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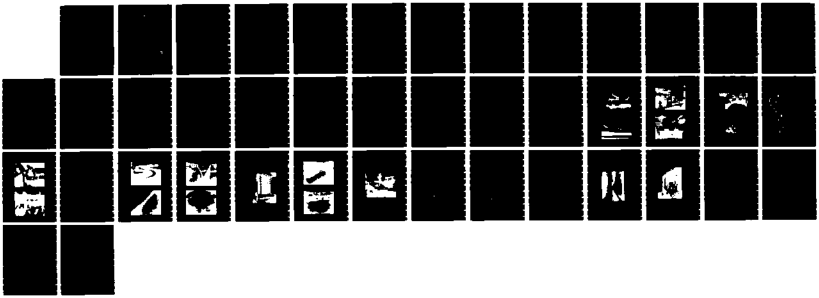

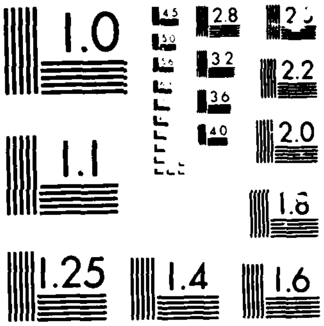
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HELICOPTER FLIGHT CONTROL RESEARCH - A DEMANDING APPLICATION OF PILOTED SIMULATION

by

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SUMMARY

Piloted simulation has been in use at RAE Bedford as a powerful tool for research in helicopter handling qualities since 1970. The most recent studies have addressed the application of advanced control systems to enhance agility in Nap of the Earth (NOE) flight. Handling qualities research places particular demands on many components of the simulator, including software environment and computing, cockpit design and simulator operation. The requirements in terms of provision of adequate visual and motion cues are especially severe for agile NOE flight.

In this Memorandum, the history of helicopter simulation at Bedford is described. The lessons which have been learned, and the special requirements which have been identified, are discussed. Finally, the new Advanced Flight Simulator (AFS), due to enter service at Bedford during 1985, is reviewed from the perspective of helcopter handling qualities research.

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1 INTRODUCTION

Pilot training has always been the principal application of flight simulation and this market might justly be regarded as the 'bread and butter' of the simulator manufacturers. Nevertheless, the importance of simulation in research and engineering development should not be underestimated. The appropriate application of piloted simulation in these fields can have a very significant impact on the evolution of new generations of aircraft. New ideas can be explored and refined in a safe and cost-effective manner. Potential problems can be revealed and resolved well in advance of the flight test phase, thereby avoiding expensive prototype modifications and programme delays. Furthermore, while those engaged in research and development of aircraft are reaping the above benefits by using simulation, the advances in simulator technology which spring from these applications can be ploughed back into the design of training simulators.

A broad range of applications are encompassed by simulators in research and development, and the types of systems in use are correspondingly diverse. For the initial exploration of a novel cockpit display a simple system, without motion or visual systems, and with a similarly simplified mathematical model of the vehicle would suffice. The integration of cockpit systems, or the engineering development of the crew station, may justify a realistic representation of a specific layout. Such applications may require more elaborate modelling of the behaviour of the aircraft systems, perhaps linked to some form of avionics rig. When the aircraft's control system design and its effects on handling qualities are the subject of research, a motion system becomes indispensable and (except in the restricted case of IFR handling qualities) a visual system is essential. The performance and capabilities required of these systems are related directly to the cues which the pilot needs to fly the aircraft, in a manner adequately representative of actual flight. This requirement must be satisfied throughout all the flight regimes which are of interest.

The assessment and enhancement of performance and handling qualities is the prime objective of trials carried out in the research simulation facilities at RAE Bedford. Trials have spanned a wide range of aircraft types and roles, and differing flight régimes. In the case of helicopters, the most recent studies have addressed the application of advanced control systems to improve handling qualities and enhance agility in Nap of the Earth (NOE) flight. This flight régime is undoubtedly one of the most demanding of environments to simulate.

In this Paper, RAE experience in the simulation of helicopters for handling qualities research is outlined. To set the scene, the history of helicopter simulation at Bedford is described and from this the lessons which have been learned, and the special requirements which have been identified, are discussed. Means to satisfy these demanding requirements are proposed. Finally, the new Advanced Flight Simulator (AFS), due to enter service at Bedford during 1985, is reviewed from the perspective of helicopter handling qualities research.

2 HELICOPTER SIMULATION RESEARCH AT RAE BEDFORD

2.1 Historical background

Piloted flight simulation research has been continuing at RAE Bedford since the early 1960's, but the first attempt to simulate a helicopter was not made until 1970. The simulation represented the Wessex helicopter (Fig 1), and explored the feasibility of helicopter simulation for handling qualities research[1-3]. Later in 1970, the Lynx helicopter (Fig 2) was simulated in advance of its first flight, and some important handling qualities consequences of its rigid rotor design were demonstrated[4]. Both the Wessex and Lynx simulations were carried out using an analogue computer (Fig 3).

A hybrid computer facility was introduced at Bedford in 1974, comprising a Xerox Sigma-8 digital computer (used to run the aircraft mathematical model) and an Applied Dynamics AD-4 analogue computer (used principally as a flexible interface to cockpit instruments, and for motion and visual systems operation) (Fig 4). The first helicopter simulation to use a digital aircraft mathematical model was created in 1977, when a generic helicopter model, known as HELISIM, was developed[5]. Data files were created to allow this model to represent the Lynx and the Puma (Figs 2,5). This model was used extensively to investigate the effects of rotor design parameters on agility and handling qualities for NOE flight[6,7]

2.2 Current research activities

In 1982, interest in handling qualities and agility led to the study of Active Control Technology for helicopters. For fixed-wing aircraft, impresive claims were being made for electrically (and later optically) signalled control systems, incorporating features such as manoeuvre demand control laws, and structural protection and manoeuvre limiting to give 'carefree manoeuvring'. RAE and Westland Helicopters therefore initiated research to investigate whether such systems could achieve similar improvements in handling qualities and reductions in pilot workload for helicopter NOE flight. Piloted flight simulation was obviously to play a key role in this work, in three distinct studies[8,9]. The first, exploratory, piloted simulation study used a simplified, idealized, helicopter mathematical model to identify the preferred modes of control. In the second study, representative control law algorithms were developed and used with a representative helicopter mathematical model to confirm that these preferred modes could, indeed, be achieved in the face of the nonlinearities and cross-couplings inherent in any real helicopter. The third study addressed the issue of control inceptors for ACT-equipped helicopters.

2.2.1 Exploratory studies using a 'conceptual' model

Active Control Technology offers a virtually infinite variety of possible control modes. The first objective of the research has therefore been to assess the relative merits of a range of differing control schemes. To facilitate these exploratory studies, a very simple 'conceptual' helicopter mathematical model was developed. In this model, cross-coupling effects are omitted, the rotational freedoms are represented by simple transfer functions driven by the control demands, and a simplified rotor model is used. Three trials using this model in 1982-3 successfully identified promising control modes, and gave an indication of the associated response dynamics and control authority requirements for agile NOE flight at speeds up to around 80 kn.

Typical of the systems studied in these trials were manoeuvre demand control laws, in which the pilot had explicit control of main rotor collective and body attitude in the conventional manner. However, undesirable cross-coupling effects were absent and pitch and roll axes were controlled by means of 'rate demand/attitude hold' laws. (An alternative 'bank angle demand' law was also explored.) The pedals demanded yaw rate in the hover, with a blend to sideslip demand at speed. Two optional augmentation functions were investigated to ease pilot workload in turning flight. The first of these automatically applied a pitch rate while the aircraft was banked, so that pitch attitude was maintained without the pilot having to apply 'back stick' in turns. The second augmentation increased collective while the aircraft was banked, so that the vertical component of rotor thrust was maintained. These laws significantly reduced workload during NOE flight, though pilots experienced some difficulty in adapting to the augmentations.

2.2.2 Confirmatory studies using a representative model

Having identified preferred types of control laws, and the benefits which they offered in the course of the 'conceptual' simulations, the next stage of research has been to demonstrate that laws could actually be produced to achieve these benefits in a 'real' helicopter. Initial work to develop such laws has been carried out both by Westland Helicopters and RAE using the control system design package TSIM2[10]. Piloted simulation was then required to confirm that the inevitable compromises made when developing these laws from the idealized laws used in the 'conceptual' simulations had not degraded the handling qualities demonstrated during the exploratory phase.

To date, two short trials have been carried out with this objective, using the HELISIM Lynx model, enhanced with manoeuvre demand control laws. For the second trial the HELISIM model was revised to ensure maximum compatibility with the HELISTAB generic model[11] used within the Flight Research Division at RAE Bedford for aeromechanics, stability and performance research. In these trials, the entire capacity of the Sigma-8 digital computer was neded to run the aircraft model within a frame time suitable for the operation of the ACT laws, and it was therefore necessary to employ a separate Gould 32/27 computer to run the control law software. Teething troubles encountered when pioneering the use of the linked Sigma-Gould computer configuration restricted the time available to explore and optimize the control laws. Nevertheless, the trials successfully proved that the benefits demonstrated while using the simplified 'conceptual' model could also be achieved with a 'realistic' helicopter model by means of suitable control laws.

2.2.3 Inceptors research

Aircraft incorporating ACT systems will almost certainly use electrical, or more probably optical, signalling from the pilot's control inceptors to the flight control computers. Unless the aircraft is designed to have a mechanical back-up control system (and this is unlikely in a production aircraft, since such a system would nullify many of the weight, cost and survivability advantages of ACT), such signalling permits much greater flexibility in the design, philosophy, configuration and location of the pilot's control inceptors. It is evident that retaining the conventional inceptor configuration may not provide the optimum pilot/control system interface for an ACT aeroplane.

To explore the desirable characteristics for inceptors for helicopters with ACT, two miniature sidestick inceptors were assessed, and compared with a conventional centre-stick during the course of the initial ACT simulation trials. Both sticks were of the two-axis displacement type, and were used in conjunction with conventional rudder pedals and collective controls. These trials demonstrated the advantages which could be achieved with miniature sticks, gaining favourable pilot comments, while being smaller, lighter, and potentially less restrictive on cockpit design. However, the trials also revealed that the mechanical design, friction, stiffness, and particularly robustness of the inceptors used were not satisfactory. In the light of these findings, and of complementary research in the US and Canada, further studies were launched, in collaboration with Westland Helicopters to identify the optimum inceptor fit for the ACT helicopter. The work has included development of two alternative designs of three-axis miniature inceptors 'pitch/roll/yaw', of the 'small-displacement' type. These inceptors have been assessed in a dedicated piloted simulation trial at Bedford.

2.3 Future research activities

The hybrid computer configuration introduced in 1974 was taken out of service in April 1985, to be replaced by the Advanced Flight Simulator (AFS) (Fig. 6), which will come on-line in the later part of the year. The particular demands of helicopter flight control research have been taken into account in the development of the AFS, and the design of this powerful research tool is described from this perspective in Section 4 below. The extent to which the AFS is capable of providing the comprehensive cues the pilot needs for agile NOE flight will be the subject of detailed scrutiny by means of simulation validation studies[12] at an early date. These studies will compare the control strategies adopted by the pilot in the simulator and in flight for various manoeuvres and are seen as a fundamental stage in establishing the capabilities of the AFS as a facility for handling qualities research.

The improvement of handling qualities and agility will continue as the principal research objective. Future research activities will therefore include further 'conceptual' simulations, with particular attention to alternative or novel control modes, to low-speed flight and to the transition between high-speed and low-speed modes. Results of these exploratory studies will feed into further 'realistic' ACT simulations. The scope of the studies will include applications such as carefree manoeuvring to improve performance whilst automatically respecting aerodynamic and structural limitations. The studies will be carried out in close liaison with associated flight control research planned on the RAE Bedford Lynx aircraft. In due course, studies may extend to encompass rotorcraft of other configurations, such as twin-rotor, tilt-rotor, or compound aircraft.

3 THE DEMANDING REQUIREMENTS OF HELICOPTER CONTROL LAW RESEARCH

The use of flight simulators in a research environment differs in several essential respects from the use of training simulators. Firstly, while a training simulator is required to replicate a defined aircraft in some detail, a research simulator may have to serve to represent a number of different aircraft types, including, possibly, hypothetical or projected designs. Furthermore, the research application is likely to include substantial modification and optimization of the aircraft or control system as a fundamental part of the experimental process. Although the research simulator is generally spared the requirement to represent exactly all cockpit switches and systems of the subject aircraft, the requirements in terms of operational flexibility and growth potential are the more severe. Secondly, a training simulator should be configured to achieve prescribed training objectives in a cost-effective manner. If extending the capability of the simulator to permit or enhance training for a particular manoeuvre or flight régime would incur an excessive cost penalty, economics will generally dictate that this part of the training be carried out in flight. In the research environment, on the other hand, it may be that safety or cost considerations preclude certain studies being carried out in flight. In such cases there will be a strong requirement to ensure that the capabilities of the simulator are adequate to achieve reliable results. Finally, although a training simulator may include some requirement to monitor a pilot's performance, the scope and magnitude of the data handling requirement is usually substantially more demanding in the case of the research simulator.

In subsequent sections, the components that together make up the total simulation are reviewed, highlighting the special considerations imposed on each in a research simulator of the kind used for handling and control law studies. The discussion draws heavily on the experience built up at RAE Bedford over 15 years of helicopter simulation.

3.1 Computing and simulation software environment

In a research simulator, the requirement to be able to develop and modify mathematical models readily and with confidence, as research objectives change and ideas develop, is paramount. Software must be designed so as to facilitate change, but such flexibility can only be achieved at some cost in terms of size and speed of execution. Meanwhile, the simulation of a new generation of high-bandwidth flight control laws creates particular demands in terms of simulation frame-rate and model complexity.

At Bedford, four utilities in particular have been employed to facilitate the development and refinement of aircraft mathematical models. Firstly, all simulations at Bedford use the simulation environment SESAME (a System of Equations for the Simulation of Aircraft in a Modular Environment)[13], which provides a set of Fortran sub-routines covering all aspects of the simulation which are common to all aircraft mathematical models. To create a 'flyable' mathematical model, the user is only required to provide modules to define the total forces and moments acting on the aircraft as a function of the pilot's control inputs and the aircraft state vector, and to specify how cockpit displays, etc, are to be driven. These modules are written in Fortran.

Secondly, the generic helicopter model HELISIM[5] has been used within SESAME for all helicopter simulations which required a comprehensive model of the helicopter and its rotor system. To date, data files have been created to model the Lynx and Puma helicopter of conventional configurations. HELISIM is related directly to, and compatible with, the HELISTAB package[11] used for non real time modelling in support of helicopter flight test research activities at Bedford.

It is not practical to include a generic representation of the flight control computer within HELISIM. The development of this component of the total aircraft model is achieved using a third utility, the control system design package TSIM2[10]. TSIM2 can be used to develop and 'prove' the combination of the aircraft and control system models in advance of the piloted simulation trials.

The final utility is the facility to inspect and reassign values to any parameter within the aircraft model while the simulator is actually in operation. This facility is considered in more detail as an aspect of the operation of the simulator in section 3.2.

The mathematical models which are created using these facilities differ from those used in training simulators in that these 'research' models are not required to replicate the operation of all cockpit systems, avionics, etc. The total mathematical model required by the research simulator is, therefore, less complex than that required to represent a similar aircraft for training*. The exploration and development of advanced control systems is now placing additional demands on the computing power needed for research simulators. The complex, high bandwidth, control laws can, in themselves, represent a substantial increase in the size of the total mathematical model. However, a far more significant factor is the consequent need for increased frame rates, and a higher level of detail in the mathematical modelling, especially of the rotor dynamics. Non real time modelling can be of very great value in identifying and eliminating undesirable interactions between the flight control laws and the higher frequency system modes. Nevertheless, the effects of such interactions, or of the steps which may have been taken to suppress them, may have an impact on the handling qualities to be assessed in the simulator. Furthermore, when the simulator is used in conjunction with flight trials in the development of a flight control system, there are strong arguments for using the simulator to exercise (in real time) the experimental flight-standard flight control computers. The confidence which can be placed in such emulations of the flight environment is directly related to the accuracy and adequacy of the total mathematical model.

At RAE Bedford, the capacity of the Sigma-8 digital computer was found to be inadequate to model a 'realistic' helicopter and advanced flight control system. As an interim measure, a Gould 32/27 computer was used to supplement the Sigma-8 for the

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* This difference in level of complexity is less marked for helicopters than for strike, or transport, aircraft because the avionics and systems of helicopters are generally simpler than those of fixed-wing aircraft, while the aerodynamics are significantly more complex in the rotary-wing case.

recent flight control studies. For convenience, the HELISIM helicopter model was retained on the Sigma-8, and the Gould 32/27 ran the flight control system model. This approach had the advantage of a natural demarcation between the tasks of the two machines, and of minimizing the changes required in HELISIM. However, even to achieve the slowest frame rate acceptable to the flight control system algorithms (about 30 frames/s), it was necessary to simplify the HELISIM model by omitting the engine dynamics and to revert from Runge-Kutta fourth-order integration to simple trapezoidal. It is therefore clear that a substantial increase in computing power will be required to exploit future modelling refinements, such as improved actuator modelling, or the individual blade modelling currently being incorporated into HELISTAB. When considering the capacity that will be required to satisfy these impending, and foreseeable, developments, it is essential that adequate provision is made for further, as yet unforeseen, developments in the future. For while the training simulator is only required to model today's aircraft using today's computer technology, after a few years in service the research simulator is certain to be required to model tomorrow's aircraft using yesterday's computer technology.

3.2 Simulator operation and the control desk

The features required at the control desk to operate a research simulator, and their relative priorities, vary widely for different research programmes. There is even variation within any particular study as it progresses from model development and verification, through pilot familiarization, to its culmination in the comparative assessment of the final candidate systems. Broadly, the features required are:

- Control and operation of simulator equipment and systems.
- Monitoring the pilot and his flying.
- Interaction with all mathematical model(s) (aircraft, control systems, etc).
- Gathering, processing and displaying data.
- The facility to 'fly' the simulation from the desk (especially in the model development phase).

The features needed to control the operation of the simulator (*eg* engaging the motion and visual systems, and setting the mathematical model into operation) and to monitor the pilot and his flying (by means of repeater displays of cockpit instruments and outside-world views) correspond directly to similar requirements in training simulators. However, in research simulators, extra flexibility may be required to cope with different displays for different research programmes.

The capability of interacting with any component of the entire mathematical model, that is to say to inspect and reassign values to any variable by name, is essential in a research simulator. Even when the model has reached the 'design freeze' stage, it will probably include several alternative control schedules or modes, whose relative merits will then be compared in the assessment phase of the trial. The selection and activation of these various schedules and modes may then be conveniently achieved by reassigning the values of a counter or flag within the model software. The desk must therefore include the computer terminal (VDU) needed to address the variables and display their values, supported by the necessary software to effect, log and, optionally, retain such changes, and a hard copy unit.

The data display, handling and analysis facilities required at the control desk will vary between different research programmes. In some cases, the facility to inspect variables on-line, described in the previous paragraph, can be put to use for data gathering. For example, the simulator software could include variables which store running means and standard deviations of, say, tracking errors. The values could be retrieved and used to quantify the pilot's performance and, by inference, the relative merits of alternative control systems. More generally, it is necessary to be able to produce recordings of any model variables, either as paper trace records, or on magnetic tape.

The ability to 'fly' the simulation from the control desk is of immense value during the model development phase, which can account for up to half the simulator utilization in the research environment. Initial checking of modifications can be carried out single handed, and the direct access to the model, via the VDU, and the ready availability of trace displays at the desk far outweigh the absence of motion cues, and the less sophisticated 'primary flying controls' (typically the kind of miniature joysticks used for radio-controlled model aircraft) which can be accommodated in the desk.

3.3 The simulator cockpit

The design of the cockpit of a research simulator is dictated by the requirements of the research programmes, rather than by the requirements to accurately replicate some particular aircraft. For handling-related studies, attention is generally restricted to primary flight controls and primary flight instruments. For some applications (*eg* validation of simulation results against flight data) it may be necessary for these components to replicate the real aircraft. In other cases it may be convenient to be guided by the layout of the cockpits with which the subject pilots will be familiar, but the overriding consideration is the need for flexibility to accommodate the changing and evolving requirements of the research programme.

At Bedford, flexibility in terms of primary flying controls has been achieved by means of a programmable 'digi-feel' system. The desired feel characteristics are modelled in a dedicated micro computer, which controls the stick and pedals through a hydraulic servo system. It is a simple matter to load a new file of feel force parameters when a new aircraft is to be simulated. Furthermore, individual parameters can be readily varied so that the sensitivity of handling qualities to control forces can be explored. The digi-feel system unfortunately can only drive the conventional centre stick and pedals, so for the recent investigations of miniature side-sticks it has been necessary to revert to simple mechanical spring systems, at some penalty in terms of flexibility of the force characteristics (Fig 7).

In the case of displays, it used to be the practice at Bedford to design an instrument panel specially for each research study (Fig 8). More recently, it has been the practice to be running several, widely differing, research studies concurrently. As a result, it has been necessary to accept the basic fixed-wing panel for helicopter trials also. Two factors have contributed to the acceptability of this expedient. Firstly, the exploratory nature of the recent helicopter control law studies avoided the need to replicate a specific aircraft cockpit. Secondly, the NOE flight régime under investigation is primarily an 'eyes-out' régime. In the real world, a pilot may glance at his instruments, but his peripheral vision will still give him some outside world cues. In the simulator, which was configured with a single-window visual system, the field of view was much more restricted, and any attempt to look at the instrument panel is at the expense of temporary loss of contact with the outside world. For these NOE studies, the conventional instrument panel was therefore supplemented by the use of a programmable head-up display (HUD). Using the HUD, the pilot was able to monitor the important flight parameters (speed, height, climb rate, torque, etc) without 'cutting out' the outside world*. A display format was developed for the helicopter trials (Fig 9), and the flexibility inherent in the programmable display system meant that helicopter and fixed-wing displays could be swapped in a matter of minutes.

Thus by exploiting programmable primary flying controls and displays, together with the minimum number of easily-installed inceptor units (*eg* side-sticks and collective) it has been possible to reconfigure the cockpit from helicopter to fixed-wing, or vice versa, in a less than half an hour. This flexibility has proved extremely valuable in maximizing simulator utilization in the face of the conflicting requirements of a range of concurrent research programmes.

3.4 The development of tasks for control law assessment

The development of the tasks used to assess handling qualities or control laws may be seen as analogous to the definition of tests or criteria used to assess the progress or ability of a student in a training simulator. The requirement is to define tasks which are sufficiently demanding, yet which can be achieved reliably and repeatably, and for which adequate cues are available to the pilot. The principal difference between the research and training applications is that, in the research simulation, failure to accomplish the task is scored against the aircraft rather than against the pilot!

The tasks used must be sufficiently demanding, otherwise inadequacies in the handling qualities may not be exposed. Essentially, the limits of performance or acceptability of a control system can only be mapped out by exercising it to these limits. When several candidate systems are to be compared, it is important that the tasks are defined closely so that repetition of the manoeuvres yields results which are amennable to direct comparison.

The importance of designing tasks to be compatible with the cues available in the simulator should be self-evident. Consistent results will not be obtained if the pilot is explicitly or implicitly tasked with basing part of his control strategy on

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* Head-up, or helmet-mounted, displays will feature increasingly in future helicopters. The related symbology and drive algorithms will become topics for research in their own right, because it is well known in the fixed-wing world that these factors can significantly affect the pilot's perception of his flight conditions and trajectory, and hence his judgement of handling qualities.

information which is either denied him, or is only available in a form he is unable to assimilate directly. The availability of adequate cues, particularly visual and motion cues, is therefore central to the process of task design. It is for this reason that the demands of research simulation, in terms of visual and motion systems, can be severe. This point is take up in more detail in sections 3.5 and 3.6 below. However, within the constraints of available cues, careful attention to the detail of the task design can reap substantial benefits. This point is best illustrated by means of two examples of assessment tasks used in the recent NOE trials at RAE Bedford.

Improvements in agility achieved could only be quantified by means of tasks which required the pilot to manoeuvre his aircraft in an aggressive manner, while maintaining precise control of his trajectory. Tasks had to be designed such that the pilot could readily perceive the required trajectory despite the vigorous motion of the aircraft and the limited field of view available in the simulator. These tasks were of necessity rather stylized and artificial. Nevertheless, they proved fully adequate for the needs of the studies, and, indeed, contributed directly to the successful outcome of the research.

The principal task used to assess lateral control characteristics was the Serpent course (Fig 10). The course was in the form of a triple bend, through a tree-lined corridor. At the target flight condition of 80 kn pilots used bank angles in excess of 50°, and reversed the turn direction in less than two seconds, while flying at a height of around 10 metres. To fly these manoeuvres, the pilot would like to look deep into the turn for the necessary perspective to establish the exact trajectory to be flown, and to identify any turn reversals at the earliest opportunity. He would also like to look sideways to judge his rotor clearance, and downwards to check height. However, the limited visual field of view in the simulator forced the pilot to look ahead, along the aircraft's fuselage axis. Features were therefore incorporated to compensate for the absence of these vital visual cues. Centre-line and edge-line markings were used to provide the pilot with the perspective to identify and maintain the required track. The pilot knew that if he remained within the edge lines he would maintain adequate lateral clearance. The simple nature of the course, with three similar curved segments of equal length and constant, equal, radius, was readily learnt by the pilots. This compensated for not being able to actually see far enough ahead into the turn to be forewarned of the turn reversals. The trees at the edge of the course and the texture of the surface provided strong height cues. Finally, the incorporation of clear displays of height and climb-rate in the head-up display further assisted the pilot to maintain good height control. Taken together, these features allowed pilots to fly the course aggressively but consistently. This is precisely what was required for trials aimed at assessing the relative merits of different flight control systems; it was not intended that the trials would identify exactly how well pilots might be able to fly a similar course in a real aircraft.

To assess longitudinal control characteristics, a hurdling task was required. Initial attempts to use simple rectangular hurdles were unsuccessful. In the absence of an adequate downwards field of view, the pilots were unable to assess when they had passed over the hurdle, and frequently descended too soon. At descent angles greater than 17° it was possible to 'land' on top of the hurdle without ever seeing it! The problem was exacerbated by the fact that the TV system incorporated a skyplate within the camera assembly. The skyplate obscured the upper part of the TV picture to prevent the camera being dazzled by the model's lighting banks. This system had the effect of imposing a 'cloud base' which was always only just above the aircraft's instantaneous height. When a low flying aircraft approached a tall obstruction, such as a hurdle, the top was obscured by the cloud, and only appeared as the pilot climbed above the obtruction. These difficulties were overcome by the design of V-notched hurdles (Fig 11). With this design, the 'wings' of the hurdle remained in view long after the bottom of the notch (which would correspond to the top of a simple rectangular hurdle) had vanished from view. The angle of the notch was matched to the shape of the conical TV camera probe. The inverted chevron marked on the face of the hurdle indicated to the pilot the position and height of the notch, even when the upper part of the hurdle was obscured by the skyplate. Model houses were placed beside the hurdles to help the pilots appreciate the size of the obstructions in real-world terms. The hurdles were placed in rows, so that straight or curving courses could be flown. Since the photographs shown in Fig 11 were taken, a horizontal line has been marked either side of the notch to indicate the minimum safe height to pass through.

These two tasks demonstrate some of the steps which can be taken to satisfy the pilot's requirement for adequate cues to fly his task. By similar means, other tasks have been developed to allow many aspects of handling qualities and control laws to be assessed.

3.5 Visual systems

For NOE flight, visual cues are of the utmost importance to the pilot in perceiving the trajectory he chooses to fly, in controlling the aircraft to achieve that trajectory, and in assessing how closely the trajectory has been followed. The handling qualities of an aircraft can be seen as a measure of how easily the pilot can achieve his desired trajectory. When a simulator is used to assess handling qualities, the provision of visual cues which are adequate for the assessment tasks is therefore a fundamental necessity. At Bedford, the single-window visual system used a TV camera viewing a 700:1 scale terrain model belt (Fig 12). The standard of realism and detail which can be achieved at this scale is illustrated in Fig 13. The belt provides a gaming area 8.5 km by 1.7 km. The image from the camera is viewed through a collimating lens on a 625-line colour monitor, giving a field of view approximately 47° by 35°. The visual information presented to the pilot must be adequate in terms of content, quality and quantity. The requirements in terms of the content of the visual picture presented to the pilot has largely been covered from the perspective of task design in the previous section. Beyond the more specific requirements of individual tasks, however, certain more general needs can be identified. The picture contents and level of detail must be sufficient to permit the pilot to retain an awareness of the 'scale' of the outside world. This can only be achieved by means of an adequate density of cultural features, especially man-made features such as roads and buildings. This is especially important when the needs of a particular task impose a requirement for 'unrealistic' features to be included in the terrain model. Texture in some form will be essential for height and speed perception in ultra-low-level flight. Finally, it is generally convenient to ensure that there is a sufficient density of unique and identifiable landmarks such as distinctive buildings, lakes, etc to assist the pilot in finding his way around the landscape. This burden is somewhat eased by the fact that, in general, research trials flying does not require a very large gaming area.

The quality of the visual information presented to the pilot in the simulator is degraded compared to the real world principally in the areas of focus, resolution and static and dynamic accuracy. The range of focus likely to be needed in a TV-based visual system stretches from perhaps a centimetre (model scale) in the hover, to several metres to the 'horizon'. Poor picture focus will be distracting and tiring to the pilot. Fortunately, these extremes of focus are usually not required simultaneously. The very close focus is needed in the hover at very low level, when the effective horizon may be relatively close, whereas the longer focus is needed at higher speeds, when the pilot's point of regard moves further ahead of the aircraft. Although the pilot may glance momentarily to the foreground even in this flight regime, blurring due to the streaming effect will usually conceal the effects of inadequate depth of field.

In past trials at Bedford it has proved practical to separate those manoeuvres which required close focus and make manual adjustments. A more sophisticated approach, computing focus setting from height, speed and pitch attitude would be desirable, but has not been found essential.

Very high standards of resolution have been specified for training simulators when there is a genuine need to detect and recognise targets in a realistic manner. In contrast, the standard required in a research simulator can be significantly lower. 625-line TV standard has been found generally adequate for task performance at Bedford. At the relatively close viewing distances used in the cockpit, the pilot will be aware of the line structure, but this criticism must be balanced against the convenience using a widely established standard. The ability to produce good quality, standard format, video recordings directly from the simulator has proved especially useful, for briefing, debriefing and presentations. The quality of the image presented to the pilot will be degraded by shortcomings in the optical components used to display the image. The lens system used to collimate the TV image in the Bedford simulator is inferior in optical performance to more modern collimating mirrors and has given rise to some criticism.

Substantial demands are placed on the static accuracy and repeatability in the visual system if meaningful data on the accuracy of the pilot's flying is required. Recent trials at Bedford have attempted to measure position holding performance to an accuracy better than a metre, which corresponded to about 0.01 per cent of the travel range of the visual system. To achieve this accuracy with an analogue-driven flexible belt terrain model and camera gantry system required daily recalibration and close control of temperature and humidity. In the future, the application of digital control throughout the visual system should improved accuracy.

The dynamic performance of the visual system must be adequate for the types of vehicle and tasks to be simulated. Low-level, low-speed flight is less tolerant of judder or unsteadiness in a camera drive system. The trend towards increased agility in battlefield helicopters will place increasing demands on the response of the visual system, but the conventional servo systems used in terrain model visual systems can, at present, achieve adequate performance. The introduction of computer image generation systems raises the question of whether the computational delays inherent in such systems might influence the pilot's perception of the handling qualities of his aircraft. The possibility must be taken particularly seriously in the case of helicopters, for several reasons. Firstly, visual cues are important and strong in NOE flight. Secondly, the high level of scene content for NOE flight and the high yaw rates attainable in agile helicopters, place heavy demands on the image generation system; in some systems this can slow down the updating process. These factors will become more pressing as the agility of helicopters increases. This problem will be the subject of research when computer-generated imagery (CGI) becomes available at Bedford.

Despite careful attention to task design, certain manoeuvres have proved impossible to carry out in a representative manner in the simulator directly as a consequence of the lack of lateral and downward view. Aggressive decelerations, either straight or turning, and sideways flight fall into this category. These limitations have imposed a real constraint on the development of control modes for low-speed flight.

Although the pilot needs a detailed visual image (TV or CGI) to assess the trajectory he is flying, his perception of the aircraft's response can be significantly enhanced by means of the addition of a simple horizon projection system. The horizon projector complements the angular acceleration cues provided by the motion system with powerful rate and attitude cues. The power of these cues is well illustrated by the fact that the horizon projector has repeatedly prevented pilots detecting that the motion system has been disengaged, even after it had been suggested to them that this might be the case. The horizon projector used at Bedford gives pitch and roll cues, but attempts to incorporate a yaw cue (by means of a 'cloud' pattern above the horizon) have not been brought to a successful conclusion. This limitation should be remembered when yaw motion cues are discussed in section 3.6 below. Multi-window, or wide angle, CGI displays may soon supplant horizon projection systems for NOE flight, but horizon projection systems are expected to remain a cost-effective alternative for some other applications.

3.6 Motion system performance

The role and value of motion in training simulation has been the subject of considerable debate. In the research environment, on the other hand, motion cues are without doubt essential to the pilot in forming an assessment of the handling qualities of his aircraft. As aircraft and helicopters have become more agile, motion cues have become both more important and more demanding. this is not to say, however, that motion cues are of equal importance in all axes: the cues are most valuable in the axes which correspond to those aircraft modes the pilot is tasked to assess. To date, all helicopter simulation at Bedford have used a single seat cockpit, mounted on a 3° of freedom motion system (Fig 14). The motion system had moderate travel in pitch and roll, and limited travel in heave. The system as originally built[14] incorporated a yaw axis, but this axis has not been used in any helicopter simulations due to difficulties in achieving adequately smooth operation.

Motion cues are essentially acceleration cues. They therefore allow the pilot to become aware of the response of the aircraft before visual cues of rates or attitudes can be detected. It therefore follows that when a pilot is denied motion cues his perception of his aircraft's characteristics is degraded and the aircraft is felt to be slower in responding. In extreme cases, the pilot may be unable to control the aircraft when the absence of motion cues introduces an additional 90° phase lag into his control loop. These effects have been clearly demonstrated during research at RAE Bedford.

In one instance, a pilot who had been evaluating a number of alternative control laws for helicopter NOE flight was given a configuration which differed from the configuration he had just assessed only in that, unbeknown to the pilot, the motion system had been disengaged. The pilot described the resulting 'aircraft' as 'markedly inferior to the previous configuration, because it took longer to respond to control inputs'.

A more comprehensive investigation of the effect of motion and visual cues on piloting technique is shown in Fig 15A. Roll control activity is compared for three tasks, with and without motion and horizon projection cues. In the first task, following a circular course at low speed, tracking is fairly loose, and bank angles remain small. Control activity is generally low, but the pilot has a tendancy towards overcontrol if he is denied both motion and horizon projector cues. In the second task, the hurdles course, the pilot is tracking more agressively, but he did not need to sustain large bank angles. In this task, motion is shown to be essential to proper control, though in the absence of motion the horizon projector is of some benefit. The final task is the Serpent course. Here the pilot is tracking fairly tightly, but large bank angles and roll rates are needed to accomplish the task. In this case, control activity is always very high, but the pilot appears to have particular difficulty when the horizon cue is removed. The absence of any clear benefit from motion cues is tentatively ascribed to the severity of the manoeuvre, which may approach the effective limits of the performance of the motion system. Fig 15B shows examples of control activity for four configurations for the hurdles task. Throughout these tests, the aircraft and control characteristics were left unchanged, though the pilot believed that these aspects were the subject of the research. The pilot was not informed when the motion system was disengaged. While the horizon projector was working the pilot did not notice when the motion was disengaged, but with the horizon projector off he realized fairly quickly when the motion was disengaged.

In Ref 3, it was stated that the simulation of the Wessex and Lynx helicopters appeared to the pilot to be a poor representation of the aircraft in the yaw axis, because the simulator was unrealistically difficult to control in yaw. A similar effect was noted in a recent trial using the HELISIM Lynx model with all autostabs switched off. These findings are attributed primarily to the absence of yaw motion. However, it is probable that the weak heave cues exacerbated the problem. In the absence of adequate heave motion cues, pilots have been observed to overcontrol on collective. Harsh use of collective couples into yaw, which is then made substantially more difficult to control in the absence of yaw motion cues.

Difficulty in collective control has also been observed with the 'conceptual' model used for the exploratory ACT studies. Pilots have been observed to flys sustained pilot-induced oscilliations (PIO) of ±½ g amplitude, and period 3, when attempting to set up an accurate height during the run-in to the Serpent course. (Fig 16).

The previous paragraphs have details examples of some of the ways in which absence of motion cues could compromise the results of handling qualities studies. It must be stressed, however, that to achieve reliable results, motion cues which are present must be an adequately faithful representation of the response of the real aircraft, particularly in terms of phase. This requirement must be satisfied over the bandwidth that the pilot can perceive and within which the pilot attempts to control the aircraft. This point is examined in detail in Ref 11, which includes a well-documented example of a case where lags in the motion system were seen to substantially degrade the benefits of motion cuing.

4 THE RAE BEDFORD ADVANCED FLIGHT SIMULATION (AFS)

A new flight simulation facility is nearing completion at RAE Bedford, to replace the simulator withdrawn from service in April 1985. The Advanced Flight Simulator (AFS) is to be used for research covering such topics as handling qualities, control laws, cockpit inceptors and head-up and helmet mounted displays, for future fixed-wing and rotary-wing aircraft. The AFS is due to enter service in late 1985.

In the following sub-sections, the components which together make up the AFS are briefly described.

4.1 Computer system and simulator operation

The principal computer system for the AFS comprises a network of Gould Concept 32 processors, linked to a shared memory system. The total aircraft mathematical model will run in a 32/87 processor, which will give approximately eight times the processing speed of the previous Sigma-8 computer. All real-time input and output will be handled by a 32/27 processor, driving two custom-designed digital data highways. All communication to simulator equipment (visuals, motion, cockpit displays, etc) will be via these highways. A second 32/27 will support the operation of the control desk, and the related data handling and displays. The display facilities to be provided at the desk include tabular and trace presentations of any selected parameters, and programmable computer-generated instrument panel displays. A third 32/27 can either be used to operate an interface to an actual aircraft flight control computer, or alternatively to operate independently as a separate stand-alone simulator. In addition, dedicated micro computers are used to drive a new programmable digi-feel system, and for a programmable head-up display.

The entire Gould computer network is linked to the Flight Systems (Bedford) Department VAX computer network. All software development and off-line data analysis will be carried out on the VAX network, thereby capitalizing on experience with the user-friendly VAX VMS operating system for these tasks, while reserving the power of the Gould network for the real-time simulation for which it is optimized.

4.2 Simulator cockpit

Interchangeable dedicated cockpits, of modular construction, will be used for research programmes on the AFS. The detailed design of the cockpits will be tailored to the needs of the research programmes. Work has started on a helicopter cockpit. This cockpit has a single seat, to optimize the visual cues that can be presented to the pilot in the simulator. Provision will be made for both conventional controls (driven by the digi-feel system), and miniature side-stick controllers. A conventional instrument panel, based loosely on Lynx, will be supplemented by provision for a HUD. A vibrating g-seat will be incorporated. It is anticipated that changing over cockpits may take up to a day. To allow greater flexibility in the running of trials, it will be possible to carry out initial development and exploratory work with a cockpit not mounted on the motion system.

4.3 Visual systems

Both TV and CGI visual systems will be available on the AFS. The CGI system will be a 3-window Singer-Link-Miles IMAGE III daylight system with texture (Fig 17). The databases available will include one developed for helicopter NOE research. The TV visual system will include a 1000:1 scale solid terrain model board (Fig 18) for helicopter NOE flight, as well as provision for up to three alternative terrain model belts at various scales. The TV visual system will provide only a single-window display. However, in some applications it is envisaged that the single TV image may be supplemented by two side windows driven by the CGI system when suitable databases are available.

The images from the visual systems in use will be presented to the pilot on colour monitors equipped with collimating optics. The monitors are to be mounted in a special frame designed so that their positions can be readily adjusted over a substantial range to cater for the needs of a wide variety of research objectives.

Provision has also been made for fitting a small radius dome over the cockpit for any trials which may require horizon and target projector displays in preference to the monitors.

4.4 Motion systems

The AFS cockpit is carried on a substantial motion system (Fig 19), capable of sustaining relatively high accelerations. The interchangeable cockpit is mounted on a carriage via a gimballing system permitting ±0.5 radian of rotation about all three axes. The carriage is in turn mounted on a track on the heave platform. The carriage has a travel of ±4 metres along the platform. The cockpit can be orientated so that this axis provides either surge *or* sway. The heave platform runs on vertical rails between the two walls which comprise the outer framework of the motion system. The heave platform has a travel of ±5 metres and a maximum acceleration of 1 g.

The development of drive laws for the AFS motion system has been the subject of considerable research effort. To obtain the most effective motion cues it must be possible to explcit the full performance of the motion system, but it is equally important to avoid false cues, such as when velocity or position limits are encountered. These conflicting requirements must be reconciled without compromising the fidelity of the motion cues.

5 CONCLUDING REMARKS

Piloted simulation has made a valuable contribution to research into helicopter handling qualities and control over the past 15 years at RAE Bedford. Over the period, a substantial degree of expertise has been established, and many lessons have been learnt; helicopter flight control research has been found to place many special demands on the flight simulator. The experience gained in the course of past research has contributed to the specification and design of the Advanced Flight Simulator. When this device enters service later in the year, it will be among the most powerful of research facilities for piloted handling and control studies in the world. With it, RAE Bedford will be well equipped to make a substantial contribution to the vital and challenging research which lies ahead in the development of future agile rotorcraft.

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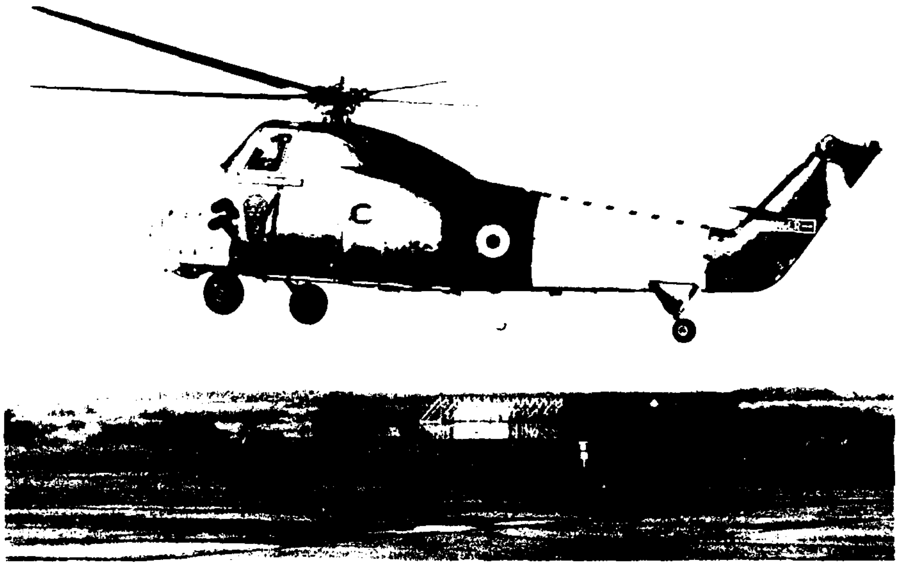


Fig 1 Westland Wessex

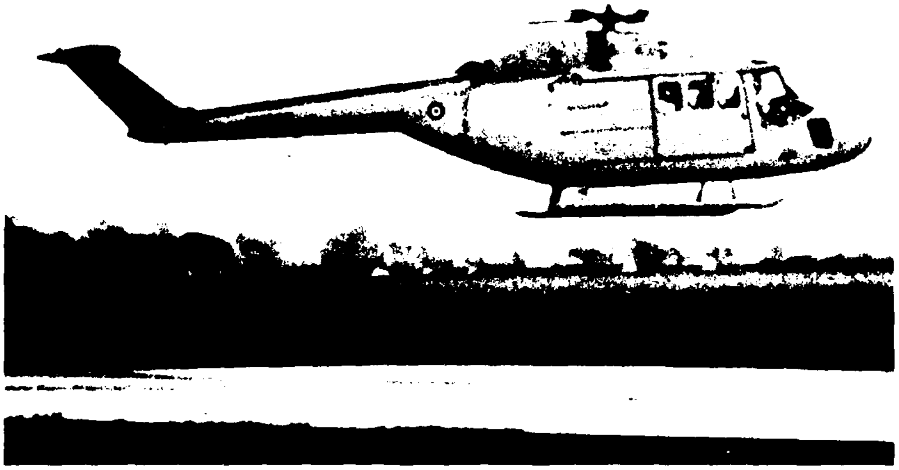


Fig 2 Westland Lynx

Fig 3a&b

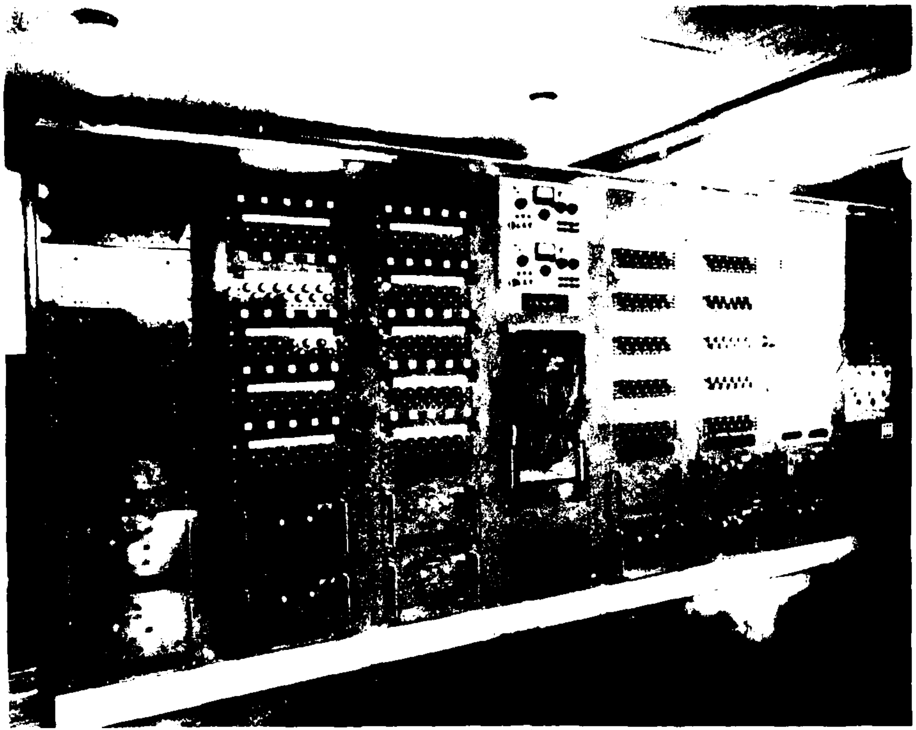


Fig 3a Aero Flight Simulator - Analogue Computer

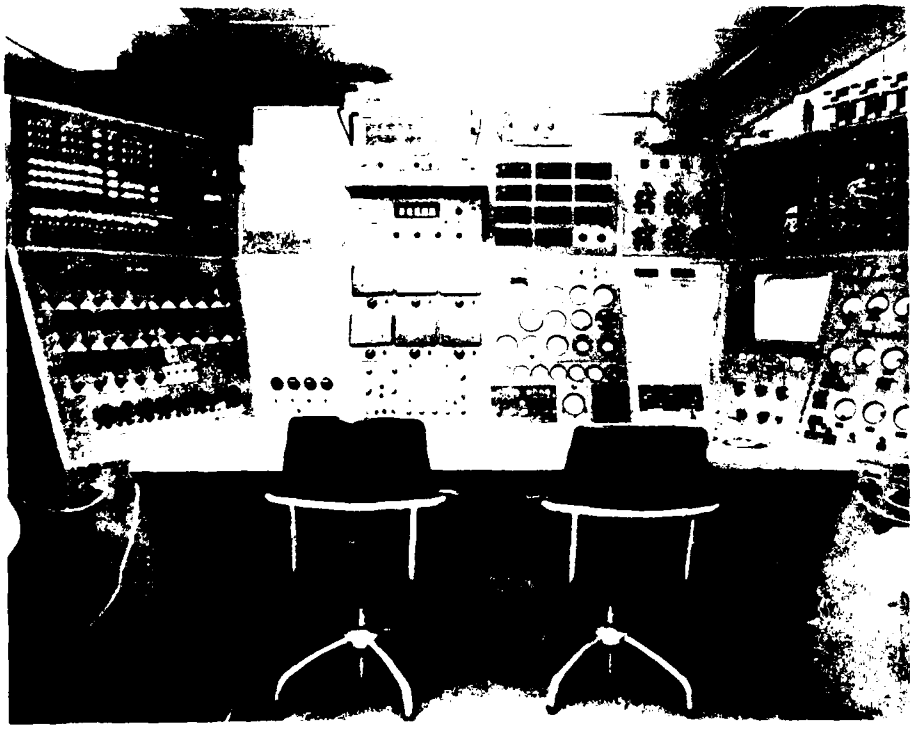


Fig 3b Aero Flight Simulator - Control Desk

Fig 4 AD-4 Analogue Computer and Control Desk

Fig 5 Aerospatatiale Puma Helicopter

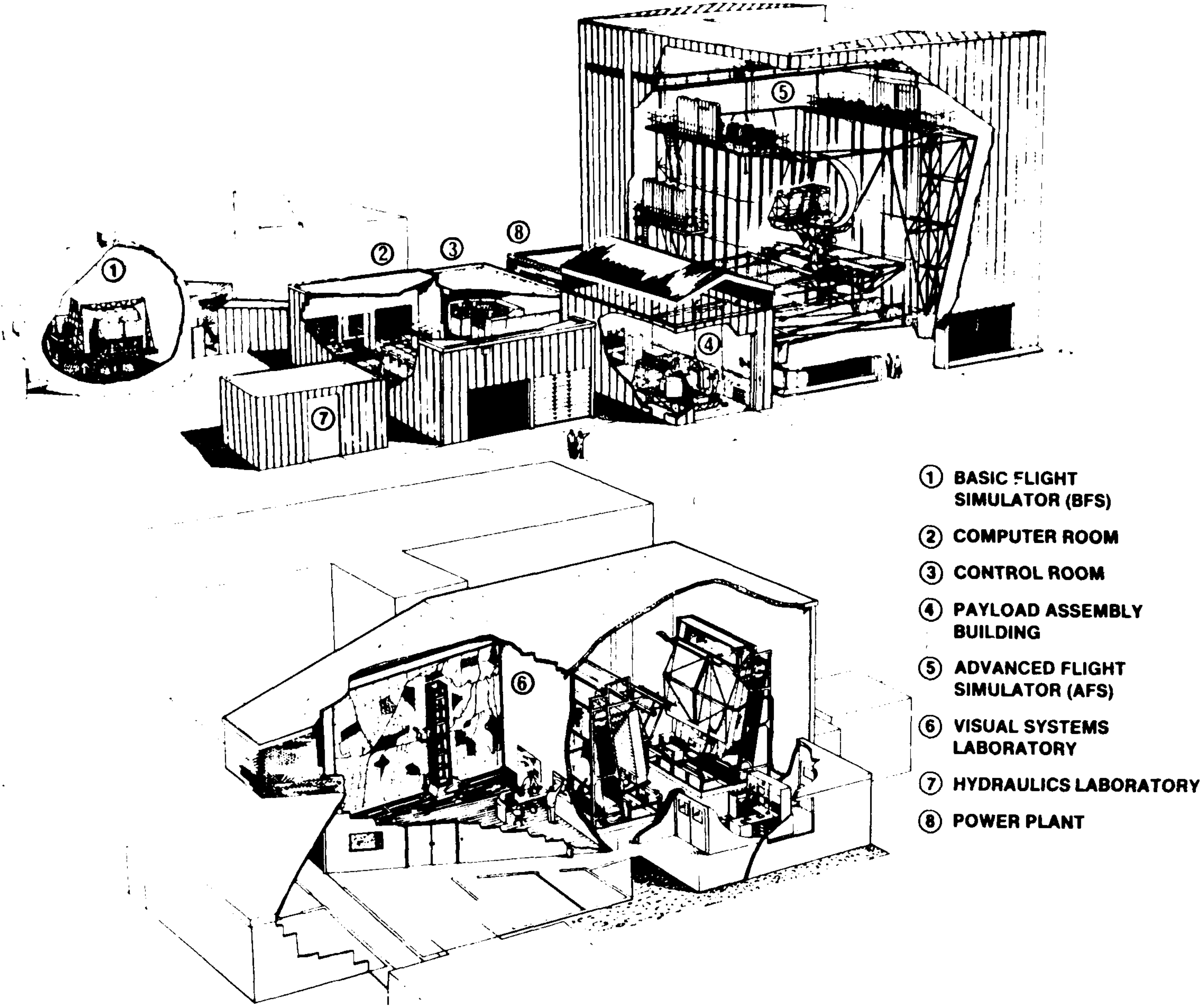


Fig 6 RAE Bedford Flight Advanced Simulator

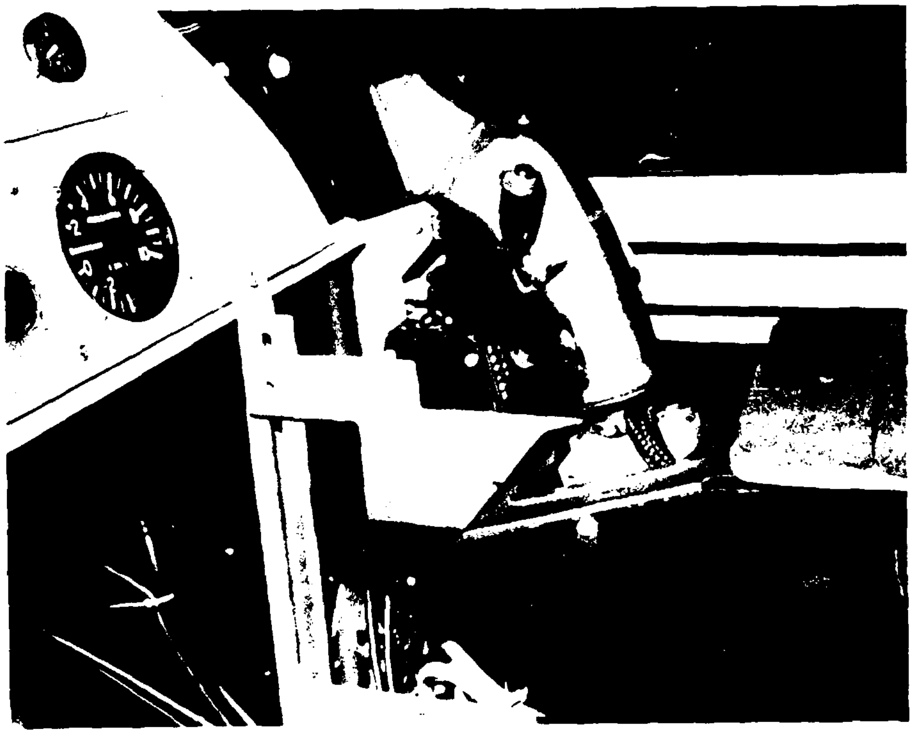


Fig 7 Miniature side-stick

Fig 8 Instrument panel for Lynx simulator

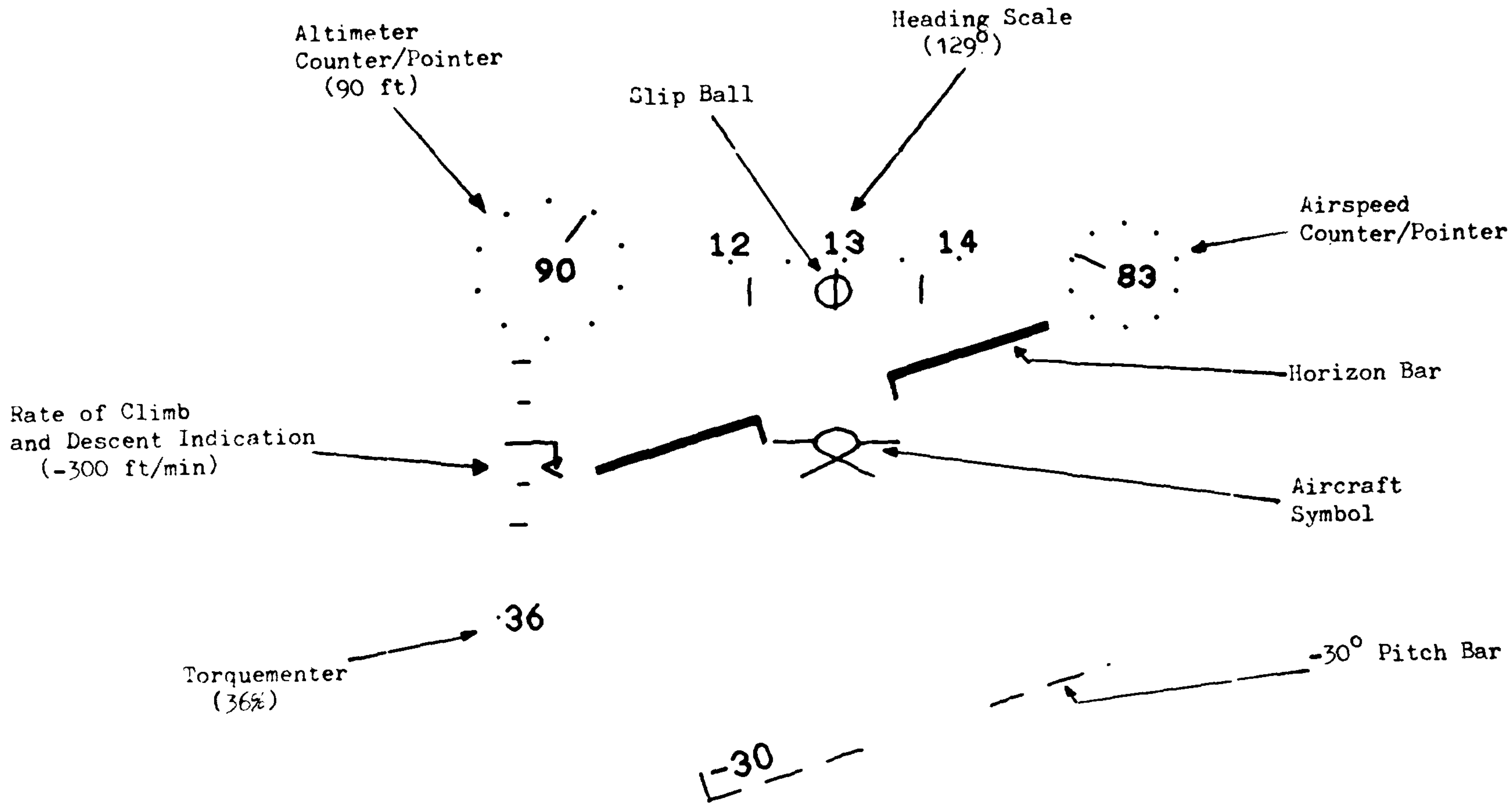


Fig 9 Helicopter HUD format

Fig 10a&b

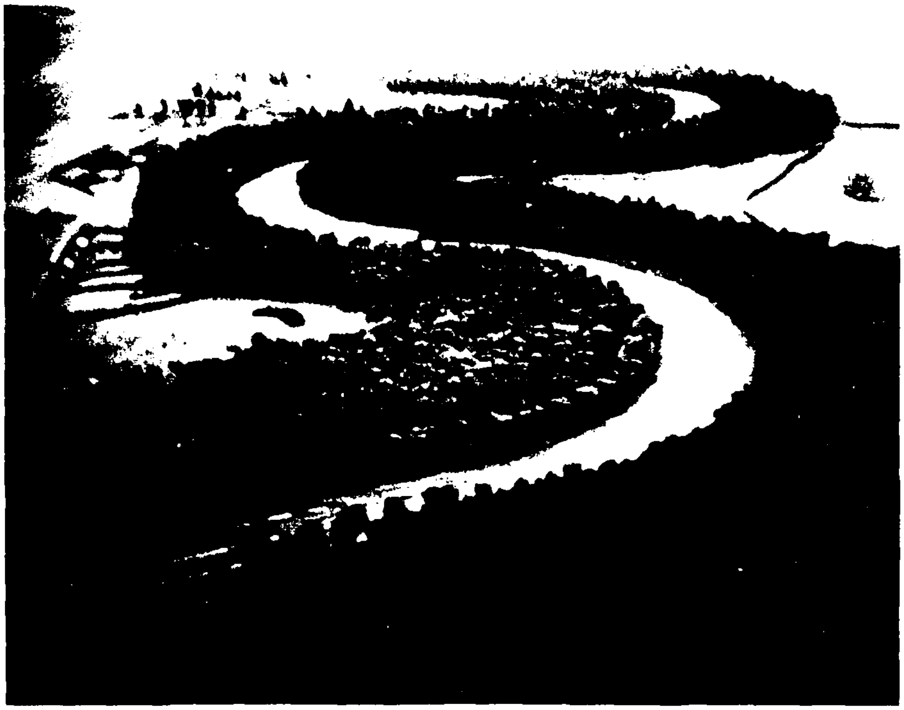


Fig 10a Serpent Course

Fig 10b Serpent Course

Fig 11a&b

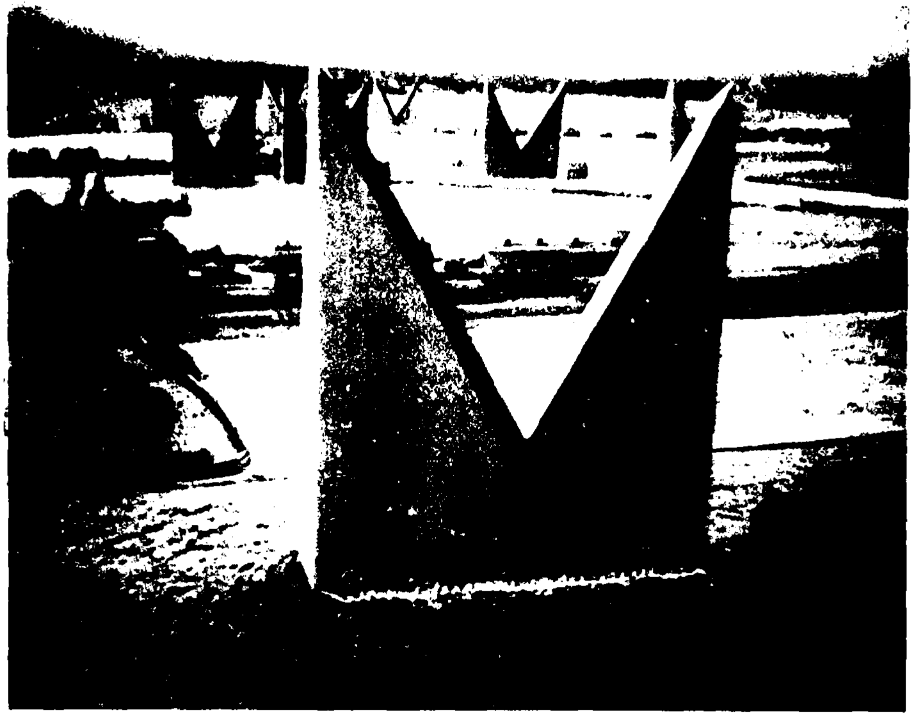


Fig 11a V-notch hurdle

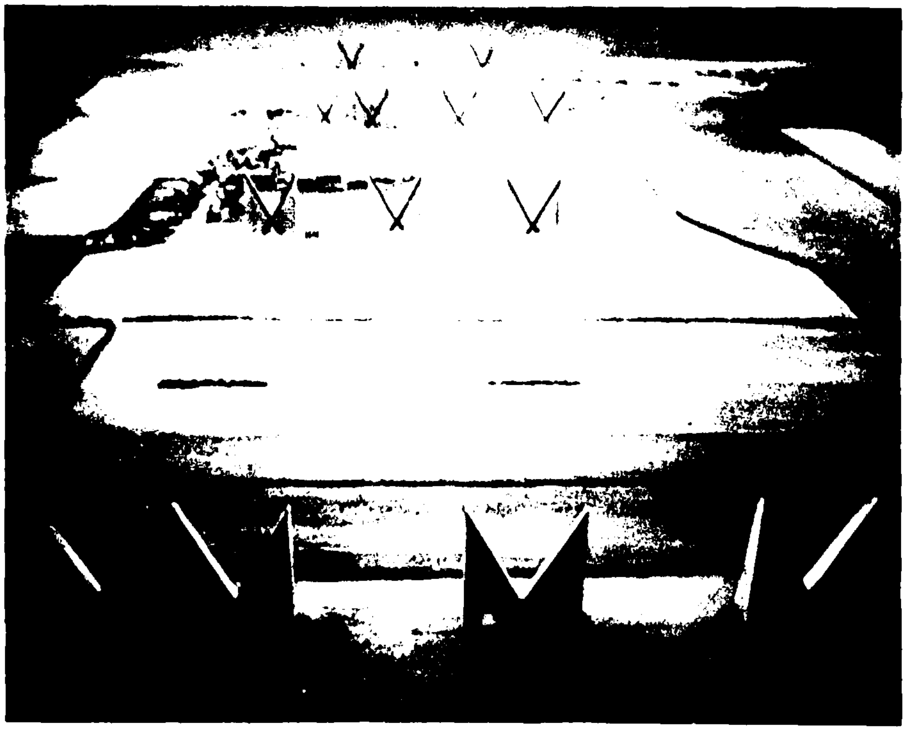


Fig 11b Array of hurdles

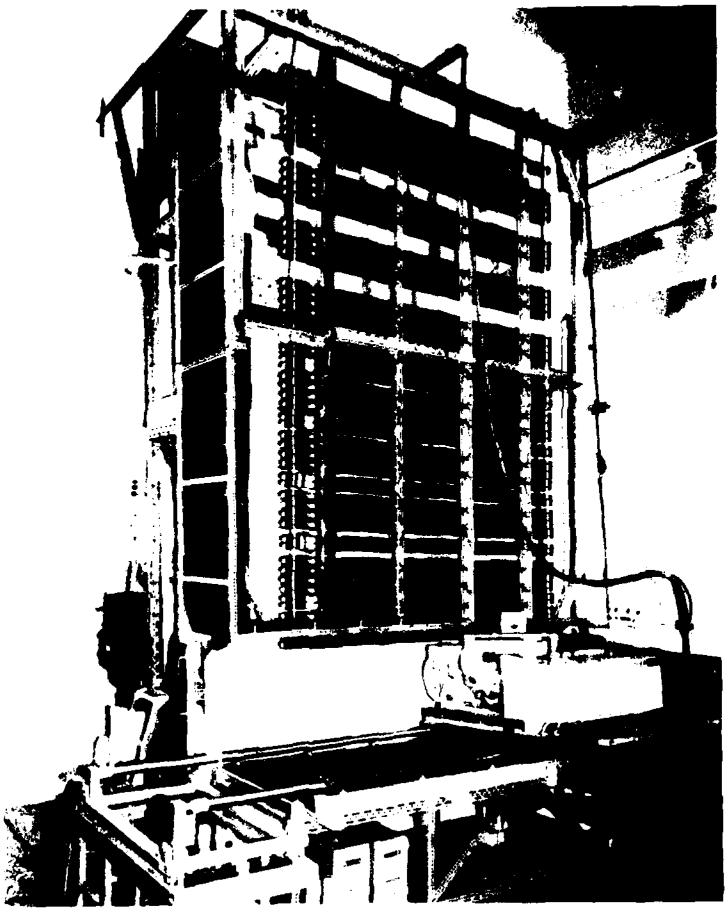


Fig 12 Terrain belt and gantry

Fig 13 a&b

Fig 13a Detail of terrain belt

Fig 13b Detail of terrain belt

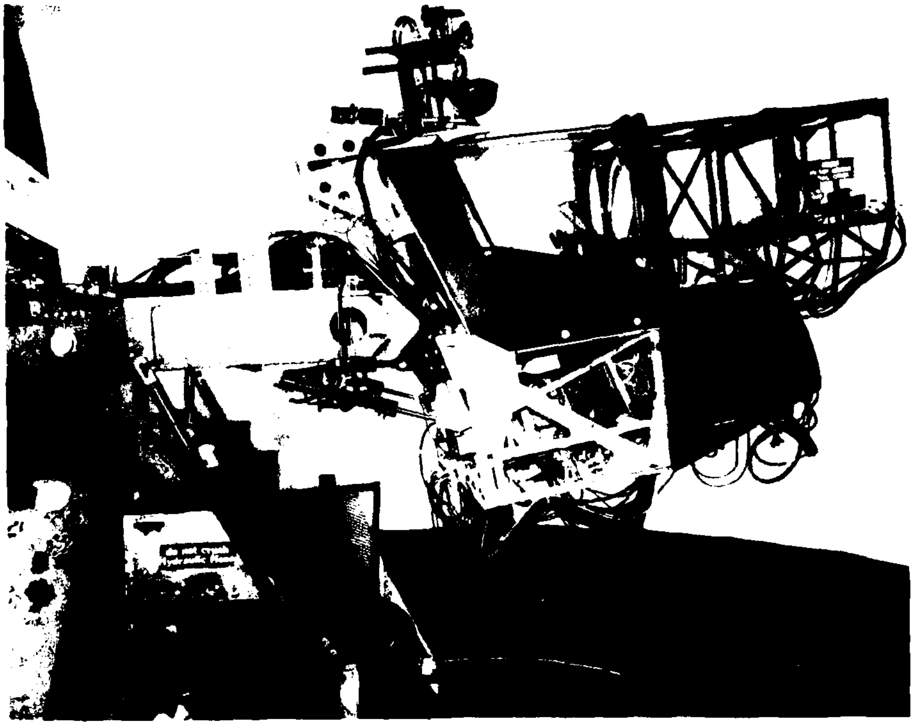


Fig 14 Single-seat cockpit and motion system

Fig 15a

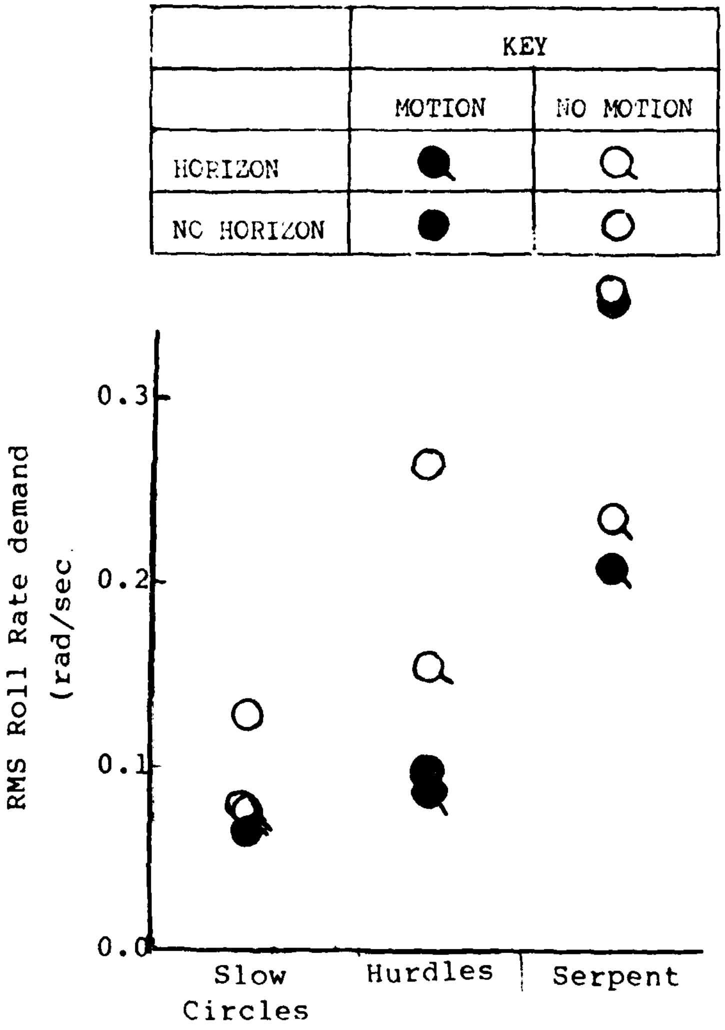
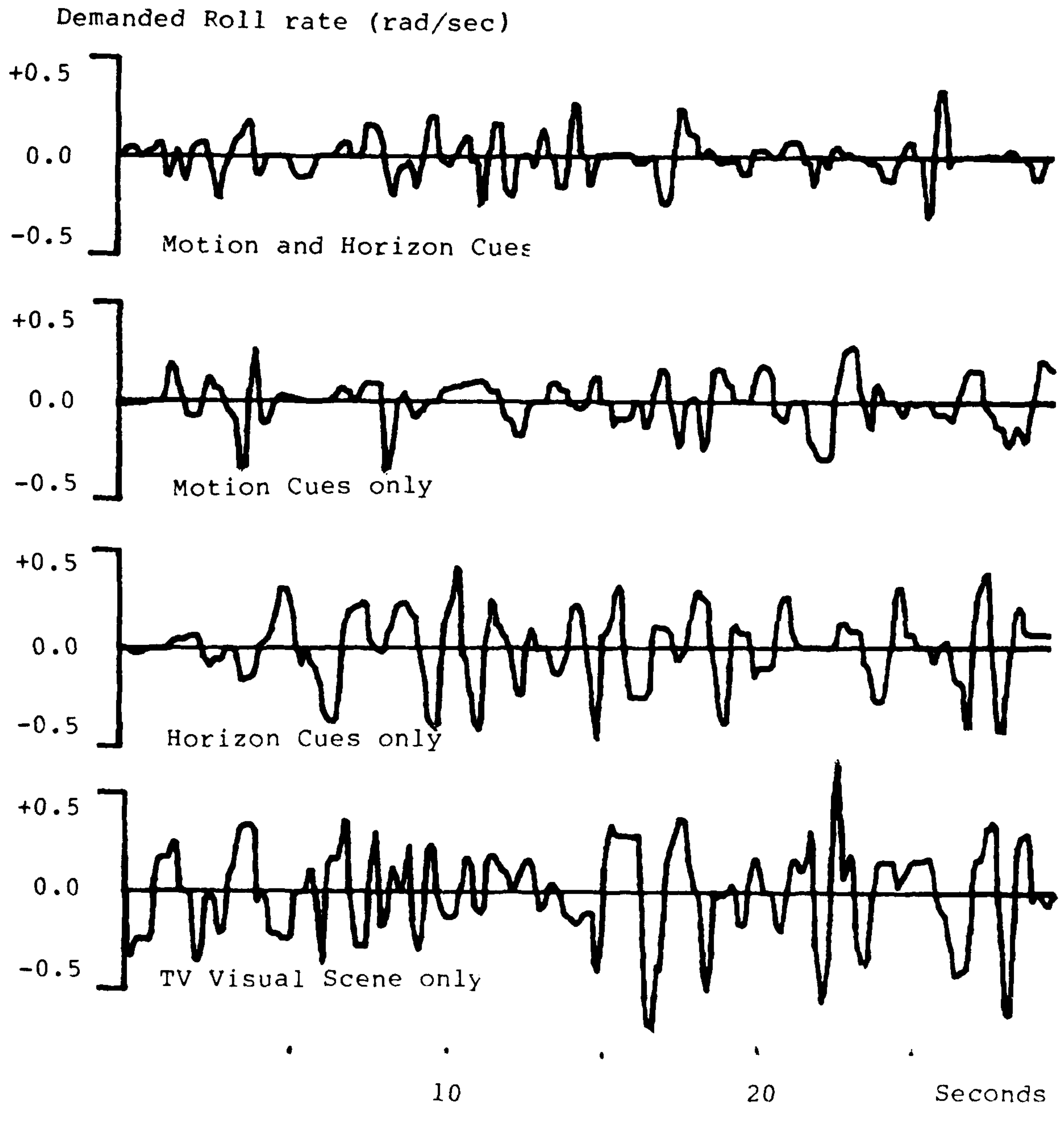


Fig 15a Effect of cues on control activity



Effects of Motion and Horizon Cues on Roll Control

Fig 15b Control activity in hurdles course

Fig 16

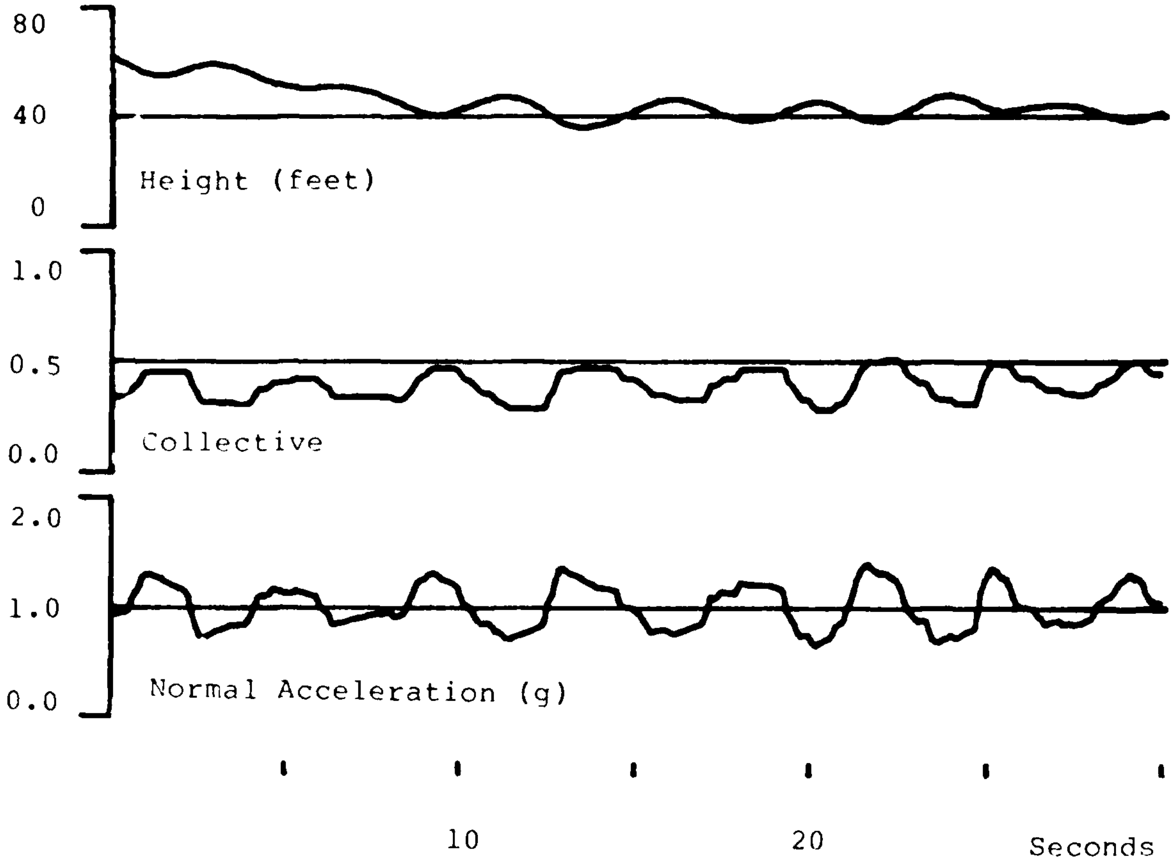


Fig 16 Collective PIO (entry to Serpent course)

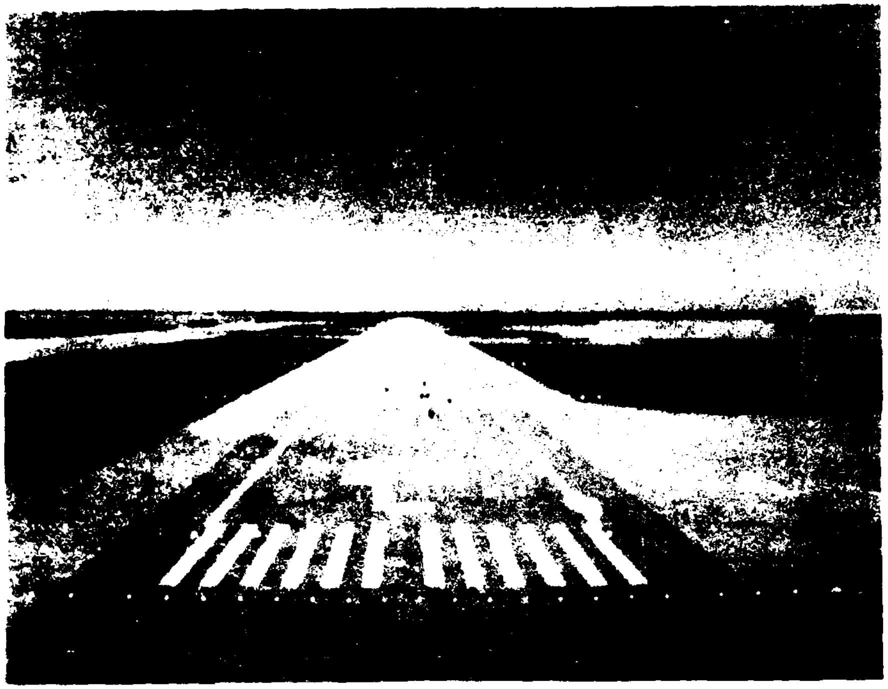
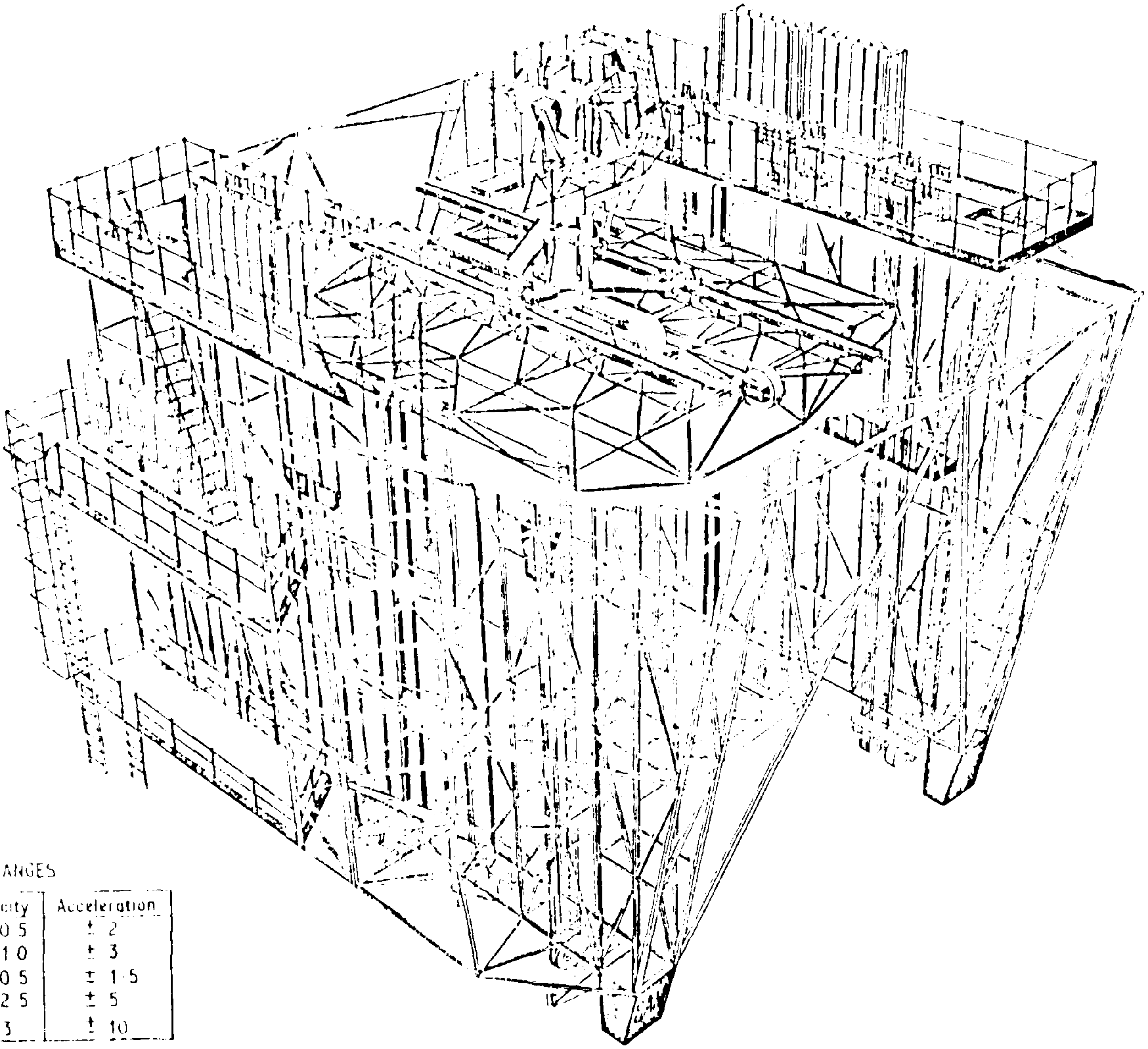


Fig 17 Singer Link-Miles IMAGE III daylight CGI

Fig 18

Fig 18 1000:1 solid model board



OPERATIONAL RANGES

Axis	Displacement	Velocity	Acceleration
Pitch	± 0·5	± 0·5	± 2
Roll	± 0·5	± 1·0	± 3
Yaw	± 0·5	± 0·5	± 1·5
Horizontal	± 4	± 2·5	± 5
Vertical	± 5	± 3	± 10

Units : m, rad, sec.

Fig 19 AFS motion system

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