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SIMULATOR EVALUATIONS OF INCEPTORS FOR ACT HELICOPTERS

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ABSTRACT

Two 3-axis inceptors have been used in ground simulation trials at RAE Bedford during which approximately seventy hours of trials were flown by four primary evaluation pilots. Both inceptors were used as 2-axis as well as 3-axis controllers and systematic evaluations of inceptor forces and control signal shaping were performed. Objective measurements of performance and workload were taken and the pilots were asked to rate various aspects of their task performance as well as rating the system in use.

Statistical analysis of these results has shown the benefits of control signal shaping and that the 2-axis configuration has performance advantages but no subjective preference compared with the 3-axis configuration. Guidance towards preferred feel forces has also been gained. The trials procedure has proved successful in producing results in which a high degree of confidence can be placed.

ABBREVIATIONS

ACT - Active Control Technology
WHL - Westland Helicopters Limited
RAE - Royal Aircraft Establishment
PIO - Pilot Induced Oscillation
C1 - Linear control shaping
C2 - Moderately non-linear control shaping
C3 - Severely non-linear control shaping

1. INTRODUCTION

The intended application of Active Control Technology (ACT) to helicopters, and the consequent change from mechanical control runs to electrical or optical systems, necessitates a revision of the primary flight controllers (inceptors) used. In addition much greater freedom of inceptor design and a wide range of possible configurations has emerged. It is important at this early stage of ACT development to progress towards selection of the preferred types and configurations for the first generation of ACT equipped helicopters.

WHL has been studying the application of ACT to helicopters for some years (Reference 1). Early studies highlighted the need for inceptors substantially different from those fitted to current helicopters, and consequently a programme of work has been undertaken funded by the Royal Aircraft Establishment (RAE), to address various aspects of the pilot/control system interface.

The overall aims of the programme were to aid the development of inceptors for the first ACT helicopters, and to gain sufficient experience to allow specifications for future inceptors to be written with some confidence.

The programme culminated in a series of simulation trials at RAE Bedford which had the specific objectives of examining the effects of inceptor configuration, force feel and control signal shaping on task performance and pilot opinion.

This paper discusses the inceptors obtained for evaluation, the simulation trials undertaken at RAE Bedford in which they were used and the results which were forthcoming.

2. INCEPTORS OBTAINED FOR EVALUATION

2.1 The Requirement

In the past a large amount of work has been undertaken assessing 4-axis side-arm controllers (references 2, 3 and 4) the philosophy being that putting all the control onto one hand will free the other hand to perform other tasks. Findings appear to suggest that small displacement controllers are preferred over rigid or large displacement types and that, whilst pilots can adjust to multi-axis inceptors, the less integrated control configurations are preferred. Rigid or negligible displacement inceptors are not favoured due to poor tactile feedback causing significant cross coupling of control inputs. Small displacement side-arm controllers have the benefits of reducing cross coupling compared with rigid types, whilst still requiring only small hand/wrist movements to control the helicopter and allowing easy provision of armrests and adjustment of seat and inceptor position to suit individual pilots.

Inceptor configurations giving the best performance as suggested by references 2 and 3 were:

(a) 3-axis right hand inceptor for pitch, roll and yaw control plus a left hand collective, and
(b) 2-axis right hand inceptor for pitch and roll control plus a left hand collective plus pedals.

At WHL there were severe doubts about the applicability of 4-axis inceptors for a two crew, high agility helicopter and no evidence was available to suggest that there were any improvements in performance compared with less integrated controllers. In particular, inclusion of the collective control on the right hand inceptor led to degraded performance. Consequently it was decided to concentrate these studies on small displacement three axis inceptors for controlling pitch, roll and yaw, which could be used in 2-axis and 3-axis configurations.

The type of control system fitted to the aircraft is very important when choosing suitable inceptors. It is currently envisaged that the first applications of an ACT system to WHL helicopters will utilise body rate control systems (reference 1) with the following modes:

- pitch rate demand/attitude hold
- roll rate demand/attitude hold with turn coordination
- yaw rate demand/attitude hold at speeds below 40 knots
- sideslip/lateral acceleration demand/suppression at speeds above 40 knots
- conventional collective.

The inceptors used therefore needed to be self centring to allow 'hands-off' trimmed flight. As already stated one of the aims of this programme was to investigate the effects of force feel on inceptor performance and pilot opinion. It was therefore, decided that the inceptors obtained should have readily adjustable force/displacement gradients. It was not apparent that any work had been done to optimise inceptor force gradients, although some indications as to acceptable forces were available. (Reference 3).

2.2 The Inceptors

Two inceptors were obtained for evaluation built to a WHL requirement specification. One was manufactured by Dowty Electrics Ltd the other by Page Engineering Company Ltd. The inceptors are shown in Figures 1 and 2 and described in Table 1.
The use of two inceptors allowed three different methods of yaw control to be examined: twist grip, thumb operated toggle and pedals. In addition comparisons of two types of sensor could be made and any results obtained which were consistent for both types were less likely to be due to particular features of one inceptor.

3. CONTROL SIGNAL SHAPING

Control signal shaping is achieved within the control system software and causes the demands fed into the control system to vary non-linearly with control displacement or force. It has been used in the past to improve the characteristics of side-arm controllers (references 2 and 4) but little experimentation has been done to determine the requirements for such shaping.

One of the principal aims of the simulator trials was to investigate control signal shaping, to establish what form this should take and whether significant improvements in performance could result from the use of non-linear shaping.

A shaping function was therefore defined to allow control signal shaping to be easily varied around a basic shaping concept. This concept was based on the following:

- o There should be a deadspace region to aid the pilot to make a zero input in a particular axis, and to allow for small changes in the inceptor null output.

- o The initial sensitivity should be low to help the pilot to make small adjustments in attitude or heading.

- o Sensitivity should be constant during gentle manoeuvring.

- o The command gradients for larger control movements should be greater to allow more severe manoeuvring without excessive control activity and force.

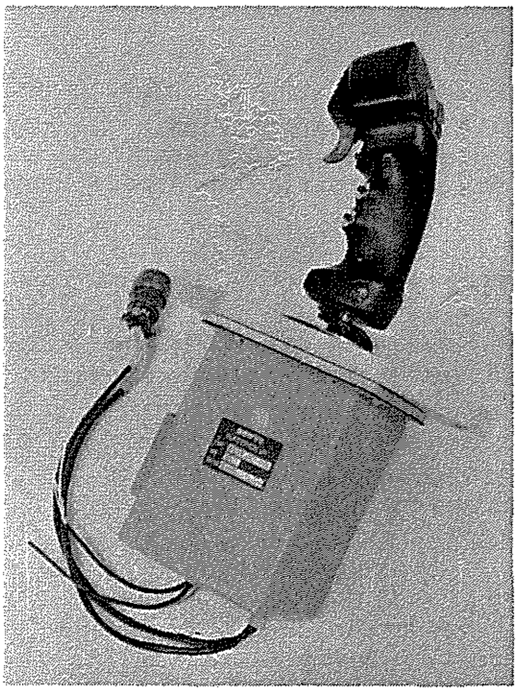

Figure 1 The DOWTY Inceptor

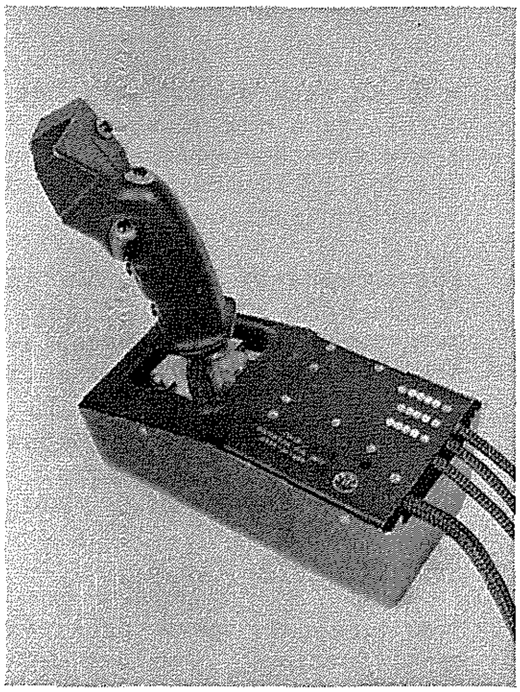

Figure 2 The PAGE Inceptor

	DOWTY INCEPTOR	PAGE INCEPTOR
TYPE	3-AXIS: PITCH - FORE/AFT DISPLACEMENT ROLL - LATERAL DISPLACEMENT YAW - THUMB TOGGLE	3-AXIS: PITCH - FORE/AFT DISPLACEMENT ROLL - LATERAL DISPLACEMENT YAW - TWIST GRIP
DISPLACEMENT	PITCH/ROLL ±10°, YAW TOGGLE ±22.5°	ALL AXES ±6°
FORCES AND MOMENTS FOR MAXIMUM DEFLECTION	PITCH AND ROLL DEPENDENT ON SPRINGS, YAW ±1N	PITCH AND ROLL: ±10N TO ±35N YAW ±0.7NM
SENSORS	ROTARY POTENTIOMETERS	LVDTs
SECONDARY SWITCHES	5	5

TABLE 1 Details of the Inceptors

- o Maximum control inputs should produce demands equal to the structural (or desired) limit of the airframe. Preferably there should be some indication to the pilot through the controls that he is approaching that limit.

- o There should be no step changes in the demand curve perceptible to the pilot.

A shaping function was designed to meet the above criteria and is given in Appendix A. It consists of a deadspace region, followed by a linear region, followed by two cubic regions as control input increases from zero to maximum. A typical command curve produced by this function is shown in Figure 3. At the break-point between the linear and the first cubic region and that between the two cubic regions, the function is continuous and has continuous first and second differentials thus giving a very smooth curve. At the maximum control input the demand gradient is zero.

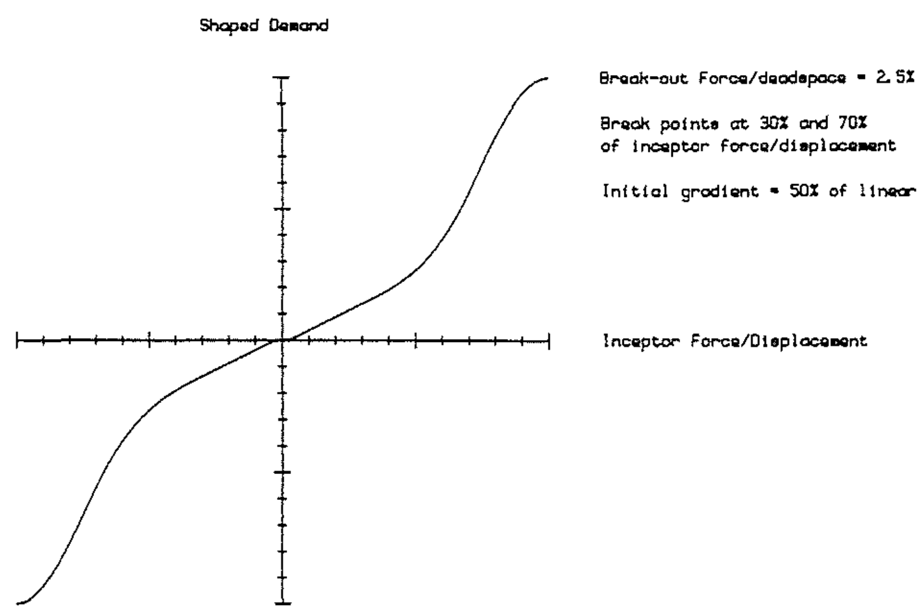

Figure 3 The Control Signal Shaping Function

Initial trials with the control shaping, as defined above, suggested that the presence of the second cubic region, designed to indicate to the pilot that he was reaching his control limit, was not noticeable to the pilot. This was because the simulator model was defined as a high agility helicopter with a rate demand system and at the very high body rates which could be generated (see Section 4.5), the subtleties of this part of the shaping were lost. This last part of the shaping curve was not therefore used in the full evaluation trials. It should be noted however that for a different application, or for an attitude demand system this part of the control shaping function might be more beneficial.

4. SIMULATION TRIALS

4.1 Simulator

The simulator used in the evaluation trials was the No. 1 Simulator at the Flight Systems Department, RAE Bedford. The simulator had a single seat cockpit, a limited motion system in pitch, roll and heave, and a single window display produced by a TV camera traversing a model belt. A simple horizon was projected onto the simulator dome to give additional peripheral vision cues.

The single window display, with limited field of view, was clearly not ideal for helicopter work where peripheral cues are so important. This is particularly true of low speed flight, and this limitation therefore had a major effect on a large part of the planned trials flying. A head-up display was incorporated to present all essential information to the pilot and allow him to make the best possible use of the visual cues available.

The simulator cockpit was based on that of a single seat fighter aircraft and hence was unlike that of any service helicopter. In particular the seat, though adjustable for height, was much lower off the floor than a typical seat and the pedals were rather widely spaced leading to a very different sitting posture than is usual for helicopter pilots.

The collective lever used was unlike a conventional collective being further forward in the cockpit and acting in a more horizontal plane. The collective displacement was, however, similar to a conventional collective and friction was adjustable.

4.2 Helicopter and Control System Model

It was decided to use a conceptual model for the inceptor trials since these models are well proven and free of quirks which might detract from the primary evaluation. In the past (reference 1) these have been used to examine various control concepts and have the advantage of being relatively unsophisticated models allowing easy changes to the aircraft characteristics. In particular it should be noted that in the conceptual model absolutely no cross-coupling is introduced, which helps to indicate whether a pilot is making inadvertent inputs when using the inceptors.

The conceptual model chosen represented a helicopter with a body rate control system (see Section 2.1) capable of roll rates of up to 100^{o}/sec and pitch and yaw rates of up to 50^{o}/sec, thus representing the type of helicopter which will probably be the first application of an ACT system and the new forms of inceptors.

4.3 The Tasks

Such a helicopter in the battlefield role, will have an operational profile which is likely to range from long periods of time in the hover or at low speed, through nap-of-the-earth flight at moderate to high speeds, to short high speed dashes across the battlefield. It is clear that the inceptors need to assist the pilot in achieving maximum mission performance from his vehicle in all these vastly different phases of flight.

It was therefore important to design tasks which investigated low speed low altitude manoeuvring as well as higher speed nap-of-the-earth flying. The desire to assess all aspects of control usage led to some rather stylised tasks; some deliberately single axis, some deliberately multi-axis, some gentle, some severe. Simulator field of view limitations also had to be considered particularly for low speed/hovering tasks: additional cues were given to the pilot to assist him in maintaining a hover, and constraints were not imposed which would be difficult for the pilot to achieve, eg. he was not asked to maintain position when performing a spot turn.

A total of eight tasks were selected during the work-up trials. In order that the tasks would show up differences in performance, they were made to be as demanding as possible yet within the normal scope of the pilot's abilities. The tasks flown were:

(i) Deceleration from 50 knots to the hover,
(ii) Spot turn through 360° to the right,
(iii) Spot turn through 360° to the left,
(iv) A circle following task (radius approximately 550 ft) flown at 15 kts,
(v) A nap-of-the-earth serpent task flown at 60 kts and 30 ft, shown in Figure 4,
(vi) The same serpent task flown at 80 kts and 30 ft,
(vii) A pointing task flown at 60 kts ie, in the sideslip demand control mode, shown in Figure 5,
(viii) A hurdles task at 80 kts, flown with pitch control alone, where the pilot had to remain below 50 ft as much as possible but climbing up over four V shaped hurdles as necessary. The hurdles were V shaped to assist the pilots' judgement of height and distance when close to the hurdles, partially overcoming the problems of limited field of view. Shown in Figure 6.

Tasks (i) to (iv) above were low speed and tasks (v) to (viii) were high speed. Tasks (iv) and (vii) generally only required gentle control inputs. Tasks (ii), (iii), (v), (vi) and (viii) were essentially single axis tasks and were used to evaluate control axes in isolation and to look for cross coupling of inputs. Tasks (i), (iv) and (vii) required inputs in all axes of control and were used to evaluate coordinated control and harmonization of the controls.

4.4 Measurements

Objective and subjective measurements were taken during the trials. The objective measures were produced by specially prepared simulator software and consisted of data relating to how well the tasks were performed eg. heading errors, track errors, task durations and control activity data to allow analyses of control usage to give measures of workload and cross coupling of inputs.

Subjective measures to support the objective data were taken by asking the pilot to rate his own performance and to assess the particular aspect of

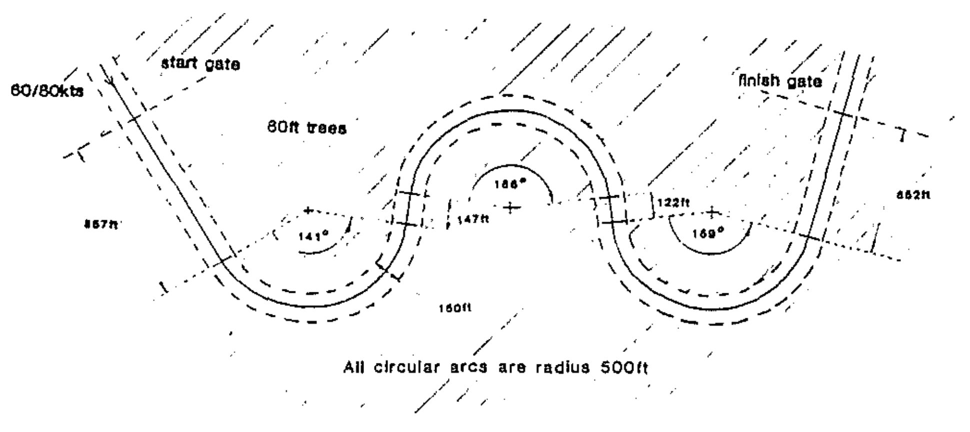

Figure 4 The Serpent Task

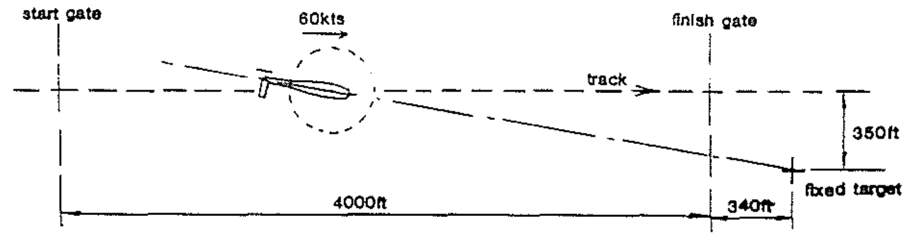

Figure 5 The Pointing Task

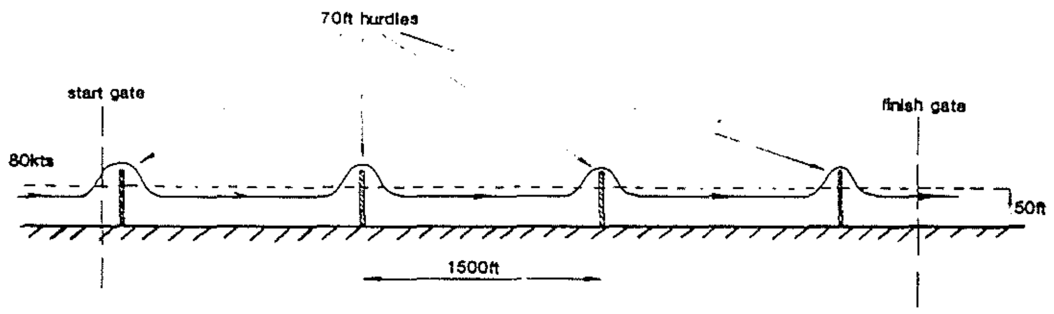

Figure 6 The Hurdles Task

control being evaluated, after completion of each task. Preprinted answer sheets were provided for this. A questionnaire was also given to each pilot to gain further subjective opinion upon completion of both sets of trials.

Software to collect data objectively during the simulation trials was written at RAE Bedford. This included recording pilot performance (eg. heading error), control activity and defining software gates for the various tasks.

4.5 Inceptor Configurations and Parameters Evaluated

Limited simulator availability and the need to use several pilots for improved statistical analysis of results, severely limited the number of inceptor configurations which could be evaluated. Table 2 shows the configurations chosen, with the inceptors used as 2-axis and 3-axis devices and each with two sets of force gradients (in pitch and roll).

Three versions of the control signal shaping were flown with the Dowty inceptor - only two of these were flown in the trials using the Page inceptor due to lack of simulator time.

2 axis:	F_1C_1	F_1C_2	F_1C_3*
3 axis:	F_1C_1	F_1C_2	F_1C_3*
3 axis:	F_2C_1	F_2C_2	F_2C_3*

F_1 = heavier force set $\quad$ F_2 = lighter force set
C_2 = linear shaping $\quad$ C_2 = moderately non-linear shaping
C_3 = severely non-linear shaping

* indicates configurations evaluated using Dowty inceptor only.

TABLE 2 CONFIGURATONS EVALUATED IN THE TRIALS

The force gradients to be used in the trials were established by RAE Test Pilots during work-up trials and were selected to represent one subjectively heavy set and one subjectively light set. The Dowty inceptor was constrained here by the springs available for the unit and the Page inceptors heaviest available forces were lighter than would have been preferred for the trials. The force gradients as used in the trials are shown in Table 3.

	FORCE FOR MAX DEFLECTION IN PITCH /N		FORCE FOR MAX DEFLECTION IN ROLL /N	
	F1	F2	F1	F2
DOWTY INCEPTOR	$\pm$ 40	$\pm$ 29	$\pm$ 20	$\pm$ 9
PAGE INCEPTOR	$\pm$ 32	$\pm$ 21	$\pm$ 16	$\pm$ 11

TABLE 3 INCEPTOR FORCE CHARACTERISTICS FOR THE TRIALS

The three control signal shapes were also established during the work up period. The first (C_1) was a linear law, with a deadband, for use as a datum case: most previous work with side-arm controllers has not used signal shaping. The second signal shape (C_3) was selected as being the most non-linear case acceptable to the work-up trials pilot. This consisted of:

- 2.5% deadspace,
- linear region (constant sensitivity) up to 30% of control displacmenet, with sensitivity of 10% of a linear law,
- cubic region from 30% to 100% of control displacement.

The third control signal shape (C_2) was then selected as feeling subjectively mid-way between the linear case and the extreme non-linear case above. The mid-way signal shape was similar to the other non-linear shape but had an initial sensitivity of 50% of the linear case.

4.6 Trials Procedure

Two sets of trials were undertaken: the first with the Dowty inceptor involved four pilots each taking part in sorties over three days; the second, with the Page inceptor, in which the same four pilots flew sorties over one and a half days each. A total of about seventy hours of trials were 'flown' including practice sorties.

During the trials with the Dowty inceptor, each pilot's first day was used purely for practice to allow familiarisation with the simulator, the helicopter model/control system and the new inceptor in all the configurations to be flown. Evaluation trials were undertaken over the next two days, each configuration being flown for ten minutes free practice flying, followed by a run through the eight evaluation tasks. Any task could be repeated upon the request of the pilot if he felt that his performance was not representative.

For the Page inceptor trials, practice flying was limited to a one hour sortie to become familiar with the twist mode of yaw control. The procedure was otherwise as for the Dowty trials except that only six of the nine configurations were assessed in full, due to the limited time available and the poor performance of the other configurations in the Dowty inceptor trials.

5. RESULTS

5.1 General

The simulation trials and subsequent analysis revealed many interesting results concerning trials methods and the way in which various measures relate to each other. These aspects are fully discussed in references 5 and 6, this section of this paper concentrating on results obtained concerning the inceptor forces, configuration and control signal shaping. It is, however worth noting two of the results concerning the measures used.

- There was a strong correlation between the measures of total control activity (defined as the rms inputs after shaping) and the pilot's subjective assessments of the system quality. This suggests that for a rate type control system, total control activity is a good measure of pilot workload.

- There was no correlation beteen the measures of total control activity (workload) and the measures of task performance. This suggests that taking task performance in isolation could be very misleading, since a good performance may be achieved at the cost of very high pilot workload.

Overall it should be noted that these results have been produced by statistical analysis of many measures - some objective, some subjective, - so that a high level of confidence can be placed in the results obtained. The statistical methods used are discussed in references 5 and 6.

The principal results are summarised in tables 4 and 5, and the following subsections discuss the effects of the various parameters under evaluation.

5.2 Control Signal Shaping

The trials showed that control signal shaping has a large effect on pilot assessment of the system and some effect on either the actual task performance or the total control activity. Performance measures showed little difference between C_1 and C_2 for both inceptors but that C_3 was always the worst for the Dowty inceptor. (Hence, with the limited time available this signal shape was not included in the Page trials).

Pilot's assessments of their own performances generally gave C_2 the best ratings although with the Page inceptor when large control inputs were required there was some tendency to rate C_1 better. This is an indication of the increased sensitivity of the non-linear control shapes at large control displacement. Pilot's opinions of the systems in use generally gave C_2 as the preferred shaping. It is interesting to note that some pilots felt that the performance in many manoeuvres using C_1 was as good as that for C_2 but that the former case was uncomfortably sensitive, which correlates with the fact that control activity was (for the Page inceptor) significantly less with C_2 than C_1.

VARIABLE		EFFECT ON TASK PERFORMANCE	EFFECT ON PILOTS SUBJECTIVE OPINION OF TASK PERFORMANCE	EFFECT ON PILOTS SUBJECTIVE OPINION OF OVERALL SYSTEM	EFFECT ON TOTAL CONTROL ACTIVITY
CONTROL SIGNAL SHAPING	DOWTY	C_1 AND C_2 SIMILAR C_3 WORST	C_2 GENERALLY BEST	C_2 GENERALLY PREFERRED	NO SIGNIFICANT EFFECT
	PAGE	C_1 AND C_2 SIMILAR	C_2 SOMETIMES BETTER	C_2 GENERALLY PREFERRED	C_2 BETTER
FORCE GRADIENT	DOWTY	LITTLE EFFECT	LITTLE EFFECT	SOME PREFERENCE TO F_1	F_1 BETTER
	PAGE	LITTLE EFFECT	F_2 SOMETIMES BETTER	SLIGHT PREFERENCE TO F_2	NO SIGNIFICANT EFFECT
INCEPTOR CONFIGURATION	DOWTY	DIFFERENCES ALWAYS FAVOURED 2-AXIS CONFIGURATION	DIFFERENCES ALWAYS FAVOURED 2-AXIS CONFIGURATION	INCONCLUSIVE	NO SIGNIFICANT EFFECT
	PAGE	DIFFERENCES ALWAYS FAVOURED 2-AXIS CONFIGURATION	DIFFERENCES ALWAYS FAVOURED 2-AXIS CONFIGURATION	SOME PREFERENCE FOR 2-AXIS CONFIGURATION	NO SIGNIFICANT EFFECT
PAGE/DOWTY	2-AXIS	NO DIFFERENCE	NO DIFFERENCE	NO PREFERENCE	DOWTY BETTER FOR SEVERAL TASKS, PAGE FOR ONE
	3-AXIS	ONE TASK PERFORMED BETTER WITH THE PAGE INCEPTOR	PAGE INCEPTOR PREFERRED IN SOME TASKS	NO PREFERENCE	

Control signal shapes: C_1 = Linear,
C_2 = Moderate non-linearity,
C_3 = Severe non-linearity.

Force gradients: F_1 = Heavier set,
F_2 = Lighter set.

TABLE 4 Summary of Simulation Trials Results

VARIABLE		EFFECT ON CROSS COUPLING OF INPUTS	EFFECT ON PERCEIVED TENDENCY TO PILOT INDUCED OSCILLATIONS	EFFECT ON PERCEIVED HARMONISATION OF PITCH/ROLL CONTROL FORCES
CONTROL SIGNAL SHAPING	DOWTY	MORE NON-LINEAR SHAPING LEADS TO LESS CROSS COUPLING	C_2 GENERALLY BEST	——
	PAGE	MORE NON-LINEAR SHAPING LEADS TO LESS CROSS COUPLING	C_2 SLIGHTLY BETTER	——
FORCE GRADIENT	DOWTY	F_1 BETTER	NO EFFECT	F_1 BETTER
	PAGE	NO EFFECT	F_2 GENERALLY BETTER	NO EFFECT
INCEPTOR CONFIGURATION	DOWTY	3-AXIS CONFIGURATION BETTER, YAW INPUTS ARE MAJOR CONSIDERATION	NO EFFECT	NO EFFECT
	PAGE	NO EFFECT	2-AXIS BETTER	NO EFFECT

Control signal shapes: C_1 = Linear,
C_2 = Moderate non-linearity,
C_3 = Severe non-linearity.

Force gradients: F_1 = Heavier set,
F_2 = Lighter set.

TABLE 5 Summary of Simulation Trials Results (continued)

It was found that with the Dowty inceptor set up for heavier forces, C_1 was preferred to C_3, but with the lighter forces this preference was reversed. This tendency was confirmed by analysis of the data specifically to look for interactive effects and suggests that greater initial sensitivity can be tolerated with higher feel forces and perhaps that the force applied to achieve a given response is more important than the displacement required.

A very significant effect of control signal shaping was that it reduced cross coupling of inputs. This would be expected, since by reducing the initial sensitivity of the inceptor, any inadvertent forces/displacments will have a smaller effect in tems of aircraft response.

An analysis of the pilots' subjective assessment of the tendency of the system to cause pilot induced oscillation (PIO) suggested that C_2 offered the best performance. Pilots commented during the trials that C_1 was too sensitive causing PIO and overcontrolling, and made precise manoeuvring difficult. The severe non-linearity of C_3 was not favoured either, since the high sensitivity approaching maximum stick travel was very uncomfortable and could take pilots by suprise. C_2 was noticeably non-linear but felt to be a good compromise.

There were some indications that the control signal shaping should not be the same in each axis, though it was not possible to test this in a structured way. In particular it was felt that with a hand controlled yaw axis a more non-linear shape might be desirable since yaw control usually consists of either fine heading adjustment requiring low sensitivity or full rate turns where maximum control input would be used.

5.3 Inceptor Forces

The control forces evaluated in the trials did not seem to have any significant effect on task performance suggesting that pilots will rapidly adjust to the inceptor forces they are given. Subjective comment was not much more conclusive either, with pilots generally stating that something between the heavier and lighter forces would be preferable for both inceptors. With the Dowty inceptor, pilots generally would prefer forces closer to the heavier set, probably due to this set's better harmonization (see below), but for the Page inceptor there was a preference for forces closer to the lighter set evaluated.

The Dowty inceptor force gradients had no effect on the perceived tendency of the system to cause PIO. However, for the Page inceptor, the lighter forces were felt to reduce PIO tendencies, reinforcing the pilot's subjective preference towards the lighter forces with this inceptor.

Significantly less control activity was recorded with the heavy set of forces on the Dowty inceptor compared with the light set. The heavier set of spring forces on this inceptor was also assessed as giving better harmonization of forces in the pitch and roll axes. This heavier set of forces gave a pitch force gradient of about twice that in roll. It is interesting to note that pilots indicated that this gave apparently similar feel in each axis. The lighter set of forces was however, assessed as giving better harmonization between the roll and yaw axes, with the light roll forces better matching the very light yaw control.

The force gradients had no effect on the perceived harmonization of forces on the Page inceptor. This is to be expected in the pitch and roll axes, because the pitch to roll force ratio for both sets of forces was about 2:1 (ie. similar to the heavier Dowty set) and both were assessed as being well harmonized. It is perhaps surprising that the harmonization of the pitch and roll axes with the yaw axis was not affected by the pitch and roll force gradients, since the yaw moment was not adjustable. This is most likely to be due to the difficulty in assessing harmonization between a force and a moment.

The heavier forces were found to produce fewer inadvertent inputs with the Dowty inceptor, but with the Page inceptor, force gradients had little effect on inadvertent inputs. It was therefore the poorly harmonized set of forces (with the Dowty inceptor, see above) which produced the worst result here, suggesting that good harmonization of forces is the critical factor rather than absolute force gradients.

There were some comments from the pilots suggesting that pitch and roll force characteristics would need to be modified in changing from a two axis to a three axis inceptor. This indicates that incorporation of a third axis into the right hand inceptor might compromise the characteristics of the pitch and roll axes.

5.4 Inceptor Configuration

Differences in performance which were detected invariably favoured the 2-axis configuration for both inceptors. Pilots' subjective assessment of their performance tended to reflect their actual performance.

Subjective ratings of the systems under evaluation showed little preference for either configuration. This was supported by the fact that there were no significant effects on the workload required by either configuration to perform the tasks.

The questionnaire gave differing opinions, with two pilots preferring 2-axis control and two pilots seeing possible benefits of 3-axis control. One pilot thought that using pedals was a particularly cumbersome method of yaw control, but it is possible that with better choice of pedal characteristics, the 2-axis configuration could be improved considerably. Overall, the results suggest that with more practice on the 3-axis configurations, differences between the two configuratons might be less marked.

The effect of control configuration on inadvertent inputs was varied. In manoeuvres where yaw control was not required, coupling between pitch and roll axes was independent of inceptor configuration as would be expected. many of these manoeuvres, however, produced more inadvertent inputs into the yaw axis for the 2-axis configuration, particularly for the Dowty inceptor. This may seem surprising at first since the 2-axis configuration has the separated means of yaw control, but can be explained by the fact that the pedals had no definite centre so that the pilot would have found it difficult to hold a zero yaw input especially when in the sideslip demand mode. The Dowty inceptor in 3-axis form performs well here because when yaw control is not required the pilot can remove his thumb from the yaw controller and eliminate the possibility of any inadvertent input. In contrast, the Page inceptor had a readily available yaw control, so that neither configuration with this inceptor produced detectably fewer inadvertent inputs. The spot turns revealed problems in the 3-axis controller configurations in that cross-coupling was evident from yaw into roll, which was clearly not likely with the 2-axis configurations.

5.5 Comparison of Page and Dowty Inceptors

Most of the characteristics of the two inceptors have been compared in the previous subsections. Analysis of the performance data showed little difference in task performance for comparable conditions on each inceptor. However, one task, the 80 kt serpent, was generally performed better with the Page inceptor. This was a demanding task and it is possible that the improved performance reflects the additional practice the pilots had gained on this task when using the Page inceptor. For a 3-axis device the pilots much preferred the twist yaw control as it was found to be much more natural and instinctive toggle yaw control which was uncomfortable to use. Neither inceptor was considered by the pilots to be better than the other when used as two axis device.

Cross coupling problems were more apparent on the Page inceptor compared with the Dowty inceptor. This also showed up in increased total control activity. This was principally due to the fact that the Page inceptor's yaw control was more readily available, increasing inadvertent inputs into yaw, and required greater effort to make yaw inputs compared with the Dowty inceptor, increasing inadvertent inputs into other axes (ie. the Dowty yaw controller was very light).

6. CONCLUSIONS

The inceptor configuration offering the best performance in 70 hours of simulation trials was the 2-axis right hand inceptor for pitch and roll control with separate collective and pedals. The 3-axis right hand inceptor with a twist grip for yaw was found to be natural to use and was liked by some pilots but did not offer any performance benefits or reduced workload.

Control signal shaping is valuable when small displacement inceptors are used for controlling a highly manoeuvrable aircraft. This shaping offers gentle initial sensitivity and yet allows rapid manoeuvring without excessive stick forces. Careful selection of signal shapes for individual applications is required, as these have been shown to have a large effect on pilot performance.

Suitable harmonization between forces in different inceptor axes, particularly pitch and roll is essential in producing good inceptor performance. Poor harmonization causes higher workload and more cross-coupling of inputs. The trials suggested that forces in pitch should be approximately twice those in roll.

If force harmonization is good, then force levels in the range evaluated have little effect on performance or workload. The force gradients evaluated in combination with non-linear control shaping were acceptable and there was insufficient variation in preferred forces to suggest that pilot adjustable force feel is required.

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APPENDIX A CONTROL SIGNAL SHAPING FUNCTION

Notation:-

XIN	-	the input to the shaping function,
YOUT	-	the output from the shaping function,
XBO	-	the break-out control signal/deadspace
XBP	-	the break-point between the linear and cubic regions,
YBP	-	the value of YOUT at XBP,
XC	-	the break point between the two cubic regions,
YC	-	the value of YOUT at XC,
XMAX	-	the maximum control input,
YMAX	-	the maximum aircraft command,
M1	-	the initial command gradient when break-out/deadspace has been overcome,
M2,M3,M4	-	shaping function gradients.

Constants are calculated as follows:

$$YBP = M1.(XBP-XBO)$$

$$YC = \frac{4.M1.(XMAX-XC).(XC-XBP) + 3.YMAX.(XC-XBP) + 6.YBP.(XMAX-XC)}{3.(2.XMAX-XC-XBP)}$$

$$M2 = \frac{(YC-YBP)}{(XC-XBP)}$$

$$M4 = \frac{(YMAX-YC)}{(XMAX-XC)}$$

$$M3 = 1.5 \times M4$$

The output then varies with the input as follows:

For XIN = 0 to XIN = XBO,
$$YOUT = 0.0$$

For XIN = XBO to XIN = XBP,
$$YOUT = M1.(XIN-XBO)$$

For XIN = XBP to XIN = XC,
$$YOUT = M1.(XIN-XBO) + \frac{(M2-M1).(XIN-XBP)^3}{(XC-XBP)^2}$$

For XIN = XC to XIN = XMAX,
$$YOUT = YC + M3.(XIN-XC) + \frac{(M4-M3).(XIN-XC)^3}{(XMAX-XC)^2}$$

For XIN > XMAX,
$$YOUT = YMAX$$

The shape of the shaping curve is varied by changing the following parameters:

XBO, XBP, XC, M1.

Overall values of the command for given control inputs are governed by XMAX and YMAX.