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SYMBOLS

A/C	aircraft
A_{1s}	lateral cyclic pitch, deg, rad
a	blade lift curve slope
B_{1s}	longitudinal cyclic pitch, deg, rad
c	blade chord, m
e	flapping hinge offset, m
I_β	blade moment of inertia about flapping hinge, kg-m^2
K_1 through K_{12}	feedforward gains
$\underline{K}_1$	feedback gain vector for longitudinal cyclic control
$\underline{K}_2$	feedback gain vector for lateral cyclic control
$\underline{K}_3$	feedback gain vector for collective control
$\underline{K}_4$	feedback gain vector for directional control
L_p	roll damping, sec^{-1}
$\hat{L}_p$	augmented roll damping, sec^{-1}
L_q	rolling moment due to pitch rate, sec^{-1}
$L_{\delta a}$	unaugmented rolling moment due to lateral stick, rad/sec^2/cm
$\hat{L}_{\delta a_p}$	augmented roll moment due to lateral stick, rad/sec^2/cm
M_p	pitching moment due to roll rate, sec^{-1}
M_q	pitch damping, sec^{-1}
$\hat{M}_q$	augmented pitch damping, sec^{-1}
$M_{\delta c}$	pitching moment due to collective input, rad/sec^2/cm
$M_{\delta e}$	unaugmented pitching moment due to longitudinal stick input, rad/sec^2/cm
$\hat{M}_{\delta e_p}$	augmented pitching moment due to longitudinal stick input, rad/sec^2/cm
N_r	yaw damping, sec^{-1}

$N_{\delta c}$	yawing moment due to collective input, rad/sec^2/cm
$N_{\delta p}$	yawing moment due to pedal, rad/sec^2/cm
p	aircraft roll rate, rad/sec
q	aircraft pitch rate, rad/sec
R	rotor radius, m
r	aircraft yaw rate, rad/sec
s	Laplace transform variable
T	transposition of a vector
u, v, w	components of airspeed along the aircraft body axes, x, y, z, respectively
V	true airspeed, m/sec
$\underline{x}$	aircraft state vector, $\underline{x} \triangleq (u, w, q, \theta; v, p, \phi, r)^T$
Z_w	vertical damping, sec^{-1}
$Z_{\delta c}$	vertical sensitivity, m/sec^2/cm
γ	Lock number, $\triangleq \rho acR^4/I_\beta$
Δ	incremental value
δ_a	lateral control displacement, cm
δ_{a_p}	lateral stick deflection, cm
δ_c	collective control displacement, cm
δ_{c_p}	collective stick deflection, cm
δ_e	longitudinal control displacement, cm
δ_{e_p}	longitudinal stick deflection, cm
δ_p	pedal deflection, cm
ε	e/R
ζ	damping ratio
θ	aircraft pitch attitude, deg, rad
κ_β	flapping hinge restraint, m-N/rad

ρ air density, kg/m^3

τ_1, τ_2 washout time constants

ϕ aircraft roll attitude, deg, rad

Ω rotor-system angular velocity, rad/sec

ω_n undamped natural frequency, rad/sec

A PILOTED SIMULATOR STUDY OF AUGMENTATION SYSTEMS TO IMPROVE HELICOPTER FLYING QUALITIES IN TERRAIN FLIGHT

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SUMMARY

A piloted simulation study assessed various levels of stability and control augmentation designed to improve the flying qualities in terrain flight of several helicopters. Four basic single-rotor helicopters, one teetering, one articulated, and two hingeless, which were found to have a variety of major deficiencies in a previous fixed-based simulator study, were selected as baseline configurations. The stability and control augmentation systems (SCAS) include simple control augmentation systems (CAS) to decouple pitch and yaw responses due to collective input and to quicken the pitch and roll control responses; SCAS of rate-command type designed to optimize the sensitivity and damping and to decouple the pitch-roll due to aircraft angular rate; and attitude-command type SCAS. Pilot ratings and commentary are presented as well as performance data related to the task. SCAS control usages and their gain levels associated with specific rotor types are also discussed.

INTRODUCTION

A research program in progress at Ames Research Center seeks to provide a data base for helicopter flying qualities and control system design criteria. In a previously reported part of the program (ref. 1), the effects of large variations of important rotor system design parameters on flying qualities and agility in terrain-following flight were investigated. The design parameters that were varied were flapping-hinge offset, flapping-hinge restraint, blade Lock number, and pitch-flap coupling. Over 40 helicopter configurations were investigated, of which few were found to have satisfactory handling qualities for the terrain-following task.

To extend the data base, further experiments have been conducted to systematically investigate the use of stability and control augmentation systems (SCAS) of several levels of sophistication to improve terrain-flying characteristics for the configurations with deficiencies identified in reference 1. Four helicopters were selected from the previous study as configurations that exemplified the deficiencies in flying qualities of their types and which lend themselves to evaluation of the SCAS concepts of interest. The helicopter configurations consisted of one teetering rotor with a high blade inertia; an articulated rotor; and two hingeless rotors with different effective hinge offset and Lock number. Specific deficiencies associated with each rotor type were (1) low control sensitivity and damping and excessive yaw due to collective for the teetering rotor; (2) strong pitch-roll coupling and high roll control sensitivity for the articulated rotor; (3) excessive pitch due to collective input for the hingeless rotor with low blade inertia and large hinge offset; and (4) low pitch and roll sensitivity for the hingeless rotor with high blade inertia and moderate hinge offset. Stability and control augmentation systems having several levels of sophistication were then defined for those four basic configurations for piloted evaluation.

The SCAS that were investigated consisted of two main groups. The first group, called decoupling and rate-command type SCAS, dealt directly with the specific deficiencies associated with the four aircraft. They include control response decoupling in pitch and yaw due to collective input; improved stability and control responses in pitch, roll, and yaw; and eliminating coupling between pitch and roll axes due to aircraft angular rate. The second group consisted of more sophisticated SCAS that required attitude feedback. This group of SCAS was expressly studied to determine the extent to which pitch and roll attitude command control could improve agility in terrain flight.

There were four specific objectives for the investigation: (1) to determine the extent to which flying qualities can be improved, (2) to determine whether there exists a preferred type of SCAS for the task, (3) to assess the SCAS gain levels required to achieve satisfactory flying qualities, and (4) to determine the SCAS control usage for determination of SCAS actuator authority requirements and other implementation considerations.

The paper discusses the specific SCAS design objectives and design procedure, the SCAS configurations for piloted evaluation, the simulation experiment, the subjective pilot data and objective performance data acquired, and the results of the experiment.

AUGMENTATION SYSTEMS

As mentioned earlier, the design objectives of the first SCAS group were to eliminate or to overcome the various deficiencies in flying qualities exemplified by the four basic helicopters selected from the previous simulation study (ref. 1). As shown in table 1, those deficiencies ranged from inadequate damping and sensitivity in pitch and roll axes for the teetering rotor helicopter with a high blade inertia to the excessive pitch coupling due to collective input for a hingeless rotor helicopter. The concept of the first SCAS group designed to overcome the observed deficiencies is described in the following.

Decoupling Pitch and Yaw Responses Due to Collective Input

Increased control power obtained through hinge offset or a stiffened flapping hinge produces a coupling in pitch moment due to collective input that can reach undesirable levels. For example, the pitching moment due to collective input for a hingeless rotor helicopter is shown in table 2 and is indicated to increase with airspeed. This pitching moment was eliminated by cross-feeding the collective input to the longitudinal cyclic. The control cross-feed gain, δ_e/δ_{c_p}, required to decouple the pitching moment, is shown in figure 1. A straight line approximation for scheduling this cross-feed gain with the airspeed was found to be adequate. Similar schedules were used for other study aircraft.

The yawing moment due to collective input existed in all the study helicopters (see tables 2-4). The magnitude of the coupling moment is shown in table 2 as an example of the hingeless rotor helicopter, H1. The control cross-feed from the collective input to the directional control required to decouple the yawing moment for this aircraft is depicted in figure 1. The cross-feed gain, δ_p/δ_{c_p}, is a nonlinear function of airspeed, the shape of which is similar to the familiar required power curve. This cross-feed control law and the control cross-feed from the collective input to the longitudinal cyclic described earlier were designed to decouple only the initial angular accelerations in yaw and pitch due to collective input. To achieve a perfect decoupling in the pitch and yaw responses due to collective input requires feedback of aircraft state variables as well as the control cross-feed. It was found, however, that using only the cross-feed control laws described above virtually eliminated the undesirable coupled responses.

A comparison of the angular rate responses of the augmented and unaugmented aircraft to a step-collective input at 60 knots is shown in figure 1(b). The strong pitch and yaw couplings for the basic hingeless rotor helicopter have been substantially reduced by the cross-feed control laws in figure 1(a). Note that the SCAS control laws included an augmentation in yaw damping in addition to the pitch and yaw decoupling functions. This was provided by feeding back yaw rate to the directional control, δ_p. This function will be further discussed later in the paper.

Decoupling Pitch and Roll Due to Aircraft Angular Rate

The articulated rotor helicopter selected for this study had excessive pitch-roll coupling due to aircraft angular rate (see table 1). Table 3 shows these coupling derivatives, L_q and M_p, along with other derivatives of interest as functions of airspeed for the basic articulated rotor helicopter. The control law used to achieve a pitch-roll decoupling (i.e., $L_q = M_p = 0$) was to feed the pitch rate to lateral cyclic and roll rate to longitudinal cyclic control. The feedback gains, δ_a/q and δ_e/p, are shown in figure 2. Since these gains vary little with airspeed, constant gains based on the nominal airspeed of 60 knots were used in the simulation experiment.

Augmentations to Improve Control Responses in Pitch and Roll Axes

The sensitivity and damping in pitch and roll axes were augmented for both the teetering rotor helicopter and the articulated rotor helicopters. The sensitivity and damping for the two agumented aircraft are shown in table 5. For the articulated rotor, the objective was to achieve the levels of sensitivity and damping in pitch and roll equivalent to those of the hingeless rotor helicopter. For the teetering rotor helicopter, the augmented sensitivity and damping were set lower than for the articulated rotor to limit the feedforward and feedback gains somewhat. A comparison of the gain levels at 60 knots for the two aircraft to achieve their respective design goals is also shown in table 5. Note that the gain levels are moderate for the articulated rotor, but are rather high for the teetering rotor, especially in pitch axis. The variation of these gains with the airspeed is shown in figure 3 for the teetering rotor helicopter and in figure 4 for the articulated rotor helicopter. Since they do not change significantly with airspeed, a set of fixed gains based on the nominal airspeed of 60 knots was used in the simulation experiment. A comparison of the response of the augmented and the unaugmented articulated rotor helicopter at 60 knots to a step input in the longitudinal stick is shown in figure 4. Note that the strong roll coupling of the basic aircraft has been drastically reduced by the augmentation system. Also, the poor pitch response of the basic aircraft has been significantly improved by the rate command type SCAS.

An alternative series of augmentation systems was designed for the teetering rotor helicopter to improve control responses in pitch and roll through use of control quickening. The design was performed using the roll axis as an example by employing a control law of the form (see fig. 6)

$$\delta_a(s) = \left[K_5 + \frac{K_7 s}{1 + \tau_2 s}\right]\delta_{a_p}(s) \tag{1}$$

which is a proportional plus a high-pass (or "washout") filter. For short-term response, assume that the roll rate to lateral control can be represented by the roll mode alone, that is,

$$\frac{p}{\delta_a}(s) = \frac{L_{\delta_a}}{s - L_p} \tag{2}$$

With the quickener (1), the roll rate to the lateral stick transfer function then becomes

$$\frac{p}{\delta_{a_p}}(s) = \frac{K_5\tau_2 + K_7}{\tau_2}\left[\frac{s + \dfrac{K_5}{K_5\tau_2 + K_7}}{s + 1/\tau_2}\right]\left[\frac{L_{\delta_a}}{s - L_p}\right] \tag{3}$$

If K_5, K_7, and τ_2 are chosen such that

$$\frac{K_5}{K_5\tau_2 + K_7} = -L_p \tag{4}$$

then (3) becomes

$$\frac{p}{\delta_{a_p}}(s) = -\frac{K_5}{L_p\tau_2}\left[\frac{L_{\delta_a}}{s + 1/\tau_2}\right] \tag{5}$$

Thus, in response to the lateral stick input, the effective roll time constant, in a short-term basis, is τ_2. Using the design objective for the teetering rotor helicopter as shown in table 5, the parameters for the roll quickener were: $\tau_2 = 0.2$, $K_5 = 2$, and $K_7 = 0.3$. A similar procedure was used for the design of the quickener for the pitch control.

Augmentation to Improve Control Responses in Yaw and Vertical Axes

The four study helicopters had almost identical sensitivity and damping characteristics in the yaw and vertical axes. The yaw damping of the basic aircraft was deemed somewhat low (at 60 knots, $N_r \approx -1.2\ \text{sec}^{-1}$); therefore it was slightly augmented (to $N_r = -1.6\ \text{sec}^{-1}$) by feeding back yaw rate to the directional control δ_p. For the piloted evaluation purposes, the vertical damping and vertical control sensitivity were augmented for some test configurations to a level twice that of the basic aircraft.

Attitude-Command SCAS

The first group of SCAS was relatively simple in its implementation, requiring simple feedbacks and cross-feed that need only rate instrumentation. Experiments were also conducted with a more sophisticated group of SCAS that require attitude instrumentation. This SCAS concept was applied to all three types of helicopters to achieve the same objectives of control and response decoupling as explored for the rate-command systems and in addition an attitude command feature in response to the pilot's pitch and roll control inputs.

The design objectives for the attitude SCAS are shown in tables 6 and 7 for the articulated rotor helicopter and the teetering rotor helicopter, respectively. For the hingeless rotor helicopter, design goals similar to those of table 6 were used; as a result, positive rate feedback, rather than the normal negative feedback, was necessary for both pitch and roll because of high inherent damping of the hingeless rotor.

The gain levels required to achieve the design objectives in pitch and roll axes are shown in table 8 for the articulated and teetering rotor helicopters. Note that the gain levels for the teetering rotor, because of the low control sensitivity, were several times higher than those of the articulated rotor. Figure 5 shows an example of the effect of attitude-command system (A15) on the response of the basic articulated rotor helicopter to a step input in longitudinal stick. Note that the rate-type response of the basic aircraft has been converted to an attitude-response system. It is interesting to note that the strong coupling in the roll response of the basic aircraft has been decoupled substantially with the employment of attitude stabilization; the decoupling control law for the pitch and roll due to aircraft angular rate as discussed earlier in the paper was not employed in these attitude-command systems.

The eigenvalues of the linearized aircraft dynamics of basic articulated rotor helicopter and the augmented aircraft with the A15 attitude-command system are shown in table 9. For comparison purposes, the eigenvalues are also shown for the simpler system employing decoupling and rate command. Note that the unstable phugoid mode of the basic aircraft has been stabilized by both augmentation systems. Table 10 gives a complete listing of the SCAS configurations that were evaluated in the piloted simulation experiment. Figure 6 shows a general block diagram of the simulation mechanization of the augmentation systems discussed in this section. The forward loop integrators in pitch and roll axes, shown in figure 6, were included for the assessment of rate-command-attitude hold systems, which were not evaluated in the present study.

SIMULATION EXPERIMENT

Simulator and Cockpit Instruments

The simulator used in this experiment was the Ames Flight Simulator for Advanced Aircraft (FSAA) (fig. 7). A detailed description of this six-degree-of-freedom, moving base simulator is given in reference 2. The pilot was provided with pedals, cyclic stick and collective controls, and a basic set of flight instruments (shown in fig. 8) including a barometric altimeter, rate-of-climb, attitude-director indicator, airspeed, and engine torque indicator. The visual scene was presented through the cab window on a color TV monitor with a collimating lens. The total field of view encompassed 36° vertically and 48° horizontally.

The collective stick was provided with some friction but with no force gradient. The force-feel characteristics of the cyclic stick and pedals were provided by an electro-hydraulic unit with adjustable breakout, static gradient, and viscous damping. The gradients and control travels are shown in table 11. The viscous damping level was adjusted to give a well-damped response to control displacements that was judged representative of production helicopters with which the pilots were familiar. The cyclic and pedal forces could be retrimmed, using a switch on the control panel, to zero for any control position. The pilots were permitted to fly the task with the control force gradient removed if they desired to do so.

Helicopter Model

The basic mathematical model used to describe the helicopter in this experiment was the same nine-degree-of-freedom model (i.e., three-degree-of-freedom tip-path-plane dynamics and six-degree-of-freedom rigid body dynamics), used in the previous study (ref. 1). The specific features of the mathematical model are that the main rotor explicitly includes the tip-path-plane dynamics and several major rotor system design parameters, such as flapping-hinge restraint, flapping-hinge offset, blade Lock number, and pitch-flap coupling. Appropriate combinations of these parameters permit exploratory study to be made of the flying qualities of helicopters with a wide variety of rotor systems.

For the present study, a general form of stability and control augmentation system was incorporated into the flight-control system (fig. 6) to accommodate the SCAS configurations of interest as described in the previous section.

Task Description

To give the pilots a repeatable task to perform that was representative of terrain flight, an obstacle course was devised on the terrain model used in the generation of the visual scene. A photograph of the terrain model is shown in figure 9. The course consisted of a series of irregularly spaced barriers with model trees arranged down the centerline. The spacing of the 10-m-high barriers varied between 140 and 280 m. Trees, approximately 15 m high, with the same spacing intervals as the barriers but shifted in phase relative to them, were placed so as to form a slalom course within the hurdles, as shown in figure 10. The pilots were given instructions to fly "as low as possible and as fast as possible" through the course, banking alternately left and right around the trees and dropping down between the barriers. The task started with an initial condition of 60-knot trimmed level flight approximately 35 m above ground level. Minimum vertical obstacle clearance was limited to 5.1 m by a device designed to protect the television camera optics from inadvertent impact with the model terrain.

Each pilot was allowed a limited number of runs with a standard configuration at the beginning of his simulation test period in order to allow him to become reaccustomed to the simulator and task.

Evaluation Pilots

Three pilots participated in the experiment. Pilot A had extensive test experience in V/STOL and conventional aircraft with over 800 hr of helicopter time. Pilot B had flown over 1500 hr in various helicopters, and Pilot C had more than 2000 hr in helicopters, including experience in combat and in Army preliminary evaluation of prototype helicopters.

Data Acquisition

Recorded data were of three types: (1) subjective pilot ratings and verbal comments recorded at the conclusion of each run; (2) post-run summaries; and (3) time histories of helicopter motion variables and control system usage recorded on digital tape for further analysis.

The pilots were asked to give a numerical Cooper-Harper rating (ref. 3) immediately upon completion of the task, and then to amplify the numerical rating with specific comments directed to deficiencies in flying qualities, such as coupling, control power, or lack of coordination, and to give subjective impressions of motion cues and performance, such as speed and altitude through the course.

The post-run summaries provided a quick-look capability for assessing mean values and standard deviations of a limited number of variables, such as height through the course, normal and lateral acceleration, control positions, and sideslip angle.

For subsequent analysis, time histories of 37 variables were recorded in the form of digital data on magnetic tape sampled at 46-msec intervals. These variables included body attitudes, angular and linear rates and accelerations, flight-path coordinates, pilot control positions, and SCAS actuator positions and rates. These data enabled objective performance comparisons between pilots and configurations to be made on the basis of time to complete the course and mean altitude through the course.

RESULTS OF THE EXPERIMENT

The results of the piloted simulation experiment were summarized in pilot ratings and commentary as well as in performance data related to the experiment task, namely, the time to complete the course and mean height above the ground.

To relate the present moving base simulation on the FSAA to the previous fixed-base simulation on another Ames simulator, the example unaugmented helicopters were first evaluated on the FSAA with and without motion. The results for the four basic helicopters of interest are shown in figure 11. The ratings of the two pilots who had flown both simulators, Pilots A and B, are generally consistent; for each of them the discrepancy in pilot ratings obtained in two experiments for the four basic helicopters was no more than one rating point.

Table 12 summarizes the complete pilot rating data for the experiment from the three evaluation pilots. In the following paragraphs, data are examined to assess the effects of (1) decoupling the pitch and yaw responses due to collective input; (2) augmentations using rate-command type SCAS and attitude-command type SCAS; and (3) control quickening for teetering rotor helicopters. An assessment was also made of the effect of the rotor type on SCAS authorities.

Effect of Decoupling Pitch and Yaw due to Collective Input

As would be anticipated, the experimental results show that the control augmentation systems designed to decouple the pitch and yaw responses due to collective input improved flying qualities. Figure 12 shows an example of the flying quality improvement for a series of decoupling CAS for a hingeless rotor helicopter. It can be seen from this figure that an increase in pitching moment due to collective input in excess of that of the basic aircraft degraded flying qualities; improvement was achieved by eliminating the coupling in pitching moment due to collective input. Further improvement was made by decoupling both the pitching and yawing moments due to collective input.

Also shown in the figure are the time to complete the course and the mean height above the ground for the corresponding CAS configurations. There was a trend toward decreasing the time necessary to complete the course as aircraft flying qualities improved; however, the mean height above the ground showed a slight reverse trend for this series of augmentation systems.

It should be noted that unless indicated otherwise, the results shown in figure 12 and in the figures that follow are the combined data from evaluation Pilots A, B, and C. The brackets encompass the extreme values, and the dot indicates the mean value of the data.

Rate-Command SCAS

As noted in previous discussions, the rate-command SCAS were designed with several functional objectives. Those objectives included the primary function of improving the sensitivity and damping in pitch and roll; decoupling yaw and/or pitch due to collective input; and decoupling the pitch-roll due to aircraft angular rate. The results of the evaluation experiment showed that this type of SCAS significantly improved the terrain-flying agility over otherwise unacceptable basic helicopters.

Figure 13 shows examples of the results for this type of augmentation system for an articulated rotor helicopter. On the far left in figure 13 is the basic aircraft. Slight improvement was achieved with an augmentation to decouple the pitch-roll due to aircraft angular rate (i.e., $L_q = M_p = 0$); further substantial improvement in pilot rating was made by increasing the level of augmentation to optimize the sensitivity and damping in pitch and roll; and finally, more improvement was made by further use of control augmentation to decouple the yaw due to collective input.

The time to complete the course for this series of augmentation systems again showed some correlation with the pilot rating data; but the mean height above the ground did not indicate a discernible trend.

Attitude-Command Augmentation

The experimental results for the attitude-command augmentation systems also showed a substantial improvement in terrain-flying agility over otherwise unacceptable helicopters (e.g., the articulated rotor helicopter and the teetering rotor helicopter).

Figure 14 shows examples of the results for a series of attitude SCAS (see table 6) for the articulated rotor helicopter. As might be expected, the sensitivity in aircraft attitude change per unit stick deflection in pitch and roll axes as well as the variations in bandwidth had significant effect on the handling qualities. Only a few combinations of these parameters were evaluated during this experiment. Perhaps further improvements can be made by optimizing these parameters.

Again, the mean height above the ground showed no definitive trend, but there was good correlation between the time to complete the course and pilot rating data for this series of augmentation systems.

It is interesting to compare directly the results of the attitude-command augmentation systems with those of rate-command systems. Figure 15 shows a comparison of improvements made by these two series of augmentation systems for Pilot A. Some major comments that Pilot A made for these augmentation systems are also shown in table 13. Pilots A, B, and C did not indicate a clear-cut preference for either type of augmentation.

Control Quickening for Teetering Rotor Helicopter

A series of control augmentation systems, designed to quicken the pitch and roll response characteristics of the teetering rotor helicopter with high blade inertia, was evaluated. No significant improvements were found for this series of augmentation.

Figure 15 shows a comparison for Pilot A of this series of control augmentation systems with rate-command and attitude-command augmentation systems for the teetering rotor helicopter studied. Significant improvements were found for both the rate- and attitude-command systems in contra t to the control-quickening augmentation systems.

Effect of the Rotor Type on SCAS Control Authorities

One of the main objectives of this study is to assess the control usage by the stability and control augmentation systems. The SCAS control usage provides a basis for determining the amount of control authority to be allocated to the SCAS. It therefore has immediate effect on the safety and redundancy design of the SCAS.

Data pertaining to the control usage by the pilot, SCAS, and the total pilot SCAS in completing a run through the course have been recorded and analyzed to obtain their extreme values as well as mean and rms values. Figures 16-18 show, for Pilots A, B, and C, respectively, the control usage for the pitch and roll axes for five augmented aircraft with good handling qualities.

To provide a basis for comparison, the control usage obtained from the three basic helicopters is shown in figure 19 for Pilots A, B, and C. In figure 19, the dots indicate the mean values of control usage, expressed in terms of the percentage of the total cockpit control displacement limits, and the brackets indicate the extreme values. Because the control gearings from the control stick to the swashplate are different for the three types of helicopters (shown in tables 2-4), it may be desirable to express the control usage in terms of swashplate displacement. Figures 20-22 show the pitch and roll control usage, expressed in terms of swashplate displacement, for Pilots A, B, and C, respectively, for the five augmented aircraft described earlier. Figures 23-25 show the corresponding control usage expressed in terms of the rms of the swashplate displacement.

The SCAS control usage for the hingeless rotor and articulated rotor helicopters was well within the total control authority for all the evaluation pilots. For the teetering rotor helicopter, the SCAS and the total pilot SCAS control usage were excessive, expecially in the pitch axis. When interpreting these data, it should be recognized that during the experiment the pilot control usage was limited to the 100% value while the SCAS and the total control usages were deliberately unlimited to permit assessment of the total control requirements.

CONCLUDING REMARKS

The piloted simulator investigation on the moving base Flight Simulator for Advanced Aircraft of stability and control augmentation systems to improve terrain-flying agility has led to the following conclusions:

1. Decoupling the yaw response due to collective input significantly improved flying qualities for terrain following

2. Decoupling the pitch response due to collective input improved flying qualities for hingeless rotor helicopters

3. Both rate-command type SCAS and attitude-command type SCAS made substantial improvements in terrain-flying agility over otherwise unacceptable helicopters; no evidence was found for a clear-cut preference for either type of augmentation for the task flown

4. The SCAS control usage and gain levels were moderate for hingeless rotor and articulated rotor helicopters, but they were excessive for teetering rotor helicopters

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TABLE 1.- BASIC HELICOPTERS FOR AUGMENTATION STUDY

Experiment configuration	Rotor system parameters	Major handling quality deficiencies
Teetering rotor helicopter		
T	Lock number $\gamma = 3$ Hinge offset $\epsilon = 0$ Hinge restraint $K_\beta/I_\beta\Omega^2 = 0$	Control sensitivity too low in pitch, roll; damping in pitch, roll too low; excessive yaw coupling due to collective input
Articulated rotor helicopter		
A	Lock number $\gamma = 9$ Hinge offset $\epsilon = 0.05$ Hinge restraint $K_\beta/I_\beta\Omega^2 = 0$	Strong pitch-roll coupling due to aircraft angular rate; roll control sensitivity too high
Hingeless rotor helicopter		
H1	Lock number $\gamma = 9$ Hinge offset $\epsilon = 0.14$ Hinge restraint $K_\beta/I_\beta\Omega^2 = 0.03$	Excessive pitch coupling due to collective input
H2	Lock number $\gamma = 3$ Hinge offset $\epsilon = 0.10$ Hinge restraint $K_\beta/I_\beta\Omega^2 = 0.03$	Control sensitivity too low in both pitch and roll

TABLE 2.- STABILITY DERIVATIVES OF BASIC HINGELESS ROTOR HELICOPTER, H1

Derivative	Unit	Airspeed, knots				
		0	40	60	80	100
Pitch						
M_q	1/sec	-2.70	-2.92	-3.00	-3.08	-3.17
M_p	1/sec	.76	.70	.69	.69	.71
$M_{\delta e}$	rad/sec^2/cm[a]	.33	.34	.34	.35	.37
$M_{\delta c}$	rad/sec^2/cm	.002	.09	.14	.19	.24
Roll						
L_p	1/sec	-9.66	-10.23	-10.23	-10.17	-9.78
L_q	1/sec	-2.79	-2.55	-2.48	-2.42	-2.37
$L_{\delta a}$	rad/sec^2/cm	1.19	1.18	1.18	1.17	1.17
Yaw						
N_r	1/sec	-0.60	-1.33	-1.20	-1.25	-1.33
$N_{\delta p}$	rad/sec^2/cm	.40	.38	.31	.35	.37
$N_{\delta c}$	rad/sec^2/cm	.19	.13	.06	.04	.038
Heave						
Z_w	1/sec	-0.21	-0.50	-0.67	-0.76	-0.81
$Z_{\delta c}$	ft/sec^2/cm	-3.70	-3.77	-3.96	-4.17	-4.40

[a]Note: Pitch and roll control gearings from the stick to swashplate are 0.49 and 0.48 deg/cm, respectively.

TABLE 3.- STABILITY DERIVATIVES OF BASIC ARTICULATED ROTOR HELICOPTER

Derivative	Unit	Airspeed, knots				
		0	40	60	80	100
			Pitch			
M_q	1/sec	-0.56	-0.68	-0.73	-0.77	-0.81
M_p	1/sec	.39	.38	.37	.37	.37
$M_{\delta e}$	rad/sec^2/cm[a]	.17	.17	.18	.18	.19
$M_{\delta c}$	rad/sec^2/cm	0	.024	.04	.05	.06
			Roll			
L_p	1/sec	-2.52	-2.94	-3.00	-3.01	-2.86
L_q	1/sec	-1.92	-1.84	-1.78	-1.72	-1.67
$L_{\delta a}$	rad/sec^2/cm	.71	.71	.71	.71	.71
			Yaw			
N_r	1/sec	-0.60	-1.33	-1.20	-1.25	-1.33
$N_{\delta p}$	rad/sec^2/cm	.40	.39	.32	.33	.37
$N_{\delta c}$	rad/sec^2/cm	.19	.13	.06	.05	.047
			Heave			
Z_w	1/sec	-0.21	-0.51	-0.68	-0.76	-0.81
$Z_{\delta c}$	ft/sec^2/cm	-3.70	-3.76	-3.93	-4.13	-4.35

[a]Note: Pitch and roll control gearings from stick to swashplate are 0.96 and 0.81 deg/cm, respectively.

TABLE 4.- STABILITY DERIVATIVES OF BASIC TEETERING ROTOR HELICOPTER

Derivative	Unit	Airspeed, knots				
		0	40	60	80	100
Pitch						
M_q	1/sec	-0.38	-0.59	-0.67	-0.71	-0.73
M_p	1/sec	.22	.21	.21	.21	.20
$M_{\delta e}$	rad/sec^2/cm[a]	.035	.035	.035	.035	.035
$M_{\delta c}$	rad/sec^2/cm	.0004	.002	.007	.011	.014
Roll						
L_p	1/sec	-1.79	-2.66	-2.85	-2.90	-2.80
L_q	1/sec	-1.06	-1.06	-.97	-.87	-.76
$L_{\delta a}$	rad/sec^2/cm	.15	.15	.15	.16	.16
Yaw						
N_r	1/sec	-0.60	-1.34	-1.21	-1.26	-1.34
$N_{\delta p}$	rad/sec^2/cm	.40	.39	.32	.35	.37
$N_{\delta c}$	rad/sec^2/cm	.19	.14	.06	.05	.05
Heave						
Z_w	1/sec	-0.21	-0.51	-0.67	-0.76	-0.81
$Z_{\delta c}$	ft/sec^2/cm	-3.70	-3.76	-3.92	-4.11	-4.32

[a]Note: Pitch and roll control gearings from the stick to swashplate are 0.52 and 0.43 deg/cm, respectively.

TABLE 5.- COMPARISON OF GAIN LEVELS FOR RATE-COMMAND SCAS AT 60 KNOTS

Teetering rotor (basic aircraft)			Articulated rotor (basic aircraft)		
Augmented aircraft (B71)	Gains		Augmented aircraft (B37)	Gains	
Pitch					
Damping $\hat{M}_q = -2.5$/sec	$\delta e/q$	−50.21 cm/rad/sec (−0.45 deg/deg/sec)	Damping $\hat{M}_q = -3.0$/sec	$\delta e/q$	−12.75 cm/rad/sec (−0.21 deg/deg/sec)
Sensitivity $\hat{M}_{\delta e_p} = 0.21$ rad/sec^2/cm	$\delta e/\delta e_p$	5.66 cm/cm	Sensitivity $\hat{M}_{\delta e_p} = 0.33$ rad/sec^2/cm	$\delta e/\delta e_p$	1.86 cm/cm
Roll					
Damping $\hat{L}_p = -5$/sec	$\delta a/p$	−13.92 cm/rad/sec (−0.105 deg/deg/sec)	Damping $\hat{L}_p = -10$/sec	$\delta a/p$	−9.88 cm/rad/sec (−0.14 deg/deg/sec)
Sensitivity $\hat{L}_{\delta a_p} = 0.55$ rad/sec^2/cm	$\delta a/\delta a_p$	3.57 cm/cm	Sensitivity $\hat{L}_{\delta a_p} = 1.10$ rad/sec^2/cm	$\delta a/\delta a_p$	1.55 cm/cm

TABLE 6.- ATTITUDE SCAS FOR ARTICULATED ROTOR HELICOPTER

Exp configuration	Approximate longitudinal dynamics			Approximate lateral-directional dynamics		
	ω_n, rad/sec	ζ	$\left.\frac{\theta}{\delta e_p}\right\|_{s.s.}$, deg/cm	ω_n, rad/sec	ζ	$\left.\frac{\phi}{\delta a_p}\right\|_{s.s.}$, deg/cm
A11	2.5	1	2.24	2.5	1	4.53
A13	2.0	1	2.24	2.0	1	7.87
A15	2.0	1	3.94	2.0	1	7.87

Yaw: rate-augmented, collective to yaw decoupled.

TABLE 7.- ATTITUDE SCAS FOR TEETERING ROTOR HELICOPTER

Exp configuration	Approximate longitudinal dynamics			Approximate lateral-directional dynamics		
	ω_n, rad/sec	ζ	$\left.\frac{\theta}{\delta e_p}\right\|_{s.s.}$, deg/cm	ω_n, rad/sec	ζ	$\left.\frac{\phi}{\delta a_p}\right\|_{s.s.}$, deg/cm
T11	2.5	1	2.24	2.5	1	4.53
T12	2.5	1	1.14	2.5	1	4.53
T13	1.9	0.9	1.93	1.8	1.2	4.49
T14	1.9	.9	1.93	1.8	1.2	6.69
T15	1.9	.9	1.93	1.8	1.2	8.90

Yaw: rate-augmented, collective to yaw decoupled.

TABLE 8.- COMPARISON OF GAIN LEVELS FOR ATTITUDE SCAS AT 60 KNOTS

Augmented aircraft dynamics	Gains		
	Parameter	Teetering (T11)	Articulated (A11)
Pitch axis			
ω_n = 2.5 rad/sec	$\delta e/\Delta\theta$ (cm/rad) (deg/deg)	142.31 (1.28)	30.73 (0.51)
ζ = 1	$\delta e/q$ (cm/rad/sec) (deg/deg/sec)	99.90 (0.90)	19.89 (0.33)
$\left.\frac{\theta}{\delta e_p}\right\|_{s.s.}$ = 2.24 deg/cm	$\delta e/\delta e_p$ (cm/cm)	6.74	1.38
Roll axis			
ω_n = 2.5 rad/sec	$\delta a/\Delta\phi$ (cm/rad) (deg/deg)	40.49 (0.31)	8.69 (0.12)
ζ = 1	$\delta a/p$ (cm/rad/sec) (deg/deg/sec)	13.74 (0.10)	2.69 (0.04)
$\left.\frac{\phi}{\delta a_p}\right\|_{s.s.}$ = 4.53 deg/cm	$\delta a/\delta a_p$ (cm/cm)	3.19	0.69

TABLE 9.- EIGENVALUES OF AUGMENTED AND UNAUGMENTED ARTICULATED ROTOR AIRCRAFT AT 60 KNOTS

Basic aircraft (A1)	Rate command (B37)	Attitude command (A15)
0.003 ± j 0.285 (ζ = -0.009; ω_n = 0.285)	-0.003 ± j 0.088 (ζ = 0.037; ω_n = 0.089)	-1.278 ± j 0.509 (ζ = 0.929; ω_n = 1.376)
-0.857 ± j 0.665 (0.790; 1.084)	-0.832 ± j 1.600 (0.461; 1.804)	-0.783 ± j 1.647 (0.429; 1.823)
-0.593 ± j 1.672 (0.334; 1.774)	-0.881 -9.872	-2.331 ± j 1.400 (0.857; 2.719)
-0.028 -2.701	-0.012 -2.829	-0.046 -0.625

TABLE 10.- EVALUATED SCAS CONFIGURATIONS

Decoupling and rate command		Attitude	
Experimental configuration	Remarks	Experimental configuration	Remarks
T Q41, Q51, Q52, Q53, Q61 B51, B52, B53, B61, B71	Basic aircraft (teetering rotor) Step-by-step improvements in control responses in (1) pitch, roll by quickening; (2) yaw, vertical axes using feedforward-feedback Step-by-step improvements in control responses in pitch, roll, yaw, and vertical using feedforward-feedback	T T11, T12, T13, T14, T15, T16	Improved pitch, roll control responses using attitude-command systems
A B32, B33, B34, B35, B36, B37	Basic aircraft (articulated rotor) Step-by-step improvements in (1) eliminating pitch-roll couplings; (2) control responses in pitch, roll, yaw, and vertical using feedforward-feedback	A A11, A13, A15	Improved pitch, roll control responses using attitude-command systems
H1 H13 H11, B11	Basic aircraft (hingeless rotor) Increased pitch due to collective input Decoupled yaw and pitch responses due to collective input		
H2 B87	Basic aircraft (hingeless rotor) Improvements in control responses in pitch, roll, yaw, vertical using feedforward-feedback	H2 UCC, U03, U05	Attitude-command systems in pitch and roll

TABLE 11.- HELICOPTER CONTROL TRAVELS AND FORCE GRADIENTS

Control	Travel, cm	Breakout, N approximate	Gradient, N/cm
Collective	25.4	2.22	0
Pedals	±8.26	8.90	3.50
Longitudinal cyclic	±15.24	4.45	2.92
Lateral cyclic	±15.24	4.45	1.75

TABLE 12.- SUMMARY OF PILOT RATING

Experimental configuration	Pilot rating: Pilot A	B	C	Experimental configuration	Pilot rating: Pilot A	B	C
T	6.5/7.5F[a]	7/8F	6/6F	T			
Q41	6	7	7	T11	7	6	7
Q51	6	8	7	T12	6/5	6	
Q52	5	7	---	T13	4/4	6	6
Q53	6	7	2	T14	4	5	5
Q61	6	7	8	[illegible]5	4(3.5)/4	5	2
B51	6	8	6	T16	---	6	3
B52	7	7	---				
B53	5(4.5)	7	2				
B61	5(4.5)	7	2				
B71	4(3.5)	7	2				
A	7	6/7/7F	7/4/3F	A			
B32	6	6	5	A11	5	6	4
B33	4	5	3	A13	4, 3/3	5/5	3
B34	4	5	---	A15	3/3	5	3
B35	4	7/6F	---				
B36	3	5	---				
B37	3	4/5/4F	3				
H1	4(5)	6/5	5				
H13	7	7	6				
H11	3	5/6	4				
B11	3/3	4	3				
H2	6.5/7/7.5F	7/7/8F	9	H2	7	7	9
B87	6/6F	8	5/4F	UCC	---	---	9
				U03	---	---	8
				U05	7/6F	8	8

[a]Fixed base.

TABLE 13.- HANDLING QUALITIES IMPROVEMENTS WITH TWO SERIES OF AUGMENTATIONS FOR AN ARTICULATED ROTOR HELICOPTER, PILOT A

Experimental configuration	Control system improvements	Major comments	Pilot rating
A	Basic aircraft (see table 1 for deficiencies)	Pitch-roll coupling; pitch, and roll responses too sensitive	6.5
Decoupling and rate-command SCAS			
B32	Pitch-roll coupling eliminated, $L_q = M_p = 0$ Yaw damping increased	Pitch-roll coupling better; damping in pitch and roll too low	6
B33	B32 plus pitch and roll responses improved	Improved pitch and roll, but still needed work	4
B34	B33 plus improved vertical response	Good configuration, but motion is not responsive enough	4
B35	B34 plus pitch coupling due to collective eliminated	Pitch response is very satisfactory; $M_{\delta_c} = 0$ was noticed, but did not help much	4
B36	B35 plus yaw due to collective eliminated	Quite good; pitch, roll dynamics could still be improved some	3
B37	B36 without improved vertical response	Collective response was slower; decoupling was not really noticeable	3
Attitude-command SCAS			
A11	Provided attitude-command system in pitch and roll ($\omega_n = 2.5$; moderate sensitivity)	Stiff in roll and pitch; lack of response in roll	5
A13	Reduced ω_n to 2.0 in pitch and roll Increased sensitivity in roll	Roll better; agility better; increased response in pitch and roll; want to lighten stick force gradient	3
A15	Increased sensitivity in pitch from A13	Very agile; increased response in pitch better	3

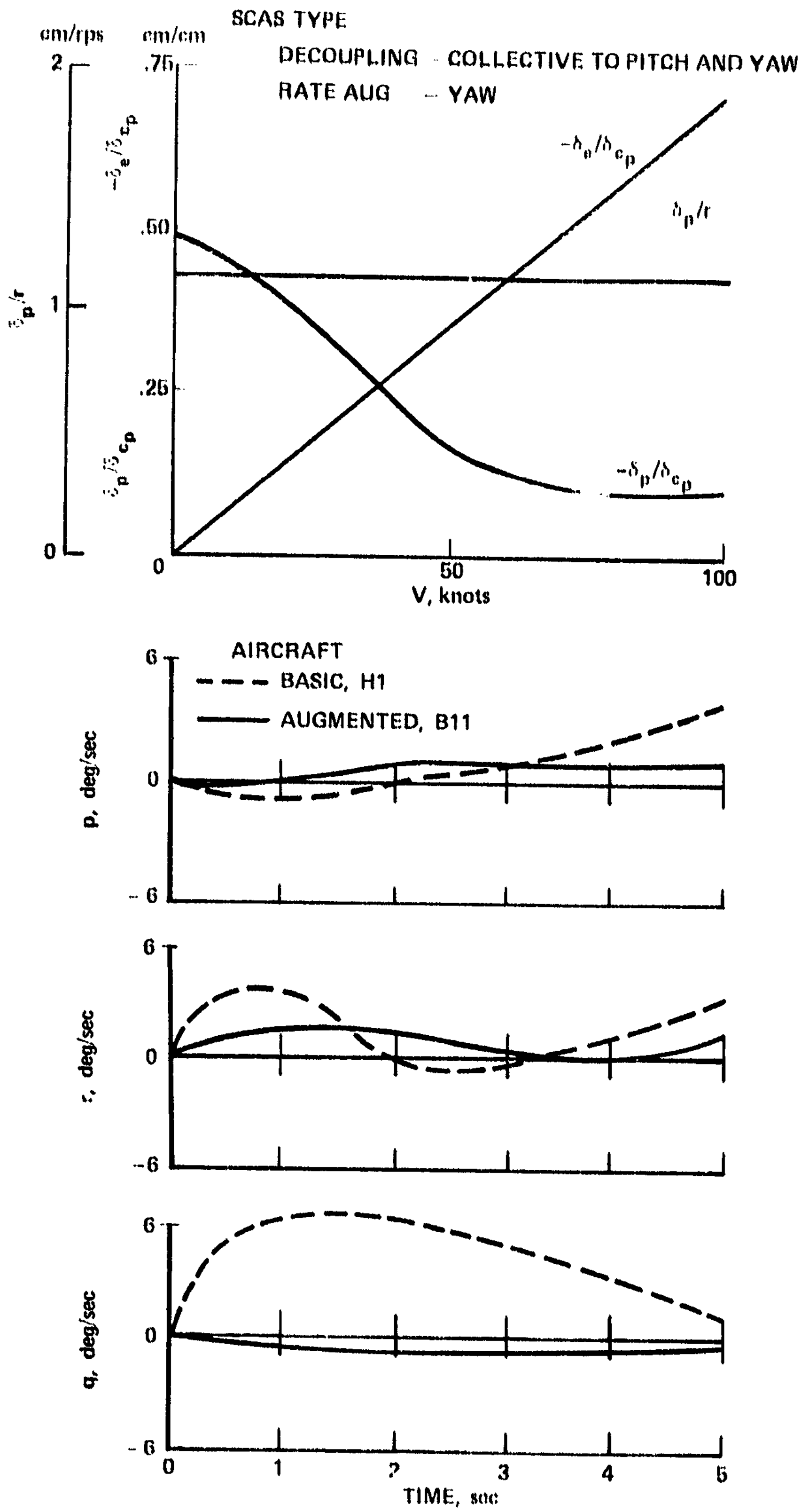


Figure 1.- Decoupling SCAS for hingeless rotor helicopter, H1.

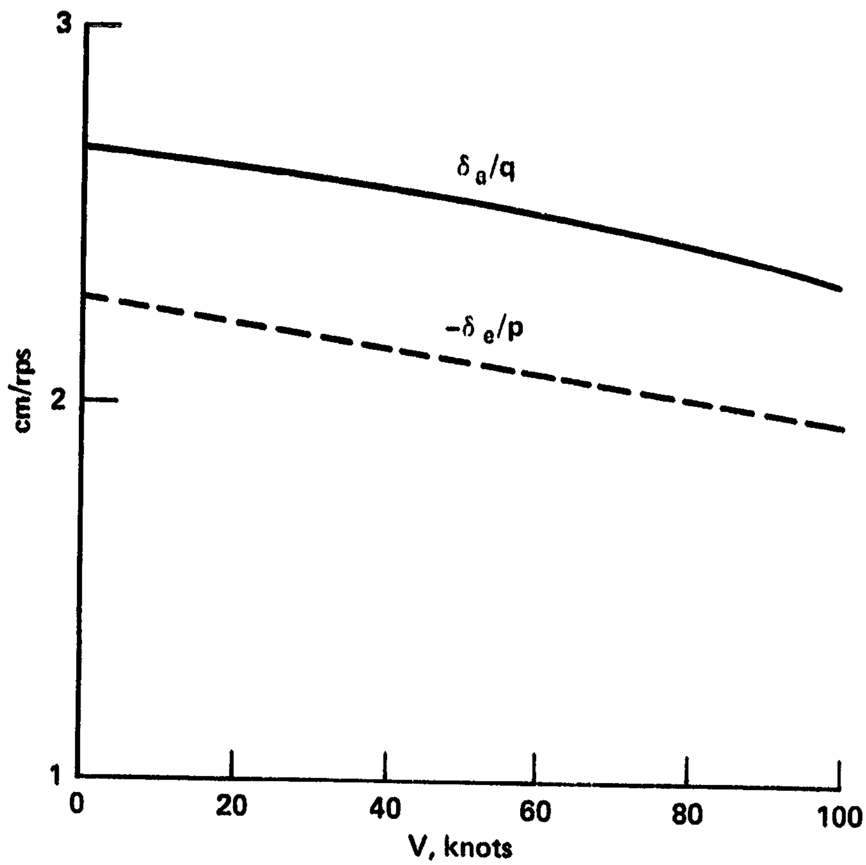


Figure 2.— Feedback gains for articulated rotor helicopter to eliminate pitch-roll coupling due to aircraft angular rate.

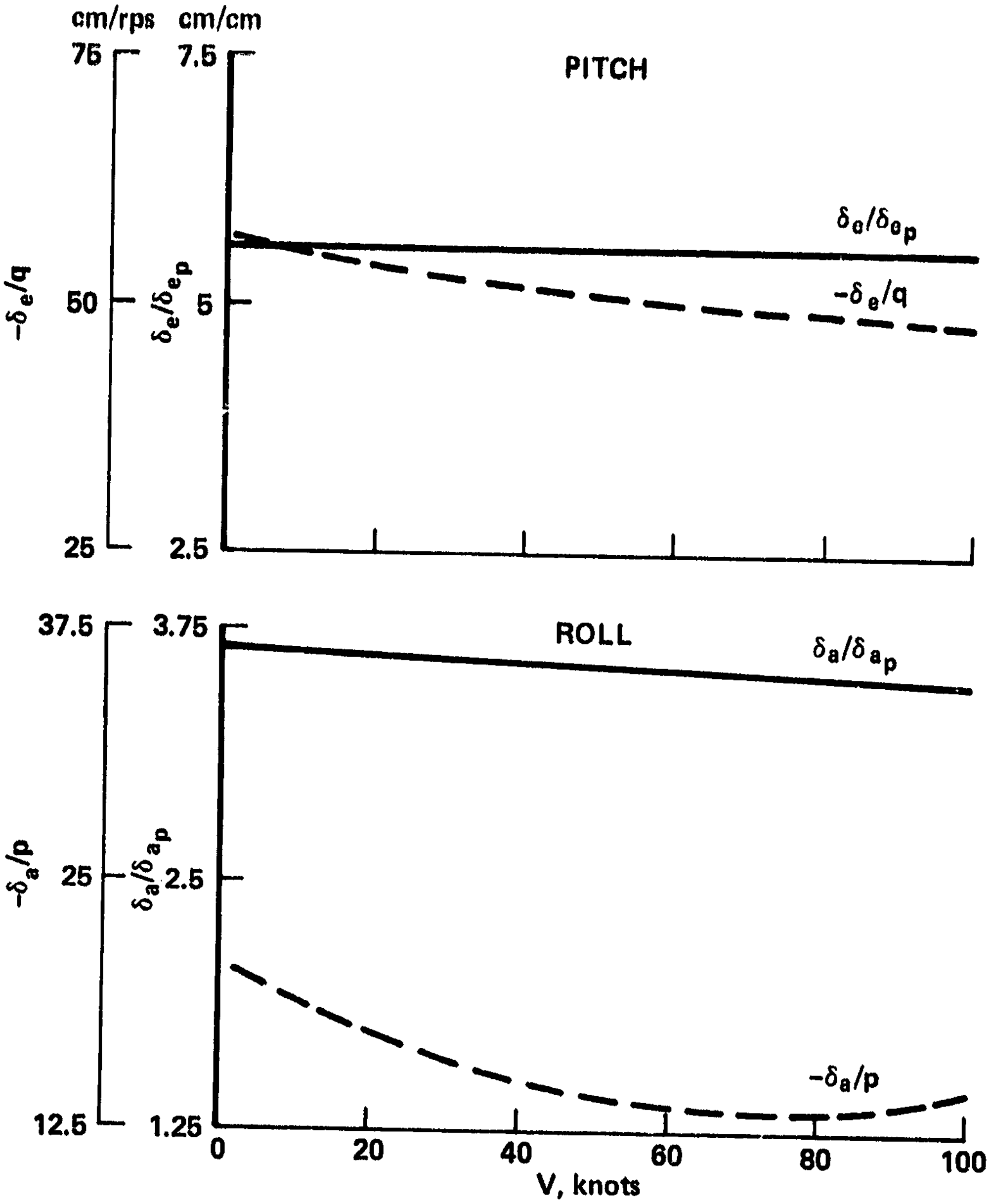
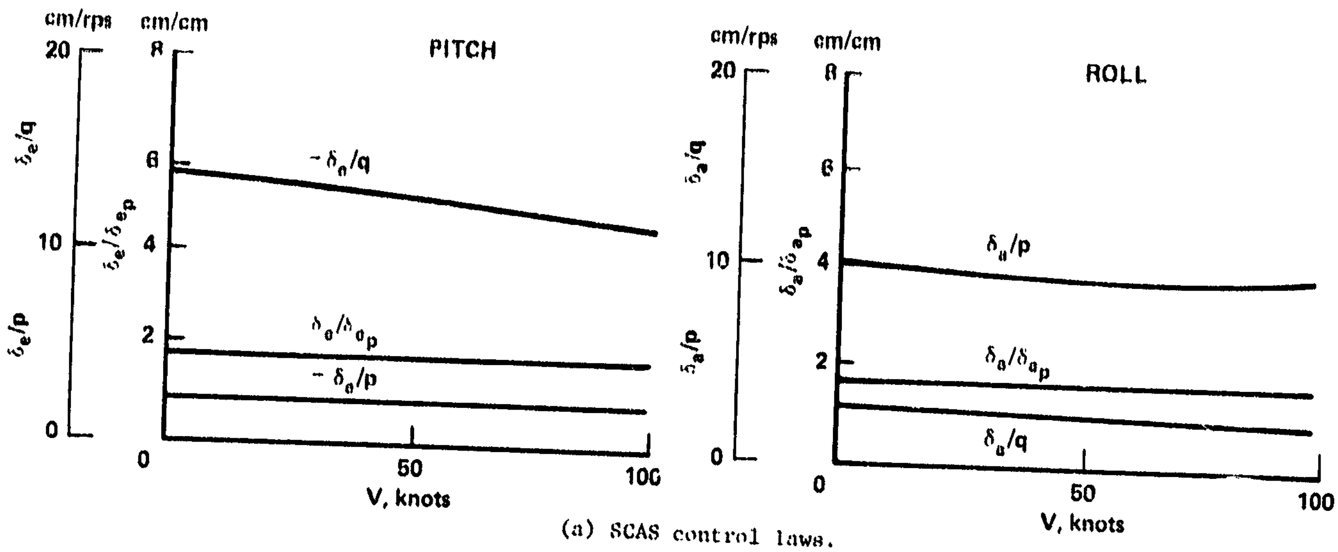


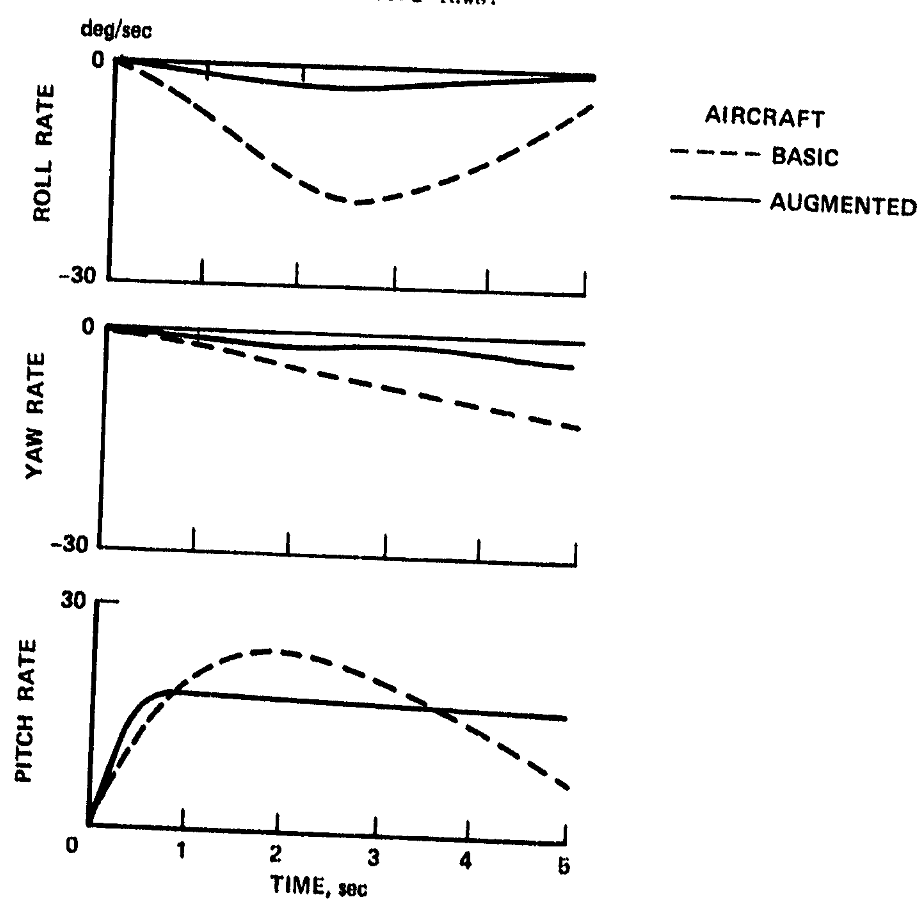
Figure 3.— Feedback and feed-forward gains for teetering rotor helicopter.

	p	q	r	δ_{e_p}	δ_{a_p}	δ_{c_p}
PITCH	X	X		X		X
ROLL	X	X			X	
YAW			X			X

SCAS TYPE:
DECOUPLING– PITCH-ROLL DUE TO AIRCRAFT RATE; COLLECTIVE TO PITCH AND YAW
RATE COMMAND– PITCH, ROLL, YAW



(a) SCAS control laws.



(b) Response to 2.54-cm (1.0-in.) longitudinal stick step at 60 knots.

Figure 4.– Rate-command SCAS for articulated rotor helicopter.

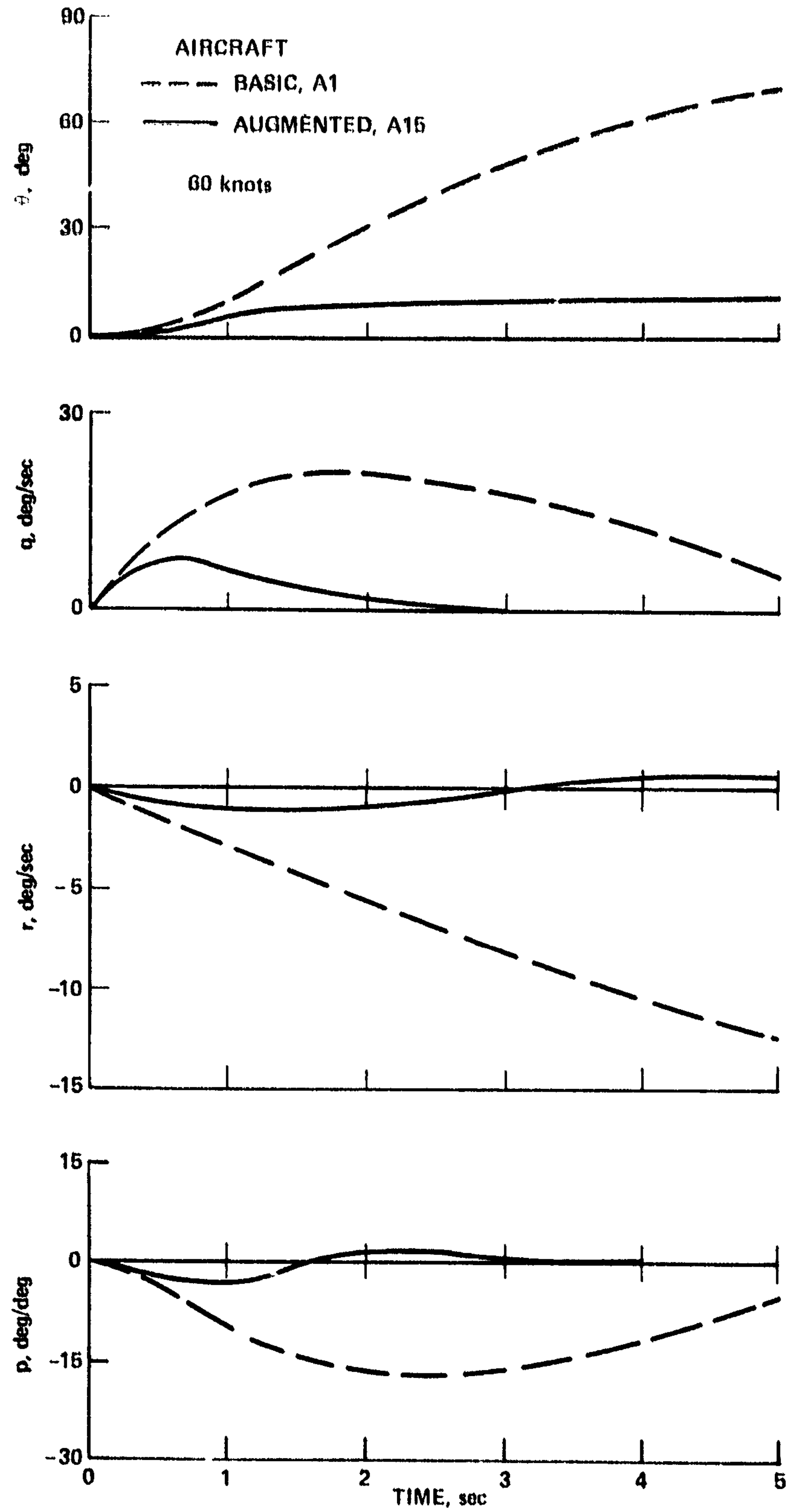
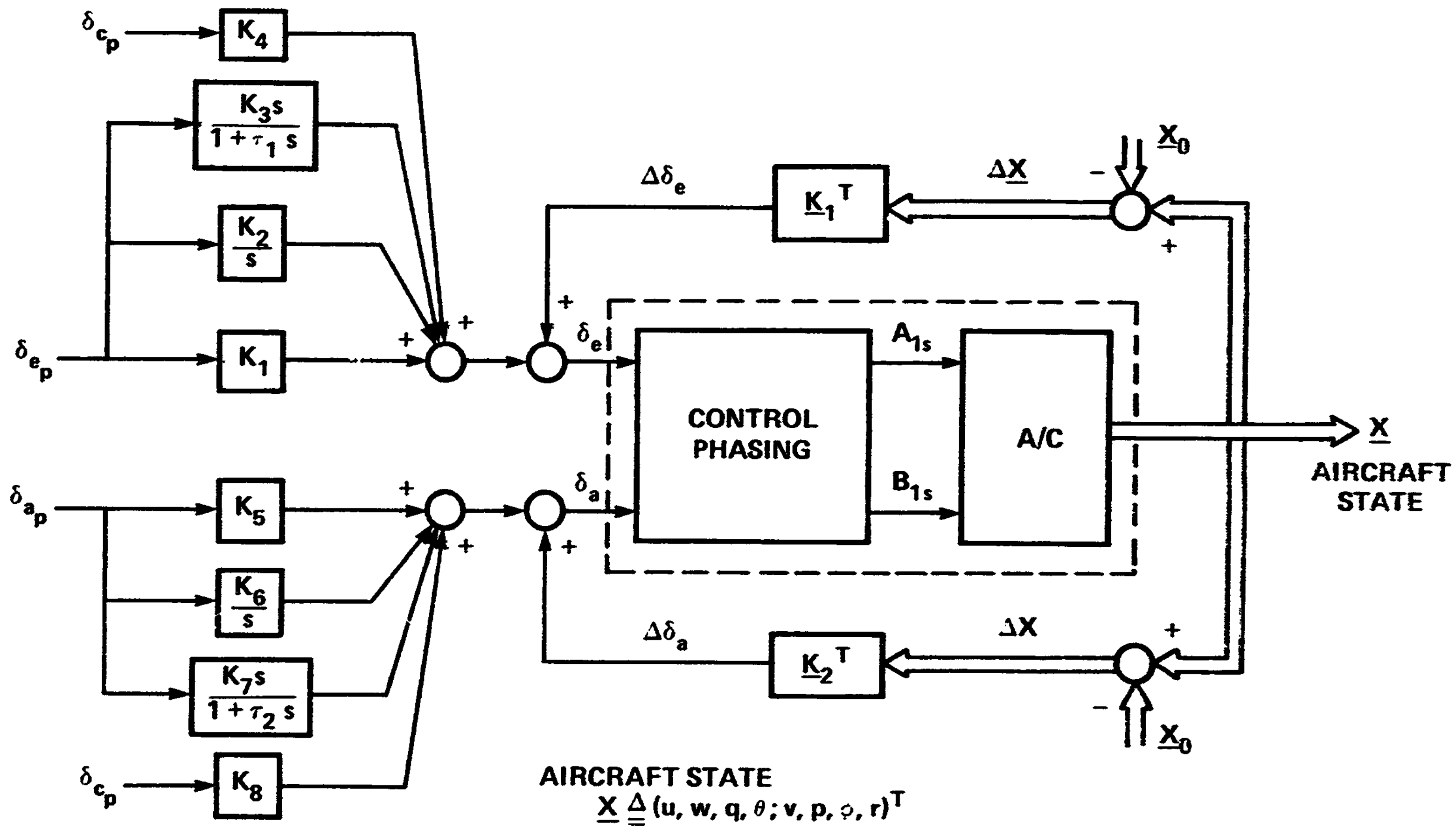
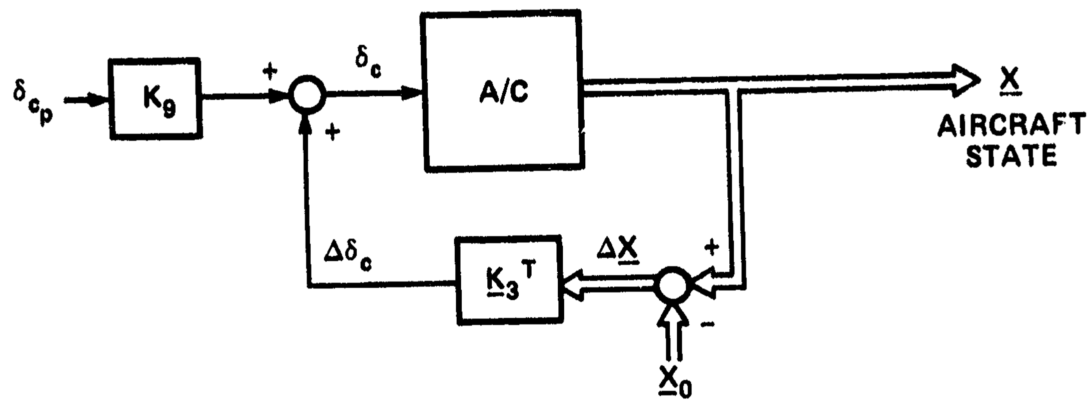


Figure 5.- Effect of attitude SCAS on response of articulated rotor helicopter to 2.54-cm (1-in.) input of longitudinal cyclic stick.

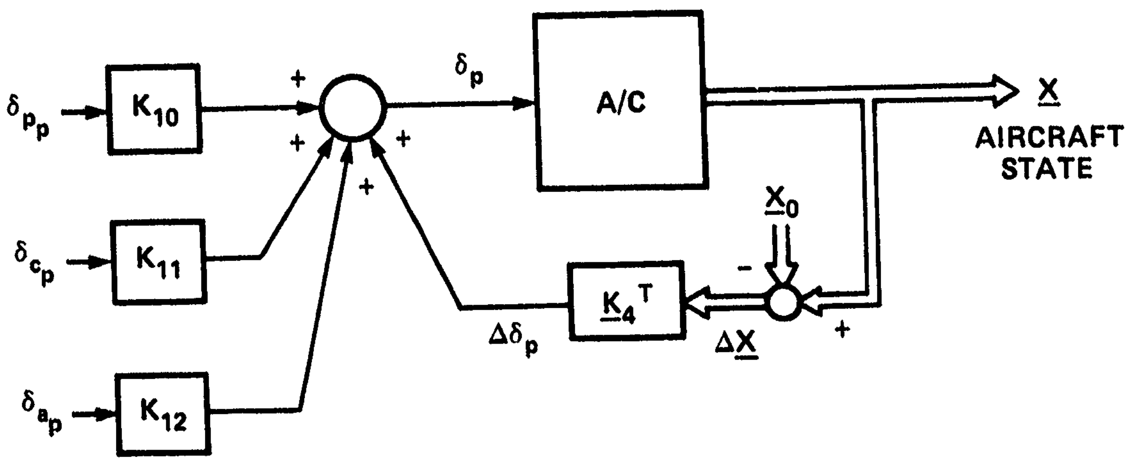


(a) Pitch-roll axes.

Figure 6.— Block diagram of simulation mechanization for the augmentation systems.



(b) Vertical axis.



(c) Yaw axis.

Figure 6.— Concluded.

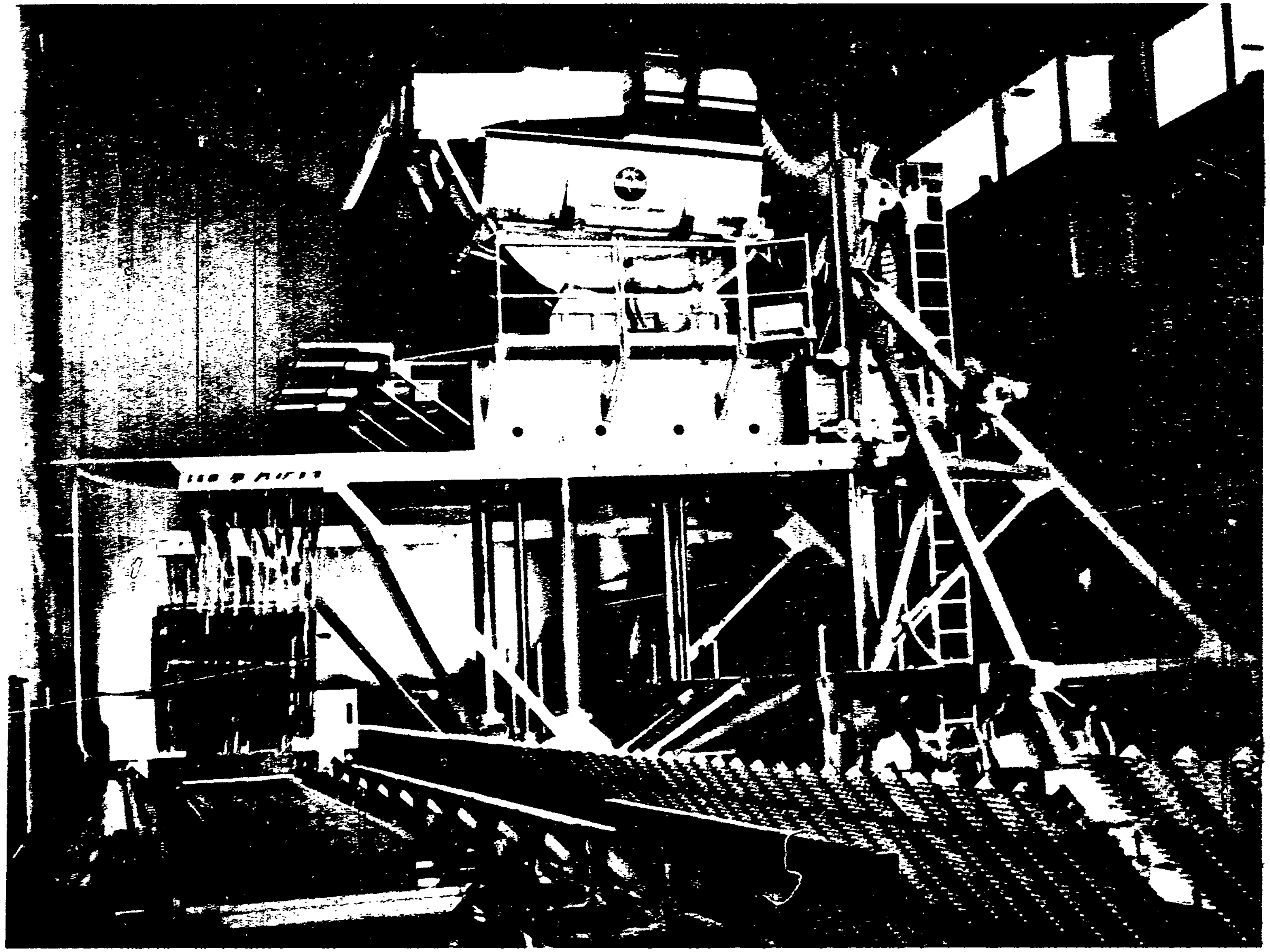


Figure 7.— The flight simulator for advanced aircraft.

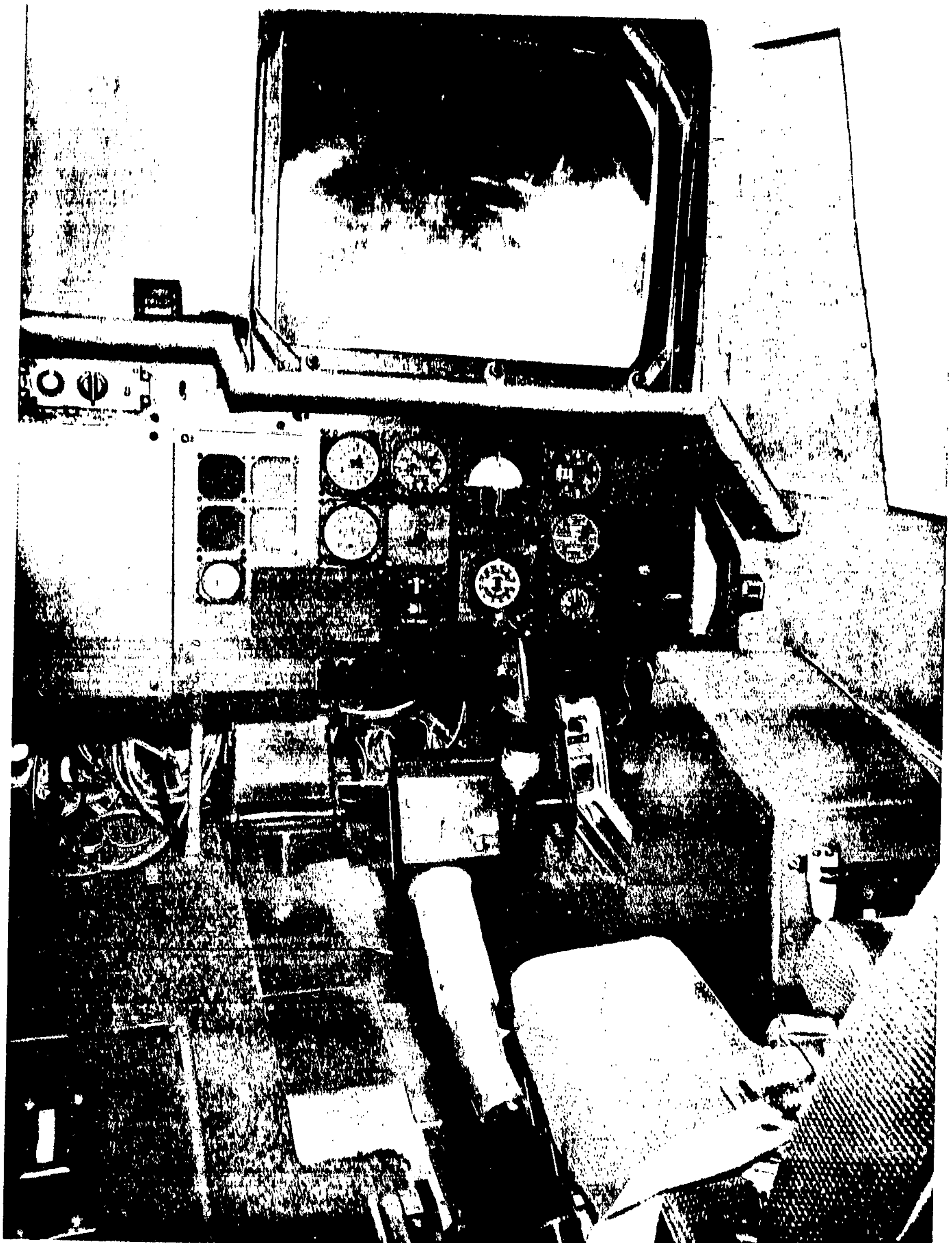


Figure 8.– Instrument configuration in simulator cab.

Figure 9.— Photograph of terrain model with nap-of-the-earth courses.

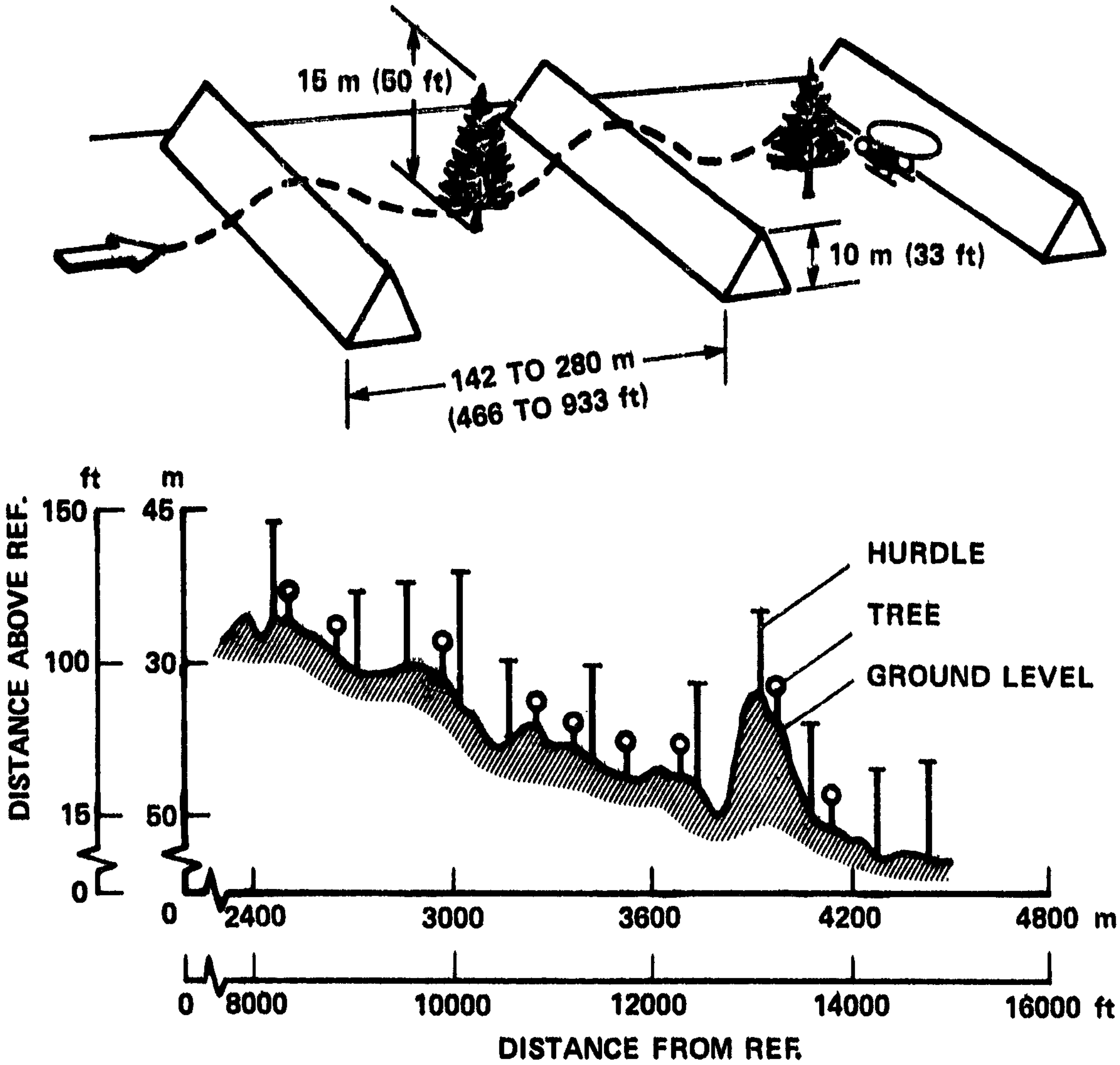


Figure 10.— Layout of nap-of-the-earth terrain avoidance obstacle course.

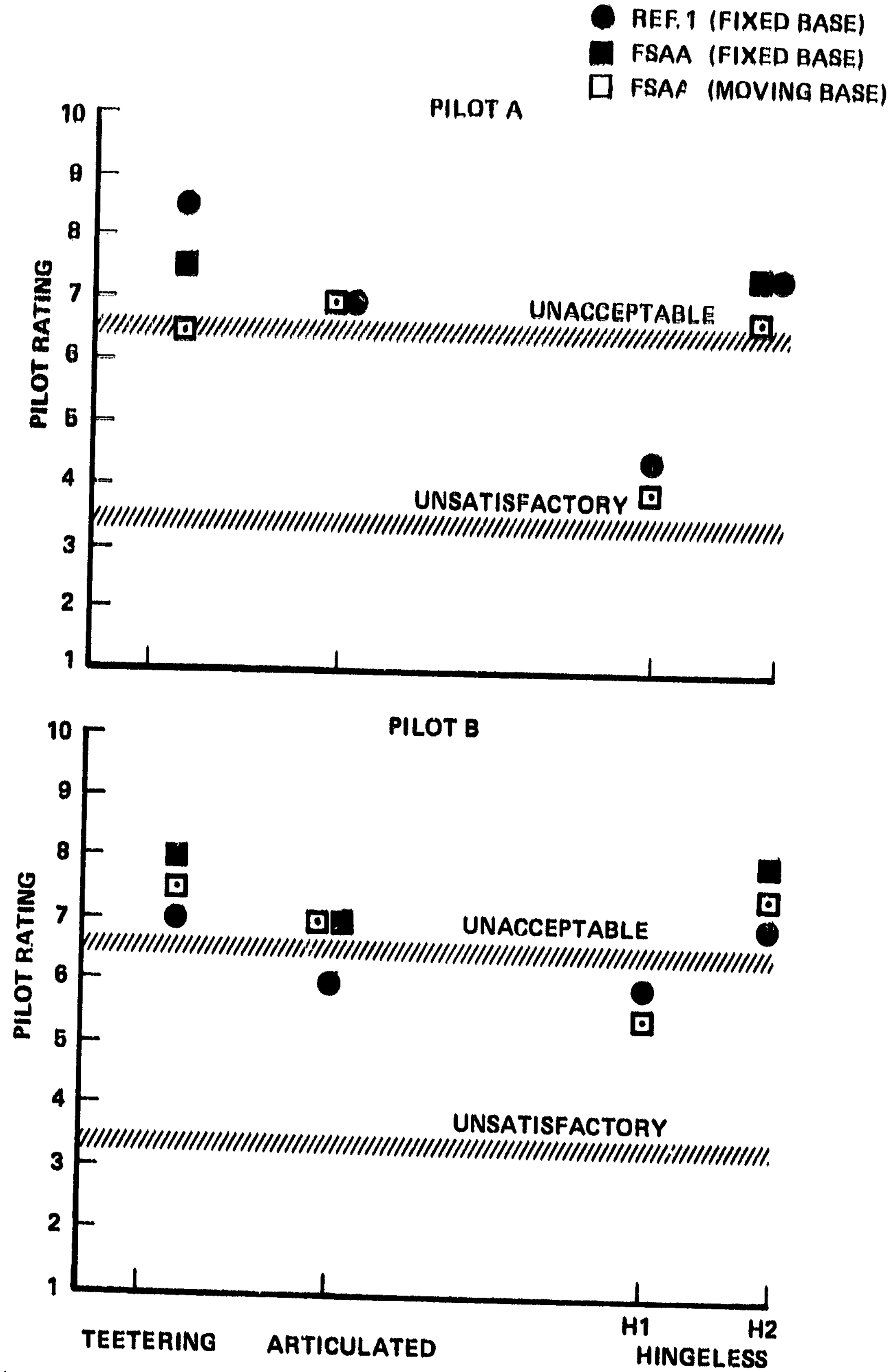


Figure 11.– Pilot rating comparison for four basic aircraft from two experiments.

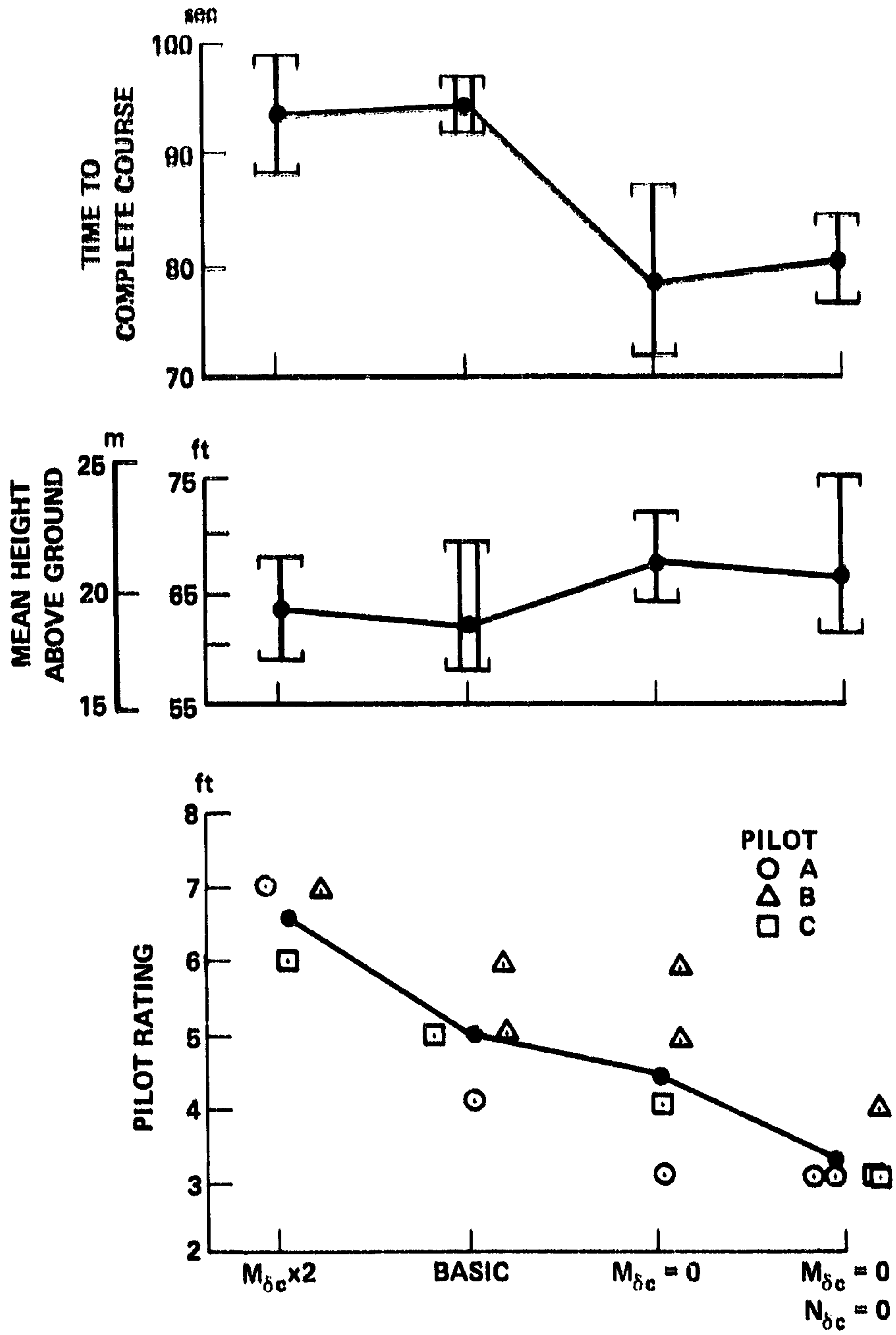


Figure 12.– Results for decoupling hingeless rotor helicopter, H1.

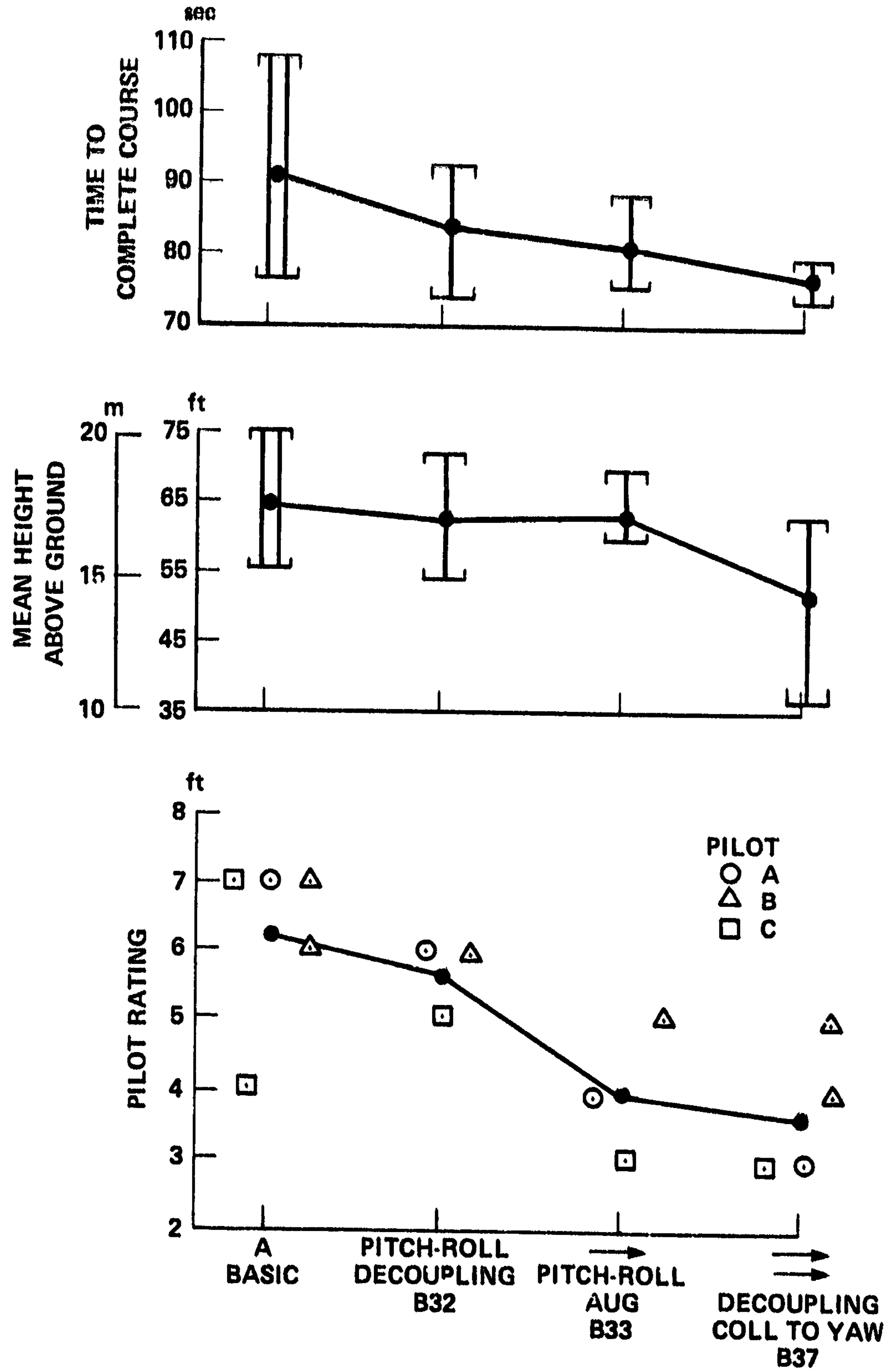


Figure 13.— Results for a series of decoupling and rate-command augmentation systems for articulated rotor helicopter.

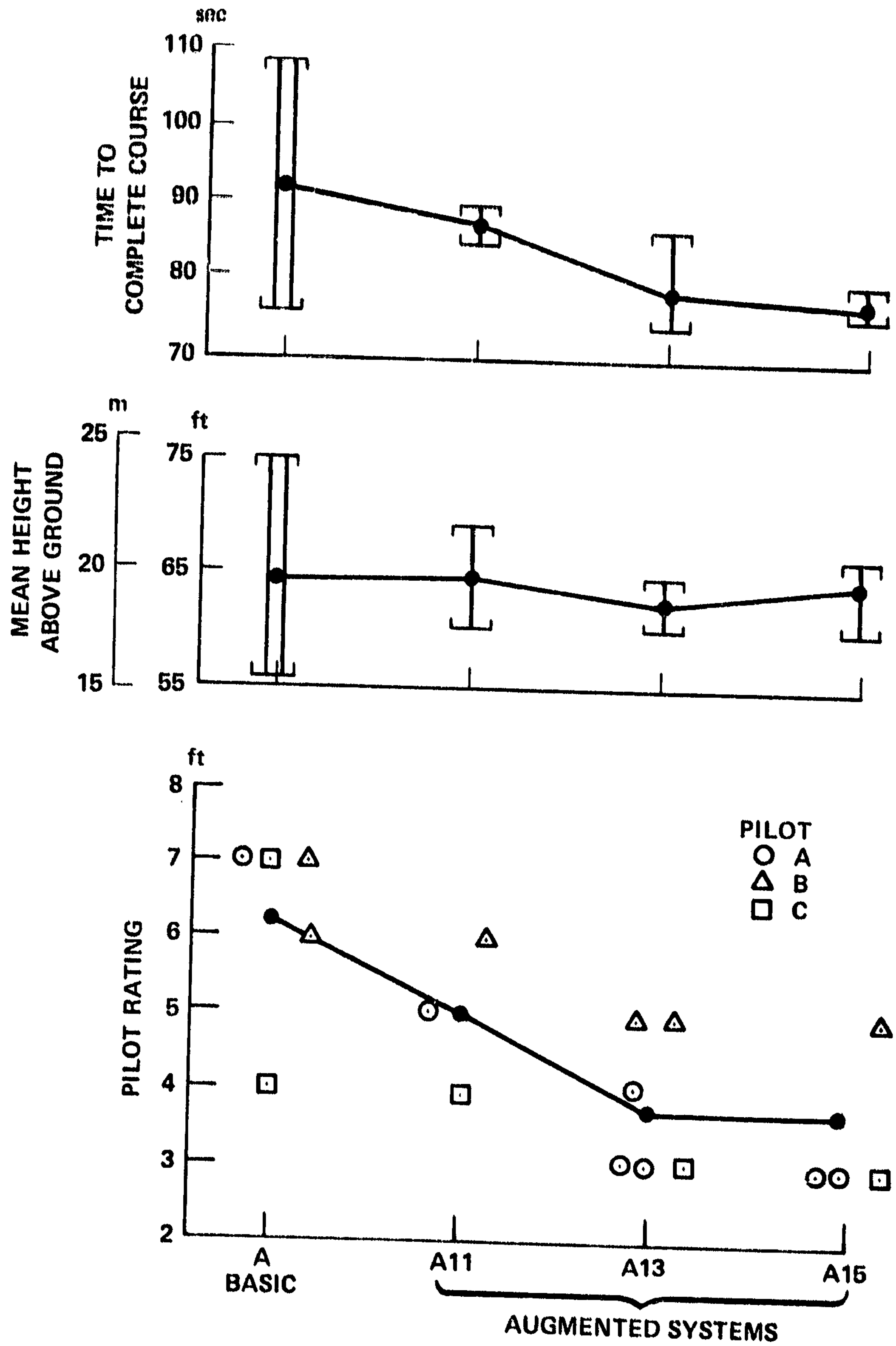


Figure 14.– Results for a series of attitude SCAS for articulated rotor helicopter.

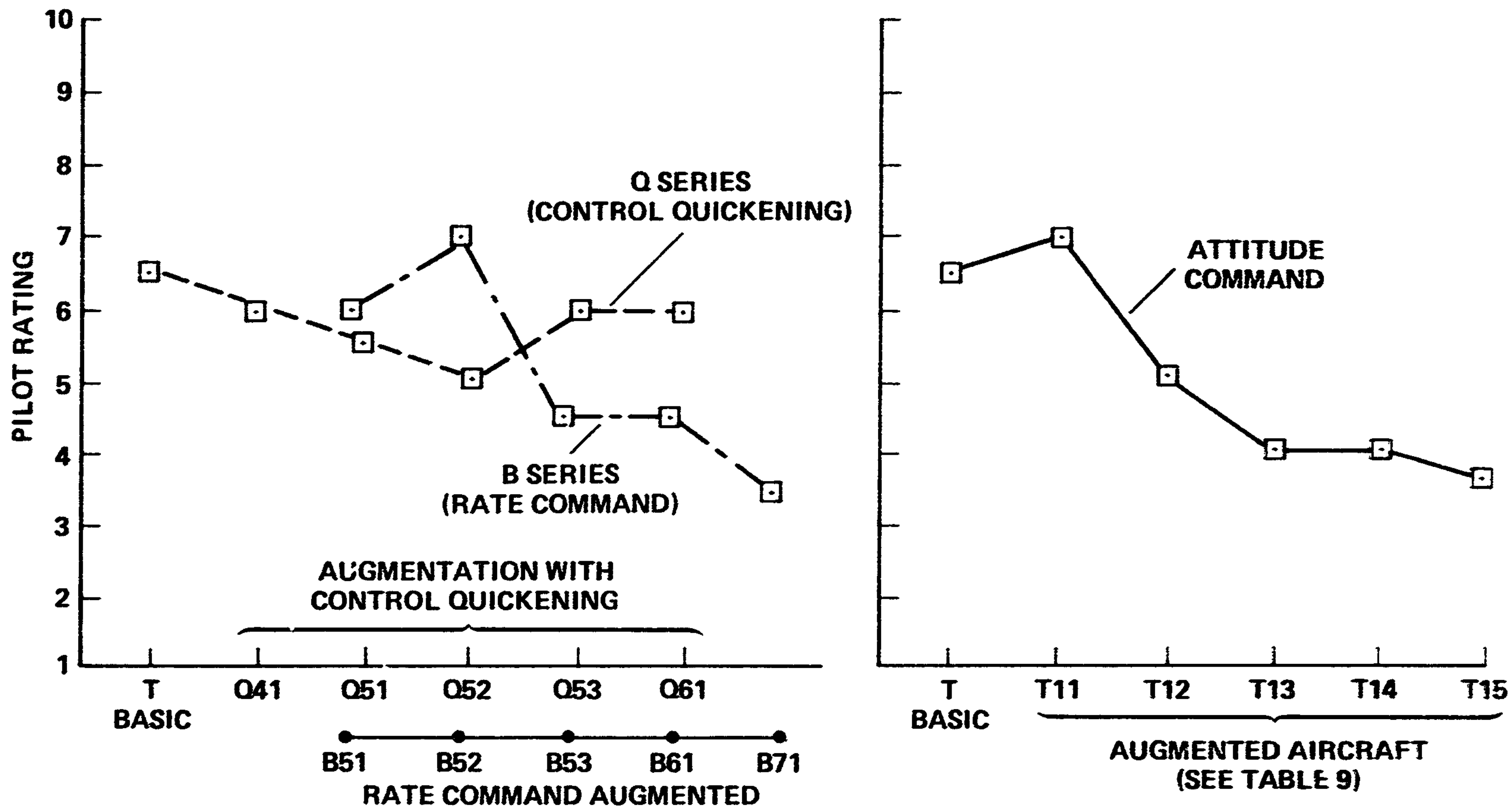


Figure 15.– Results for three series of augmentation systems for teetering rotor helicopter, Pilot A.

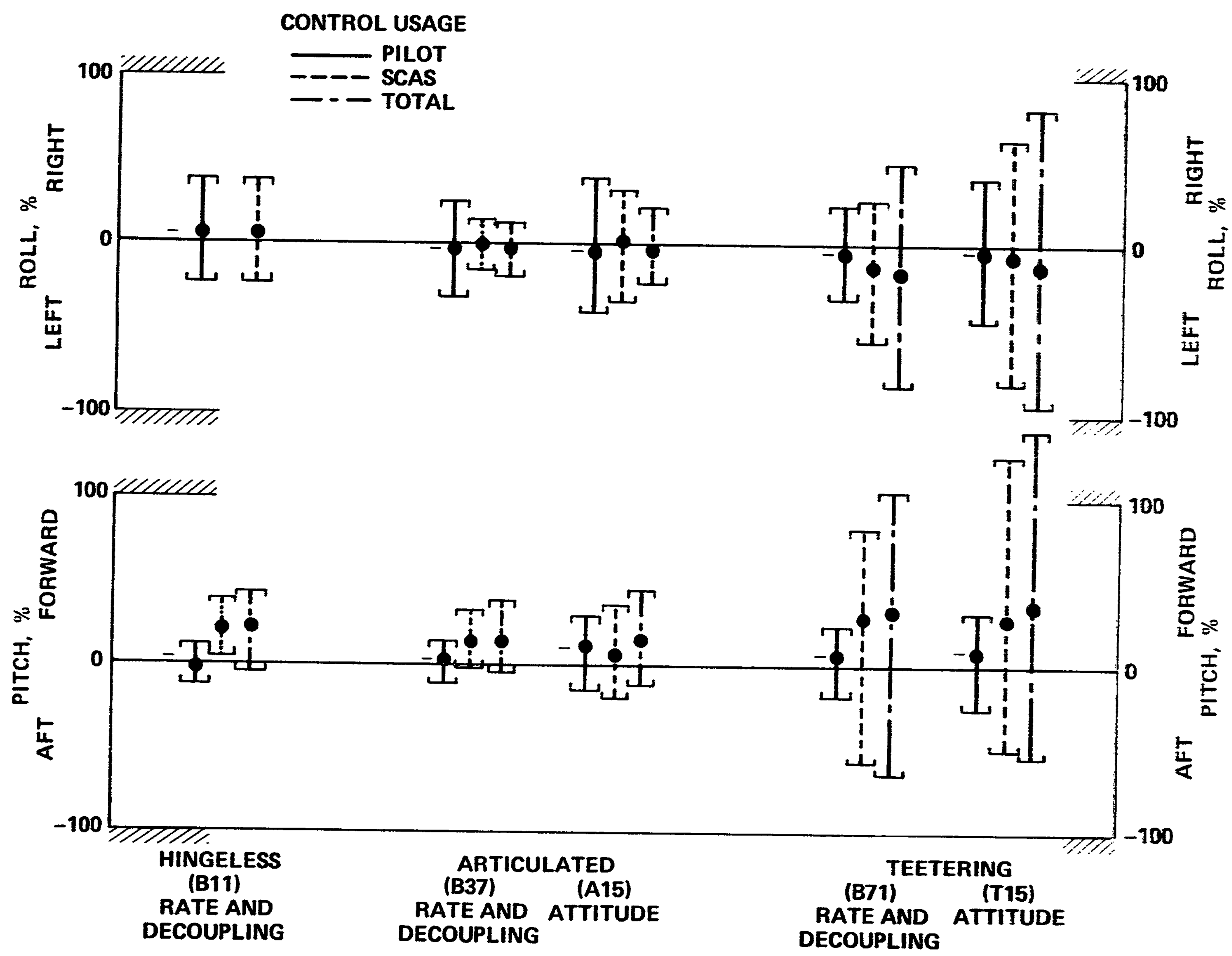


Figure 16.— Pitch and roll control usage for five augmented aircraft, Pilot A.

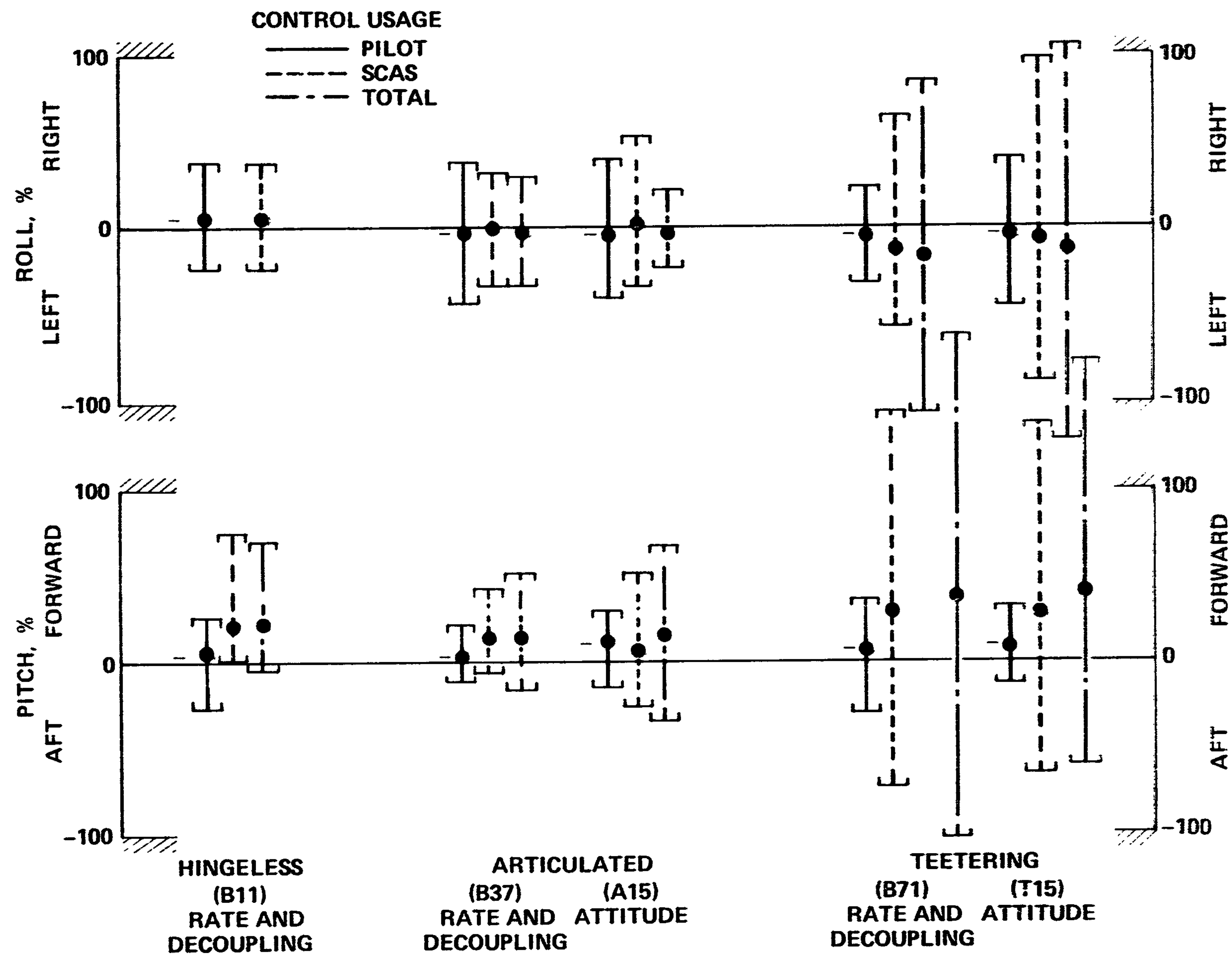


Figure 17.– Pitch and roll control usage for five augmented aircraft, Pilot B.

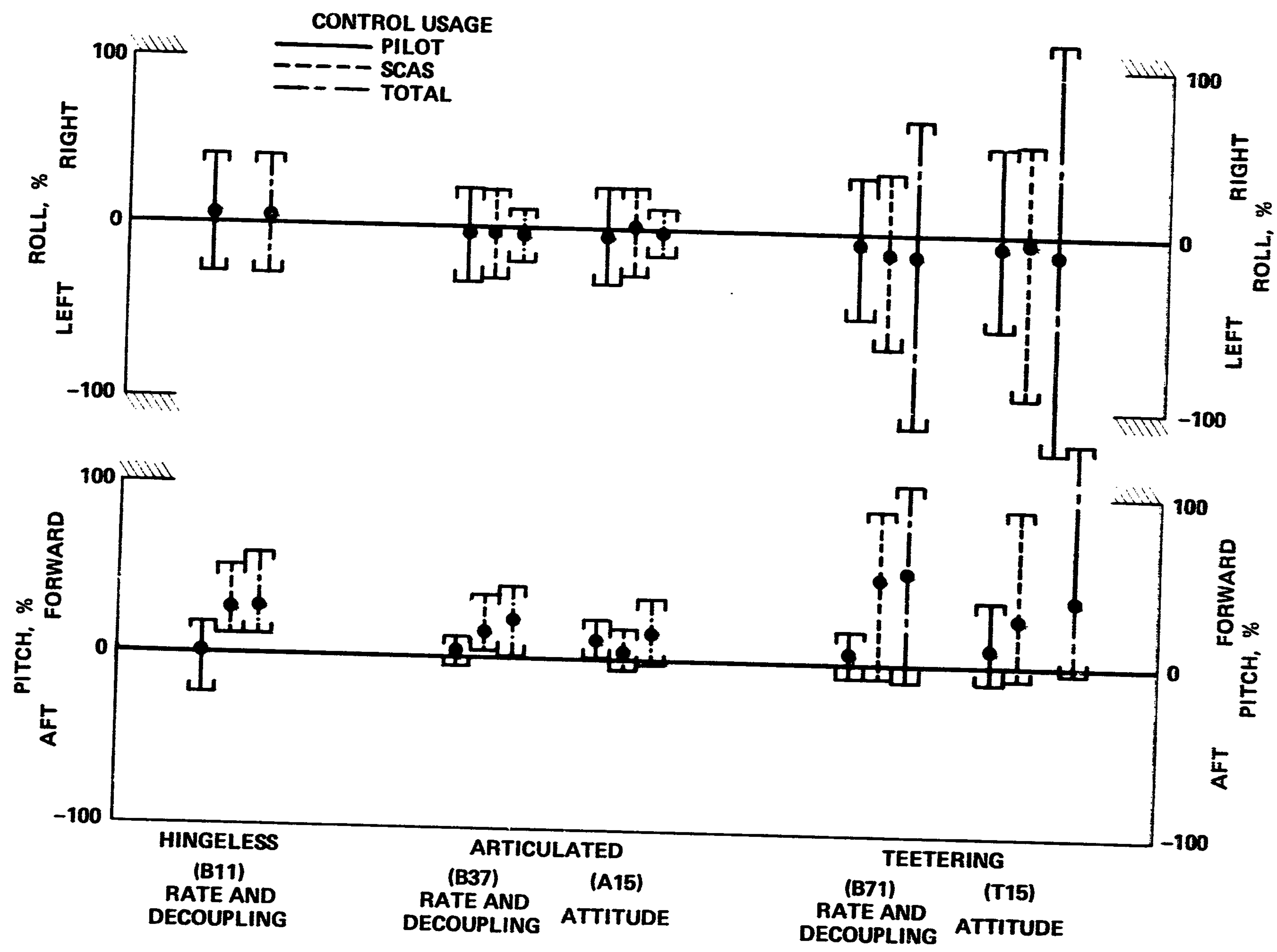


Figure 18.— Pitch and roll control usage for five augmented aircraft, Pilot C.

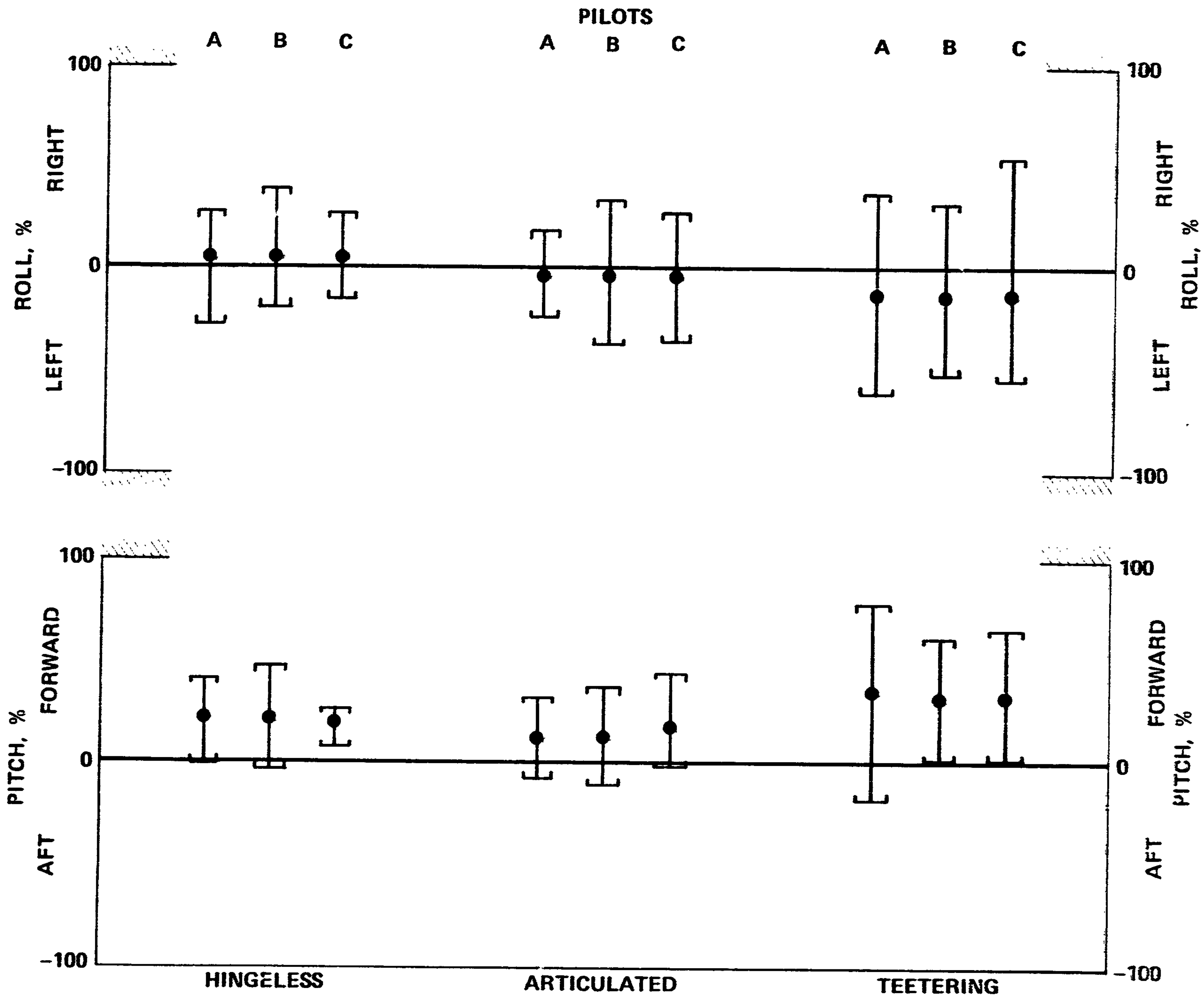
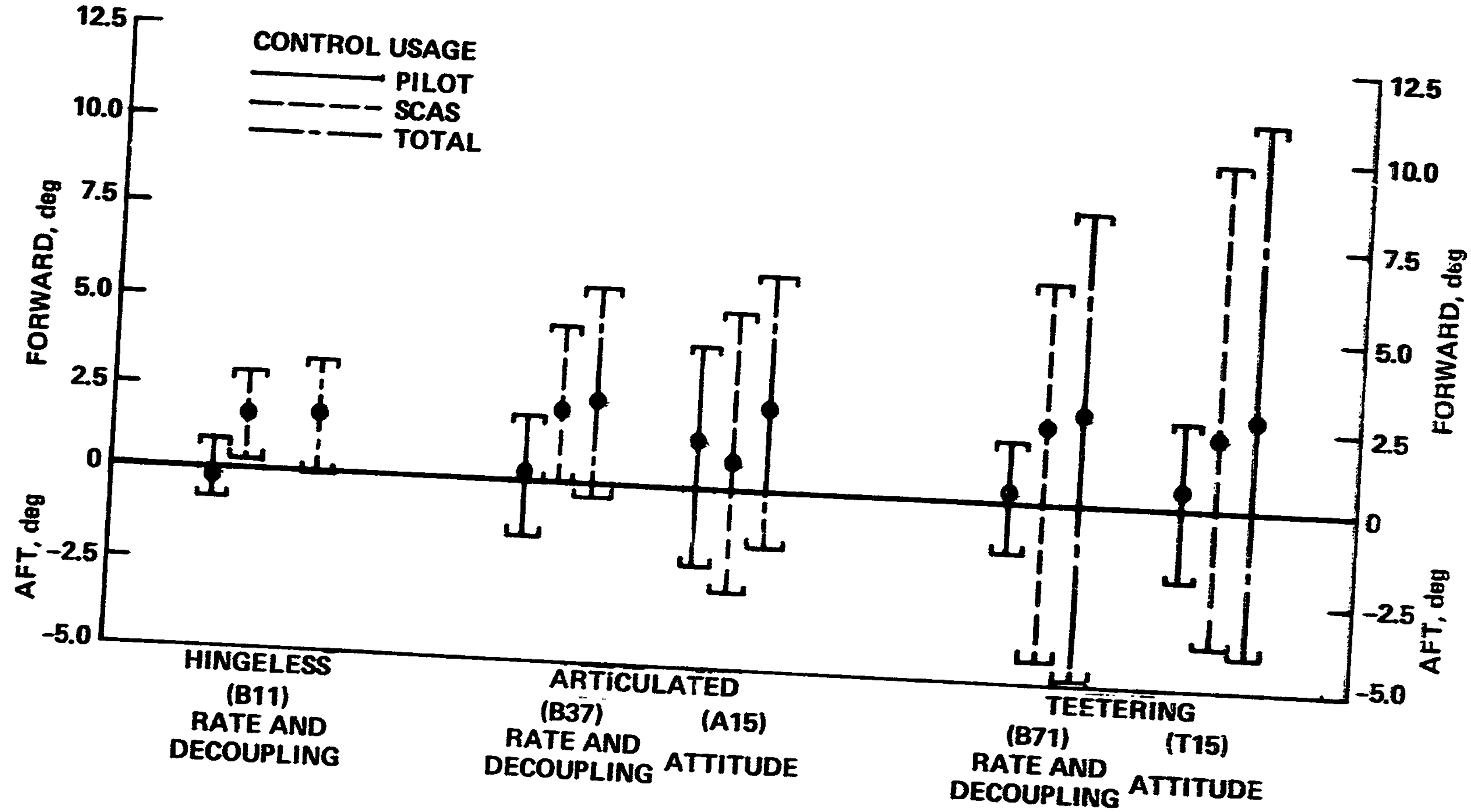
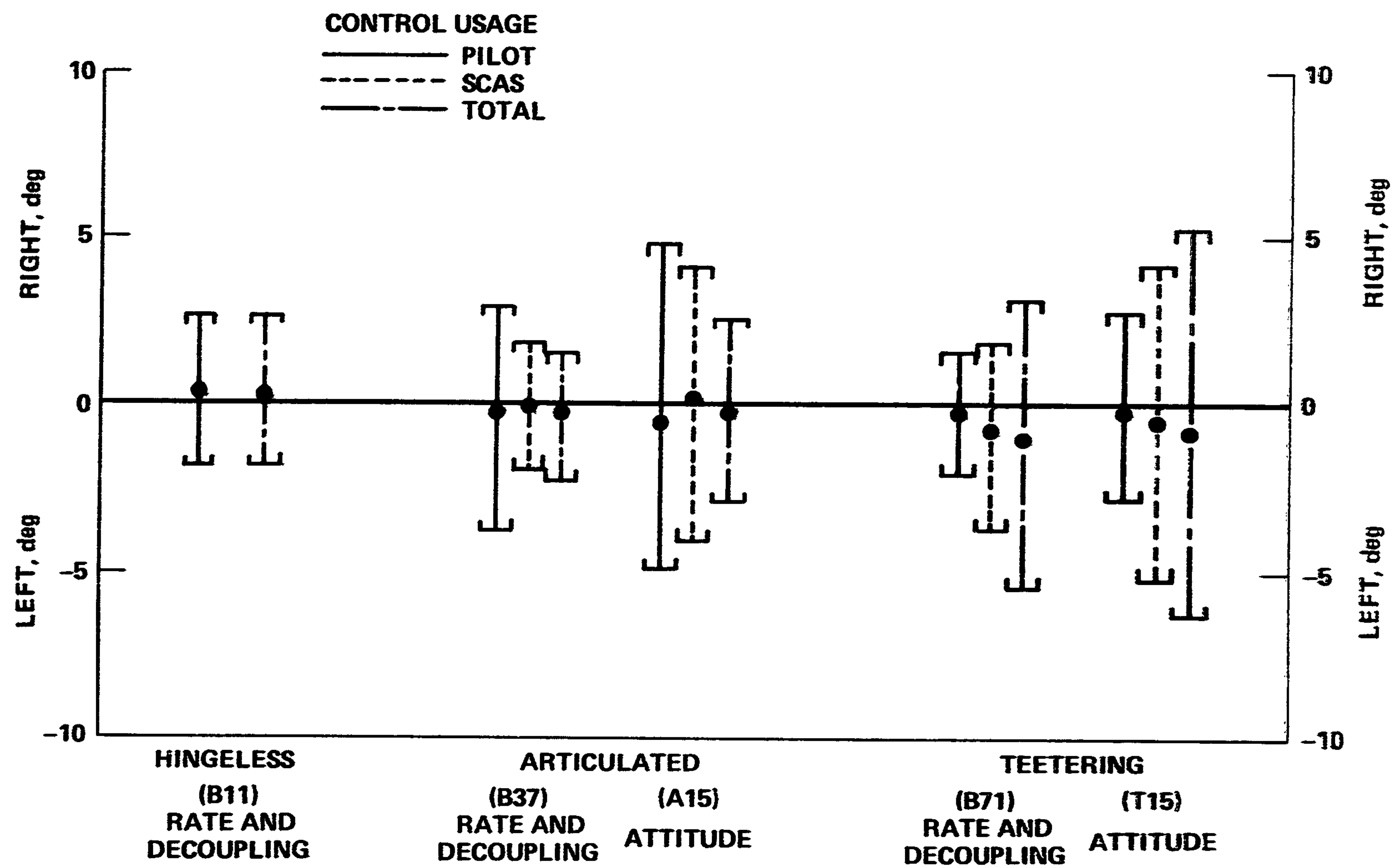


Figure 19.— Pitch and roll control usage for three basic aircraft.



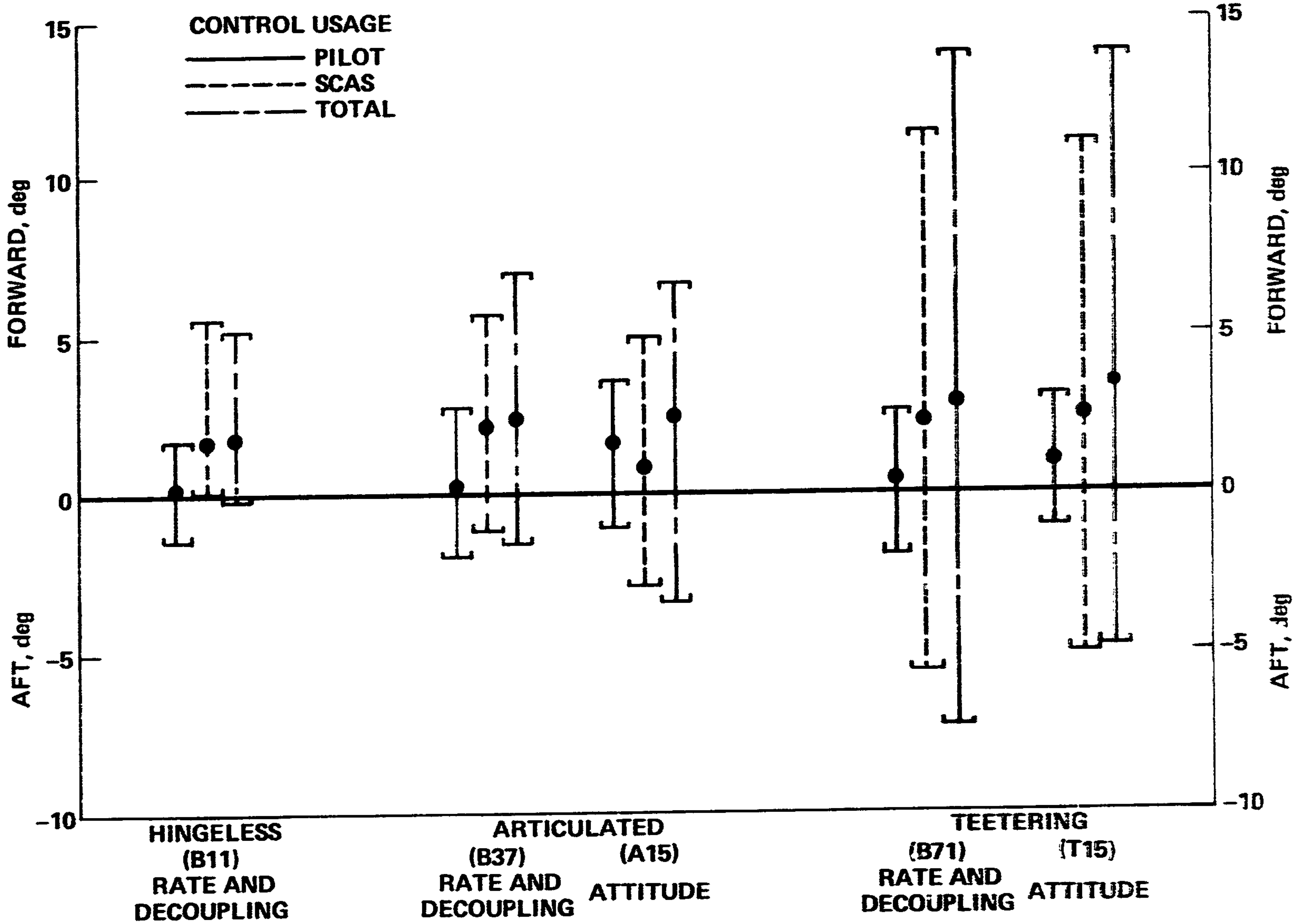
(a) Pitch control usage.

Figure 20.– Pilot A pitch and roll control usage (expressed in terms of swashplate displacement).



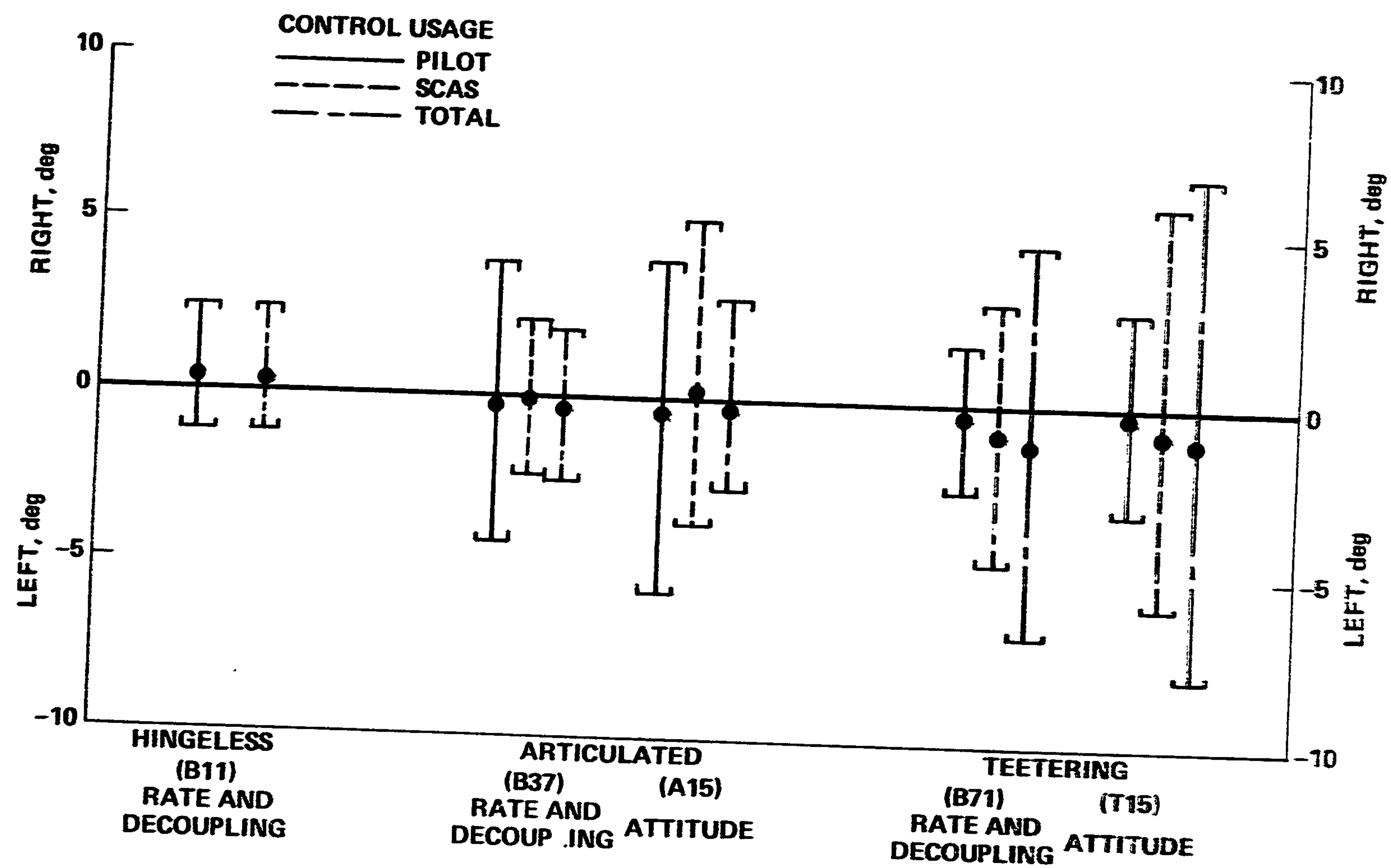
(b) Roll control usage.

Figure 20.— Concluded.



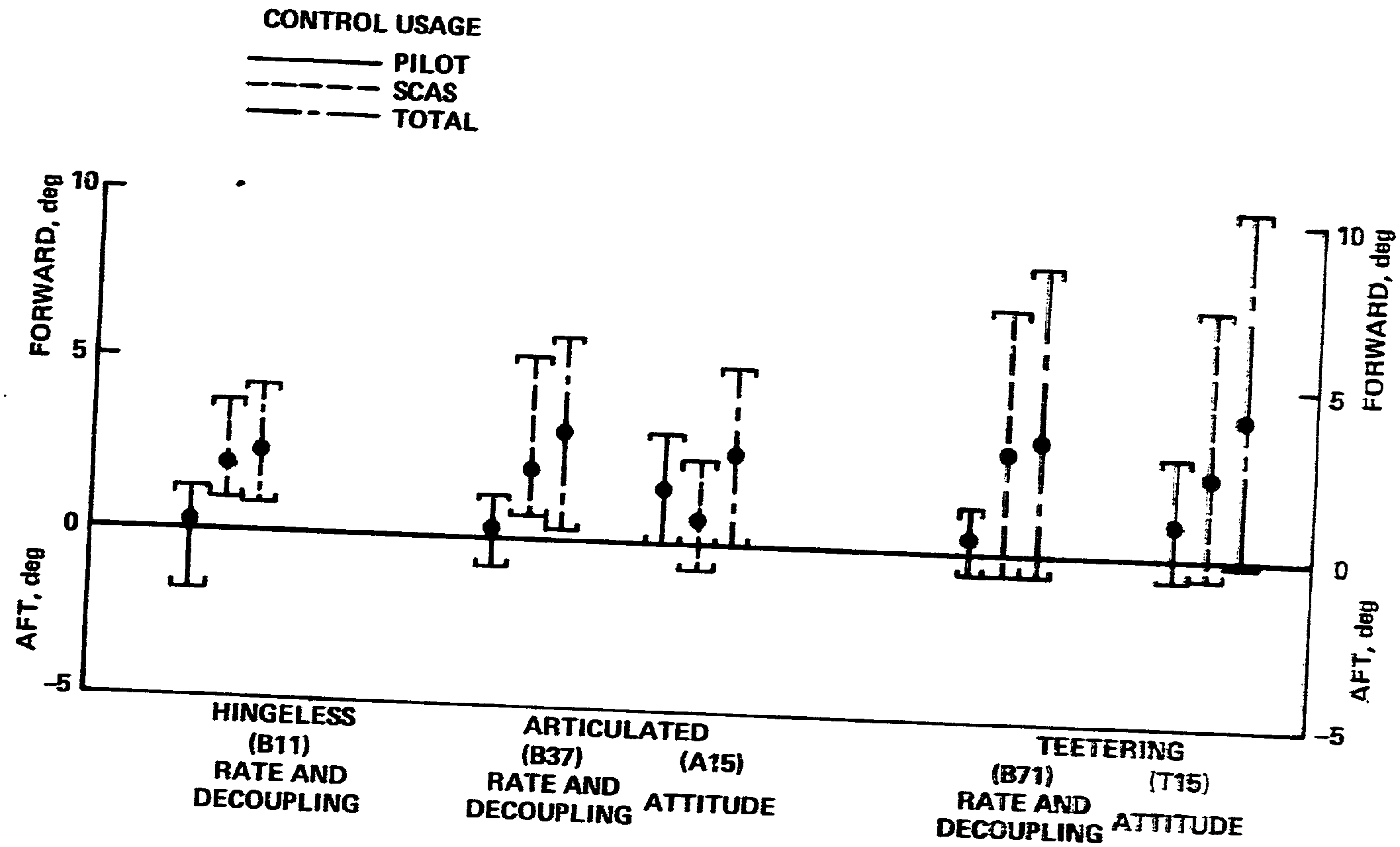
(a) Pitch control usage.

Figure 21.— Pilot B pitch and roll control usage (expressed in terms of swashplate displacement).



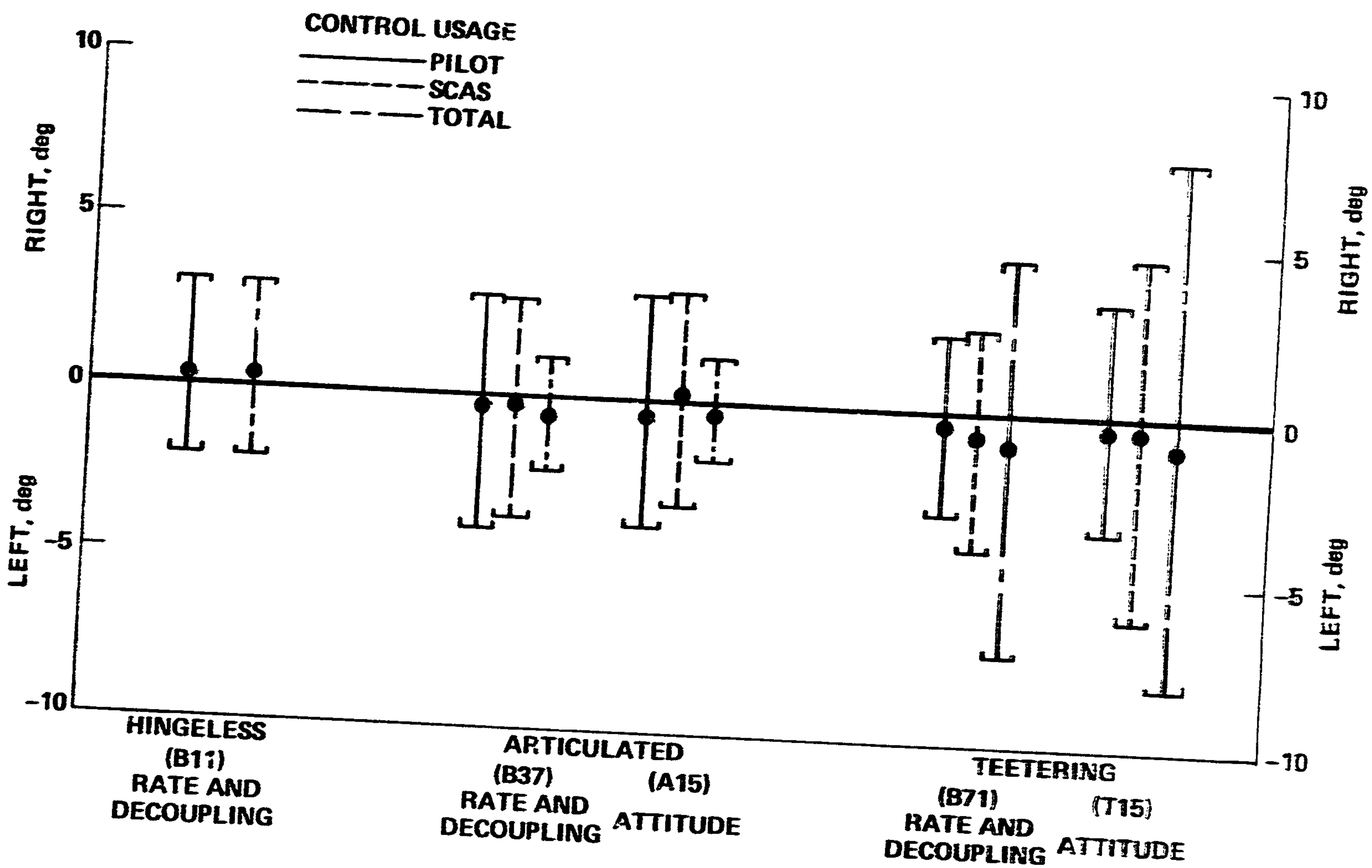
(b) Roll control usage.

Figure 21.– Concluded.



(a) Pitch control usage.

Figure 22.— Pilot C pitch and roll control usage (expressed in terms of swashplate displacement).



(b) Roll control usage.

Figure 22.– Concluded.

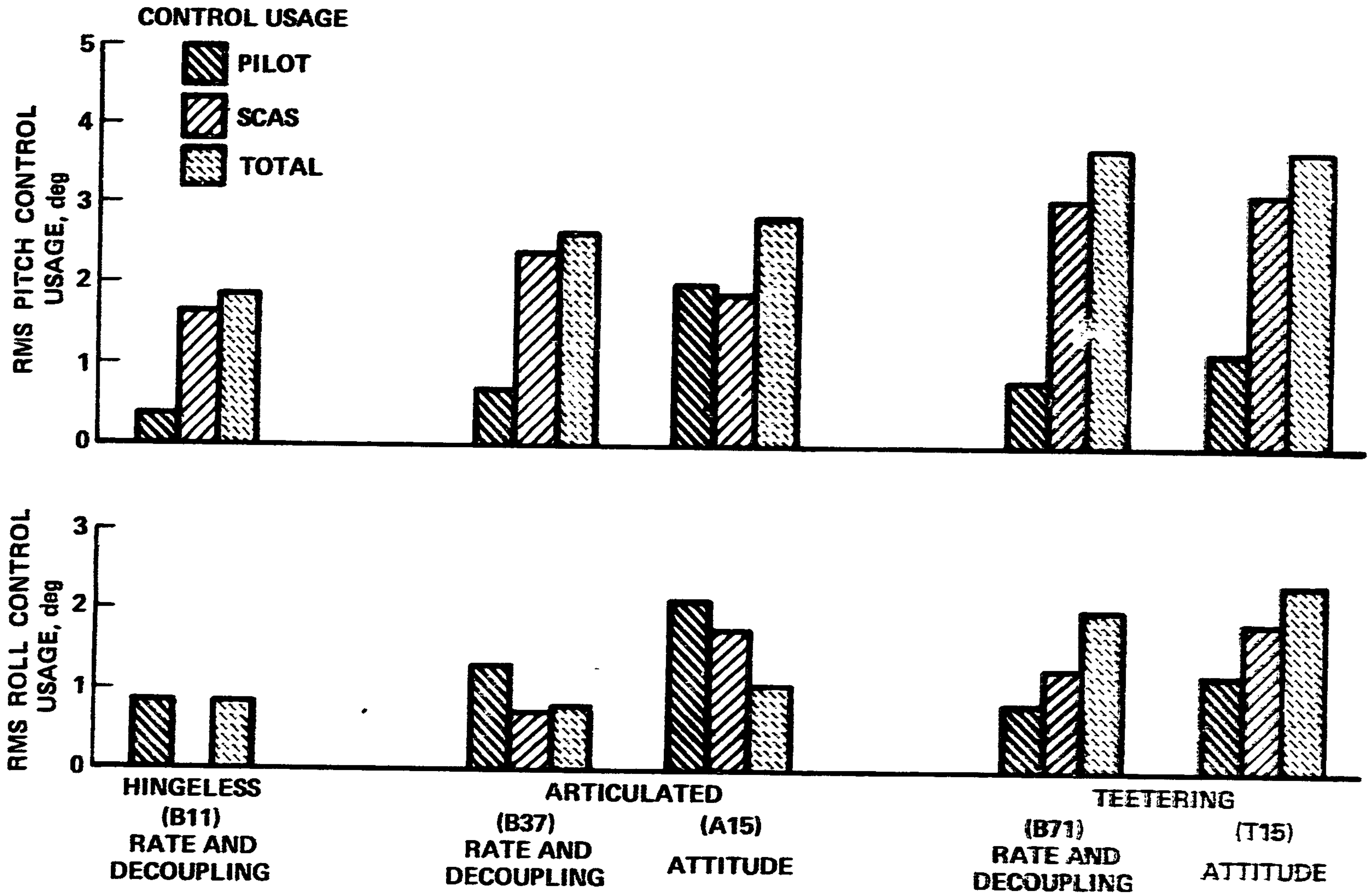


Figure 23.– Pilot A control usage (expressed in terms of rms swashplate displacement).

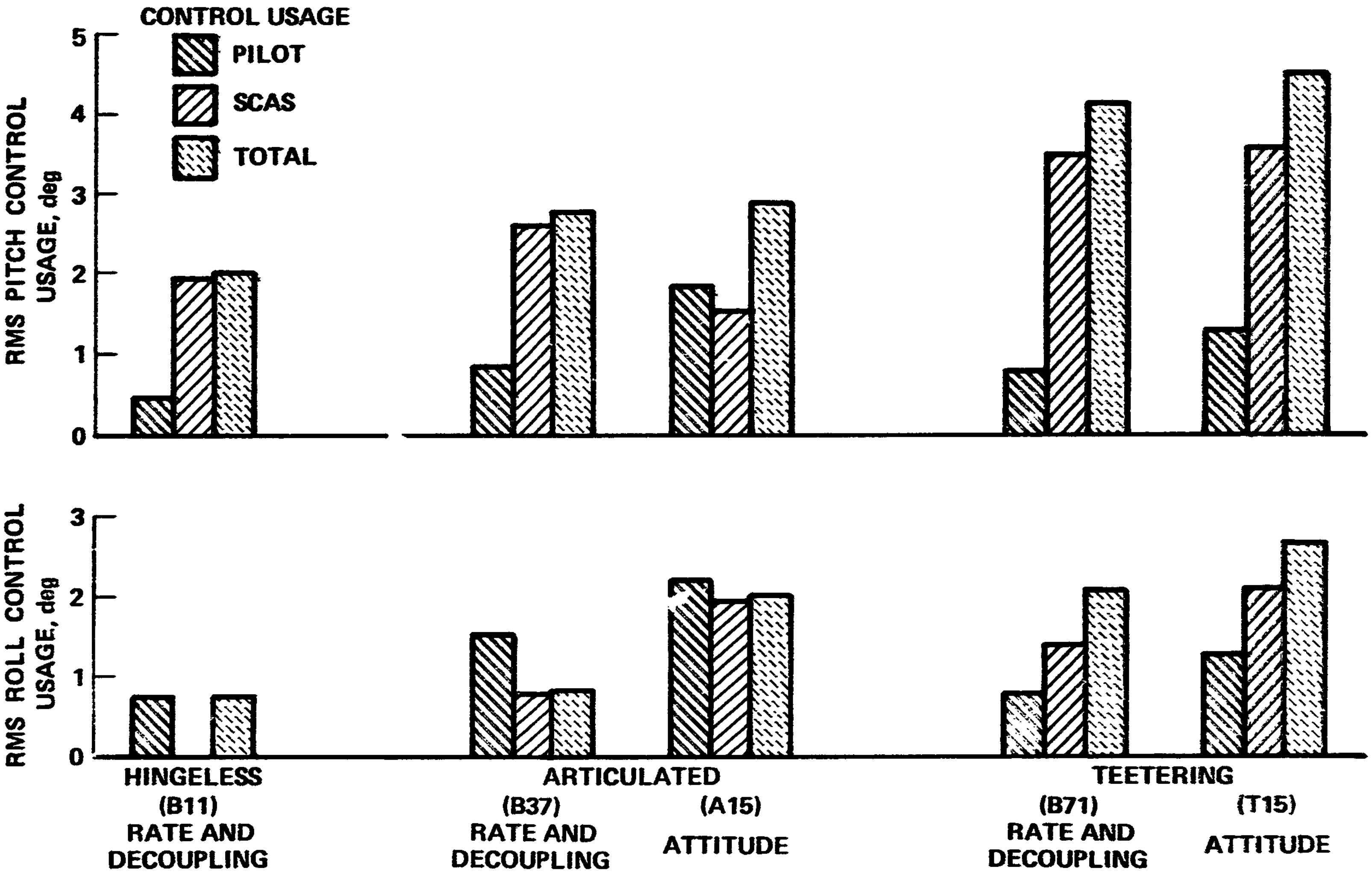


Figure 24.— Pilot B control usage (expressed in terms of rms swashplate displacement).

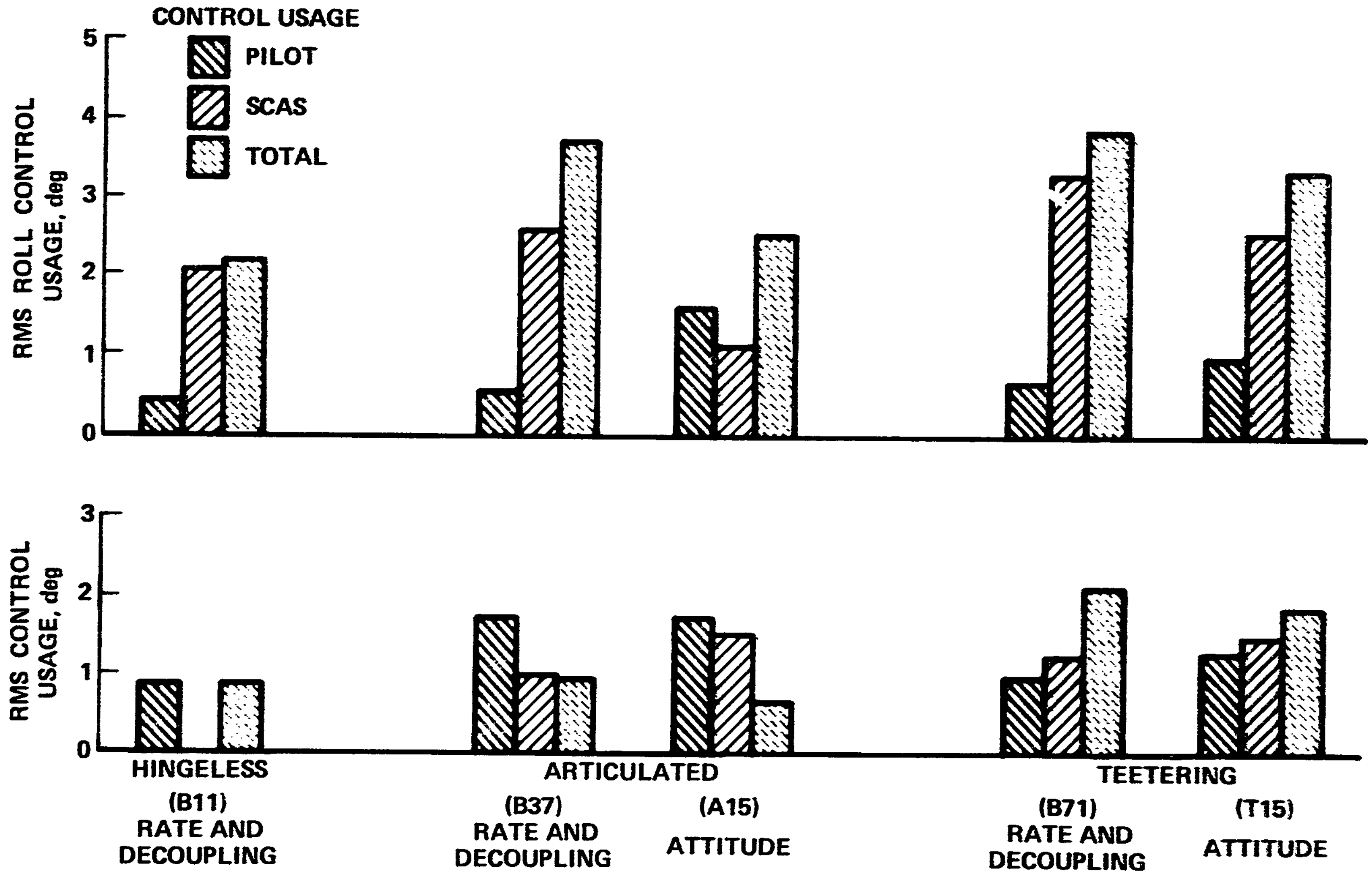


Figure 25.— Pilot C control usage (expressed in terms of rms swashplate displacement).