure 19 and 20 show some first results from the flight test compaign, described in section 3.2.3. For the roll axis hover and low speed task (Sidestep) as well as for the pitch axis forward flight task (Transition to Climb), the reduction of pilot workload can be derived from time history plots: Using the rate command attitude hold system, the control activity could be reduced significantly in both manoeuvres.

For these trials, the control laws were designed at ECD, implemented in the BO105 S3 and tested together with DLR. The main objective for this phase was to check this complementary workshare between ECD and DLR as well as to test the harmonized method of assessment (Realization of mission task elements, pilot questionaires etc.). The design and evaluation of an optimized, robust control law with advanced control features will be the objective for phase 2 of this programme.

5. Conclusion

The activities performed during phase 1 of this programme all fulfilled the philosophy of the programme: The joint elements formed the major part of the programme with individual elements having high visibility with the other partners.

The collection of missions and definition of mission task elements, the selection of appropriate rate response parameters, the definition of test configurations and the definition of the method of assessment formed the common baseline of the programme. The implementation of one mathematical model on the three simulators at DRA, ECF and ECD enabled the ACT group to perform very effective simulation work.

For the execution and analysis of trials a real complementary use of the facilities available in Europe was achieved:

- Realization of the same tasks for flight tests and simulation trials
- Execution of the trials with four pilots and engineers from the participating nations:

  - Comparison of 3 simulators, efficient in different roles
  - Recommendation of optimum handling qualities parameters related to Rate Response Types
  - Evaluation of FBW/L RCAH control laws on BO105 S3 and Dauphin 6001.

According to this basic work during phase 1, the next two phases will be dedicated to the following main activities:

- Investigation of advanced response types
- Design of improved control laws
- Integration and evaluation of new inceptors (WT1 and WT2)

Acknowledgement

We thank all of the people not previously mentioned who have supported and contributed to the success of the programme. Special thanks are extended to the pilots engaged in the flying, particularly for their fortitude and patience in enduring a sometimes ambitious sortie schedule! We look forward with confidence to the continuation of this fruitful cooperation during future phases of the programme.

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