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Helicopter Flying Qualities in Critical Mission Task Elements

Initial Experience with the DRA(Bedford) Large Motion Simulator

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Summary

Striving for improvements in helicopter flying qualities has been an activity pursued relentlessly by Industry and Government Research Agencies over the years. Simulation has played a key role, but only relatively recently have the acquisition policies demanded compliance demonstration using simulation prior to flight, placing a new and increased emphasis on high fidelity. At the DRA Bedford in the UK, the simulation of helicopter flying qualities has featured as a research topic for two decades; in 1991 the large motion system element of the Advanced Flight Simulator was made available for research activities and a series of helicopter simulations undertaken to calibrate the facility and evaluate the effects of fundamental response characteristics and external influences on flying qualities. New mission task elements were developed on the CGI visual system and motion drive laws configured for low - mid speed aggressive flying tasks. This paper describes the AFS facility and presents key results from an evaluation of helicopter flying qualities relative to the US Army's ADS33C requirements. The results are very encouraging, and indicate that Level 1 flying qualities can be achieved on the AFS up to moderate levels of pilot aggressiveness. At higher agility a degradation in pilot handling qualities ratings emerges that is consistent with previously presented DRA flight results. The importance of motion cues, particularly in the vertical axis, is stressed.

1 Introduction

The simulation of helicopter flying qualities using ground - based facilities has long presented a technical challenge in terms of the required fidelity of the task cue environment. As air-vehicle/mission attributes, flying qualities are especially task-sensitive and the fidelity of visual and motion cueing needs continuous assessment and validation for new applications. While many studies, spanning more than 20 years, have produced useful results and general guidelines, it is a relatively recent acquisition initiative to require demonstration of flying qualities compliance in simulation prior to flight (Ref 1). There are, however, no definitive fidelity standards or validation criteria for helicopter research and development simulators with respect to their use in this context. What is becoming clear is that the standards required are likely be very high for some critical flying qualities, beyond that currently available from simulation technology. During the development of ADS33C, for example, data from research simulators were used to support the development of criteria boundaries. One of the most demanding handling criterion relates to the (frequency) response bandwidth between the pilot's control input and aircraft's attitude response. A conclusion from the ADS33 development work was, "there were too many unresolved questions about data from rate response types obtained from simulation to use them in a specification development effort", and that "only flight test data can be reliably used to define bandwidth boundaries" (Ref 2, p111-112). Problems stemmed from visual scene generation transport delays, lack of scene texture and anomalies in motion/visual cueing, particularly intrusive during nap-of-the-earth mission task elements. These problems were encountered on the world's most advanced flight simulator at that time, the NASA Ames Vertical Motion Simulator (VMS), suggesting that less capable facilities would have an even smaller usable envelope of realistic fidelity.

Simulation technology has advanced considerably over the five years since the first publication of ADS33. The VMS has been upgraded to improve many of the deficiencies identified in the ADS33 database development. Still, Reference 3 reports that VMS simulations of nap-of -the-earth manoeuvres conducted in 1989 produced pilot handling qualities ratings up to 1.5 points worse than in flight. Degraded visual cueing in the simulator was a source of many of the adverse pilot comments, particularly relating to field of view, scene resolution and depth perception. Reference 3 also concludes, from a study of the effects of motion quality, that "as the difficulty of the task increases, the effects of motion cueing become more pronounced" and that "small motion cues, poorly tailored to the task, may degrade performance more than no motion cues". A recent simulation of the First Team's LH contender during the Demval phase, reported in Reference 4, modelled the ADS33C flight test manoeuvres as part of the compliance demonstration. Reference 4 makes the point that "the performance parameters and the manoeuvres themselves were chosen for ease of flight testing and were not specifically developed with simulation in mind." This is clearly a challenge to the compliance requirements set in ADS33C. Reference 4 also raises a caution, that "even with the sophisticated motion platforms and visual systems that exist in the Industry, it is still not clear that they can accurately support assessments of air-vehicle design under certain conditions." Specific shortcomings and problem areas for rotorcraft simulation were identified as;

i) lack of rich visual cues during high speed flight contributed to lower (*poorer*) than expected handling qualities ratings (HQRs)

ii) in steep turns (70deg bank), weak vertical cues resulted in altitude variations that were difficult to correct

iii) radial position and heading deviations during the pirouette were difficult to perceive because ground texture cues were not as sharp as in the real world

iv) ground cues were inadequate to judge the stopping phase of the accel-decel manoeuvre

The first team simulator at Sikorsky, as described in Reference 4, is close to state-of-the-art in terms of visual cueing and air vehicle modelling,; in addition, the washout dynamics of the small motion system can be adaptively tailored to different tasks, although the kinematic envelope is small. However, the facility clearly had some shortcomings simulating flying qualities for the ADS33 tasks.

In Europe, experience with dedicated handling qualities simulations in support of product development has been reported by Eurocopter Deutchland (Ref 5). A comparison between pilot handling qualities ratings derived from simulation and flight is presented; for the ADS33 low speed MTEs, a mean degradation of 2 points on the Cooper-Harper scale is reported - in flight the Bo108 is Level 1, while poor Level 2 results were returned by the same pilot in the simulator.

Defining tasks for pilots to judge flying qualities is a critically important activity, full of pitfalls. How should the task performance levels be set to delineate Level 1, 2 and 3 flying qualities? How should the task cues be presented to the pilot? How far should 'clinical' stylised tasks be augmented with unnatural features to compensate for degraded visual cues? The resolution of these questions raises problems, not only in simulation, but also in flight trials, where the test environment is often artificially created on an airfield to enable tracking measurements to be made. A common goal of all flight and simulation activities in this area has to be the determination of the impact of different flying qualities on mission effectiveness. A major issue then becomes the degree of similarity between the real 'operational' world and simulated flight tasks, a problem Sikorsky faced with the simulation of the ADS33 flight test manoeuvres.

In the UK during the last 18 months, the Defence Research Agency (formed from the Government research establishments, including RAE) has begun operations with the Large Motion System (LMS) element of the Advanced Flight Simulator (AFS) complex. This new facility offers the potential to expand the range of configurations and tasks that can be simulated with high fidelity. The need to support a range of helicopter research activities led to a concentration on helicopter simulation during the first year of operations, with some notable exceptions relating to pilot-induced-oscillations in fixed wing handling qualities (Ref 6). Tasks needed to be developed on the computer-generated-image

(CGI) database and an initial set of motion drive laws appropriate to tactical flying in the low to mid speed range prepared. A particular trial series supported the EuroACT collaborative programme with the goal of defining flying qualities standards achievable by the current maturity level of Active Control Technology (ACT). A companion paper at this Forum, by the EuroACT team, will outline the progress and describe some key results from this activity (Ref 7).

This paper reviews the results of a series of preliminary,'calibration', trials on the AFS during 1991/2, including the 'task' workup and a detailed examination of the ADS33 attitude response criteria for rate command types in low - mid speed tasks. A particular area of interest, where DRA have flight research experience, related to the effects of the level of task urgency or pilot aggressiveness on task performance and workload. How the DRA AFS would fare in addressing these issues in the context of demanding mission task elements (MTE) was a key question impacting future activities. The results are developed below. Section 2 reviews the topic of helicopter simulation, placing the current activities in context. Section 3 & 4 describe the AFS facility and the various trials goals and procedures; Section 5 presents and discusses results and Section 6 forms conclusions and recommendations.

2 Simulating Helicopter Flying Qualities - *overview of the topic*

The current generation of flying qualities requirements are mission or task oriented, which means that on the one hand they have been generated from test data gathered in experiments that try to emulate operational situations and, on the other, that they reflect the many and varied flight phases of a given mission. This is particularly true for the US Army's rotorcraft handling qualities requirements ADS33C, which requires Level 1 handling qualities throughout the operational flight envelope (OFE). The framework for specification is summarised in Figure 1 (Ref 8), illustrating how the required response type characteristics at the deepest level, are linked to the user-defined mission and environment at the highest level. The mission and environment together shape the required OFE of the aircraft. The response types required to achieve Level 1 handling qualities, eg. rate, attitude, are driven by two key aspects - the user - required mission task elements (MTE) and the usable cue environments (UCE). Generally speaking, the poorer the task visual cues, the more augmentation is required from the helicopter's automatic control system to confer good handling qualities. ADS33 quantifies this relationship in much greater detail than has previously been available. MTEs are the fundamental stylised manoeuvres from which the flight phases and whole missions can be assembled - they are generally independent of aircraft size or class. The UCE , designated 1,2 or 3, refers to the perceived quality of the visual cues, including any displays, for controlling attitude and velocity (Ref 1).

Mission oriented flying qualities therefore make the link between the vehicle's internal attributes - its open loop response characteristics, displays and inceptors, and the operating environment. This concept is expressed in Figure 2, highlighting the impact of the task urgency, as an external influence, on flying qualities. This is a critical effect, allowances for which are not currently embodied in formal specifications like ADS33C. Briefly, the sensitivity is encapsulated by the results of Figure 3 , derived from flight tests with a Lynx at DRA Bedford (Ref 9). The agility factor is derived as the ratio of **ideal time**, calculated assuming instantaneous development of maximum acceleration, to **measured time** for a given MTE. The agility factor is increased by increasing the level of aggression or urgency in the manoeuvre to the point when maximum achievable performance is used. Figure 3 shows how pilot handling qualities ratings (HQR) degrade as the agility factor is increased in the MTEs. At maximum agility factors of 0.7, when the pilot is attacking the manoeuvre with attitudes of up to 30deg, level 2/3 ratings are being returned, indicating that the pilot can barely achieve the adequate performance levels. A number of factors combine to produce the results shown in Figure 3, associated with a degradation in response characteristics and task cues, but the phenomenon is believed to be characteristic of all existing operational types; limited authority stability and control augmentation with no carefree handling features providing little pilot relief from the rough and unpredictable handling at high agility factors. It is important in flying qualities testing to assess the characteristics at the manoeuvre limits of the OFE, and hence high agility factors, to establish any potential danger areas. This requirement has considerable impact on the required level of simulation fidelity.

Pilot HQRs are related to the workload required to achieve a defined task performance. Several pilots are normally required in a handling qualities experiment and it is therefore important that there is consistency between pilots on the interpretation of workload and task performance. It is usually assumed that a test pilot's training programme will acquaint him with the self-assessment of workload, but varying levels of pilot skill and experience, as well as technique, are an inevitable source of scatter in the results. Setting task performance levels would appear at first sight to be straightforward, but requires a careful approach integrated with the design of the MTE, to ensure that two key results are obtained. Firstly, that the task cues and their precision requirements can be directly related to some measure of mission effectiveness. Secondly that the pilot-perceived task performance and the actual task performance achieved correlate. For handling qualities evaluations using a simulator, a third issue arises concerned with the MTE fidelity relative to flight. The outside visual cues need to be similar to the real world and induce a similar control strategy from the pilot. To an extent this requirement is satisfied if the simulated UCE is correct, but the latter is rather coarse and so intimately associated with the handling qualities themselves, that a finer measurement is required.

In the simulation trials described in this paper, the impact of these critical external influences , MTE design and urgency level, were investigated in some detail; the key results are presented below. The results of the UCE trials will be reported at a later date.

Turning to the vehicle's response characteristics, a convenient framework for discussion is offered by Figure 4. Here, the different requirements are mapped onto the frequency-amplitude plane; the concept applies to any of the aircraft's kinematic degrees of freedom. The nominal OFE line represents a manoeuvre boundary in this case, reflecting the natural constraint that the larger the amplitude, the lower the achievable frequency. Each dimension is conveniently divided into three regions as shown, providing a useful framework for characterising the details of the response shape. For the simulation of high agility, it is intuitive that the most critical characteristics lie at the OFE. When the OFE manoeuvre boundary in Figure 4 reaches into the high amplitude and high frequency range at the two extremes, the two most important handling parameters emerge - control power and bandwidth respectively. Figure 5 shows an example of the current ADS33 requirements for these two parameters in the roll axis for low speed MTEs. The bandwidth is plotted with another key parameter, phase delay, reflecting the shape of the frequency response phase at high frequency. Linking these two extremes, a new handling qualities or agility parameter has been defined in ADS33 - the attitude quickness or attack parameter. This ratio of peak rate to attitude change provides a useful measure of handling for moderate amplitude manoeuvres; Figure 6 illustrates the criterion boundary in the roll axis, again for the low speed MTEs. A major issue for the AFS was whether the existing requirements for bandwidth, quickness and control power relating to rate command systems in ADS33C could be reproduced and whether any new trends at high agility factors could be detected. The results are presented below in Section 5.

3 Description of Simulation Facility

3.1 The Advanced Flight Simulator

The AFS constitutes the DRA's flight simulation facility at Bedford in its entirety. It is a general purpose research tool that retains a high degree of flexibility to enable tailoring for a wide range of fixed and rotary wing applications. For an individual simulator sortie, a facility configuration, including both software and hardware requirements, can be user defined and selected to suit the needs of a particular trial. Key elements include the motion and visual systems, cockpit modules, pilot's controls and primary flight instrumentation. As noted in the Introduction, the facility was recently enhanced with the addition of the LMS and a CGI visual system. These systems offer a major advance in the DRA's capability for simulating helicopter handling qualities, and an inaugral workup phase was planned to gain a working knowledge of the new capabilities and limitations, and to assess the fidelity of the cues generated. In many respects, an activity of this nature may be regarded as a 'calibration' exercise concerning the integration and functioning of all of the software and hardware cueing elements for a total simulation, in support of some specific trial objectives. As such, calibration is viewed as an ongoing activity that is geared to developing the the AFS as a facility for helicopter handling qualities simulations and establishing the degree of fidelity achievable throughout the available operating envelope.

Following on from the discussion in Section 2, a principal objective for the enhanced AFS was an exploration of the facility's capabilities for establishing definitive criteria for key handling qualities parameters eg bandwidth, control power etc. To meet the trial objectives, some preliminary preparations were carried out; suitable CGI flight task data bases were developed and steps taken to optimise the LMS drive laws for those specific tasks (see section 4 below); in addition, an exercise was undertaken to investigate, and as far as possible to minimise, the total simulation latency. The following sections discuss these aspects in more detail and describe the facility configuration adopted for the trial, including the various devices used to provide the principal visual and sensory cues to pilot.

3.1.1 Motion System

Motion cues or, more precisely, platform motion cues, as opposed to those from other sources, eg. visual system, 'G' seat, were generated by the LMS. The system provides motion in the roll, pitch, yaw and heave axes, and, depending on the cockpit alignment when mounted on the motion platform, in either the surge or sway axis. Figure 7 shows the general arrangement of the motion system together with its performance characteristics; it is capable of large accelerations, velocities and displacements and, notably, the maximum performance can be achieved simultaneously in all five axes. The principal function of the system is to provide those all important cues of the onset of acceleration, through stimulation of the pilot's vestibular, kinaesthetic and somatic (pressure, touch etc.), motion sensory mechanisms (Ref 10).

A set of motion drive laws has been developed to transform the simulated aircraft manoeuvre commands into demands for the motion hardware. Figure 8 illustrates a simplified motion drive law. 'Washout' filters form the main components of the motion software; these can be tuned to generate the appropriate acceleration onset cues, while removing the long term demands on the motion and keeping the hardware's movements within permissable limits. The drive laws generate rotational and translational demands that are associated with either aircraft specific angular acceleration and body forces or hardware specific compensatory motion for example, pilot's head position offset. Prior to the trials, an optimisation exercise was carried out to tune the drive laws for the tasks to be flown and the principal filter frequencies and gains are listed in Table 1 (series 1). Further modifications were made to the drive laws during the trials (see Table 1, series 2 data) to improve motion cueing, especially in the roll and sway axis.

3.1.2 Visual system

A Link-Miles Image IV computer generated imagery graphics system was used to provide visual cueing, via three, collimated TV monitors mounted in the cockpit. The monitors were mounted in a centre window plus side windows arrangement, giving a horizontal field-of-view (FoV) of +/-63deg and a vertical FoV of +/-18 deg and +/- 24deg for the centre and side windows respectively. The image system provides a number of general landscape and seascape data bases, with more detailed representations of specific features, including airfields, buildings, ships etc. Surface texturing is also available. Although much of the scene content is rather rudimentary, the system does allow the user to adopt a 'hands on' approach, with considerable scope for scene creation and enhancement. Specific task scenarios can be created off-line, using a Silicon Graphics Iris work station, and then transferred to the CGI processor for examining on a larger scale, through a set of repeat monitors (of the main cockpit displays) at the AFS's main control desk. Prior to piloted evaluation, the tasks can also be tested in a real-time simulation, through a set of joystick controls at the desk.

3.1.3 Cockpit and controls

The layout of the cockpit used for the trials is shown in Figure 9. For the purpose of the trials, it was configured as a single seat helicopter with conventional collective and rudder pedal controls, and a two axis Dowty sidestick controller. The cockpit has a head-up-display (HUD) for information regarding roll/pitch attitudes, heading, airspeed, height, rotorspeed, torque and normal 'g' and a 'head-down' display (HDD) of primary flight instruments was also provided. When switched on, the HUD provides a continuous display of flight information in the pilot's forward FOV, in the format illustrated in Figure 10.

The pedals and collective were modelled on the geometry and shape of those of a Westland Lynx. Regarding their characteristics, the pedals are spring centred with a total displacement of +/-50mm and a force of 220N at the maximum displacement, while the collective was configured with variable coulomb friction, with a control range of 125mm. The sidestick controller has a maximum displacement of +/-10deg (approximate stick top travel +/- 25mm), and features positive centring with maximum forces of 40N and 20N for the pitch and roll axes respectively, at the maximum displacements. It also has a deadband of some +/- 2.5% of the total travel, with a break-out force of approximately 2N. In comparison, the conventional centrestick (not used in the trials reported here) control throws and forces at maximum displacement are +/-84mm/18N and +/-114mm/35N for the lateral and longitudinal axes respectively. The stick has a force trim control button but has no significant break-out force.

A 'G' seat was used to provide vibration and onset of normal acceleration cues. The vibration cues were driven at a simulated 4R frequency and modulated by airspeed and normal 'g' effects. Previous studies at the DRA (Ref 11), have demonstrated the effectiveness of 'G' seat cues for tasks featuring aggressive heave axis excitation. Reference 11 concludes that 'G' seats provide direct stimulii to the body's somatic and kinaesthetic sensory systems, acting as an important source of cues to supplement those provided by platform motion, and which add to the 'realism' of a simulation. Although this work was carried out using the AFS's small motion system, which has a relatively restricted performance capability compared with the LMS, it was still considered worthwhile to use the seat for the trials.

3.1.4 Computing System & Latency

The AFS computing system, as illustrated in Figure 11, has four main processors for supporting real-time piloted simulation activities. The processors, four Encore CONCEPT-32 computers, include the 'Primary Modelling Processor' (PMP), the 'Linkage Management Processor' (LMP), the 'Desk Management Processor' (DMP) and finally, the 'Secondary Modelling Processor' (SMP). The PMP handles the aircraft model while the LMP handles the linkage to various simulation sub-systems including the cockpit and 'G' seat, the sound system, motion system etc. The DMP is used as the medium for operational control of the simulator via the AFS control desk; it supports a relational data base for configuration management and for interactive monitoring of the state of a simulation. The SMP handles the interface with the CGI processor.

Reference 12 describes AFS computing system architecture and its functioning in more detail, and discusses the steps taken to minimise the computing transport delays. From Reference 12, the arrangement of software tasks in a multi-processor environment, such as the AFS's, exerts a major influence on how quickly a pilot's control input is converted into a simulator cue demand. The requirement to be able to simulate vehicles with Level 1 handling qualities has a direct bearing on the degree of latency that can be tolerated. A survey of the system was under taken to quantify the throughput delay, with the objective of identifying the most efficient means of synchronising the execution of the individual real-time tasks. Following a subsequent rationalisation of the computing architecture, with a basic system frame rate of 50hz an improvement of some 50ms was achieved, with a reduction in total computing throughput delay from 84ms down to 35ms.

Figure 12 shows a timing diagram that traces the system response to an initiating input at the pilot's cockpit controls, through to the corresponding change in the visual display. The example shown illustrates the case for a total delay of 114ms. Note that the visual system hardware and software are responsible for a time delay increment of some 80ms. Because it is a proprietary system, the CGI itself was exempt from the rationalisation exercise. The rate at which control inputs are sampled, which is governed by the system frame rate, introduces a variability factor of +10ms, while the interface with the CGI system, which also has a frame rate of 50hz, can give a further +10ms increment. Hence the total throughput delay can vary by up to +20ms

3.2 Vehicle Model and Configurations

3.2.1 DRA Conceptual Model

The vehicle model used for the trials was a 'conceptual simulation model' (CSM), developed to explore different fundamental response types in a previous study (Ref 13). The CSM allows for a range of different response types (eg rate, attitude), modelled as first or second order equivalent systems, augmented with a pure time delay; the parameters can be easily changed on-line to modify the handling qualities. Full details can be found in Reference 13; below is a summary of the modelled characteristics in each axis as configured for the 1991/2 AFS trials.

primary axes - pitch and roll

A common structure was used to provide rate response types in pitch and roll in the transfer function form;

$$\frac{p}{\eta_{1C}} = K \frac{e^{-\tau s}}{(\frac{s}{\omega_m} - 1)(\frac{s}{\omega_a} - 1)} \qquad 1$$

where p (q) is the body axis roll (pitch) rate (rad/s), and η_{1c} (η_{1s}) is the pilot's lateral (longitudinal) cyclic stick displacement (± 1). ω_m is the fundamental first-order break frequency or pseudo-roll (pitch) damping (rad/s) and ω_a is a psuedo-actuator break frequency (rad/s). K is the steady state gain or control power (rad/s. unit η_{1c}) and τ is a pure time delay.

secondary axis - yaw

The yaw axis is modelled as a second order equivalent system with yaw rate command at low speed, blending to sideslip command/hold in forward flight. The gain of the sideslip command mode varies inversely with forward speed to confer realistic control powers..

secondary axis - heave (rotor thrust)

A simple rotor thrust/inflow model provides collective blade angle (effectively height rate) command to collective control; engine/rotorspeed governing and torque are modelled by a third order equivalent system (Ref 13). The rotor thrust is modelled from simple momentum and blade element considerations and acts along the rotor shaft; a simple rotor drag force is included. The CSM can be manoeuvred by rotating the thrust vector through the body rate commands; rotor thrust then varies with disc incidence in the usual way.

auxiliary features

Transient and steady-state turn coordination in pitch, roll and yaw is provided in forward flight manoeuvres up to a limiting bank angle of 70deg. A height hold system is pilot selectable, operating through the collective channel and back - driving the pilot's collective lever when functioning, although this function was not used during the current trials.

fuselage aerodynamic modelling

Fuselage drag and sideforce are modelled with realistic coefficients that vary with the full range of incidence and sideslip, derived from look-up tables. The baseline values for rotor and fuselage aerodynamic parameters are selected to be Lynx-like.

cross coupling

For the reported series of trials, all cross couplings were set to zero enabling pure on-axis response evaluations.

Vehicle Configuration and Handling Parameter Matrix

The principal objective, to evaluate the effects of pitch and roll bandwidth on helicopter handling qualities, can be realised in the CSM through a variation of the parameters in the equivalent system, equation 1. Before setting down the configuration matrix, the rationale for establishing a suitable parameter range will be explained; the discussion will be restricted to the roll response initially.

First we can consider the case with ω_a set to zero, to examine a pure first order system with time delay. The bandwidth and phase delay parameters of Figure 5 can be derived analytically in the form;

$$\bar{\omega} = \frac{\omega_{bw}}{\omega_m} = \frac{1 - \tan\omega_{bw}\tau}{1 + \tan\omega_{bw}\tau} \qquad 2$$

where ω_{bw} is the phase bandwidth (Ref 1) and the attitude phase itself, ϕ, can be written as a function of frequency ω,

$$\phi = -90 + \tan^{-1}\left(\frac{-(\sin\omega\tau + \cos\omega\tau)}{(\cos\omega\tau - \sin\omega\tau)}\right) \qquad 3$$

The phase delay τ_p is then calculated from the expression (Ref 1),

$$\tau_p = \frac{\phi_{2\omega180} - \phi_{\omega180}}{57.3*(2\omega180)} \qquad 4$$

at the appropriate values of frequency.

The bandwidth and phase delay can then be calculated as a function of the fundamental parameters, ω_m and τ, as shown overlayed on the ADS33C criteria in Figure 13; the matrix covers the range of ω_m from 3 -> 12 and τ from 0.05 -> 0.2 and maps over the Level 1 and 2 handling qualities range. As described above in Section 3.1.4, the average delay for the CGI visual scene generation is about 120ms without compensation; this sets the minimum achievable value for phase delay of about 80-90ms as shown in Figure 13. It can be seen that to achieve bandwidths well into the Level 1 region for tracking tasks ($\omega_{bw} > 3.5$) requires very high values of damping (ω_m>12). In terms of helicopter design parameters this would imply high rotor stiffness if this level of bandwidth is required to be achievable at higher amplitudes. In practice this is usually required, and an active control system can artificially augment the small amplitude bandwidth of a soft rotor by overdriving the controls. Initially, the baseline configuration was selected with a bandwidth close to 3rad/s which should exhibit Level 1 handling for non-tracking tasks; variations in ω_m would then allow the bandwidth to be changed with negligable effect on phase delay, as shown.

Setting values for the control power parameter K was more difficult. ADS33C requires minimum values of roll rate of ±50 deg/s for sidestep and slalom type tasks; higher values up to 90deg/s only being required for air-combat tasks. Flight and simulation trials conducted previously at DRA suggest that the higher values are usable and preferred by pilots in the NoE tasks - up to 70deg/s in a sidestep (Ref 9) and 100deg/s in a slalom (Ref 14). One of the principal aspects being explored in the current trials was the effect of pilot aggression, or agility factor, on the HQRs. It was therefore considered important to have a baseline configuration with high agility in terms of control power - a max roll rate of 96deg/s was selected. The matrix should then allow for reductions into the Level 2 area. An initial (3*3) target matrix was configured with the parameter sets;

$$\omega_m = (3, 6, 9) \text{ rad/s}; \qquad K = (32, 48, 96)/57.3 \text{ rad/s}$$

For the equivalent system given by equation 1, this parameter set uniquely defines the outstanding handling qualities parameter - control sensitivity in rad/s^2.inch - for a given controller. While common for centresticks, this is not the most convenient general measure of control sensitivity, being so dependent on the pilot's inceptor type. A more appropriate measure is rad/s^2.% inceptor movement (where 100% is full stick from left to right). ie.

$$\dot{p}_{max}.\% = \frac{K\,\omega_m}{50} \text{ rad/s}^2.\% \qquad 5$$

The simulation configurations are mapped onto the bandwidth/sensitivity diagram in Figure 14. There are no ADS33C requirements on control sensitivity per se, accept that it should be harmonised for the defined roles. On Figure 14 the 'preliminary' Level 1/2 handling qualities boundary derived by DLR with a BO105 helicopter (Ref 15) has been superimposed. It was clear from the development sorties with a pilot in the LMS that the control sensitivities associated with the higher bandwidth/higher control power configurations were too high; the motion was too jerky when abrupt control inputs were made. The pseudo-actuator lag in series with the vehicle equivalent system in equation 1 serves to attenuate the acceleration as shown in Figure 15. With ω_a included, the maximum roll acceleration $\dot{p}_{max}$ and time to reach this, are given by the expressions;

$$\dot{p}_{max} = \frac{K\omega_a}{\gamma} e^{\omega_a t} \qquad \omega_a t = \frac{\log\gamma}{1-\gamma} \qquad \gamma = \omega_m/\omega_a$$

A value of 20 rad/s for ω_a was selected following pilot evaluation, to give an amplitude attenuation to 60% and a time to maximum acceleration of about 80ms. The revised baseline configuration, shown in Figure 14. is now located just outside the DLR Level 1 region.

There is one further point relating to sensitivity and control power that needs to be discussed to complete the story on configurations. While linear command gradients are acceptable with large throw centre-sticks (O(10in, 0.25m)), there is strong evidence that, for sidesticks, nonlinear gradients are required (Refs 13, 16). With typical sidestick throws of just a few inches, applied with a twist of the wrist, achieving the large amplitude response (control power) requirement makes for too high a sensitivity for small amplitude precision-control. Much of the workup and development sorties described in this paper were carried out with a two axis sidestick. The fixed nonlinear gearing developed in a previous study was adopted (Ref 17), giving linear sensitivity (50% nominal) for inputs up to 30% throw, with a cubic increasing sensitivity up to maximum of over 300% nominal at max throw. The form is shown in Figure 16.

The corresponding test configurations for the pitch axis were selected with a similar guiding rationale. Pitch (roll) axis parameters were changed when changing roll (pitch) configurations to maintain control response harmony. The yaw and collective axes parameters were fixed for the trials described in this paper. The final configuration matrix for roll and pitch are overlayed on the handling qualities diagrams in Figure 17a -b. While the full configuration range described above was selectable during the trials, most of the development was concentrated on configurations T103, T306 and T509, providing variations in bandwidth at constant control power. The parameter sets for these primary configurations are summarised in Table 2.

4 Trials Conduct and Procedures

In the design of tasks used in the evaluation of flying qualities, the relationship with mission effectiveness needs to be established. In this way, flying qualities can be brought into the attribute trade-off that eventually dominates the design process. Without this link, flying qualities become merely 'nice to have', without any clear benefits of compliance or penalties for non-compliance. The current MTEs, and indeed most of those in ADS33C, were designed as re-positioning or avoidance manoeuvres where the mission effectiveness can be related to the flight safety margins and survivability/stealth issues associated with flight path accuracy on the one hand, and the mobility associated with the speed of the manoeuvres, on the other.

4.1 General

The test technique adopted for the simulation trials was largely centred on that developed for the flight handling and agility trials (Ref 9). A core set of flight tasks were defined, similar to those described in Ref 1. The tasks chosen were based on MTEs considered appropriate to the battlefield roles of an agile combat helicopter, and included a number of hover-low speed tasks for each of the primary control axes, such as the sidestep, quickhop, bob-up and spot turn, and forward flight tasks such as a slalom, hurdle-hop etc.

In accordance with the test objectives, the tasks were intended to require a simple and repeatable control strategy, with well defined task performance goals supported by good task cues. As discussed above, task aggression was also a key aspect of the tests, where the objective was to investigate its influence on handling and agility, ie the levels of pilot workload and task performance achieved, across the full range of available performance. To achieve this, target levels of aggression were set, expressed in terms of the main controlled variable used by the pilot in determining the precision and time taken to complete a given task. For example, for the sidestep, the roll attitude used during the initial acceleration phase was used as the aggression parameter, where for example 10, 20 and 30 degrees represented low, moderate and high levels of aggression respectively.

Also in the flight trials, task performance requirements were specified in terms of the desired flight path margins for height, speed, track, heading and terminal position. To enable the pilots to fly the tasks within defined kinematic constraints, task cues were devised, in the form of ground tracks and markers, and together with the aircraft's instruments, were used for observing the task performance requirements. For a typical evaluation, the pilot would fly a given task at increasing levels of aggression, until the limiting performance was achieved. At each level of aggression, pilot ratings for handling qualities were awarded using the Cooper-Harper scale. Flight data, recorded via the aircraft's onboard recording system, were used to provide a means for assessing pilot control workload and achieved levels of agility, task aggression and performance, while flight path accuracy was measured via a Kinetheodolite ground tracking station. Supporting comments for pilot ratings were recorded via knee-pad data, pilot de-briefings and questionnaires.

Given the commonality of objectives, the basic flight test technique described above was adapted to suit the handling qualities simulation trials. The tasks themselves, task performance requirements and levels of task aggression were essentially similar, and corresponding records of objective data and subjective pilot comments and ratings were also taken. There were however, some significant and obvious differences between the simulation and flight tests, eg. pilot's primary flight data displays, presentation of visual cues etc. The following Sections discuss development of the simulation tasks and test procedures in more detail. In point of fact, it should be noted that the task development formed a integral activity with the EuroACT work discussed in Ref 7, and, in some cases, eg. slalom or 'lateral jinking', the tasks were identical.

4.2 Simulation task development

For the evaluation of roll and pitch control flying qualities two hover-low speed tasks, the lateral sidestep and the quickhop, and two forward flight tasks, the lateral jinking and the hurdles, were selected. All of the tasks except the hurdles had been developed in flight trials; the hurdles task was designed to provide an equivalent pitch axis control task to the slalom for the roll axis. An intensive phase of task development and workup activities took place as a precursor to the first AFS trials to create a suitable CGI data base and to develop the evaluation procedures using the simulator. A key concern here was that the tasks created for the simulator would require a control strategy that was essentially the same as that for the aircraft in flight. Preliminary piloted evaluations were conducted to check this and to review feasibility of the task aggression and task performance requirements, and the suitability of the task cue arrangements for pilot handling qualities evaluations. Some comparisons with flight data are discussed in the section on results below.

Visual cues aspects

Regarding visual cues, for the aircraft trials the tasks were flown within the environs of an airfield, where natural features such as runway edges, walls of buildings etc, were exploited whenever possible, and additional point markers or painted lines within the ground plain were employed as necessary. Testing was carried out in good daylight visibility conditions with the attendant 'richness' of real world scene texture. In comparison, while the CGI was configured to represent similar daylight conditions, the contrast and levels of brightness were poorer, and although some degree of surface texturing was incorporated, the general scenario represented a relatively sparse view of the outside world. Moreover, the available FOV was relatively limited, particularly in azimuth and downward, 'over the nose'. However, the CGI does have the facility for over-laying user defined, textured objects on to the background scene data base and this was exploited as a means of generating enhanced task cues.

Initially the tasks were evaluated on the simulator using a CGI airfield database with similar task cue arrangements as for the flight trials. It was soon apparent that the cues were insufficient to support the levels of task aggression and task performance requirements. Better cues were needed to enable the pilot to judge the progress of the manoeuvre and the levels of task performance achieved. In particular, there was a need for enhanced depth of field for positioning in the longitudinal axis and improved cues for height keeping. To illustrate a typical case, Figure 18 shows the evolution of the visual cue arrangement for the lateral sidestep. Firstly, Figure 18a shows the initial arrangement used for the aircraft trial. The fact that pilots were able to achieve the task repeatably with such simple cues reflects abundance of natural supporting cues in the background environment; these help to create a whole level of spatial awareness not easily achievable in the simulator. To improve matters, the more sophisticated sighting device shown in Figure 18b was adopted as a means to give better height and plan position cueing; the wall features with textured surfaces, see Figure 18c, were added to improve the perception of depth of field. Finally, vertical posts and lines on the ground plane were added as a means of improving the longitudinal positioning and translational rate cues, and to give additional cues for control of height. The other MTEs were developed in much the same way and Figs 19-22 illustrate the final CGI layouts achieved. The following sections address the task descriptions and the levels of aggression and task performance requirements that evolved during the task workup, see Table 3, and which were subsequently used for the trials.

i) Sidestep task description (Figure 19)

For the sidestep task, the objective was to re-position the aircraft in sideways flight over a distance of 150ft/45M, from an initial hover at 8M AGL (above ground level). As noted above, the initial roll attitude was used to define agggression, and in the event, attitudes of 10, 20 and 30deg proved acceptable to define low, moderate and high levels of aggression (corresponding to about 0.2, 0.4 and

0.6g initial lateral acceleration). Concerning task performance requirements, positional cueing in the longitudinal axis was the main problem for this task, both during the hover and translational phase of the task. Performance tended to be erratic which made it difficult to adjust the requirement to an acceptable value. Hence pilots were briefed to avoid giving undue weighting to longitudinal positioning when awarding ratings. From Figure 18, height and plan cues for the precision hover and terminal positioning elements of the task were given by the diamond and square sighting arrangements. At the correct fore-aft position, alignment of one of the diamond's points with the centre of the square indicates a 10ft/3m height and/or lateral position offset.

ii) Quickhop task description (Figure 20)

The quickhop task is the equivalent longitudinal axis task to the sidestep, where the objective is to re-position the aircraft over a distance of 500ft/150M from an initial hover at 15M AGL. Similarly, task aggression was set through the initial pitch attitude; again values of 10, 20 and 30deg where used for the three levels of aggression. Loss of height and lateral drift during the translation and final flare, and overshoot of the terminal hover position were the most common problems found in setting the task performance requirements. Although additional cues considerably removed the first two problems, the performance limits on terminal position had to be increased by a factor of 3 (from +/-10ft to +/-30ft). The design of the task was also driven by problems caused by the large changes in pitch attitude during the acceleration and deceleration phases, and the resulting constraints imposed on and by the pilot's forward FOV. Although this is a common problem in real aircraft, on the simulator it was exacerbated by the relatively poor CGI forward FOV, and limited downward and horizontal FOV from the side windows. From Figure 20, the task was flown between two 'walls' incorporating a height cueing line feature, with additional tramlines on the ground and large vertical posts in the forward FOV to provide lateral displacement cues during the pitch up and down phases of the manoeuvre. The black vertical lines were added to the wall to provide initial hover and terminal position cues.

iii). Lateral Jinking task description (Figure 21)

The lateral jinking or slalom is essentially a roll axis task and comprises a sequence of 'S' turn manoeuvres followed by line tracking elements. Task aggression was defined in terms of the maximum roll attitude to be used during the turning phase, and values of 15, 30 and 45deg were found to be suitable. The task objective was to fly through the course whilst maintaining a height of 8M and speed of 60Kn, turning at the designated gates to acquire the new tracking line as quickly as possible, within the constraints of the set level of aggression. Although pilot impression indicated that the slalom was particularly aggressive relative to the other tasks, there were no specific problems encountered in setting the task performance requirements.

From Figure 21, the task was based on a typical slalom course with offset turning 'gates' positioned on the centre-line and outer tramlines of a runway. The turning gates were represented by two adjacent vertical posts, which also provided height cueing; the white band on the posts delineates the desired performance margin. The intermediate gates were added to give enhanced tracking cues to supplement the runway lines. The width of the gates was determined by the adequate margin of performance for the tracking task (+/-20ft/6M). While this dimension would be unacceptable for an aircraft trial, where in fact ground markers were used, the gates proved to be an excellent cue in the simulator; generally speaking they were not considered to be too unrealistic or intrusive by the pilots, ie. they did not reduce the task to the realms of 'video-gaming'!

iv). Hurdles task description (Figure 22)

In common with the slalom, the hurdles task was a mix of flight path repositioning and tracking phases, but primarily in the pitch and vertical axes. The task objective was to negotiate a series of vertical obstacles, with a cyclic pitch control strategy (collective to be used only to retrim height/speed when clear of each obstacle), returning to the initial task height and speed conditions as quickly as possible between obstacles. Performance criteria were set for height overshoot, and height and speed control during the tracking element. Task speed was used to specify level of aggression, with values set at 60, 75 and 90kn.

In place of gates, the task cues consisted of a sequence of four rectangular hurdles, with 'V' notches in the top edge, positioned along the centre-line of a runway. The dark area on the hurdle delineates the target height for clearing each obstacle, while the bottom of the notches represents the task height between the hurdles.

4.3 Handling qualities trials procedures

The test matrix for the preliminary handling qualities trial was limited to the three baseline configurations, T103, T306 and T509, each of which were evaluated using the four tasks described above. For evaluation sorties, all three configuration were assessed against one of the tasks, flown in turn in a random sequence firstly at low, then moderate and finally high levels of aggression. Repeat runs for confirmation or checking any anomalies in the pilot comments or recorded data were made at the end of an evaluation sequence. Pilots were allowed from 2-3 familiarisation and task training sorties (3-5 hours simulator time) before performing their assessments, and further training runs were also allowed before individual evaluation runs. Data was logged for each evaluation and the parameters recorded are listed in Table 4. At the end of a run, the simulation was stopped so that pilot comments and ratings could be recorded. A specifically designed questionnaire, developed during the EuroACT programme (Ref 7), was used for this purpose. The questionnaire covered four main topics including task cues, aggression, performance and workload and was formatted so as to assist the pilot in selecting a rating (Figure 23).

In the event, seven different pilots successfully completed evaluations of the tasks and the results are discussed in Section 5 below. A summary of the tests cases achieved is given in Table 5.

5 Results

The results presented and discussed below are taken from the 11 sorties flown by pilots P5, P6 and P7 with the sidestick controller in sidestep, lateral jinking and quickhop MTEs. The data for the hurdles MTE shows far less consistency and there appears a strong case for a task re-design here. HQRs for both trial series are presented, but to date attention has been focussed on more detailed analysis of the recorded data from the second series. As discussed above, a brief evaluation of the UCE for the various MTEs was carried out. The results indicate a UCE of 1 for all four MTEs, when using the sidestick controller for low-moderate aggression levels, with a degradation to UCE 2 at high aggressiveness. The evaluations raised several questions about the adequacy of the UCE approach to visual cue analysis however and a further, dedicated, trial is planned with the objective of resolving these.

5.1 Sidestep

Figure 24 illustrates the pilot HQRs for the sidestep task for the three bandwidth configurations T103, T306 and T509 at three levels of aggression. The two sets of data at each bandwidth (open and full symbols) correspond to results obtained in the first and second trial phases as described above. The level 1/2 HQ boundary appears to be crossed between configurations T306 and T509 at low - moderate aggression, at a slightly higher bandwidth than the 2 rad/s set by ADS33C (Figure 17a). The effect of aggression level is generally as expected, with a degradation of between 1 to 3 HQRs, the biggest fall being experienced with the (solidly) Level 2 configuration T103.

During one sidestep sortie with pilot 4 (sortie 9), the large motion system became unserviceable for a short period and the opportunity was taken to record some repeat runs with motion off, although the 'g' seat remained on. Figure 25a shows a comparison of time histories for the two cases, flown in sequence (runs 4 and 5), of the pilot's controls and key task variables - bank angle, height, track, and speed. The configuration is T509 at high aggression, and the pilot returned an HQR of 5 for both cases. Although the lateral cyclic appears similar in both cases, the pilot claimed that the motion-off case felt less sensitive, encouraging him to attack the manoeuvre more aggressively and achieve a lower task time. A 20% increase in maximum speed can be seen, although at the expense of track following in the terminal phase - in the motion-off case the pilot found that the aircraft had drifted backwards and some final re-positioning within +/- 5kn was required. The most striking difference between the two cases can be seen in the collective activity and corresponding height variations. For the motion-off case, height excursions include a 6sec period oscillation, 5->10ft in amplitude, persistent throughout the manoeuvre. The pilot described this as a collective PIO and the collective trace confirms the driving mechanism with a 15->20% amplitude. This is directly attributable to the lack of heave motion cues in the motion-off case and has been documented in a previous study (Ref 11). Basically, the visual cues alone are inadequate for controlling height precisely in manoeuvring flight. The phenomenon is unlikely to be a PIO as such, but more a feature of the higher threshold for detecting height and height rate cues from the visual scene alone. Figure 25b shows the same picture for the moderate aggression case.

Two key results emerge from this brief and opportune comparison of motion on and off;

1 pilots will tend be more aggressive without motion and can approve of control/response characteristics that may be less satisfactory and too sensitive with motion cues.

2 motion cues in the vertical axis are essential for stimulating the correct height control strategy, particularly in manoeuvring flight.

These conclusions are not new, but confirm and strengthen the findings of previous investigations into simulation fidelity.

The roll 'quickness' parameters, computed from the response data for all the sidesteps, are shown in Figures 26a - c, for the three primary configurations at the different aggression levels. The ADS33C Level 1/2 boundaries for both the tracking and 'other' MTEs are overlayed on the Figure. The increase in achieved quickness with aggression is clearly shown and is, of course, expected. Also it can be seen that pilots have been able to just achieve quickness values for all three configurations in the Level 1 region for tracking tasks. In theory, pilots should be able to achieve higher quickness with the higher bandwidth configurations. From the data it appears that, up to a point, the pilots actually used higher values with the lower bandwidth configuration T103. This important observation is worth further discussion and two points are worth highlighting.

1 At low aggression levels, pilots are achieving quickness levels with T103 in the low amplitude (<10deg) range as high as with T509. At moderate aggression, configuration T306 achieves higher values than T509. Finally, at high aggression, again for small amplitude, the lower bandwidth configurations eventually run out of performance and only T509 achieves values up to 5 rad/s. This result suggests that pilots are choosing to use higher roll rates with the lower bandwidth configurations, when they can.

2 A similar observation can be made for the moderate amplitude cases (10 -> 60deg), with the highest quickness values at, say, 40 deg roll attitude change, being achieved with configuration T103. All configurations have the same control power (96deg/s) and the highest roll rate of nearly 80 deg/s was measured with T103.

This characteristic has been observed before (Ref 14) and indicates that pilots will try to achieve the same overall performance with a low bandwidth system by using greater roll rates, essentially trading off the poorer acceleration performance, and hence agility, with increased rate commands. This leads to greater control activity, higher workload and poorer HQRs. According to ADS33C, all three configurations are Level 1 for quickness and control power, with T103 falling into Level 2 for bandwidth and control sensitivity according to Figure 14. These three parameters are closely linked together as described in Sections 2 and 3 and illustrated in Figure 4; the results reinforce this and suggest that low bandwidth aircraft actually require greater quickness and control power than high bandwidth aircraft. The implications on the minimum requirements set by ADS33C are probably not significant, but the linkage does offer the designer some freedom in the trade-off studies.

Finally for the sidestep, Figure 26d shows the envelope of quickness results derived from flight tests with the DRA research Lynx (Ref 9), an aircraft with inherently high control power, sensitivity and bandwidth. The envelope corresponds closely with the maximum achieved in the simulation giving increased confidence in the fidelity of the control strategy adopted by pilots in the AFS.

5.2 Lateral Jinking

Handling qualities ratings for the jinking task are presented in Figure 27. Again the degradation with level of aggression is clear and the Level 1/2 handling boundary crossed between configurations T306 and T509 up to moderate aggression, as for the sidestep. All configurations are Level 2 to borderline Level 2/3 at high levels of aggression; at the higher levels, this task was very difficult to fly accurately, the ground poles making a narrow corridor that increased the task demand, to the point where the frequency and amplitude of control inputs expanded significantly relative to the sidestep, for example. Figure 28 shows the time variation of lateral cyclic inputs for pilot P3 flying configuration T306 (Sortie 8); low (HQR 3) and moderate (HQR 5/6) aggression levels are compared. The control amplitude clearly increases in the moderate case (middle diagram) with the pilot commanding > 80% of the control range. The corresponding spectral density plot in Figure 29a shows that the frequency range also increases for the moderate amplitude case, with significant power up to 2 Hz. The comparison draws out the differences between a Level 1 and Level 2 aircraft, when the vehicle dynamics are identical, highlighting again the task oriented nature of handling qualities.

The matrix covered by the second trial series included configurations with added time delay (the parameter τ in equation 1) and this had a most dramatic effect in the jinking manoeuvre. The lower plot in Figure 28 shows the lateral cyclic control with an added time delay of 80ms, taking the overall phase delay up to the τ = 200ms line on Figure 17a, ie $\tau_p \approx 0.17$. Figure 17a also indicates that this addition should shift the configurations into a degraded handling region. The time history and frequency spectrum comparison, shown in Figure 29b, are striking. The low aggression case (Run 3) is still rated as level 1 (HQR 3), but with the added time delay, the moderate aggression case (Run 9) is rated as Level 3 (HQR7). The pilot complained of an incipient PIO in roll for this latter case; Figure 30 shows a comparison of the ground track for the two cases which illustrates the piloting problems. The PIO tendency for the 200ms case has caused the aircraft to develop a lateral oscillation with flight path excursions of the order 10 m at the third gate. The pilot breaks out of the task performance boundaries and rates the aircraft as unacceptable. This single selected case showing the effects of added time delay, while dramatic, is insufficient to confirm or challenge the ADS33C criteria boundaries; more analysis of the set of runs with added delay is required. It is interesting to note that, at the moderate aggression level, the jinking task does exhibit a significant tracking phase; here pilots complain of incipient PIO problems. In this case it would then be more appropriate to consider the tracking MTE boundaries on Figure 17a. At 200ms delay, configuration T306 then moves from Level 2 to Level 3, consistent with the results discussed above.

Finally for the jinking task, Figure 31 shows the computed quickness for low and moderate aggression levels (not distinguished) for T306 and T509. As with the sidestep, higher values are achieved for T306, reinforcing the point that pilots will compensate for lower bandwidth by using more of the available control power for a given manoeuvre amplitude. The high values achieved in the small amplitude range (<10deg) are consistent with the recommended use of the tracking boundary at high aggressiveness.

5.3 Quickhop

HQRs for the quickhop MTE are shown in Figure 32, plotted against configuration bandwidth. The ADS33C Level 1/2 boundary for tracking lies at 2 rad/s and for other MTEs at 1 rad/s, as shown in Figure 17b. The improvement in ratings with increasing bandwidth and degradation with increasing aggressivness are evident but not nearly as marked as for the lateral manoeuvres. There is even some evidence that the pilots prefer to use the higher levels of aggression to attack the quickhop. Pilot comments confirm this; at higher pitch angles the manoeuvre can be flown more continuously, improving pilot judgement in the reversal and deceleration phases. The Level 1/2 boundary from this data would seem again to lie between T306 and T509, higher than set by ADS33C, although some pilots awarded Level 1 ratings for T103 at low aggression. Both the sidestep and quickhop are geometrically similar manoeuvres but it appears that pilots do not try to exploit the pitch agility to the same extent as the roll agility. Figure 33 illustrates time histories for pilot P1 flying configuration T306 at three levels of aggression, highlighting the point further. For these cases the familiar pattern of a degradation of handling with aggressiveness can be seen (run 2, HQR 3; run 4, HQR 4; run 5, HQR 5). But the manoeuvre kinematics and associated control activity are much less urgent, as further demonstrated by the quickness values shown in Figure 34; generally there are only three distinct attitude changes picked up by the quickness spotter - the initial, reversal and terminal phase. In the moderate amplitude range, the quickness hardly rises above 0.6, 30% of the corresponding values for roll quickness, and considerably lower than the maximum achievable agility. Of course, it is considerably more difficult to engineer a high bandwidth in the pitch axis, because of the much higher aircraft moment of inertia; this should not in itself be a constraint in a conceptual simulation, however. It appears that pilots are more constrained from using pitch agility for other reasons - large for/aft body (pilot and aircraft) tilt, obscured field of view, higher pilot accelerations positioned ahead of rotation point and less precise control with for/aft hand movements. The results carry over to flight, as shown by the Lynx envelope in Figure 34 (Ref 9) although much higher quickness values were computed from measured Lynx data.

6 Conclusions

This paper has reported on the first experiences with the Large Motion Simulator at DRA Bedford for simulating the flying qualities of helicopters in NoE mission task elements. A framework for defining flying qualities in terms of an aircraft's response characteristics and the key external environmental influences have been described. The criteria formats of ADS33C were adopted and a suite of hover/low speed and forward flight mission task elements created on a CGI database for flying qualities evaluation. The vehicle mathematical model adopted was the DRA Conceptual Simulation Model, configured with simple rate response types in roll, pitch and yaw. The paper describes the background to the research, placing the activity in context with other current helicopter simulation efforts. The simulation facility is described along with the special developments in modelling, motion and visual cueing undertaken to support the trials. Of primary research interest was whether the Bedford AFS could reproduce the Level 1/2 flying qualities boundaries set by ADS33C for the attitude response of rate response types in pitch and roll; a second, equally important, objective was to investigate the degrading effects of pilot aggression or manoeuvre attack on perceived handling qualities, found to be so critical in previous flight experiments at DRA. From the results analysed and presented in this paper, the following conclusions can be drawn;

1 Concerning the ADS33C bandwidth criterion, the location of the Level 1/2 handling boundary depends critically on the level of pilot aggression; for low to moderate aggression levels the pilot HQRs suggest a slightly higher bandwidth than the 2 rad/s set in ADS33C, perhaps as high as 2.5 rad/s. At high aggression, even the highest bandwidth configurations evaluated were rated Level 2 and even 3 on some occasions. The trends indicate that improvements are still possible at higher bandwidth but it seems unlikely that Level 1 HQRs will be reached at full performance levels (highest aggression factors) due to deficiencies in simulation fidelity.

2 While most of the MTEs were designed without a specific tracking (high task bandwidth) phase, at high aggressiveness in the jinking task, pilots experienced incipient PIOs in roll, and the frequency content of control activity rose well above (O(2Hz)) that normally associated with re-positioning/avoidance tasks. The tracking boundary for roll at 3.5 rad/s seems more appropriate for this case.

3 The primary configurations, T103, T306 and T509, all met the ADS33C Level 1 requirements for attitude quickness and control power by design, although in many cases the pilots used less than the minimum required values for both roll and pitch MTEs. There is a clear trend that pilots actually (need to) use higher values of quickness with the lower bandwidth configurations, at the expense of increased workload, a feature observed in previous simulations at DRA. This would suggest that, to achieve the same agility, low bandwidth configurations need higher control power, hence pulling up the achievable quickness in the moderate-amplitude range. This trade-off is, of course, a familiar 'old chesnut'; whether the current ADS33C requirements adequately cover the issue cannot be judged from the limited analysis conducted. It is a topic for further study.

4 The importance of motion cueing was demonstrated most effectively in the heave/collective axis. Results for the sidestep MTE flown with and without motion reveal marked differences in the collective control strategy and resulting height excursions, with the motion-off case revealing a three-

fold increase in amplitude. Heave axis cueing is essential for investigating flying qualities in the vertical axis.

5 A second feature observed from the comparison of motion on and off was the tendency for pilots to be more aggressive without motion, exploiting more agility. This classic phenomena needs better quantification than time allowed in the research described in this paper, and is a planned activity in a future simulation trial.

The simulations described in this paper have provided high value data contributing to the definition of Level 1 helicopter flying qualities. The performance of the DRA AFS has enabled key issues of simulation fidelity to be addressed - the need for high definition MTEs, the value of motion cueing etc. Future research will aim at expanding the performance to define the upper limits, both in terms of simulation fidelity and vehicle agility.

The use of ground-based simulation to aid decision making and problem solving in helicopter flying qualities requirements capture, design and compliance demonstration is emerging from years of prototyping as a cost effective and definitive tool in acquisition strategies. Several key technical areas need increased attention before the full potential is realised, however. Fidelity criteria and associated validation techniques are needed that have a widespread and international recognition and understanding, to judge the quality of a wide range of simulations. The DRA AFS will be able to play an important role in this endeavour.

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TABLE 1. Principal LMS Motion Drive Algorithm Parameters

Motion Axis	Gain	Washout Frequency(rad/s)
Sway	0.1 - series 1 0.5 - series 2	0.3 - series 1 0.4 - series 2
Heave	0.2	0.5
Roll	0.3 - series 1 0.15 - series 2	0.5
Pitch	0.5	0.2 - series 1 0.5 - series 2
Yaw	0.3	0.3

TABLE 2. TEST CONFIGURATIONS

A. NAMING CONVENTION

Indices Sensitivity	1 0.10	2 0.15	3 0.20	4 0.25	5 0.30	6 0.35	7 0.40
Wm = 3	103	203	303	403	503	603	703
6	106	206	306	406	506	606	706
9	109	209	309	409	509	609	709
12	112	212	312	412	512	612	712
15	115	215	315	415	515	615	715

B. TEST CONFIGURATIONS:

Test point	Roll Wm	Roll Wbw	Roll Tp	Roll control power sens*	Pitch Wm	Pitch Wbw	Pitch Tp	Pitch control power sens*	Total time delay ms
T103	3.0	1.6555	0.1202	96 /s 0.100	1.5	1.0442	0.1236	48 /s 0.025	120
		1.3980	0.1753			0.9272	0.1810		200
T103A	3.0	1.6555	0.1202	96 0.100	1.5	1.0442	0.1236	96 0.050	120
		1.3980	0.1753			0.9272	0.1810		200
T306	6.0	2.3921	0.1144	96 0.200	3.0	1.6555	0.1202	48 0.050	120
		1.9101	0.1657			1.3980	0.1753		200
T306A	6.0	2.3921	0.1144	96 0.200	3.0	1.6555	0.1202	96 0.100	120
		1.9101	0.1657			1.3980	0.1753		200
T312	12.0	3.1277	0.1058	48 0.200	4.5	2.0780	0.1171	48 0.075	120
		2.3653	0.1528			1.6988	0.1702		200
T309	9.0	2.8322	0.1097	64 0.200	3.0	1.6555	0.1202	48 0.050	120
		2.1890	0.1584			1.3980	0.1753		200
T509	9.0	2.8322	0.1097	96 0.300	4.5	2.0780	0.1171	48 0.075	120
		2.1890	0.1584			1.6988	0.1702		200
T509A	9.0	2.8322	0.1097	96 0.300	3.0	1.6555	0.1202	96 0.100	120
		2.1890	0.1584			1.3980	0.1753		200
T512	12.0	3.1277	0.1058	48 0.300	4.5	2.0780	0.1171	48 0.075	120
		2.3653	0.1528			1.6988	0.1702		200
T515	15.0	3.3402	0.1026	57 0.300	7.5	2.6362	0.1119	57 0.150	120
		2.4869	0.1484			2.0673	0.1618		200
T609	9.0	2.8322	0.1097	111 0.350	3.0	1.6555	0.1202	96 0.100	120
		2.1890	0.1584			1.3980	0.1753		200
T709	9.0	2.8322	0.1097	127 0.400	4.5	2.0780	0.1171	64 0.100	120
		2.1890	0.1584			1.6988	0.1702		200
T715	15.0	3.3402	0.1026	76 0.400	4.5	2.0780	0.1171	64 0.100	120
		2.4869	0.1484			1.6988	0.1702		200
Yaw	4.5	2.0780	0.1171	64 0.100	120ms time delay				
		1.6988	0.1702		200ms				

* units = rad.s-2 / %

TABLE 3. TASK PERFROMANCE REQUIREMENTS

TASK			REQUIRMENT				
			SPEED	HEIGHT	TRACK	HEADING	END POINT*
SIDESTEP	Translation	Adequate	-	+5m	+3m	+10deg	+3m
		Desired	-	+2.5m	+3m	+5deg	+6m
	Hover	Adequate	-	+6m	-	+10deg	-
		Desired	-	+3m	-	+5deg	-
QUICKHOP	Translation	Adequate	-	+5m	+3m	+10deg	+15m
		Desired	-	+2.5m	+3m	+5deg	+9m
	Hover	Adequate	-	+6m	-	+10deg	-
		Desired	-	+3m	-	+5deg	-
LATERAL JINKING	Translation	Adequate	+7.5kn	+5m	-	+10deg	+6m
		Desired	+5kn	+2.5m	-	+5deg	+3m
	Tracking	Adequate	-	+5m	+6m	+10deg	-
		Desired	-	+2.5m	+3m	+5deg	-
HURDLES	Hurdle hop	Adequate	-	+6m	+6m	+10deg	-
		Desired	-	+3m	+3m	+5deg	-
	Tracking	Adequate	+7.5kn	+3m	+6m	+10deg	-
		Desired	+5kn	+1.5m	+3m	+5deg	-

* Terminal positioning constraints

TABLE 4 LOGGED DATA (AT 25Hz)

Description	Fortran Variable	Units
Longitudinal control position	ETAP	+/- 1
Lateral control position	XIP	+/- 1
Pedal control position	ZETAP	+/- 1
Collective control position	COLLP	0 - 1
Angular acceleration , roll	PDOT	r/s**2
Angular acceleration , pitch	QDOT	r/s**2
Angular acceleration , yaw	RDOT	r/s**2
Normal acceleration	AZCG	g
Lateral acceleration	AYCG	g
Angular rate , roll	PD	r/s
Angular rate , pitch	QD	r/s
Angular rate , yaw	RD	r/s
Total airspeed	VTKT	kn
Lateral airspeed	VBKT	kn
Pitch attitude	THETAD	deg
Roll attitude	PHID	deg
Heading	PSID	deg
Barometric height	H	ft
Longitudinal position	X	m
Lateral position	Y	m
Engine torque	QPCNT	%
Rotorspeed	OMPCNT	%

TABLE 5. SUMMARY OF TEST CASES FOR HANDLING QUALITIES EVALUATIONS

Series 1 Pilots: P1 - Berryman P2 - Warren P3 - Coyle P4 - Brown
Series 2 Pilots: P5 - Daniels P6 - Downey P7 - Churms

PILOT:	SORTIES:	TASKS:	CONFIGURATIONS:	LEVEL OF AGGRESSION:
P1	12	Task workup	All configurations	Low, Moderate & High
		Sidesteps	T103,T306,T509	Low, Moderate & High
			T103*	High
		Quickhops	T103,T306,T509	Low, Moderate & High
			T103*	High
		Lateral jinking	T103,T306,T509	Low, Moderate & High
			T103*	High
		Hurdles	T103,T306,T509	Low, Moderate & High
			T103*	High
P2	7	Task training	T103,T306,T509	Low, Moderate & High
		Sidesteps		
		Quickhops	T103,T306,T509	Low, Moderate & High
		Lateral jinking		
		Hurdles		
P3	5	Task training	T103,T306,T509	Low, Moderate & High
		Sidesteps		
		Quickhops	T103,T306,T509	Low, Moderate & High
		Lateral jinking		
		Hurdles		
P4	5	Task training	T103,T306,T509	Low, Moderate & High
		Sidesteps		
		Quickhops	T103,T306,T509	Low, Moderate & High
		Lateral jinking		
		Hurdles		
P5	12	Task training	T103,T306,T509	Low, Moderate & High
		Sidesteps	T103,T306,T509	
			T309,T512,T515	Low, Moderate & High
			T306+80ms,T309+130ms	
			T512+80ms	
		Quickhops	T103A,T306,T306A	
			T515,T103A+130ms	Low, Moderate & High
			T306A+80ms	
		Lateral jinking	T306,T309,T512	
			T306+130ms,T309+130ms	Low, Moderate & High
			T512+130ms	
		Hurdles	T306,T103+130ms	Low, Moderate & High
			T306+130ms	
P6	2	Task training	T103,T306,T509	Low, Moderate & High
		Sidetseps	T103,T306,T509	Moderate & High
		Lateral jinking	T306,T306+200ms	Low & Moderate
			T509,T509+200ms	
P7	4	Task training	T103,T306,T509	Low, Moderate & High
		Sidesteps	T306,T509,T509*	
			T306+80ms,T509+80ms	Moderate & High
			T715,T715+80ms	
		Lateral Jinking	T306+80ms,T509+200ms	Low & Moderate
			T509+200ms*	
		Quickhops	T103A,T103A+200ms	Low & Moderate
			T509A	

* Motion Disengaged

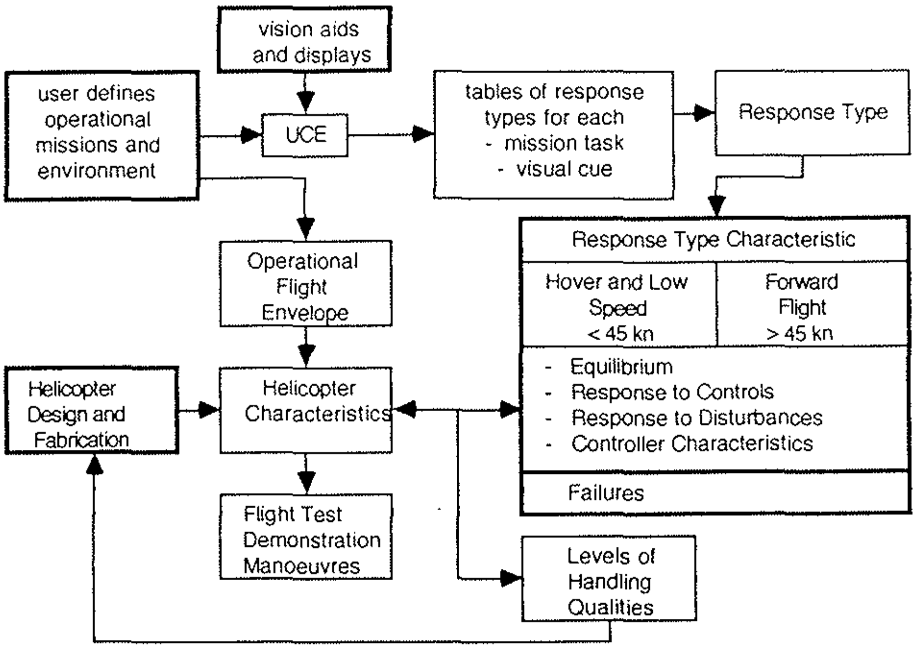


Fig 1 Conceptual Framework for Handling Qualities Specification

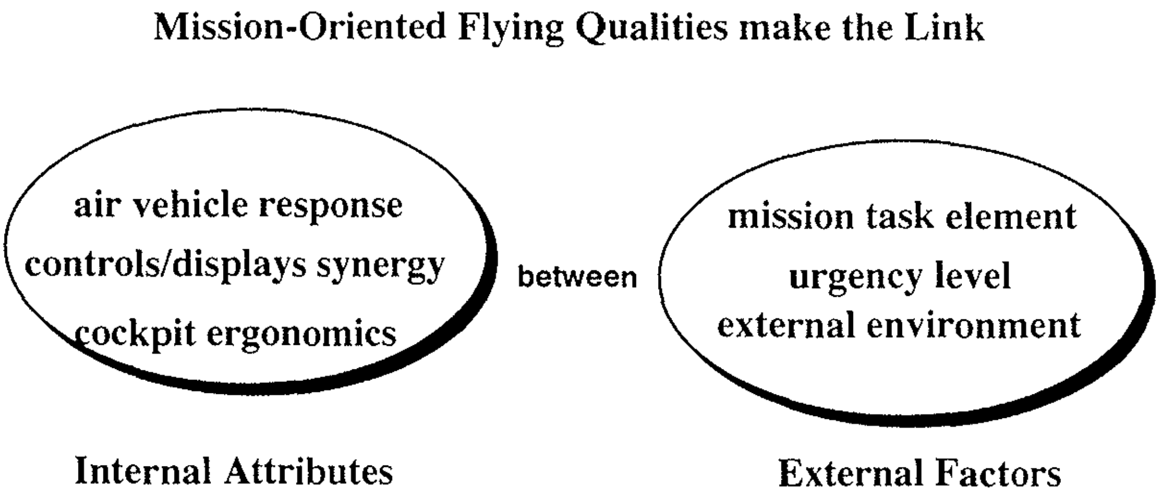


Fig 2 Mission Oriented Flying Qualities

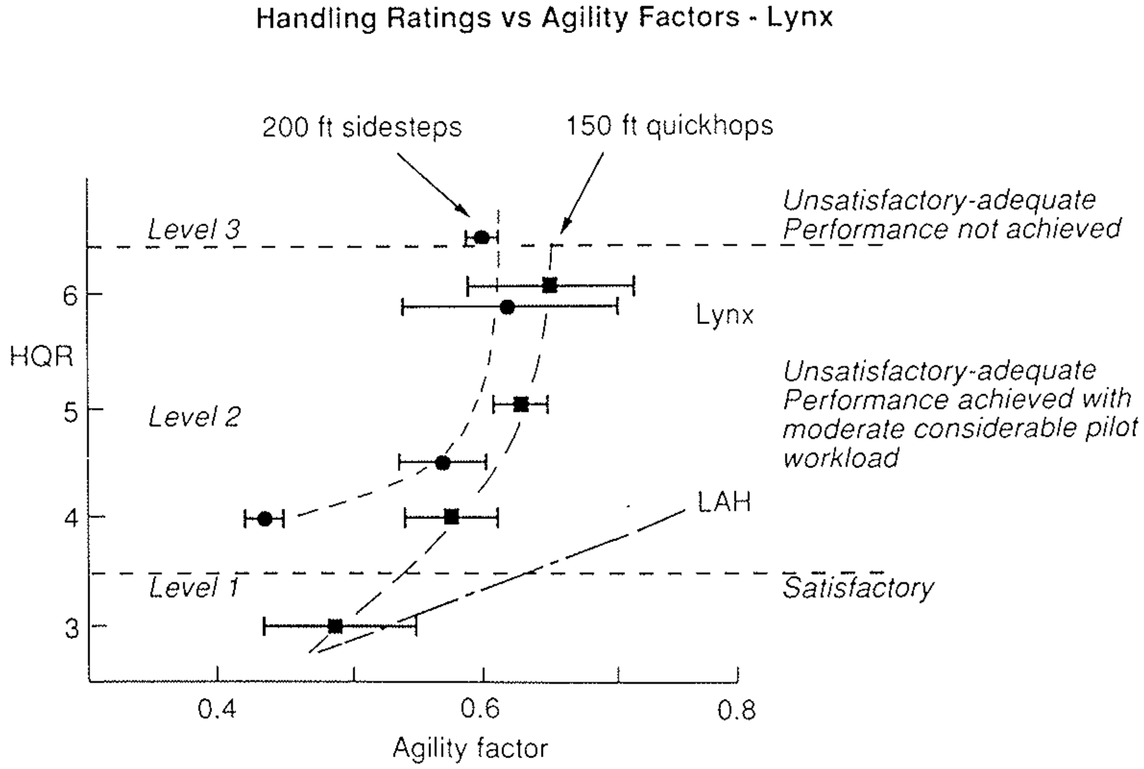


Fig 3 Variation of Handling Qualities with Agility Factor

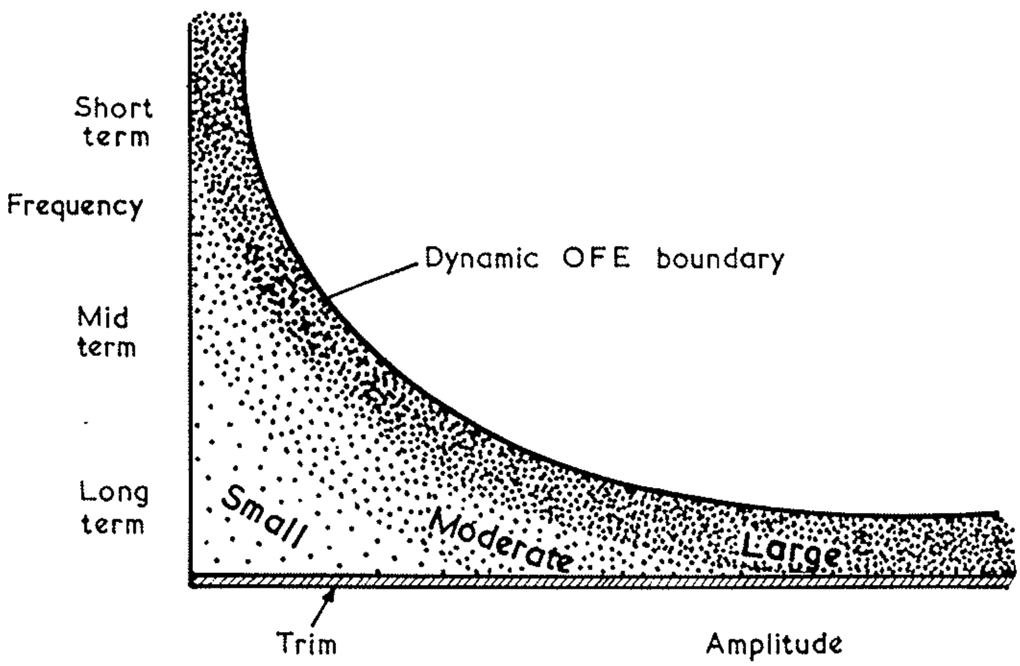
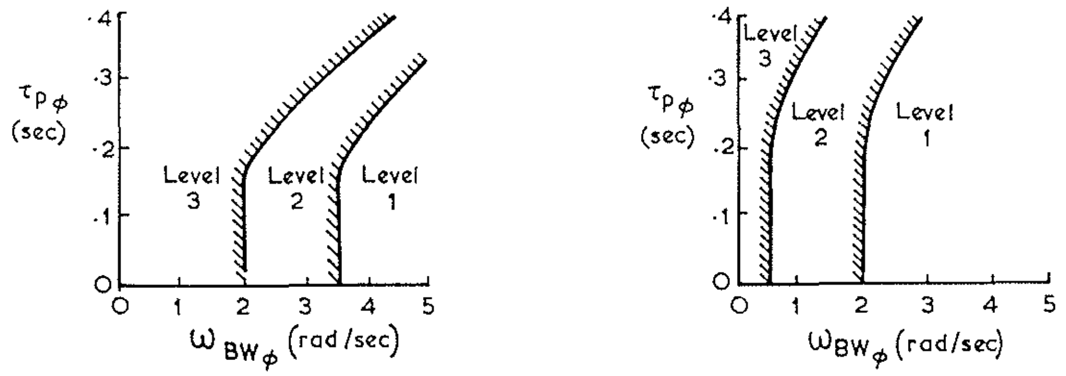


Fig 4 Response Characteristics on the Frequency-Amplitude Plane



a) Target Aquisition and Tracking (roll)

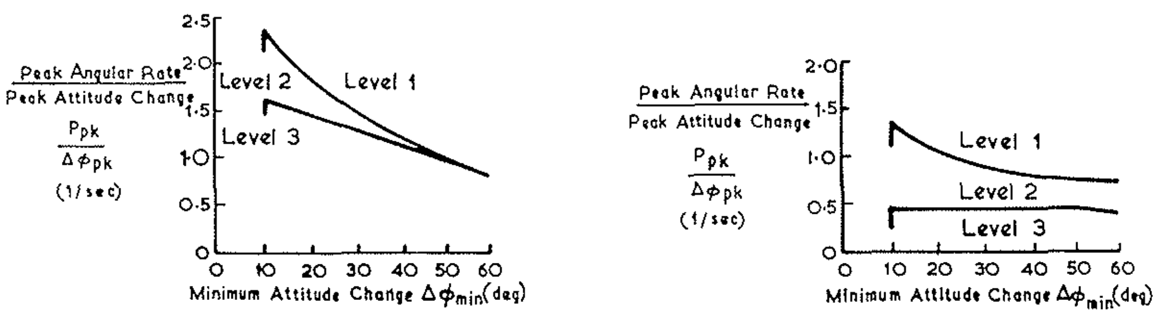
b) All Other MTEs-UCE=1 & Fully Attended Operations (roll)

Requirement for Small Amplitude Roll Attitude Changes

Minimum Achievable Roll Rate (deg/s)	
Level 1	Level 2 & 3
Limited Manoeuvres ± 21	±15
Modest Manoeuvres ± 50	± 21
Aggressive Manoeuvres ±50	±50

Requirement for Large Amplitude Roll Attitude Changes

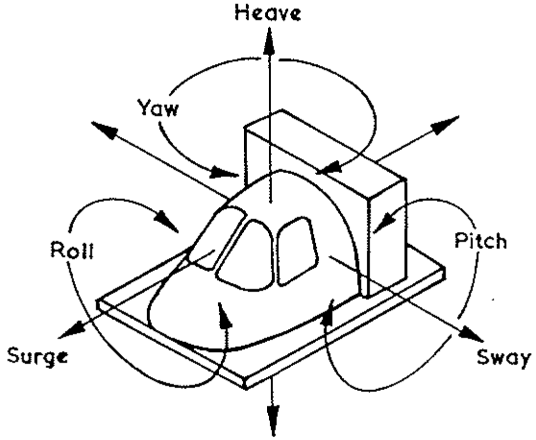
Fig 5 ADS33C Roll Bandwidth and Control Power Requirements



a) Target Acquisition and Tracking (roll)

b) All Other MTEs

Fig 6 ADS33C Roll Quickness Requirements



PERFORMANCE ENVELOPE

Axis	Displacement	Velocity	Acceleration
Pitch	± 0.5 Rad	± 0.5 Rad/s	± 2 Rad/s^2
Roll	0.5 Rad	1.0 Rad/s	3 Rad/s^2
Yaw	0.5 Rad	0.5 Rad/s	1.5 Rad/s^2
Sway (Surge)	4m	2.5 m/s	5m/s^2(0.5g)
Heave	5m	3 m/s	10m/s^2(1.0g)

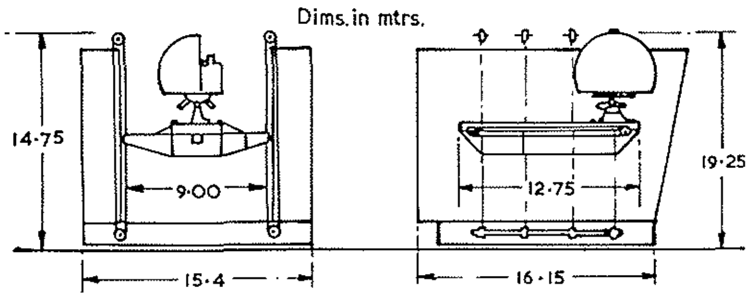


Fig 7 The DRA Large Motion System

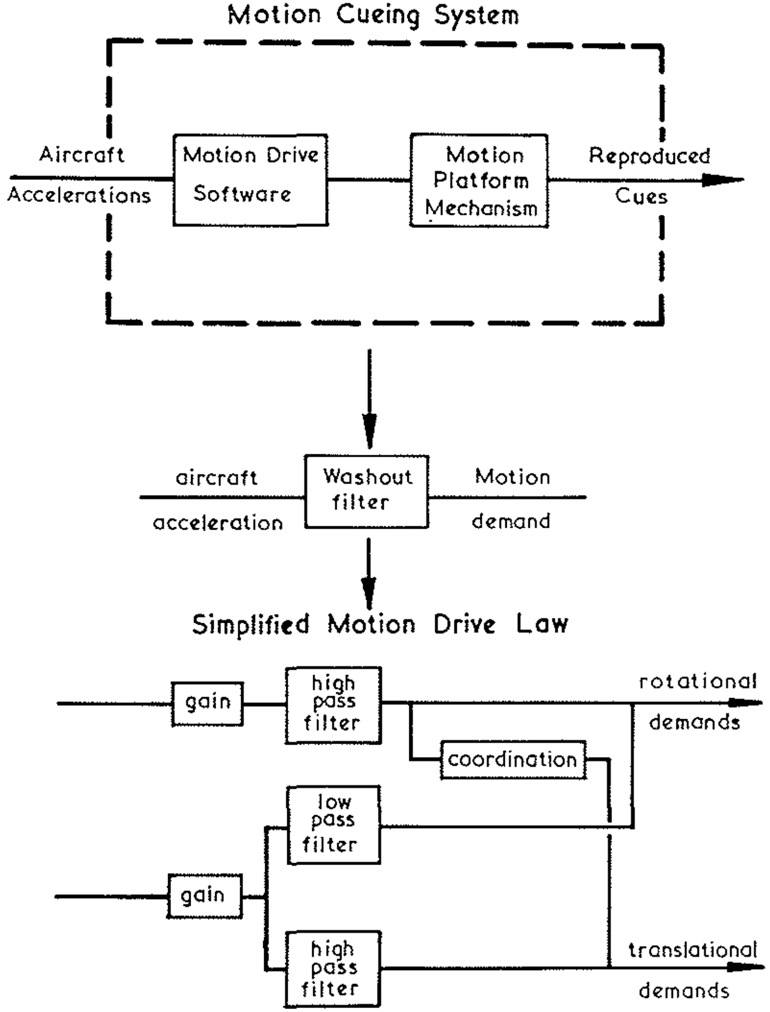


Fig 8 AFS Motion Cueing Schematic

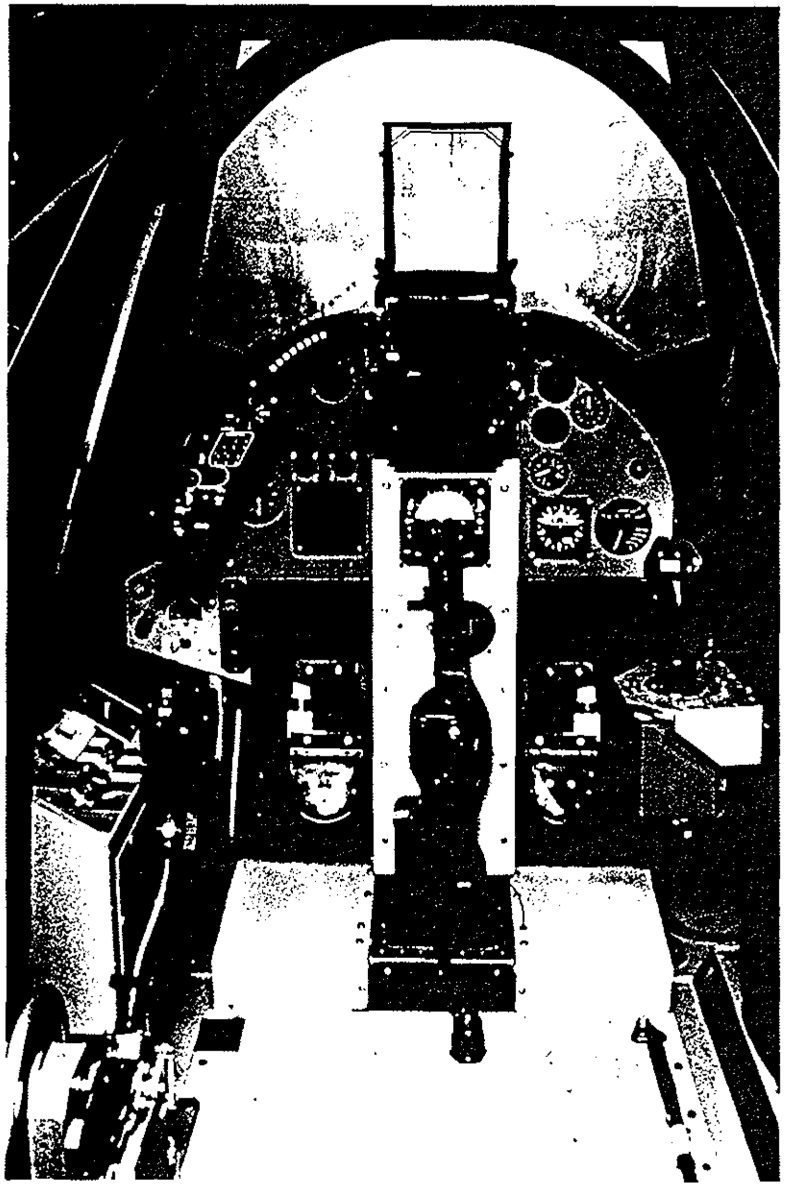


Fig 9 AFS Cockpit Layout

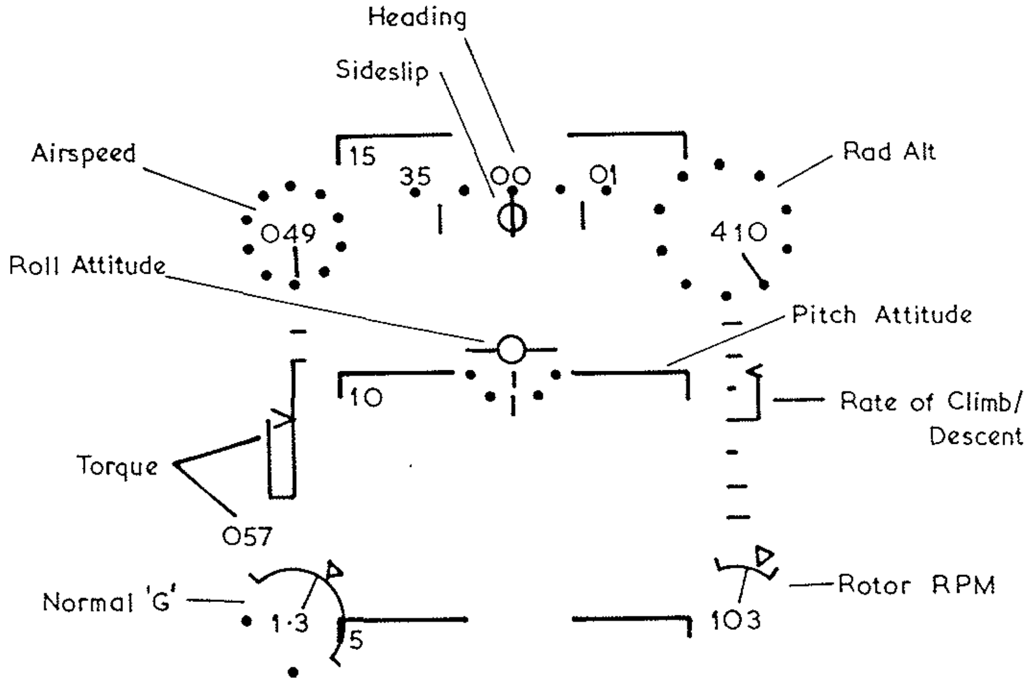


Fig 10 HUD Format

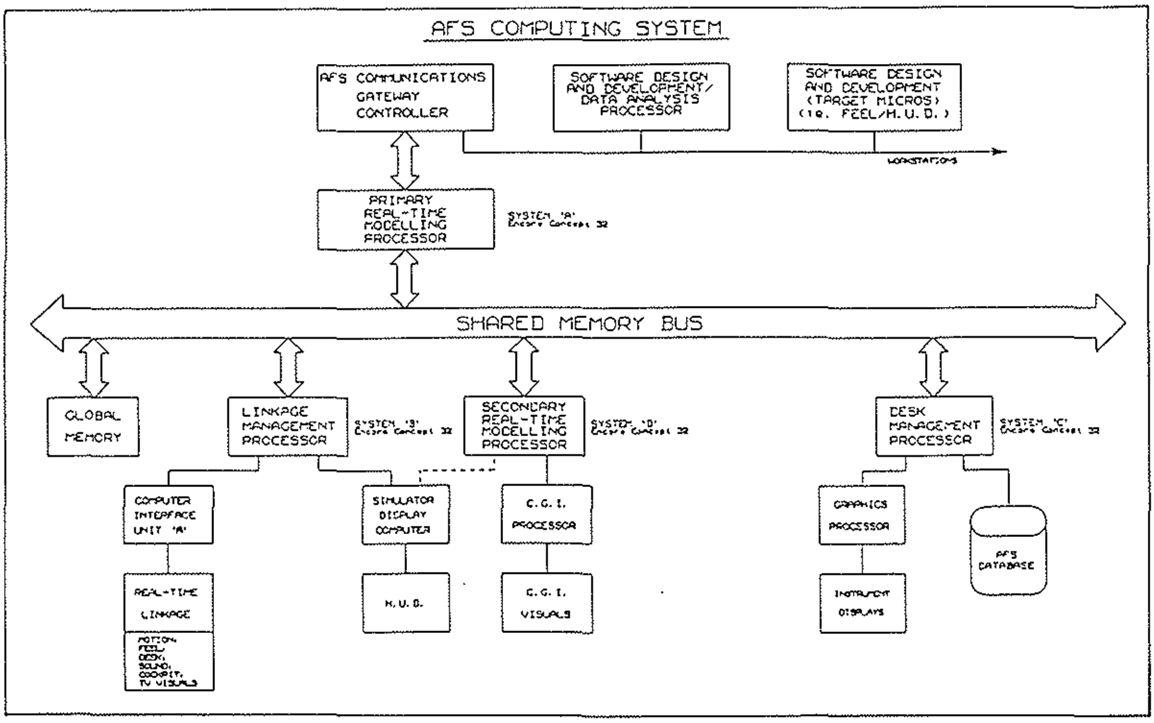


Fig 11 AFS Computing System

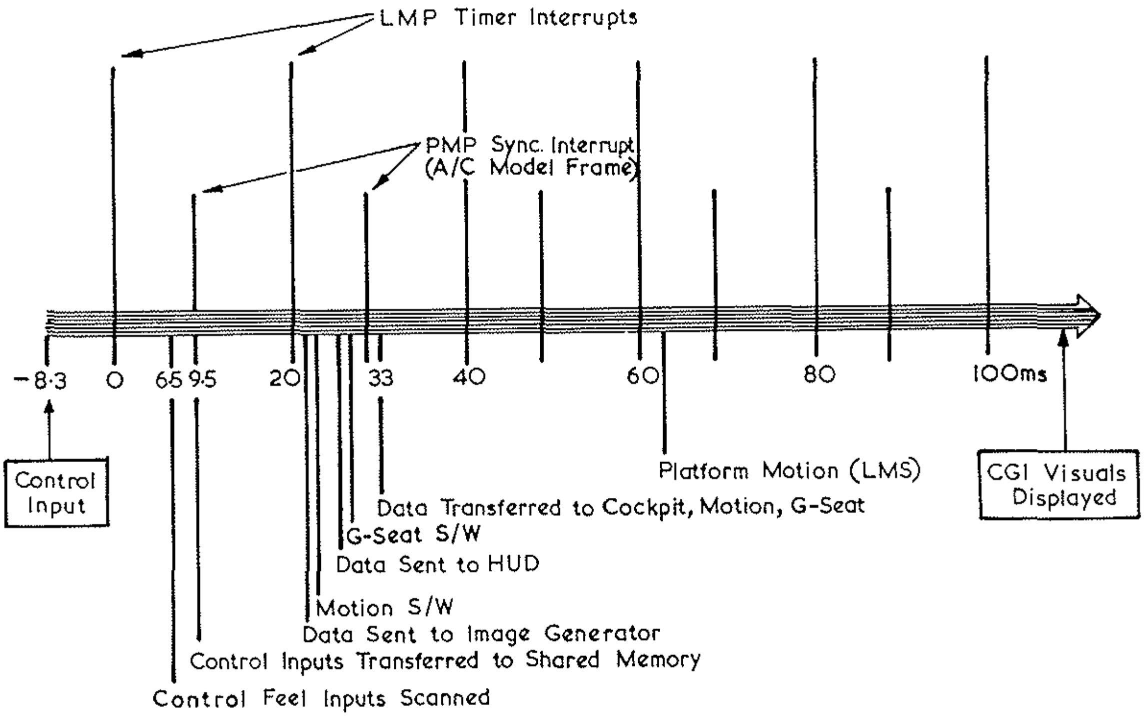


Fig 12 AFS Timing Diagram

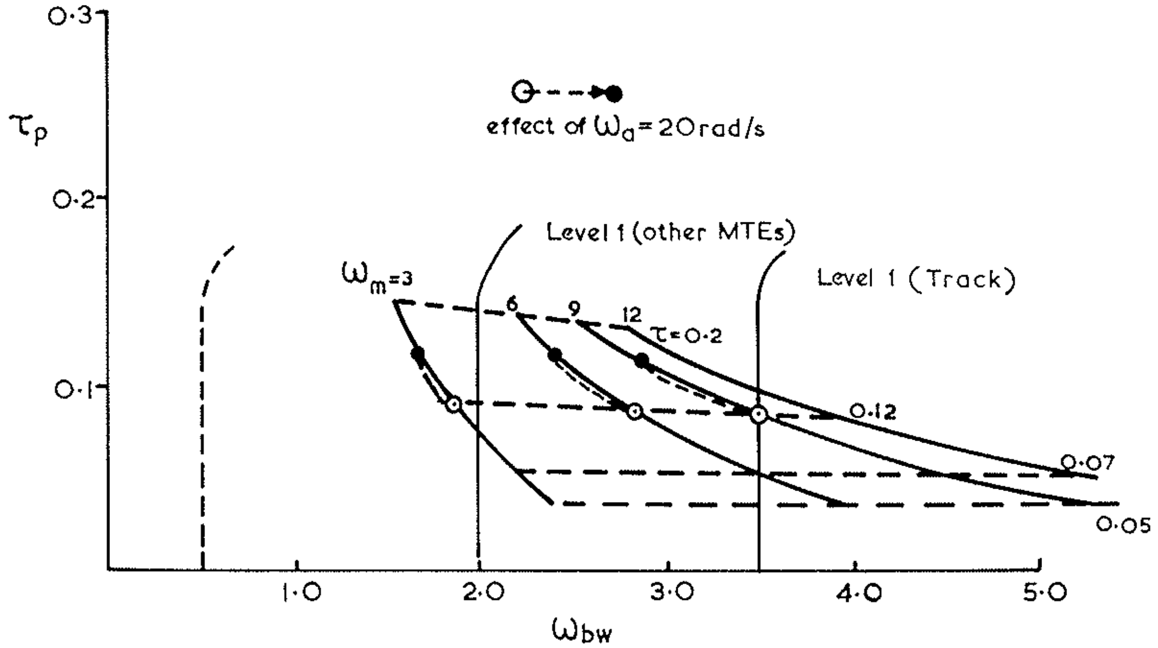


Fig 13 ω_m / τ Configurations Overlayed on ω_{bw}/τ_p Diagram

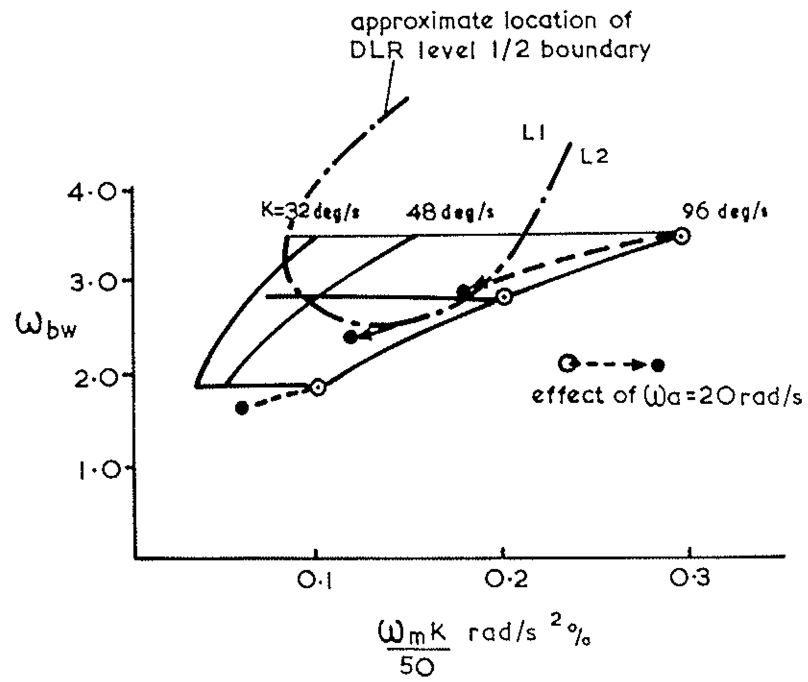


Fig 14 Simulation Configurations on Bandwidth/Sensitivity Diagram

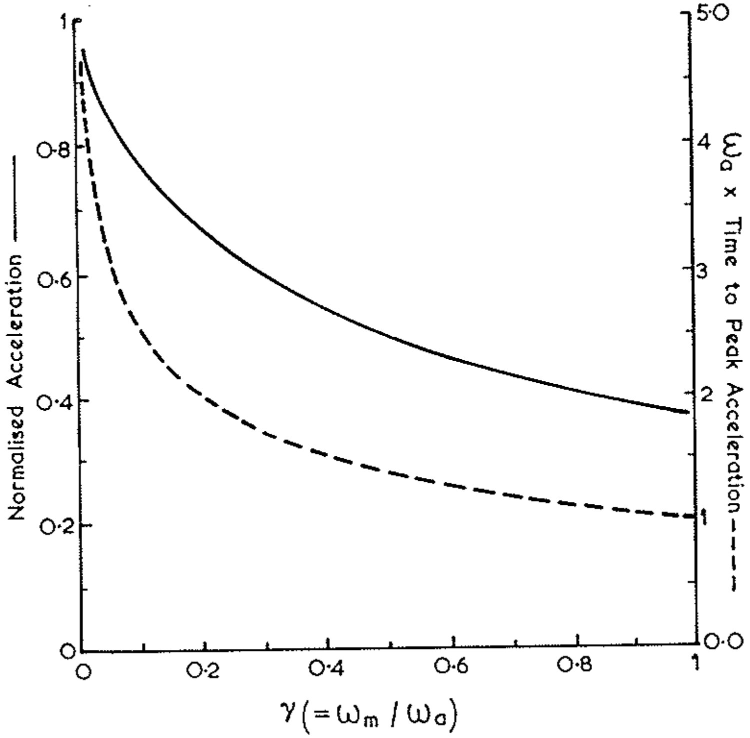


Fig 15 Attenuation of Acceleration Peak and Time Constant by ω_a

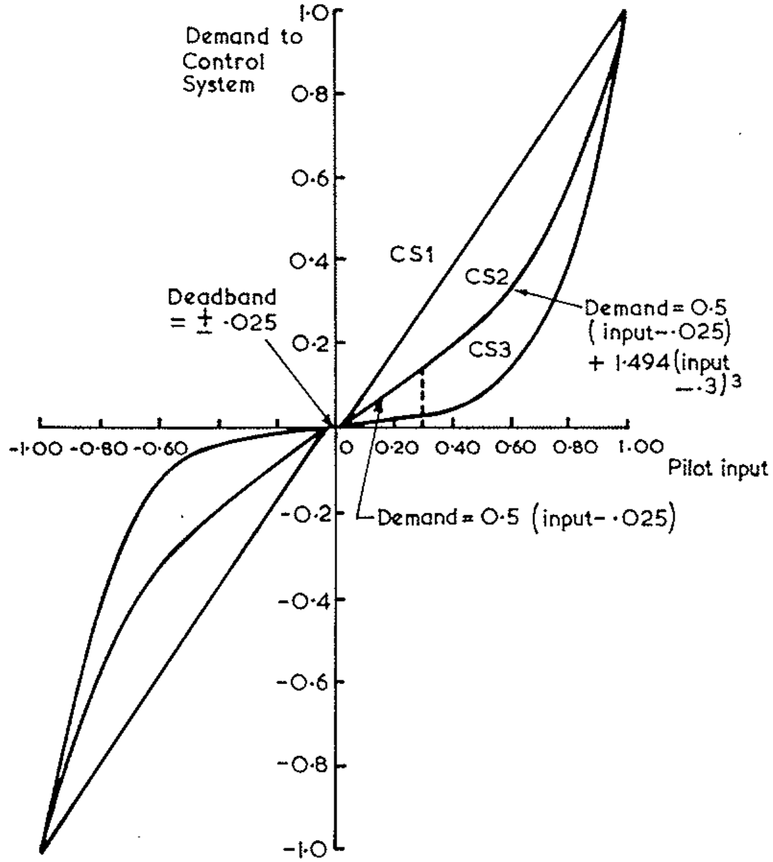
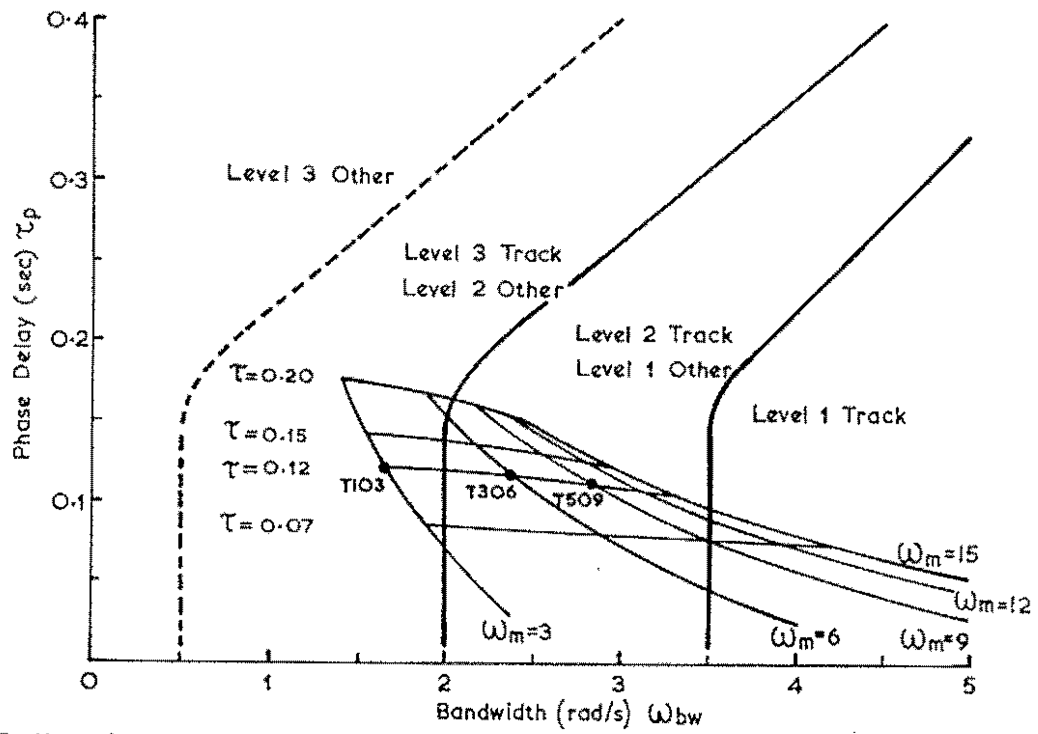
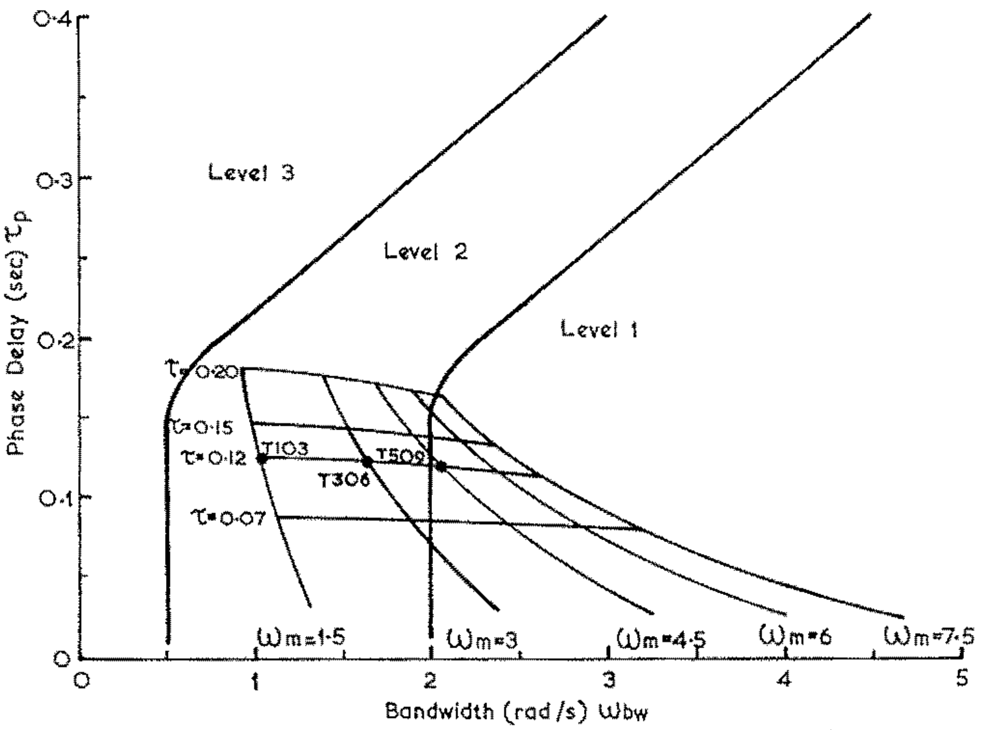


Fig 16 Nonlinear Sidestick Control Input Shaping

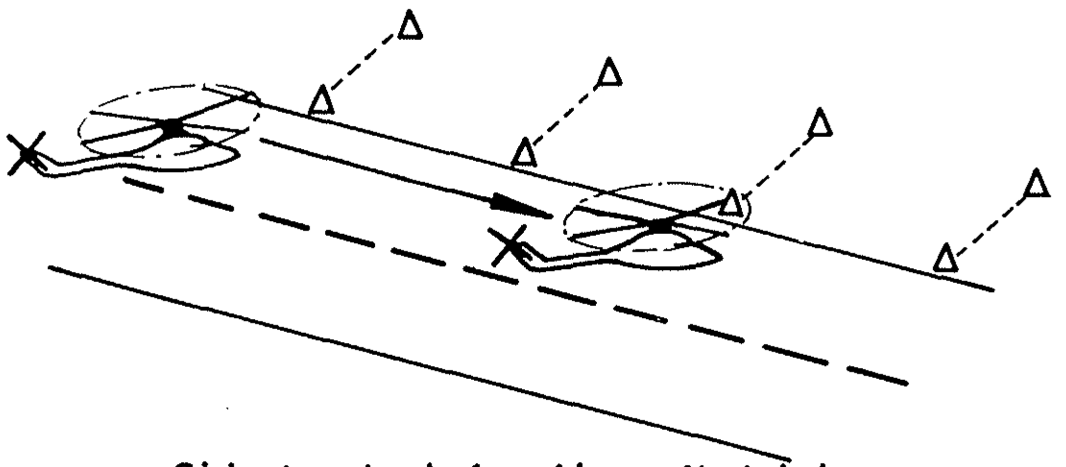


a) **Roll Axis**

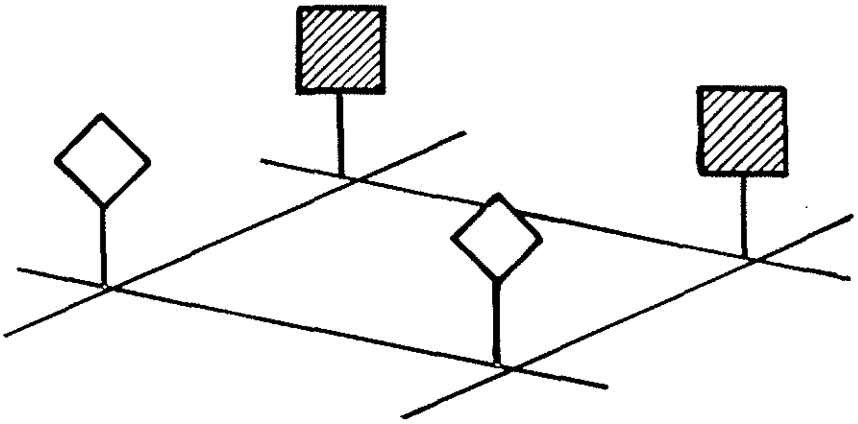


b) **Pitch Axis**

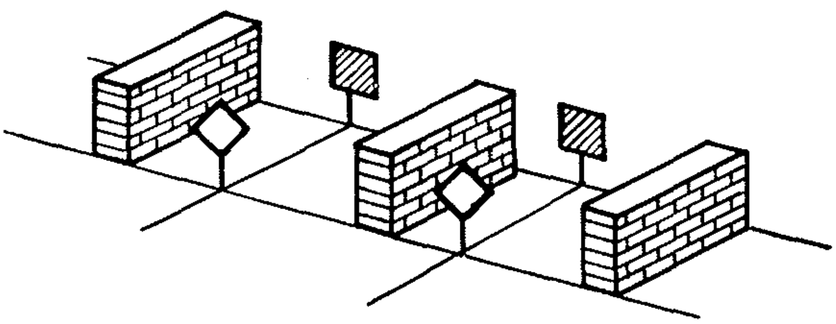
Fig 17 Summary of Bandwidth/Phase Delay Configurations



a. Sidestep task for Aircraft trials



b. Stage 1 Sidestep task for Simulator trials



c. Stage 2 Sidestep task for Simulator trials

Fig 18 Evolution of CGI MTE Development - Sidestep

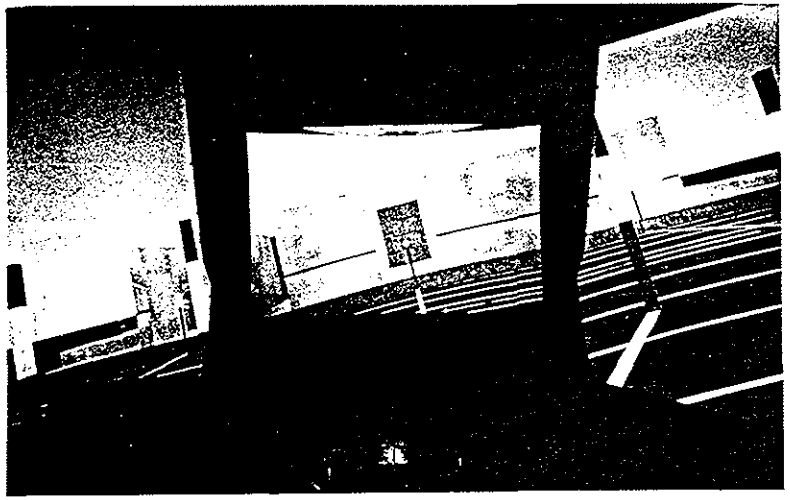


Fig 19 Sidestep

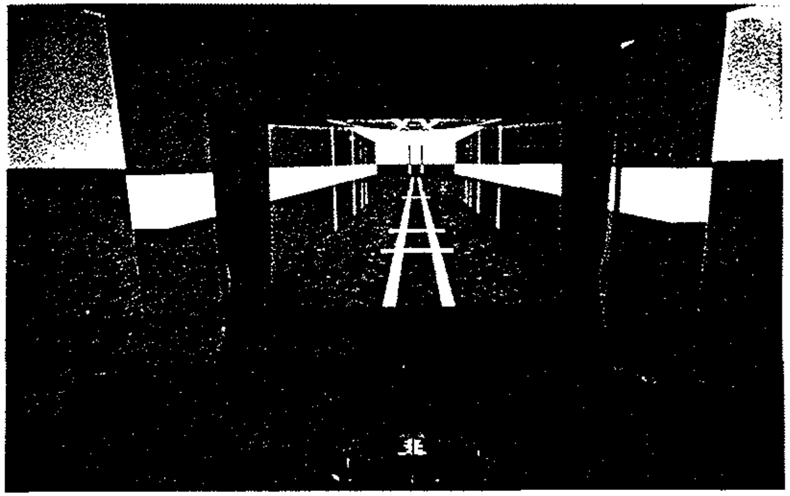


Fig 20 Quickhop

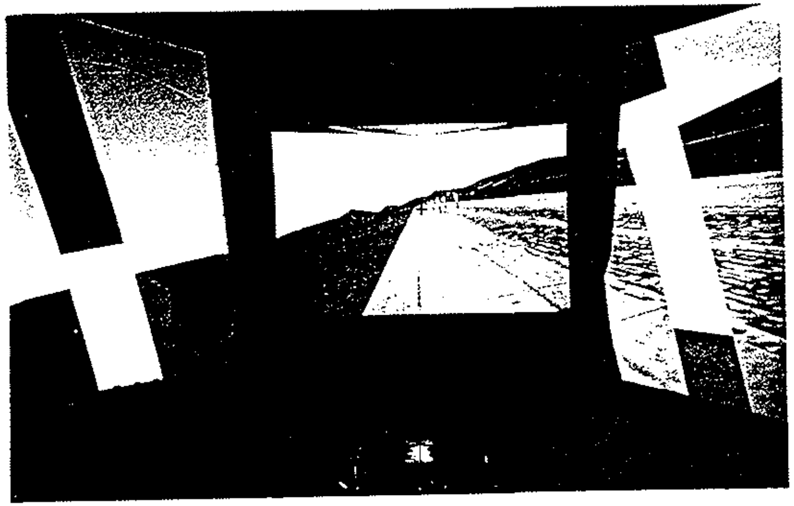


Fig 21 Lateral Jinking

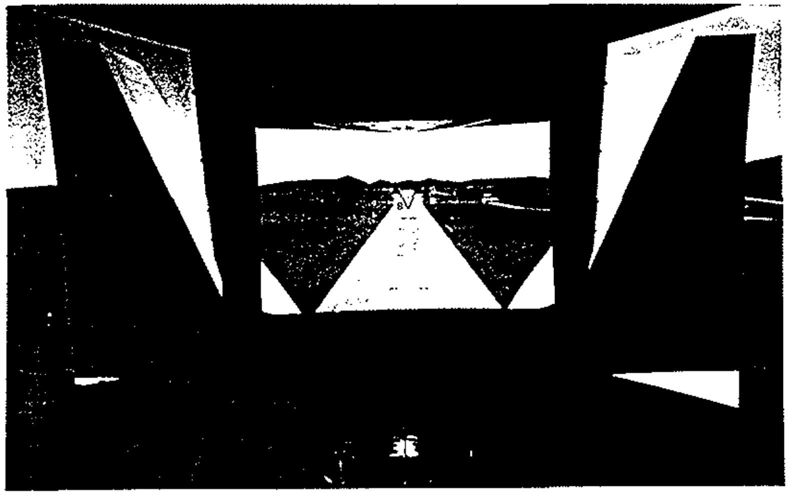


Fig 22 Hurdles

IN-COCKPIT QUESTIONNAIRE: DATE: SORTIE:

PILOT: MTE: CONFIGURATION:

DESIGNED LEVEL OF AGGRESSION:

	INADEQUATE TO COMPLETE THE TASK [1]	POOR [2]	FAIR [3]	GOOD [4]	VERY GOOD [5]
A. TASK CUES:					

Comments: FOV/SCENE CONTENT/MOTION/DISPLAYS

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
B. PERCEIVED LEVEL OF AGGRESSION:					

Comments: % OF HELICOPTER PERFORMANCE

	ADEQUATE PERF UNACHIEVABLE	ADEQUATE PERF ACHIEVED WITH DIFFICULTY	DESIRED PERF ACHIEVED WITH DIFFICULTY	DESIRED PERF ACHIEVED SATISFACTORILY	DESIRED PERF ACHIEVED EASILY
C. TASK PERFORMANCE:					

Comments: TIME/PRECISION/TASK TOLERANCES

	NOT A FACTOR	MINIMAL	MODERATE	CONSIDERABLE	EXTENSIVE
D. TASK WORKLOAD:					

Comments: SPARE CAPACITY/CONTROL ACTIVITY

E. HANDLING QUALITIES RATING:

F. INFLUENCING FACTORS:	[1] -VE	[2] O	[3] +VE
PRIMARY RESPONSE			
COUPLING			
CONTROL HARMONY			
INCEPTOR			
VEHICLE LIMITS			
STABILITY			
MOTION			
OTHERS >			

Fig 23 In-Cockpit Pilot Questionnaire

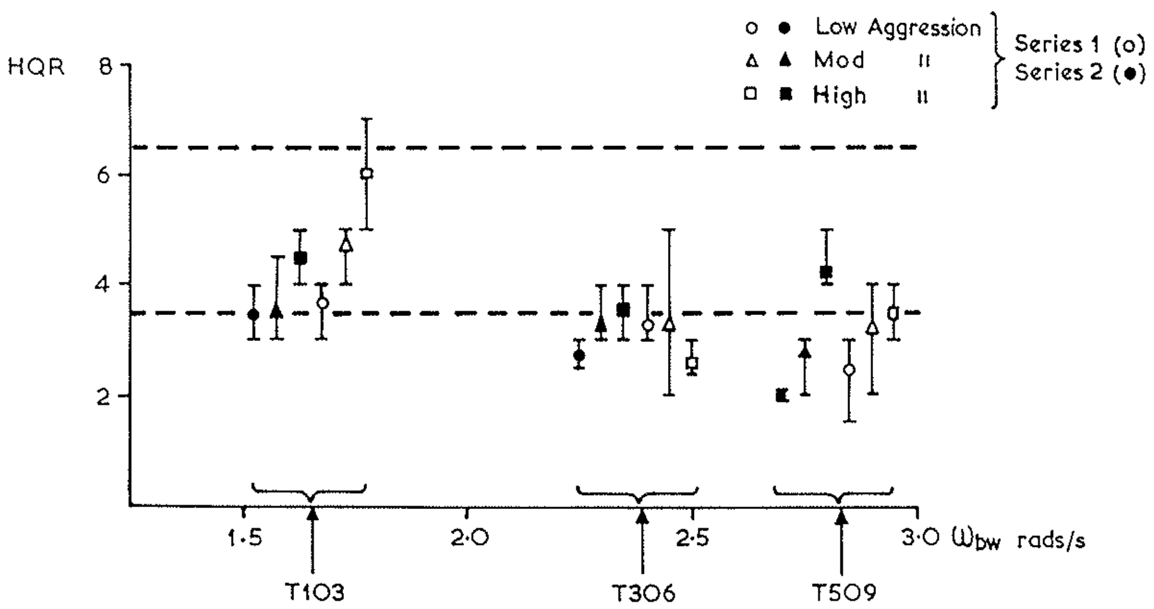
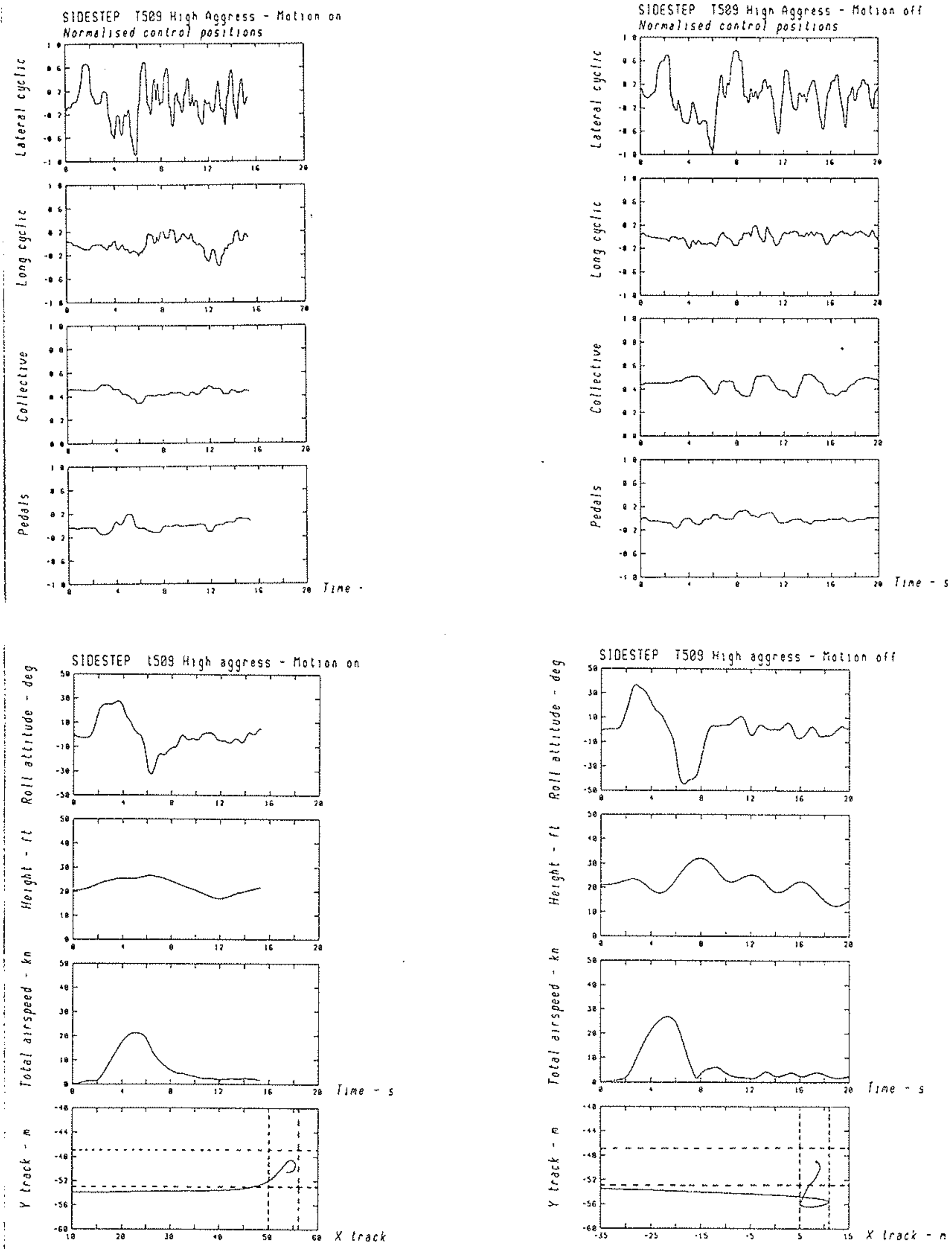
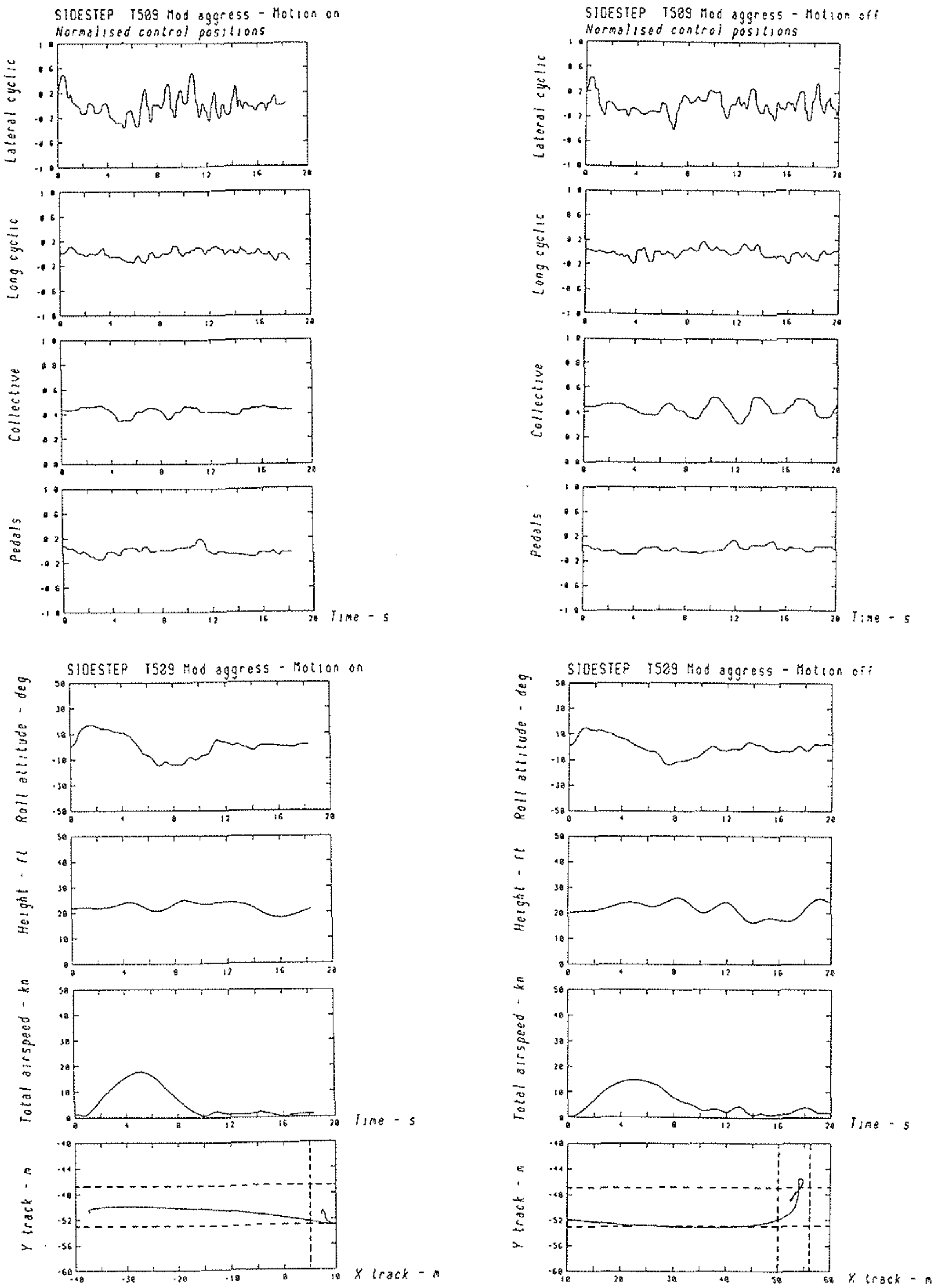


Fig 24 Sidestep HQRs vs Configurations



Motion On **Motion Off**

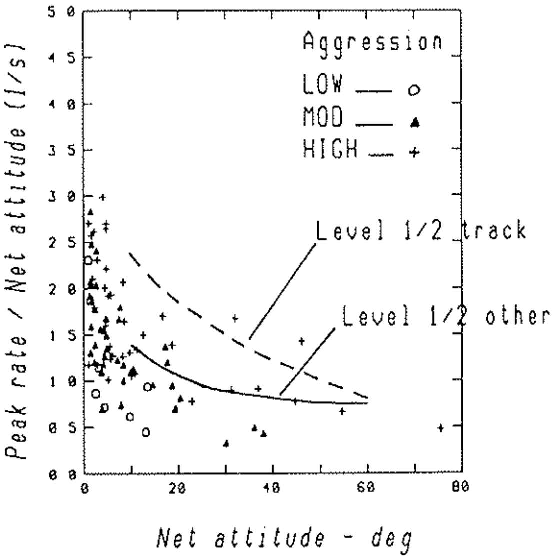
Fig 25 Sidestep Time Histories With and Without Motion
a) configuration T509 - high aggressiveness



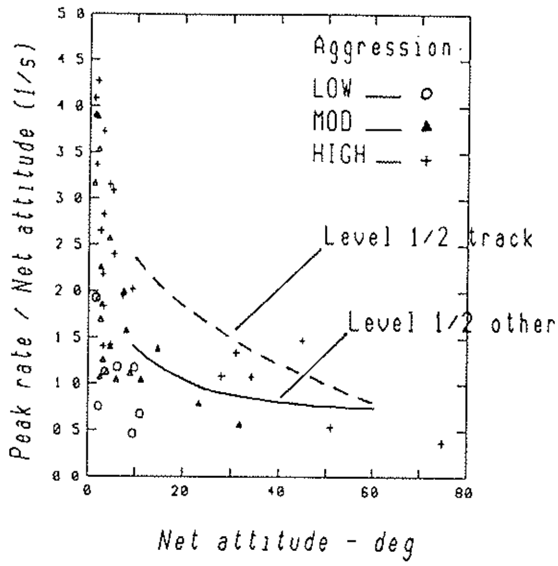
Motion On

Motion Off

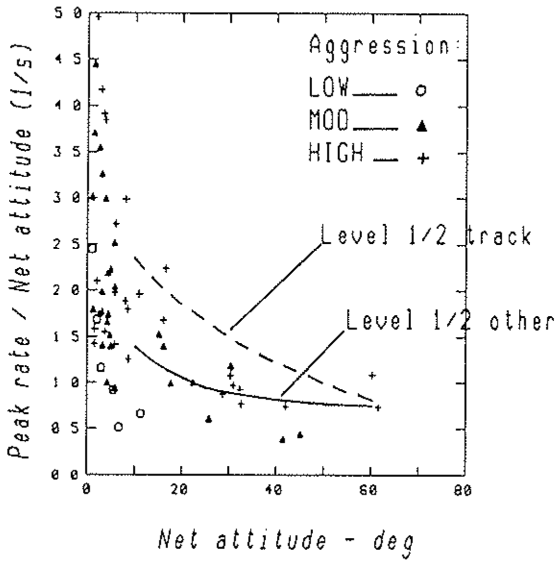
Fig 25 Sidestep Time Histories With and Without Motion
b) configuration T509 - moderate aggressiveness



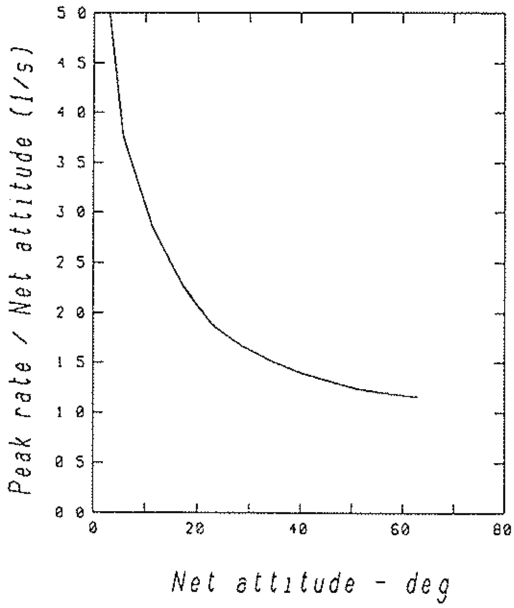
Configuration T103



Configuration T306



Configuration T509



Lynx Flight Data (45m Sidesteps)

Fig 26 Sidestep Quickness Parameters; low - high aggressiveness

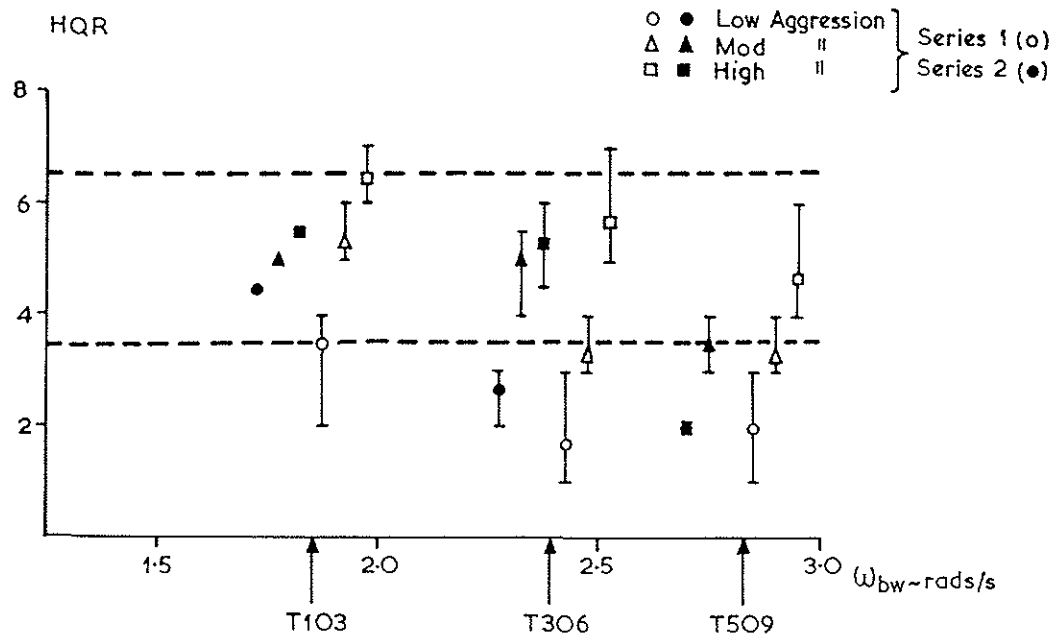


Fig 27 HQRs for Lateral Jinking

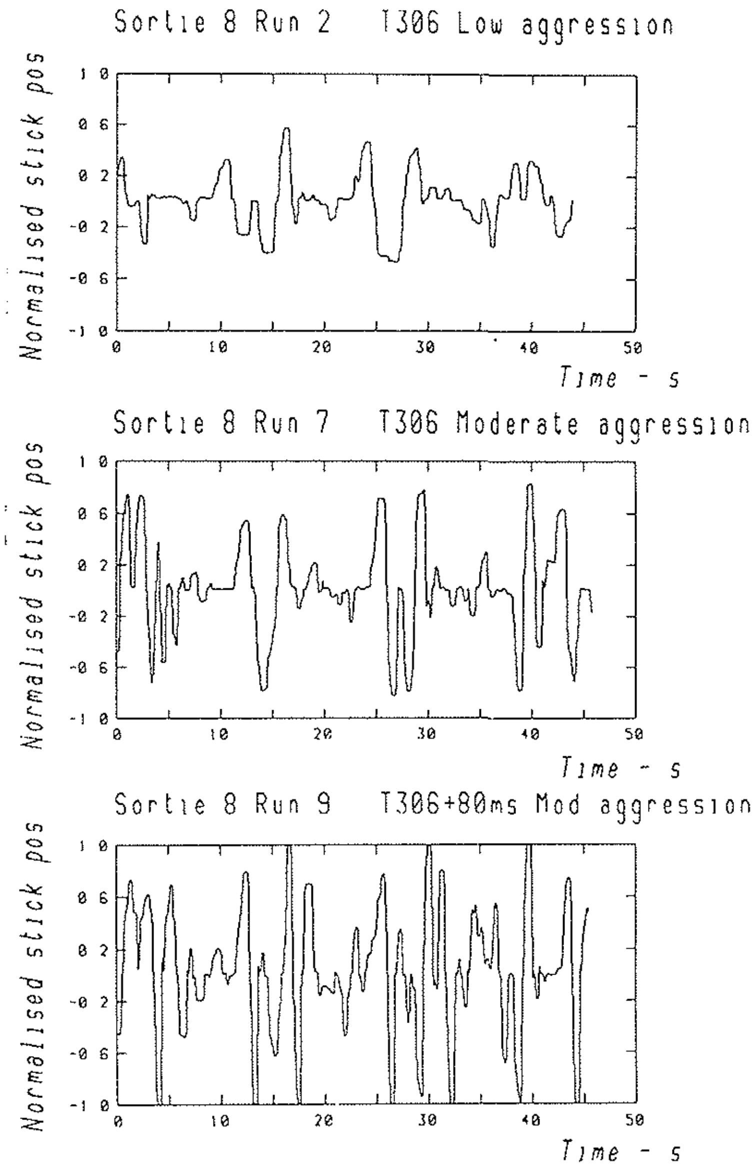
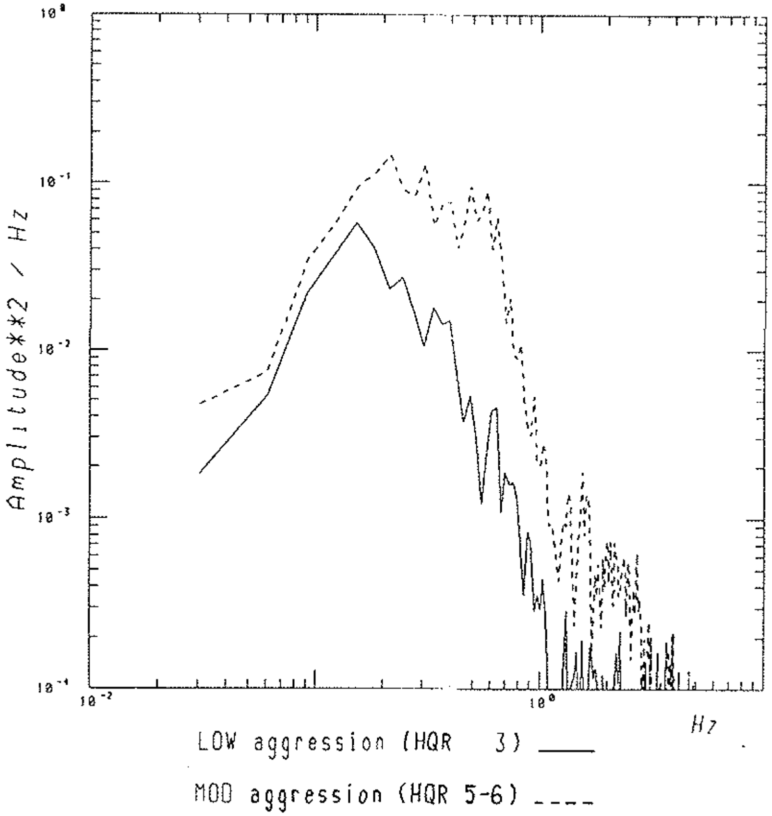
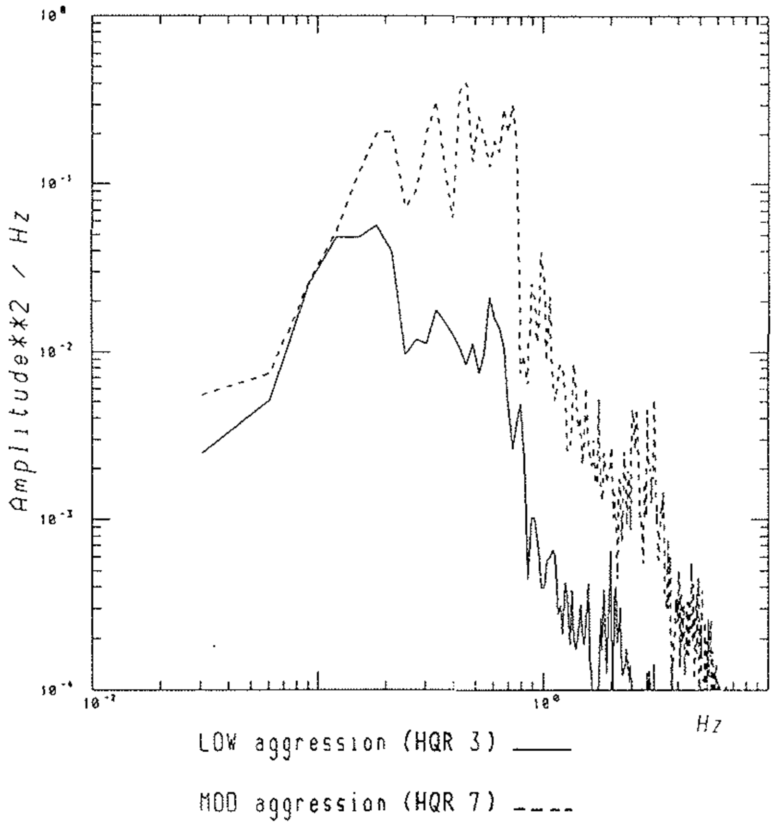


Fig 28 Control Activity for Lateral Jinking with Configuration T306



a) configuration T306



b) configuration T306 + τ = 80ms

Fig 29 Power Spectra of Lateral Cyclic

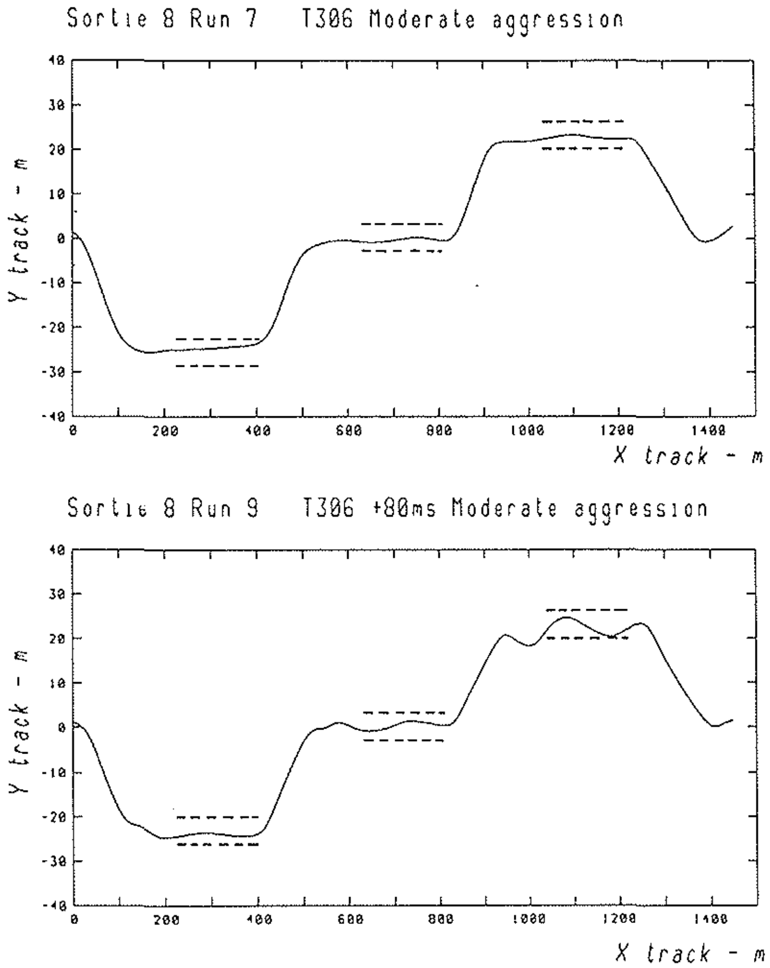


Fig 30 Ground Track for Lateral Jinking MTE Showing PIO Tendency

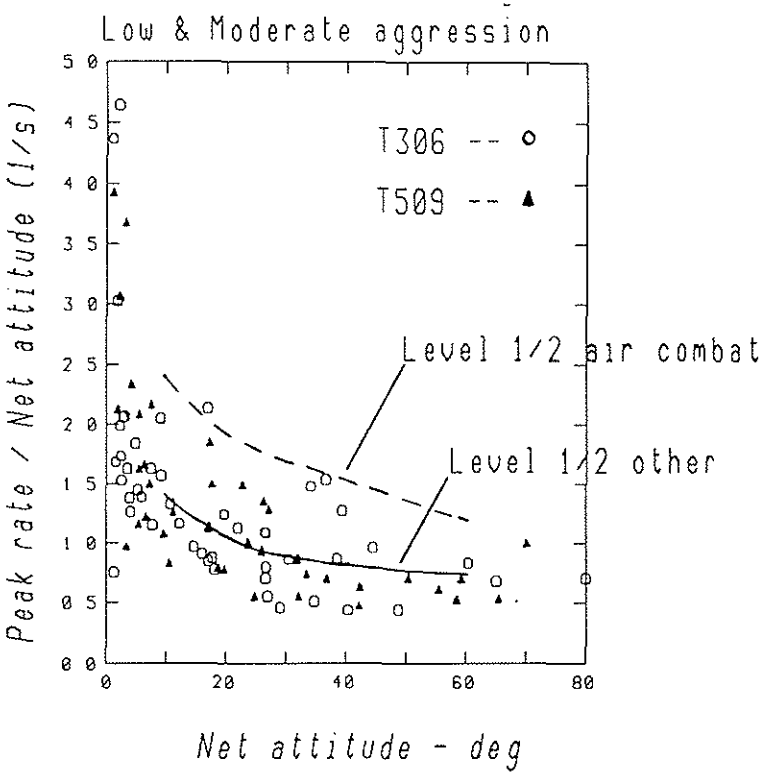


Fig 31 Lateral Jinking Quickness

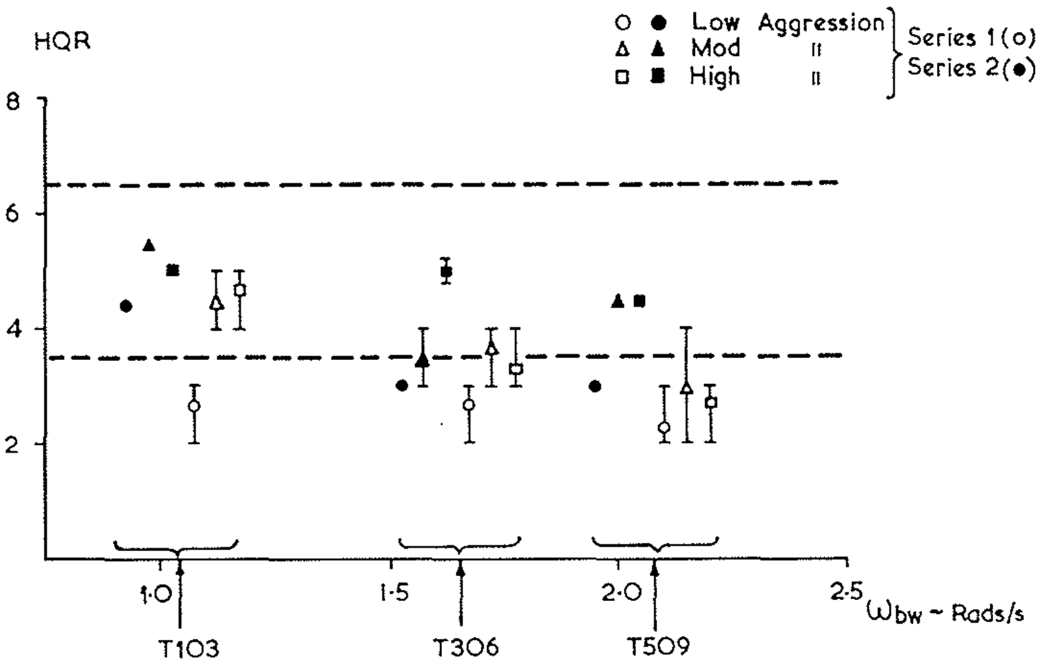


Fig 32 Quickhop HQRs

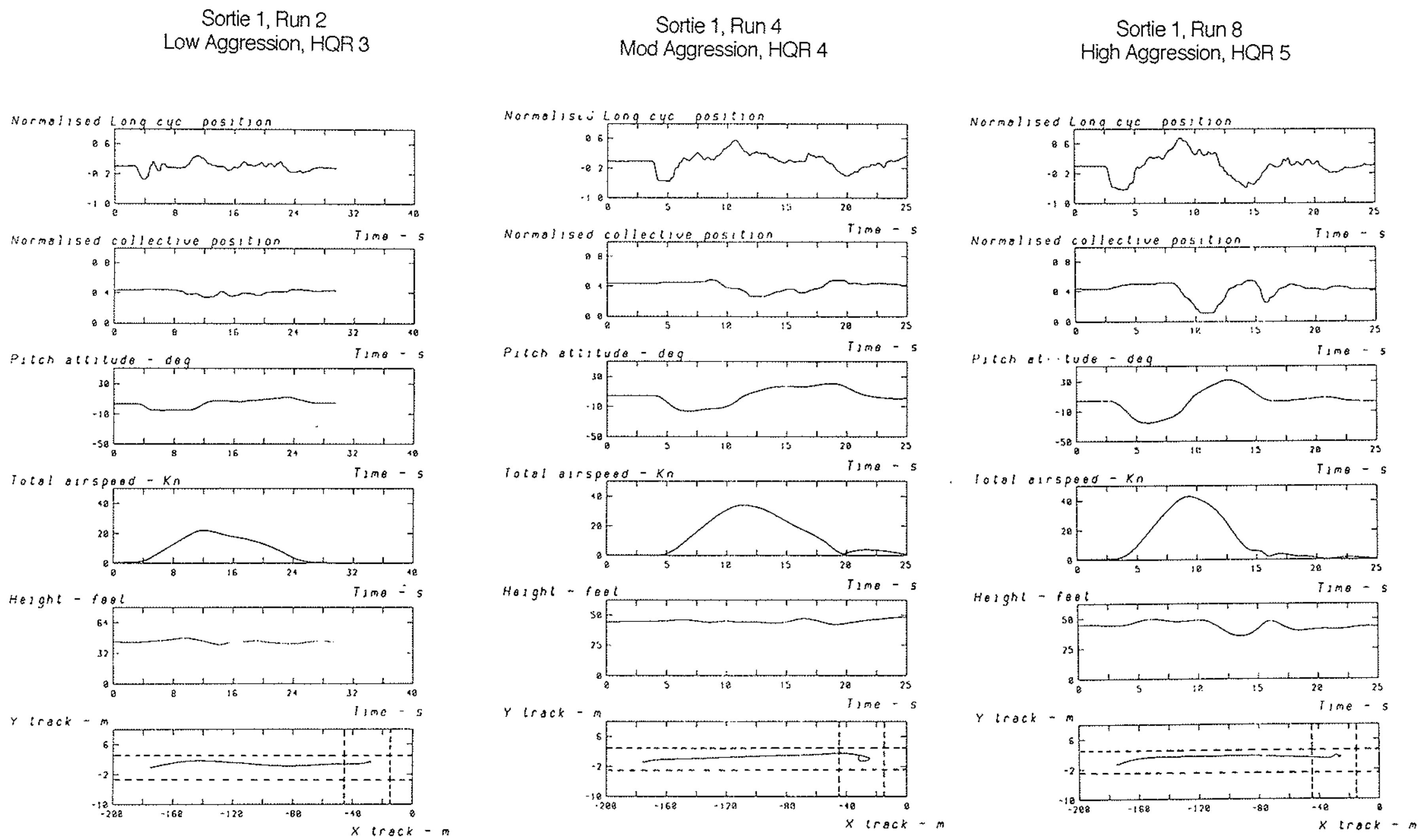


Fig 33 Time History Variations in Quickhop MTE

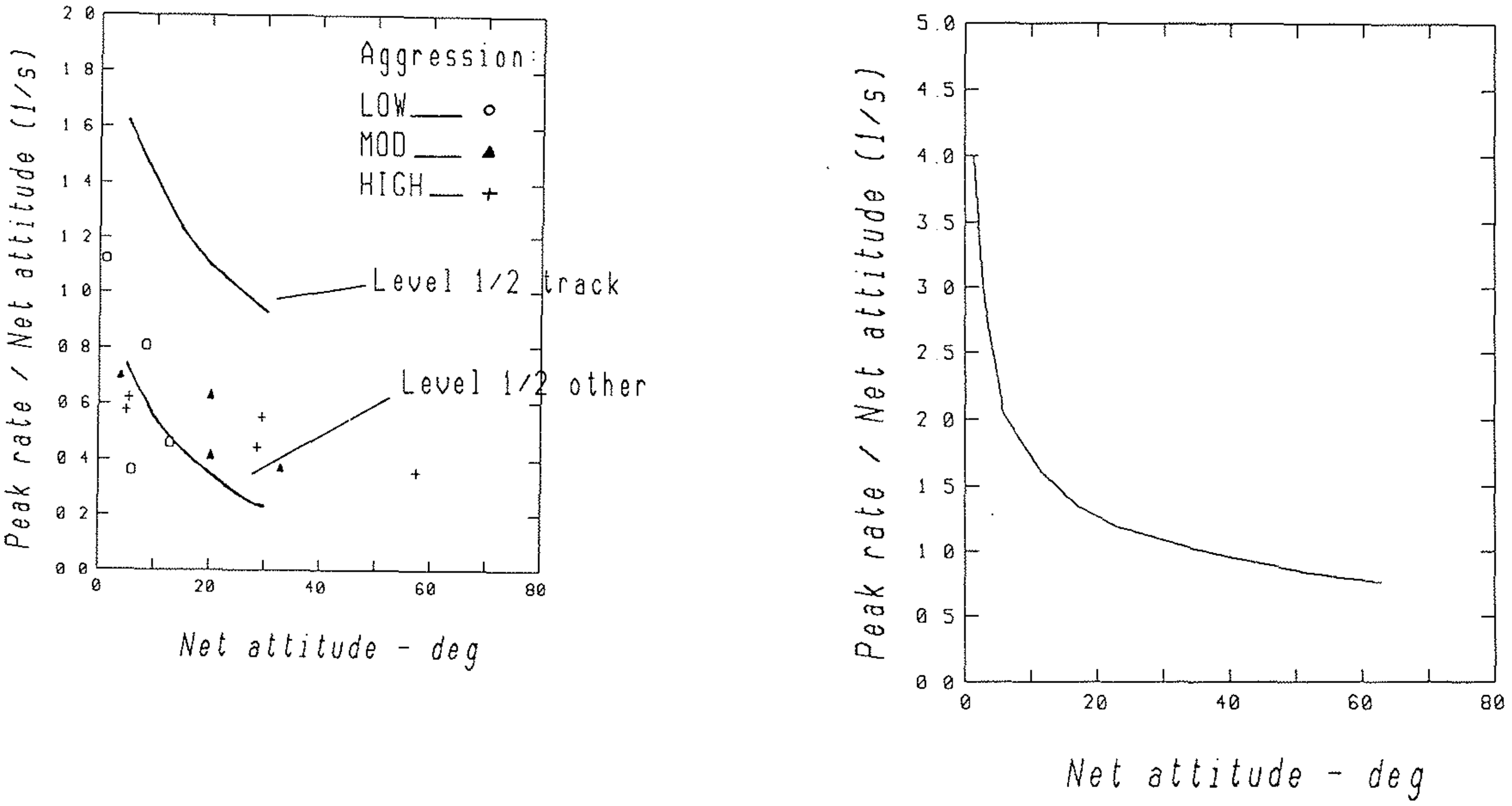


Fig 34 Quickhop Quickness