NASA Technical Memorandum 86683
USAAVSCOM Technical Memorandum 85-A-1

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April 1985

NASA
National Aeronautics and Space Administration

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Edwin W. Aiken
Aeromechanics Laboratory, U.S. Army Research and Technology Laboratories - AVSCOM
NASA Ames Research Center
Moffett Field, California 94035 U.S.A.

Abstract

Pertinent fixed- and rotary-wing feasibility studies and handling-qualities research programs are reviewed and the effects of certain controller characteristics on handling qualities for specific rotorcraft flight tasks are summarized. In particular, the effects of the controller force-deflection relationship and the number of controlled axes that are integrated in a single controller are examined. Simulation studies conducted as part of the Army's Advanced Digital/Optical Control System (ADOCS) program and flight research programs performed by the National Aeronautical Establishment of Canada provide a significant part of the available handling qualities data. These studies demonstrate the feasibility of using a single, properly designed, limited-displacement, multi-axis controller for certain relatively routine flight tasks in a two-crew rotorcraft with nominal levels of stability and control augmentation. However, for the more demanding terrain flight tasks, unless high levels of stability and control augmentation with a high degree of reliability are incorporated, separated three- or two-axis controller configurations are required for acceptable handling qualities.

Introduction

Advanced flight control systems which employ fly-by-wire or fiberoptic technology provide the control system designer with the flexibility to synthesize the system based upon pilot-oriented design criteria. In addition to multimode control laws which vary as a function of mission task and flight condition, these systems will include advanced pilots' controllers with designs that are no longer constrained by the characteristics of a mechanical flight control system. One particularly appealing design concept is the replacement of the conventional set of primary controllers by a single side-stick controller. This approach to controller design provides significant benefits to the cockpit designer by increasing the available cockpit space, by a savings in weight, and by improvements in reliability; pilot safety and comfort may also be enhanced by the resultant improvements in visibility, ingress/egress, crashworthiness, and by the elimination of the poor posture caused by conventional controller location. However, until recently, the effects of this advanced controller concept on the ease and precision with which a pilot is able to perform terrain flight tasks were largely unknown.

Much of the background information presented in this paper is based upon investigations of the effects of controller characteristics on aircraft handling qualities: "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role."[1] Handling qualities are, therefore, influenced not only by aircraft stability and control characteristics but also by factors such as the design of the cockpit interface--the controllers and displays provided for the required tasks. All of these handling qualities studies have assumed a two-crew situation; no duties such as navigation, communication, and battle-captain functions, which would be performed by the pilot of a single-crew combat rotorcraft, were assigned to the pilots. Therefore, extrapolation of these results to the single-crew situation must be based upon sound engineering and piloting judgment. The controller tradeoffs addressed in this paper are: 1) conventional versus side-stick controllers, 2) displacement versus force controllers, and 3) separated versus integrated controllers.

Conventional versus Side-Stick Controllers

Cockpit Design Implications

The replacement of the conventional set of primary controllers by a single side-stick controller can yield significant benefits. An increase in available cockpit volume provides valuable room for the additional avionics required to perform the advanced scout/attack mission. In a comparison of conventional cockpit controllers with a configuration consisting of a two-axis side-stick and small-displacement collective and pedals, Ref. 2 reports a 30% weight savings with the side-stick configuration. This same study claims significant improvements in both flight

Presented at the International Conference on Rotorcraft Basic Research, Research Triangle Park, North Carolina, February 19-21, 1985.

safety and mission reliability using the advanced controllers.

Certain human factors and man-machine integration benefits can also be derived from a cockpit design which employs a side-stick controller. Potential benefits include improvements in: 1) visibility caused by the removal of the pedals and cyclic stick; 2) ingress and egress, especially if the side-stick can be mounted on a movable armrest as in Ref. 3; 3) crashworthiness, caused by the removal of potentially lethal objects from the cockpit; and 4) pilot comfort, by eliminating the need for the traditional helicopter pilot slouch over the controls, and by allowing feet-on-the-floor flight. However, "any benefits gained in a substantial deviation from this (conventional) arrangement must be weighed against the costs of retraining the pilot's spontaneous control command patterns, particularly in high workload and emergency situations."[4]

Feasibility Studies

Simulator and flight investigations have demonstrated the feasibility of the use of a side-stick controller in both fixed- and rotary-wing aircraft for certain tasks. All of the fixed-wing studies involved side-sticks with two axes of control: pitch and roll. In a 1957 NACA-sponsored program, a Navy F9F was equipped with a side-stick controller to investigate the control implications of such a device.[5] All of the pilots were able to execute precision flying tasks with no performance degradation. Pilot effort was felt to be reduced because of the lighter control forces and the comfort provided by the controller armrest. In 1970, the Air Force Test Pilot School flew an F-104 equipped with a side-stick controller.[6] The side-stick was unanimously preferred to the conventional center stick and provided superior trajectory control with drastically reduced pilot workload. Over 60 pilots flew with the side-stick and accumulated 870 hr of flight time with no controller failures. A direct comparison of pilot performance with a center-stick and a side-stick was performed at Wright-Patterson AFB in 1970.[7] The study concluded that a side-stick was feasible for use in high-speed, high-altitude maneuvering tasks; it resulted in improved performance for landings and other precision maneuvers, but it yielded degraded performance for large-amplitude maneuvers at low altitudes.

Feasibility studies of the use of side-stick controllers in helicopters began in 1968 with the Tactical Aircraft Guidance System (TAGS) program.[8] That system was implemented in a CH-47B aircraft and initially included a four-axis displacement controller; because of anatomical coupling problems between the longitudinal and vertical axes, a three-axis controller was eventually implemented with vertical control effected through a standard collective lever. Pilots were also critical of the longitudinal control implementation; the large displacement (4.5 in.) and viscous damping created a controller which felt massive and heavy. Both the lateral axis (a base-pivot design) and the directional axis (a twist-grip) were considered acceptable. The use of multi-axis controllers was rejected for the Heavy Lift Helicopter (HLH) primary flight control system[9]; however, a four-axis finger-ball displacement controller was implemented at the load-controlling crewman's station in that vehicle for precision cargo handling tasks requiring a high level of stability and control augmentation.

In a three-degree-of-freedom moving-base simulation of the unaugmented Lynx helicopter at the Royal Aircraft Establishment (RAE) Bedford, a two-axis displacement side-stick was compared with the conventional cyclic controller for 11 different flight tasks.[10] When a suitable control sensitivity was selected, the side-stick compared favorably with the conventional controller and, in fact, was preferred for some of the tasks which required only small control movements. Manual trimming was considered to be difficult because of the trim-button location and the force required to operate it; inadvertent control inputs were the result. A simple armrest drew no adverse comments, but a wrist support was recommended. In a piloted simulation of an Advanced Scout Helicopter (ASH), an A-7/F-16 two-axis side-stick was found to be feasible for an ASH mission when employed with suitable levels of stability and control augmentation.[2]

A feasibility study of a four-axis isometric (rigid) side-stick controller was conducted for a wide range of flight tasks[11] in the Canadian National Aeronautical Establishment (NAE) Airborne Simulator, a variable stability Bell Model 205A-1. Two primary side-stick configurations, a four-axis controller and a three-axis controller with normal pedal control, were evaluated together with variations in the level of stability and control augmentation. A conclusion of this study was: "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 work load demands." In a follow-on flight investigation,[12] a comparison of conventional controllers with the same two isometric side-stick configurations was conducted by flying the Airborne Simulator with augmented pitch, roll, and yaw-rate damping through a low-altitude course involving both maneuvering and precision flight. For this experiment, "the pilots generally considered isometric (side-stick) control to be more difficult and less precise, in this type of closely bounded task, than conventional control."

Handling Qualities Studies

Handling qualities studies--those which elicit both Cooper-Harper pilot ratings[1] and pilot commentary--which include a comparison of conventional controllers with side-stick controllers are rare. The Ref. 11 flight data, as interpreted in Ref. 12, revealed that, when appropriate gains, shaping, and prefiltering were applied to the pilot's force input in each controlled axis, pilot ratings comparable to those that were obtained with conventional controls were achieved by both primary side-stick configurations. In two moving-base simulations of helicopter visual terrain flight,[13] it was determined that the employment of a properly designed two-axis displacement side-stick controller could, in fact, improve handling qualities over those provided by conventional controllers (Fig. 1) but that increased levels of stability augmentation were required to achieve comparable pilot ratings if a three- or four-axis isometric controller was employed (Fig. 2).

Summary (Conventional versus Side-Stick)

The use of a single side-stick controller to replace the conventional set of helicopter controllers offers significant advantages to the cockpit designer and has the potential for enhancing pilot safety and comfort. However, based upon the results of the feasibility and handling qualities studies cited in this section, a single, multi-axis side-stick controller has never been demonstrated to improve handling qualities for any helicopter flight tasks; in fact, there is a strong indication that increased levels of stability and control augmentation are required to achieve even comparable handling qualities for visual terrain flight tasks similar to those required of advanced combat rotorcraft. Only a properly designed two-axis side-stick has been shown to offer the potential for improved handling qualities when it is compared to a conventional cyclic stick; it is very possible, however, that improved conventional cyclic stick force characteristics would negate, or reduce the significance of, this advantage.

Displacement versus Force Controllers

Input Bandwidth

With a conventional set of controllers, the position of each controller with respect to some reference point is the pilot's input to the control system; the relationship between the applied force and the resultant displacement may be expressed as a second-order response with characteristics determined by the force-feel system of the aircraft. The use of a force controller eliminates this second-order "filter" on the control input, thus allowing closer control of the flightpath of the aircraft since the applied force is itself the input quantity. As a result, the inputs as seen by the control system could have a much higher frequency content, or bandwidth, than when displacement controllers are employed. This characteristic provides the potential for a more precise control of the flightpath but also makes the control system, and hence the aircraft response, more sensitive to sharp control inputs, to inertial forces such as those experienced in high-g maneuvers, and to aircraft vibrations that are fed through the controller grip. It was for these reasons that the original force-sensing stick of the F/A-18 was replaced by a displacement controller during full-scale development testing.[14] In that program, forward-path prefilters were employed in the digital flight control system to smooth the pilot's inputs from the force stick, but those filters also yielded degraded controllability. Extra weight was required to mass-balance the stick against the forces caused by catapult launch. Notch filters in the flight control software were required to prevent structural interaction through the inertia of the grip and the pilot's arm at structural resonance frequencies; these filters also caused additional time delays which further degraded handling qualities and caused pilot-induced oscillations.

Advantages and Disadvantages

The advantages of a force controller lie in its inherent simplicity, reliability, and low parts count.[3] In addition, no force-feel system is required to provide the control force characteristics that are dictated by handling qualities requirements. However, the lack of explicit control position information from a force controller can be a significant disadvantage. Although the human pilot is not a particularly accurate sensor of controller displacement, the lack of any displacement cues can degrade the ability to make smooth and precise control inputs. An operational problem that is caused by this lack of control position information was highlighted in the Refs. 11 and 12 flight experiments. Because of the use of the force controller, the analogies between conventional cyclic-stick position and main rotor tip-path plane orientation and between pedal displacement and the remaining yaw-control authority were eliminated. The former relationship is particularly important for slope takeoffs whereas the latter provides important information when operating with large yaw rates or in the presence of large sideslip angles. A visual presentation of this information was added to the instrument panel to compensate for the loss of control position cues. Problems caused by the lack of absolute collective pitch-angle information were revealed in simulations conducted to support the JVX development. The conventional collective stick position, as an analog for collective pitch angle, provides important information to the pilot during takeoffs, autorotations, or maneuvers at high power. As a result, the original force controller used for vertical control inputs was replaced by a small displacement controller.

Because of the lack of motion of a pure force controller, both trimming and control transfer become more difficult to implement. With a sophisticated flight control system the need for manual trim inputs may be eliminated by incorporating automatic trim logic in the control laws. Similar logic may be incorporated to assist in control transfer to minimize aircraft transient response. However, in situations with a degraded flight control system, trimming and control transfer may have to be performed unaided. Low-force trim switches are required to eliminate the possibility of inadvertent control inputs while trimming; in addition, the rate of removal of steady trim forces must be carefully selected to minimize any transients.

In a related area of concern, any secondary control functions or selectors that are mounted on the grip of a force controller must be implemented so as to minimize any hand motion or application of force which might cause inadvertent primary control inputs. Low force switches or buttons are a requirement when using a force controller.

Results of Force/Deflection Studies

Results of both fixed- and rotary-wing handling qualities research in the investigation of the relative benefits of force and displacement side-stick controllers indicate significant advantages for limited-displacement controllers. In several fixed-wing flight investigations typified by Ref. 15, an "optimum" region for force-deflection relationships was defined for two-axis side-stick controllers. Typically, isometric force controllers yielded performance which was very sensitive to the control sensitivity provided (aircraft response per-unit-of-applied-force); adequate performance was only possible for a very restricted range of control sensitivities. As the amount of controller compliance increased, the region of acceptable control sensitivities also increased to some maximum value.

With further increases in controller deflection-per-unit-applied-force, degraded handling qualities occurred with comments about excessive stick motion requirements and overshoots in aircraft response. the results of these flight experiments were incorporated in a design guide for two-axis side-stick controllers used in fighter aircraft.[16] Aircraft design experience also substantiates the limited-displacement requirement. The original side-stick design for the F-16 prototype incorporated a virtually zero-displacement force controller (±0.030 in. at the grip); subsequent refinement for the production F-16 showed that a ±0.2 in. displacement was desired for longitudinal control and a ±0.10 in. displacement was desired for lateral control.

A total of seven different four-axis side-stick controllers, exhibiting a wide range of force-deflection characteristics, was evaluated for use in helicopter terrain flight during the ADOCS Advanced Cockpit Controls/Advanced Flight Control System (ACC/AFCS) simulator investigations.[17-19] Three of these controllers are illustrated in Fig. 3. Early in that program, it was found that, as in the fixed-wing investigations, the introduction of a limited amount of deflection in the pitch and roll axes yielded improved task performance and handling qualities (Fig. 4). Comments on sluggish control response and less precise attitude control resulted when there was too much deflection. Later in the program, harmony among the four control axes was also found to be an important consideration; a controller with two limited-deflection control axes (pitch and roll) and two rigid control axes (vertical and directional) was judged to be only marginally acceptable (Fig. 5). All pilots felt that deflection in all control axes improved the ability to modulate single-axis forces, produced less tendency for overcontrol and anatomical coupling, and enhanced control precision for high-gain piloting tasks such as precision hover.

To compensate for the potential of an increased control input bandwidth with a force-sensing controller, both the ADOCS and NAE[20] side-stick implementations included some preprocessing of the control force input before it was used to drive the control systems. A nonlinear shaping function, consisting of a dead zone (or breakout) and quadratic (NAE) or piecewise-linear (ADOCS) control sensitivity function, was employed to provide acceptable levels of control sensitivity around zero force with minimum coupling of control inputs while permitting large, short-duration inputs to be made without the use of excessive control force. In addition, to guard against the response of the aircraft to sharp pilot inputs such as the rapid release of large control forces, both systems incorporated techniques to smooth the control input. The NAE system employed a 16 rad/sec first-order filter in each control axis whereas the ADOCS control laws included a "derivative rate limiter" designed to limit peak accelerations for large control inputs without affecting control precision for small force inputs.

Summary (Displacement versus Force)

A summary of the advantages and disadvantages of a force-sensing controller is presented in Table 1. Small-displacement force controllers have been shown to provide significant handling qualities advantages over rigid controllers. However, the control system software employed with this type of controller must provide: 1) the means to compensate for sharp pilot inputs and vibratory forces; 2) the capability for both automatic and manual trimming; and 3) control transfer in a two-crew situation. Low-force buttons and switches are required for any grip-mounted secondary controllers or selectors. The lack of explicit control position information may pose a problem under operational conditions such as slope takeoffs or in flight with large sideslip angles, and in emergency conditions such as engine and flight-control system failures.

Separated versus Integrated Controllers

For the purposes of this discussion, fully "integrated" controllers are those which combine all primary control functions on a single device. "Separated" controllers are produced when one or more of these functions is removed from the integrated controller. Levels of integration evaluated in both the ADOCS and NAE investigations range from a fully integrated four-axis device to a separated-controller configuration consisting of a two-axis side-stick and conventional collective and pedals (Fig. 6). Two primary issues are discussed in this section: 1) human factors requirements for controller integration; and 2) handling qualities effects of the level of integration.

Human Factors Requirements

Three "human factors" requirements directly related to the integration of multiple control axes on a single controller are discussed: 1) the selection of an appropriate controlled axis reference system; 2) grip design requirements; and 3) compensation for human pilot characteristics in both hardware and software.

A number of two- and three-axis hand controllers have been investigated for fighters, spacecraft, and helicopters. These controllers have used a variety of reference systems for the control inputs. The roll-control axis has been parallel to the forearm and beneath the hand in almost every controller tested. With this roll axis, the most intuitively correct pitch-control axis is horizontal and is perpendicular to, and intersects, the roll axis. This axis system, used for the conventional center stick and for the F-16 side-stick, requires some forearm motion for pitch inputs to a displacement controller, which is a possible disadvantage in a high-g or vibratory environment. As a result, other pitch pivots which allow operation without arm movement, such as wrist- or palm-pivots, have been investigated. Both the ADOCS and the NAE research programs employed a more conventional base-pivot set for pitch and roll to minimize the risk that is inherent in a transition to a side-stick controller. The yaw axis of control in a hand controller has been implemented in several ways; the most prevalent has been the grip twist about the vertical axis of the hand grip itself. Alternatives, such as a thumb lever to avoid the input cross-coupling problems that are inherent in the grip twist approach, result in hand-fit problems and pilot fatigue. To maintain control input-aircraft response compatibility, vertical control was effected through the application of pure up and down forces in both the ADOCS and NAE programs. A configuration that was evaluated by the NAE using grip twist as the vertical input was confusing and unacceptable.

Much more stringent requirements for grip design exist for integrated controllers than for separated, conventional controllers. The grip must be shaped so as to assist the pilot in identifying the controlled axes by providing a constant hand position with respect to the grip. It must be designed to allow the pilot to make clean control inputs into each axis with a minimum of inadvertent inputs into other axes. The original hand grip that was supplied with the isometric controller and evaluated by the NAE was found to cause vertical-to-pitch and roll-to-yaw input cross-coupling; a redesigned grip was found to be more acceptable.[12] This new grip formed the basis for the design of the integrated controller grip which is implemented in the ADOCS demonstrator helicopter.

Other design factors, while important for separated controllers, become critical for integrated controllers. The controller location, orientation, and armrest/wrist support design are crucial factors in determining the pilot's ability to make smooth, uncoupled control inputs with minimum of effort and maximum comfort. The ADOCS program has supplied a significant number of lessons learned in this regard (Fig. 7). Finally, to compensate for relative arm/armrest/controller geometry effects, it may be necessary to provide asymmetric control sensitivities in certain control axes. For example, the NAE program revealed that it was significantly easier for the pilot to produce an upward vertical force than a downward force using the four-axis controller configuration; a larger value of control sensitivity in the downward direction was provided as a result. Additionally the ADOCS program provided a higher control sensitivity in the yaw axis for a clockwise directional input than it did for a counterclockwise torque to compensate for a similar human asymmetry.

Handling Qualities Effects of Controller Integration

A significant handling qualities data base has been created to substantiate an interactive effect which must be assessed during the advanced rotorcraft cockpit design process: the interaction between controller integration and the level of stability and control augmentation. In general, for a given piloting task, increasing levels of controller integration must be accompanied by increasing levels of stability and control augmentation to ensure that performance and handling qualities are not degraded. In the ADOCS ACC/AFCS simulations it was found that controller configurations which included a separated vertical controller--with either a three- or two-axis side-stick--exhibited handling qualities which were generally improved when compared to the integrated four-axis controller configurations for the lower levels of stability and control augmentation that were investigated (Fig. 8). Separation of the vertical controller eliminated any inadvertent coupling of control inputs from the vertical axis to the pitch or roll axes, and reduced pilot workload for multi-axis tasks such as NOE maneuvering. For the higher levels of stability and control augmentation that were investigated, handling qualities were less affected by the level of controller integration. There was a general preference for side-stick rather than pedal control of the yaw axis, despite a tendency to couple yaw inputs into the roll axis, because of the precise directional control which could be achieved with a hand controller.

In a four flight-hour "validation" of the ADOCS simulation results for the lower levels of stability and control augmentation that was conducted in the NAE Airborne Simulator, Boeing Vertol pilots found that many of the simulation results were substantiated by the flight evaluation. Pilot comments indicate that the integrated four-axis side-stick created high workload and degraded flightpath performance, especially during the multi-axis maneuvering tasks. The three-axis controller which incorporated pitch, roll, and yaw control on the side-stick was the preferred controller configuration because of the decoupling of vertical control inputs and improved directional control. With all stability and control augmentation removed, a fully separated controller configuration was required to perform a decelerating approach to hover and landing; the four-axis configuration resulted in an uncontrollable aircraft for this task. Pilots indicated that they would have preferred conventional displacement controllers for landing the aircraft in this condition.

From the handling qualities investigations conducted in flight by the NAE, it is apparent that integrated controllers are certainly feasible and do not degrade aircraft handling qualities when compared to conventional controllers for nonprecision tasks such as cruise flight and maneuvering at altitude. However, for precision flight tasks and high workload situations such as encountered in NOE flight, the ADOCS simulation studies and limited flight validation results indicate that, unless high levels of stability and control augmentation are employed, integrated controllers can cause significantly degraded handling qualities when compared to separated controller configurations.

A single, integrated controller may be a requirement for a single-crew combat rotorcraft in order to allow the pilot to perform the other supervisory and control functions required during the mission. Accordingly, an experiment was conducted to investigate the use of multi-axis side-stick controllers for flightpath control together with a keyboard entry task using the free hand.[21] The results show that keyboard entry tasks interfere with the performance of flightpath tracking and, conversely, that flightpath tracking interferes with keyboard entry. If a degradation in performance occurs, the use of a multi-axis controller to free a hand for mission management tasks may not be appropriate.

Summary (Separated versus Integrated)

Flight and simulation studies have shown the feasibility of using properly designed limited-displacement, integrated controllers for certain relatively routine flight tasks in two-crew rotorcraft with nominal levels of stability and control augmentation. However, for the more demanding flight tasks typical of an advanced combat rotorcraft mission, unless high levels of stability and control augmentation with a high degree of reliability are incorporated, separated controller configurations are required for acceptable handling qualities.

Concluding Remarks

This paper has highlighted several significant advantages of employing a limited-displacement, integrated side-stick controller in certain areas, including human factors and man-machine integration issues such as improved visibility, ingress/egress, crashworthiness, and pilot comfort. However, in order to provide acceptable handling qualities with an integrated controller, high levels of stability and control augmentation with a high degree of reliability are required; flight control or propulsion system failures may cause this acceptable aircraft to become uncontrollable.

Design criteria which include pilot-oriented requirements are crucial in the development of an acceptable integrated-controller configuration. Details such as controller location and orientation, armrest and wrist support design, and grip design including buttons and switches that are important for conventional controllers, are critical for integrated, limited-displacement, force-sensing controllers. An equally important set of design criteria involves the flight-control system software which is used with the controller; the characteristics of the control input preprocessing and the type of stability and control augmentation system have a dominant effect on the suitability of a particular controller. As with many other aspects of advanced rotorcraft cockpit design trade-offs, an effective analysis of controller issues must be based upon an integrated application of principles and guidelines employed by several communities including pilots, avionics engineers, engineering psychologists, control engineers, and human factors specialists.

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Table 1 Force-sensing controller attributes

Advantages	Disadvantages
High control input bandwidth	Susceptible to sharp pilot inputs, inertial forces, vibratory inputs
Simplicity	
Reliability	Lack of control position information
Low parts count	
No force-feel system required	Manual trimming and control transfer more difficult
	Low-force buttons and switches required to prevent inadvertent inputs

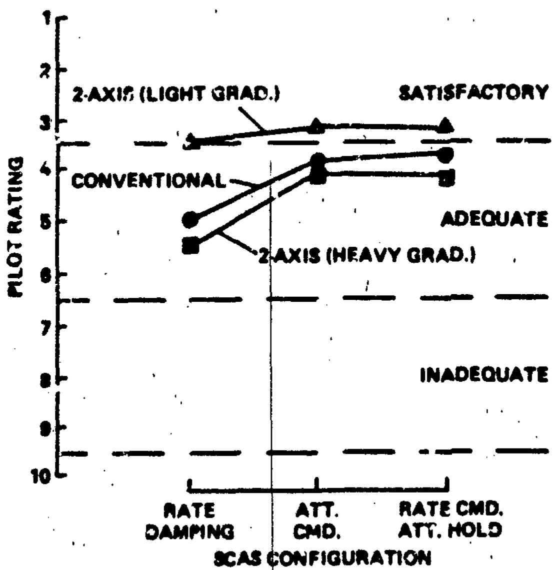

Fig. 1 Conventional versus two-axis side-stick controllers (Ref. 13).

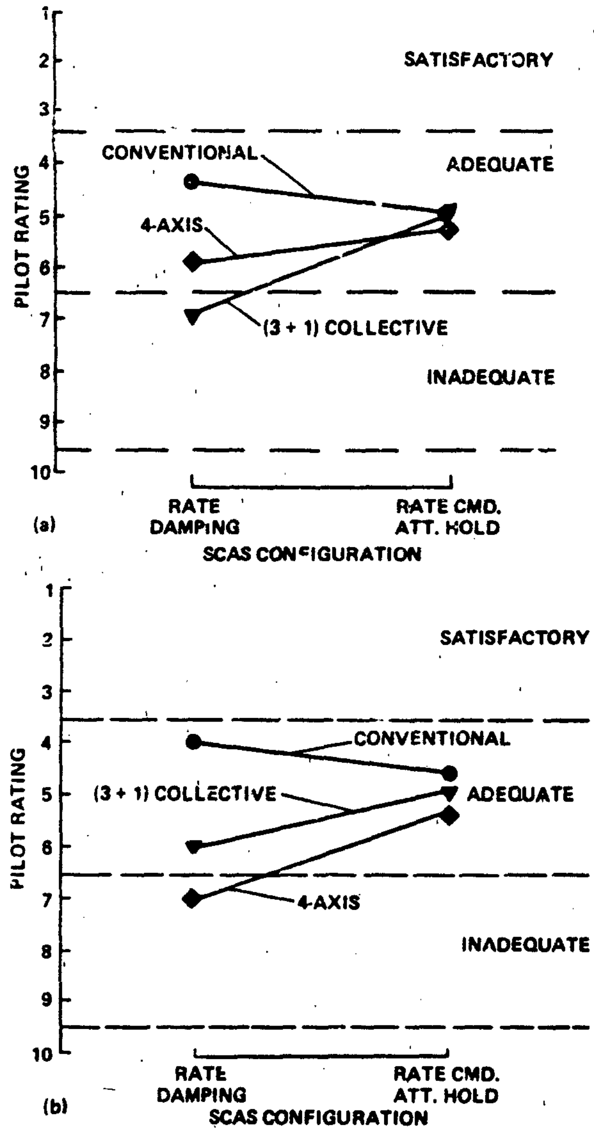

Fig. 2 Conventional versus multi-axis side-stick controllers (Ref. 13). a) NOE traveling; b) hover/bob-up.

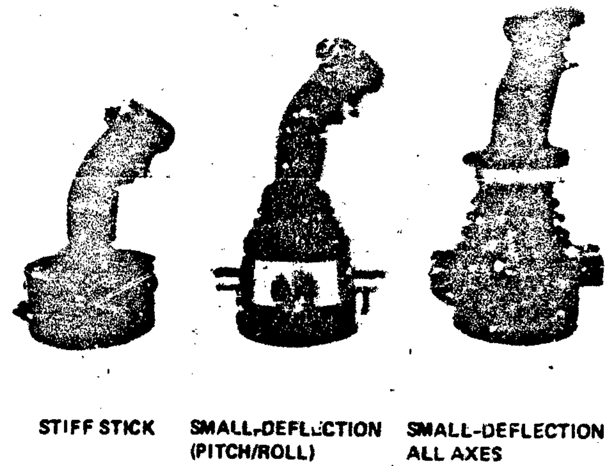

Fig. 3 ADOCS four-axis side-stick controllers (Ref. 18).

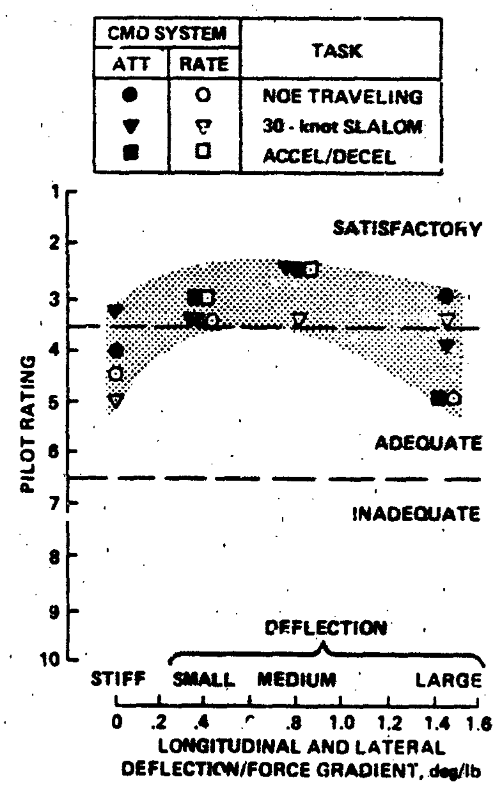

Fig. 4 Effect of side-stick controller deflection/force gradient on pilot ratings (Ref. 17).

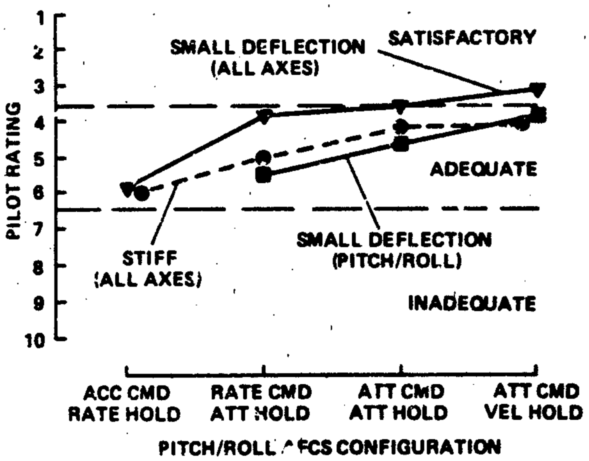

Fig. 5 Effects of control harmony (NOE traveling).

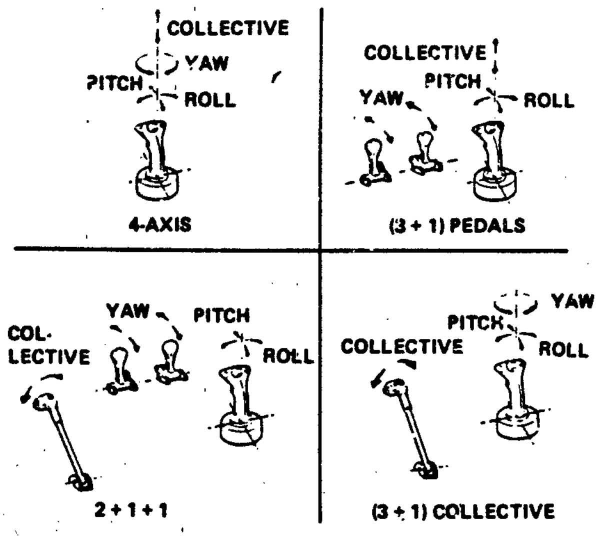

Fig. 6 Levels of controller integration.

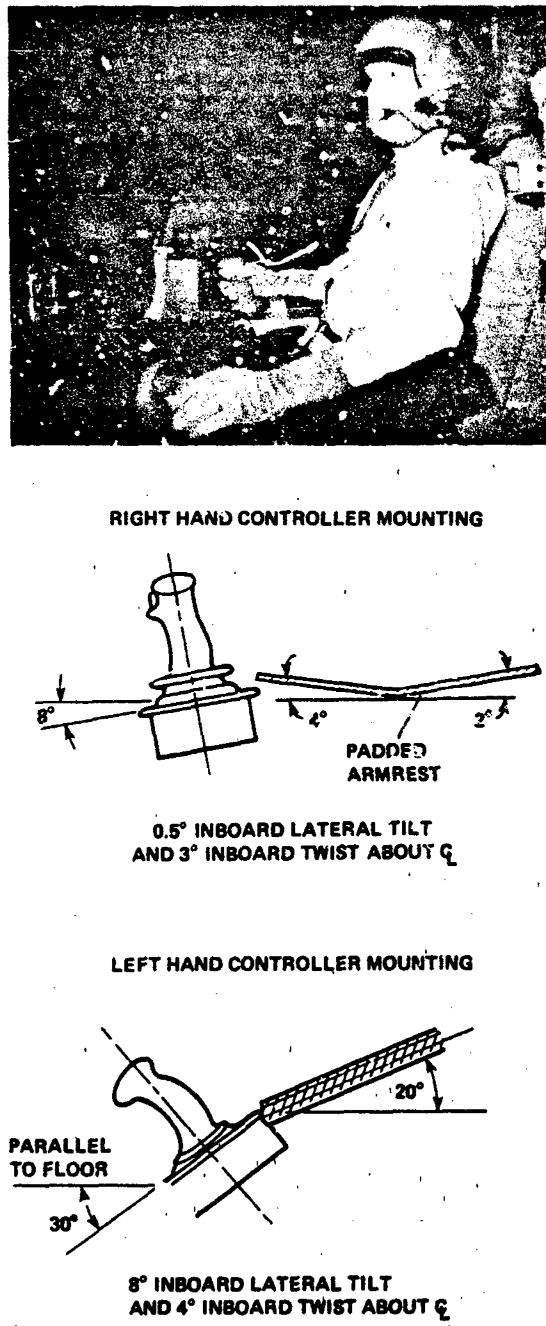

Fig. 7 Side-stick controller orientation (Ref. 19).

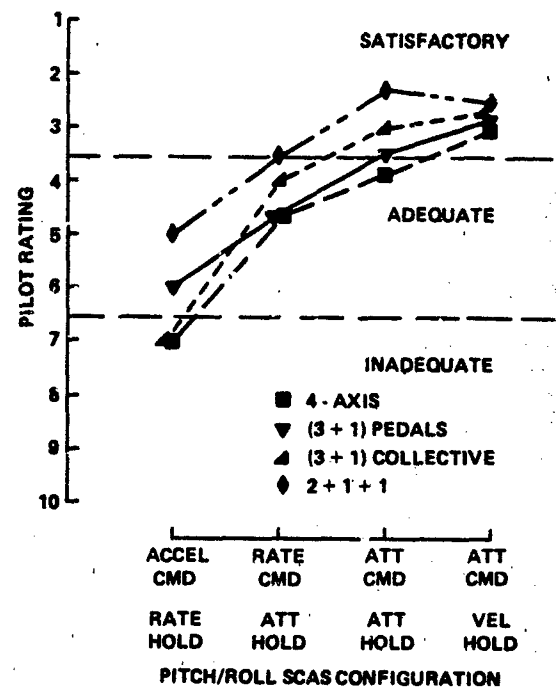

Fig. 8 Effects of controller integration on handling qualities (30-knot slalom).

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-86688 USAAVSCOM TM 85-A-1		

4. Title and Subtitle
EFFECTS OF SIDE-STICK CONTROLLERS ON ROTORCRAFT HANDLING QUALITIES FOR TERRAIN FLIGHT

5. Report Date
April 1985

6. Performing Organization Code

7. Author(s)
Edwin W. Aiken

8. Performing Organization Report No.
NASA-A-85141

9. Performing Organization Name and Address
Ames Research Center and Aeromechanics Laboratory, U. S. Army Research and Technology Laboratories (AVSCOM), Ames Research Center, Moffett Field, CA 94035

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration, Washington, D. C. 20546 and U. S. Army Aviation Systems Command, St. Louis, MO 63120

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes
Point of Contact: Edwin W. Aiken, Ames Research Center, MS 211-2, Moffett Field, CA 94035 (415)694-5362 or FTS 464-5362

16. Abstract

Pertinent fixed- and rotary-wing feasibility studies and handling-qualities research programs are reviewed and the effects of certain controller characteristics on handling qualities for specific rotorcraft flight tasks are summarized. In particular, the effects of the controller force-deflection relationship and the number of controlled axes that are integrated in a single controller are examined. Simulation studies conducted as part of the Army's Advanced Digital/Optical Control Systems (ADOCS) program and flight research programs performed by the National Aeronautical Establishment of Canada provide a significant part of the available handling qualities data. These studies demonstrate the feasibility of using a single, properly designed, limited-displacement, multi-axis controller for certain relatively routine flight tasks in a two-crew rotorcraft with nominal levels of stability and control augmentation with a high degree of reliability are incorporated, separated three- or two-axis controller configurations are required for acceptable handling qualities.

17. Key Words (Suggested by Author(s))
Flying qualities
Flight control systems
Side-stick controllers
Helicopter

18. Distribution Statement
Unlimited

Subject Category 08

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	14	

*For sale by the National Technical Information Service, Springfield, Virginia 22161