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EURO-ACT: A COMMON APPROACH TO IDENTIFY THE POTENTIAL OF ACTIVE CONTROL TECHNOLOGY

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ABSTRACT

A European collaborative programme on Active Control Technology (ACT) was launched in 1990 to define a common approach to certain aspects of ACT helicopter flight control systems. The programme was a three nation collaboration between Eurocopter France assisted by ONERA, Eurocopter Deutschland assisted by DLR, and Westland Helicopters and the DRA in the UK. The programme was largely based around trials in ground simulators at ECF, ECD, and DRA, and in flight research helicopters at ECF and DLR. This paper summarizes the main results obtained during the programme which was divided into three phases.

The first phase work concentrated on a review of handling qualities requirements, the analysis of military and civil missions, the definition of methods of assessment, and initial handling qualities trials. These trials concentrated mainly on the pitch, roll and yaw axes. This paper presents the methodology developed and describes how this was successfully applied to the evaluation of handling qualities criteria and the assessment of control laws and inceptors in flight.

The second phase developed various control laws which were evaluated in simulators and in flight. The paper describes the control laws and presents the results obtained which generally showed encouraging handling characteristics.

The third phase evaluated new inceptors which had been developed during the programme. The inceptors main characteristics are presented and the results of initial evaluations are described.

The programme is now complete and the collaborative work has enhanced European knowledge in ACT for helicopters and in handling qualities criteria. A further programme is planned to build on the various ACT elements which have been developed and to try to quantify the operational benefits which ACT should provide.

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1. INTRODUCTION

Recent years have seen the widespread adoption of Active Control Technology (ACT) flight control systems in civil and military fixed wing aircraft. Significant research and development effort is now being expended on the development of ACT flight control systems for helicopters, and some of the next generation of helicopters will be equipped with such systems.

ACT flight control is a radically different form of control from conventional flight control. The essential difference is that the flight control computer is put into the forward control path with full authority control over the actuators. This means that the pilot is no longer constrained to demanding blade pitch angles and can now directly demand his required flight state, resulting in what can be termed a manoeuvre demand control system. The control laws within the flight control computer interpret the pilot's manoeuvre demands and the current flight state of the helicopter to determine the required actuator positions.

ACT flight control systems offer many potential advantages including reduced weight, reduced life cycle cost, reduced vulnerability and improved cockpit ergonomics. However, the greatest potential benefit of ACT is the improvement to the handling qualities of the vehicle with manoeuvre demand strategies, reduced cross coupling and crisp well damped responses throughout the flight envelope. This improvement in handling qualities should provide reductions in pilot workload, improvements in safety and improved mission performance.

The major change to helicopter handling qualities brought about by ACT highlights the need for a good understanding of the handling qualities required, so that specifications for the control systems can be produced. It is recognised that existing handling qualities specification do not accommodate ACT equipped helicopters and this has led to the extensive programme in the USA to produce ADS-33 (Reference 1).

The application of ACT to helicopters and the consequent change from mechanical control runs to electrical or optical systems also necessitates a revision of the inceptors (primary flight controllers), and provides much greater design freedom.

A European collaborative programme in Active Control Technology was launched in 1990 to define a common approach to the issues identified above. The programme is a three nation collaboration between Eurocopter France (ECF) assisted by ONERA, Eurocopter Deutschland (ECD) assisted by DLR, and Westland Helicopter Limited (WHL) and the Defence Research Agency (DRA) in the UK. The programme was sponsored by the Ministries of Defence of France (STPA) and Germany (BMVg), and in the UK by MoD(PE) Directorate of Future Systems.

The aim of this programme was to form a European view on ACT handling qualities and inceptors. This was partly to encourage standardisation within European industry but also, in recognition of the large amount of work being undertaken on ADS-33, to ensure that European Industry has an intelligent view of the handling qualities requirements emerging from the USA.

The current programme is now complete and preparations for a follow on programme are well advanced. This paper presents the work undertaken over the last 5 years, describing the objectives, activities, facilities used, results obtained and plans for the follow-on programme.

2. OBJECTIVES AND PROGRAMME STRUCTURE

The main objectives of this programme were:

- to develop European handling qualities requirements for ACT helicopters,
- to develop European inceptor requirements for ACT helicopters,
- to develop methods of evaluating handling qualities,
- to increase confidence in the ability to implement ACT and in the benefits which ACT should provide.

The general organisation is shown in Figure 2.1:

- The Technical Working Group, comprising representatives of the Ministries of Defence of each participating country, was responsible for general monitoring of the programme,
- The Project Management Group, comprising representatives of the industrial partners, was responsible for the general management, contractual aspects and important technical decisions,
- Two working groups were responsible for co-operative work on Handling Qualities and Cockpit Controls.

The programme was divided into three phases based around ground and airborne simulation trials, which had both 'National' and 'International' elements. Phase One concentrated on preparatory work, including handling qualities trials, comparing the facilities available and flying a first set of active control laws. Phase Two evaluated new control laws developed under this programme both in ground and airborne simulation, and investigated further handling qualities issues. Phase three evaluated new inceptors developed under the programme.

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

3. DESCRIPTION OF THE FACILITIES

For this programme, five facilities were available, three ground simulators and two Fly-by-Wire/Light helicopters. In the UK, the Advanced Flight Simulator (AFS) at DRA Bedford was used. In Germany, the dome simulation facility at the DASA site in Ottobrunn was used, together with the DLR BO105-S3 in-flight simulator, based at Braunschweig. In France, the Eurocopter France SPHERE simulator was used together with the DAUPHIN 6001 FBW helicopter, both at Marignane. All these facilities are described in detail in References 2 to 6; only the key features will be given below.

3.1 DRA Advanced Flight Simulator

Figure 3.1 shows a general view of this simulator. Key components include the Large Motion System (LMS) and a Link-Miles Image IV computer generated image (CGI) visual system. The LMS provides platform motion cues in 5 axes (pitch, roll, yaw, heave and sway or surge) and notably, the maximum performance in each axis can be achieved simultaneously. A single seat cockpit was used in which three CRT monitors were mounted to provide a centre and two side windows; the total horizontal field of view (FOV) was approximately ±63°, while the forward window's vertical FOV was ±18° and the side window's ±24°. Other notable features included a 'G-seat' for normal 'g' onset cueing and a sound system for providing representative background noise. The mean total latency between pilot input and visual response was measured to be 114 ms.

3.2 DASA Simulation Centre

Figure 3.2 shows a general view of this simulator. 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 computer image generator using the photo mapping method, a HARRIS Nighthawk simulation cockpit, and an interface computer linking the cockpit and simulation computer for I/O operations and signal conditioning. The field of view of the projection system has been adapted for helicopter simulation: ±70° in azimuth and +70°/-40° vertically. The cockpit used for the ACT programme is representative of a 2/3 ton class helicopter. It is equipped with conventional controls for the left hand seat and an adjustable mounting for sidestick controllers for the right hand seat. Both seats were used for comparison during this programme. A 15 x 15 nautical miles detailed area was the visual data base used during this programme. The total system time delay between pilot input and visual response is about 120 ms.

3.3 ECF SPHERE Simulator

This is a new research and development facility specifically for helicopter piloted simulation and is shown in Figure 3.3. The ACT trials were the first to use this facility; its characteristics were enhanced during the programme. The visual system consists of a 8m diameter dome screen on which is projected computer generated imagery. The global field of view presently available is ±90° in azimuth (only ±30° was available for phase 1 and ±60° for phase 2), and +30°/-50° vertically. The database used during the programme was specifically developed for helicopter piloted simulations to allow a realistic nap-of-the-earth (noe) flight environment. Specific obstacles were implemented for the mission task elements (MTEs) realisation. The cockpit was designed for Man Machine Interface studies for 7/9 tons helicopters, having side by side seating and equipped with conventional collective and pedals controls, and a two axis sidestick controller to ensure consistency with flight trials in the Dauphin 6001. Head down, there are two CRT displays. The main computer comprises several standard microprocessors linked on a VME bus. The total system time delay between pilot input and visual response is about 120 ms.

3.4 DLR BO105-S3 FBW/L Helicopter

The BO105-S3 test vehicle is shown in Figure 3.4. It is equipped with a full authority non-redundant fly-by-wire control system for the main rotor and a fly-by-light control system for the tail rotor. It requires a two-man crew, consisting of a simulation pilot and a safety pilot. The safety pilot is provided with mechanical links to the rotor controls, whereas the simulation pilot's controls 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 controls. 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: FBW/L disengaged mode, where the safety pilot has exclusive control; 1:1 FBW/L mode, where the simulation pilot has full authority to fly the basic helicopter; and finally the control law mode, where the simulation pilot flies a full authority control law. In the FBW/L modes, 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.

3.5 FBW Dauphin 6001

The FBW Dauphin 6001 is shown in Figure 3.5. It has a duplex electrical system with a mechanical back-up and requires a two-man crew, consisting of a simulation pilot and a safety pilot. The evaluation pilot has modified right-hand controls, while the safety pilot retains conventional mechanical controls, which are back driven. Special 12 Hz bandwidth servos have been developed with two electrical and one mechanical input. Their maximum travel speed reaches 150 mm/s allowing full travel in one second. Switching to the standby mode (or mechanical back-up mode) can be initiated at any time. Return to mechanical mode can be performed either manually, by deliberate safety pilot action, or automatically on detection of a FBW system failure. The aircraft computers are programmed in two different languages (PASCAL and LTR) by two different teams, thus reducing the sources of error in the programming of the onboard software. The FBW system sensor data, comprising stick positions, helicopter motion sensors and servo control positions, is processed internally according to the computers' control laws. The sensors are duplicated, each set of sensors keeping its corresponding computer informed. The FBW laws generate duplex control commands, which are sent to dual input stages of each servo control. The duplex architecture allows flight in the FBW mode in the whole flight domain including take-off and landing.

3.6 Complementary Use of the Facilities

These different facilities have been used throughout the ACT programme in a complementary way. The DRA simulator with its large amplitude motion system was used for the majority of the ground based handling qualities evaluations. The ECF and ECD simulators have similar features and were used to assess different response characteristics, the influence of time delay, and to validate and develop the control laws and inceptors to be implemented on the Dauphin 6001 and on the BO105-S3. While the ground simulators allowed a large number of testpoints to be covered efficiently, use of the two aircraft ensured that practical aspects were addressed and allowed comparison of simulation and flight test results.

4. HANDLING QUALITIES

4.1 Method of Assessment

Different types of tasks were derived from a mission analysis using the following procedures:

- Breakdown of missions into well described mission phases.
- Selection of important mission phases using handling qualities oriented criteria such as pilot workload.
- Reduction of a mission phase into well defined and reproducible mission tasks which can be used for handling qualities evaluations. This type of task refers to the MTE of Reference 1.

From these MTE's, a set of common tasks were selected for the handling qualities trials:

Sidestep: Hover and low speed task primarily requiring roll axis control.

Lateral Jinking: Forward flight task primarily requiring roll axis control.

Quickhop: Hover and low speed task primarily requiring pitch axis control.

Pitch Tracking: Forward flight task primarily requiring pitch axis control.

Spot Turn: Hover task primarily requiring yaw axis control.

Yaw Pointing: Low speed multi-axis task primarily controlled about the yaw axis.

Most of the tasks were flown at three levels of aggression. The visual conditions were good for all tasks. The influence of reduced visibility was therefore not investigated within the programme.

The exact definition and precise implementation of the MTE's ensured a clear baseline for consistent evaluations.

The pilot assessment procedure was also carefully defined to achieve maximum consistency. The following three aspects were the most important for the achievement of this goal:

- Use of different questionnaires, one of them referring directly to the Handling Qualities Rating (HQR, used also in Reference 1).
- Breakdown of the HQR into assessments of pilot workload, task precision, and the system characteristics, checking the task performance and level of aggression by an objective method and recording the influencing factors on the overall HQR.
- Development of a consistency check method which defined a reproducible relationship between individual assessments and the overall HQR.

These three aspects created additional confidence in the pilot rating, making it more consistent, and ensuring that only valid HQR's fed into the results.

4.2 Mapping of Handling Qualities

Following a review of handling qualities criteria for rotary wing aircraft performed during phase 1 of the programme, it seemed to be reasonable to begin with rate command systems and to select two formats for the mapping of important parameters: the more recent bandwidth/phase delay criterion (from Ref. 1) in combination with the more classical damping/sensitivity format (e.g. Ref. 7). These formed an appropriate focus for initial investigations into the optimum response characteristics of a helicopter. Using the parameters of these two formats, the most important handling qualities aspects for the primary control response characteristics could be assessed and related to quantitative values:

- Required quickness of the helicopter response: open loop behaviour,
- Optimum sensitivity: to avoid large inceptor displacements or any over control tendency,
- Reasons for PIO tendency: closed loop behaviour,
- Optimum tracking characteristics: small amplitude closed loop behaviour.

4.2.1 **Damping versus Sensitivity Format**

The baseline of this method is the approximation of the rate response of the helicopter due to a step input to a first order equivalent system. Because several interpretations exist for this format, a common definition on the basis of Reference 7 was established, described by the following parameters:

- Time to 63% (reciprocal value is plotted on the vertical axis): time from the idealised step input or averaged ramp input to the 63% value of the equivalent system rate response. The reciprocal of this value is defined as damping ($1/T_1$, Lp, Mq, Nr).
- Control Power (diagonals of the diagram): the achieved rate per stick input. This value can be defined per inch (typically used in the controllability diagram) or per full stick range (maximum control power, used in Ref. 1).
- Sensitivity (horizontal axis): the rate increase (acceleration) per stick input. Because of the very rough approximation at small amplitudes by the first order system, the approximated value is difficult to compare with the process of the acceleration of the real helicopter. It lies typically between the lower initial response and the higher maximum acceleration of the real helicopter. Therefore, the interpretation of this parameter is less important at very small amplitudes. The interpretation for larger amplitudes is that for the same damping, higher sensitivity leads to a higher rate response per input. For the small amplitude short-term behaviour, the bandwidth/phase delay format is the better criterion.

A further set of parameters was defined on the basis of a first order system with a time delay term included:

ω_m Damping parameter
τ Equivalent time delay
$\tau + 1/\omega_m = T_{63\%} = 1/\text{Damping}$.

The parameters of this additional first order equivalent system were not directly used as handling qualities parameters, but represent the response characteristics better in the small amplitude region and can be easily related to the bandwidth/phase delay format. Therefore, this set of parameters was an optimum for the definition of the test matrices. The magnitude of the equivalent time delay τ which includes the pure time delay (e.g. frame time) as well as non-linear and high order effects at small amplitudes, can be related to the precision of the helicopter response. Together with a term for the attenuation of the initial acceleration, this type of model formed the basis for the command model of the Conceptual Simulation Model (CSM) which was mainly used for the handling qualities investigations to avoid the constraints normally associated with full non-linear models (Reference 2).

Using the described parameters which are directly or indirectly related to the controllability diagram, the following benefits could be identified for the method of mapping applied:

- Comparison with existing criteria for centre stick evaluations.
- Simple and quick method for the identification of the main parameters of the primary response characteristics.
- Relation to the bandwidth/phase delay format using the damping parameter ω_m together with an equivalent time delay term.
- Criterion for the inceptor (response per deflection) included.

However, some important aspects are not or only partly covered by this format:

- System characteristics at high frequencies and small amplitudes are difficult to identify.
- Further important inceptor characteristics especially for small stick ranges and a programmable force-deflection response characteristic are not included:
  - Breakout force
  - Force gradient
  - Variable sensitivity
  - Tactile feedback

4.2.2 **Bandwidth versus Phase Delay Format - Relation to Damping Criterion**

In addition to the damping criterion, the more recent bandwidth versus phase delay format was used. Because the criterion is extensively described in many references (e.g. Refs. 8), the method is not explained in this paper. As mentioned above, a low order equivalent system was used for most of the evaluations. Using this model, a simple relationship between the two formats can be identified. Together with the relationship between time to 63% and damping

$$T_{63\%} = 1/\text{Damping} = \tau + 1/\omega_m,$$

a correlation between the parameter of the controllability diagram and the bandwidth can be derived using the pure time delay and the damping parameter as connecting elements. The orientation of the line of constant $T_{63\%}$ (see Figure 4.1) shows that the bandwidth and the $T_{63\%}$ are similar handling qualities parameters used in different formats.

However, it should be noted that this explicit correlation is only possible if a reduction to the described low order equivalent system is performed. Because this reduction is necessary for the controllability diagram in any case, it was interesting to show these time domain parameters also in the bandwidth versus phase delay format. Nevertheless, the following two main aspects should be regarded in order to keep also in mind the differences between bandwidth and time to 63%:

- The $T_{63\%}$ (1/damping) includes non-linear effects and high order dynamics only indirectly by the breakdown into a pure time delay part (τ) and a pure damping parameter ω_m. Important information can be lost by this reduction to the low order equivalent system.

- The bandwidth versus phase delay requirements evaluated by the low order equivalent system can be fully applied to a general system, but additional requirements may be necessary in order to exclude further deficiencies of the overall system which are not represented by the low order equivalent system representation. The additional requirement for the bandwidth defined by the gain as included in Reference 1 is a typical example for such an effect which is not represented in the described low order equivalent system.

4.3 Results

In the following, the assessments of the roll, pitch, and yaw axes are described. All the evaluated criteria are related to high pilot workload tasks close to the ground which demand high precision together with a high level of aggression. The typical application of such manoeuvres is related to military missions or complex civil missions. In addition to the evaluations performed under this programme, further background information and experience were brought to the programme by the partners which helped to define reasonable boundaries around the test points and to extrapolate the results where not enough test points were available (Refs. 9, 10).

4.3.1 Roll Axis

Controllability Criteria: Figure 4.1 summarizes the evaluated test points for the roll axis. The evaluation was mainly performed in the DRA AFS. Additional simulation trials were performed on the simulators at ECD and ECF. Some preliminary results have already been presented in Reference 2. A further check of the results from the simulator was performed by the evaluation of a rate command attitude hold system on the BO105-S3 by varying the sensitivity. The consistency between the results from the helicopter and simulator was quite good with a tendency for the simulator to allow a higher control sensitivity. The shaded boundary on Figure 4.1 defines the recommended area evaluated within this programme. For comparison further existing criteria are included (Refs. 7, 11, 12). The different width of the shaded area indicates that the pilots were quite sensitive to a certain minimum damping, but more tolerant to some variation of the sensitivity.

Phase Delay versus Bandwidth Diagram: Figure 4.2 shows the results in the bandwidth/phase delay format. In addition to the test points used in the controllability diagram, further pure time delays were included for additional evaluations (200 ms and 300 ms overall lag). Compared to Reference 1, the boundary evaluated within this programme identified a higher sensitivity for an increased time delay, but a less stringent requirement for the bandwidth (referring to the boundary for tracking tasks). A recently revised version of Reference 1 (publication in progress) confirms this trend.

4.3.2 Pitch and Yaw Axes

Figures 4.3 and 4.4 show the results for the pitch and yaw axes in the bandwidth/phase delay format. As for the roll axis, a higher sensitivity to an additional time delay was identified for both the pitch and yaw axes. Although not enough testpoints could be performed for the yaw axis with and without additional time delay, a horizontal boundary was assumed for this axis too. As all evaluations of the pitch and roll axes confirmed that the pilot identified and criticised the effect of time delay above a certain value, a boundary following the line of constant time delay seemed to be reasonable in general. Using two types of task (one of them including tracking), two recommended boundaries for the bandwidth could be defined: for the pitch axis, the results for optimum bandwidth confirm Reference 1, whereas the results for the yaw axis are less restrictive compared to Reference 1.

5. CONTROL LAWS

5.1 Activities

While ACT control law development was not one of the major aims of the programme, control laws were produced to support the handling qualities and inceptor activities. Control laws were required to allow correlation of airborne handling qualities tests with the conceptual simulation handling qualities results. A variety of response types were required to allow comparison between response types and to allow the inceptors to be evaluated with different response types.

The control laws which were produced under the programme are summarised in Annex A. The ECD RCAH and ECF RCAH and ACAH control laws were developed through ground simulation for implementation on the B0105S3 and Dauphin 6001 airborne simulators and therefore had to take into account the constraints of the airborne simulators, in particular, the sensors available. The WHL TRC control laws, which were to be evaluated in ground simulation only, had no such constraints and therefore offered higher levels of augmentation, with carefree handling features to protect airspeed, torque and rotorspeed limits. Two TRC configurations were developed; the major difference being in forward flight where one configuration used the pedals to control coordinated turns, the other used the lateral inceptor.

5.2 Results

The results obtained from evaluation of the control laws arise from pilot assessment of the control laws themselves and, in the French and German ground and airborne simulation trials, from comparison with a direct 1:1 mode.

For all response types, ergonomic aspects, inceptor characteristics, displays, task cues and simulator fidelity had a large impact on the results obtained as well as the characteristics of the actual control laws.

Results for the different response types are discussed below.

5.2.1 Rate Command Attitude Hold

Results from ground and airborne evaluation of the ECD and ECF RCAH control laws are shown in Figures 5.1 and 5.2.

Pilots generally adapted easily to the RCAH strategy and returned handling qualities ratings which were generally 1 or 2 better than for the 1:1 mode, and mostly Level 1 or good Level 2. The RCAH strategy was confirmed as being well suited to aggressive manoeuvring flight but less well suited to precision tasks. The importance of well harmonised inceptor characteristics was identified; pilots need well defined neutral (zero rate) stick and pedal positions.

5.2.2 Attitude Command Attitude Hold

Results of ground and airborne evaluation of the ECF ACAH control laws are shown in Figure 5.2.

Pilots in the ECF SPHERE simulator generally preferred the ACAH control laws to the RCAH laws due to greater precision of control and stability. In flight the results were less positive; it was felt that pilots needed more familiarisation, and results / comments were dominated by ergonomic aspects and inceptor characteristics.

5.2.3 Translational Rate Command

Results of ground based evaluation of the WHL TRC control laws in the DRA AFS are shown in Figure 5.3.

The TRC control laws generally returned Level 1 and good Level 2 handling qualities ratings despite some inceptor and display deficiencies. Evaluations concentrated on the low speed flight envelope where the strategy was well liked; more work is required to examine the forward flight aspects. The second configuration, where coordinated turns were initiated using the lateral inceptor was thought to be more natural. The carefree handling features incorporated within the control laws reduced pilot workload and many tasks were reduced to simply judging when to make the appropriate control demand.

5.3 Lessons Learned

During the programme a range of full authority control laws were successfully developed for ground and airborne simulation. The development and evaluation of these laws highlighted some important lessons.

It is important to provide control strategies with natural responses, especially for helicopter pilots used to conventional helicopter responses.

Transferring control laws from simulation to flight does require retuning of many control law parameters. While models should be kept as simple as possible to minimise design effort, higher order modelling, including actuator modelling, to cover modes up to 20 rad/sec should be developed.

More highly augmented strategies such as TRC and carefree handling reduce pilot workload and are especially useful for flight in poor visual conditions. However, objective requirements to ensure good handling qualities for these strategies are immature.

The results showed that ergonomics, inceptor characteristics and displays can be equally important to the quality of the control law in achieving good handling qualities.

6. INCEPTORS

The aim of the inceptor activities was to begin to establish appropriate inceptor characteristics in order to derive design guidelines for ACT helicopters. This was based on using the different facilities available to evaluate various new ground and flightworthy inceptors designed and developed within this programme, based on common preliminary analysis of the factors influencing inceptor design.

Ergonomic aspects of inceptors are also important. Because of their smaller size, side-stick controllers (SSC's) allow the designer more freedom in placing displays and cockpit equipment. This gives the potential for improved pilot comfort and more efficient operation of the helicopter. Areas of interest during this programme included inceptor position and orientation, seat position and orientation, and the control range available in each axis of the inceptor.

6.1 Terminology

The following terminology is used to describe inceptor characteristics.

A passive inceptor responds to applied force only according to mechanical means. The inceptor outputs are force or displacement and the only means of providing trim is through the flight control computer software.

A trimmable inceptor has some means of changing the null position and may include variable force/ displacement gradients.

A fully programmable inceptor (Figure 6.1) features closed loop high bandwidth control of force and displacement with the primary output to the flight control computer being force or displacement depending upon the situation. Variable force/displacement characteristics, soft and hard stops, damping and inertial feel etc. are all under "software" control and can be changed during flight. This concept allows the inceptor force/displacement characteristics experienced by the pilot to be manipulated by the flight control computer as a function, for example, of flight state, to give additional information to the pilot. These programmable characteristics are generally based on the following elements:

- Breakout force: the force that must be overcome to start movement of the inceptor.

- Force gradient: the rate of change of force with inceptor displacement.

- Soft stop: a step change in force or force gradient above the baseline value; the pilot will normally be able to push through this step change.

- Hard stop: a step change in force above the baseline value which results in the maximum available force. The pilot will, in general, be unable to push through a hard stop.

Mechanical components should exhibit minimum friction and freeplay if satisfactory force/displacement characteristics are to be obtained.

Control demand shaping can be defined as the vehicle response per increment of inceptor displacement or force. It is possible to use linear shaping (i.e. constant change in response with respect to change in inceptor displacement) or non-linear shaping. The latter introduces the possibility of reduced sensitivity for small displacements (for ease of precision manoeuvring) and higher sensitivity for more aggressive manoeuvring at larger displacements.

6.2 Design, Manufacture and Evaluation of the Inceptors

Based on an initial bibliography analysis and on some specific trials on the DRA simulator where various configurations were compared, the following configurations were selected for evaluation:

- A 3 axes, right hand, displacement inceptor, programmable in the 2 axes of pitch and roll and passive in yaw was developed by ECD for ground and flight test.

- A 2 axes, right hand, displacement inceptor, programmable in both axes was developed by WHL for the ground evaluation in the AFS.

- A 1 axis, left hand, programmable, displacement inceptor for heave control was developed by ECF for ground and flight test.

6.2.1 WHL/DRA Inceptor

The WHL inceptor was designed to allow a wide range of characteristics to be evaluated in ground simulation, including characteristics suitable for providing carefree handling features (through moving hard and soft stops). This inceptor also has the capability to simulate stick locked and stick free conditions.

The bulk of the design work was carried out by Stirling Dynamics Ltd in the UK against a WHL design specification. The stick general arrangement is shown in Figure 6.2.

Actuation is provided by brushless DC motors which drive the inceptor through a lead screw arrangement. A high voltage supply (60V) is used. Micro switches are mounted on the assembly to contain motor travel beyond the design limits. A semi-conductor strain gauge mounted on a beryllium copper spring is used to measure the applied forces. Encoders on the lead screw are used to sense the position of the grip.

The control law is formed around position and velocity loops. The measured applied force is used in the force/position law to define the demand to the control loop.

The inceptor force/displacement characteristics are described by look-up tables downloaded by the flight control computer during initialisation. Soft stops can be superimposed on the normal force/position curve: the flight control computer specifies the maximum force value and the starting and finishing position; two stops may be specified on each axis at any one time. The soft stops move at a default rate, stored in firmware, but may be specified by the flight control computer. Hard stops can be superimposed on the same curve in similar manner to the soft stop: the flight control computer specifies the starting and finishing position, at which the force increases to the maximum available force (i.e. 100N).

6.2.2 Trials at DRA Bedford

For evaluation the DRA AFS, the rate command Conceptual Simulation Model (CSM) was used with pitch, roll and yaw characteristics preferred by pilots during handling qualities trials described in Section 4. Four different MTEs were flown: two around the hover (side-step and quick hop) and two in forward flight (lateral jinking and pitch tracking).

The first objective was to examine the influence of the basic stick force and displacement characteristics on handling qualities as well as to demonstrate the programmable features provided by the inceptor, in particular, the use of active tactile cueing.

Four different sets of force, displacement and breakout characteristics were used during these trials, as shown in the table below. All were linear with a small range of displacement so that control inputs required only hand/wrist movements. Non-linear control input shaping was associated with these linear force/displacement laws.

Configuration	Pitch Axis		Roll Axis	
	Displ/Force max. nose up	Displ/Force max. nose down	Displ/Force max. roll left	Displ/Force max. roll right
FD1	-6°/10N	6°/10N	-6°/10N	6°/10N
FD2	-6°/17.5N	6°/17.5N	-6°/15N	6°/12.5N
FD4	-6°/30N	6°/30N	-6°/25N	6°/12.5N
FD5	-12°/15N	12°/15N	-12°/15N	12°/15N

Control Characteristics of the Inceptors

All pilots commented positively on the position of the inceptor in the cockpit. As the stick moved, some mechanical vibrations could be felt as the worm gears operated although, during evaluations, this vibration was not intrusive. The very low inherent friction and the lack of any discernible backlash enabled a deadband of around 0.5% of full scale travel to be employed. This also allowed low breakout forces to be employed (around 2N). There were no problems encountered with making single axis inputs with the breakout forces chosen. In general, pilots were able to make large and rapid control inputs, being more aggressive than with a centre stick, although overall workload was no higher than in previous trials. The sensitivity was considered too high for lateral tasks leading to over-control when trying to acquire a bank angle, with the force gradient insufficient to discourage excessively aggressive inputs. Increasing the gradient reduced the tendency to over-control. The pilot ratings obtained during this evaluation are given in Figure 6.3. More work is needed to tune the response characteristics of the total system: in particular the use of non-linear force gradients should be considered to reduce the impression of high sensitivity, perhaps coupled with increased travel.

In order to evaluate tactile cueing, the inceptor was evaluated with rate control laws which included carefree handling features. The operation of both hard and soft stops, driven either by simple limit recognition routines, or working in conjunction with direct intervention routines within the control laws was demonstrated. Flying the task with these features required a different piloting strategy that was not always accepted by the pilots. The technique of controlling torque either through attitude or bank angle using a high bandwidth rate command system caused necessarily rapid movement of the inceptor which was not always liked by the evaluation pilots. Overall, desired performance could be achieved with low workload, but the combination of features to achieve this depended on pilot preference. In general though, soft stops were preferred to operate alone, and hard stops were preferred with Direct Intervention. Additional work is needed to refine the Carefree Handling features for the rate command system, and for other response types, such as attitude command and translational rate command, where it is expected that the operation of the stops would be more harmonised to the helicopter response.

6.2.3 ECD Inceptor

The ECD inceptor was designed for use on the ECD simulation facility and on the DLR BO105-S3 helicopter. An existing 2-axis programmable (pitch and roll) SSC was modified with the addition of a passive twist yaw control. The stick general arrangement and integration in the Bo105 is shown in Figure 6.4.

Actuation is provided by DC motors which drive the inceptor. Each motor is controlled by Pulse Width Modulated signals, has an integrated tacho generator for rate measurement and drives the inceptor via a lead screw arrangement. The forces applied by the pilot are detected by a Force Measurement Package in which the deflections of 4 flexible rods due to the applied forces are measured using LVDTs. An LVDT attached directly to the motor casing is used for position sensing. For the passive yaw axis, the moment/angular displacement characteristics defined by exchangeable torque springs. The grip twist is measured by an RVDT.

The force signal is transmitted to the flight control computer where it is translated into a position demand using the force deflection law. The structure and parameters of the control law can be easily modified as the law is programmed on the I/O controller of the sidestick computer.

The inceptor force/position law is fully defined by a set of parameters (breakpoints and slope) which are sent by the flight control computer in accordance with the flight control laws and the flight conditions. These parameters are transmitted via an ARINC 429 bus.

6.2.4 Trials on the DASA Simulator

This new inceptor was evaluated against four MTEs: hovering turn, side-step, quick hop and lateral jinking by use of the Conceptual Simulation Model already mentioned in this paper. In general, the scatter of the results was higher than in earlier trials, but, given that an advanced inceptor concept was evaluated, this scatter may be explained by the fact that the pilots were not familiar with the system. In general, it can be said that the position in the cockpit was found to be comfortable; an improvement compared with the centre stick. The sidestick characteristics were acceptable despite a feeling of high inertia which degraded precision of control. The main problem was the inertia of the grip which could induce oscillations for small inputs and increase the workload in some mission phases.

In the 3-axis configuration, the well designed rotational function of the grip provided easy control of the yaw axis. This led to improved Cooper Harper ratings for the yaw axis compared with the conventional pedals. For multi-axis tasks, some undesirable ergonomic control couplings led to poor precision of control.

6.2.5 Airborne Trials on the DLR BO105-S3

The same inceptor was evaluated in flight with the RCAH control law against different MTEs including a reference mission, hovering turn, side-step and quick hop. The same force/displacement characteristics as in the simulation trials were used, only the break-out forces being slightly modified. The Cooper Harper ratings collected in flight are compared with the simulation trials in Figure 6.5.

Helicopter vibrations did not appear to adversely influence the results. Adjustments and experience gained from simulation were generally applicable to flight. This initial evaluation in flight especially of the 3-axis control strategy was promising, although some ergonomic aspects could be improved. The static control characteristics were well received and no cross couplings were noticed between the roll and pitch axes.

Compared with simulator experience, gravitational forces acting on the grip were measured by the sidestick sensors at high aircraft attitudes, generating small unintended control inputs and a tendency to drift. Additional inertial coupling between sidestick control and aircraft accelerations led to a slight overshoot tendency in the pitch and roll axes. Nevertheless, this first flight test of a programmable 2-and 3-axis sidestick on a helicopter in Europe was encouraging. The generally positive assessment of the 3-axis configuration which allowed precise and predictable directional control inputs, is promising and will be further investigated.

6.2.6 ECF Inceptor

The ECF inceptor was designed for use on the ECF simulation facility and on the FBW Dauphin 6001. The design and manufacturing work was carried out by the RATIER FIGEAC company in France against an ECF design specification. The stick general arrangement is shown in Figure 6.6. A passive yaw axis is implemented in order to allow a twisting motion of the grip for yaw control but this configuration was not evaluated during the programme.

Actuation is provided by a brushless DC motor which drives the inceptor via an irreversible screw with nut having a large reduction ratio (around 730). The force is derived via an LVDT which measures the deflection of a flexible rod. Rotating potentiometers are used to measure the position of the grip near the pivot of the reduction gear.

The force signal is transmitted to the flight control computer where it is translated into a position demand using the force deflection law. The computing is duplexed for safety reasons, with two different teams developing the software in each channel. As the motor is simplex, only one channel provides the input of the motor, with the other channel monitoring the first one.

The inceptor force/displacement law is fully defined by a set of parameters: two gradients can be defined, one for normal operation and another increased gradient for when flight envelope limits are approached/exceeded. These gradients as well as the various breakpoints can be easily modified through nine potentiometers located at the back of the inceptor box. A further step, after having selected acceptable values, will be to "actively" modify these values taking into account helicopter behaviour (attitude, limit approach, etc.).

6.2.7 Trials on the ECF/SPHERE Simulator

The new collective inceptor was integrated with the SPHERE simulator with the trimmable cyclic SSC and the spring-centred pedals originally tested during the previous trials using the FBW Dauphin 6001 non-linear simulation model and the RCAH control law. Since the objective of these trials was to evaluate the heave axis, new MTEs were defined to complement the reference mission: a Bob-up and Bob-down manoeuvre, and an Acceleration/Deceleration task.

The different configurations tested were:

- Conventional collective stick with friction law,
- Collective SSC tilted 15° forward with spring law,
- Collective SSC tilted 15° forward with friction law,
- Horizontal collective SSC with spring law,
- Horizontal collective SSC with friction law.

Concerning ergonomic aspects, the arm-rest was well liked, especially when only wrist movements were required for precise control rather than whole arm movements. Conversely, the large control inputs needed for the Acceleration/Deceleration task were made more difficult by the friction of the arm-rest surface. Non-linear stick sensitivity could be one solution but was not tested during these trials.

Initial impressions suggested that the horizontal orientation improved comfort allowing a symmetrical posture. However, the final ratings showed that the 15° tilted orientation was preferred (see Figure 6.7). After a few manoeuvres, some pilots found the horizontal position unpleasant; the conventional up and down movement of the collective stick is changed to a fore and aft movement as in a fixed-wing aeroplane, but with the drawback that increasing power was made through an aft movement instead of forwards as on a fixed-wing aircraft. While pilot training and familiarisation may be important, these trials suggest that the stick displacement must be at least reasonably well-aligned with the motion that it induces on the aircraft.

The "spring law" was generally preferred to the "friction law". Precise piloting was easy with the "spring law" and the main drawback was the "force trim release" function, needed for large and rapid inputs, which was not optimised for these trials so that the pilots had difficulty adjusting to the required trimmed position. The "friction law" was well suited to large stick movements with low effort required for manoeuvring, but the sensation of high inertia with this law demonstrated that this law was not well adapted for precise control.

6.2.8 Airborne Trials on the FBW Dauphin 6001

The new collective SSC was installed on the left side of the evaluation pilot's seat of the FBW Dauphin and the RCAH control law was selected. Vertical and longitudinal adjustments of the inceptor's position were available. Two inclinations were evaluated as in the simulator: the horizontal and the 15° tilted forward positions. The force feel law for these trials was mechanical friction.

The 15° tilted forward configuration was found to be similar to a conventional collective stick; piloting remained very instinctive in spite of a slight feeling of forward/backward displacement in the inputs. The horizontal position, which was badly rated in simulation, was also not well liked in flight and was even found to be dangerous because it led to a reversal of the required reflex. In this configuration, during large inputs no mistakes were made in the direction of the inputs, due to full pilot attention. However, some mistakes were noticed during precise manoeuvring, increasing the pilot workload, with additional attention required for control actions which were no longer instinctive.

The symmetry of the posture due to the two SSCs was generally thought to improve pilot comfort. The lack of fore and aft adjustment for one pilot led to a poor arm position on the armrest, leading to difficulty making small inputs and hence higher task workload and decreased comfort. The general size of the stick box and its position prevented the pilots from reaching some controls on the bottom of the instrument panel leading to further adverse comment from the pilots. This of course relates to the particular implementation of the inceptors in the Dauphin cockpit. On a new aircraft cockpit, the design would take into account the SSCs constraints, and these problems would be avoided. However this does show the importance that minor factors can have on ergonomic assessment.

6.3 Lessons Learned

Based on this common inceptor development and evaluation, the following lessons can be drawn:

- Increased knowledge of the technical issues relating to programmable inceptor development has been obtained and many important findings have been exchanged by the different teams in charge of the development (motor design parameters, force and position transducers, actuation devices, control algorithms, etc.).

- Increased knowledge of the potential of Active Control Technology has been gathered through the different trials and evaluations performed.

- Programmable force/displacement characteristics are now better understood, but further work is needed to optimise these characteristics and to determine their relationship with non-linear control demand shaping.

- Ergonomic aspects must be carefully taken into account at the beginning of the cockpit design: the implementation of new inceptors in an existing cockpit is unlikely to provide an optimum solution.

- Programmable inceptors are promising for providing tactile cues as part of a carefree handling system but further work is needed.

- The need for pilot training must not be underestimated: it is difficult to change instinctive behaviour especially when safety issues are concerned.

- Required inceptor characteristics are strongly dependent on the control law characteristics and their development must therefore be harmonised.

7. RECOMMENDATIONS AND FUTURE ACTIVITIES

The evaluation of many important aspects of Active Control Technology has identified numerous potential benefits. However, the overall objective of this programme was based on the development and evaluation of particular aspects of the technology. For a full demonstration of the potential benefits, two further aspects have to be taken into account in more detail:

- Evaluation against realistic operational mission environments,

- Integration of complete ACT systems adapted to specific missions.

Both aspects will define the future activities and support the confidence in this technology. A planned follow-on programme will therefore investigate special mission environments (with workshare between the participating nations) together with complete ACT systems in order to demonstrate the operational benefit of this technology. A major part of this work will be performed on the simulators available in UK, France, and Germany. Some selected elements will be demonstrated in flight on the Dauphin 6001 helicopter. In parallel to this activity, co-operative preparatory work will be started to define requirements for a common European ACT Demonstrator.

8. CONCLUSIONS

The European ACT programme has been a successful collaboration bringing together the helicopter industries and research organisations of France, Germany and the UK.

The programme, largely based around the complementary use of ground and airborne simulation, has promoted expertise in key aspects of active control technology within Europe. This has begun the process of developing common requirements for ACT helicopters in Europe and allowed intelligent assessment to be made of the US ADS-33 requirements.

Outputs from the programme include:

- An initial design guide. This includes handling qualities requirements for rate command control systems and guidelines on appropriate inceptor characteristics for ACT helicopters. It is envisaged that this design guide will be refined and expanded as results emerge from future programmes.

- A common evaluation methodology. This has allowed results gathered from a range of different facilities to be compared and correlated.

- Programmable sidearm inceptors. These inceptors have allowed initial guidelines to be determined for ACT inceptor characteristics, including tactile cueing. The inceptors' programmable feel and cueing characteristics will make them valuable for continuing the determination of appropriate characteristics for a range of response types and carefree handling features.

- Active control laws. A range of full authority control laws have been successfully developed and evaluated in simulation and in flight. These have allowed various response strategies to be compared, have allowed handling qualities requirements to be validated in flight and have shown the benefits of higher levels of augmentation.

The success of the programme, the methodologies, control laws and inceptor developed, place the consortium in a strong position to pursue ACT through technology demonstration and into production.

ACKNOWLEDGEMENT

The authors thank all who have supported and contributed to the succes of the programme. We look forward with confidence to the continuation of this fruitful cooperation during the follow-on programme.

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Annex A Control Laws Produced by the Programme

	ECD		ECF(RCAH)		ECF(ACAH)		WHL	
	Hover/Low Speed	Forward Flight	Hover/Low Speed	Forward Flight	Hover/Low Speed	Forward Flight	Hover/Low Speed	Forward Flight
Collective	Direct		Direct		Direct		Height Rate Command/Height Hold plus Torque Protection	
Longitudinal	Rate Command/Attitude Hold		Rate Command/Attitude Hold		Attitude Command/Attitude Hold		Translational Rate Command plus Torque and Rotorspeed Protection	
Lateral	Rate Command/ Attitude Hold	Rate Command/ Attitude Hold plus Turn Coordination	Rate Command/Attitude Hold		Attitude Command/Attitude Hold		(i) Translational Rate Command (ii) Translational Rate Command	Attitude Command/Attitude Hold plus Turn Coordination
Yaw	Rate Command Heading Hold	Rate Command Heading Hold (RC short term only)	Rate Command	Lateral Acceleration Command/ Suppression plus Turn Coordination	Rate Command	Lateral Acceleration Command/ Suppression plus Turn Coordination	(i) Heading Rate Command/ Heading Hold (ii) Heading Rate Command/Heading Hold	Heading Rate Command/Heading Hold plus Turn Coordination

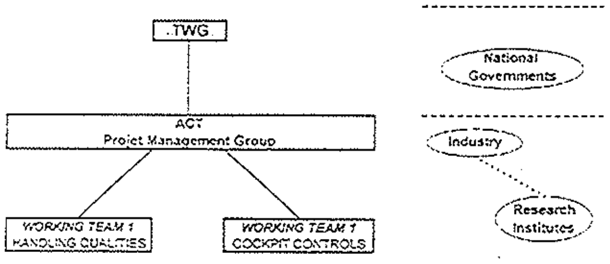

Figure 2.1 : Organisation of the ACT Programme

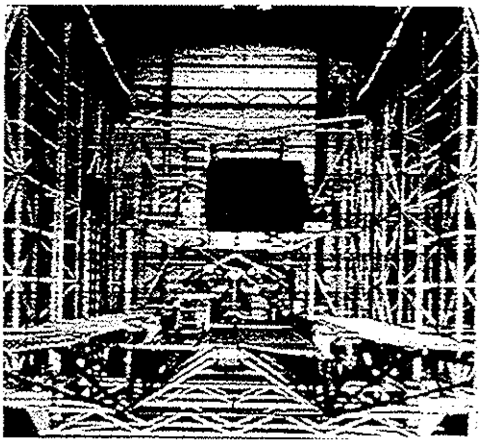

Figure 3.1 : DRA Advanced Flight Simulation Centre

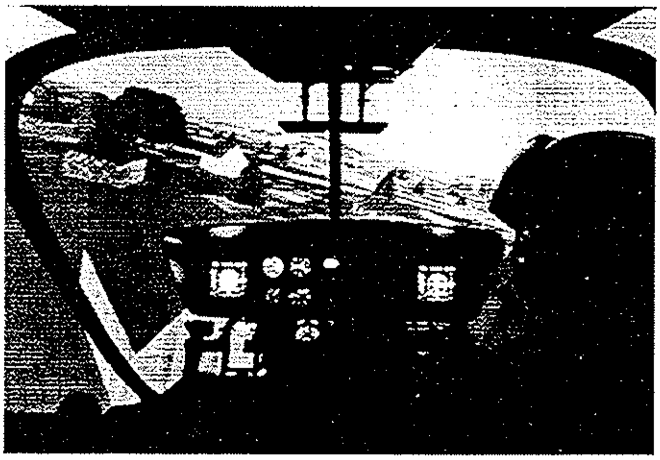

Figure 3.2 : DASA Simulation Centre

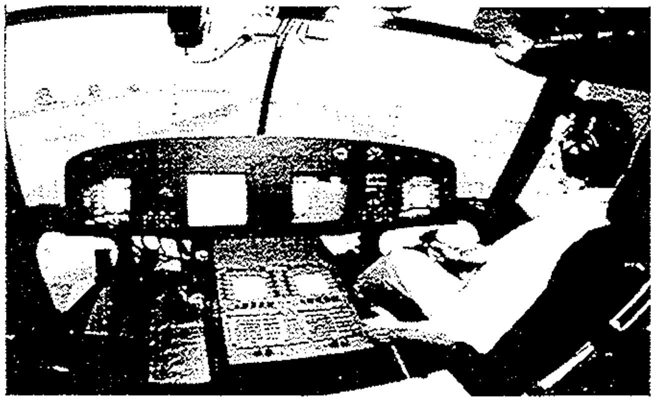

Figure 3.3 : ECF Simulation Centre (SPHERE)

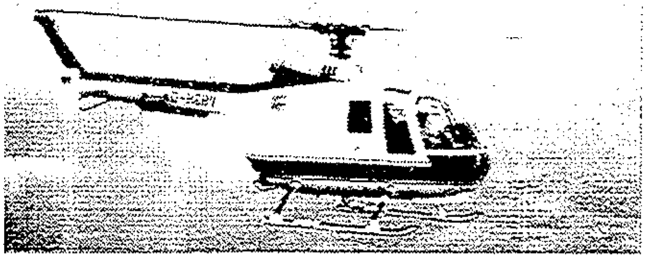

Figure 3.4 : DLR BO105-S3 FBW/L Helicopter

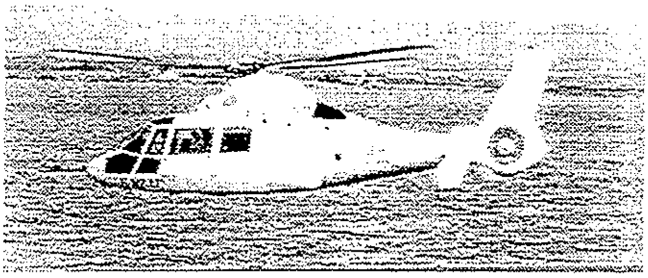

Figure 3.5 : FBW Dauphin 6001

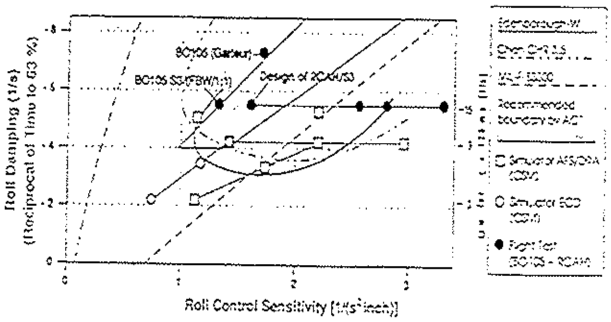

Figure 4.1 : Damping vs Sensitivity - Roll Axis

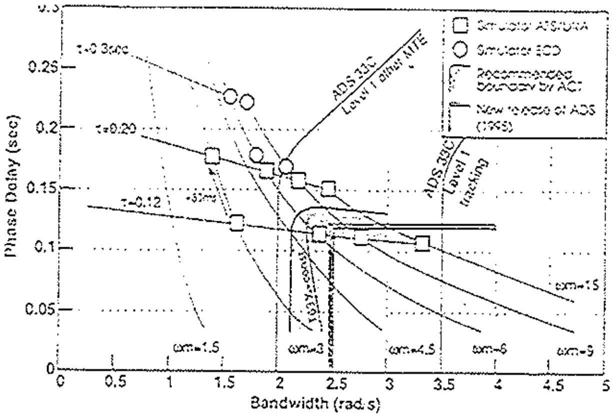

Figure 4.2 : Phase Delay vs Bandwith - Roll Axis

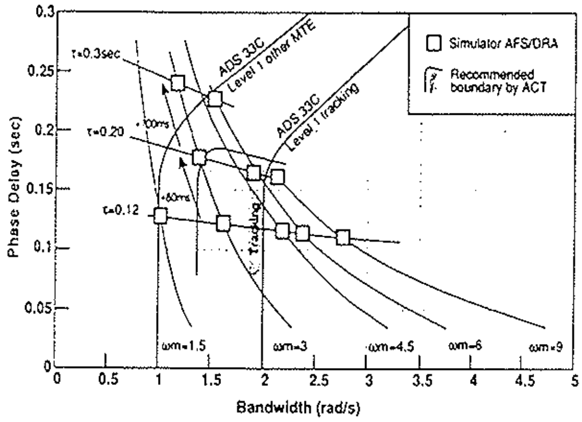

Figure 4.3 : Phase Delay vs Bandwith - Pitch Axis

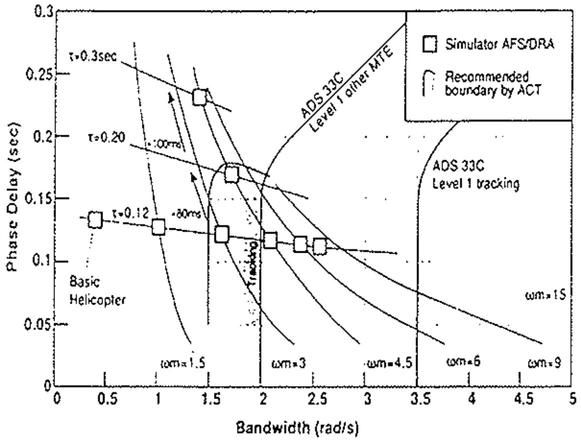

Figure 4.4 : Phase Delay vs Bandwith - Yaw Axis

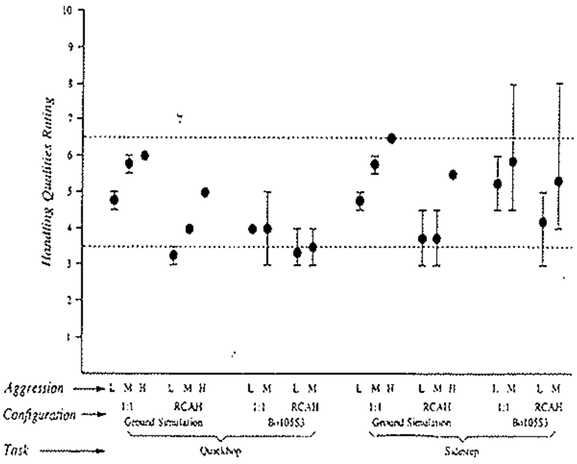

Figure 5.1 : ECD RCAH Results
(average and range of ratings)

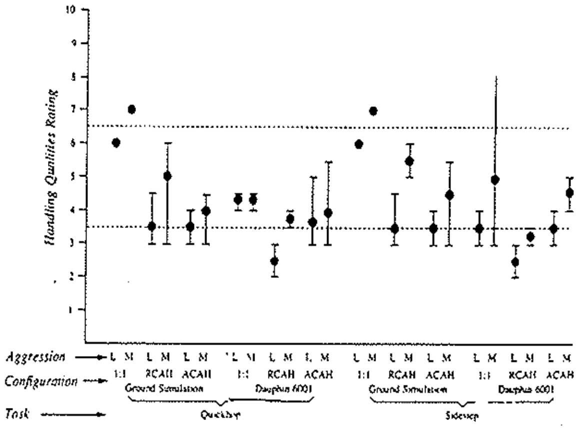

Figure 5.2 : ECF RCAH/ACAH Results
(average and range of ratings)

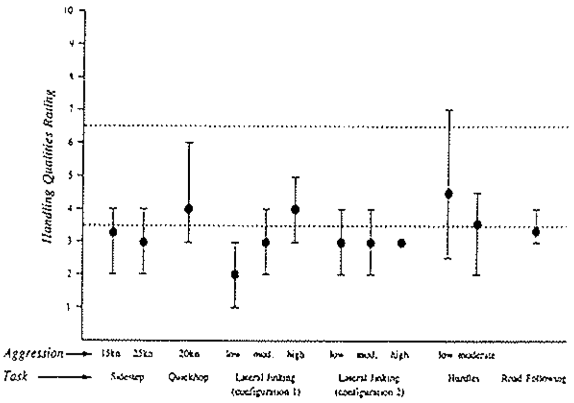

Figure 5.3 : TRC Simulation Results
(average and range of ratings)

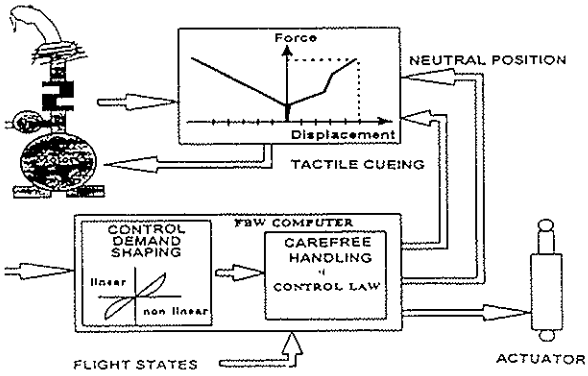

Figure 6.1 : Principle of Programmable Inceptors

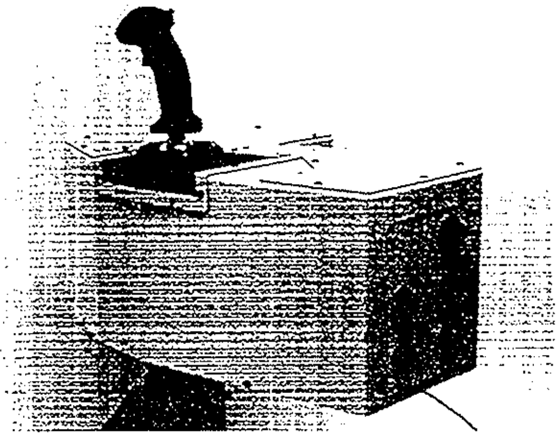

Figure 6.2 : Arrangement of the WHL Inceptor

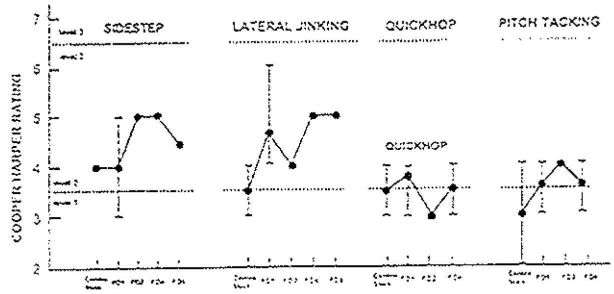

Figure 6.3 : Results of WHL/DRA Inceptor trials

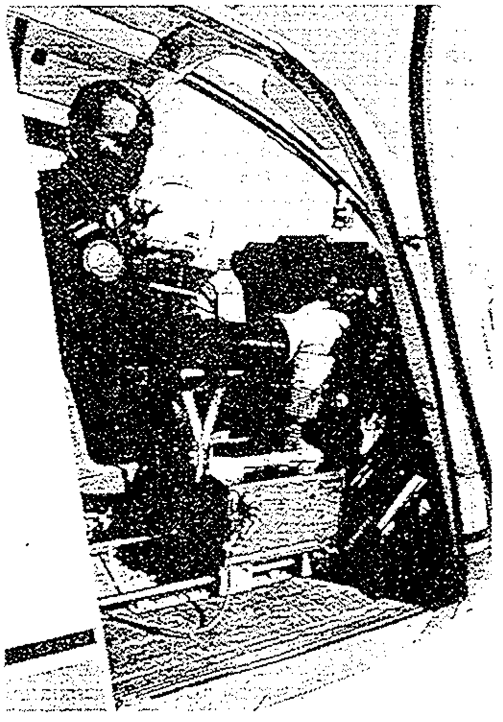

Figure 6.4 : Arrangement of the ECD Sidestick

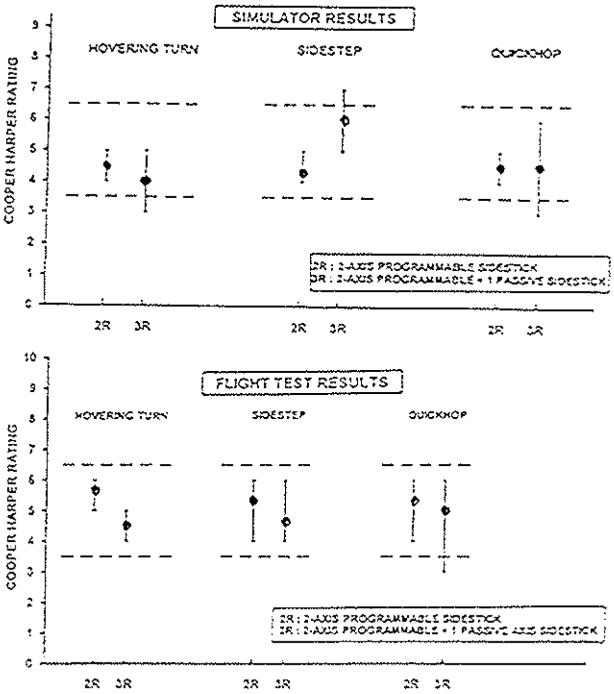

Figure 6.5 : ECD trials results with the 2-axis and 3-axis Inceptor

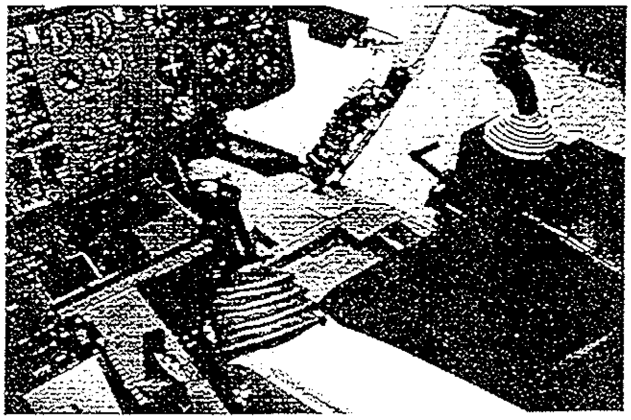

Figure 6.6 : Arrangement of the ECF Collective Sidestick

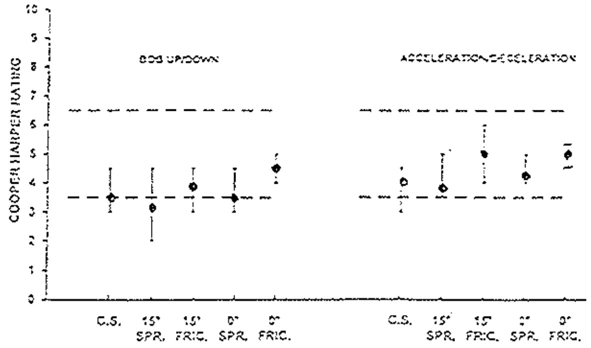

Figure 6.7 : ECF trials results of the Collective Inceptor