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# AN INVESTIGATION OF MULTI-AXIS ISOMETRIC SIDE-ARM CONTROLLERS IN A VARIABLE STABILITY HELICOPTER

by

M. Sinclair, M. Morgan

National Aeronautical Establishment

OTTAWA

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AN INVESTIGATION OF MULTI-AXIS ISOMETRIC SIDE-ARM  
CONTROLLERS IN A VARIABLE STABILITY HELICOPTER

(ÉTUDE DE SYSTÈME DE CONTRÔLE LATÉRAL ISOMÉTRIQUE À AXES MULTIPLES  
À BORD D'UN HÉLICOPTÈRE À STABILITÉ VARIABLE)

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M. Sinclair, M. Morgan

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## ABSTRACT

Several helicopter control configurations, each incorporating a pair of multi-axis, isometric side-arm controllers, were evaluated in a flight test program using a variable stability helicopter. The test aircraft was the NAE Airborne Simulator, an extensively modified Bell Model 205A-1, and the evaluation flights encompassed a wide range of demanding tasks from hover manoeuvring and transitions to cruising flight, to nap-of-the-earth flight and precision IFR tracking. The isometric control systems included several two-handed and one-handed configurations with force-pedals for directional control, and one fully-integrated system which provided full control of the helicopter with either hand. Evaluations of these unconventional systems were performed by five experienced test pilots.

## SOMMAIRE

L'évaluation en vol de différentes dispositions des commandes, chacune incorporant une paire à axes multiples de contrôleurs isométriques latéraux, s'est effectuée à bord d'un hélicoptère à stabilité variable. L'appareil utilisé pour ces tests était un Bell modèle 205A-1, très modifié, appelé aussi simulateur volant de l'EAN. Les vols d'évaluation ont porté sur une gamme étendue de manoeuvres exigeantes: évolutions en vol stationnaire, passages au vol de croisière, vols en rase-motte et vols de précision aux instruments (IFR). Les systèmes de commandes isométriques comprenaient différentes combinaisons d'opérations manuelles, nécessitant soit l'utilisation d'une seule main, soit des deux; la commande de direction s'effectuant au palonnier, ainsi qu'un système totalement intégré permettant la maîtrise de l'hélicoptère avec l'une ou l'autre main seulement. Cinq pilotes d'essai éprouvés ont participé à l'évaluation de ces systèmes hors du commun.

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## AN INVESTIGATION OF MULTI-AXIS ISOMETRIC SIDE-ARM CONTROLLERS IN A VARIABLE STABILITY HELICOPTER

### INTRODUCTION

The application of fly-by-wire and fly-by-light technologies to the design of helicopter control systems will have far-reaching effects on many other areas of conventional design practice for these aircraft. Some of the most visible and potentially significant changes resulting from the use of electric control systems will take place in the cockpit where many of the physical constraints which have favoured the standard helicopter controller arrangement will be eliminated. In the absence of these constraints, the designer will be free to consider alternative cockpit configurations which cater to the comfort, convenience and efficiency of the pilot, to an increase in his unobstructed viewing area and to improvements in the crashworthiness of the structural volume surrounding the cockpit.

The conventional helicopter control configuration is nevertheless an integral part of the pattern-of-control learned by every helicopter pilot and consequently has the status of an international standard. The benefits gained in any substantial deviation from this arrangement must be weighed against the costs of retraining the pilot's spontaneous control-command patterns, particularly in high workload and emergency situations. It was these ergonomic trade-offs which formed the basis for the flight research program described in the report.

In the fall of 1979 Sikorsky Aircraft initiated a project in collaboration with the National Aeronautical Establishment (NAE) to evaluate, as primary flight control system elements for a helicopter, a set of multi-axis, isometric side-arm controllers. The test aircraft was the NAE Airborne Simulator (Figure 1 and Reference 1), an extensively modified Bell Model 205A-1 teetering-rotor helicopter with a full authority fly-by-wire control system at the evaluation pilot's station. Two isometric controllers and supporting side-arm structures were built into the evaluation pilot's seat in the Airborne Simulator and the force-sensing systems for both left-hand and right-hand control were integrated into the fly-by-wire system. With this arrangement pilots flew several unconventional control systems including two-handed and one-handed configurations with force-pedals for directional control, and one system which provided full control of the helicopter with either hand.

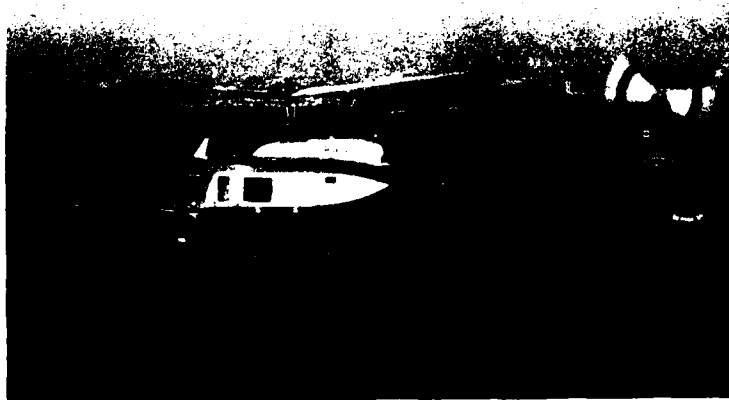


FIG. 1: THE NAE AIRBORNE SIMULATOR

From the designer's point of view the appeal of the isometric or pressure controller is evident: it is a mechanically simple (no "moving" parts), light-weight, rugged and compact system which can readily be incorporated into a side-arm fly-by-wire system. On the other hand the flying

qualities implications of eliminating the direct control position feedback provided to the pilot by conventional position controllers must be evaluated. The balance sheet on these issues will be addressed later in the report but first the physical characteristics of the isometric controllers are described, the form of the control signal processing and control law software developed for the program is presented and the subjective assessments of the NAE and Sikorsky pilots who flew the various systems are discussed.

The specific objectives of the experiment were:

- (a) to develop the necessary control system software for flight evaluation of a series of isometric controller configurations in the Airborne Simulator,
- (b) to identify the configurations which warrant serious consideration as practical helicopter control systems and,
- (c) to evaluate and "fine-tune" these configurations in a variety of operationally relevant tasks.

### SYSTEM DEVELOPMENT AND INTEGRATION

The system which was installed in the right-hand cockpit of the Airborne Simulator is shown in Figures 2 and 3. The inclined left supporting arm shown in Figure 2 was used only during the development flight test phase where it was employed with a control system which interpreted fore-and-aft forces on the left controller as down-and-up collective commands respectively. (The inclination aligned the axis of the collective command in a somewhat conventional direction.) All of the evaluated configurations were flown using the symmetrical controller arrangement (Figure 3).



FIG. 2: THE EVALUATION PILOT'S SEAT WITH SIDE-ARM CONTROLLERS



FIG. 3: SIDE-ARM CONTROLLERS INSTALLED

## Hardware

The isometric hand controllers used in the flight experiment are "off-the-shelf", 4-axis controllers which use semi-conductor piezo-resistive elements as force sensing and transducing units (Figure 4). The four sensing "axes" are the ones shown in Figure 4b: fore and aft, left and right, up and down forces, and torque about the vertical axis. The nominal values of the command-to-electrical-output sensitivity for each of these channels is shown below:

| Command                     | Sensitivity      | Maximum Output    |
|-----------------------------|------------------|-------------------|
| Left/right                  | 0.5 volt/lb      | 10 volts (Linear) |
| Fore/aft                    | 0.5 volt/lb      | 10 volts (Linear) |
| Up/down                     | 0.25 volt/lb     | 10 volts (Linear) |
| Clockwise/counter clockwise | 0.167 volt/in-lb | 10 volts (Linear) |

These raw signals have infinite resolution and the combined sensor-transducer-signal conditioning system has a bandwidth which extends well beyond the deliberate control command bandwidth of the human operator.

Each handle incorporates three discrete function switches — one contact-closure switch on either side of a standard "Chinese-hat four-way trim button. Circuitry was provided to generate separate logic levels for the open and closed positions of the two switches and three logic levels each for the longitudinal and lateral trim selections of the Chinese-hat.

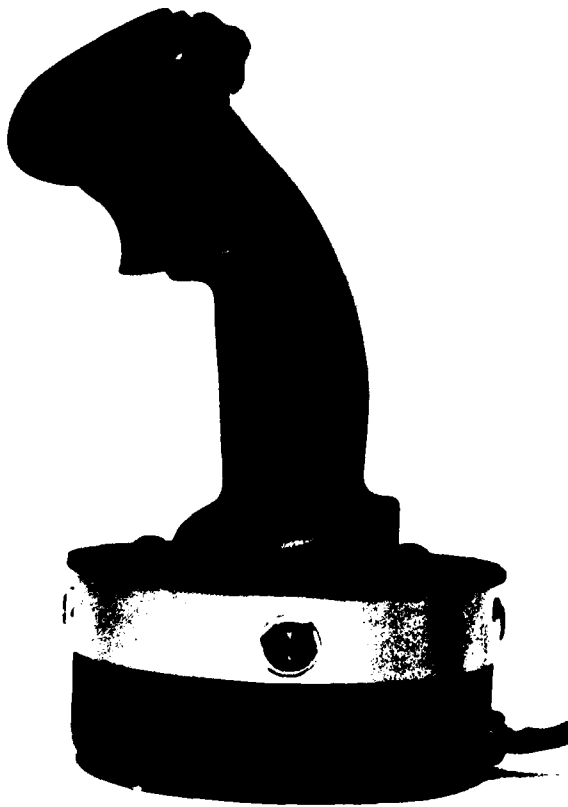


FIG. 4a: ISOMETRIC HAND  
CONTROLLER

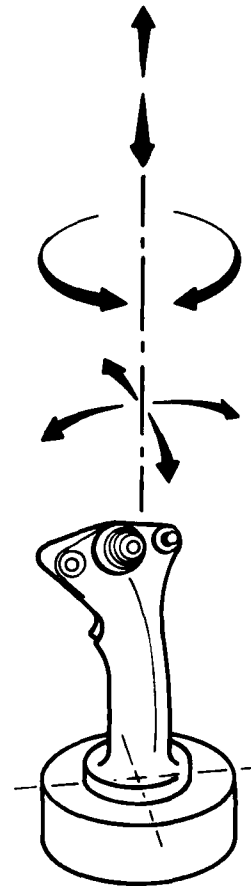


FIG. 4b: FORCE AND MOMENT  
SENSING AXES

The handles are elastically very stiff but not rigid. Forces and moments within the transducing limits produce small deflections of the handle relative to its mounting ring and these deflections were augmented in the installed system by the compliance of the supporting structure. The deflections resulting from fore-and-aft or sideward force levels of 20 lb. were nevertheless small, approximately 0.03 in. at the mid-hand position, and the system was sensibly rigid for vertical force and twist commands.

One additional, but fundamentally important hardware item — a control actuator-position indicator — was added to the experimental system late in the evaluation phase. The indicator is shown in Figure 5 mounted above the instrument panel combing in the evaluation pilot's forward field of view. The display, which was adapted from a conventional fixed-wing aircraft autopilot system, provided the evaluation pilot with easily-interpreted information concerning tip-path-plane orientation, and main-rotor and tail-rotor collective actuator positions.

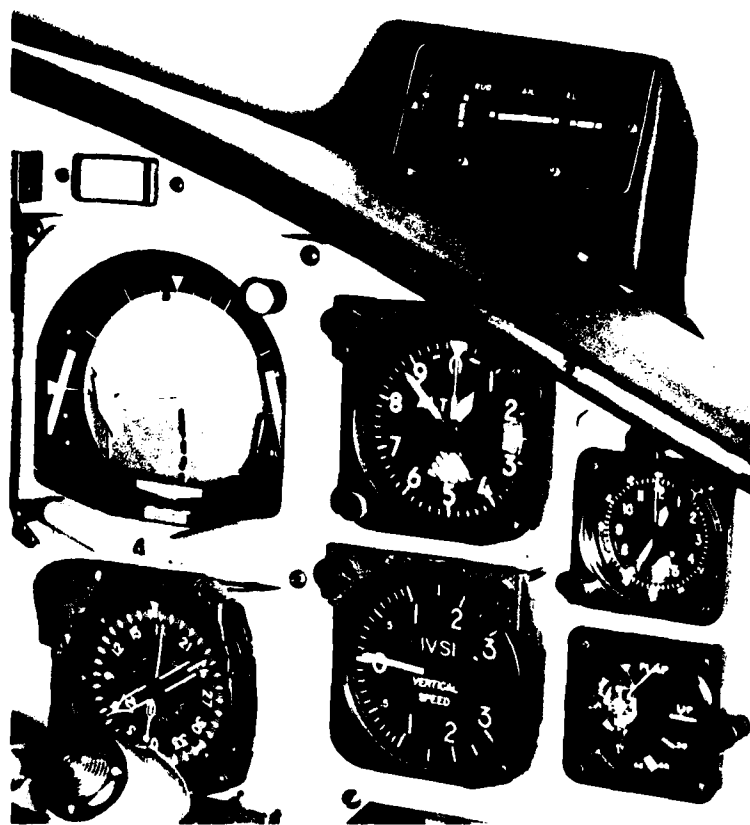


FIG. 5: ACTUATOR POSITION INDICATOR

#### Software

The command and logic signals from each handle and a force-proportional signal from the evaluation pilot's pedals were all sampled and transferred to the simulator's master digital computer. Figure 6 shows schematically the physical arrangement of the control system elements and the logical flow of the side-arm controller simulation program. All of the software was relatively unsophisticated, with none of the redundancy or self-monitoring features which would be required in a "production" model. The program was nevertheless sufficiently flexible to provide five distinct controller/control

channel combinations, and two levels of helicopter stability and control augmentation in addition to a direct-drive, unaugmented configuration. A brief description of the major routines of this system program is given below.

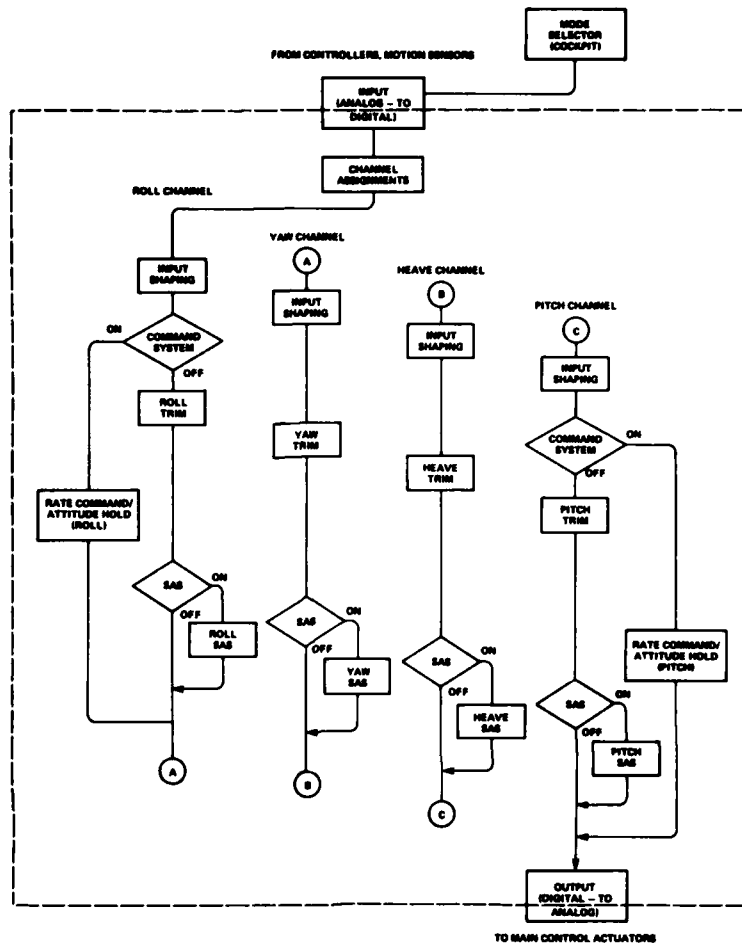


FIG. 6a: CONTROL CHANNEL SCHEMATIC

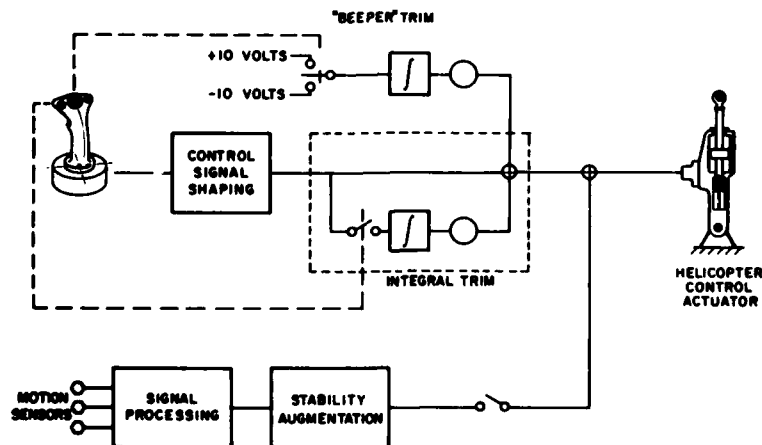


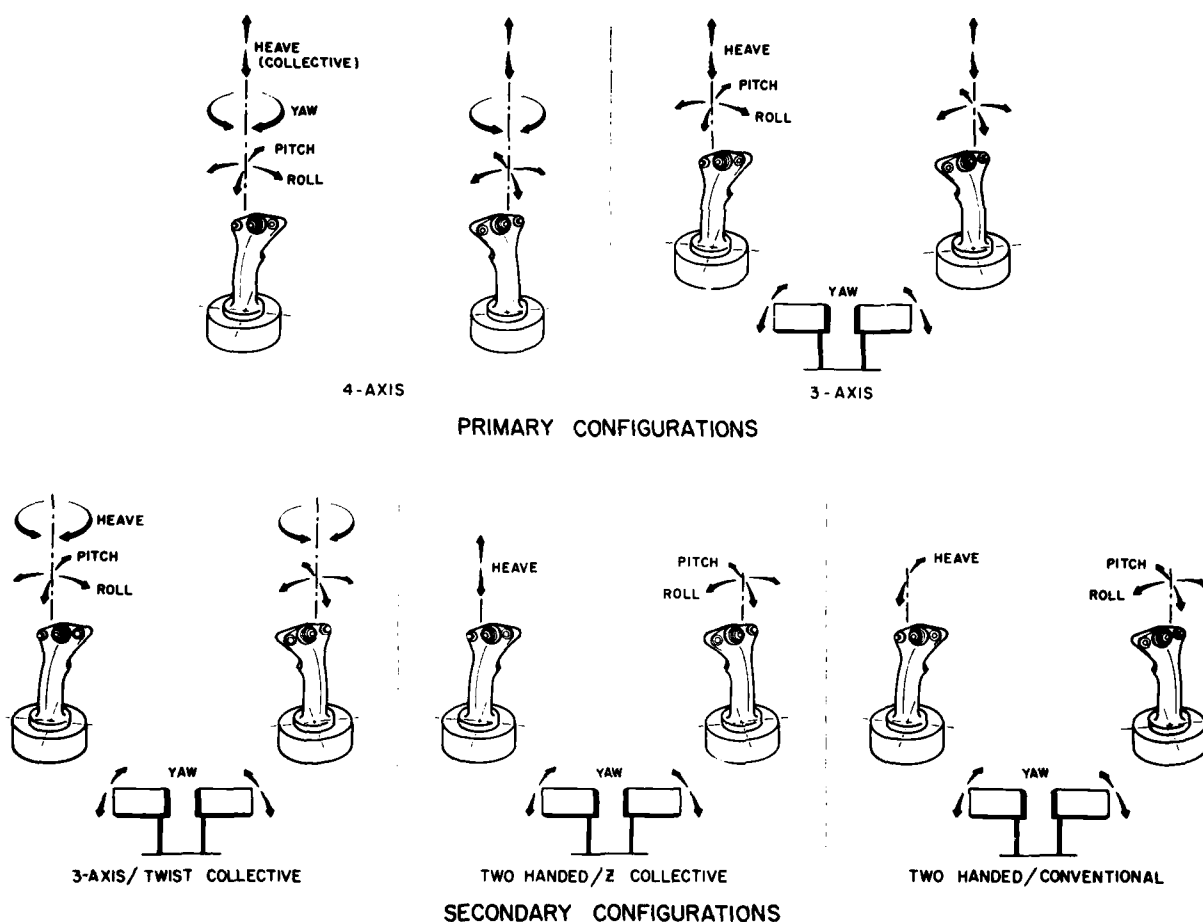
FIG. 6b: SIMULATION PROGRAM

**Mode Selection** Before control of the helicopter was passed to the evaluating pilot, the computing system established an internal vectoring structure, based on a cockpit mode selection, which assigned the appropriate controller signals to each fly-by-wire channel. For example, in the 4-Axis mode the following assignments were made:

|              |                                         |
|--------------|-----------------------------------------|
| roll         | left/right forces on either controller* |
| pitch        | fore/aft forces on either controller    |
| yaw          | twisting moments on either controller   |
| heave        | up/down forces on either controller     |
| (collective) |                                         |

This, and four other modes which were flown in the formal test phase are illustrated schematically in Figure 7.

\*For all systems which had duplicated functions on the left and right controllers, the configuration was designed to be flown with one (but either) hand; however, forces or moments applied simultaneously to both controllers were *summed* within the computer.



**FIG. 7: CONTROL MODES FOR THE ISOMETRIC SIDE-ARM CONTROLLER EVALUATIONS**

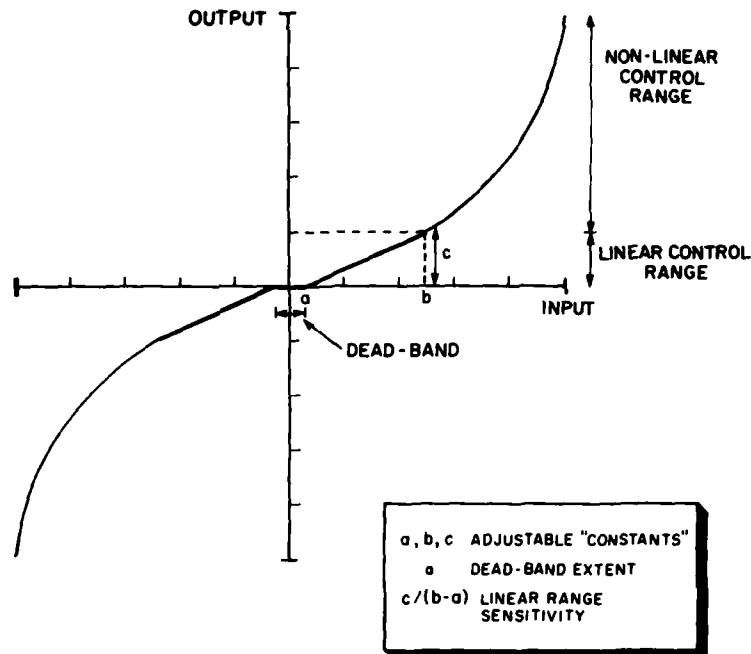


FIG. 8: CONTROL SIGNAL SHAPING

**Input Signal Shaping** After the command signals were sorted by the mode selection software, the signal assigned to each control channel was passed through a shaping system of the type depicted in Figure 8. The deadband, linear control slope and the extent of the linear control region were preprogrammed for each of the four channels, but any or all of these values could be changed during the test flight while the fly-by-wire system was disengaged.

**Force Trimming** Two systems were provided to eliminate the need for long-term or steady-state input forces. Simple, constant-rate integrators were activated by Chinese-hat selection and deactivated upon its return-to-centre. The outputs from these integrators were summed with the appropriate control signals to provide trimming inputs to the control actuators. In addition to this conventional system, a selectable, continuous integral trim system provided integral-plus-proportional paths between the control signal shaping program and the control actuator input. The "integral trimming" system is depicted in Figure 6a and is discussed in more detail below.

**Stability and Control Augmentation** The control configurations were evaluated in conjunction with three levels of stability and control augmentation or autostabilization. These were:

- (i) rate-command/attitude hold in roll and pitch with augmented yaw rate damping
- (ii) augmented roll, pitch and yaw rate damping
- (iii) direct-drive, i.e. the Bell Model 205A-1 with stabilizer bar removed and horizontal stabilizer fixed.

## DEVELOPMENT FLIGHT TEST PHASE

In a preliminary series of flight tests, preceding the formal evaluation phase of the experiment, detailed design of the signal shaping and force trimming systems was accomplished and a number of mission-oriented evaluation tasks were defined. These tests were flown by one of the research pilots: each of the other pilots began his flight evaluations with essentially developed systems which had been successfully flown through the operational task sequences.

The problems addressed in the development phase and the results of the development flight testing are summarized in the paragraphs which follow.

**Force Trimming Systems** When a human operator attempts to establish or change the command from a conventional position controller, his central nervous system is provided with good feedback information not only on the magnitude of the command but also on its first and second time derivatives. This derivative information, sensed from the rate of change of limb extension and increment in applied force, is an important ingredient of stable, precise closed-loop position control. With the isometric controllers on the other hand, instead of being "two-integrations-away from" the command, the applied force *is itself* the command signal and the kinesthetic sensation of the force is the only useful feedback. It is difficult therefore to hold a precise, constant non-zero command with such a controller and the difficulty increases as the force levels increase. An effective force-release trimming system is essential.

On several counts the conventional Chinese-hat trim button does not meet this need satisfactorily. Both the actions of repositioning the hand to make thumb-contact with the trim button and of applying sufficient force then to overcome the breakout level of the switch, produced transient forces on the handle which in turn disturbed the helicopter's state. Although these spurious inputs were manageable and the system was used successfully in flight, the level of control interference was nevertheless deemed to be incompatible with the precision-control demands of many operational tasks.

There is a more fundamental objection to the conventional trim button approach when a single handle provides the inputs to three or four control channels: for these multi-axis configurations the four-way, two channel trim switch is clearly inadequate for the job. It was necessary therefore to implement an alternative approach to force trimming before the three-axis and four-axis isometric controllers could be flown through a useful operational envelope. Of the several candidate systems considered, the best of these was a self-trimming system which provided an integrating path in parallel with the normal proportional path between the signal shaping routine and the input to the main control actuator (Figure 6a). In the system which was implemented for these experiments, integral paths for all of the control channels served by one of the handles could be "turned-on" by depressing a discrete-function switch on that handle. (The button on the thumb-side of the Chinese-hat was used.) A second actuation of this switch grounded the inputs to the integrators and re-established pure proportional control.

It is clear that the introduction of an integral path increases the lag in a control channel and that the magnitude of the increment in phase-lag depends upon the relative emphasis given to the proportional and integral paths. (The resulting open-loop transfer function has an additional pole at the origin and an associated zero on the negative real axis at  $s = -K_{ip}$ , when  $K_{ip}$  is the ratio of the integral-to-proportional gains.) It is equally clear that the use of pressure controllers in place of conventional deflection systems decreases the total system (man-machine) lag. There is, however, no simple way to quantify the net effect of these two elements on the closed-loop system since the human operator is a highly adaptable component and defies generalization when faced with unfamiliar or unconventional tasks. For the initial flight tests a compromise was struck between high-gain integrators for rapid trim follow-up and low integral gain to reduce system lag in the manoeuvring control frequency range. The value of the gain ratio,  $K_{ip}$ , for each channel was set equal to the magnitude of the rate damping derivative of the controlled degree of freedom, that is,  $K_{ip}$  was set equal, respectively, to  $-L_p$ ,  $-M_q$ ,  $-N_r$ ,  $-Z_w$  for the roll, pitch, yaw and heave channels. Although changes to higher values in the yaw and heave integral paths were made during the evaluation phase (Table 1), these original settings proved to be valid starting points for the empirical design.

The rate command/attitude hold (RC/AH) mode which was also available in this program as an option for the roll and pitch control channels, is an inherently self-trimming system and is therefore compatible with the isometric controller. When this control mode was flown during the evaluations, it was used in conjunction with yaw and heave integral trimming of the type described above.

TABLE 1

INTEGRAL TRIM SYSTEM GAINS

Integral-Trim Gain Ratio  $K_{ip}$

$$K_{ip} = \frac{(\text{Gain of Integral Path})}{(\text{Gain of Proportional Path})}$$

|               |                |
|---------------|----------------|
| Roll Channel  | $K_{ip} = 1.0$ |
| Pitch Channel | $K_{ip} = 0.5$ |
| Yaw Channel   | $K_{ip} = 1.9$ |
| Heave Channel | $K_{ip} = 1.5$ |

**Control Signal Shaping** During this preliminary phase of the flight program, a set of "workable" values was established for the constants of the input signal shaping software (Figure 8). The objective was not to optimize these characteristics since this would have entailed an adaptation to each pilot and each task: a detailed investigation of these preferences and task dependencies was beyond the scope of a short test program although such an adaptive approach would be practical in a sophisticated fly-by-wire control system. Some modifications were made to the shaping numbers during the evaluation flights but one final set was identified which found general acceptance with the sample of evaluating test pilots for a variety of flying tasks (Table 2).

TABLE 2

CONTROL SIGNAL SHAPING SYSTEM CONSTANTS

Dead-Band

|               |           |
|---------------|-----------|
| Roll Channel  | 0.5 lb    |
| Pitch Channel | 0.5 lb    |
| Yaw Channel   | 1.5 in-lb |
| Heave Channel | 1.0 lb    |

Linear Control Range Sensitivities

|                |                                           |
|----------------|-------------------------------------------|
| Roll Channel   | 0.23 deg. swash plate/lb                  |
| Pitch Channel  | 0.27 deg. swash plate/lb                  |
| Yaw Channel    | 0.14 deg. tail rotor collective/in-lb     |
| Heave Channel* | 0.13 deg. main rotor collective/lb (up)   |
|                | 0.20 deg. main rotor collective/lb (down) |

Extent of Linear Control Range

|               |          |
|---------------|----------|
| Roll Channel  | 4 lb     |
| Pitch Channel | 4 lb     |
| Yaw Channel   | 12 in-lb |
| Heave Channel | 8 lb     |

\*Asymmetry in heave channel.

**Evaluation Tasks** A number of flying tasks were defined to provide a uniform basis for evaluating the various control system configurations. The list of operationally-oriented tasks and standard flight test procedures included take-off and landing, hover manoeuvring, circuits, nap-of-the-earth flight, precision instrument approaches and slope operations.

## FLIGHT EVALUATIONS

Five test pilots\* conducted formal evaluations of the two primary control configurations — the "4-Axis" and "3-Axis" systems depicted in Figure 7. A third system, the one designated "3-Axis/Twist-Collective" in the same figure, was evaluated thoroughly by one pilot and several other channel assignments were flown briefly to assess their value as transition or training configurations. This phase of the experiment consisted of approximately 50 hours of test flying, spent predominantly in high-workload visual flight tasks which demanded precise control of the helicopter close to the ground and ground level obstacles.

The pilots' assessments were recorded in their responses to two questionnaires and in a general narrative addressing any additional impressions which they considered significant. The first questionnaire was completed immediately following the test flight sequence with each combination of control configuration and helicopter stabilization level. The responses in this case included pilot ratings for each of the major task groups and general comments on the handling qualities which dictated these ratings. The pilot rating data from the evaluations of the "4-Axis" configuration (the only system which was investigated thoroughly by *all* of the evaluation pilots) have been summarized for two of the major task groups in Figure 9.

The second questionnaire was administered after all of the test flying was completed. In this case, the pilots were asked to respond to six specific questions which were designed to highlight the benefits and deficiencies of the multi-axis isometric control system. The questions and abbreviated versions of the responses are reproduced as Appendix A.

Finally, each pilot provided a short narrative summary of his impressions of these unconventional control systems, including suggestions for improvements in the controller hardware, in the presentation of control position information to the pilot and in the system software. These impressions and general assessments provided in response to the first questionnaire are reflected in the discussion which follows.

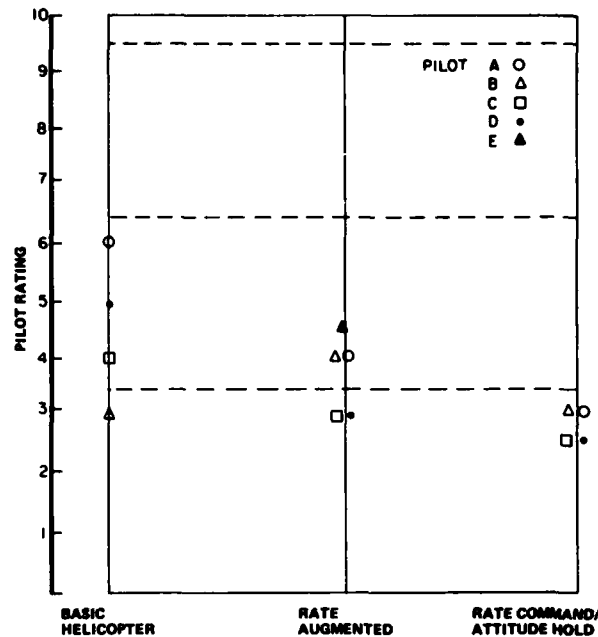
TABLE 3

### SUMMARY OF THE EVALUATION PILOTS' FLYING EXPERIENCE

| Pilot | Total Hours | Helicopter/Fixed Wing |
|-------|-------------|-----------------------|
| A     | 3500        | 3250/250              |
| B     | 5700        | 400/5300              |
| C     | 6900        | 900/6000              |
| D     | 6500        | 4000/2500             |
| E     | 5600        | 1550/4050             |

\*Table 3 gives a brief summary of the flying experience of the evaluating pilots.

TASK: MANOEUVRING AT OR NEAR HOVER  
CONTROL CONFIGURATION: 4-AXIS



TASK: MANOEUVRING AT HIGH SPEED  
CONTROL CONFIGURATION: 4-AXIS

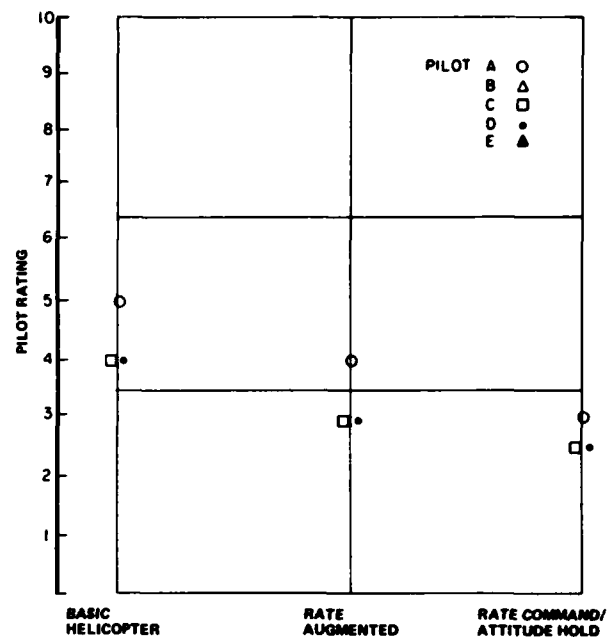


FIG. 9: PILOT RATINGS FROM 4-AXIS CONTROLLER ASSESSMENTS

## DISCUSSION OF RESULTS

One of the most interesting and perhaps most surprising observations in these experiments was the ease with which pilots adapted to multi-function isometric controls. All pilots were able to fly the test helicopter with confidence, using the developed systems, after a very brief familiarization flight following ground briefing. Nevertheless each one of the experimental configurations presented the pilot with unfamiliar and conceptually new control demands. In the following paragraphs some of the distinctive features of the tested systems are discussed in the light of the evaluation pilots' assessments. The pilot comments relevant to each of these subjects may be found in Appendix A.

**Multi-Axis Controllers** In many operational situations a helicopter pilot is required to perform auxiliary manual tasks while he stabilizes or manoeuvres the aircraft. Often these "secondary" tasks are intricate and demanding manual operations which, in a conventional cockpit, must be accomplished with the left hand on a stolen-time basis, while engine torque management (collective control) is temporarily suspended. Since it is not always possible to schedule the two left-hand activities conveniently, the pilot's mental and physical workload is increased as he attempts to deal with these conflicting demands. The integration of the collective function into the right-hand controller is a major step toward resolving the helicopter pilot's dilemma of too-many-jobs for too-few-hands. The left hand can in this way be freed to perform non-control tasks such as armament system or communication and navigation system management without interrupting control of the helicopter. The three-axis and four-axis controller configurations which were evaluated in the flight program provide this convenience.

It is clear from these experiments that a helicopter can be flown through a wide range of visual and instrument flight tasks using either a three-axis or four-axis isometric side-arm controller — without requiring exceptional pilot skill or concentration and within the bounds of normal helicopter workload demands. This was demonstrated in the flight program with the NAE Airborne Simulator, a single-rotor, medium transport helicopter.

When the multi-axis isometric controllers are used in conjunction with an advanced manoeuvring control mode the combination is an effective system for precise helicopter control.

**Left or Right Hand Control** It is a simple extension of the integrated controller philosophy, although not a trivial design problem, to make the one-handed control system "ambidextrous" by installing controllers for both left and right hand operation. Such a system would have a fundamental influence on cockpit layout since the pilot could then be expected to perform auxiliary manual tasks with either hand — interacting with systems on either side of his seat position. In the instrument flight environment this controller arrangement would further reduce the workload of a right-handed pilot when he must select charts and maps and copy clearances — tasks which he performs more easily with the right hand.

Although left-hand operation was not emphasized in the test planning, several of the pilots developed the skill to the extent that they could perform the experimental tasks satisfactorily using the left-hand controller.

**Control Position Feedback** The lack of any direct mechanical feedback of control position information — via the controllers, to the pilot — is a significant factor in the use of isometric controllers in helicopter flight control systems: other suitable means must be provided to inform the pilot of the control actuator positions since this information is necessary for the safe and efficient operation of a helicopter in many routine flying situations.

It is important that the control position information be presented in an easily-interpreted form (the pilot is often interested in control-authority-remaining and tip-path plane orientation), and in such a way that the assimilation of the information does not detract from normal out-of-the-cockpit or instrument panel visual scans.

The results of this experiment suggest that sufficient feedback information may be provided by a well-designed control position indicator (CPI). Using the rudimentary CPI shown in Figure 5 the pilots were able, for example, to perform slope landings and take-offs with the required degree of control precision. An improved display and greater familiarity with the control and display systems would undoubtedly increase pilot confidence in performing such tasks using the isometric controllers. A final judgement on this point should nevertheless be reserved until these systems have been evaluated in simulated emergency situations which require rapid, large-amplitude recovery control action.

**The Primary Configurations** Pilots adapted quickly to either of the two primary controller configurations — the 3-Axis or 4-Axis systems — indicating that the relationship between control input and helicopter response was natural and intuitive in both cases. After a short familiarization period the evaluation pilots found that control cross-coupling or channel "cross-talk" was not a major factor in performing the experimental tasks, even with the fully integrated (four-axis) controller. The pilots who expressed a preference for this fully integrated controller assessed the flying qualities of the 3-Axis and 4-Axis systems to be equivalent but based the choice between the two on considerations of simplicity in the overall system design and added comfort with feet-on-the-floor. Those who favoured the 3-Axis system were concerned that the fully integrated controller might be more vulnerable to cross-coupled inputs in emergency situations and that assignment of four distinct functions to one hand could overload that member during high-workload operations. A design choice between these two methods of control could therefore be dictated by considerations which were not addressed in these experiments, in particular by the handling qualities of the combined aircraft-control system in emergency situations such as recovery from system failures, degraded system operations after a failure, entry into autorotation and landing from an autorotative approach.

**The Secondary Configurations** The "3-Axis/Twist Collective" mode depicted in Figure 7 — the mode which assigned the twist function to main rotor collective control — had significant drawbacks and no redeeming features. Although it might be argued that the twisting action is indirectly associated in the helicopter pilot's mind with power control — through familiarity with the conventional collective-mounted throttle — the association with collective is tenuous and the

relationship between an input torque and the vertical response of the helicopter is not intuitive. The system could be mastered and was flown successfully but it was considered to be markedly inferior to the 3-Axis version which used vertical forces on the controller to command the collective channel.

The two-handed configurations (Figure 7), both of which controlled pitch and roll with the right hand, heave with the left hand and yaw with pedals, were not evaluated systematically in this program but were flown briefly by several of the pilots. These systems could be flown with ease and presented no problems peculiar to their essentially-conventional assignments of the control functions to the left and right hand controllers.

**Hand Control of the Yaw Axis** Operations with the four-axis controller bring to light some interesting facets of conventional directional control systems. With the exception of the pedals, the conventional controllers are installed in such a way that the aircraft responds in the direction of the applied control input. If this philosophy were extended to the pedals the aircraft would be expected to yaw to the *right* when the pilot pressed forward on the *left* pedal, but with the standard control system the opposite response occurs. The situation is complicated during airmass-referenced flight when the pedal control is used to eliminate sideslip, and sideslip is displayed — indirectly — by the displacement of the ball in the needle-and-ball instrument. This rather involved compensatory task is simplified in training by teaching the pilot to "step on the ball" with the appropriate foot, that is, if the "ball is to the left — press left pedal".

When the pilot is given a "consistent" control for the yaw axis, one which produces a yawing response in the direction of the moment applied to the controller, (e.g. the four-axis handle used in this program), the subconscious, trained control action with reference to the needle-and-ball does not work. It is necessary then for the pilot to overwrite the old message with one which reads "turn the aircraft toward the ball". This adjustment was easily made. When the pilots performed instrument flight tasks using the 4-axis controller, the initial uncertainty concerning the proper response to a displacement of the ball was quickly replaced with the new "instinctive" reaction in the correct sense.

## CONCLUDING REMARKS

In the field of manual control there is often a great gap between what *can* be done — even what can be done with ease — and what ultimately proves to be the accepted way. Clearly, a short flight test program such as this cannot answer all of the questions which the helicopter designer must ask concerning the viability of multi-axis isometric side-arm control. Nevertheless the experiment has demonstrated the feasibility of controlling a helicopter through a wide range of demanding flight tasks, with the desired degree of precision and acceptable workload, using these unconventional integrated flight control systems. In light of the design and operational benefits which these systems offer, the investigations of integrated isometric control systems should be extended to include an assessment of handling qualities improvements associated with task-optimized control laws and an evaluation of safety-related aspects of control following system failures.

## ACKNOWLEDGEMENT

The names and affiliations of the participating test pilots are listed below in alphabetical order:

|             |                   |
|-------------|-------------------|
| S. Kereliuk | NAE               |
| G. Kohler   | Sikorsky Aircraft |
| M. Morgan   | NAE               |
| R. Murphy   | Sikorsky Aircraft |
| A.D. Wood   | NAE               |

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Rotorcraft Design, AGARD CP 233.

#### APPENDIX A

This appendix presents the responses of the pilots to a set of questions concerning various aspects of multi-axis isometric side-arm control.

RESPONSES TO QUESTIONNAIRE

| QUESTION                                                                                                                           | PILOT "A"                                                                                                                                                                                                          | PILOT "B"                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | PILOT "C"                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | PILOT "D"                                                                                                                                                                                                                                                                                                                                                                                                       | PILOT "E"                                                                                                                                                                                                                                                                                                                                      |
|------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. Does the lack of position feedback in the controllers contribute significantly to pilot workload in any of the evaluated tasks? | Not in any task in which the aircraft responds, i.e. lack of feedback not a problem in flight. It was a factor in accurately positioning the rotor for a lift-off from a slope, but CPI's eliminated that problem. | Control positions are integral part of helicopter pilot's assessment of performance capability and handling margins. Through most of flight envelope alternative cues are adequate but for gross manoeuvres where control authority remaining is important, and during exercises requiring great finesse (e.g. partial contact hovering and off-level operations) control position information is vital. Absence of control position information leads directly to both an increase in pilot workload and due to resulting caution, a reduction in effective flight envelope. CPI's, provided they are precise and optimally mounted for the head-up task, will restore the information sufficiently for all operations. | Considering collective cue, significant portion of visual scan was devoted to engine torque meter when making power changes - until familiarity with integral trims was gained. Training and use of CPI may provide necessary feedback.<br><br>Lack of control position cues in pitch, roll and yaw became very apparent on take-off and landing. This resulted in slower collective increase during take off to provide time to assess control demands in other three axes. Pilot does not have readily available information on the balance state of the aircraft provided by displacement controls - what would have been extremely comfortable workload was in fact an increased-gain environment.<br><br>Lack of control position cues also inhibited aircraft operations near limits in sideward flight, crosswinds etc., to extent that pilot tended to be conservative in his estimate of operating envelope. | Lack of position feedback of lateral stick gave a problem in slope landings/take offs.<br><br>Yaw was only a problem initially in keeping ball in centre. Training took care of this.<br><br>It remains to be seen whether the lack of collective cue will be a problem in autorotation. At present, with power, the pilot can use torque. In autorotation this will not be possible. Perhaps CPI will suffice. | Yes, although not so much a problem in normal forward flight as in exercises associated with hovering. For example, careful monitoring of CPIs required during lift-off or landing, particularly on a slope, adds significantly to pilot's workload. This could be a disadvantage in operational situations with various distractions present. |
| 2. Does the upright position with arm supports have significant benefits?                                                          | Significantly reduces both fatigue and backache compared to conventional helicopter pilot's slouch. Also, side arm controller allows pilot to adjust seat for best visibility rather than control reach.           | Much preferred to standard "helicopter crouch". Comfort definitely improved while exposure to inadvertent inputs due to aircraft movement and its inertial effect on the usual cantilevered hand and forearm is markedly reduced. Anticipated that pilot fatigue would be reduced considerably, especially during long flights.                                                                                                                                                                                                                                                                                                                                                                                          | Tasks in this research program were selected to give pilot high control activity throughout each sortie. In this intense environment, the pilot's physical workload was noticeably eased. Upright position is an important improvement and should decrease incidence of "helicopter back".                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Yes. It allows pilot to sit comfortably and relaxed in the seat.                                                                                                                                                                                                                                                                                                                                                | Yes, with some provision to allow the pilot to adjust the geometry to suit his own arm, wrist and hand limitations.                                                                                                                                                                                                                            |

| QUESTION                                                                                                                                                                                                | PILOT "A"                                                                                                                                                              | PILOT "B"                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | PILOT "C"                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | PILOT "D"                                                                                | PILOT "E"                                                                                                                                                                                                                                                                                                                                            |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 3. Do you consider left-or-right hand control capability to have significant operational implications?                                                                                                  | Only for single-pilot military aircraft to enhance serviceability.                                                                                                     | Major implications for military in providing capability to recover machines following partial incapacitation of pilot. Same capability promising for normal operations for both civil and military. During system development flying in this program freedom to use either hand for ancillary tasks — radio tuning, switch selection, closing door which became unlatched — was pleasant convenience. Advantages for civil single-pilot IFR may be significant. Simply transferring collective to right hand could reduce stability augmentation requirements for certification.                                                                                                                                                                                                                                                                                                                                                                  | In addition to obvious military concern about incapacitation of a limb, ability to control aircraft with either single hand may provide significant benefits in IFR flight — freeing either hand for use in auxiliary tasks.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | No. Not in 2-pilot aircraft.                                                             | Yes, significant advantages:<br>(a) in allowing the pilot some choice in using one or other hand for secondary tasks,<br>(b) in providing some alternative in the event of an arm injury in a combat situation.<br><br>Several alternative combinations involving from 2 to 4-axis hand controllers and pedals would be worth further investigation. |
| 4. Are "integral trims" required in all controls when flying the basic or augmented aircraft with force controllers? Do these integral inputs present any problems during normal helicopter manoeuvres? | Required with the force controllers. A "beeper"-type trim is more work with no advantages. The integral inputs present no problems during any of the manoeuvres flown. | Collective. Integral trim essential. Yaw. When yaw controlled by twist on handle, integral trim probably essential; when yaw inputs via pedals perhaps possible to optimize sensitivities such that some form of program trim could be used. Major disadvantage of integral trim is that it gives pilot no indication control remaining when 100% control occasionally met and frequently approached.<br><br>Pitch and Roll. For greater part of flight envelope integral trims considered essential. Action of using "Chinese Hat" button introduces inadvertent inputs of unacceptable magnitude. For only one task — landing in presence of turbulence — control without integral trims was preferred. Task requires frequent small amplitude inputs about sensibly constant mean and these can be achieved with greater confidence with integral trims disabled — but must have established basic hover datum at zero force before disabling. | Operation without integral trim in all axes where control force demands were within shallow linear force gradient of controller posed no problem. However this would severely restrict operational envelope. Location, mode of operation and forces required on "Buzz" trimmer made this control unacceptable due to involuntary introduction of force inputs. Consequently integral trimmers found to be essential in all axes.<br><br>No problems with these trimmers in roll, pitch, yaw. However, with collective on vertical axis of controller the integration rate caused an apparent lag in leave control, particularly evident in "Quick-Stop" and other manoeuvres requiring large, rapid collective changes. Problem diminished with increasing familiarity with configuration.<br><br>Autorotation entries were not attempted but likely to highlight problem with integration rate used for normal flight in this program. | Yes. Necessary.<br><br>No. They work well and are improvement over present trim systems. | Consider integral trims to be necessary.<br><br>Not a problem for the manoeuvres investigated, but do not consider them to have been fully evaluated during the program.<br><br>For example, autorotations were not attempted and could also influence opinions on the controllers themselves.                                                       |

| QUESTION                                                                                                                                                                           | PILOT "A"                                                                                                                       | PILOT "B"                                                                                                                                                                                                                                                                                                                                                                                                                                          | PILOT "C"                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | PILOT "D"                                       | PILOT "E"                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
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| 5. Are there any manoeuvres or operational tasks which are more easily accomplished with the side-arm force controllers than with a conventional helicopter control configuration? | No manoeuvres were considered easier with force controllers but neither were they more difficult.                               | As experience with force system accumulated, all manoeuvres were performed more easily with side-arm force controllers than with conventional position controls - with exception of off-level operation. (See discussion for Question #1.)                                                                                                                                                                                                         | Feature of absolute controller trim retention with integral trims on was very useful when releasing controller to perform auxiliary tasks. When landing the aircraft it appeared to be easier to set and control descent rate through ground cushion in all side-arm configurations because of ability to make very small collective changes very smoothly. Small control demands in all axes appeared to be met more smoothly.                                                                                                                    | All tasks were at least as easy with side-arm.  | Manoeuvres, no. Operational tasks, probably depending upon display format sophistication intended and the need for using hands for secondary tasks.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| 6. Would you prefer to have three or four functions on each hand controller? (i.e. pedals or no pedals?)                                                                           | Either configuration would be equally practicable to fly. Total system simplicity would seem to favor the four axis controller. | Preference, though a marginal one, is for pedals. Due to previous conditioning, pedal inputs are more natural in gross manoeuvres, especially those involving multi-axis inputs such as rapid stops and abrupt into-wind turns. However, tendency toward excessive yaw control activity when very near ground - which some pilots exhibit - disappeared (for Pilot "B") when yaw was hand controlled.<br><br>Preference for pedals is very slight. | The four-function control configuration was assessed to be acceptable for all and satisfactory for most flight conditions. However, because of past training, when yaw control was introduced on pedals this control axis was accommodated automatically, pitch and roll control axes were similar to conventional (deflection) control inputs, and the heave inputs were in an entirely natural sense. This decreased pilot's workload somewhat and decreased pilot's tendency to introduce inadvertent cross-coupled inputs in rapid manoeuvres. | Positively no pedals. Do not like force pedals. | No more than three on each hand and possibly only two (pitch and roll) for right hand. Retain pedals for yaw.<br><br>Yaw control on pedals helps considerably in decoupling. May largely be because a requirement to twist the controller necessarily entails gripping the handle. For pitch and roll inputs alone it is possible to avoid gripping or to do so almost instantaneously. When large heading change is required, however, yaw control must be applied over a considerable period of time during which the hand cannot be released. Necessity to grip controller probably affects adversely longitudinal and lateral control just before touchdown. |

| QUESTION                       | PILOT "A"                                                                                                                                                                                                                                                        | PILOT "B" | PILOT "C" | PILOT "D"                                                                                                | PILOT "E"                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|--------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|-----------|----------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>7. Additional Comments.</p> | <p>In addition to CPI's, some sort of stick vibrator or buzzer (not aural) to warn of full control displacement would be helpful in manoeuvring flight.</p> <p>The control grip used in this program needs improvement - needs to be built-up in thumb area.</p> |           |           | <p>Controller needs to be modified to provide better grip for those modes requiring twisting action.</p> | <p>Concerned about "vulnerability" of force-type hand controllers to jerky inputs - particularly in circumstances where sharp inputs may be introduced inadvertently or as a result of operational factors, e.g. surprise, gunfire . . . Have impression that "upsets" caused in this way are less easily rectified than with conventional controls.</p> <p>Force-controller concept is interesting and, in many ways, attractive. However, see no over-riding merit in putting feet out of work.</p> <p>Placement of force-pedals is probably amenable to considerable variation so that the provision of downward view should not be a significant factor favouring their elimination.</p> <p>So why give the hands, which can be used for so many other purposes, an extra job which the feet can do?</p> |

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