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IN-FLIGHT EVALUATION OF FOUR COCKPIT CONTROLLER CONFIGURATIONS IN A VARIABLE STABILITY AIRPLANE

DONALD W. RHOADS
CORNELL AERONAUTICAL LABORATORY, INC.

TECHNICAL REPORT AFFDL-TR-70-95

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FOREWORD

This report was prepared for the United States Air Force by the Cornell Aeronautical Laboratory, Inc. (CAL), Buffalo, New York in partial fulfillment of Contract F33615-69-C-1023, Project No. 6190, Task 619015.

The work reported herein was performed by the CAL Flight Research Department under the sponsorship of the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The AFFDL Project Engineer was Mr. David E. Frearson (FDCR).

The project was directed by Donald W. Rhoads of the Flight Research Department. Significant contributions to the investigation were made by Messrs. G. Bull, M. Harris, R. Siracuse, and R. Ductor of the same department. Evaluation pilots were Major J. Heye and Captain N. Fritz of the USAF and Messrs. R. Harper and J. Mitchell of CAL.

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ABSTRACT

An in-flight evaluation of four cockpit controller configurations has been made. These configurations include a conventional wheel and column, and three new concepts: a circumferential wheel and column, a circumferential wheel and column with a hand controller mounted on the right hand side of the wheel segment, and a dual side arm configuration integral with the pilot's seat. Evaluation was based on three tasks; up-and-away cruise condition maneuvers, low level terrain following simulated at altitude, and approach, landing and takeoff. Each task was performed under conditions of different simulated static and dynamic characteristics of a B-1 type airplane, using one of CAL's B-26 variable stability airplanes. Four evaluation pilots, two USAF and two CAL, flew all four controller configurations four times each through each of the three tasks. Data obtained was both qualitative and quantitative. Qualitative data consisted of pilot in-flight comments in response to a prepared comment guide. Quantitative data consisted of pilot ratings based on the latest Cooper-Harper handling qualities rating scale, and measured tracking error data obtained during the simulated terrain following task and the approach maneuver of the approach-landing-takeoff task. Results of analysis of all types of data obtained indicate that all three new concepts would be accepted by pilots of large airplanes with only a nominal associated learning period, that all three new concepts are preferable to the conventional wheel and column, and that the dual side arm configuration, despite some detailed design deficiencies, is the most preferred of the three new configurations. The data also indicate areas for improvement in detailed side-arm controller design, and the need to establish new handling qualities criteria for side arm controllers, particularly when integrated with other factors affecting overall flight control systems design.

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LIST OF SYMBOLS

C_{L_α}	lift coefficient due to angle of attack
C_{m_α}	pitching moment due to angle of attack
$C_{m_{\delta_e}}$	pitching moment due to elevator deflection
C_{m_q}	pitching moment due to pitch rate
C_{n_r}	yaw damping derivative
F_{AS}	aileron stick force, pounds
F_{ES}	elevator stick force, pounds
g	acceleration constant, 32.2 ft/sec
h	altitude, feet
L_α	rolling moment due to angle of attack
$L'_{\delta_{AS}}$	rolling moment due to aileron stick deflection
n_z	incremental normal acceleration, g's
$N'_{F_{RP}}$	yawing moment derivative due to rudder pedal force
N_r	yawing moment due to yawing velocity
$N_{\dot{\beta}}$	yawing moment due to rate of change of sideslip angle
N'_{δ_r}	yawing moment due to rudder deflection
p	roll rate, rad/sec or deg/sec
q	pitch rate, rad/sec or deg/sec
r	yaw rate, rad/sec or deg/sec
S	area of wing, ft^2
t	time, seconds
u	velocity along x axis
V	velocity, knots
W	weight of airplane, pounds
Y_β	change in Y force due to angle of sideslip

α	angle of attack, radians or degrees
β	angle of sideslip, radians or degrees
δ_a	aileron deflection, radians or degrees
δ_{AS}	aileron stick deflection, inches
δ_{ES}	elevator stick deflection, inches
δ_r	rudder deflection,
δ_{RP}	rudder pedal deflection,
ζ	damping ratio
θ	pitch angle, radians or degrees
ρ	air density
τ	time constant
$\lvert\phi/\beta\rvert_d$	ratio of bank angle to sideslip angle in the Dutch roll mode
ω	frequency, rad/sec

Subscripts

d	refers to Dutch roll mode
p	refers to phugoid mode
SA	refers to side arm
SP	refers to short period mode
c	controller

SECTION 1

INTRODUCTION

Current programs for the development of fly-by-wire flight control systems require a concurrent evaluation of new concepts in two-axis controllers (pilot hand controls) to provide system performance capability and acceptance by pilots for application in next generation aircraft.

Eventual acceptance of new concepts of flight control systems for aircraft will be to a great extent dependent on the manual link (the hand control) between the pilot and the vehicle system. Future evaluations of the overall control system will be strongly influenced by the characteristics of the hand control itself in terms of size, shape, force gradient, displacement, breakout force, damping, comfort, and ease of precision control.

To implement the investigation of these concepts, Hughes Aircraft Company, under sponsorship of the Air Force Flight Dynamics Laboratory, undertook a study to evaluate, in terms of pilot opinion, several promising controller concepts based on observation of mock-ups.

The results of this study are given in Reference 1, and to a significant extent, helped shape the experimental design philosophy of the present investigation. First, it noted that certain concepts should be subjected to dynamic testing in a flight simulator. Secondly, it led to a refinement of these concepts and finally to the development and fabrication of three designs suitable for installation in an aircraft (Reference 2). These designs (described in detail below) all had one common characteristic, namely, improved visual access to important flight instruments. It is reasonable to assume that such a characteristic can be critically and accurately judged from a ground mock-up on the basis of observations of the physical configuration. It is also reasonable to assume (as pointed out in Reference 1) that a design which improves instrument panel visibility is not necessarily the best design for the overall pilot-control-mission airplane system.

Thus, if one now proceeds on the basis that a significant design improvement has been made, the next step is to determine whether characteristics of the total system will outweigh or nullify this improvement.

There are two basic questions to be answered. Is the pilot able to perform his assigned mission at least as well with the new concepts as with the conventional configuration, and considering the possibility that these new concepts will be used as an integral part of his control system under operational conditions, is there significant evidence that all of these concepts will be accepted by the pilots? The answers to these questions must be affirmative in order to take advantage of the cockpit environmental design improvement already considered significant.

In an effort to gain these answers, an in-flight investigation of the characteristics of these controllers has been conducted using a Cornell Aeronautical Laboratory (CAL) B-26 variable stability airplane as a test vehicle. In addition to the configurations supplied by the Air Force, the normal B-26 wheel and column, with wheel rotation about a center hub, was investigated. The supplied configurations were: circumferential wheel segment and column, with wheel rotation achieved by moving its circumference through a point on the top of the column, the circumferential wheel segment with a hand-size controller mounted on the right hand top of the segment, and finally, dual side-arm, hand-size controllers integral with the aircraft seat.

The controllers were evaluated by the pilots while performing various up-and-away and approach flight maneuvers. The B-26 variable stability airplane was mechanized to simulate the characteristics of a B-1 type airplane in three task flight phases. The first configuration was representative of the high-subsonic, medium altitude condition for which a variety of maneuvers were performed such as obstacle avoidance turns, clearing turns, zero "g" arcs, climbing and descending turns. The second configuration was representative of high-subsonic terrain following maneuver which as mechanized in the B-26 airplane, provided a precision tracking task at altitude. The third configuration was representative of the ILS approach, touchdown and takeoff maneuver.

The experimental design was constructed so that two U.S. Air Force pilots and two CAL pilots evaluated each controller configuration four times, resulting in a total of sixteen evaluations for each pilot and sixty-four evaluations for the complete flight program. Controller configurations were chosen at random for each pilot. Each evaluation included all three B-1 type simulations and the maneuvers noted above.

In-flight data was obtained in two fundamental forms for each evaluation. The first was qualitative and consisted of wire recorded pilot comments in response to a comment guide prepared by the engineer. This guide was designed to extract pertinent information from the evaluation pilot in the areas of longitudinal and lateral-directional handling qualities, and cockpit environment. The pilot was free to use as much time as needed to fully explain and give his estimate of the configuration. The second form of data was quantitative and consisted of pilot ratings for the combined airplane-controller-mission as outlined by the Cooper-Harper handling quality rating scale (Reference 3), and oscillograph recorded controller input and airplane response data. The latter was obtained during the tracking and ILS approach tasks wherein deviations between command and actual pitch and yaw motions were noted. The raw data was reduced to obtain comparative power spectral density, RMS and variance.

Although the primary objective of this study was to determine the relative merits of the controller concepts as presented in an overall airplane-mission oriented environment, it was of equal importance to determine both the attributes and deficiencies of the controller designs themselves.

SECTION II

TEST EQUIPMENT

This section describes the equipment used in this investigation. It pertains primarily to airborne components which contributed significantly to the program.

1. THE CONTROLLERS

a. Conventional wheel and column (Figure 1). This is of basic B-26 design with the wheel rotating about a center hub. For normal B-26 variable stability system (VSS) operation it is instrumented to provide electrical signals proportional to position and force. It is connected to a longitudinal feel system providing various amounts of column travel per unit of column force, and also has provision for simulating breakout force and hysteresis. Mechanical springs provide lateral control force gradients. The wheel and column are not mechanically linked to the aileron or elevator, rather, electrical pick-offs are used to generate command signals for the variable stability system which drives the control surfaces using electrohydraulic actuators.

b. Circumferential wheel and column (CW). This configuration, shown in Figure 2, differs physically from (a) above in that the circumference of the wheel rotates in a track at the top of the column. The center hub has been eliminated. Installation will afford the same capabilities as (a), the differences being only in the motion geometry. The grips contain switching for communications and VSS disengage as well as a pitch trim control. Also visible is a modes select panel which was not evaluated.

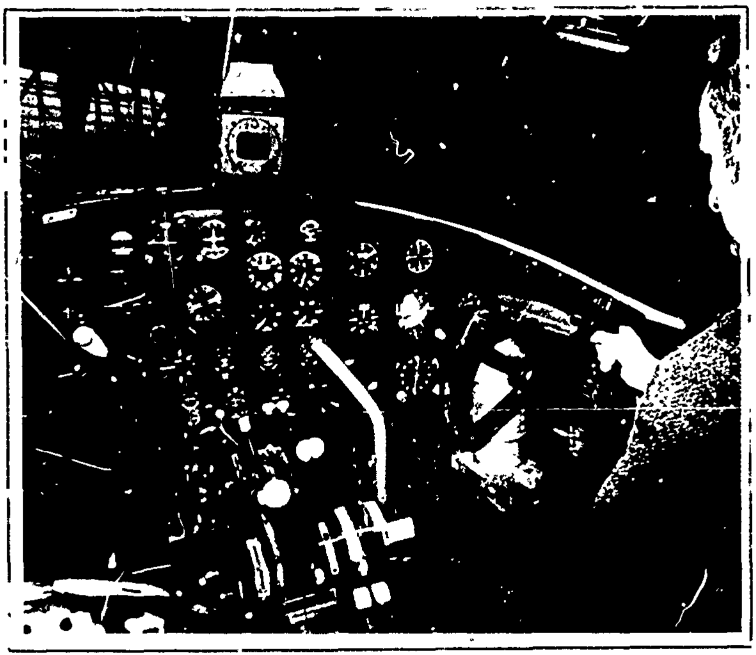


Figure 1 B-26 CONTROLLER AND TEST INSTRUMENT PANEL

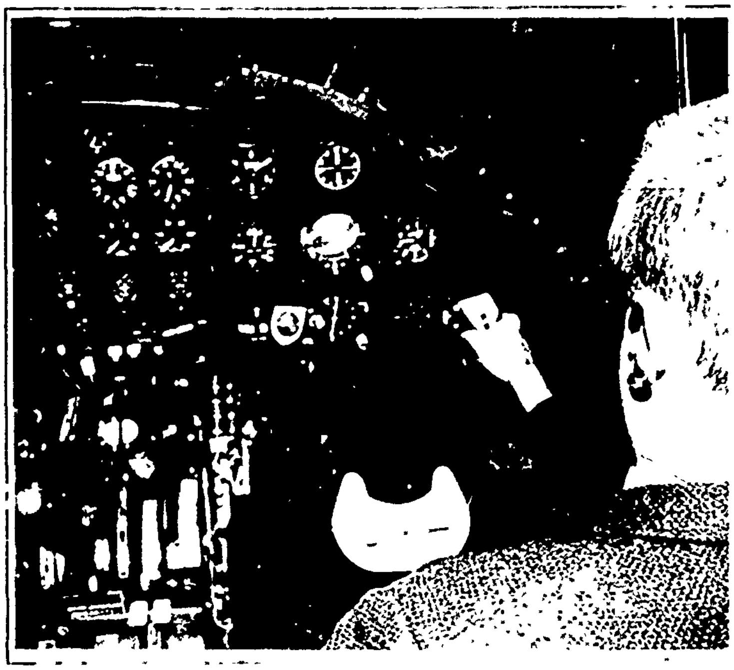


Figure 2 CIRCUMFERENTIAL WHEEL CONTROLLER WITH ALTERNATE HAND CONTROLLER

c. Circumferential wheel and column with alternate hand controller (CW-AHC). This configuration differs from (b) only in that the right hand grip can be unlocked to provide two axis, limited authority control in combination with the circumferential wheel and column. Pitch control is accomplished by fore and aft motion of grip about a pivot at the center of the hand and roll control is accomplished by left and right motion of the grip about a pivot just below the hand. These details are more evident in the closeup of the controller shown in Figure 3. Feel is provided by fixed springs.

d. Dual side-arm controllers (DSC). This configuration is shown in Figures 4 and 5. The slaved left and right hand grips, their adjustments, and their feel system are mounted as integral parts of the seat (the normal B-26 seat is removed). This concept assumes a fly-by-wire flight control system and features quadruply redundant synchro transducers. The feel system has variable force gradients (replaceable springs), breakout forces and damping. As with the other configurations, the grips contain pitch trim, communication and system disconnect controls.

Additional photographs of the new concepts are shown on Figures 6 and 7.

2. CONTROLLER SYSTEM MODIFICATIONS

The following is a description of several modifications made to the new concept control systems. These were made because of malfunction or as deemed necessary to permit performance of the investigation.

Circumferential Wheel

One of the recurring problems of any mechanical control system is

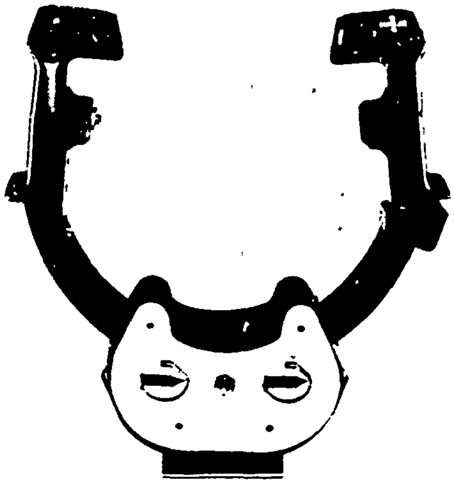


Figure 3 CLOSEUP OF CIRCUMFERENTIAL WHEEL

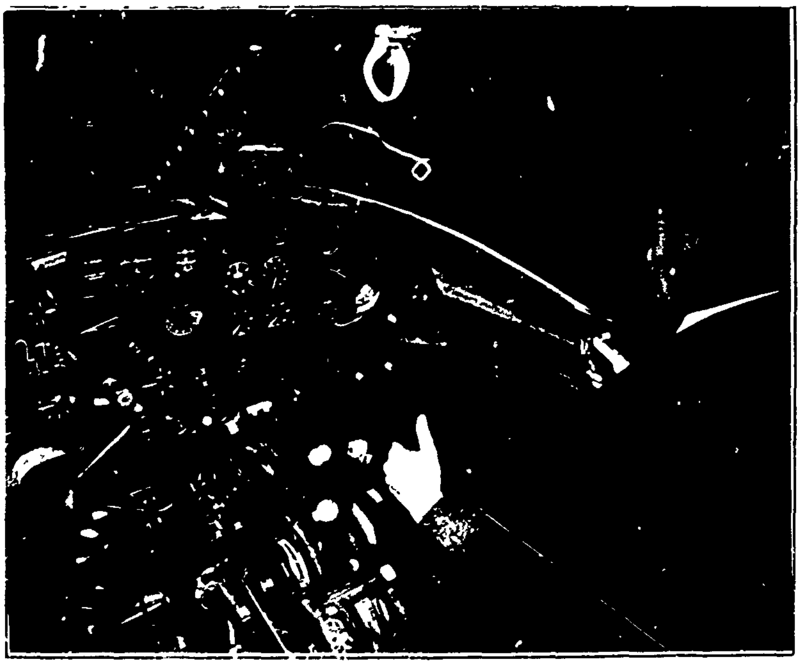


Figure 4 SIDE-ARM CONTROLLER

NOT REPRODUCIBLE

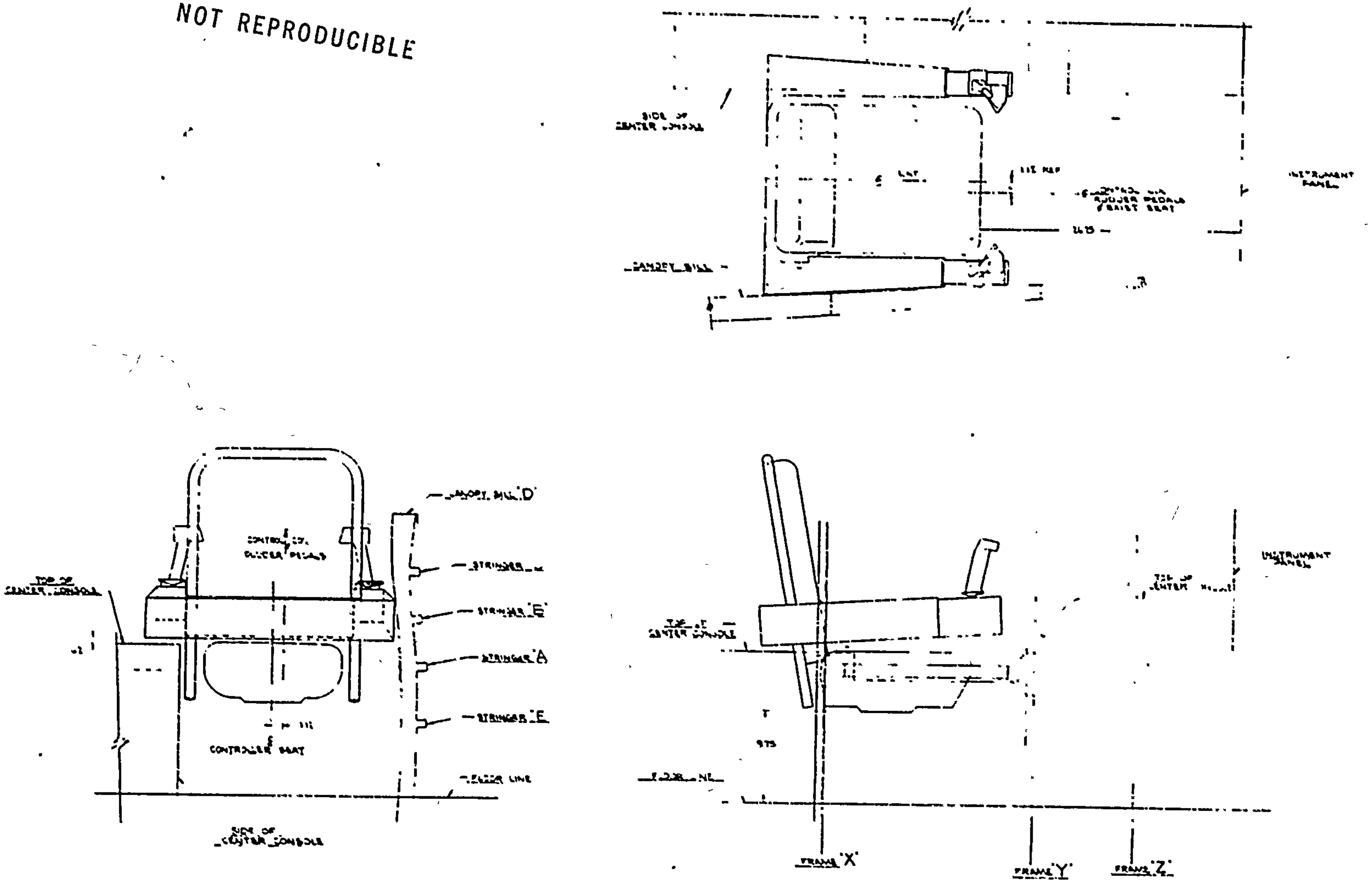


Figure 5 SIDE-ARM CONTROLLER INSTALLATION IN B-26 AIRPLANE

Figure 6 CW AND CW-AHC CONFIGURATIONS

Figure 7 DSC CONFIGURATION

lack of centering of a control element, usually caused by friction which is contributed by many parts of the system, e.g., pulleys and springs. After some usage, (pre-evaluation flights and part of the evaluation flights) the circumferential wheel began to exhibit a lack of centering which was felt to be just slightly greater than tolerable. Examination revealed some wear of the nylon type rollers and some evidence of misalignment. The rollers were replaced by CAL - fabricated aluminum types, which, combined with realignment, reduced the lack of centering to within a tolerable limit.

However, later during the evaluation flights a notable increase in wheel rolling friction was evidenced when the column was pushed full forward. This became intolerable and the unit was again modified. The cover of the box-like structure containing the rollers which seat the wheel segment was refastened in a manner which was hoped would maintain alignment. (This procedure had been previously suggested by Hughes Aircraft, the designer.) In addition, the rollers were split in a vertical plane such that the front and rear portions could rotate independently. Thus, if because of load, looseness or misalignment, the chamfered end of the roller rode in its chamfered seat at some radius slightly different from that of the other end, it would do so independently without contributing sliding friction. This was the final adjustment made to this unit, and no difficulty was experienced throughout the remainder of the program.

Dual Side Arm Controller

The modifications described below are primarily electronic in nature and, with one exception, were not applied to the controller unit itself, but were made part of the overall control system.

In order to provide consistent and positive centering of the two hand grips in the roll mode, it was necessary to reduce the unit's mechanical damping to a low value. On the ground, this was accepted by the pre-evaluation pilots. However, during the pre-evaluation flight testing, it was noted that it was easy to bang the full throw stops, which in turn caused a high frequency "ringing" which, when transmitted through the B-26 servo system, caused unrealistic airplane motions. To counteract this, a first-order lag circuit with a time constant of 0.2 seconds was installed between the controller and aileron servos. The in-flight difficulty was corrected, and pilot comments and records indicated no significant change in the roll response of the simulated airplane.

During the pre-evaluation flights a controller displacement to elevator deflection linear gain $(\delta_e / \delta_{e_{SA}})$ was selected that was thought to provide adequate authority (δ_e) to perform large maneuvers including landing the airplane, while limiting the sensitivity to a point where pilot-induced oscillations (PIO) would not occur during precision maneuvers. As experience accumulated, it became evident that the selected gain, in fact, did not provide adequate authority for the landing maneuver. Increasing the gain provided adequate authority, but resulted in a sensitivity that produced PIO. At least a partial answer to the problem is to assume the gain required for large maneuvers and increase the spring gradient (stick force per stick displacement) so that the stronger force cues will preclude PIO. However, it was determined that in order to achieve this, a modification to the dual side arm controller (DSC) would be required which would be beyond the scope of this program. A quick and inexpensive solution was to stuff the cores of the mechanical springs with resilient materials such as hard rubber and plastics. This resulted in an increase in spring gradient by a factor of four. This configuration was flight tested by Evaluation Pilot A (USAF), who commented that there was a significant improvement, but that it was insufficient. Because it did not appear feasible to modify the DSC at that time, it was decided to conclude the evaluation by Pilot A without performing the landing maneuver. Likewise, Pilot B did not perform the landing maneuver as part of his formal evaluation.

However, it was felt that the landing maneuver was essential to the evaluation. Thus, another method of partially solving the problem was envisioned. This was to mechanize a nonlinear function expressing elevator deflection output as an ever increasing function of controller deflection input.

This function is shown on Figure 8. The design criteria are: 1) the slope, $\delta_e/\delta_{e_{SA}}$, around $\delta_{e_{SA}} = 0$ is the sensitivity desired for small precision maneuvers, and 2) the maximum δ_e at the maximum controller deflection is that required to land the airplane. This function was electronically mechanized and used throughout the remainder of the evaluation program.

This configuration was separately flight tested and found by CAL pilots to be at least a partial answer to the problem. However, proper operation does assume that all deviations are from a trim condition, which is not always the case. Operation from a nontrim condition (toward the extreme of the curve) can result in undesirably high sensitivities. Furthermore, additional evaluation indicated that higher force cues are desirable, and that the use of nonlinear gearing is not the complete solution to the problem.

As a result of the above, it is important to note that:

1) Pilots A and B did not use the landing flare maneuver as part of the evaluation task for the DSC because of lack of elevator authority.

2) The other two evaluation pilots did use the landing flare maneuver as part of the evaluation task for the DSC, but with less than optimum feel characteristics.

3. TEST VEHICLE CAPABILITY

The test vehicle used was one of CAL's B-26 variable stability airplanes (see Figures 9 and 10). These airplanes are able to simulate a wide range of aircraft statics and dynamics in flight. Details of this capability are given in References 4, 5, and 6. A brief summary is given here.

The response-feedback method was used in this study, to alter the natural stability derivatives and dynamic characteristics of the airplane by

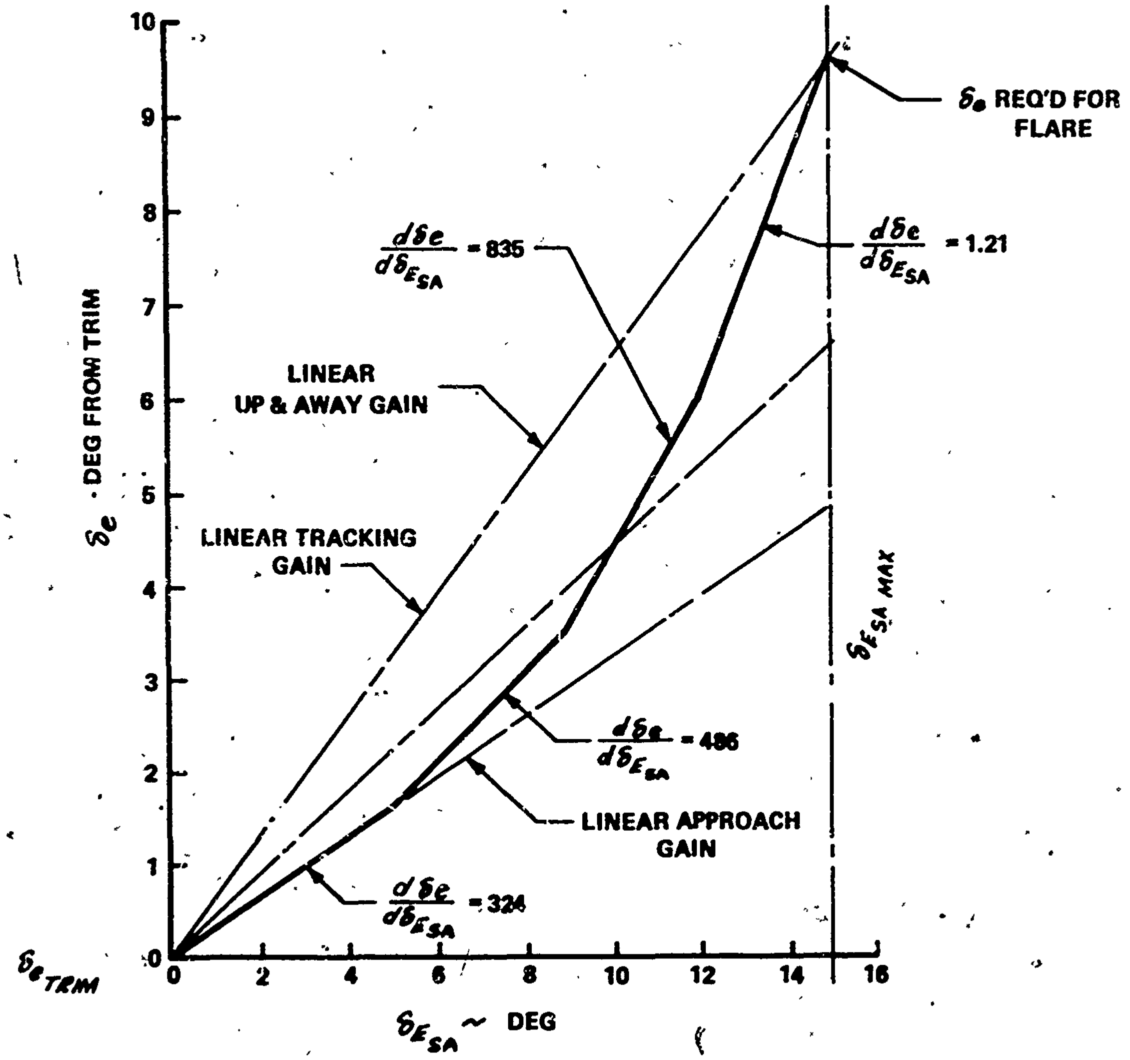


Figure 8 CONTROL FUNCTION ADAPTED TO DUAL SIDE-ARM CONTROLLER FOR TASK c

Figure 9 B-26 THREE AXIS VARIABLE STABILITY AIRPLANE

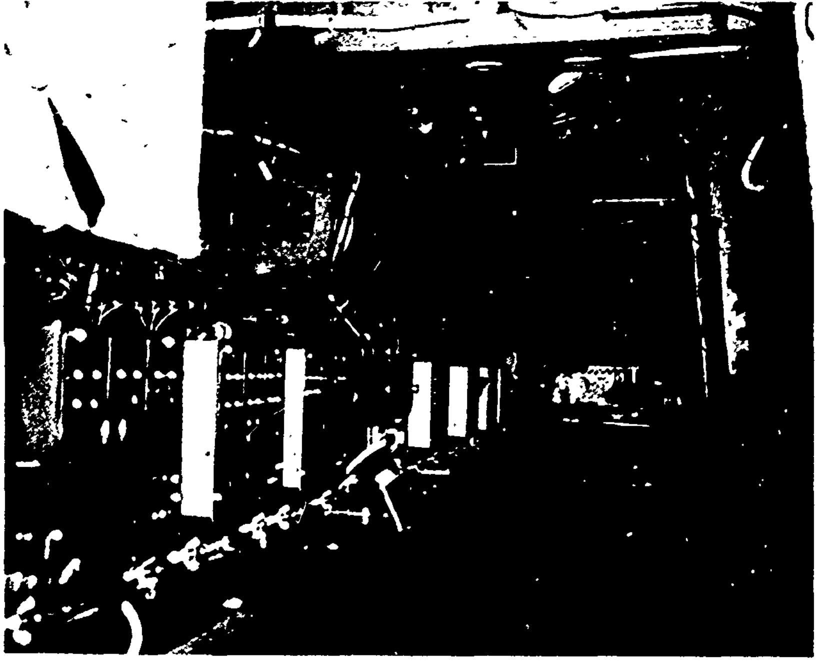
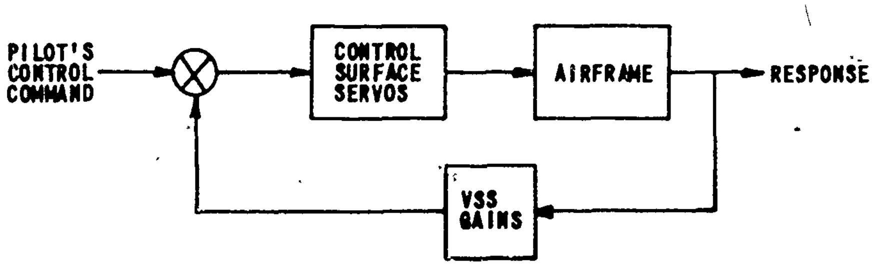


Figure 10 VARIABLE STABILITY INSTALLATION IN B-26 BOMB BAY, LOOKING FORWARD

moving the control surfaces proportional to sensed airplane motions. For example, a change in the derivative C_{m_α} by the increment ΔC_{m_α} is obtained as $\Delta C_{m_\alpha} = C_{m_{\delta_e}}(\delta_e/\alpha)$. Similarly, a change in the derivative C_{m_q} is obtained as $\Delta C_{m_q} = C_{m_{\delta_e}}(\delta_e/q)$. The former has a primary effect on short period frequency and the latter has a primary effect on the short period damping ratio. A simple diagram illustrating the general concept is shown below.



The B-26 is presently mechanized to vary the frequency and damping ratio of the longitudinal short period and phugoid modes by sensing α, q, u, and their derivatives, and feeding these to the elevator servo.

In addition to matching the dynamic modal characteristics (ω_{sp}, ζ_{sp}, ω_p, and ζ_p), it is desirable to match the static stick force per incremental normal acceleration ($F_{ES}/\Delta n_z$), and stick force per unit stick travel (F_{ES}/δ_{ES}). Stick force per incremental normal acceleration is defined as

$$\frac{F_{ES}}{\Delta n_z} = \frac{F_{ES}}{\delta_{ES}} \cdot \frac{\delta_{ES}}{\delta_e} \cdot \frac{\delta_e}{\Delta n_z} = \frac{F_{ES}}{\delta_{ES}} \cdot \frac{\delta_{ES}}{\Delta n_z} .$$

where $\delta_e/\Delta n_z$ is a characteristic of the basic B-26 airplane, but F_{ES}/δ_{ES} and δ_{ES}/δ_e are capable of being varied.

Other longitudinal control system characteristics such as breakout force, hysteresis, etc., can be simulated by the B-26 feel system.

Simulation of lateral-directional modal characteristics was also accomplished by using the response-feedback technique. The concept is similar to that described above for the longitudinal case. Correct combinations of the feedback gains also provide the desired Dutch roll characteristics (ω_d , ζ_d and $|\phi/\beta|_d$), the roll mode time constant (τ_R) and spiral mode time constant (τ_s).

In addition to matching the lateral-directional modal characteristics, it is desirable to match control effectiveness, i.e., essentially the initial moment outputs due to control inputs. Ideally, one would like to match both the output due to control force input and the output due to control displacement input. To accomplish this, two adjustable gains must be available, one to vary the control column forces versus control column displacement gradient, and one to vary the control surface displacement versus control column displacement gradient. In the B-26 lateral-directional variable stability system, only the latter is readily available for aileron and rudder control. (Force displacement ratios can and have been varied by changing the mechanical springs in the rudder and aileron control systems, but the process is cumbersome and so is seldom used.)

Assuming the availability of only the one electronic gain, either the control force or deflection gradients can be matched, but a choice must be made. Experience has shown that the pilot is more sensitive to forces than to displacements. Therefore, the gear ratio gain is used to match the moment output to force input. As an example of this matching process, consider $N'_{F_{RP}}$ (yawing moment output due to rudder pedal force input). It is required that $\left.N'_{F_{RP}}\right)_{B\text{-}26} = \left.N'_{F_{RP}}\right)_{SIM.\ A/C} = \dot{r}(0)/F_{RP}$, the initial yawing acceleration for an F_{RP} step input. This relationship may be developed in terms of the variable stability B-26 gain,

$$\frac{\delta_r}{\delta_{RP}} = \frac{N'_{\delta_r}\,(\delta_r/F_{RP})_{SIM.\ A/C}}{N'_{\delta_r}(\delta_{RP}/F_{RP})_{B\text{-}26}}$$

With a knowledge of the control characteristics of the two airplanes, together with a calibration of the δ_r/δ_{RP} cockpit gain, the desired matching can be obtained.

4. MISCELLANEOUS

In addition to the controllers and VSS test equipment noted above, there were several specialized units installed in the B-26 airplane pertinent to the experiment. These were:

a. Lear Flight Director System used by the pilot to fly the airplane in the simulated tracking tasks.

b. C.G. sensor package. A compact unit containing a three-axis linear accelerometer, three-axis angular accelerometer, three-axis rate gyro and associated amplifiers and power supply.

c. Eighteen-channel CEC oscillograph recorder. This unit was used to record time histories of all pertinent data, both in the calibration and evaluation phases of the program.

d. Evaluation pilots' instrument panel including flight director system indicators.

SECTION III

TEST DESCRIPTION

The tasks chosen as a basis for evaluation of the controllers include a wide variety of maneuvers, and are categorized as follows:

a. Up-and-away maneuvers - subsonic cruise flight condition.

b. Terrain following (tracking) maneuver - high speed, low altitude flight condition.

c. Landing approach and takeoff maneuver - low speed, low altitude flight condition.

The tasks provide the basic framework for VSS simulation of the B-1 type airplane, because they defined the flight test regions and associated airplane characteristics. Also affecting the details of the simulation was the handling quality acceptability level; the airplane characteristics should be neither too "good" nor too "bad" so that subtle differences among the controller configurations are not masked by either extreme of pilot rating.

As was previously noted, the response-feedback method of simulation was used for both the longitudinal and lateral-directional modes. For reasons of convenience, simplicity, reliability and ease of maintenance, the primary longitudinal feedback signals used in this experiment were α and $\dot{\alpha}$. The use of these variables can produce characteristics as specified by the revised Military Specification for Flying Qualities (Reference 7), i.e., short period frequency and damping within certain limits. Because these limits are shown to be functions of n_z/α , a simulated flight condition (velocity and altitude) is chosen to match the required value of this parameter.

Recent interest in fly-by-wire flight control systems has centered on use of normal acceleration, pitch rate and pitch acceleration feedback signals together with the C^* time history envelope criteria developed in Reference 8.

It was not the purpose of this investigation to examine in detail the relative merits of the revised flying qualities specification or the C^* flying qualities criterion. However, it was of interest to compare the results of using the B-26 feedback mechanization (α , $\dot{\alpha}$, q) with the n_z , q , $\dot{q}$ mechanization. To this end, an analytical study was performed which indicated that within the constraints of the present investigation, the longitudinal system as mechanized in the B-26 simulator (α , $\dot{\alpha}$, q feedback) was suitable. In particular, it is shown that α , $\dot{\alpha}$, and $\dot{q}$ augmentation will satisfy both the frequency-damping flying qualities criteria of Reference 7 and the C^* envelope criteria proposed in Reference 9.

The following discussion of simulated B-1 type airplane characteristics will use the aforementioned tasks for reference because, as noted, each defines a set of airplane characteristics and a flight condition.

For each task, the basic unaugmented longitudinal characteristics were analyzed by first formulating a set of three-degree-of-freedom equations of motion. The pertinent characteristics resulting from the solution of these equations are noted in the table below along with the requirements as stated in Reference 7.

	Unaugmented characteristics					Requirement of Reference 7 for noted n_z/α			
Task	ω_{sp} (rad/sec)	ζ_{sp}	n_z/α (g/deg)	ω_p (rad/sec)	ζ_p	ω_{sp} (rad/sec)	ζ_{sp}	ω_p (rad/sec)	ζ_p
a)	1.1	.4	10.1	.05	.04	1.8-6.0	.35-1.3	No requirement	≥ .04
b)	1.52	.47	18.4	.044	.084	2.4-8.0	.35-1.3	No requirement	≥ .04
c)	.7	.63	3.1	.19	.07	.7-3.1	.35-1.3	No requirement	≥ .04

Choice of the B-26 flight conditions for the stated tasks begins with matching $n_z/\alpha = (\rho S V^2/2W)(C_{L_\alpha})$. Without direct lift control (thereby having the capability of changing C_{L_α}), only altitude (h) and speed (V) can be selected for this purpose. At a nominal test altitude of 8000 ft, velocities necessary to match n_z/α are 160 knots for Task a and 214 knots for Task condition b, both within the capabilities of the B-26 simulator. In the case of the landing approach maneuver, however, altitude is fixed as is the minimum approach velocity of the B-26. The 120 knots chosen results in an n_z/α slightly higher than that estimated for the B-1. However, flight test data has indicated insignificant differences in pilot performance between these lower values of this parameter.

Because it was desirable to evaluate the controllers on the basis of the augmented B-1, equations of motion were developed (for each of the above chosen flight conditions) in terms of the feedback gains required to achieve the required augmented characteristics. These gains were then used as a starting point for the in-flight calibration necessary to finalize the longitudinal portion of the evaluation configuration. Values of the simulated longitudinal modal characteristics are noted below.

Task	ω_{sp} rad/sec	ζ_{sp}	ω_p rad/sec	ζ_p
a	3.3	.7	$\sim .1$	$> .05$
b	4.2	.7	$\sim .1$	$> .05$
c	1.5	.7	$\sim .05$	$\geq .05$

The stick force per incremental acceleration, $F_{es}/\Delta n_z$ was matched to the B-1 type airplane characteristics for the conventional and circumferential wheel configurations as follows:

Task	$F_{ES}/\Delta n_z$ (lb/g)
a	27
b	26
c	56

The stick force per stick travel, F_{ES}/δ_{ES} (conventional and circumferential wheel) was chosen by CAL pilots during the pre-evaluation flights and was approximately 33 lb/in. for all tasks.

The lateral-directional characteristics simulated for each of the above flight conditions were based on estimated data for a B-1 type augmented airplane. From the table below, it may be noted that the simulated parameters compared favorably, but not exactly, with estimated data. Although more exact matching could have been obtained through additional calibration flight testing, it was felt such effort would be unwarranted, and the degree of mismatch would not detract from the validity of the experiment.

Task	ζ_d		T_d (sec)		τ_R		$\lvert\phi/\beta\rvert_d$	
	SIM.	EST.	SIM.	EST.	SIM.	EST.	SIM.	EST.
a	.45	.43	8	9	<1.0	.71	1.8	2.5
b	.52	.63	7.7	7.8	.30	.2	6.9	10
c	.4	.39	7	10.4	<1.5	1.3	1.3	2.0

For the conventional and CW controller configurations, rolling moment output due to aileron stick force input [VSS gain δ_a / δ_{AS} combined with fixed aileron spring constant δ_{AS} / F_{AS}] was based on estimated data ($\dot{p} / \delta_{AS}$) for Tasks b and c. For Task a, a value of δ_a / δ_{AS} was chosen by CAL pilots during the pre-evaluation flight test phase somewhat lower than that indicated by the estimated data. This was done on the basis of achieving reasonable harmony with other characteristics of the simulation.

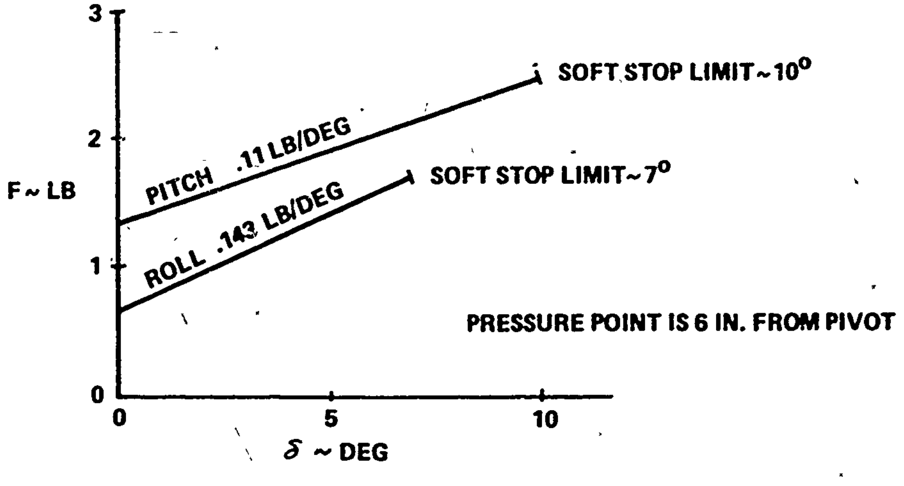
Due to lack of specific feel characteristic data for the AHC portion of the CW-AHC configuration and the DSC configuration, values of $\delta_a / \delta_{AS_{SA}}$ were chosen by CAL pilots, again to provide for simulation harmony. This was done for all three tasks.

Likewise, and for the same reasons noted directly above, yawing moment output due to rudder pedal force (VSS gain δ_r / δ_{RP}) and yawing moment due to aileron stick force input (VSS gains δ_r / δ_{AS} and $\delta_r / \delta_{AS_{SA}}$) were chosen prior to the evaluation flight phase by CAL pilots. The latter coupling gains were chosen to minimize the coupling characteristics. This was done for all controller configurations and tasks.

For the roll power VSS gains actually used for each task, values of the roll power parameter $L'_{\delta_{AS}} = \dot{p} / \delta_{AS}$ are given in the table below. These are based on in-flight measurement of $\dot{p} / \delta_{AS}$. These can be converted to the parameter $L'_{F_{AS}}$ by multiplying $L'_{\delta_{AS}}$ by the appropriate spring constant δ_{AS} / F_{AS}. For the conventional and CW configurations this value was 2.27. Values for the AHC part of the CW-AHC configuration and the DSC configuration may be obtained from the table of controller characteristics.

Controller / Task	$L'_{\delta_{AS}}$ (deg/sec^2/deg)				
			CW-AHC		
	Conv.	CW	CW	AHC	DSC
a	.5	.5	.5	.22	.9
b	.83	.83	.83	.28	1.0
c	.33	.33	.33	.22	.56

Controller Characteristics	Force/Displacement	
Controller	Pitch	Roll
Conventional	33 lb/in.	.45 lb/deg
Circumferential Wheel	33 lb/in.	.45 lb/deg
Alternate Hand Controller	.2 lb/deg	.06 lb/deg
Dual Side-Arm Controller	see diagram below	see diagram below



Block diagrams of the complete control feel and augmentation systems used in the configuration simulation are shown on Figure 11.

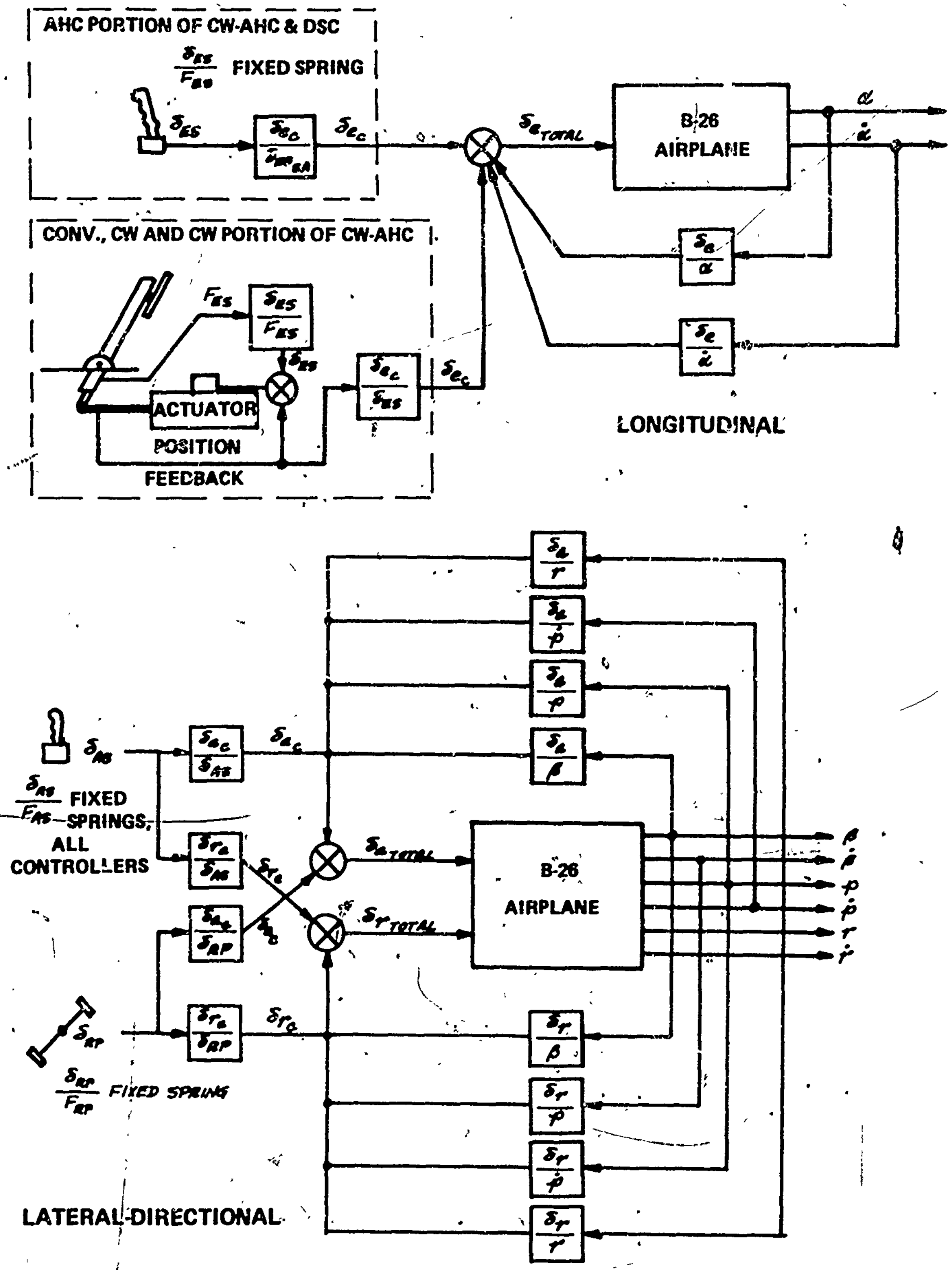


Figure 11 CONTROL FEEL AND AUGMENTATION SYSTEMS USED FOR CONFIGURATION SIMULATION

The basic structure of this experiment was patterned after the many in-flight evaluations performed by CAL, i.e., a relatively small sample of subject evaluators (four pilots in this case) is allowed to use as much time as is needed to observe the performance of a particular configuration and formulate their opinions (see Reference 10). This concept forms the basic framework for the present experiment. The four pilots evaluated each of the four controller configurations four times.

From this point on, design of the experiment was concerned with several options relative to the order of configurations to be flown, the number of configuration changeovers required, evaluation pilot availability, etc. The system finally decided upon was as follows: One pilot would fly all configurations and their replications before another began flying. Configuration order would be chosen on the basis of random selection. Although this procedure could produce a maximum number of configuration changeovers of 60, it was felt to be justified on the basis of good experimental design.

Details of the evaluation tasks (noted at the beginning of this section) are given below.

a. Up-and-away flight, cruise configuration was simulated using a lower airspeed but correct n_z/α including the following specific maneuvers:

    1) climb and climbing turns
    2) level flight with accelerations and decelerations
    3) constant altitude S turn
    4) maximum g turn followed by a 5 to 10 second zero g arc
    5) descents and descending turns.

b. Up-and-away flight, terrain-following configuration was simulated at high altitude by a tracking task provided through the flight director.

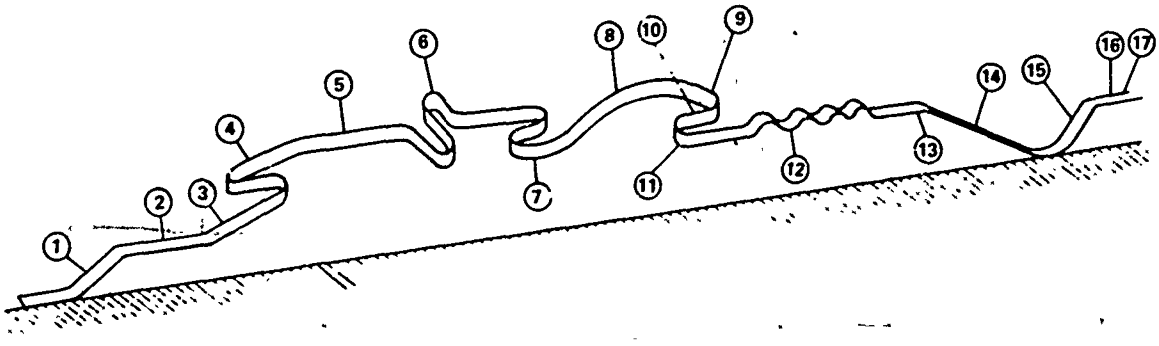
c. Approach, landing and takeoff were simulated directly with the correct airspeed.

A flight profile of a, b, and c is shown in more detail on Figure 12.

The approach maneuver consisted of a simulated IFR approach (pilot under the hood) and was initiated by capturing the localizer beyond the outer marker and completed by following the ILS beam down to the runway. Soon after the airplane touched down, it was accelerated for the takeoff maneuver. Nominally, three such approaches and takeoffs were made and consumed approximately one hour. Pilot comments were wire recorded during and after the maneuver.

The test times averaged about 15-20 minutes for preliminary maneuvers (takeoff to VSS_a), 40 minutes for the up-and-away maneuvers and 60 minutes for the approach maneuvers, or a total of approximately 2 hours per controller configuration evaluation. The evaluation pilot was made aware that he was not time limited and no pressure was placed on him to complete either his maneuvers or comments in a given time.

The up-and-away tasks, by definition, indicate a wide spectrum of airplane maneuvers on which the controller evaluation is based. However, the "terrain following" maneuver deserves special mention.

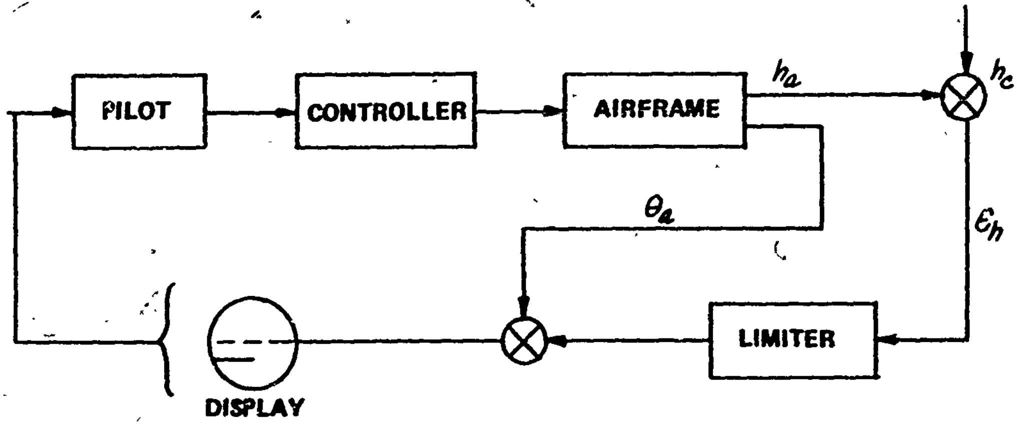


Sequence of Events

Task a 160 kt	1.	Climb to Test Altitude
	2.	Engage VSS_a and Check System; Evaluation Pilot Familiarization
	3.	Climb
	4.	Two 180° Climbing Turns
	5.	Straight and Level (Accelerate and Decelerate)
	6.	Constant Altitude "s" Turn
	7.	Two 180° Max g Turn
	8.	Zero g Arc
	9.	One 180° Descending Turn
Task b 214 kt	10.	Evaluation Pilot Comment, Safety Pilot Setup VSS_b Familiarization
	11.	One 180° 2.5-3 g Turn
	12.	Tracking Maneuver
Task c 120 kt	13.	Evaluation Pilot Comment, Safety Pilot Setup VSS_c Familiarization
	14.	ILS Approach
	15.	Takeoff and Climb
	16.	Evaluation Pilot Comments
	17.	Go-Around for Next Approach

Figure 12. FLIGHT TEST PROFILE

An electronic command signal (h_c) was generated proportional to an altitude time history describing flight over a typical terrain segment (Figure 13). This signal is compared with a signal (h_a) proportional to the actual altitude of the airplane. The difference (ϵ_h) is displayed as an altitude error signal (needle displacement) on the Flight Director System attitude director indicator. The pilot pitches the airplane (θ_a) to drive the error to zero with a signal from his pitch gyro. The altitude error signal is limited to a voltage equivalent to a θ_a of 15 degrees. As long as the commanded needle is coincident with the airplane position indicating needle, the pilot is flying as commanded.



The approach task (to touchdown) consisted of both precision flying (tracking the glide slope under instrument conditions) and the requirement to adequately compensate for trim changes due to flap deflection, power changes, gear let down and ground effect. The takeoff maneuver demonstrates the latter requirement under slightly different environmental conditions. For the purposes of this study, the takeoff maneuver began upon application of power after touchdown and concluded with the airplane in a flight condition defined by gear and flaps up, constant climb angle, velocity, and throttle setting.

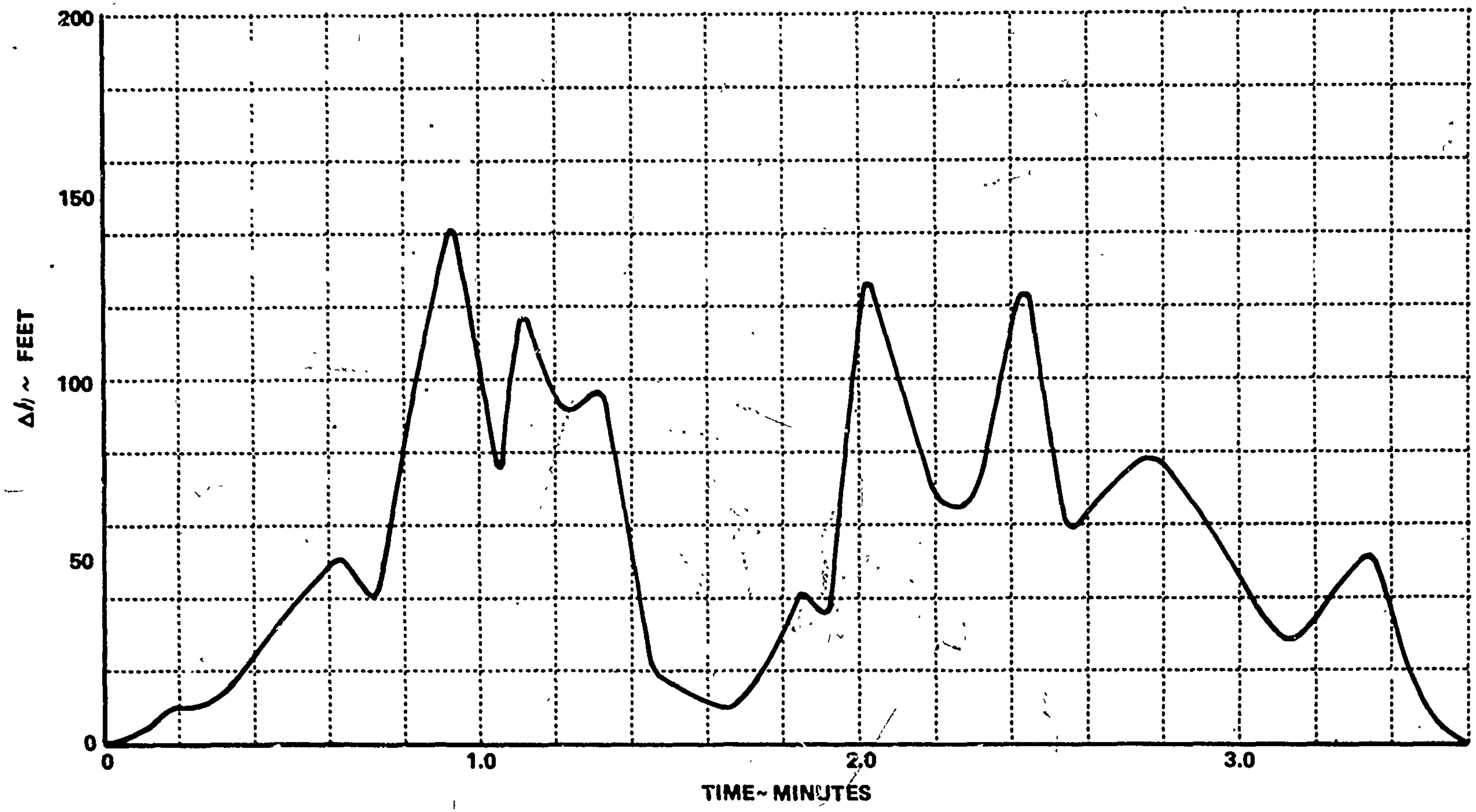


Figure 13 TRACKING COMMAND, TERRAIN ALTITUDE VS. TIME

The general procedures for data acquisition and reduction have been implied previously. The following deals more specifically with these procedures.

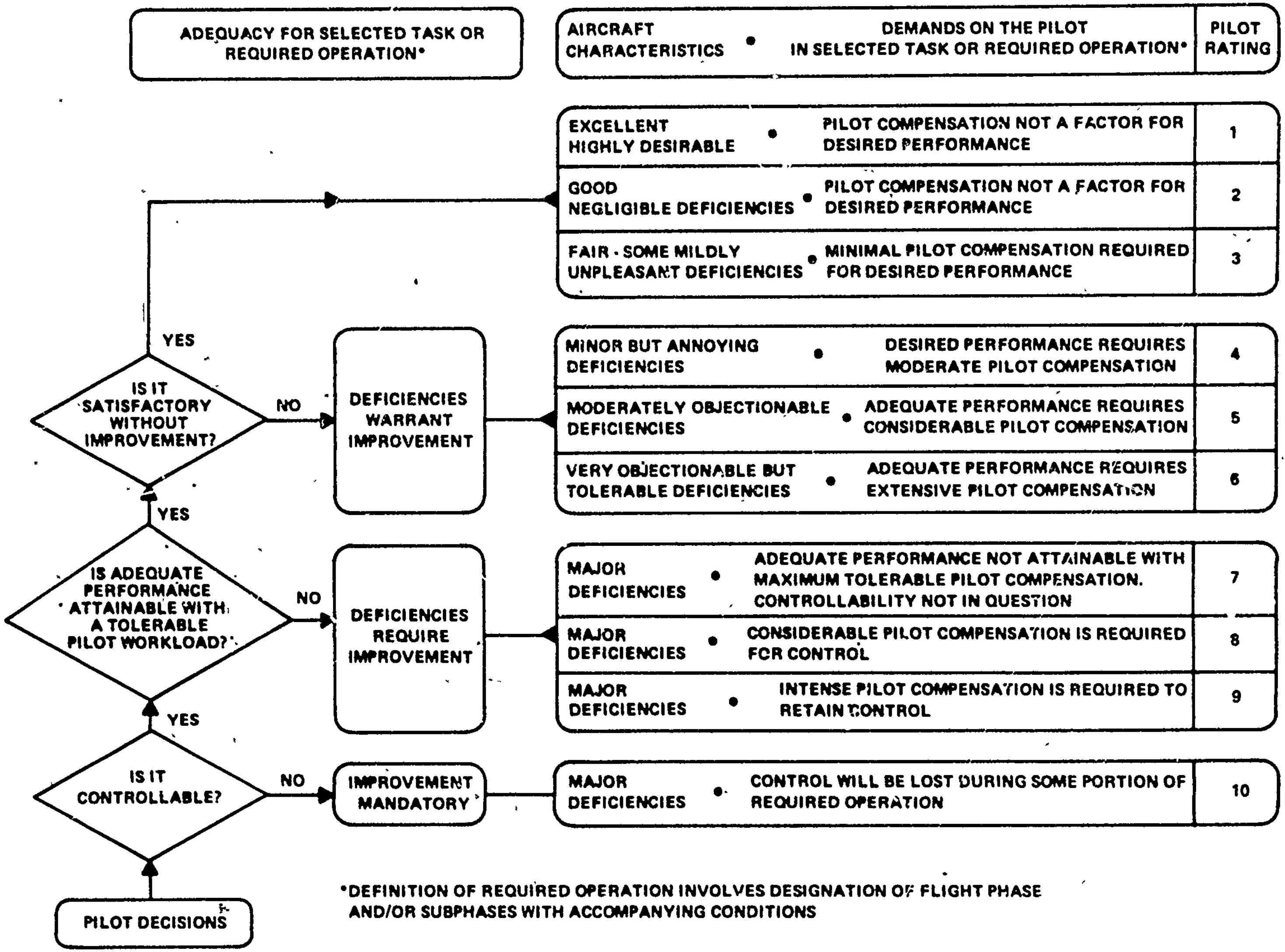
The data obtained consists of two types.

a. qualitative - pilot comments based on the pilot comment guide

b. quantitative - numerical pilot rating (Cooper-Harper Scale, Figure 14), and performance measures based on recorded quantities.

The pilot's comment guide is the basis on which the evaluation pilot considers and evaluates the particular configuration he is flying. His response to this guide, plus preflight briefing and post flight debriefing, forges the link between the pilot and his experience with the configuration and the engineering understanding and analysis which follows. For detailed philosophy of communication between evaluation pilot and engineer, the reader is referred to Reference 3.

For this study, the pilot's comment guide was presented in two parts. The first deals primarily with overall system performance - pilot, cockpit environment (including controller, instrument panel, comfort, etc), the airplane response, and those factors which result from coupling these. Overall system performance is itself divided into two tasks: up-and-away maneuvers and the approach, landing and takeoff maneuvers. The second part deals primarily with cockpit environment with particular attention to the controller itself. There is some overlap and redundancy between the two in order to better define and resolve the evaluation. The following guide (which was reduced to suitable card size form) was carried in flight by each evaluation pilot, and used at the time noted on the flight profile (Figure 12).



*DEFINITION OF REQUIRED OPERATION INVOLVES DESIGNATION OF FLIGHT PHASE AND/OR SUBPHASES WITH ACCOMPANYING CONDITIONS

Figure 14 HANDLING QUALITIES RATING SCALE

OVERALL SYSTEM PERFORMANCE

I. Up and Away Flight

A. Longitudinal

1. Ease and precision of making small pitch corrections - technique used - tendency to PIO?
2. Does the airplane stay at a given pitch angle and airspeed?
3. Is the trim well defined? Sensitivity? Does longitudinal response affect ability to locate trim?
4. Comment on longitudinal control during turn entries, steady turns and level flight recoveries.
5. Force level, gradient, and friction suitability.
6. Stick travel suitability.
7. Ability to change and maintain altitude.
8. Does longitudinal control motion cause excessive lateral control motion?
9. Turbulence level.
   - a) light
   - b) moderate
   - c) heavy.

B. Lateral-Directional

1. Heading control and ease of initiating and stopping turns on desired heading - technique used.
2. Bank angle control; ability to start and stop and maintain constant bank angle.
   - a) ability to pick up a wing
   - b) roll authority suitability
   - c) tendency to overshoot and oscillate
   - d) type and relative amount of control used.
3. Instruments used most of the time.

4. Does lateral control motion cause excessive longitudinal control motion?
5. Turbulence level.
   - a) light
   - b) moderate
   - c) heavy.

II. Approach (IFR ILS) Landing and Takeoff

A. Approach and Landing

1. Ability to capture ILS beam.
   - a) Localizer.
   - b) Glide slope.
2. Ability to track ILS beam (ability to make small corrections).
   - a) Localizer.
   - b) Glide slope.
   - c) Airspeed.
3. Control technique used (relative amounts of elevator, throttle, aileron and rudder).
   - a) Localizer.
   - b) Glide slope.
   - c) Airspeed.
4. Workload.
   - a) Excessive?
5. Oscillation in
   - a) altitude?
   - b) attitude?
   - c) heading?
   - d) How do you stop oscillation?
6. Are trim changes
   - a) small?
   - b) moderate?
   - c) large?
7. Ability to compensate for trim changes.
   - a) Easy - no problems.
   - b) Moderately difficult - could be improved.
   - c) Very difficult - should be improved.

B. Takeoff

1. Are trim changes
   - a) small?
   - b) moderate?
   - c) large?
2. Ability to compensate for trim change.
   - a) Easy - no problem.
   - b) Moderately difficult - could be improved.
   - c) Very difficult - should be improved.

C. Which maneuver of the above sequence was the most difficult to perform and why?

COCKPIT ENVIRONMENT

I. Instrument Panel Visibility

A. Primary Cluster

1. Good - no problems.
2. Adequate - could be improved.
3. Bad - definitely should be improved.

B. Secondary Cluster

1. Good - no problems.
2. Adequate - could be improved.
3. Bad - definitely should be improved.

C. Adverse effect on mission performance.

1. Minimal.
2. Moderate.
3. Large.

II. Accessibility to cockpit controls (switches, circuit breakers, etc.).

1. Good - no problems.
2. Adequate - could be improved.
3. Bad - definitely should be improved.

Adverse effect on mission performance.

1. Minimal.
2. Moderate.
3. Large.

III. Interference (controller) with other cockpit tasks.

1. Minimal.
2. Moderate.
3. Large.

Adverse effects on mission performance.

1. Minimal.
2. Moderate.
3. Large.

IV. Head movement required to evaluate instrument readings.

1. Minimal - no particular problems.
2. Moderate - could be improved.
3. Excessive - definitely should be improved.

Adverse effect on mission performance.

1. Minimal.
2. Moderate.
3. Large.

V. Necessity for changing position of hand on grip with change of controller position.

1. Not necessary.
2. Occasionally required - annoying.
3. Too much required - definitely should be improved.

VI. Overall contribution of controller to fatigue.

1. Minimal.
2. Moderate.
3. Excessive.

What controller characteristics contribute most to the degree of fatigue indicated?

VII. Do you feel as though you are an integral part of the control-airplane-response system, or do you feel "detached" from this system? Is your feeling significant in terms of task performance?

VIII. Assuming you had to fly this configuration for a longer time than during these tests (hours), do you think your evaluation would be significantly affected? If so, in what way?

IX. For any of the configurations evaluated, do you anticipate problems in acceptance by the majority of large airplane pilots?

X. Comment on:

1. Control harmony.
2. Breakout forces and deadband.

XI. If conditions of X undesirable, what would you like to see?

Because the scope of the up-and-away maneuvers represents nearly all of the requirements for airplane maneuvering performance at altitude, pilot comments and a single pilot rating were requested which encompassed all maneuvers. The same procedure applied to the approach, landing and takeoff maneuvers; the pilot was asked for ratings for this total task. In addition to overall ratings, two detailed ratings were asked for to include the tracking maneuver of the up-and-away phase and the approach portion of the landing phase. For these cases, a rating of these particular maneuvers was asked for in addition to those for the overall phases in order to correlate tracking performance measures with pilot rating.

In order to insure easy and continuous progress during the pilot evaluation phase, it was necessary that variable stability operation, controller operation, and experimental test procedures be thoroughly checked in flight prior to the actual evaluation. In addition, the variable stability system had to be calibrated to provide the required simulation.

The largest single element of test equipment to be calibrated in flight was the B-26 variable stability airplane. In essence, this means determining settings of the electronic gain controls so that the various static and dynamic characteristics of the airplane to be simulated can be matched by the B-26 VSS airplane. These characteristics manifest themselves in airplane motion responses to control inputs, cockpit control forces and displacement, etc. The type and extent of calibration required is related to the degree of simulation and other factors noted below. Obviously, how well a given airplane is simulated depends upon detailed knowledge of its geometric, inertial, and stability and control characteristics as well as the range of the simulator's capabilities. Most of the benefits of in-flight simulation of a new design concept come during early stages of the design process, when results of the simulation may indeed alter the design itself. Obviously, at this stage, not all the characteristics of the airplane to be simulated are well known so one must compromise fidelity of simulation for timeliness of results. However, this is not inconsistent with the basic objectives of the experiment. Likewise, the B-26 variable stability airplane has some limitations. For example, matching all the dynamic response characteristics would be possible if all derivatives of the simulated airplane could be matched. Because the B-26 system has neither direct lift control nor variable side force capability, derivatives such as L_{α} and Y_{β} cannot be matched. However, many of the important dynamic response characteristics can be matched by mismatching some derivatives and by introducing derivatives not inherent in most airplanes, e.g., $N'_{\dot{\beta}}$.

Generally, experience has shown that many limitations fall outside the evaluation pilot's ability to detect differences, often because they do not affect the characteristics to which he is most responsive. Furthermore, experience has indicated which characteristics need to be simulated and how they contribute to the pilot's evaluation of the configuration. (This is not meant to imply that all characteristics to which the pilot may be significantly responsive have been defined. Indeed, research in the field is constantly expanding.)

In general, it can be noted that the degree of simulation achieved and the program of in-flight calibration are dependent upon:

a. knowledge of the simulated airplane's characteristics.
b. capability of the simulation.
c. knowledge of those characteristics to which the evaluation pilot is responsive.
d. methods of calibrating the VSS for these characteristics.
e. well executed in-flight calibration procedures.
f. careful data reduction.

"Proof" flights provided a final check of all experimental systems and procedures prior to the evaluation phase. These flights were designed to:

a. check time required to perform required maneuver profiles.
b. check VSS operation.

c. check controller operation - in particular, determine reasonable values for controller spring rates.
d. determine the effect of the dual side arm controller arm rests as an experimental parameter.

Results of this flight phase were generally as expected. The total time required to perform the maneuver profile and evaluation was essentially that originally estimated, i.e., approximately 2 hours.

Desirable longitudinal spring ratios (stick force/stick displacement) for the conventional and circumferential wheel configurations were chosen on the basis of pilot preference.

SECTION IV

PILOT COMMENT ANALYSIS RESULTS

This section presents the characteristics of the pilot-controller-airplane-task system, based on pilot comments recorded in flight. The great majority of comments were in response to the comment guide described in Section III. However, results of the analysis of comment data include the comments obtained from post flight debriefings as well as from the primary source noted above.

It is worthwhile to explain various assumptions made and procedures followed to arrive at the statements made below. For example, response to a single question was made four times by each of the pilots with respect to a given controller and mission. Assuming these four comments were not all the same, and assuming no major factor such as turbulence appeared to influence the results, the overall assessment as noted here was based on the number of "positive" comments versus the number of "negative" comments. If there was one negative and three positive comments, it is assumed that the decision was generally positive. If the comments were equal in polarity, but showed a trend with flight replication, then it is assumed that some learning effect is present, and the comments given on the latter flights were more heavily weighted. If the decisions were random, and again no significant "outside" factors were evident, it was assumed that no decision was forthcoming from the subject pilot.

A similar procedure was followed for determining an overall assessment for the whole pilot sample. If three of the four pilots indicated a positive decision, then the decision was generally assumed as positive, etc.

It may be noted that such inconsistencies, particularly with respect to "within" pilot comments do not appear as a high percentage of the total number of different comment responses. In the case of "among" pilot inconsistencies, reasons, if distinguishable, are noted.

Turbulence was not a specific test parameter in this investigation. Its input to the airplane system resulted only from natural phenomena and occurred significantly only sporadically during the flight test program. However, its level was noted throughout, and its effect is used wherever possible to weight the data.

For convenience and consistency, pilot comment results are presented in the following sequence: up-and-away flight, 160 knots; up-and-away flight, terrain following, 214 knots; approach, landing and takeoff; cockpit environment, and general comments. The first two tasks are further divided into longitudinal characteristics and lateral-directional characteristics.

1. TASK a, UP-AND-AWAY FLIGHT, 160 KNOTS

For the majority of cases where turbulence was not considered to be a significant factor, longitudinal characteristics and control for this simulated airplane configuration were generally good, particularly when flying the conventional, CW and CW-AHC controller configurations. Control precision suffered somewhat when using the DSC, primarily due to a lack of anticipation of airplane motion following a control input, a condition ascribed to insufficient force cues. In direct response to controller force feel questions, both the force level and force gradient (force/unit deflection) of the DSC were considered to be light. In many cases the DSC was considered slightly too "sensitive". (It is to be remembered that the DSC sensitivity in terms of elevator deflection per unit stick displacement had to be chosen at least high enough to provide sufficient authority to perform the large disturbance maneuvers of the up-and-away task.)

Those maneuvering characteristics which in large part define the longitudinal stability and control role of the airplane, i.e., the ability to make small pitch angle corrections, the ability to change and maintain altitude and the ability to maintain a given pitch angle and airspeed, generally did not exhibit significant problems. Use of the DSC, however, did tend to cause a "bobble" when precise pitch angle corrections were attempted, and at times a slight to moderate pilot-induced oscillation was precipitated. As noted above, the pilots commented that the DSC was slightly sensitive, particularly when attempting to change and maintain altitude, and maintain pitch angle and airspeed.

In general, longitudinal control was good in turn entries, steady turns, and recoveries. However, use of the DSC sometimes made it difficult for the pilot to obtain the precise g desired due to over-sensitivity of the controller.

Longitudinal characteristics of the simulated airplane actually had a favorable effect on the pilots' ability to trim the airplane. Trim was, in general, well defined. However, the small trim wheel on the right hand grip (identical on all controller configurations) exhibited several undesirable characteristics. First, the detent in the trim wheel was annoying and not necessary. Second (and more important), trim was too sensitive, while at the same time, the amount of trim provided was insufficient. For a given diameter wheel with only a single turn, it's quite possible that providing sufficient authority will produce too high a sensitivity for small inputs. This is, of course, analogous to the side stick controller sensitivity-authority problem.

The other controller characterisitics, friction and stick travel, appeared suitable and satisfactory in all cases.

Comments relative to the lateral-directional characteristics indicated a slightly greater diversity of opinion as compared with the longitudinal mode. This diversity was revealed to a small degree in both "within" pilot comments and "among" pilot comments. This was not so much related to controller configuration characteristics as it was to control techniques used which were directly associated with the characteristics of the simulated airplane. However, the two sets of characteristics are not totally unrelated because airplane characteristics requiring undesirable techniques can, of course, emphasize any controller deficiencies.

The problem was associated with the ease of initiating, stopping and maintaining a constant bank angle. The general complaint was the necessity for too much control coordination - too much directional control was required. This resulted in what was felt to be too large a workload - too much pilot compensation was needed.

It is reasonable to assume that at least a portion of the rudder requirement is due to the simulation itself - the amount of N_r (VSS gain δ_r/r) required to obtain the high Dutch roll damping estimated for the B-1. In a steady turn condition, the amount of δ_r required is directly proportional to N_r ; the B-26 has no washout circuitry to minimize this effect when the Dutch roll damping is augmented through use of the δ_r/r VSS gain. This situation was, of course, realized when the VSS configurations were being calibrated during the pre-evaluation flight test phase, and a value of δ_r/r was chosen which was felt would adequately match the Dutch roll damping, while at the same time would not necessitate inordinate amounts of rudder.

The spiral mode of the simulation was stable with $T_{1/2}$ approximately equal to 12 seconds. From previous experiments, this value was found to give good handling qualities, while not requiring large amounts of rudder.

Only two pilots did treat this characteristic as a predominant element in their assessment of the configuration and one of these, Pilot D (USAF) commented on this only occasionally. However, Pilot B (CAL) felt this to be a major deficiency (for all controller configurations) and, as will be shown later, it was the dominant factor in his overall rating.

Other lateral-directional characteristics presented no significant problems. Heading control was generally good throughout. Roll authority and ability to pick up a wing were fair to good in all cases. Two pilots, A (USAF) and D (USAF), felt that the lateral-directional response of the airplane had no effect on their ability to locate or define trim; one pilot, Pilot B (CAL) thought there was an adverse effect, and Pilot C (CAL) thought there was a favorable effect.

Differences among the various controller configurations were small. However, those that did exist were primarily associated with the bank control maneuver noted above, in particular with respect to the tendency to overshoot the desired bank angle. This tendency was neither consistent with replication nor with pilots. Generally all configurations varied from "no" tendency to "slight" tendency. However, once for each controller, "extreme" tendency was noted. Thus it can be seen that the data does little to warrant establishment of a trend.

In summary of the up-and-away 160 knot task, it may be said that the simulated airplane characteristics were generally good (with the possible exception of bank angle control); that there were small differences among controllers with the exception of the DSC in the longitudinal maneuvers, where an apparent lack of adequate force feel caused some loss of maneuver precision; and that some thought should be given to redesign of the longitudinal trim function to provide a better balance of authority and sensitivity.

The maneuvers of this task were performed only in a "none" to "slight" turbulence environment. However, there is a distinct indication from the pilot comments that an increase in the turbulence level would tend to emphasize deficiencies in some areas of control.

2. TASK b, UP-AND-AWAY FLIGHT, 214 KNOTS

The tracking maneuver portion of this task tended to emphasize the pitch control characteristics more than those in the previous configuration. Although it was generally not difficult to make small pitch corrections, a certain amount of bobble and overshoot was encountered, along with some pilot-induced oscillation (PIO) tendency. The latter characteristic ranged from "slight" to "moderate" for the DSC configuration and from "no" to "slight" for the other configurations. In particular, the DSC again appeared to lack sufficient force cues for precision tracking. This was manifested in part by an inability of the pilots to pull and maintain "g" forces without what was felt to be too much compensation and undue workload. The force gradient was noted specifically to be good on all configurations except the DSC which was thought to be too light. The above also applied generally to the force level. Friction level was not significant in any controller configuration. The pilots considered stick travel satisfactory throughout, except for Pilots C (GAL) and D (USAF), who felt that the DSC had slightly too much stick travel.

Trim was well defined throughout, but was generally too sensitive. The longitudinal characteristics had little or no effect on the pilots' ability to locate trim. When it was commented upon, it was noted as a favorable effect.

There was no problem in maintaining altitude throughout the controller-pilot matrix, and the airplane stayed at the pitch angle and airspeed selected.

The simulated lateral-directional characteristics were the primary cause of adverse comment in this flight task. The objections centered about precise bank control capability and were reasonably consistent with pilot, controller and task replication. Although this task is primarily a longitudinal one, the maintenance of a constant heading also requires lateral-directional control inputs which, in this case, revealed some objectional characteristics. Comments centered about insufficient roll power using ailerons alone, and the need for large amounts of rudder to produce the additional roll power required. The coordination technique required to attain precise bank control under these circumstances was a sensitive procedure and pilot comment varied depending on whether or not he could master it without too large a workload. One example of undesirable control coupling occurred when power application (a part of the longitudinal tracking control) was made unequally between the two engines, causing a yaw disturbance, resulting in roll, which in turn affected heading control. Attempting to minimize the results of such a disturbance in many cases required too much attention and was tiring.

The primary difficulty with this simulated airplane configuration was the high $|\phi/\beta|_d$ (a value which as noted in Section III is lower than that estimated for the B-1). It was recognized in the pre-evaluation flight phase that small changes in β and r due to gusts, rudder or other inputs would cause large changes in bank and roll rate. For this reason, a conservative value of aileron roll power was chosen (for each controller configuration) in order to minimize expected large excursions. Rudder required to maintain a steady turn, though probably greater than that estimated for the B-1 (due to augmented C_{n_r} required to obtain the high Dutch roll damping and a more highly damped spiral mode) was not particularly noted and was probably eclipsed by the undesirable coupling characteristics.

Coupling between longitudinal motion and lateral control motion did not appear excessive in most cases. However, slight coupling was in evidence throughout, but no particular trend with respect to controller configuration was noted.

3. TASK c, APPROACH, LANDING AND TAKEOFF

Because of the aforementioned gain problem with the DSC (Section II) the landing maneuver was not made by pilots A and B using the controller, except for a few cases which were of an exploratory nature. It was not considered part of their evaluation.

The approach portion of this task was by far the easiest of the three maneuvers to perform. This was verified by the ease with which the ILS beam was captured and tracked, with all controller configurations. Only one pilot noted "some problems" with the CW and conventional configurations, and these did not appear significant. The ease with which this maneuver was performed can be attributed to the displayed information of the flight director system, and while laudable for operational purposes, there is some doubt that its use contributes to a sufficiently sensitive task for experimental purposes.

The takeoff maneuver was the most difficult to perform, judged by comments in an approximate ratio of 3 to 4. This was primarily due to the trim changes required as a result of gear retraction, and flap and power changes. Trim changes on takeoff were generally noted as moderate to large for all configurations and replications. The ability to compensate was characterized as "moderately difficult" for all controller configurations for pilots A (USAF) and B (CAL). Pilot C (CAL) felt all configurations were moderately difficult with the exception of the DSC which was termed very difficult. Pilot D (USAF) thought compensation was easy for all configurations except the conventional one which was thought to be slightly more difficult.

Workload was generally minimal to moderate throughout the test matrix. Turbulence, when encountered, generally increased the workload.

As previously noted, turbulence was not a specific test parameter because its input to the airplane system resulted from natural phenomena and occurred only sporadically throughout the flight test program. However, when it did occur it was usually light, or when it was occasionally simulated by the pilot introducing disturbances, some important characteristics of the controllers were emphasized. When using the CW-AHC, for example, transfer from the AHC control (used for precise ILS path control) to the CW control (required for greater authority to counteract large disturbance), presented a somewhat confusing situation, primarily because of the abrupt change in force and displacement characteristics. Then too, the pilot would occasionally get the two control functions mixed and not know at the moment which one to use. The necessity for sorting out this situation appeared extremely burdensome and annoying under conditions of increased workload.

Slight turbulence also tended to emphasize deficiencies in the DSC feel mechanization, generally manifested by slight oscillations in attitude angle. Lack of anticipation of airplane motion due to low stick force cues had a tendency to produce an out-of-phase relationship between input and output causing "spastic" control of attitude.

Landings were accomplished by Pilots C and D using the DSC modified with the nonlinear gain curve described in Section II and shown in Figure 6. Although this partially solved the sensitivity-authority problem, the lack of force cues mentioned above tended to downgrade the DSC configuration. The nonlinear gain was helpful only when the pilot trimmed the airplane with the controller centered in its travel. Otherwise, he could be operating about a point of high sensitivity when trying to make precision changes in flight path and experience a PIO tendency.

The lateral-directional response characteristics generally had no effect on ability to locate trim. In those few cases where some effect was apparent, it was in a favorable direction.

Throughout the evaluations of Task b, the turbulence varied generally from a smooth air condition to a light turbulent condition. As in the case of Task a, it is apparent that assessment of both simulated airplane and controller characteristics may vary significantly with turbulence level.

4. COCKPIT ENVIRONMENT

Comments relative to cockpit environment are considered to apply to all three tasks (or flight phases) of the flight test program. They are analyzed with respect to flight replication to take into some account the effect of repeated exposure to the environment.

Instrument Panel Visibility

Primary instrument cluster: the comment ratings ranged from good (no problems) to bad (definitely should be improved) with adequate (could be improved) as an intermediate step. The conventional configuration provided generally adequate visibility, with two pilots rating it as adequate to bad. Primary instrument cluster visibility for both the CW and CW-AHC configurations was considered good by three pilots and adequate to good by the other. Visibility was considered good by all pilots in the evaluation of the DSC.

Secondary instrument cluster: the same rating definitions apply here as above. The conventional configuration provided for somewhat less visibility than for the primary cluster with one pilot considering it adequate, two adequate to good, and one adequate to bad. Visibility for both the CW and CW-AHC units was considered adequate to good by two pilots, good by one pilot and good to bad by the other. Again as in the case of the primary cluster, the visibility for the DSC was considered good by all pilots.

Controller interference with other cockpit tasks: this was felt to be minimal for all configurations and flight replications. Consequently, any adverse effect on mission performance due to such interference was also considered minimal.

Head movement required to evaluate instrument readings: the CW and CW-AHC were considered as requiring minimal to moderate head movement. The DSC was rated as minimal throughout. Two of the pilots (one USAF and one CAL) felt the conventional configuration required moderate head movement. Adverse effect on mission performance was felt to be minimal throughout except for the two conventional configuration ratings noted above for which adverse effect was considered to be minimal to moderate.

Necessity for changing position of hand on grip with change of controller position: this procedure was necessary only for approximately 19% of the pilot-configuration matrix and then only occasionally. It was noted once for all controllers except the conventional configuration, where none of the pilots found it necessary.

Overall contribution of controller to fatigue: for all controllers except the DSC, contribution to fatigue was generally considered minimal to moderate. For the DSC, it was considered minimal.

Thus, only one controller, the DSC, was rated good (no problems) for the entire instrument panel by all the evaluation pilots. The conventional configuration provided the least visibility, with some improvement noted for the CW and CW-AHC.

With respect to differences of assessment of visibility between individual pilots, it may be noted that the two CAL pilots were slightly less sensitive to the differences between the effect of configurations than the two USAF pilots. One USAF pilot rated all configurations adequate to bad except the DSC, which as previously noted, was rated good.

Generally, the degree of visibility was thought to have a minimal adverse effect on mission performance, with the exception of the two USAF pilots' assessment of the conventional configuration. One considered it to have a minimal to moderately adverse effect; the other a moderately adverse effect.

Accessibility to cockpit controls: the pattern of this characteristic was similar to that of visibility. Generally, accessibility was considered adequate to good for all configurations except for the DSC, which was considered good throughout. One USAF pilot did rate the conventional configuration bad (definitely should be improved). Adverse effect on mission performance due to the degree of accessibility was generally considered minimal. However, for the case where the conventional configuration was rated bad, the adverse effect tended to be moderate.

The bulk of the cockpit environmental comments indicates that in each category (visibility, accessibility, etc.) at least slight gains are made by using the dual side arm controller. The cumulative effect of these gains would appear to be significant and warrant its use at least on the basis of improving the working area of the pilot.

5. GENERAL COMMENTS

The following is based on response to questions included in the Cockpit Environment part of the pilots' comment guide. However, because the answers to these questions essentially apply to all tasks, they are presented below as a separate part of this section.

Response to the question as to whether or not the pilot felt he was an integral part of the control-airplane-response system was generally affirmative through the pilot-configuration matrix. In those few cases (three out of sixteen) a certain detachment was felt, not due to the control concept, but due to detail mechanization and feel characteristics. The two CAL pilots, both commenting on the DSC, sometimes felt a certain irrelevancy to the overall system due to lack of anticipation of airplane response, ascribing it to lack of sufficient force feel. Much of this has been noted in detail in previous sections with regard to specific maneuvers.

The only reservations any of the evaluation pilots had relative to acceptance of these controllers by large-airplane pilots was with regard to detail mechanization, not the concepts. Normal training and experience (as with most man-operated devices) is all that is required.

Generally, all pilots thought evaluation time was sufficient, and that their assessment would not be significantly altered by flying a given configuration for several hours.

Control harmony, breakout force and deadband characteristics were generally satisfactory for all controllers.

The two USAF pilots (A & D) had significant spontaneous comments relative to their overall preference for controller configurations. Pilot A felt that both the CW-AHC and DSC configurations were a significant improvement over the conventional wheel and column for the tasks used in the investigation. Pilot D felt the DSC was superior to all others evaluated, but recognized the need for improving its feel characteristics.

SECTION V

PILOT RATING ANALYSIS RESULTS

The evaluation pilots were instructed to rate the combined airplane-controller configuration combination for each individual task, using the handling qualities rating scale shown in Figure 14. Thus, a reported rating reflected the pilots' assessment of the complete pilot-airplane-controller (and cockpit environment) - task complex. However, in the case of Task c, comprising the landing, approach and takeoff maneuvers the pilot often thought the differences among these maneuvers were significant enough to warrant separate ratings within the defined task. This was also prompted in part during the early stages of the evaluation when it became evident that the compromise elevator gain selected for the DSC (see Section II) was actually biased to a point where although the airplane could be landed, it would always receive the lowest possible rating due to lack of control authority. Subsequently, the landing maneuver using the DSC was eliminated from Task c for Pilots A (USAF) and B (CAL) except for the exploratory effort mentioned previously. This led to separate ratings for approach and takeoff and in the case of the other controller configurations, separate ratings for each of the three maneuvers of Task c. The exception was Pilot B (CAL) who reported a single rating for Task c, which in the case of the DSC was limited to the approach and takeoff only.

After mechanizing the nonlinear gain for the DSC, the landing maneuver was reinstated as part of the Task c evaluation. However, it still seemed prudent to examine the individual parts of the task, and this course was followed by Pilots C (CAL) and D (USAF).

Much use of simple averaged numerical rating data is used in this analysis; average of replications, average of pilots, etc. It is recognized this is mathematically inconsistent because it implies linearity among the rating numbers which in themselves are merely a shorthand indication of the adjective description which best fits the pilot's assessment of the configuration. Although the word descriptions obviously indicate strong trends, there is presently no way to show that these descriptions form a linear progression. Thus, applying any linear mathematical concept to the data is not rigorous.

However, despite this inaccuracy, the advantages in terms of reducing large amounts of data to a form where trends can be easily recognized appears to warrant the linear approach.

Pilot rating data is presented in this section, and illustrated by the appropriate figure in the following forms:

a. Individual pilot rating vs controller configuration for each task (or task component where appropriate) and each replication.

b. Averaged replications to denote a single trend of the above.

c. Direct pilot comparison of b for each task.

d. Averaged pilot trend to denote overall rating trend for each task.

e. Effect of replication on rating - pilot rating vs replication for each configuration, task and pilot.

f. Replication rating spread for all tasks for each pilot.

g. Average of all pilot replication spreads.

h. Comparative rating of controllers for each pilot for all tasks.

i. Average of all pilot comparative ratings for all tasks.

Individual pilot ratings vs. controller configurations are shown on Figures 15, 16, 17, and 18 for Pilots A, B, C, and D respectively. Replication spread is noted, as are trends based on averaged replications.

Pilot A

The ratings given by Pilot A (USAF), Figure 15, the first time he examined each configuration appeared to be too low (high level of assessment) on the basis of pre-evaluation flying by CAL pilots and previous knowledge of airplane characteristics - rating relationships. Review of these results with Pilot A indicated the possibility of a lack of understanding and definition with respect to the handling qualities rating scale. This is the responsibility of the engineer directing the experiment, not the evaluation pilot. Subsequent dialogue appeared to rectify the situation. The "first round" data is shown for interest, but succeeding analysis considers only three replications.

Task a shows little preference difference among controllers, either in terms of replication spread or averaged replications, with a maximum variation of approximately 1/2 rating. Overall average assessment was between a rating of 3.0 and 3.5.

Task b indicates some preference for the CW-AHC configuration, about a one rating improvement over the other configurations. Replication spread is only 1 rating and the overall average assessment was approximately 5.0.

Task c ratings were given for the tasks' three basic components, approach, landing and takeoff (no ratings were given for landing with the DSC for reasons previously noted). For the approach, rating differences were again small; however, all three new concepts fared better than the conventional configuration by about 1/2 rating. Rating spread was greater than for Tasks a and b, about two rating units. Overall average assessment was between a rating of 2.5 and 3.0.

The landing maneuver produced a controller rating difference of 1/2 to 1 rating unit with a replication spread similar to the approach, with overall assessment between a rating of 3.0 and 4.0.

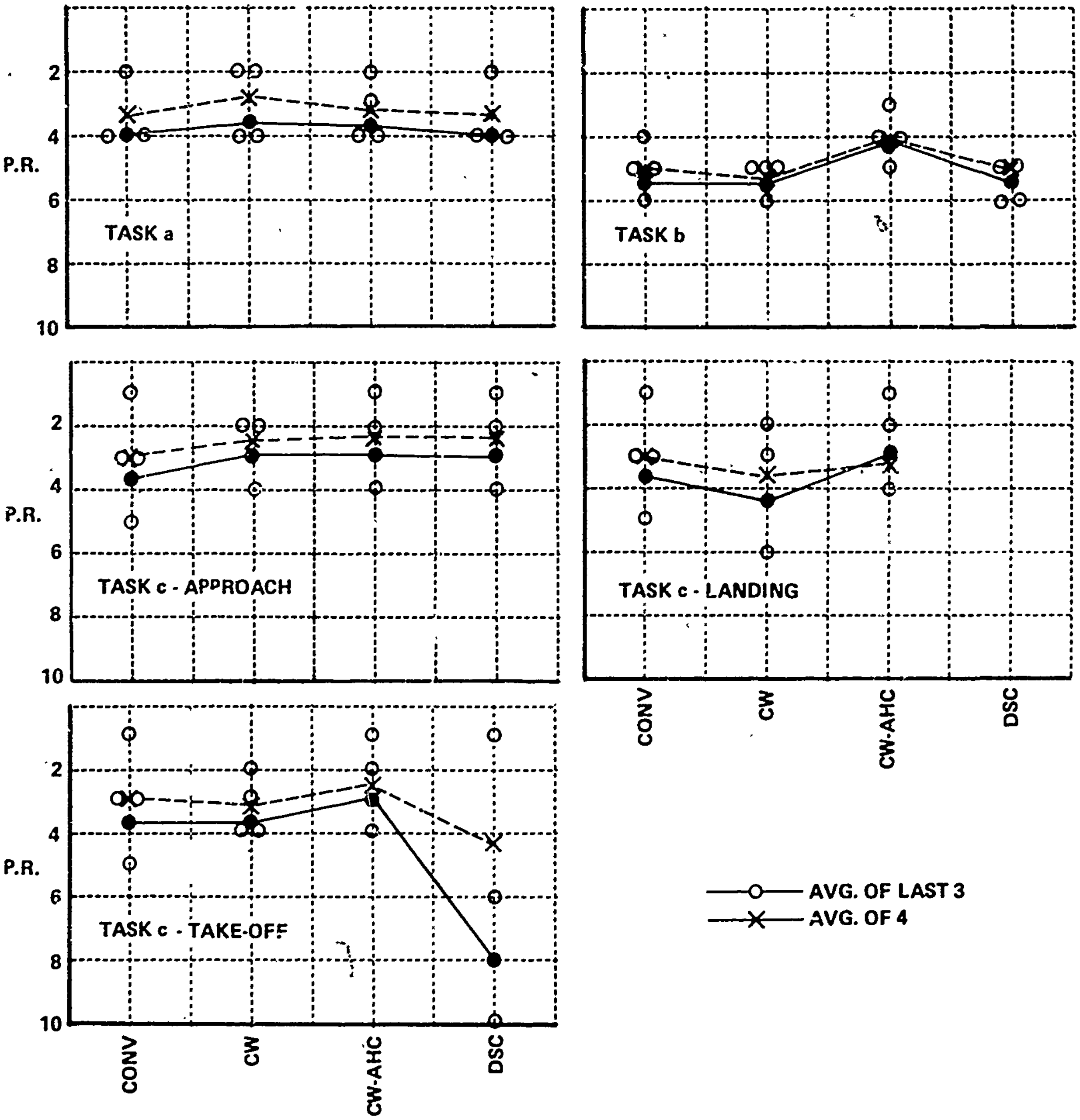


Figure 15 CONTROLLER RATINGS - PILOT A (USAF)

The takeoff maneuver showed a rating preference for the CW-AHC configuration of almost one full rating unit as compared to the conventional and CW configurations. The DSC suffered from the sensitivity-authority problem previously noted and was severely downgraded. With the exception of the DSC, the overall rating was between 3.0 and 4.0.

The indication from the rating differences described is that Pilot A preferred the CW-AHC configuration by a small margin. This is substantiated by his comments. (He commented similarly about the DSC, but, by definition, the ratings if correctly applied cannot show this.)

Pilot B

The ratings of Pilot B (CAL), Figure 16, were generally higher (lower assessment) for all tasks than those of the other pilots. His comments do not directly substantiate this assessment; his objections to both controller and airplane characteristics in terms of specific deficiencies were similar to those of the other evaluations. However, they do indicate a greater sensitivity to these deficiencies and this is reflected in his ratings.

Task a showed the least variation in replication spread and among controllers, a difference of one rating unit. The overall assessment level was high numerically, between 7.0 and 8.0 in sharp contrast to Pilot A.

Task b was rated in two parts in this case, entry to the tracking maneuver (see Figure 12), and the tracking maneuver itself. It was thought here that separate ratings were warranted because of the different dynamic nature of the two maneuvers, one primarily a large disturbance lateral-directional maneuver, the other a larger disturbance longitudinal maneuver coupled to precise lateral-directional control. (This philosophy was discarded for the last two pilots in favor of overall task assessment.) Again overall levels were numerically high for both cases and showed a greater replication spread than Task a, 2 to 3 rating units. For the entry maneuver, all three concepts were rated substantially better than the

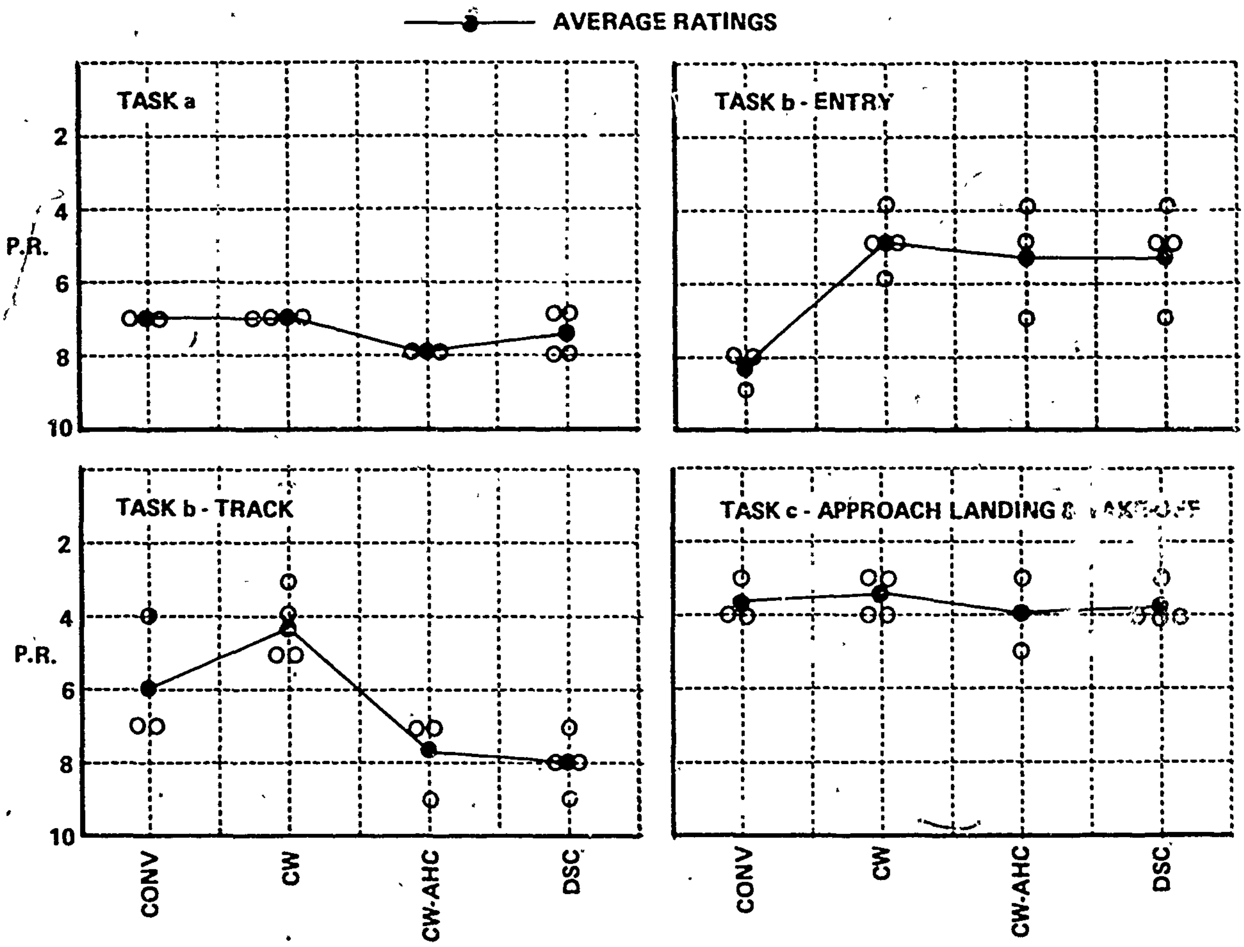


Figure 16 CONTROLLER RATINGS - PILOT B (CAL)

conventional configuration, with the CW having a slight edge. For the tracking maneuver, the CW was preferred by approximately 1 1/2 rating units over the conventional configuration and three to four rating units over the CW-AHC and DSC configurations. The overall averaged rating spread for both maneuvers was substantial,from about 3.5 to 8.0.

Task c, assigned a combined rating of approach, landing and takeoff in this case, exhibited the usual slight differences in preference among controllers with the CW preferred by only the slightest of margins. Overall assessment level was between ratings of 3.5 and 4.0.

Pilot C

Pilot C (CAL), Figure 17, showed less than a one rating unit spread among controllers for Task a, with a slight preference for the conventional configuration. Maximum replication spread was two rating units occurring for the CW configuration. The conventional configuration had a single replication spread and the CW-AHC and DSC had none. Overall assessment level was between 3.0 and 4.0.

For Task b, all new concepts were preferred over the conventional configuration by approximately one rating unit. Very slight preference was shown for the CW and CW-AHC configurations. Replication spread was nominally one rating unit and total overall average assessment ranged from 5.6 to 6.8.

Separate ratings were made for the maneuvers of Task a, with insignificant differences among controllers for the approach maneuver. Nominal replication rating spread was less than 2 rating units and the general acceptance level was between 3.5 and 4.0.

The landing maneuver indicated about a 1 rating unit difference among the conventional, CW and CW-AHC controllers and had a comparable replication rating. Overall assessment for these three controllers was a rating of about 4.0. Pilot C was the first evaluator to use the DSC modified to include the nonlinear gain function, described in Section II and shown on

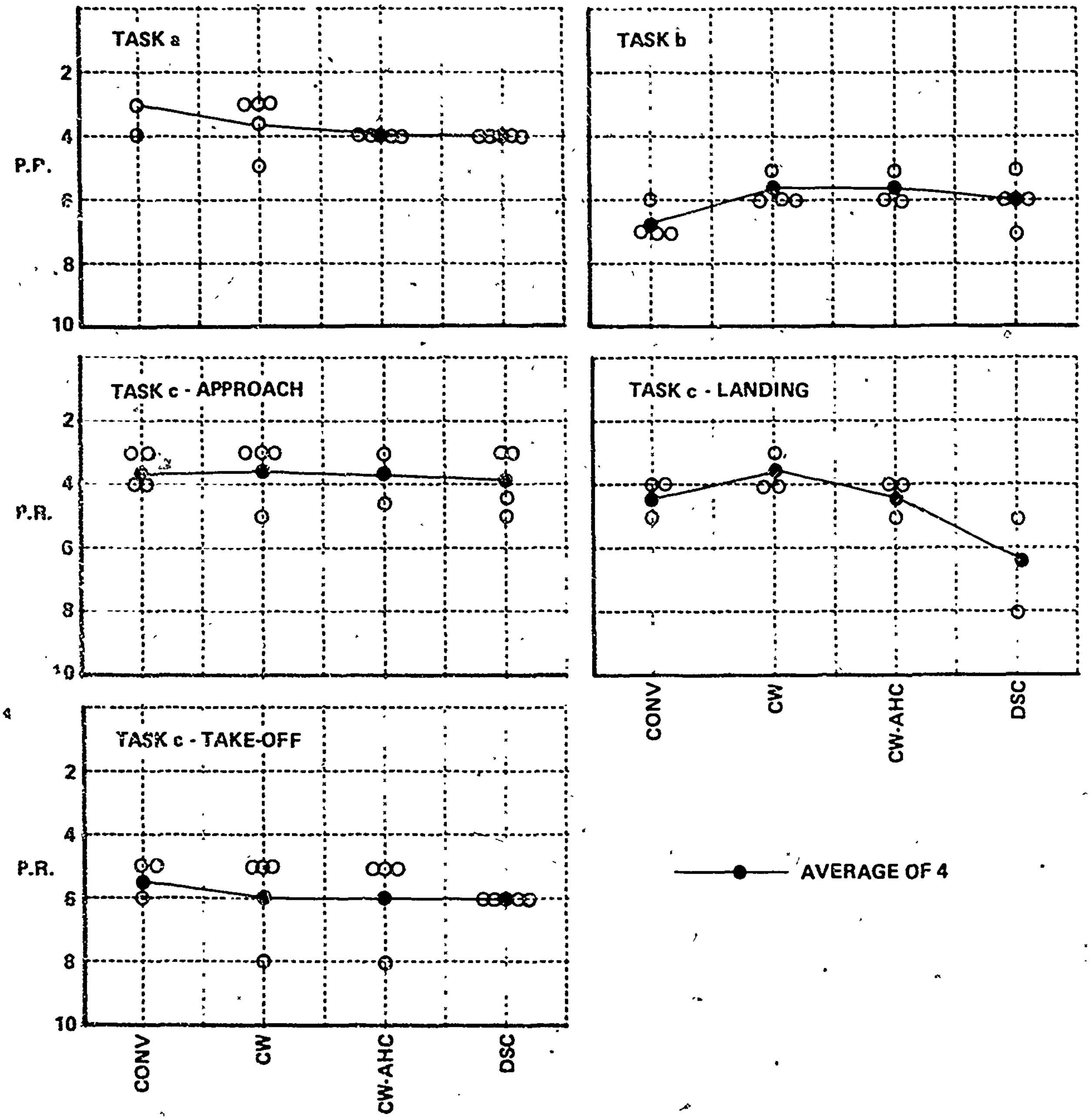


Figure 17 CONTROLLER RATINGS - PILOT C (CAL)

Figure 8, was used. Despite the fact that this function partially solved the sensitivity-authority problem, an apparent lack of sufficient force cues resulted in an incremental downgrading of about 2 rating units (to about 6.5) as compared to the other configurations. Replication rating spread was greater for the DSC, 3 rating units.

The takeoff overall rating of about 6.0, with little differences among controllers, emphasized the difficulty of this maneuver as compared with the others of Task c. Replication spread differed widely with controllers, with 3 rating units for the CW and CW-AHC, one for the conventional configuration and none for the DSC. Low assessment ratings of 8 were given for the CW and CW-AHC for one of the four replications in each case. These takeoffs occurred in a light to moderate turbulence environment which tended to amplify the deficiencies of basically 5.0 to 6.0 rated airplane-maneuver combination.

Pilot D

Pilot D (USAF), Figure 18, generally had the largest replication rating spread for all evaluators, the average of which however did not differ greatly from his predecessors. Task a showed replication rating spreads of from two to five rating units, depending on the controller configuration. Averaged replications produced a low rating of 2.0 for the CW configuration and high ratings of about 4.5 for the conventional and DSC configurations.

Task b was rated generally lower (as with previous pilots) with a large replication rating spread (six rating units) for the CW-AHC configuration. Variation was one unit for the conventional configuration, three for the CW and two for the DSC. Averaged replication ratings varied from a 4.5 for the preferred CW to the highest for the conventional configuration, a 7.3.

As with the previous pilot, Task c was rated separately for each of its maneuvers. In the approach, all three new concepts were rated better than the conventional configuration, a maximum of two rating units for the CW and a minimum of one-half rating unit for the DSC. Replication rating

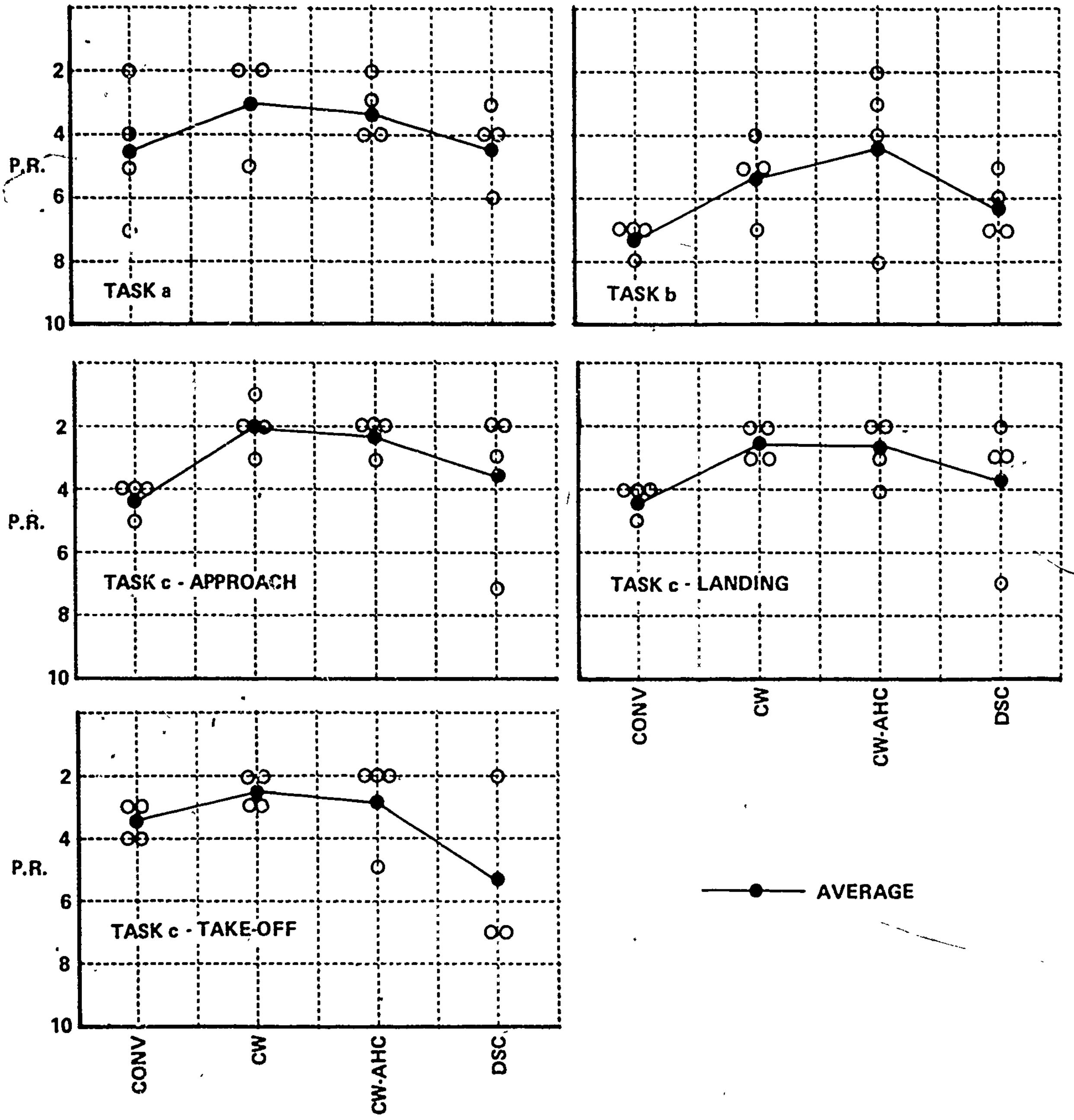


Figure 18 CONTROLLER RATINGS - PILOT D (USAF)

spread was nominal except for the DSC where the last evaluation produced a high numerical rating, resulting in a spread of five rating units. A similar trend is noted for the landing maneuver. In both cases, turbulence tended to magnify the lack of sufficient force cues which was characteristic of the DSC. Again, the CW was preferred; by two rating units over the conventional configurations, one unit over the DSC, but only marginally over the CW-AHC.

For the takeoff maneuver, replication spread was greatest for the DSC; it was also rated the worst, an average 5.3. The CW again received preference, with an average 2.5. The conventional configuration was third best with an average 3.8.

Figure 19 shows a comparison of pilot replication averaged ratings for each task. For Task c, one average represents all task maneuvers for each pilot. Also shown is the resulting task - configuration ratings based on the averages of all four pilots.

Except for Pilot B, Task a produced remarkable consistency of averaged ratings among pilots. Pilots' average produced results similar to the individual trends; small differences among controllers, less than a one rating spread. Including the results of Pilot B, an overall task rating (including all controllers) of from 4.2 to 4.8 is noted, in the "deficiencies warrant improvement" category of Figure 14.

Consistency of ratings for Task b was again good except where the contribution of Pilot B downgraded the CW-AHC and DSC thus enlarging the nominal overall rating spread from less than two rating units to approximately 4. Pilot average rating varied from about 5.3 to 6.3, also nominally in the "deficiencies warrant improvement" category of Figure 14, but with a greater degree of objectionable deficiencies and the need for more pilot compensation to perform the task.

Task c indicated the least differences in preference among controllers, with an overall task-controller rating for all pilots of from 3.5

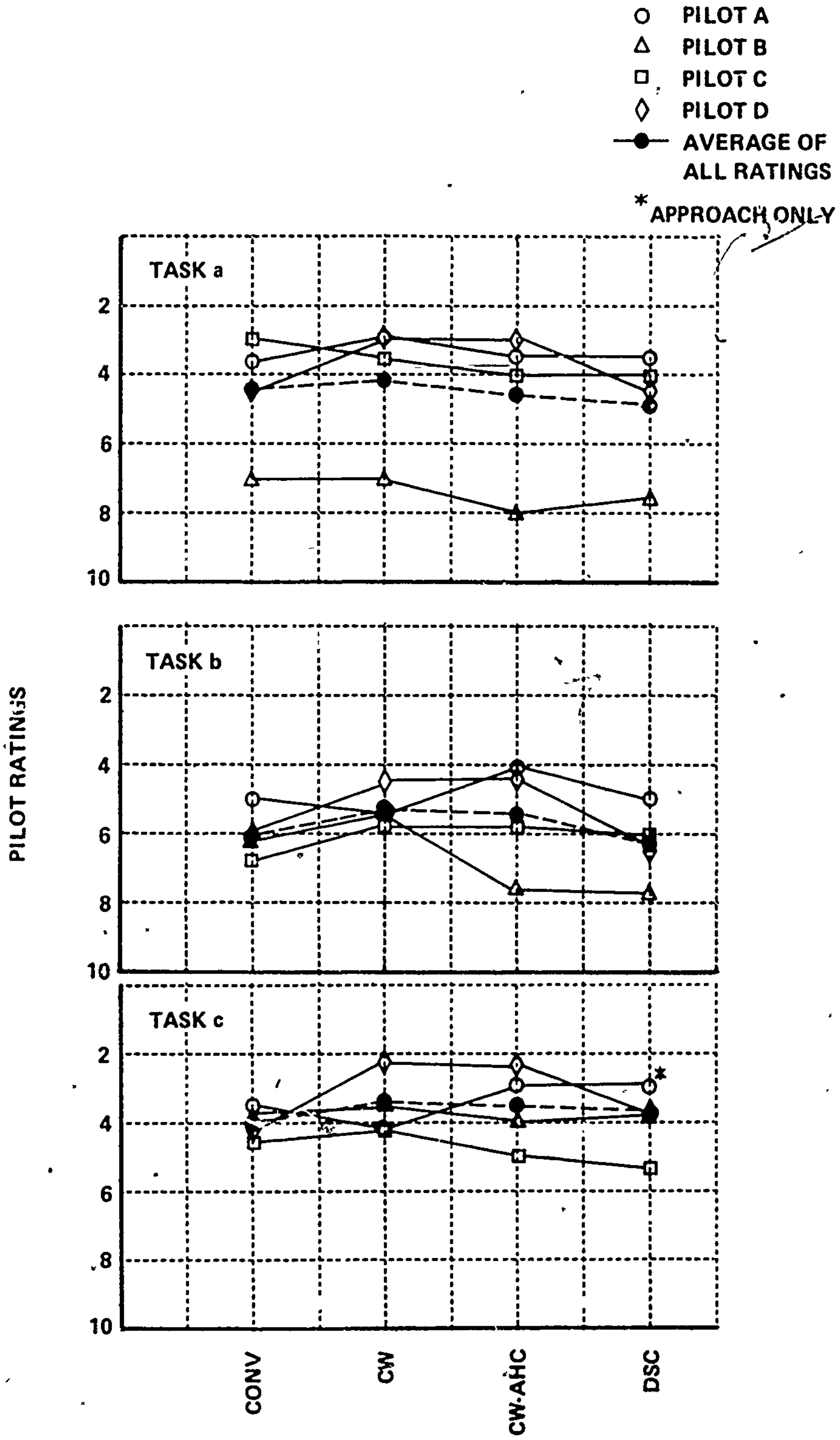


Figure 19 AVERAGE PILOT RATINGS

to 4.0. This, at worst, places this task in the upper part of the same category as Tasks a and b with minor but annoying deficiencies and moderate pilot compensation required.

It was desired to determine to what extent replication had an effect on pilot rating. Figure 20 illustrates this for each pilot, configuration, and task. The obvious scatter of the data makes it difficult to pinpoint trends. However it may be noted, for example, that Pilot A generally downgraded his assessment with replication for all tasks except in the case of the DSC for Task b. Pilot B indicated a gentle downgrading for Task c, but in the case of Task b showed some upgrading for all three new concepts. Pilot C showed a downgrading trend for Task b, but a slight upgrading trend for Task c. The randomness of the data of Pilot D masks general trends; some configurations show an upgrading trend, some a downgrading trend.

The significance of most of these observations cannot be realistically determined. Pilot comments indicate a varying sensitivity and awareness by the pilot of overall configuration deficiencies which include, in some cases, an indeterminate effect of turbulence.

A measure of replication rating spread is shown in Figure 21, where replication rating spread (in terms of rating units) is shown as a function of number of ratings given (in terms of percent of total). This is shown for each pilot and for the average of all pilots. The averaged curve shows that over 78% of all cases (74) documented had a rating spread of two ratings or less and 45% had a rating spread of one rating or less. In 8% of the cases, replication ratings were the same.

Figure 22 illustrates a slightly different look at comparative controller ratings. Averaged replication ratings for each task were placed in "best"and "worst" category. This was done by observing the lowest numerical rating (best) and its appropriate controller configuration, and the highest numerical rating (worst), and the controller configuration for which it was given. If two configurations were rated the same, (either best or

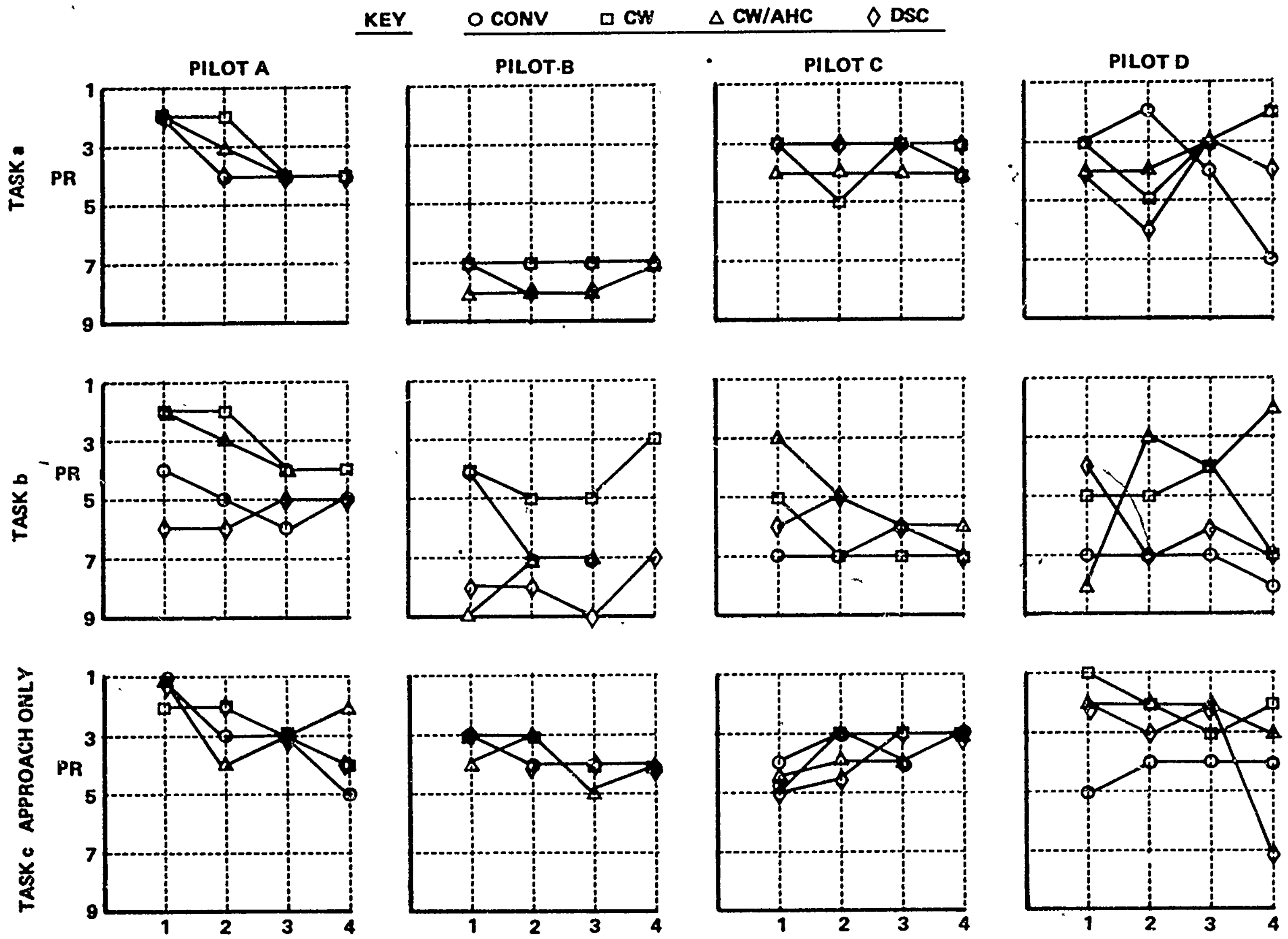


Figure 20. EFFECT OF REPLICATION ON PILOT RATINGS

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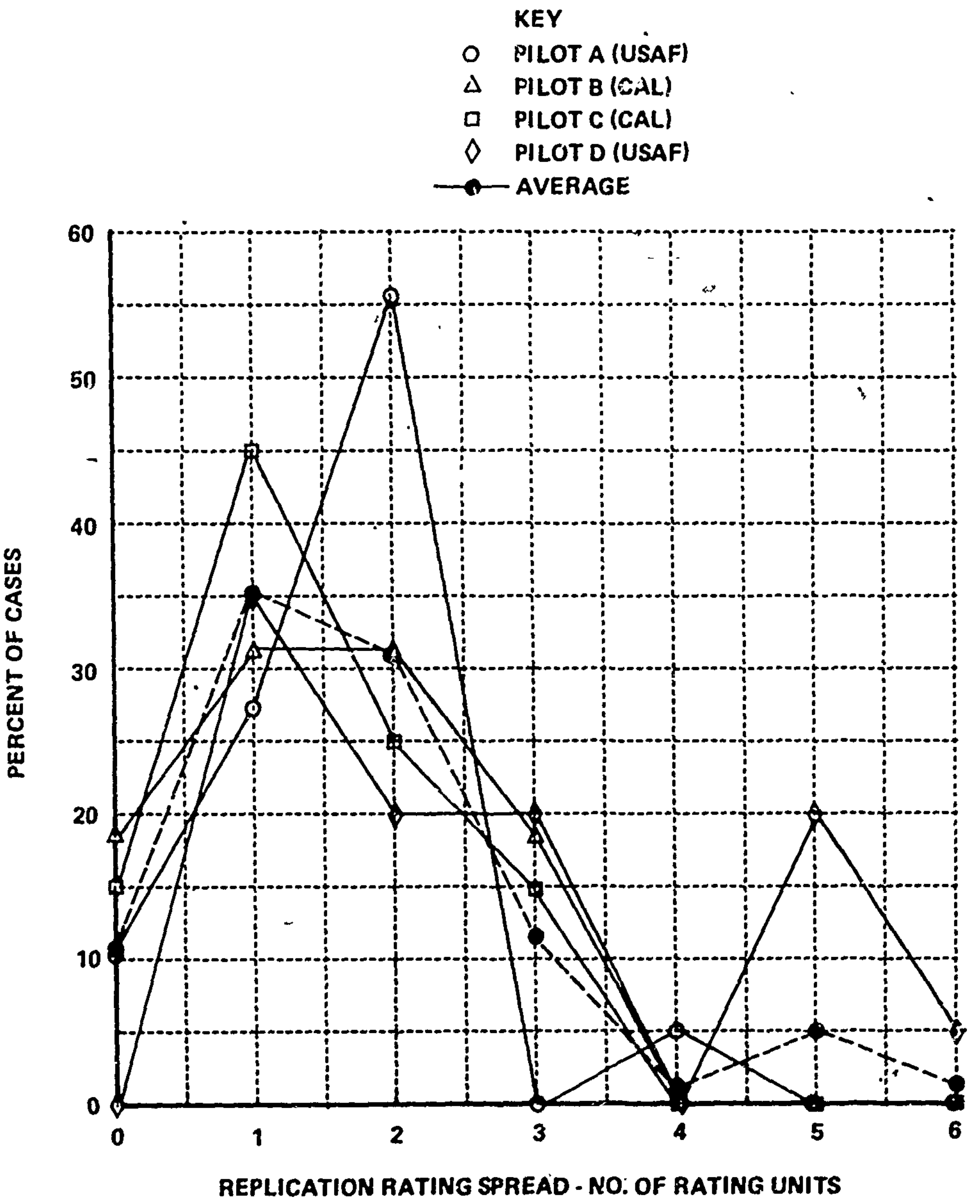

Figure 21 REPLICATION RATING SPREAD - ALL TASKS

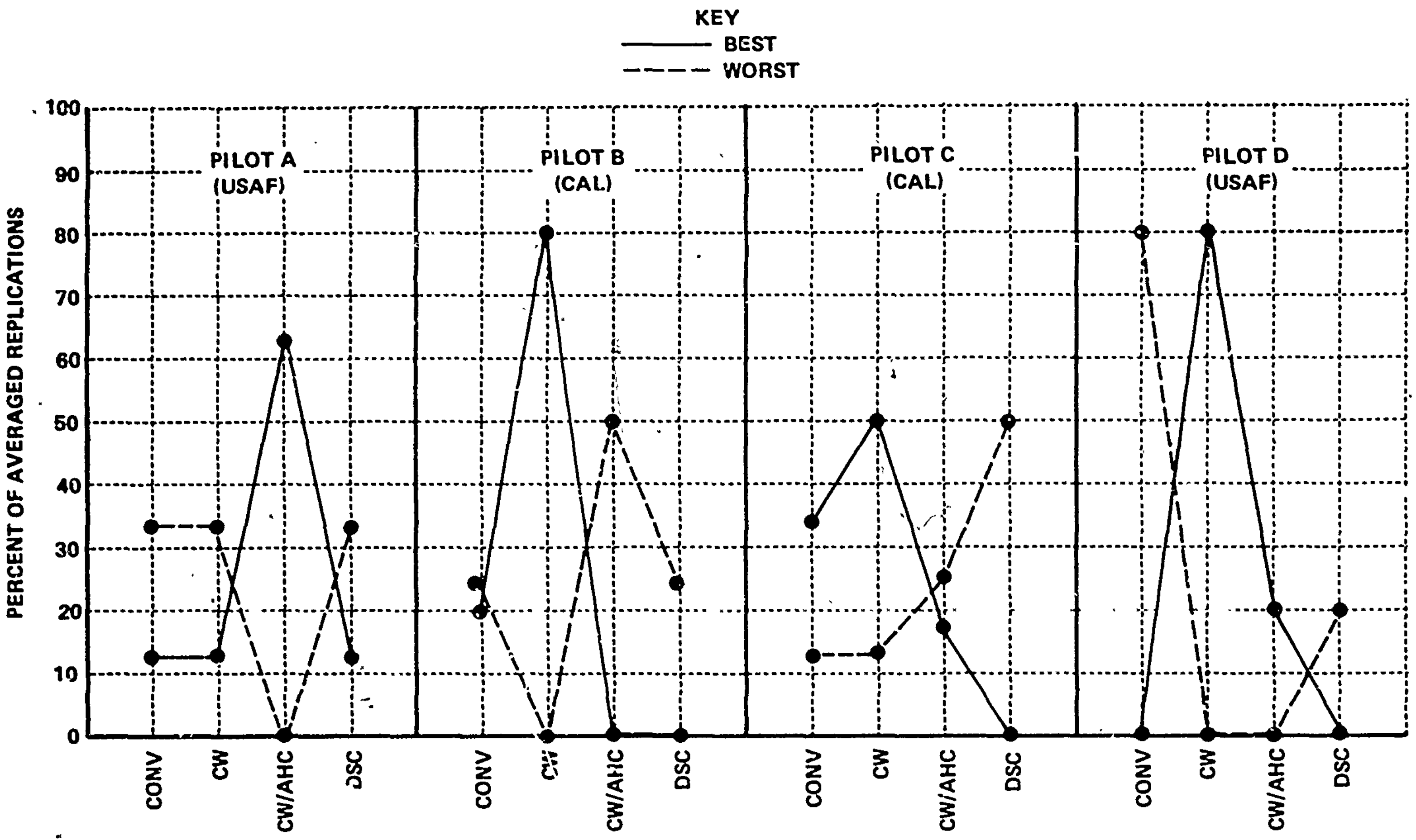

Figure 22 COMPARATIVE RATING OF CONTROLLERS, BASED ON AVERAGED REPLICATIONS, INDIVIDUAL PILOTS, ALL TASKS

worst), both were put in the same appropriate category. The number of bests and worsts for all tasks were put in terms of percentages of the total number of each category and plotted vs controller configuration. Examination of Figure 22 shows that for Pilot A (USAF), over 60% of his best ratings were applied to the CW-AHC configuration. His worst assessments were equally divided among the other three controllers.

Pilot B (CAL), on the other hand, had 80% of his best ratings for the CW configuration, and 50% of his worst ratings applied to the CW-AHC.

Of the best ratings for Pilot C, 50% were ascribed to the CW configuration and of the worst, 50% were ascribed to the DSC.

For Pilot D, the CW configuration received 80% of his best ratings and the conventional configuration 80% of his worst ratings.

Figure 23 shows the best-worst relationship, averaged for all four pilots, and indicates that the CW received almost a majority of the best ratings, with the conventional configuration and the DSC both receiving a large percentage of the worst ratings, about 35% each.

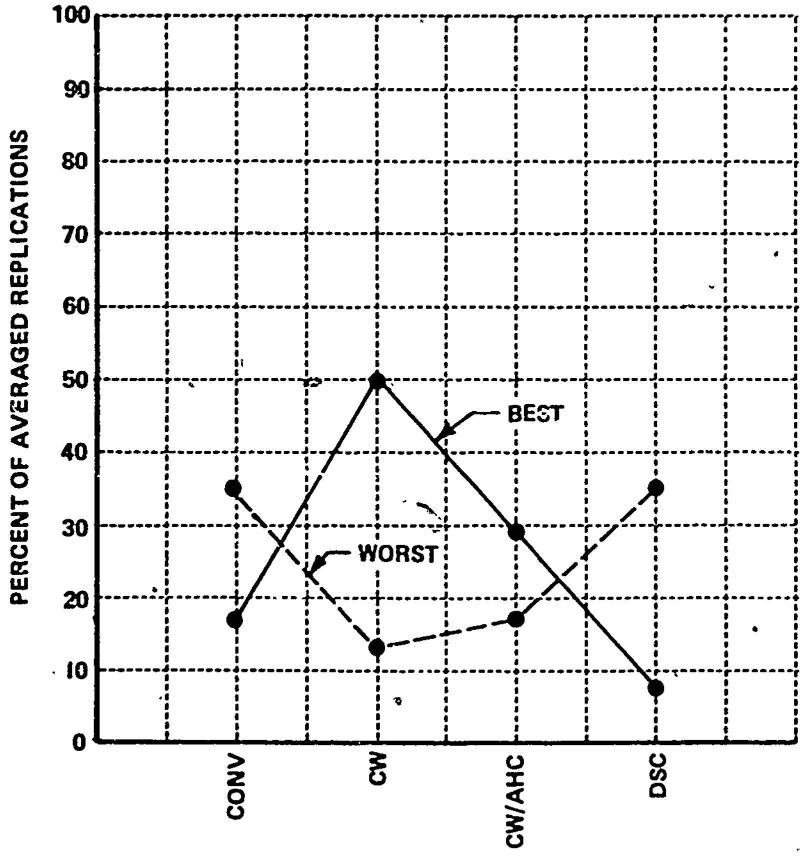

Figure 23 COMPARATIVE RATINGS OF CONTROLLERS, BASED ON AVERAGED REPLICATIONS, ALL PILOTS, ALL TASKS

SECTION VI

ANALYSIS OF TRACKING DATA

As previously noted measured tracking data was obtained from two sources, the "terrain following" maneuver of Task b, and the ILS approach maneuver of Task c.

The basis for observed and recorded data was the flight director system, which through its computer and display instruments provided the necessary command information for the pilot to perform the required tracking maneuvers. In particular, the horizontal and vertical cross-pointer needle deflections from reference provided the tracking error data.

Mechanization of the pitch portion of the terrain following maneuver has been described in Section III. In addition, the pilot was asked to hold a preset heading during the maneuver, thus providing needle deflection data in both the longitudinal and lateral-directional modes. It must be noted that normal operation of the flight director system, used for all measurements except the pitch portion of the terrain following maneuver of Task b, displays needle deflections in response to combined signals from the systems computer and do not necessarily indicate raw error from a desired flight path. For example, in the lateral-directional mode (either terrain following or ILS) the vertical needle can coincide with the reference (zero error) when the bank angle is such that intersection with the correct azimuth is assured. Thus needle deflections relative to the reference indicate steering commands to the pilot.

For each maneuver, a substantial amount of recorded data was collected for each pilot and controller, which included needle deflection errors in both the longitudinal and lateral-directional modes and controller deflections for the three modes of operation (rudder pedal deflections were included). Not all the data taken was reduced or shown in this report. This was due primarily to the fact that after careful examination, it was felt that only certain key portions were significant to the evaluation of the controllers.

Raw data was oscillograph recorded for approximately 3 minutes of both the Task b tracking maneuver and the ILS approach maneuver of Task c. Data was read each .1 second, and punched and inserted in a program designed to produce variance spectral density, variance and standard deviation. This was accomplished using the CAL IBM 360/65 Digital Data Processing System.

Comparison of results during the early stages of data analysis indicated a data time length of 1 minute would be sufficient, and that data reduction for the entire 3 minutes would be unnecessary. (The actual in-flight time of the maneuvers did not change and raw data continued to be recorded for the full 3 minutes.)

A limited amount of raw data was reduced to a variance spectral density form. This form in essence indicates variance as a function of frequency and shows the variance present in any frequency bandwidth throughout the spectrum, (and hence a frequency bandwidth for maximum variance) and the overall variance for the parameters of the maneuvers.

Some general observations can be made from this data form.

For the Task b maneuver, the horizontal needle deflection error ϵ_{ND_θ}, (measured in inches observed on the ADI display) show substantially greater variance than the vertical needle deflection error. Likewise, the frequency band for maximum variance was more sharply defined for the pitch error than for the heading error. This is, of course, to be expected in view of the more demanding command input in pitch. Examination of the oscillograph traces (comparing the command input with the error output) indicates that the frequencies at which the maximum variance occurred in pitch were those associated with the response immediately after an abrupt change in command.

Both the longitudinal and lateral errors of the ILS approach maneuver of Task c show characteristics similar to the yaw portion of Task b. Again, this was a simpler maneuver to perform compared to the pitch maneuver of Task b, a fact substantiated by pilot comment.

The frequency bandwidth of maximum variance of ϵ_{ND_θ} varied from replication to replication and from pilot to pilot but generally fell between .05 and .15 hertz. The manual inputs for this maneuver (all controllers) showed a wider and more random frequency bandwidth for maximum variance, from as little as .03 hertz to as high as .6 hertz.

Figures 24, 25, 26, and 27, show the overall variance of ϵ_{ND_θ} as a function of flight replication for each pilot and each controller. Variance is defined as:

$$\sigma^2 = \frac{\sum (x - \bar{x})^2}{N} \qquad \text{(inches of } \epsilon_{ND_\theta})^2$$

where

$\bar{x}$ is the arithmetic mean of all the measurements

x is the measurement from the zero reference

N is the number of measurements.

The standard deviation, or RMS of deviations from the arithmetic mean is simply σ or $\sqrt{\frac{\sum (x-\bar{x})^2}{N}}$ (inches of ϵ_{ND_θ}).

Pilot A (USAF), Figure 24, indicates a general learning curve for all configurations except the conventional one, with a substantial reduction in variance for the last two replications of the tracking maneuver of Task b. A similar, but lesser trend, is noted for the ILS maneuver of Task c. The relative amplitude of variance for the two maneuvers is evident.

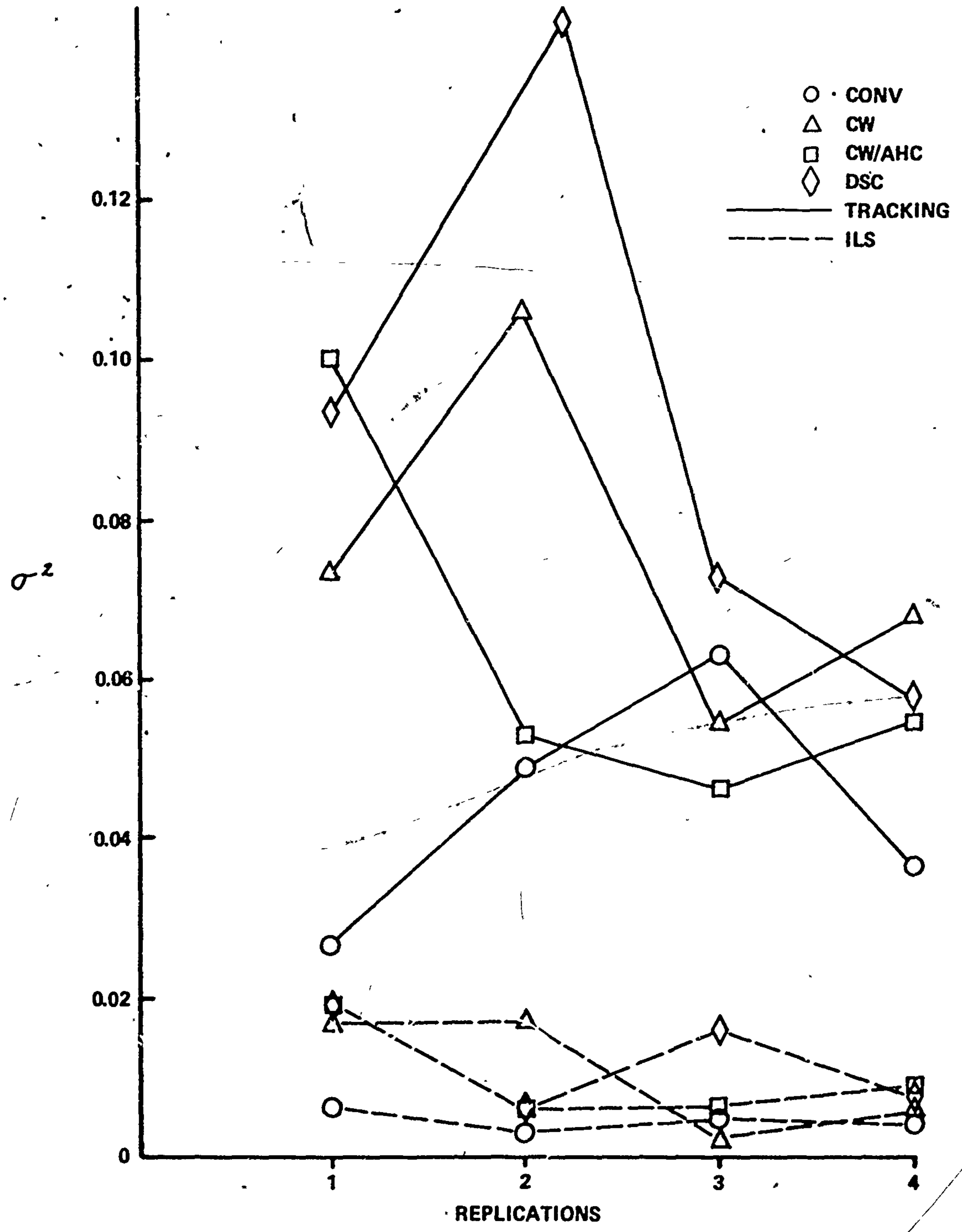

Figure 24 MEASURED VARIANCE IN PITCH VS FLIGHT REPLICATION, PILOT A (USAF)

Pilot B (CAL) Figure 25, shows a less defined learning trend with replication for Task b except for the DSC. Amplitudes were generally lower and closer to those of Task c.

Pilot C (CAL) Figure 26, showed improvement with replication except for the CW-AHC configuration. It may be noted that comments and ratings showed a comparative dislike for this configuration. As in the case of Pilot A, a less steep learning trend is noted for Task c than Task b. A significant difference in variance amplitudes is also evident.

Pilot D (USAF) Figure 27, showed the greatest randomness in ϵ_{ND_θ} of all, and a less well defined overall learning trend, although variance amplitude was essentially the same for all controllers for his last replication.

Figure 28 shows the averaged replication variance and standard deviation for each pilot and an overall average for all pilots as a function of controller configuration. The overall average shows little variation among controllers, the greatest difference being that for the CW-AHC, which was strongly biased by the performance of Pilot C (CAL).

It is difficult to determine from the numbers given the actual significance of these variations in terms of maneuver performance. If one examines the standard deviation in terms of needle widths (one needle width $\approx$ .033 inches), then the maximum variation in σ is the highest, 8.5 for the DSC, minus the lowest, 5.8 for the conventional configuration, or 2.7 needle widths.

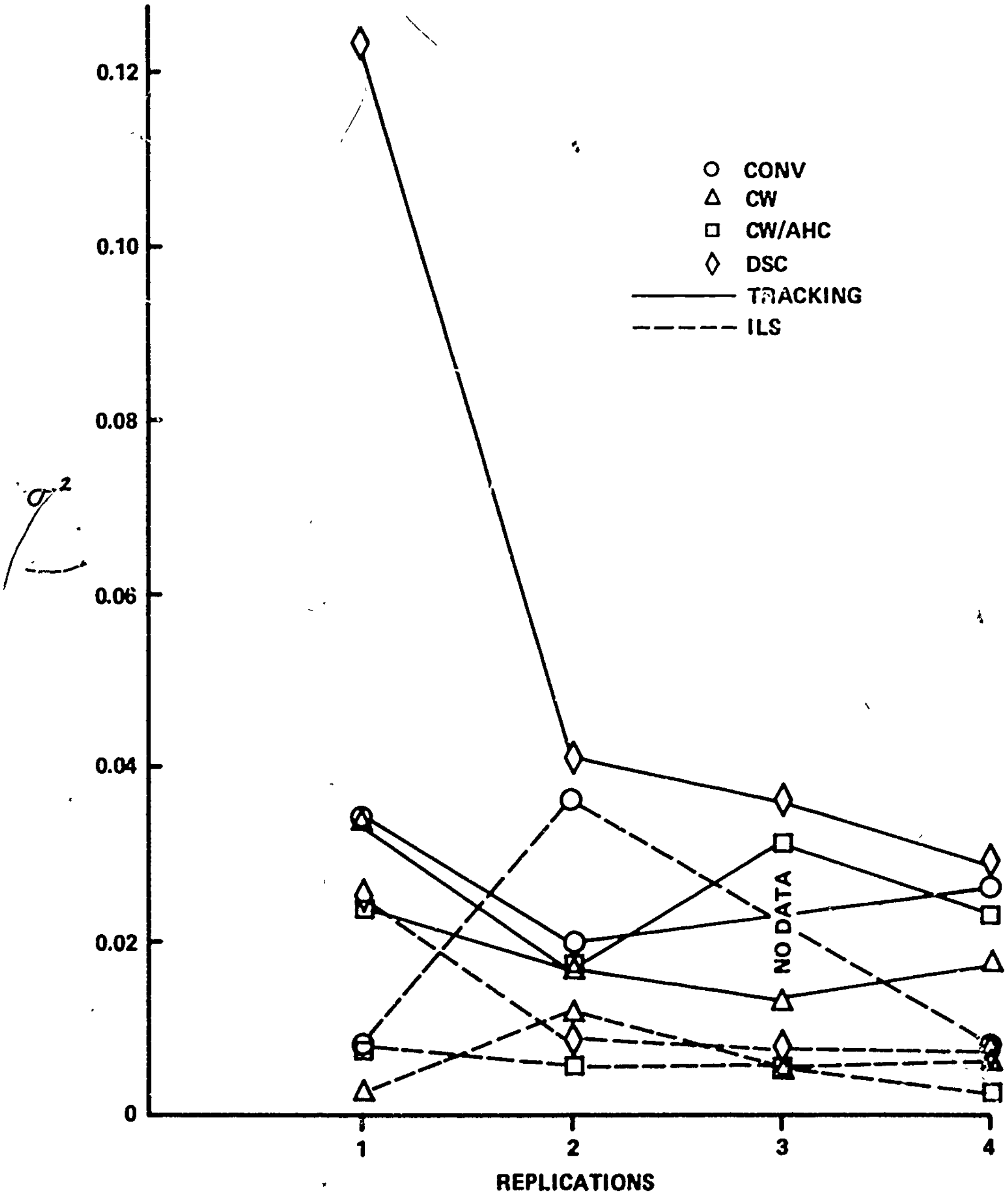

Figure 25 MEASURED VARIANCE IN PITCH VS FLIGHT REPLICATION, PILOT B (CAL)

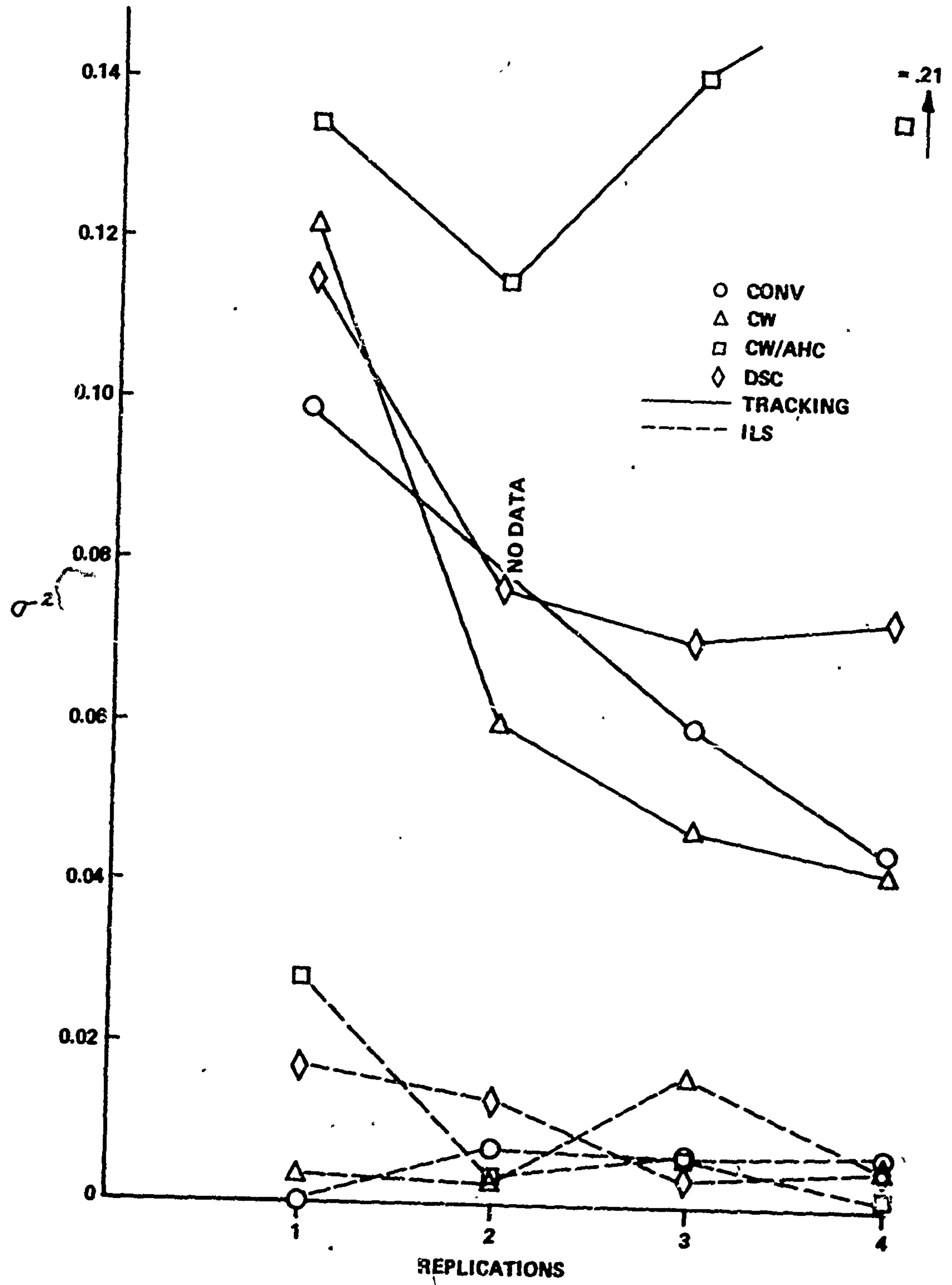

Figure 26 MEASURED VARIANCE IN PITCH VS FLIGHT REPLICATION, PILOT C (CAL)

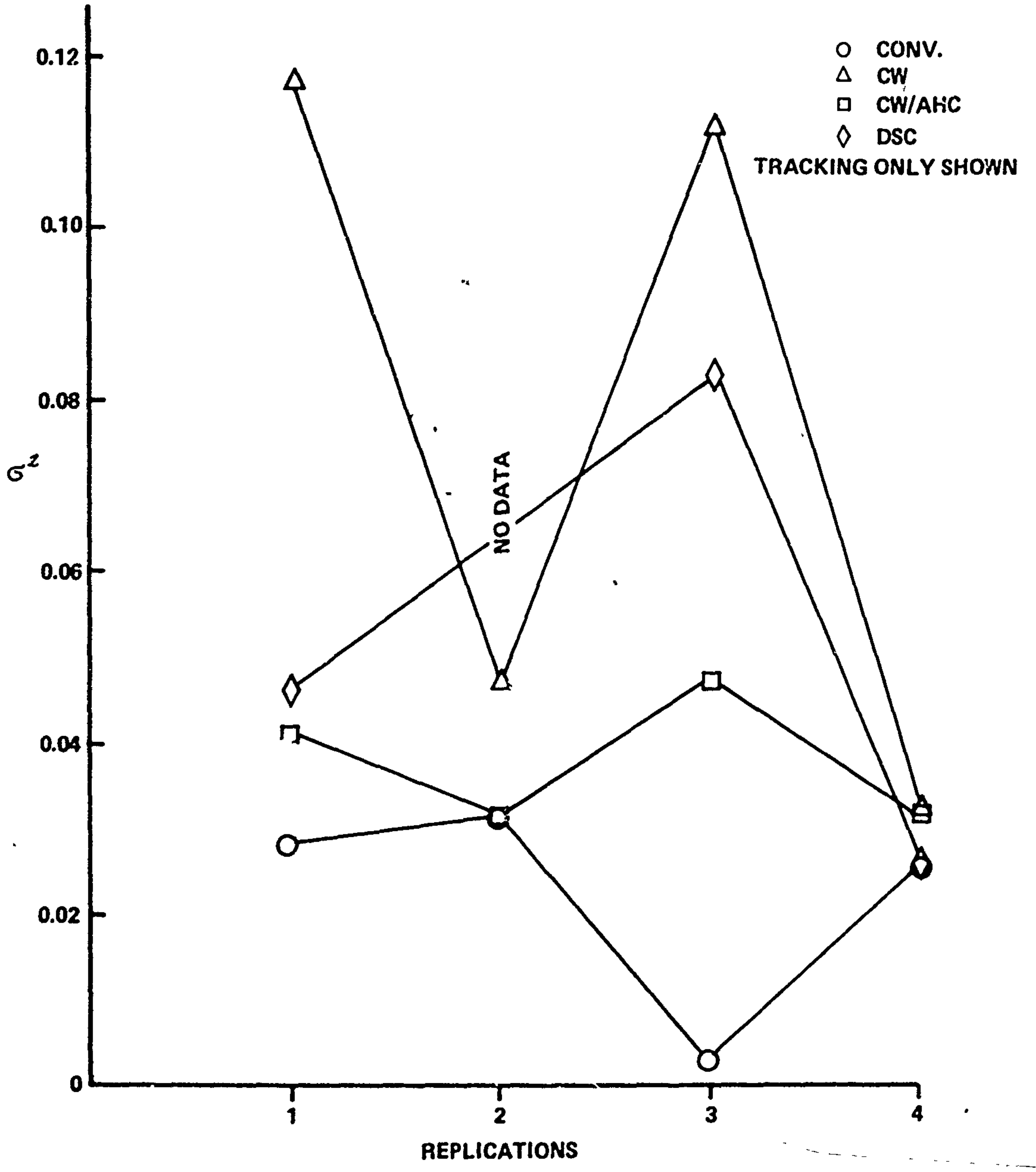

Figure 27 MEASURED VARIANCE IN PITCH VS FLIGHT REPLICATION, PILOT D (USAF)

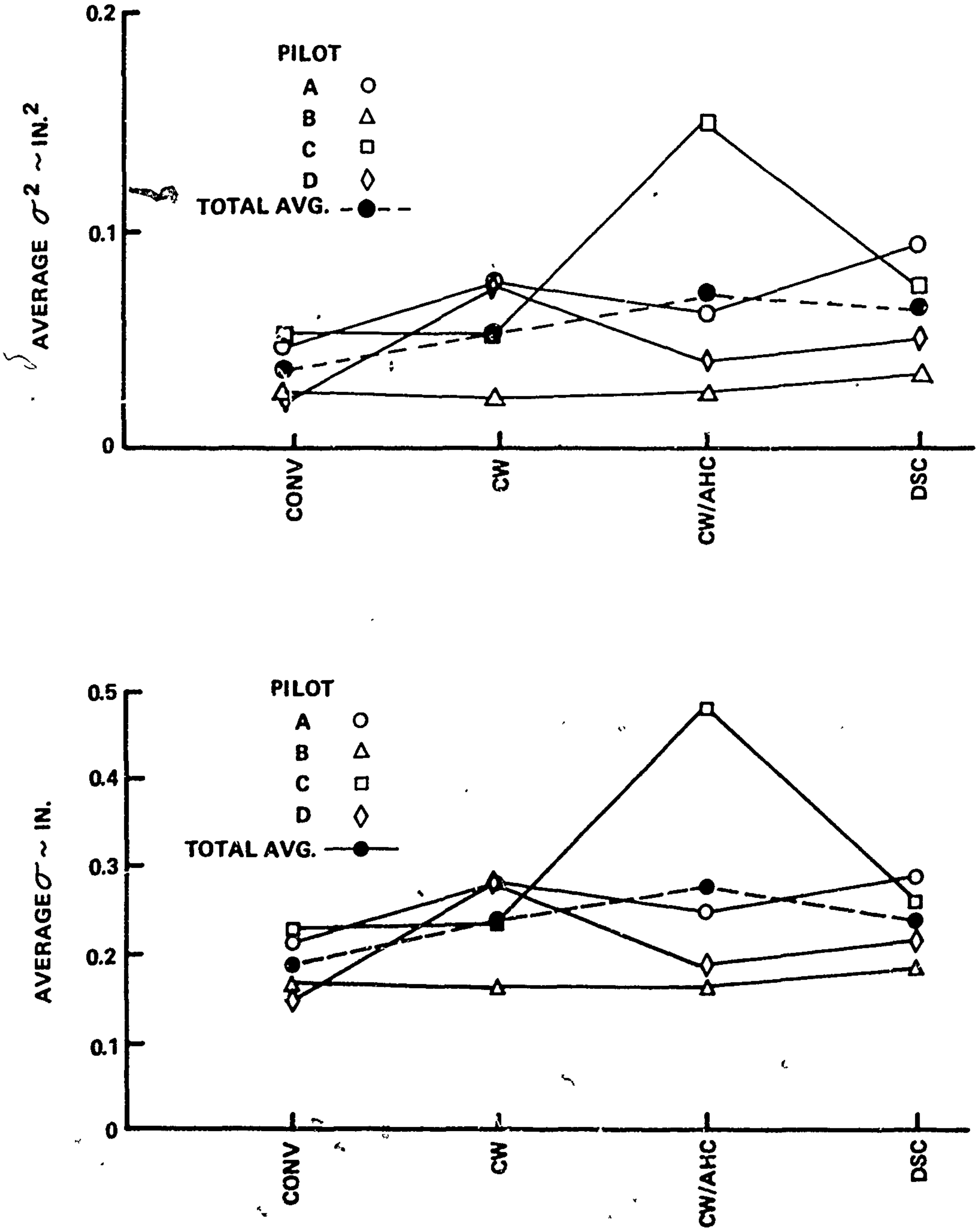

Figure 28 AVERAGE VARIANCE AND STANDARD DEVIATION, TASK b TRACKING

SECTION VII

CONCLUSIONS

On the basis of in-flight pilot evaluation of the subject controller configurations, the results of which have been presented herein, the following conclusions can be drawn.

1. The effusiveness and variety of pilot comment, and the different type and complexity of control problems encountered due to the wide spectrum of maneuvers and airplane dynamic characteristics explored, supported the initial and primary concept of the experimental design; that it provide for a suitable background against which any differences in controller concept and detailed design would be highlighted. A desirable element not included in the experiment is one which provides for variable and defined turbulence levels.

2. Average differences of acceptance level among controller configurations for a given task, based on pilot comments and pilot ratings were small. Differences in acceptance level among tasks were slightly larger but dependent primarily on the handling qualities of the simulated airplane.

3. Any one of the new concepts evaluated in this investigation would be accepted by a majority of large-airplane pilots. The degree of acceptance, in terms of detail design, will of course depend on proper integration of the configuration with other characteristics of the cockpit work area, proper feel characteristics and its compatibility with other features of control system design and airplane characteristics. A learning time of some small magnitude can be anticipated, one not unlike that associated with normal adaptation to a slightly different environment.

4. Average quantitative performance data for the tracking maneuver (variance and standard deviation) show relatively small differences among controllers. The CW-AHC configuration exhibited the worst average score, but this average was significantly influenced by the results for one pilot.

Individual performance data as a function of configuration replication show [with the exception of Pilot B (CAL)] a considerable amount of scatter, but with the lowest values generally appearing on the last flight of the configuration. A "maneuver" learning trend is indicated; all controller configurations either indicate the same trends or where no trends are explicit, random scatter is shown.

5. Comparative variance and standard deviation data for the up-and-away tracking maneuver and the ILS approach maneuver indicate the former to be the more demanding, as shown by greater deviations, more scatter, and in some cases a better defined learning trend with increased replication. Values for the ILS approach are more consistent and are lower in amplitude. The relative ease of performance of the latter maneuver is substantiated by pilot comment. This suggests the use of displayed computed flight director system data as a measure of performance is not sufficiently sensitive for experimental purposes and that "raw" ILS data should be used instead.

6. Pilot ratings of the overall pilot-airplane-controller-task complex were moderately scattered. With respect to replication rating spread, over 78% of the number of ratings given by all pilots had a rating spread of two ratings or less and 45% had a rating spread of one rating or less. In 8% of the cases, replication ratings were the same.

In terms of "best" and "worst" rating (a comparative basis regardless of specific rating), 62.5% of Pilot A's best ratings were for the CW-AHC configuration. His percentage of worst was evenly divided among the conventional, CW and DSC configurations. Pilots B, C, and D favored the CW configuration (in terms of percent of best ratings) with measures of 80%, 50% and 80% respectively. The percentage of worst ratings for these three pilots was: Pilot B - CW-AHC, 50%, Pilot C - DSC, 50% and Pilot D - conventional, 80%. The overall preference was, of course, for the CW at 50%. The overall worst were the conventional and DSC, each at 35%.

It must be remembered,that by definition, these ratings take into account all facets of the system (including recognizable and rectifiable deficiencies), and that final assessment must be based, to a large degree, on pilot comment.

7. Cockpit environment is significantly improved with the use of the dual side arm controller as compared with the standard wheel and column. Somewhat lesser improvement results from use of the circumferential wheel (with or without the alternate hand controller). This improvement with use of the DSC manifests itself primarily in greater instrument panel visibility, accessibility to other cockpit controls and to some extent a lessening of fatigue.

8. The controller feel characteristic most commented upon was force gradient, pounds per unit control deflection. As previously noted, longitudinal (pitch) force gradients for the conventional and CW configurations were selected (using the B-26 variable feel system) by CAL pilots prior to the evaluation phase. Likewise, specific springs were selected to give desirable roll force gradients. The pitch gradients, combined with the simulated stick force per incremental normal acceleration estimated for the B-1 airplane, produced generally acceptable longitudinal feel characteristics for these two controllers. In roll, these characteristics were generally adequate, but in some cases, aileron roll power was marginal or insufficient.

In the case of the AHC and DSC, however, force gradients in pitch (selected to be the highest within the constraint of the present design) were considered to be too light. The consequence was not so severe with the AHC, because designed as it was to supplement the high authority of the CW in the CW/AHC configuration, it had low gain and was more compatible with the light force gradient. On the other hand, the DSC was required to achieve full authority for large maneuvers (in particular the flare portion of the landing maneuvers). This requirement necessitated high gain to the elevator, which, when combined with the low force gradient, produced undesirable sensitivity for smaller and more precise maneuvers. A primary and simple solution to this problem is to provide for stiffer springs in the DSC. The nonlinear function provided for task C (landing, approach, takeoff) and used by the last two evaluation pilots was an approach based on expediency, and though satisfactory in most cases has not been sufficiently evaluated to warrant recommendation of its use..

9. The trim wheel on the right hand grip of each of the controller configurations (pitch trim) was in many cases too sensitive while at the same time providing insufficient trim authority. Change of trim gain will, of course, not suffice; i.e., an increase in gain to increase authority will simply increase sensitivity, which is contrary to the desired result. Increasing the diameter of the trim wheel would decrease sensitivity while maintaining authority. However, there is a physical limit to this approach. A wheel attached to a multi-turn potentiometer could, if of proper design, provide the correct balance between sensitivity and authority.

The detent associated with the trim wheel was deemed unnecessary, and in fact a deterent to precision trimming.

10. Pilot comment revealed several physical controller design and installation characteristics, which though not of extreme significance to the experiment, nevertheless emphasize design criteria which are important when conceiving a specific cockpit-controller complex.

The contour and physical feel of the hand controllers (both the AHC on the CW/AHC and the DSC) was thought to be good; they were comfortable and hand on grip fatigue was never a problem.

At times the distance between the pilot and the wheel and column configurations appeared too large resulting in the comment of "arm fatigue". This distance was standard B-26, and the comment was probably due to a significant contrast with the much more comfortable arm rest design of the DSC.

There was occasional annoyance when attempting to use the trim wheel with the hand controllers in a forward of neutral position. This was due to a slightly unnatural extension of the thumb which caused mild discomfort.

The DSC was located approximately 5 inches further aft from the instrument panel than was the seat used for the other configurations. This was an installation compromise made prior to the evaluation and was felt by CAL pilots to have no significance relative to the experiment. The evaluation pilots did notice the difference, but indicated rapid adaptation and that it had no effect on their relative judgment of the configuration.

There was some comment that the inside width of the DSC seat should be greater. The DSC was designed, of course, to fit the B-26, and size was therefore a significant restriction. This should be no problem of course when considering an integrated cockpit-controller design.

Some discomfort was occasioned because of too short a distance from the pilot's body to the DSC hand grips. This is not necessarily a fault of the configuration design as presented to CAL. It was designed to use a seat parachute pack and the back cushion provided. Instead a back pack was used with the back cushion removed. This pushed the pilot forward perhaps an inch or so more than the basic design configuration, and may account for the comment. It may be pointed out, however, that in either case, the angle between the forearm and upper arm is close to 90° and this may not be the optimum situation for minimum fatigue and maximum comfort. It is quite conceivable, that with a closely coupled control linkage, i.e., small stick displacement, and restricted wrist and forearm muscle movement, arm (and to some extent shoulder) geometry is a significant factor for minimum fatigue.

There is evidence that the neutral position (in pitch) of the hand grip is important to comfort and precision of movement. This was variable in the DSC design and a position was chosen by CAL pilots prior to the evaluation phase, a position thought to be reasonable from a control standpoint. This was fixed and remained so throughout the evaluation. However, it was evident that this position was not optimum for all evaluation pilots (a slightly greater forward pitch was desired) probably because of differences in wrist and hand configurations.

11. Most promising controller configuration. The data obtained during this investigation- pilots' comments, pilots' ratings and measured performance-tend to show a contradiction in preference, if such methods of assessment are viewed separately, one without regard for the other, or if the basic definition of these methods is not emphasized. Pilot ratings (indicating a preference for the CW configuration) report the overall desirability of the configuration and by definition can be no better than the effect which the least desirable element contributes to its performance. On the other hand, pilot comments report the "why" of an assessment, which may not only be of importance in modifying a design, but depending upon their significance, may dictate ultimate preference. Measured performance, of course, may or may not show a decisive edge.

In the present evaluation, measured performance data did not show a decisive tendency in controller proficiency, and as noted above, overall ratings indicated a preference for the CW configuration. However, pilot comments provided sufficient evidence to postulate which controller configuration should receive further development and ultimately be integrated into an overall control system design for large aircraft.

Pilot comments indicated that, in concept, the DSC was preferred. They also indicated certain deficiencies present in the tested configuration (already described) which downgraded their overall ratings. Most important, their comments indicated the significant improvement in cockpit environment with the DSC. In weighing all the data obtained, and recognizing that the detail design deficiencies of the DSC can be rectified with little relative effort (possibly resulting in improvement in measured performance), it is concluded that the dual side-arm controller configuration is the most promising for future application.

APPENDIX

HOURS OF EVALUATION PILOT FLIGHT EXPERIENCE

Pilot	Total	Medium and Large Aircraft	Flight Testing		Operational		Total Hours for Year Preceding Evaluation
			Military	Commercial	Military	Commercial	
A	3986	2350	2150	36	1800	0	550
B	3693	3034	0	32	3196	565	211
C	5000	1200	0	1400	2500	1100	203
D	3374	2828	100	0	3274	0	---

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13. ABSTRACT

An in-flight evaluation of four cockpit controller configurations has been made. These configurations include a conventional wheel and column, and three new concepts: a circumferential wheel and column, a circumferential wheel and column with a hand grip mounted on the right hand side of the wheel segment, and a dual side arm configuration integral with the pilot's seat. Evaluation was based on three tasks: up-and-away cruise condition maneuvers, low level terrain following simulated at altitude, and approach, landing and takeoff. Each task was performed under conditions of different simulated static and dynamic characteristics of a B-1 type airplane, using one of CAL's B-26 variable stability airplanes. Four evaluation pilots, two USAF and two CAL, flew all four controller configurations four times each through each of the three tasks. Data obtained was both qualitative and quantitative. Results of analysis of all types of data obtained indicate that all three new concepts would be accepted by pilots of large airplanes with only a nominal associated learning period, that all three new concepts are preferable to the conventional wheel and column, and that the dual side arm configuration, despite some detailed design deficiencies, is the most preferred of the three unconventional configurations. The data also indicate areas for improvement in detailed side arm controller design, and the need to establish new handling qualities criteria for side arm controllers, particularly when integrated with other factors affecting overall flight control systems design.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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