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SYMBOLS

a	blade lift-curve slope
a_1	longitudinal first-harmonic flapping coefficient, rad
B_{1C}	longitudinal cyclic pitch, rad (or deg)
b_1	lateral first-harmonic flapping coefficient, rad
c	blade chord, m
e	flapping hinge offset, m
h_{hub}	rotor hub, height above aircraft center of gravity, m
I_β	blade moment of inertia about flapping hinge, kg-m^2
k_1	pitch-flap coupling ratio, $\triangleq \tan \delta_3$
k_β	flapping hinge restraint, N-m/rad
$L_{B_{1C}}$	rolling moment due to longitudinal cyclic input, rad/sec^2/deg
L_p	rolling moment due to roll rate (roll damping), (sec)$^{-1}$
L_q	rolling moment due to pitch rate, (sec)$^{-1}$
L_{δ_a}	rolling moment due to lateral stick input, rad/sec^2/cm
$M_{B_{1C}}$	pitching moment due to longitudinal cyclic input, rad/sec^2/deg
M_p	pitch moment due to roll rate, (sec)$^{-1}$
M_q	pitch damping, (sec)$^{-1}$
M_w	pitching moment due to change in vertical velocity, (m-sec)$^{-1}$
M_β	blade weight moment about flapping hinge, N-m
M_{δ_c}	pitching moment due to collective stick input, rad/sec^2/cm
M_{δ_e}	pitching moment due to longitudinal stick input, rad/sec^2/cm
p	aircraft roll rate, rad/sec
q	aircraft pitch rate, rad/sec

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R	rotor radius, m
V	true airspeed, m/sec
Z_w	vertical damping, $(\text{sec})^{-1}$
γ	Lock number, $\triangleq \frac{(\rho a c R^4)}{I_\beta}$
δ_3	pitch-flap coupling, deg; nose-down feathering with increased flapping is positive
δ_a	lateral stick deflection, cm
δ_c	collective stick deflection, cm
δ_e	longitudinal stick deflection, cm
δ_p	pedal deflection, cm
ε	$\frac{e}{R}$
θ	pitch attitude, rad (or deg)
θ_1	total blade twist (tip with respect to root), deg
ρ	air density, kg/m^3
σ	rotor solidity ratio
ϕ	roll attitude, rad (or deg)
Ω	rotor-system angular velocity, rad/sec

ABBREVIATIONS

NOE	nap-of-the earth
PIO	pilot-induced oscillation
SPSP	short period stability parameter

EFFECTS OF ROTOR PARAMETER VARIATIONS ON HANDLING QUALITIES OF UNAUGMENTED HELICOPTER IN SIMULATED TERRAIN FLIGHT

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SUMMARY

A coordinated analysis and ground simulator experiment was performed to investigate the effects on single rotor helicopter handling qualities of systematic variations in the main rotor hinge restraint, hub hinge offset, pitch-flap coupling, and blade Lock number. Teetering rotor, articulated rotor and hingeless rotor helicopters were evaluated by research pilots in special low-level flying tasks involving obstacle avoidance at 60-100 knots airspeed. The results of the experiment are in the form of pilot ratings, pilot commentary and some objective performance measures. Criteria for damping and sensitivity are reexamined when combined with the additional factors of cross-coupling due to pitch and roll rates, pitch coupling with collective pitch and longitudinal static stability. Ratings obtained with and without motion are compared.

Acceptable flying qualities were obtained within each rotor type by suitable adjustment of the hub parameters; however, pure teetering rotors were found to lack control power for the tasks. A limit for the coupling parameter $|L_q/L_p|$ of 0.35 is suggested.

INTRODUCTION

Current tactics which make use of helicopters as an integral part of ground forces anticipate their use against armor and as a defense for attack helicopters employed against friendly forces. A strong emphasis has been placed on flying at low altitude to take advantage of concealment afforded by vegetation and variations in terrain height.

By U.S. Army definition in Field Manual 1-1 (ref. 1), terrain flying includes the following modes of flight:

1. Low Level – Flight conducted at a selected altitude, generally over a straight route, to minimize or avoid detection or observation. Airspeed and indicated altitude remain constant.

2. Contour – Flight at low altitude conforming generally and in close proximity to the contours of the earth. Airspeed and altitude vary as vegetation and obstacles dictate.

3. Nap-of-the-Earth (NOE) – Flight as close to the earth's surface as vegetation or obstacles permit, while generally following the earth's contours. Airspeed and altitude are varied and routes are weaving and devious.

To take maximum advantage of the cover and concealment afforded by the terrain and vegetation, NOE flight has been characterized by extremely low and slow flight. At Fort Rucker, Alabama (the Army Aviation Center), NOE is literally flown in and among the trees and is characterized by weaving through the tree tops at speeds too slow to register on the airspeed indicator out to perhaps 20 knots indicated airspeed.

The flying tasks associated with terrain flying place strong demands on the maneuvering and precision control capabilities of the helicopter and have raised questions concerning the flying qualities needed for such tasks and the means to achieve them. Among those characteristics found to be desirable are: (1) adequate control power at all levels of load factor encountered in maneuvering flight (positive as well as negative); (2) a proper balance of damping and control sensitivity in roll and pitch; and (3) an absence of coupling between axes resulting either from control inputs or motions of the aircraft. If these characteristics are to be achieved without stability augmentation they must be obtained entirely through variations in main and tail rotor design and other physical parameters which have a direct influence on the vehicle's stability and control characteristics. Obtaining a satisfactory level of flying qualities without stability and control augmentation is desirable from the standpoint of both cost and reliability.

The main rotor's contribution to the helicopter's dynamic behavior is substantial: Through variations in the design of the hub and blades, large changes in parameters which directly affect flying qualities such as control power and damping can be obtained. These changes are quite limited in the case of a pure teetering rotor, which derives its control moments entirely through tilt of the main rotor thrust vector about the hub. At the low g-levels encountered in maneuvering flight, the low thrust levels during transient maneuvers result in a serious reduction in available control power. The main rotor's contribution to pitch and roll damping is derived from its flapping response to aircraft pitch and roll rates. This response offsets the thrust vector and generates moments that are proportional to the blade Lock number, γ, so that the helicopter roll and pitch damping are correspondingly influenced. In the case of the teetering rotor, however, both the absolute magnitude and the range of the damping that can be obtained are limited.

Hingeless rotors and rotors with offset flapping hinges are capable of generating hub moments that add to and can be much larger than those available from thrust tilt alone. Consequently, they are capable of providing greatly augmented control power and damping to the helicopter. Similar increases can be obtained by stiffening the flapping hinge of teetering or offset hinge rotors. These direct benefits are attended by increases in coupling terms such as rolling moments due to pitch rate and an unstable contribution to the angle of attack stability term, M_w, which may have undesirable effects on the handling qualities of the helicopter.

To understand the effects of these physical parameters on flying qualities in the context of terrain flight, a coordinated analysis and ground-based simulation experiment was undertaken. The general objective of this experiment was to make an initial exploratory investigation of the terrain flight regime to provide a contribution to the understanding of single-rotor, unaugmented helicopter handling qualities. A more specific goal was to help clarify the relationship between variations in the design of certain important features of main rotor geometry and the resulting handling characteristics. The results of the analytical study, as reported in reference 2, illustrate the influence of the major rotor design features — flapping hinge offset, flapping hinge restraint, blade Lock number, and pitch-flap coupling — on the helicopter stability and control characteristics that were expected to significantly influence handling qualities, namely pitch and roll control effectiveness and damping, pitch-roll cross coupling, vertical damping and collective-yaw coupling. This information provided a basis for selecting values of the design parameters so as to appropriately vary the stability and control characteristics for evaluation in the simulation experiment. The evaluation was both qualitative, through subjective pilot assessments, and quantitative, through the effects of these parameters on important derivatives known to have a fundamental bearing on control responses or aircraft stability.

The simulation experiment had three specific objectives. In an earlier study (ref. 3), Edenborough and Wernicke had proposed desirable ranges for the damping and sensitivity in pitch and roll of the helicopter for NOE operations. Their work, like this, considered NOE to be mainly contour flying as it is currently defined. One objective of this study was to investigate combinations of damping and sensitivity considerably beyond the ranges discussed in reference 3 in order to have a thorough mapping of the damping-sensitivity plane in terms of pilot ratings, each point being directly identifiable with a specific set of rotor system design parameters. The criteria of reference 2 are illustrated in figures 1 and 2 from which the dominant influences of hinge restraint, hinge offset and Lock number on sensitivity and damping, as identified in reference 2, can also be seen. Configurations associated with this test objective were established by selecting appropriate combinations of the three noted design parameters.

A second objective was to investigate the effects of coupling due to aircraft pitching and rolling rates (L_q, M_p) on helicopters which otherwise had good damping-sensitivity characteristics. This would help determine what levels of coupling were noticeable and objectionable in these flying tasks. Figure 3 presents an example from reference 2 that shows that the influence on pitch-roll coupling of hinge offset in combination with Lock number. It is evident that wide variations of coupling are associated with these rotor parameters. For an equivalent flapping frequency, the contribution of hinge restraint is similar but less pronounced than that due to hinge offset. Of course, cross-coupling due to cyclic control inputs can be altered through appropriate phasing of pitch and roll cyclic pitch.

The third objective was to determine if the angle of attack instability associated with stiff-hinged rotors in forward flying was objectionable for the speeds and tasks flown. Whether or not it is beneficial to add a large enough amount of pitch-flap coupling (δ_3) to neutralize the angle of attack instability was also examined. Pitch-flap coupling also contributes to pitch and/or roll damping (fig. 4) and to pitch-roll coupling (fig. 5).

The four design parameters were varied over a broad range to simulate different rotor systems on a common fuselage, tail rotor and empennage. Based on the analysis, 44 helicopter configurations representing teetering, articulated and hingeless rotors were selected and evaluated in special tasks designed to be representative of terrain flight. The initial part of the experiment was performed with two research pilots on a fixed-base simulator, and a summary of the results was reported in reference 4.

A follow-on experiment was also performed on a large motion base simulator with selected configurations from the initial experiment that were evaluated as having particularly good or particularly bad handling qualities. This simulation permitted subjective evaluations of the same configurations to be made consecutively with and without motion.

This report discusses the results of the initial experiment and extends the results to cover the comparative evaluations of six selected configurations on the motion base simulator. Since a large range of rotor system types could be examined in a relatively short period of time, it was expected that some general conclusions could be reached regarding the best flying qualities of an unaugmented helicopter. It was also planned that the experiment would help establish a good basis for choosing the kinds of augmentation systems that are most desirable for terrain flying tasks.

EXPERIMENT DESIGN

Configuration Test Matrix

The test configurations that were evaluated consisted of three main groups and two subgroups of specially modified configurations. The three main groups are referred to for convenience as teetering (two-bladed, hinge offset zero, spring restraint variable), articulated (four-bladed, hinge offset 5%, spring restraint variable), and hingeless (four-bladed, hinge offset and spring restraint variable). Characteristics of the configurations are shown in table 1. Each main group was further subdivided into sets of three with Lock numbers of 3, 6 and 9 within the set. One of the three sets of both the teetering and articulated rotors was a pure example of the type; the other two had increasing amounts of spring restraint added about the flapping hinge in such a way as to maintain the value of augmented rotating natural flapping frequency constant within the set. The spring restraint greatly augmented the hub moment available for maneuvering compared with the pure teetering or articulated rotors. The "hingeless" rotors were approximated by an equivalent hinge offset and spring restraint, also keeping the flapping frequency constant within each set of three Lock numbers. Natural flapping frequencies varied from a minimum of 1.0 Ω for the pure teetering rotor to 1.14 Ω for the stiffest rotor within each group.

By adjustment of the control gearing, a broad range of vehicle damping and control sensitivities was achieved with these 27 different rotor types as shown in figure 6. Within these types, large variations in coupling existed, notably roll coupling due to pitch rate, pitch coupling due to roll rate, and pitch coupling due to collective pitch inputs. In this experiment control cross-coupling (e.g., rolling moments due to longitudinal control inputs), which occurs with offset or stiffened flapping hinges, was eliminated by control crossfeed.

To evaluate the effects of coupling due to roll and pitch rates while holding damping and sensitivity constant, four sets of three configurations were selected from the main group. The ratio of damping to control sensitivity was made constant by adjustment of the inertia and control gearing of each configuration as shown in figure 6. The ratio was selected to lie midway between the range suggested as optimum by Edenborough in reference 3. Within each set of three configurations the damping in roll and pitch was approximately constant, but the coupling parameters L_q and M_p varied significantly, so that the effects of coupling could be evaluated separately.

The last group consisted of configurations with significant values of unstable pitching moment due to angle of attack, to which a sufficiently large value of pitch-flap coupling was added to make this derivative zero or slightly negative. Gearing and inertia were also adjusted to keep the ratios of damping to control sensitivity constant for each of these configurations.

Helicopter Math Model

The helicopter math model (ARMCOP) developed for this simulation consisted of equations for the separate aerodynamic force and moment contributions of the main rotor, tail rotor, fuselage, fin, and horizontal stabilizer. The aerodynamics of the fuselage and empennage and the inertias were based on characteristics of the AH-1G "Cobra" helicopter. Equations for the fuselage were based on those presented in reference 5. Equations for the fin and horizontal stabilizer were adapted from standard equations for isolated wings of medium aspect ratio. No interference effects were included except those due to main rotor downwash on the horizontal stabilizer and tail rotor inflow on the vertical fin.

The tail rotor model included three orthogonal forces with a quasi-static representation of flapping.

The model of the main rotor (ref. 6) was derived from a linearly twisted rigid blade with flapping degree of freedom only, having an offset flapping hinge with a spring restraint about the flapping hinge. Rotor speed was assumed constant. Inflow was assumed constant across the disk, and reverse flow, stall and compressibility effects were ignored. A set of differential equations was used to represent the dynamics of the three degrees of freedom of rotor tip path plane motion – coning, longitudinal and lateral flapping. The tip path plane dynamic equations are identical to the flapping equation of a three-bladed rotor system in nonrotating coordinates with periodic terms dropped. The effects of aircraft angular rates and accelerations were included in the derivation of the flapping equations, as described in reference 6. The rotor forces and moments incorporated terms due to flapping rates, accelerations, and flapping angles.

A limited attempt was made to validate the simplified generic math model (ARMCOP) for this study. The constants of the generic math model representing helicopter geometry and aerodynamic characteristics were changed to those for a UH-1H, OH-6, and BO-105, representing, respectively, a teetering, an articulated, and a hingeless rotor helicopter. The trim attitudes, control positions, stability and control derivatives, and eigenvalues were then compared with existing calculated data for these helicopters. Figure 7 shows a comparison of the aircraft trim attitudes and control positions calculated from ARMCOP and C-81 for a UH-1H aircraft. The collective stick and pedal positions matched reasonably well, but the aircraft pitch and roll attitudes and the longitudinal and lateral stick positions show some discrepancy in the two computer simulations. Some major stability and control derivatives from C-81 and ARMCOP are compared in table 2 along with those of a Bell 205 model obtained from flight data using a parameter identification procedure (ref. 7). These comparisons show that derivatives exhibited by the ARMCOP model are comparable to those obtained from other reliable sources. Reasons for individual discrepancies have not been pursued. It is believed that variations of these values, with center-of-gravity changes for the ARMCOP model, are similar to variations obtained from other sources also. Figure 8 shows a comparison of eigenvalues of the six-degree-of-freedom rigid body modes from C-81 and ARMCOP at 60 knots. The basic characteristics of having three pairs of complex roots and two real roots associated with a typical basic teetering rotor helicopter are present, but some slight discrepancies in frequency of the oscillatory modes exist in the two computer simulations.

The ARMCOP generated data for simulation of BO-105 configuration generally matched well with Boeing-Vertol data (ref. 8). The trim attitudes and control positions are shown in figure 9 to have good agreement. A comparison of major derivatives at 60 knots is shown in table 3. The significant coupling from collective to pitching moment for hingeless rotor helicopters at forward flight does exist in both computer simulations. The coupled six DOF rigid body eigenvalues are shown in figure 10. Some discrepancy in frequency between the two computer simulations does exist, but the basic characteristics of two pairs of complex roots and four real roots are consistent.

For the articulated rotor helicopter configuration, the ARMCOP simulation of the Hughes OH-6A also matched reasonably well with the Hughes data (ref. 9).

Simulation Facility

Due to facility limitations, simulation fidelity was less than desired for NOE tasks as follows: limited helicopter math model in the very low speed region; field of view restrictions, both to the sides and downward; two-dimensional perception of obstacles and clearances; scaling; and lack of rotor disk perception. Within the capabilities of the simulators and visual facilities, a compromise had to be made and tasks were designed to evaluate the agility of the helicopter. The result was a combination of NOE and contour flight at higher speeds and altitudes than those normally associated with pure NOE.

The major part of this study was performed on a fixed-base simulator. The simulator cab consisted of a Bell UH-1A forward fuselage section having the original helicopter control system, including hydraulic actuators at the swashplate (fig. 11). The force displacement characteristics, force-release feature and magnetic brake trim system of the pedals and cyclic control stick were therefore identical to those of the UH-1A. The pilot's instrument panel is shown in figure 12. Torque pressure and percent RPM were not required since constant rotor speed was assumed for the simulation model. Little reference was made to instruments in this task since the pilot's attention was constantly focused outside the cockpit. This is representative of NOE flight as practiced by the U.S. Army. For the motion experiment, the Flight Simulator for Advanced Aircraft (FSAA) was used.

The FSAA (fig. 13) is described in detail in reference 10. The cab is normally configured for fixed-wing transport-type aircraft. For this experiment the right-hand seat was provided with helicopter controls and a basic set of instruments (fig. 14) consisting of an altimeter, rate-of-climb, radio compass indicator, attitude-director indicator, turn and bank, airspeed, and engine torque. The pilot's visual display is a color TV monitor with a 420 scan line capability, placed behind a collimating lens that both magnifies the image and makes it appear at infinity.

The collective stick was provided with sufficient static friction to overcome its weight moment about the rotational axis and had light frictional resistance to motion with no force gradient. The force-feel characteristics of the cycle stick and pedals were provided by a McFadden electro-hydraulic unit with adjustable breakout, static gradient and viscous damping values. The gradients and control travels are shown in table 4. Viscous damping was adjusted until it appeared satisfactory to the pilots. A force-release switch on the panel enabled the stick to be moved without force gradients and allowed the helicopter to be retrimmed in a manner analogous to the magnetic brake system on a UH-1H helicopter.

The simulator linear motion travel limits are ±1.05 m longitudinally, ±12.19 m laterally, and ±1.28 m vertically. A complete description of the motion logic is given in reference 10. The general objective of the motion logic is to present as faithful a reproduction of the helicopter linear accelerations and angular accelerations and rates to the pilot as possible.

A Redifon visual system was used with a rear-projection system which presented a 48° horizontal by 36° vertical color television scene on the back of a translucent screen placed 3.66 m in front of the pilot's window. The terrain model was scaled 1:400 and was based on a section of Hunter-Liggett military reservation in central California. It has natural features such as hills, river beds, and wooded areas combined with roads, telephone poles, vehicles, and other man-made objects to help create some kind of reference scale for the viewer. Three special obstacle courses were placed on the model to create repeatable terrain flying tasks for the pilots. A sketch of the course layout is shown in figure 15 and a photograph of part of the courses is shown in figure 16.

The longitudinal or hurdles course consisted of barriers 15 m high spaced irregularly from 213 to 416 scale meters at 1:600 scale. (The motion was scaled 1:600 for this part of the experiment to give an adequate course length and flying time for the evaluations.) The course was designed to focus attention on the longitudinal flying qualities of the helicopter, emphasizing pitch and vertical flightpath control.

The lateral-directional or slalom course was a straight line of trees spaced similarly to the barriers, requiring the pilots to fly a curving s-path alternating left and right around successive trees to negotiate the course, emphasizing lateral-directional flying qualities.

Trees were placed down the centerline of a second set of barriers to form a third course combining the flightpath variations of the other two, referred to as the combination course.

Except for details, the equipment and procedures of the motion experiment were the same as for the fixed-base experiment. The combination course created from the longitudinal course by placing the trees from the slalom course down its centerline was used for the comparative evaluations. The visual motion scaling was changed from 1:600 to 1:400, so the motion scaling and terrain model scaling were properly matched. The pilots felt that the subjective impressions of speed and altitude were then more like the instrument indications. At this scale the barriers were 10 m high and spaced between 142 and 284 m apart.

Task Description

Two research pilots were used for evaluating all configurations on the fixed-base simulator. Pilot A had a majority of hours in conventional and V/STOL aircraft and approximately 800 hr of helicopter time. Pilot B had a fixed and rotary wing background which included over 1500 hr in helicopters of many types. Both pilots had participated in numerous helicopter and fixed-wing simulator and variable stability aircraft experiments Each pilot was required to fly each configuration through the three courses and give a separate evaluation for each course. In each instance, the initial condition was 40 knots level flight at approximately 18 m above ground level. The instructions to the pilots were to fly "as fast as possible and as low as possible" through the course. The longitudinal course was flown first, the lateral-directional second, and the combination last in order to allow concentration on one set of aircraft axes at a time before attempting a coordinated task.

Two additional pilots participated in the motion phase of this experiment. Pilot C had over 200 hr in helicopters including combat experience and preliminary Army evaluations of prototype helicopters. Pilot D had over 2300 hr in helicopters in a variety of utility missions with some flight test experience in addition. Both pilots also had a large amount of fixed-wing time. The initial condition of the course for the motion experiment was 60 knots level flight at approximately 35 m above ground level.

Prior to each test period, a few minutes of familiarization were allowed each pilot. Also, each pilot was allowed a trial run on each configuration away from the course to get a general impression of its flying qualities independently of the task. Thus, each pilot was individually familiar with the configuration before a final rating was assigned. After completing the course, a pilot rating was given for the task. General and specific comments were written on a pilot questionnaire (table 5), and voice comments were recorded.

The main group configurations were not presented to the pilots in any specific order. For the subgroups (coupling and δ_3 evaluation) configurations related by common values of damping and sensitivity were given as a sequence of three so that effects of the parameter varied could be directly compared.

The Cooper-Harper handling qualities rating scale (fig. 17) was used to rate the helicopter and task combinations.

RESULTS OF EXPERIMENT

Effects of Damping and Sensitivity Variations in Pitch and Roll Axes

The ratings assigned by each pilot to the main group of configurations, for the longitudinal and lateral-directional tasks, are shown with the associated values of helicopter damping and sensitivity in figure 18. "Acceptability" boundaries from two references are also shown. The "satisfactory" region for NOE (actual, contour) operation suggested in reference 3 is shown by dashed lines. The upper and lower boundaries correspond to fixed ratios of control sensitivity to damping and also to fixed values of steady-state rate response of an idealized first order system to a unit control input. The lower horizontal boundary is a minimum damping value cutoff.

Despite the broad range of sensitivity and damping investigated, the ratings of the pilots did not show a corresponding wide variation. For pilot A, satisfactory ratings were obtained well outside the boundaries suggested by reference 3. Pilot B's ratings were 4.0 or greater for the lateral-directional task, and some configurations with damping-sensitivity values outside of the boundaries received better ratings than those within the boundaries.

Pilot rating is plotted versus L_p/L_{δ_a} in figure 19. These data alone would suggest that, for this kind of task (lateral-directional), the ratio of damping to sensitivity does not have a primary effect on the handling qualities. Pilot A found acceptable configurations across the entire range of

L_p/L_{δ_a} values tested; pilot B's ratings seem equally insensitive to this ratio.

The pilot ratings for the longitudinal and lateral-directional courses are plotted versus damping and sensitivity in figures 20 through 23. The pilot ratings do not correlate well with control sensitivity for either task. For pilot A, the longitudinal task ratings appear to be consistently good when M_q decreases below about -3.0 $\sec^{-1}$, but since pilot B's ratings do not show similar behavior, the result may be fortuitous. Pilot A's ratings for the lateral-directional task seem to indicate a consistent variation with L_p, with an optimum range for L_p between -10 and -25 $\sec^{-1}$. Pilot B's ratings are a little lower in the same range than at the extremes of the test L_p values, but the influence of L_p is not as convincing as pilot A's results suggest.

In general there was a lack of agreement between the two pilots in the numerical ratings that were assigned to the main group of helicopter configurations, whose characteristics were varied so as to cover a broad range of damping and control sensitivity combinations. One reason is that each pilot used different evaluation criteria for his numerical ratings.

Pilot A used the criteria of maneuverability and suitability of the helicopter as a gun platform. His ratings reflected pilot compensation required to correct deficiencies such as low control power, overcontrol tendency, cross-coupling, or low stability. A rating of 8 or greater reflected a controllability problem or near collision; ratings from 5 to 7 indicated high workload; ratings from 2 to 3, a good gun platform. He felt his extreme ratings were most significant.

Pilot B looked for agility and precise control while flying at maximum speeds and lowest tolerable altitudes. His perception of exaggerated pitch coupling due to collective pitch consistently biased his pilot ratings by 1 to 2 rating points toward unacceptable. The resulting longitudinal cyclic pitch changes to correct the coupling overshadowed inputs required for speed changes. The coupling affected performance of the lateral-directional and combination tasks as well.

The pilot comments indicate an awareness of the helicopter's damping and sensitivity and are more in agreement than the numerical ratings. Factors affecting the ratings and a comparison of pilot comments are discussed in a special section on pilot comments. To ascertain whether the subjective impressions represented by the written comments were relatable to the sensitivity and damping of the helicopters, the configurations with a common characteristic description were plotted on sensitivity-damping plots similar to those used to show pilot opinion ratings (figs. 24 and 25). The categories plotted are low sensitivity-sluggish, too sensitive, low damping, and adequate-to-good handling qualities.

There is substantial agreement between the two pilots about the low sensitivity-sluggish configurations, especially in the roll axis. Most of those so noted had very low ratios of sensitivity to damping and consequently a very low steady-state rate response per unit of stick deflection. These results, while qualitatively in agreement with the Edenborough criterion, indicate that the upper boundary is too conservative. Those combinations of damping and sensitivity, substantially to the left of the upper boundary and also too near the corner of the damping-sensitivity plot, are to be avoided.

Fewer configurations were criticized for being too sensitive in roll and pitch. Pilot A made reference to high sensitivity more frequently than pilot B, especially in pitch. Only the configurations with the highest values of sensitivity to damping ratio, or very low values of damping and sensitivity, were so described. For these tasks, both pilots seemed to prefer a very responsive helicopter to one that appeared to be unresponsive or having low control power. Those configurations that were described as having low damping exclusively or in addition to other qualities are shown as filled symbols. These points emphasize the need for adequate pitch and roll damping and, in the case of roll, that a higher value of damping than that called for by the Edenborough criterion may be acceptable.

Those configurations that were either called good or deemed to be adequate by the lack of negative comments are also shown for reference. As was indicated by the pilot opinion ratings, they are found over a rather broad range of sensitivity and damping and often near clearly undesirable configurations. In pitch, both pilots seemed to find sensitivity to damping ratios in the region of the Edenborough criterion or lower to be adequate. In roll, both pilots found adequate configurations with higher and lower sensitivity to damping ratios than the criterion. Pilot B, in particular, did not object to those helicopters with the highest ratios of sensitivity to damping.

These results indicate that the damping-sensitivity region for satisfactory handling qualities is broader than that indicated in reference 3. Because unsatisfactory ratings were obtained even within the boundaries and some very unsatisfactory ratings were found immediately adjacent to satisfactory ratings, factors other than damping and sensitivity were evidently significant to the pilot's perception of the flying qualities.

Both pilots found the pure teetering rotor ($K_\beta = 0$) configurations to be unacceptable and substantiated these ratings with comments criticizing primarily the lack of control power, the low sensitivity and damping, and the low agility. With this exception, no particular type of rotor system (augmented teetering, offset hinge and hingeless) was found to be uniformly superior to any other.

The lack of a clear preference for any one type of rotor system is surprising since the hingeless rotor was acclaimed at its inception for its superior flying qualities. Part of the reason for its acceptance seems to have been the extremely low time constant and flat rate response in roll or pitch of the hingeless rotor helicopter. In a British evaluation of the Lockheed XH-51N "rigid" rotor helicopter, mechanical changes were made to the rotor control gyro which directly affected the sensitivity and, to a lesser extent, the damping (ref. 11). The "rate command" nature of the control response seemed to be particularly pleasing to the pilots. It is contrasted with that of a UH-1H teetering rotor helicopter (taken from ref. 12) in figure 26. At low values of sensitivity, however (M_q = -2 sec^{-1}; M_{δ_e} = 0.079 rad/sec^2/cm in pitch; L_p = -7 sec^{-1}, L_{δ_a} = 0.55 rad/sec^2/cm in roll), the pilots described the XH-51N as "ponderous." This result agrees with descriptions of some of the 300 configurations of this simulation. The most sensitive combination tested on the XH-51N in roll was evaluated as being "over-geared." Configurations in this simulation were not described as too sensitive until the roll control sensitivity was more than twice that of the "over-geared" XH-51N.

Effects of Cross-Axis Coupling

Coupling between axes was frequently criticized as an additional source of workload that caused the pilots to downgrade configurations. The three types of coupling most often referred to were: pitching moments due to collective pitch inputs, M_{δ_c}; yaw coupling due to collective inputs, N_{δ_c}; and pitching and rolling moments due to roll rate and pitch rate, respectively (M_p and L_q). Of these, only the pitch and roll coupling due to rates were examined in a systematic manner, and some quantitative estimates for limiting values made.

Pilot B found any noticeable pitch coupling, due to collective inputs, to be highly objectionable. A rather large range of this derivative was in the configurations tested, from M_{δ_c} = 0.008 to M_{δ_c} = 0.151 rad/sec^2/cm. The pilot rating did not appear to be related to the value of this derivative, however, as shown in figure 27. Pilot B's comments were reviewed to determine which configurations were criticized for this characteristic. Based on the wording used, comments fell into three rough categories: very exaggerated, large, and noted. Then the values of pitch coupling M_{δ_c}, the ratio (M_{δ_c}/M_q) and the ratio ($M_{\delta_c}/M_{\delta_e}$) were examined to see if their magnitudes corresponded to the categories used to describe the coupling. Both high and low values of these parameters were found in each category. Values of M_{δ_c} as low as 0.071 rad/sec^2/cm (at 60 knots) were described as "exaggerated," and values as high as 0.122 were described as "reduced." A teetering rotor with a value of 0.0079 rad/sec^2/cm was described as having "a lot." From these results it is not possible to determine what value of collective to pitch coupling is objectionable. Qualitatively the coupling can be a significant source of increased pilot workload. Pilot A also remarked about the presence of this coupling but was either not concerned about it or felt that it actually helped in the performance of the longitudinal task, since the direction of the resultant pitch motion was consistent with his technique of pitching up as the barriers were approached and pitching down as they were cleared. Records of speed also showed that pilot A allowed the helicopter to slow while climbing, whereas pilot B attempted to keep the speed constant a task made more difficult by the coupling.

Another significant factor that interfered with the task performance was collective to yaw coupling, N_{δ_c}. Pilot B felt that the simulated helicopters had exaggerated collective to yaw coupling and inadequate yaw damping which was most noticeable at speeds below 60 knots. It was considered by him to be a major problem in terms of pilot compensation required, resulting in poor precision in the control of heading and sideslip angle and decreasing confidence in his ability to fly low and fast. The yaw dynamics were the same for all the test helicopters as this axis was not changed during the experiment. In configurations with reduced damping in pitch and roll, however, the disturbances induced by collective to yaw coupling were more obvious and interfered more with the task. Pilot A also commented on this coupling but did not seem to consider it to be as seriously degrading as pilot B felt it was.

Roll coupling due to pitch rate and pitch coupling due to roll rates were evaluated with 12 special configurations selected from the main group. By adjustment of fuselage inertias and control gearing, the ratios of sensitivity to damping of each configuration were made the same as shown in figure 6 (Series A configurations). The test configurations consisted of four groups of three helicopters with constant pitch and roll damping in each group having a variation in coupling among the three. The pilots evaluated the handling qualities on the combination course.

Pilot ratings are plotted versus the rolling moment due to pitch rate derivative L_q in figure 28. No distinct trend is evident. Good pilot ratings were obtained even at fairly large values of coupling, and some with low values of coupling received poor ratings. According to reference 13 the pitch and roll damping of the helicopter must be taken into account in evaluating the coupling. The ratios of the coupling terms to the damping (L_q/L_p and M_p/M_q) appear to be more important than the values of the coupling terms themselves.

The data in figure 28 were replotted in figure 29 to show the variation of pilot rating with the parameter L_q/L_p. The pattern of pilot A's ratings supports the hypothesis that the ratio of coupling to damping is the significant coupling parameter. Pilot B's ratings were almost all unfavorable and did not convey any distinct picture. His pilot commentary on these configurations indicated that collective to pitch coupling was a dominant feature that lowered the ratings. Also shown in figure 29 are boundaries discussed in reference 13. The boundaries are meant to indicate that unacceptable ratings ($PR > 6.5$) are to be expected if L_q/L_p exceeds 0.5 and no better than acceptable ratings ($PR > 3.5$) can be expected if L_q/L_p exceeds 0.3. Ratings of all configurations of the main group for both pilots were examined to see if these boundaries were valid for the results of this experiment. Generally, the agreement was good. The data suggest that the boundary between satisfactory and acceptable ratings is closer to $L_q/L_p = 0.35$ than to $L_q/L_p = 0.30$. The parameter M_p/M_q was also examined for a correlation with pilot rating. Its effect could not be clearly isolated from those due to roll coupling L_q/L_p, since both kinds of coupling occurred simultaneously in these experiments. Values of M_p/M_q as high as 0.35 received a pilot rating of 3. For one configuration with $M_p/M_q = 0.75$, the pilot noticed extreme roll coupling rather than pitch coupling.

Effects of Pitch-Flap Coupling

A selected group of five configurations were modified (Series F, fig. 6) by adding 39° of pitch-flap coupling (δ_3) to the main rotor. Inertia and control gearing were also changed, as with the A group, to maintain a constant ratio of damping to sensitivity. The value of δ_3 was made large enough so that the angle-of-attack stability term, M_w, was zero or negative. This was thought to be important because of the direct effects of M_w on the longitudinal short period stability characteristics. Hingeless rotors make an unstable contribution to M_w which increases with speed. It was thought that reducing the angle of attack instability might have a significant effect on the flying qualities of the stiffly hinged configurations. These configurations were evaluated on the combination course.

The pilot ratings and pilot comments for these cases were largely unfavorable. The ratings in some cases were worse than configurations from the main group with similar damping and sensitivity and large unstable values of M_w.

Pilot ratings for all configurations flown on the longitudinal course were plotted against their respective values of M_w to see if the ratings reflected the variation. No dependency on M_w was evident, and good pilot ratings were given to some cases with the highest unstable values of M_w (to $M_w = 0.023$ m-sec^{-1}). Having some unstable (positive) value of this derivative, therefore, appears to be acceptable in this kind of task. The addition of δ_3 to the main rotor also had unwanted side effects in the form of increased pitch-roll coupling (up to $L_q/L_p = -1.18$) and decreased pitch and roll damping. These factors evidently were more detrimental to the handling qualities than any benefit that might have been felt due to decreasing M_w.

A ground-based simulator study reported in reference 14 established a relationship between the pilot rating and a parameter which represents the "spring" term in the short period mode of the longitudinal dynamics — the so-called "short period stability parameter" ($Z_w M_q - M_\alpha$). The data of that study showed a rapid deterioration in pilot rating as the value of this parameter approached zero. Calculated values of this parameter at 60 knots for the main group of configurations and also for the δ_3 group are shown with the corresponding pilot ratings in figure 30. For the δ_3 group, the short period stability parameter (SPSP) values are quite low (below 2.0 sec^{-2}), the reduction in M_q due to the addition of δ_3 being more pronounced than the reduction in M_α. Pilot A's ratings deteriorate as the SPSP value decreases below 2.0 sec^{-2}. This result is qualitatively in agreement with reference 14, but the deterioration of pilot ratings begins at lower values of the SPSP and the ratings degrade more rapidly than in that reference. Also, pilot B's results are quite dissimilar. Because of the experiment design, it is not possible to interpret derivative-pilot rating cause-effect relationships unambiguously.

The approach taken here deliberately chose to compare physical configurations directly rather than independent variations in derivatives.

Pilot Performance

A typical flightpath record for the longitudinal course is shown in figure 31. The minimum ground clearance was limited by a crash protection device on the Redifon visual system to approximately 6 m. One pilot's perception of speed and scale was distorted, perhaps by the combination of 1:400 modeling scale and 1:600 motion scaling of the visual system. Pilot B commented that occasionally the speed appeared to be one-half of that shown by the airspeed indicator, and the barriers had the appearance of being much smaller than 15 m high. Pilot A did not comment on this discrepancy.

Time and average height through the courses were used as measures of performance. Figure 32 shows the relationship between mean height and course times for the longitudinal course. Pilot A's height performance was very consistent, and for almost all configurations he flew lower and slower than pilot B. The data did not show any height-speed tradeoff for either pilot on this course or on the combination course. Records of height versus time were integrated to give a kind of exposure index for the run (a large value indicating either a very high mean altitude or very slow speed) to see how exposure was influenced by average speed. In all cases exposure was decreased by flying faster. In particular, there was no speed for minimum exposure, where increasing speed and decreasing flightpath excursions resulted in an increased exposure.

Frequently the pilots commented that a configuration with good flying qualities enabled them to fly faster or lower or more confidently. Pilot ratings were plotted versus time to complete the course and mean altitude to verify these impressions. No relationship between pilot rating and course time was found, but for pilot B a definite relationship between his rating and his mean altitude performance seemed to exist (fig. 33).

In trying to rationalize the pilot ratings that were given, a number of flightpath and control variables were examined to see if they correlated in any way with the ratings. Among these were standard deviations of longitudinal, lateral, collective, and pedal control movements, and standard deviations of lateral excursions, heading, altitude, sideslip, and angle of attack. Except in some extreme cases (e.g., large control motions used for a teetering rotor helicopter with low control power), these measures did not prove to be a good index of pilot rating.

Pilot Comments

The differences between the numerical ratings of the two pilots were difficult to reconcile partly because they represented a mixture of deficiencies. An additional source of information on the differences between the main group of configurations was available from the questionnaires completed by the pilots at the end of each run (table 5).

When the individual pilot comments were reviewed for a few cases with particularly poor agreement (e.g., 301, 308 and 306) it was clear that a "minor but annoying" deficiency (see Cooper-Harper scale) to pilot A might become a "very objectionable" to "major" deficiency to pilot B. Yet both pilots might agree qualitatively on the problem: "Lacks rapid response for NOE" (pilot A) compared to "very poor for NOE — low sensitivity-low damping" — for pilot B. The comments may therefore be compared, but the rating numbers have meaning relative to each other only for each pilot.

The comments on the questionnaires were reviewed and are briefly summarized in table 6, using descriptions that paraphrase the actual comments written by the two pilots. The comments are segregated into groups relating to longitudinal handling qualities, cross-coupling, and lateral-directional handling qualities.

The data for six configurations — three good and three bad — that were flown fixed-base in the lateral-directional or combination tasks and had well correlated ratings were examined to see what the pilots most liked and disliked about them. They were selected subsequently for the motion experiment.

The "good" configurations (201, A204 and A308) all had fairly high values of damping, with damping to sensitivity ratios near or within the boundaries of the Edenborough criterion. Pitch-roll coupling was noticed but not objectionable. Values L_q/L_p were less than 0.30. Both pilots liked 201 because they were able to fly the course fast with it. Pilot B remarked on the good pitch and roll damping of A308. Two configurations had Lock numbers of 3 and one had a Lock number of 6. Both pilots seemed to like A204 best — pilot A for its good response and insignificant pitch-roll coupling and pilot B also for lack of coupling. Both pilots independently compared A204 to A301 and found A204 much superior.

The "poor" configurations (101, 301 and 203) were quite dissimilar in their damping and sensitivity. Both pilots complained about the excessive sensitivity of 203 and the associated tendency toward overcontrol and PIO. This configuration is identical to the popular 201 except for decreased blade inertia that made its Lock number 9 instead of 3. In fact, 201, 202, and 203 represent a steadily worsening pilot rating and an increase in Lock number. Configuration 101 was criticized for its slow roll response and low sensitivity — pilot A called it sluggish. Configuration 301 was called sluggish by both pilots. Pilot A found 301 hard to coordinate in turns. One pilot considered it to have low sensitivity, the other to have low control power.

Based on these and some other observations it would appear that, to have desirable characteristics in roll, the unaugmented single rotor helicopter should have L_p between -12.5 and -30 sec^{-1}; a ratio of sensitivity to damping between 3.0 and 10.6 deg/sec/cm of stick; and cross-coupling $|L_p/L_q|$ less than 0.30.

Effects of Motion

All of the foregoing results derive from a fixed-base experiment, which may be a significant limitation considering the emphasis on agility and maneuverability in these tasks. Both pilots indicated that they probably took more risks in the experiment than they might have in an actual helicopter, such as approaching very close to trees and using high bank angles at very low levels. A limited motion experiment was therefore conducted which removed additional differences between the simulator and flight tasks. Designed and carried out on the FSAA, a large motion simulator, the experiment was intended to compare directly subjective impressions of the same configurations with and without motion.

For contrast, three configurations rated "good" and three rated "poor" in the fixed-base experiment were selected for the motion, no-motion comparison. The "good" configurations were 201, A204 and A308; the "poor" were 101, 301 and 203. Each pilot first flew the helicopter, with the simulator in the fixed-base mode, down the combination course. After assigning a rating and recording comments, the task was repeated with motion.

The pilots felt that the motion fidelity for this simulation was reasonably good. However, travel limits (particularly vertical limits) were sometimes encountered during a run because of either extreme maneuvers being attempted or because of individual pilot technique in flying.

There was a marked difference in the motion amplitude of the simulator between pilots flying the same task and configuration. With two of the pilots (A and C) the simulator motions appeared to be relatively mild and small, particularly in lateral displacement. The behavior for the other two (B and D) was characterized by impressively large and rapid lateral excursions accompanied by full amplitude heaving motions that carried the simulator to at least the software limits in vertical travel. When these excursions actually resulted in contact with the limits, the resulting false motion cues interfered with the assessment of the motion.

The difference in the pilot rating for a single configuration between motion and no motion never exceeded 1.0, with only one exception, for all pilots. For most configurations the rating with motion was either the same or better than that for the fixed-base run. As with the previous experiment, ratings of the different pilots were often poorly correlated.

The comments comparing the fixed-base and motion runs were mixed. Each pilot's comments are reviewed separately.

All of pilot A's ratings improved with motion. He was able to handle all couplings better because of motion cues, particularly collective to yaw coupling. In one case, a tendency to overcontrol in pitch, due to high sensitivity or low damping, was reduced with motion. One configuration had a very uncomfortable ride quality, perhaps due to roll-pitch coupling that only revealed itself with motion. He felt he was helped most by motion in the vertical axis (i.e., by the simulation of vertical g forces).

Most of pilot B's ratings improved with motion. He felt the cues were helpful and not misleading, particularly the sensation of vertical accelerations. A difficult configuration having a combination of low pitch damping combined with strong collective to pitch coupling was more easily controlled with motion than without. He felt that motion caused him to slow down through the course, with an attendant improvement in his ability to perform the task. The data confirm that he flew slightly slower with motion than fixed-base, in all cases. In another case, motion did not help in the task performance, but made the lack of damping in that configuration more apparent.

Pilot C's ratings were the same or worse with motion. His general impression of the addition of motion cues was very favorable. In two cases he felt forced to fly the helicopter more gently with motion because of jerky motions resulting from hitting motion stops, making the helicopter more difficult to fly compared with fixed-base operation. Motion cues helped with control coordination, making one helicopter slightly easier to fly in another instance.

Pilot D's ratings were almost all the same or worse with motion. Motion cues were a big help with directional control in one case. In another, the presence of motion contributed toward a PIO tendency. He also complained of hitting motion stops at times. More than one comment seemed to imply that control of the helicopter was more difficult with motion than without.

These comments indicate that some important characteristics were revealed by the presence of motion, and it is therefore desirable to include it in low level helicopter simulations. The small differences between the ratings for fixed-base operation and motion, however, indicate that the essential trends of flying qualities with the dominant aircraft characteristics can be determined quite adequately without motion in this type of task.

Some of the recorded variables were examined to see if there were differences between the fixed-base and motion values, among them average height and speed; standard deviations of cyclic and collective control positions; and standard deviations of pitch attitude, roll attitude and normal acceleration. For all pilots, average height through the course was about the same with and without motion. For pilot B average speed was consistently lower, by about 5%, with motion, and both higher and lower for the others. The standard deviations of control positions with motion were lower in almost every instance for all pilots, and markedly so for collective pitch for pilot B. Normal acceleration standard deviation was also much lower with pilot B with motion. Many values were about 60% of the fixed-base amount. For the other pilots, there were no consistent differences for this quantity between fixed-base and motion runs. The standard deviations of pitch and roll attitude were similar with and without motion, except for pilot B's roll attitude which was less with motion.

Maximum and minimum values of several variables were also examined, including normal acceleration; pitch attitude, rate and acceleration; and roll attitude, rate and acceleration. For almost all pilots and configurations the extremes of the fixed-base values of normal acceleration were greater than those for the motion runs. For pitch and roll attitude, maximums and minimums were about the same for motion and fixed-base. For pitch rate and acceleration, however, fixed-base extreme values were greater than those with motion in most cases. For roll rate and acceleration, values were about the same in all cases.

The similarity of the attitudes between fixed-base and motion runs indicates that the same kind of maneuvering performance was demanded by the pilots. The decrease in control excursions, accelerations and rates appears to indicate that motion feedback inhibited the pilots from using large inputs, but their comments did not show a conscious awareness of this.

DESIGN IMPLICATIONS

The damping versus sensitivity criterion for pitch and roll axes is a rather restricted view of the complex flight dynamics of a single main rotor helicopter.

For the generic math model used in this study, the flapping frequency was varied over a wide range to cover teetering rotors as well as stiff, hingeless, single main rotors. The stability characteristics as well as the direct and the cross-coupling response characteristics to control inputs varied significantly as the four-rotor system design parameters were varied over a wide range, as shown previously in table 1. Nevertheless, the damping-sensitivity criterion may serve as a necessary condition for the short-term direct response requirements in the pitch axis and roll axis individually, especially in the demanding tasks such as those evaluated in this study, wherein less attention was paid to long-term response characteristics. While being a good candidate for a necessary condition for terrain flight, it is by no means a sufficient condition; many qualifications such as stability characteristics of the vehicle and the cross-coupling response characteristics need to be defined to achieve some form of necessary and sufficient requirements.

Another point needing clarification is the quasi-static nature of the damping and sensitivity parameters that were shown in figure 12. With rotor dynamics included, the apparent vehicle damping and control sensitivity can be substantially different from the quasi-static values given in these figures.

Closely related to the damping in roll and pitch are the roll subsidence mode and the pitch subsidence mode (or the "longitudinal short period mode" in the case of a teetering rotor helicopter). The eigenvalues of the roll subsidence mode and the pitch subsidence mode of the coupled 6 DOF rigid body mode are approximately equal to the roll damping, L_p, and pitch damping, M_q, respectively. Modal characteristics requirements of other rigid body modes are less amenable to quantification, however. Figure 34 shows the root loci of a teetering rotor (configuration 101), an articulated rotor (201) and a hingeless rotor (301), all with a heavy blade ($\gamma = 3$). Airspeeds are indicated in these figures. The eigenvalues for the Dutch roll, heaving mode, spiral, and the phugoid of configuration 201 are similar to those for configuration 301, yet pilots rated 201 much better than 301. The reason for the difference in ratings is attributed to cross-coupling in pitch and roll due to aircraft angular rate and the low control sensitivity of 301.

These couplings are shown in figure 35, comparing the aircraft responses u, w, q, θ, v, p, ϕ, r to a 2.54 cm step input in the longitudinal stick for configurations 201 and 301. The short-term response characteristics in pitch rate and roll rate can be estimated with a reasonable accuracy using the values of M_q, $-M_{\delta_e}/M_q$, and $(M_{\delta_e}/M_q)(L_q/L_p)$ (as shown in table 7) for the inverse of pitch subsidence time constant, short-term pitch rate and roll rate peak, respectively. Note that for configuration 201, the aircraft mildly rolls to the left initially with aft stick input, but for 301 the aircraft strongly rolls to the right instead, as predicted in the sign and magnitude of $(M_{\delta_e}/M_q)(L_q/L_p)$ for the two aircraft. If the value of M_{δ_e}/M_q were the same for the two aircraft, the roll coupling to the aft stick input would have been even more pronounced for 301 as indicated in the sign and magnitude of L_q/L_p. (Note: As discussed previously, a proper control phasing was used, therefore the control couplings L_{δ_e} and M_{δ_a} are approximately equal to zero.)

The initial pitch-roll responses of these two aircraft to a step lateral stick input can also be estimated using the values of L_p, $-L_{\delta_a}/L_p$, and $(L_{\delta_a}/L_p)(M_p/M_q)$. The initial pitch rate response to a collective input can also be estimated with good accuracy for these two aircraft using the value of $-M_{\delta_c}/M_q$ as shown in table 7.

As indicated earlier, the parameters, L_q/L_p and M_p/M_q play an important roll in the initial response in the pitch and roll coupling. Their importance has been shown in figure 29. To fully explore these coupling parameters, the values of L_q/L_p at 60 knots were plotted for all the 27 basic configurations, including configurations 201 and 301 discussed above, as shown in figure 36. As evidenced in this figure, the effects of the pure hinge offset, the flapping restraint and Lock number are rather strong and independent. This point was discussed earlier in the paper for the hover case with the main rotor contribution only. The equivalent hinge offset based on the flapping frequency for the combination of pure hinge offset and flapping hinge restraint does not serve as a combined parameter to achieve a one to one correspondence to the coupling parameter L_q/L_p for all the three families of rotor systems. This figure indicates several interesting and important points related to blade inertia and rotor type:

1. For a heavy blade, a high inertia rotor system ($\gamma = 3$) with a large equivalent hinge offset the aircraft will have a strong initial right roll tendency in response to aft stick, even though a proper control phasing has been used ($L_{\delta_e} = 0$). For $\gamma = 3$, an equivalent hinge offset of less than 12% should be used for all the rotor systems to keep $L_q/L_p \leq 0.35$. An optimum range of equivalent hinge offset to minimize L_q/L_p is 3.5% to 6% with the lower value for teetering rotor with flapping hinge restraint and the higher value for a pure hinge offset (articulated rotors).

2. For a moderately heavy blade ($\gamma = 6$), the optimum equivalent hinge offset varies widely with rotor systems: 6% for teetering rotor, 11.5% for articulated rotor, and 14.6% for hingeless rotor helicopters.

3. With a light blade ($\gamma = 9$), the optimum equivalent hinge offset varies even more widely with type of rotor systems: 8% for a teetering rotor at the lower end and substantially higher values for articulated and hingeless rotor helicopters.

Adding a pitch-flap coupling (in the sense of reducing the blade pitch with up flapping) produces a well known effect of improving the static stability in pitching moment due to angle of attack in forward flight. Adding a large amount ($\delta_3 = 39°$ considered in this investigation) produces many poor side effects, however. Effects on the eigenvalues and major parameters discussed in this section are shown in tables 8 and 9, respectively. Note that the damping in pitch (and also roll) decreases drastically and the magnitude of the pitch-roll coupling parameters, L_q/L_p and M_p/M_q, increases substantially.

A recent simulator study by the RAE (ref. 15) on helicopter agility is worth comparing to this one, because of the similarities in tasks and test configuration variables (Lock number and spring restraint) examined. The 12 configurations investigated by them (fig. 37) were from mid to low ratio of damping to sensitivity compared to this study (i.e., there were no very sluggish configurations). They found that no great preference was shown for any one type of rotor, but that the stiff rotors (high K_β) were disliked. One of them (D3) was very close to the A107 configuration of this study in terms of sensitivity damping, and the value of $(K_\beta/I_\beta\Omega^2)$ (table 10). The pilot ratings were also similar in the two experiments. In this study, some of the stiff hinged rotors (107, 108, 109, 207) exhibited poor flying qualities for the lateral-directional task only. Reference 15 also found an occasional wide variation of up to three pilot rating units in repeat evaluations of the same configuration flying the same task by the same pilot. A similarly wide variation in ratings was occasionally seen in this experiment for configurations that were almost identical — for example, A's ratings for A109 and 109 in the combination task.

Another point of comparison was the coupling of collective pitch into pitching moments. This was mentioned in the RAE report as a handling qualities problem because of its tendency to destroy precise pitch control in turning maneuvers, by exciting unstable longitudinal modes of the test configurations. On a hurdles course, in contrast, their pilots found it noticeable but in the correct sense to aid the anticipated maneuver — and therefore, presumably, not especially harmful. Pilot A participated in both experiments.

Our pilots found the low damping, low sensitivity configurations (101, 102, 103) to be very unsatisfactory. No RAE configurations are quite comparable. The closest ones (A1 and A2) with low K_β were found to be quite satisfactory. They are comparable to our configuration 106 which our pilots found unsatisfactory in pitch.

The RAE study identified speed as an important factor affecting the pilots' ratings. Slower flying resulted in "significant improvement in the ratings." Higher mean course speed may thus have been the cause of pilot B's consistently poorer ratings in the fixed-base experiment of this study.

CONCLUSIONS

The conclusions that follow must be considered in the context of the task: low level, relatively high speed maneuvering around obstacles. Also these conclusions are based on experiments in simulators, both fixed and moving base, obtained from only a few pilots.

No one type of rotor system was uniformly superior to the others for these tasks. Good to adequate handling qualities were found in more than one member of each rotor group. All pilots were, however, unanimous in downgrading the pure teetering rotor configurations, primarily for having insufficient control power.

The ratio of control sensitivity to damping was used as a guide in selecting test configurations and was thought to be a significant handling qualities parameter. The results of this experiment imply that control sensitivity/damping is not a strong determinant of pilot opinion for these tasks within the range of values tested. At minimum, the acceptable range of sensitivity and damping is considerably broader than that indicated by the Edenborough criterion. The levels of minimum damping and minimum control power probably are important but cannot be determined from these test results.

Coupling in the form of rolling moments due to pitch rate is important. The absolute value of L_q/L_p should be less than 0.35. Collective to pitch and collective to yaw coupling were also very objectionable and should be minimized.

Unstable values of M_w (angle-of-attack static stability derivative) did not seem to be objectionable within the range tested. The SPSP was examined as an index of pilot opinion rating. At least for one pilot, values of this parameter less than 2.0 $\sec^{-2}$ resulted in poorer pilot ratings. These findings tentatively support its use as a design parameter.

The evaluation of selected configurations on a motion-base simulator did not greatly alter these conclusions. Although motion gave insights and had a definite effect on control motion amplitudes used for the task, valuable information was gained from the fixed-base simulation.

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TABLE 1.- PHYSICAL CHARACTERISTICS OF THE CONFIGURATIONS

(a) Configuration test matrix

Configuration	γ	ε	$K_\beta/I_\beta\Omega^2$	δ_3	Remarks
101	3	0	0	0	Control throws for ALL configurations: δ_e = ±13.97 cm δ_a = ±13.97 cm δ_c = 0 - 25.4 cm δ_p = ±8.26 cm
102	6				
103	9				
104	3	0	.15		
105	6				
106	9				
107	3	0	.30		
108	6				
109	9				
201	3	0.5	0		
202	6				
203	9				
204	3	.05	.075		
205	6				
206	9				
207	3	.05	.225		
208	6				
209	9				
301	3	.10	.03		
302	6				
303	9				
304	3	.14	.03		
305	6				
306	9				
307	3	.18	.03		
308	6				
309	9				
A109	9	0	.300		Within each group of 3 configurations, damping and sensitivity were held constant in both pitch and roll.
A209	9	.05	.225		
A303	9	.10	.030		
A306	9	.14	.030		
A205	6	.05	.075		
A108	6	0	.300		
A305	6	.14	.030		
A308	6	.18	.030		
A104	3	0	.150		
A107	3	0	.30		
A301	3	.10	.03		
A204	3	.05	.075		

TABLE 1.- Continued

(a) Concluded

Configuration	γ	ε	$K_\beta/I_\beta\Omega^2$	δ_3	Remarks
F108	6	0	0.30	38.6°	$M_w < 0$
F205	6	.05	.075	↓	
F204	3	.05	.075		
F301	3	.10	.030		
F104	3	0	.150		

TABLE 1.- Continued

(b) Selected stability and control derivatives of the test configurations

[Lateral-directional characteristics: mid c.g., 60 knots]

Configuration	L_{δ_a}, rad/sec^2/cm	L_p, sec^{-1}	L_q, sec^{-1}	N_{δ_c}, rad/sec^2/cm	Remarks
101	0.154	-2.85	-0.97	0.059	$N_r = -1.20$ sec^{-1}
102	.153	-1.46	-.49	.061	
103	.152	-1.00	-.34	.061	
104	1.304	-23.60	8.62	.048	
105	.727	-7.38	1.00	.062	
106	.535	-3.73	.14	.065	
107	2.464	-31.69	24.66	.022	
108	1.300	-11.99	4.32	.054	
109	.915	-6.17	1.28	.063	
201	1.517	-18.35	-.71	.056	
202	.911	-5.70	-2.09	.060	
203	.709	-3.00	-1.78	.061	
204	2.741	-29.20	8.58	.044	
205	1.524	-9.37	-.56	.058	
206	1.124	-4.75	-1.26	.061	
207	5.209	-36.57	28.98	.015	
208	2.749	-14.88	4.18	.047	
209	1.938	-7.82	.44	.058	
301	1.117	-39.06	14.38	.032	
302	.605	-13.58	-1.28	.021	
303	.436	-6.91	-2.45	.059	
304	1.550	-46.92	29.13	.012	
305	.817	-19.53	1.00	.044	
306	.576	-10.31	-2.50	.055	
307	1.158	-27.77	21.03	.005	
308	.605	-14.44	1.11	.015	
309	.736	-14.32	-1.49	.048	
A109	.582	-5.09	1.05	.063	
A209	.316	-2.79	-.08	.031	
A303	.329	-2.90	-1.52	.032	
A306	1.176	-10.23	-2.48	.056	
A205	1.185	-10.28	-.62	.023	
A108	1.172	-10.23	3.68	.054	
[illegible]05	2.364	-20.55	1.04	.044	
A308	2.342	-20.41	4.53	.036	
A104	2.362	-20.53	7.49	.050	

TABLE 1.- Continued

(b) Continued

Configuration	L_{δ_a}, rad/sec^2/cm	L_p, sec^{-1}	L_q, sec^{-1}	N_{δ_c}, rad/sec^2/cm	Remarks
A107	3.551	-30.87	24.03	0.023	N_r = -1.20 sec^{-1}
A301	3.526	-30.65	11.28	.038	
A204	3.670	-30.91	9.09	.043	
F108	.500	-4.35	5.04	.020	
F205	.507	-4.35	2.33	.033	
F204	1.246	-10.85	10.71	.033	
F301	1.262	-10.98	6.33	.026	
F104	1.[illegible]0	-10.91	12.84	.043	↓

(b) Continued

[Longitudinal characteristics: mid c.g., 60 knots]

Configuration	M_{δ_e}, rad/sec^2/cm	M_q, sec^{-1}	M_{α}, sec^{-1}	M_{b_c}, rad/sec^2/cm	M_w (m-sec)$^{-1}$	SPSP, sec^{-2}
101	0.036	-0.665	0.207	0.007	-0.021	1.101
102	.036	-.397	.102	.007	-.021	.921
103	.036	-.307	.067	.007	-.021	.861
104	.327	-5.02	-1.732	.112	.009	3.120
105	.183	-1.640	.194	.070	-.002	1.169
106	.134	-.881	-.028	.052	-.007	.818
107	.612	-6.724	-5.017	.156	-.023	5.204
108	.327	-2.607	-.874	.117	.012	1.390
109	.231	-1.393	-.259	.089	.004	.821
201	.380	-3.934	.171	.076	-.0004	2.650
202	.229	-1.294	.439	.048	-.008	1.112
203	.178	-.730	.371	.038	-.011	.819
204	.270	-6.207	-1.733	.122	.012	3.786
205	.384	-2.062	.127	.079	.0008	1.356
206	.282	-1.097	.265	.061	-.004	.862
207	1.288	-7.758	-5.912	.158	.023	4.485
208	.691	-3.218	-.846	.128	.015	1.695
209	.489	-1.741	-.085	.101	.008	.931
301	.279	-8.287	-2.916	.142	.018	5.007
302	.153	-2.952	.275	.100	.007	1.770
303	.111	-1.554	.512	.077	.001	1.015

TABLE 1.- Concluded

(b) Concluded

Configuration	M_{δ_e}, rad/sec^2/cm	M_q, sec^{-1}	M_p, sec^{-1}	M_{δ_c}, rad/sec^2/cm	M_w (m-sec)$^{-1}$	SPSP, sec^{-2}
304	0.384	-9.951	-5.937	0.155	0.002	6.000
305	.206	-4.207	-.189	.130	.015	2.354
306	.146	-2.272	.520	.103	.008	1.263
307	.284	-5.952	-4.289	.086	.005	3.824
308	.152	-3.150	-.216	.089	.006	1.919
309	.186	-3.119	.312	.129	.016	1.602
A109	.171	-1.503	-.279	.096	.004	.885
A209	.094	-.870	.028	.049	-.003	.672
A303	.097	-.908	.420	.044	-.007	.816
A306	.344	-3.003	.688	.137	.011	1.669
A205	.343	-3.003	.184	.115	.001	1.975
A108	.343	-3.009	-1.009	.135	.013	1.604
A305	.572	-5.008	-.225	.154	.018	2.803
A308	.571	-5.007	-1.049	.139	.020	2.746
A104	.572	-5.003	-1.725	.112	.009	3.060
A107	.802	-7.004	-5.226	.162	.024	3.965
A301	.898	-6.998	-2.462	.120	.015	4.228
A204	.838	-7.008	-1.956	.137	.014	4.274
F108	.116	-1.020	-1.062	.040	-.006	.884
F205	.117	-1.016	-.470	.344	-.011	.848
F204	.273	-2.379	-2.214	.045	-.006	1.494
F301	.272	-2.379	-1.264	.058	-.009	1.530
F104	.273	-2.381	-2.618	.051	-.007	1.810

TABLE 2.- A COMPARISON OF ARMCOP GENERATED DERIVATIVES FOR A UH-1H WITH OTHER DATA SOURCES

Derivative	ARMCOP		Bell C-81		NRC Bell 205 param. i.d., V = 70 knots
	60 knots	80 knots	60 knots	80 knots	
X_u, sec^{-1}	-0.017	-0.0202	-0.024	-0.034	-0.1117
X_w, sec^{-1}	.032	.035	.012	.057	.0084
X_q, m-sec^{-1}	.610	.615	.043	.053	1.064
Z_u, sec^{-1}	-.0048	.0102	.066	.079	-.009
Z_w, sec^{-1}	-.696	-.775	-.875	-.946	-.875
Z_q, m-sec^{-1}	-.070	-.152	.036	-.058	.427
M_u (m-sec)$^{-1}$	.0049	.0039	.121	.127	.020
M_w (m-sec)$^{-1}$	-.033	-.046	-.121	-.203	-.022
M_q, sec^{-1}	-.556	-.633	-.523	-.612	-.848
L_p, sec^{-1}	-1.436	-1.445	-.987	-1.002	-.806
N_p, sec^{-1}	-.289	-.278	.132	.0175	-.037
L_r, sec^{-1}	.282	.293	-.741	-.704	.174
N_r, sec^{-1}	-1.077	-1.149	-1.42	-1.64	-1.303
L_v (m-sec)$^{-1}$	-.026	-.020	-.499	-.62	-.048
N_v (m-sec)$^{-1}$	.091	.096	.066	.088	.058
$\left.\begin{matrix} L_{\delta_a} \\ N_{\delta_a} \end{matrix}\right\}$ (sec^2-cm)$^{-1}$	.218 .033	.219 .033	.206 .0014	.207 .001	.111 .015
$\left.\begin{matrix} L_{\delta_r} \\ N_{\delta_r} \end{matrix}\right\}$ (sec^2-cm)$^{-1}$	.104 .284	-.114 .309	-.439 .589	-.506 .678	-.102 .194

TABLE 3.- A COMPARISON OF ARMCOP GENERATED DERIVATIVES FOR A BO-105 WITH DATA OF REFERENCE 7

Derivatives	ARMCOP BO-105 60 knots	Boeing-Vertol BO-105 60 knots
X_u, sec^{-1}	-0.0339	-0.0338
X_w, sec^{-1}	.0128	.0311
X_q, m-sec^{-1}	.607	.638
Z_u, sec^{-1}	-.0362	-.0563
Z_w, sec^{-1}	-.6568	-.7885
Z_q, m-sec^{-1}	.250	.056
M_u (m-sec)$^{-1}$	.048	.059
M_w (m-sec)$^{-1}$	-.020	.042
M_q, sec^{-1}	-3.3077	-3.6151
M_{δ_e} (sec^2-cm)$^{-1}$	.321	.392
M_{δ_c} (sec^2-cm)$^{-1}$	.149	.203
L_p, sec^{-1}	-8.46	-9.35
N_p, sec^{-1}	-.7119	-.022
Y_p, m-sec^{-1}	-.662	-.716
L_r, sec^{-1}	.1151	-.0251
N_r, sec^{-1}	-.8849	-.6627
Y_r, m-sec^{-1}	.277	.181
L_v (m-sec)$^{-1}$	-.022	-.226
N_v (m-sec)$^{-1}$	.119	.083
Y_v, sec^{-1}	-.1469	-.091
L_{δ_a} (sec^2-cm)$^{-1}$	.894	1.03
N_{δ_a} (sec^2-cm)$^{-1}$	.092	.012
Y_{δ_a}, m-(sec^2-cm)$^{-1}$	.0766	.0926
L_{δ_r} (sec^2-cm)$^{-1}$	.369	-.426
N_{δ_r} (sec^2-cm)$^{-1}$	.667	.581
Y_{δ_r}, m-(sec^2-cm)$^{-1}$	-.2464	-.2081

TABLE 4.- HELICOPTER CONTROL TRAVELS AND FORCE GRADIENTS

Control	Travel, cm	Gradient, N/cm	Breakout, N (approx.)
Collective	0-25.4	0	2.22
Pedals	±8.26	3.50	8.90
Longitudinal cyclic	±13.97	2.92	4.45
Latitudinal cyclic	±13.97	1.75	4.45

TABLE 5.- PILOT QUESTIONNAIRE

Longitudinal task	Lateral-directional task
1. Overall Cooper rating 2. Vertical response to collective a) Sensitivity? b) Damping? 3. Pitch response to longitudinal cyclic a) Sensitivity? b) Damping? c) Speed of response? 4. Coupling a) Roll-pitch? b) Collective-yaw? 5. Dynamic stability 6. General comments	1. Overall Cooper rating 2. Yaw response to pedals a) Sensitivity? b) Damping? c) Speed of response? 3. Roll response to lateral cyclic a) Sensitivity? b) Damping? c) Speed of response? 4. Symmetry of response 5. Coordination of stick, pedals and collective required? 6. General comments Combination task 1. Overall Cooper rating 2. General comments

TABLE 6.- SUMMARY OF PILOT COMMENTS – ALL TASKS

Pilot comments	Configurations																										
	101	102	103	104	105	106	107	108	109	201	202	203	204	205	206	207	208	209	301	302	303	304	305	306	307	308	309
Poor response to longitudinal cyclic; low sensitivity; sluggish; poor precision	A B	B	B			B	B	A	A			A				A B		B		B	A B		A B	A B		B	B
Low longitudinal control power	B	B																	B		B			B			B
Low damping in pitch		B				A	A		A	B	B	B			A B		B	B									
Overly sensitive in pitch; possibility of pilot induced oscillations						A					A						A B	A									
Good or adequate handling qualities in pitch axis				A B	A B			B	B	A			A B	A	A				A	A						A	A
Excessive collective to pitch coupling	B	B	B		B	A B	B	B	B		B			B	A B	B	B	B		A	B		B	B		B	B
Roll due to pitch rate or pitch due to roll rate							A	B			A	A B	A B		B	B					B			A			
Collective to yaw coupling	A B				A B	A		A B			B		B	B		A B	A B		A B	A B	A					B	A B
Low yaw damping	B	B		B	B			B		B	B							B									
Poor response to lateral cyclic; low sensitivity; poor precision; sluggish	A B	B	B			B	B		A							A B			A B	B	A		A B	A B		B	A B
Low lateral control power																			A B					B		B	
Low damping in roll		B									A B	A			A												
Difficult to coordinate	A B	B			B		B	A	A																		
Too sensitive in roll – possibility of pilot induced oscillations					B	A					A B	A B						A									
Good or adequate lateral directional handling qualities				A B	A		A	B	B	A B			B	A B	A B		A B	B		A	B					A	

TABLE 7.- A COMPARISON OF SOME MAJOR PARAMETERS FOR THREE TEST CONFIGURATIONS

[Mid c.g., 60 knots]

Parameter	Configuration		
	101	201	301
γ	3	3	3
ϵ	0	0.05	0.10
$K_\beta/(I_\beta\Omega^2)$	0	0	.03
M_{δ_e}, rad/sec^2/cm	0.035	0.381	0.280
M_q, sec^{-1}	-.67	-3.93	-8.29
$-M_{\delta_e}/M_q$, rad/sec/cm	.053	.097	.034
L_q/L_p	.341	.044	-.364
$(M_{\delta_e}/M_q)(L_q/L_p)$, rad/sec/cm	-.018	-.004	.012
L_{δ_a}, rad/sec^2/cm	0.150	1.468	1.083
L_p, sec^{-1}	-2.70	-17.85	-38.00
$-L_{\delta_a}/L_p$, rad/sec/cm	.056	.082	.028
M_p/M_q	-.313	-.043	.351
$(L_{\delta_a}/L_p)(M_p/M_q)$	.017	.004	-.010
M_{δ_c}, rad/sec^2/cm	0.008	0.075	0.142
$-M_{\delta_c}/M_q$, rad/sec/cm	.011	.019	.017
Pilot rating (comb. course)			
Pilot A	8.5	3	7.5
Pilot B	7.0	5	7.0

TABLE 8.- EFFECT OF PITCH-FLAP COUPLING (δ_3) ON SOME MAJOR PARAMETERS AND PILOT RATINGS

[Mid c.g., 60 knots]

Config.	104		108		205		301	
Parameter	$\delta_3 = 0$	$\delta_3 = 38.6°$	0	38.6	0	38.6	0	38.6
M_w (m-sec)$^{-1}$	0.0098	-0.0069	0.0131	-0.0066	0	-0.0111	0.0164	-0.0095
Z_w, sec^{-1}	-.68	-.67	-.68	-.672	-.68	-.489	-.68	-.526
M_q, sec^{-1}	-5.02	-2.38	-2.61	-1.02	-2.06	-1.02	-8.29	-2.38
SPSP, sec^{-2}	3.120	1.810	1.390	.884	1.356	.848	5.007	1.530
Pilot rating								
Pilot A	4	6.5	6	5	2.5	4	7.5	3
Pilot B	6.5	7	4.5	6.5	6	5.5	7	6
(combination task)								
M_p/M_q	.345	1.099	.333	1.042	-.063	.463	.351	.532
L_q/L_p	-.360	-1.176	-.354	-1.159	.066	-.535	-.364	-.576

TABLE 9.- EFFECT OF δ_3 ON EIGENVALUES OF FOUR TEST CONFIGURATIONS AT 60 KNOTS

Config. / δ_3	104	108	205	301
0	0.00812 ±j 0.2662 -.0233 -.6051 -.6345 ±j 1.7870 -5.6097 -22.7709	0.0427 ±j 0.3754 -.0404 0.552[illegible] -3.2465 -.6148 ±j 1.7971 -11.6048	0.0219 ±j 0.3294 -0.0306 -0.673 -2.1385 -.6149 ±j 1.7805 -9.3899	0.00227 ±j 0.2354 -.01842 -.6003 -.6332 ±j 1.7758 -9.8305 -37.6189
	F104	F108	F205	F301
38.6°	0.00818 ±j 0.2895 -.0283 -.6296 -.6318 ±j 1.7897 -6.6852 ±j 3.9932	0.0326 ±j 0.3708 -.0452 -.6346 -.5988 ±j 1.8029 -2.7689 ±j 1.6707	0.01797 ±j 0.3425 -.0443 -.7868 -1.1920 -3.9640 -.6076 ±j 1.7670	0.0107 ±j 0.3137 -.037 -.576 -3.506 -.612 ±j 1.765 -9.866

TABLE 10.- COMPARISON OF NASA AND RAE TEST CONFIGURATIONS

Config.	Lock no. γ	$\frac{K_\beta}{I_\beta \Omega^2}$	Damping, M_q, sec^{-1}	Sensitivity, M_{δ_e}, $rad/sec^2/cm$,
RAE D3	4.10	0.30	-7.00	0.787
NASA A107	3.00	.30	-7.00	.802
RAE A2	8.20	.05	-.60	.153
RAE A1	11.71	.05	-.40	.122
NASA 106	9.00	.15	-.881	.134
NASA 101	3.00	0	-.665	.036

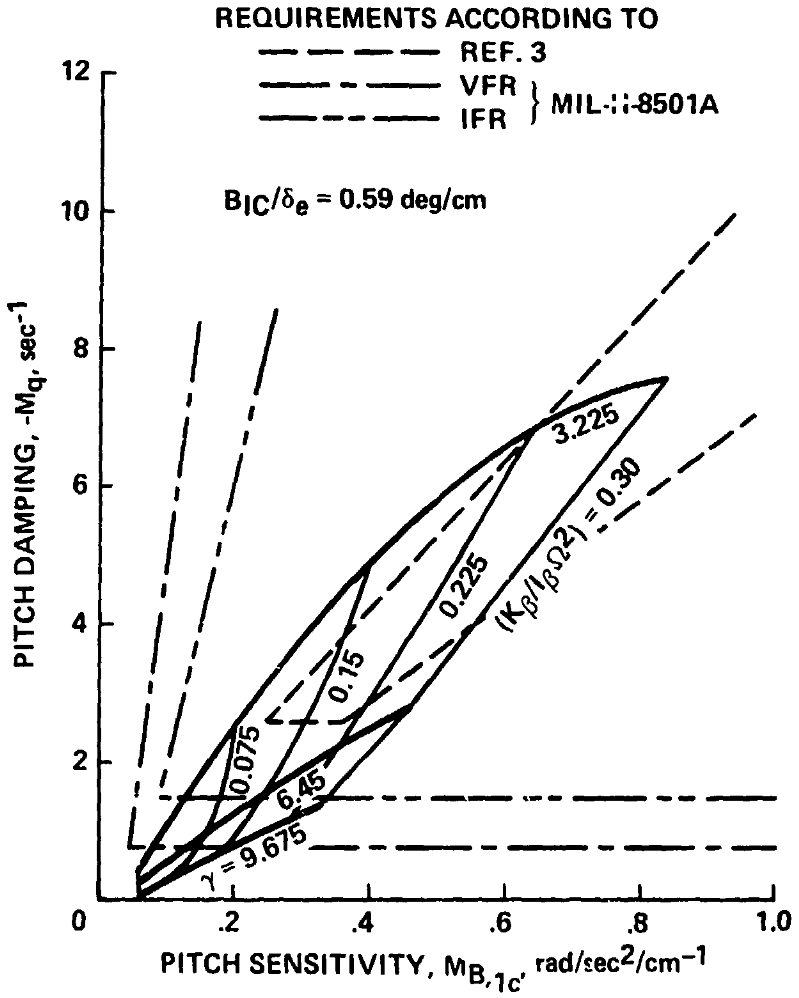


Figure 1.- Effect of spring restraint and Lock number on pitch damping and sensitivity.

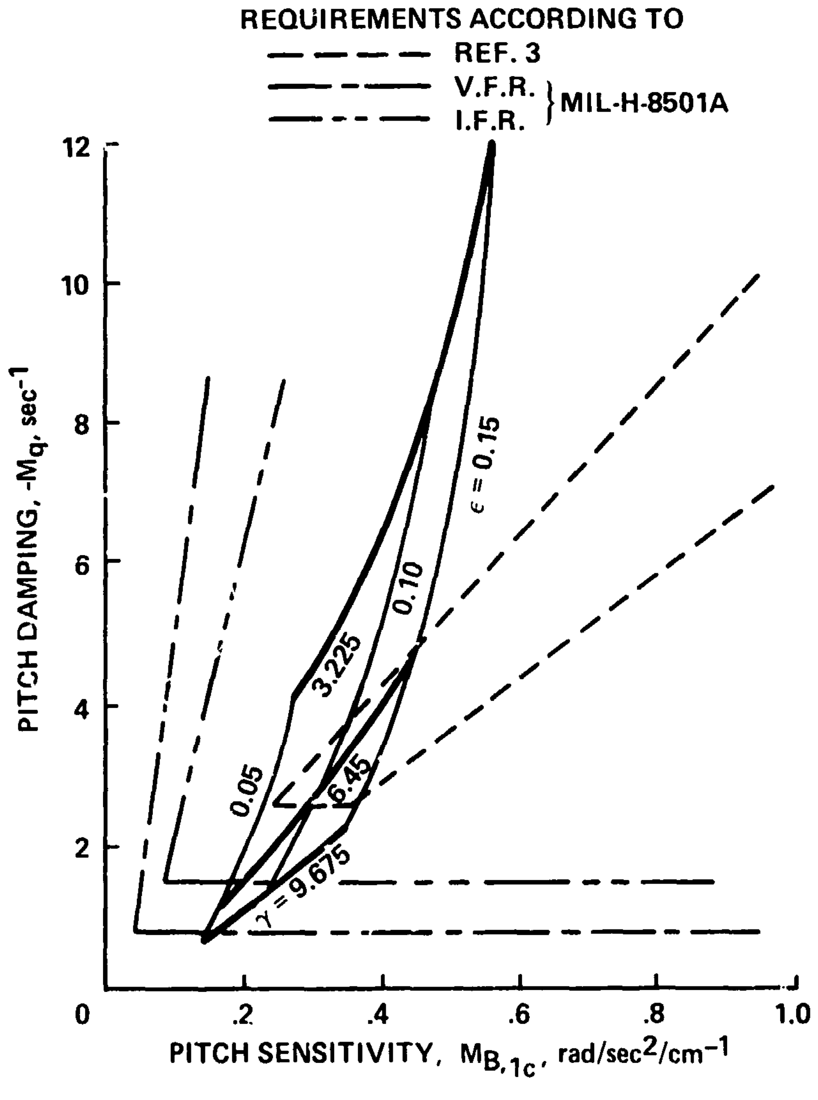


Figure 2.- Effect of hinge offset and Lock number on pitch damping and sensitivity.

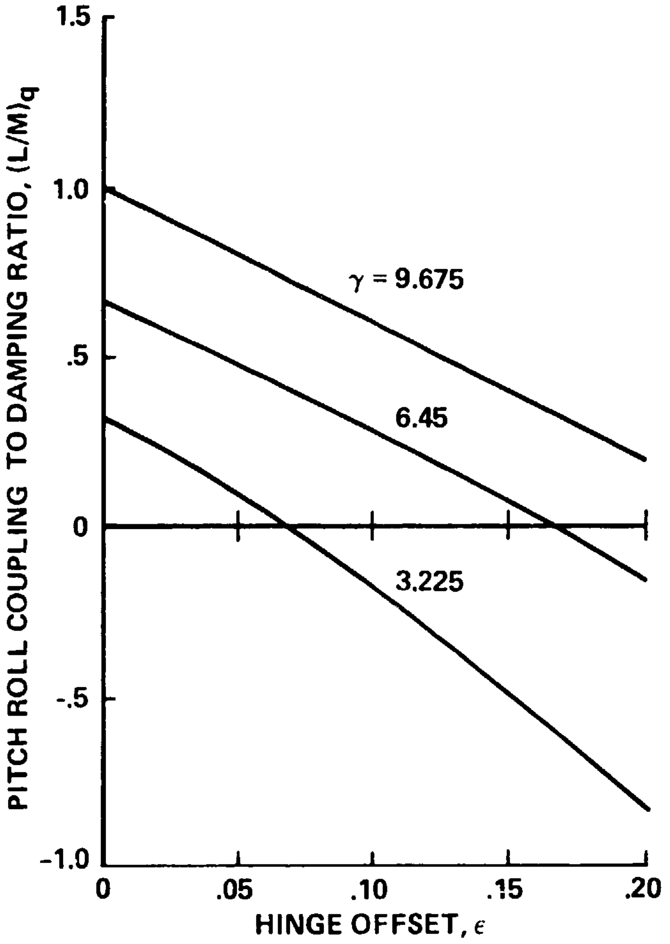


Figure 3.- Effect of hinge offset and Lock number on pitch-roll coupling at hover.

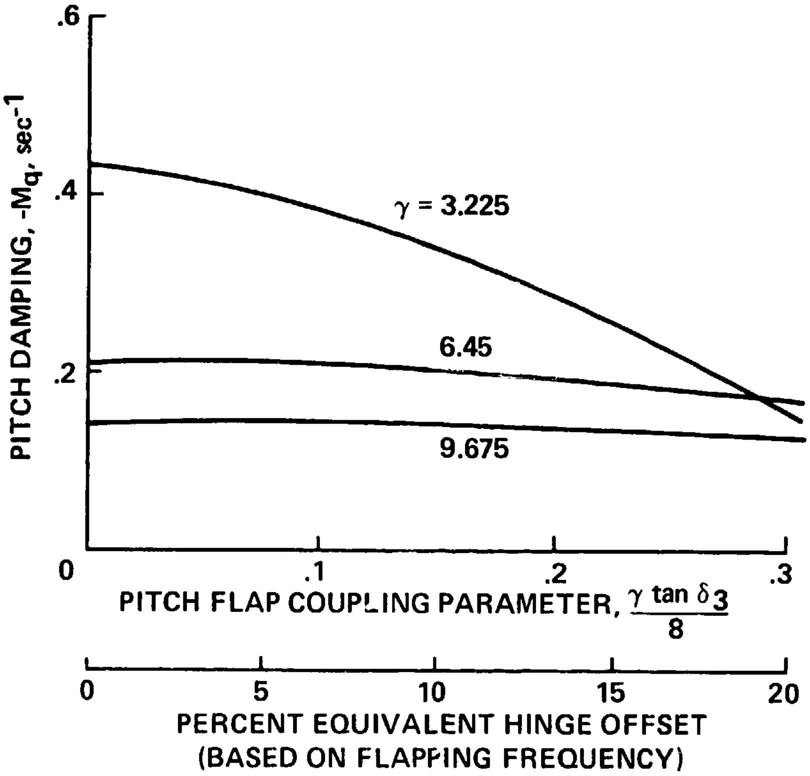


Figure 4.- Effect of pitch-flap coupling on pitch damping (hover).

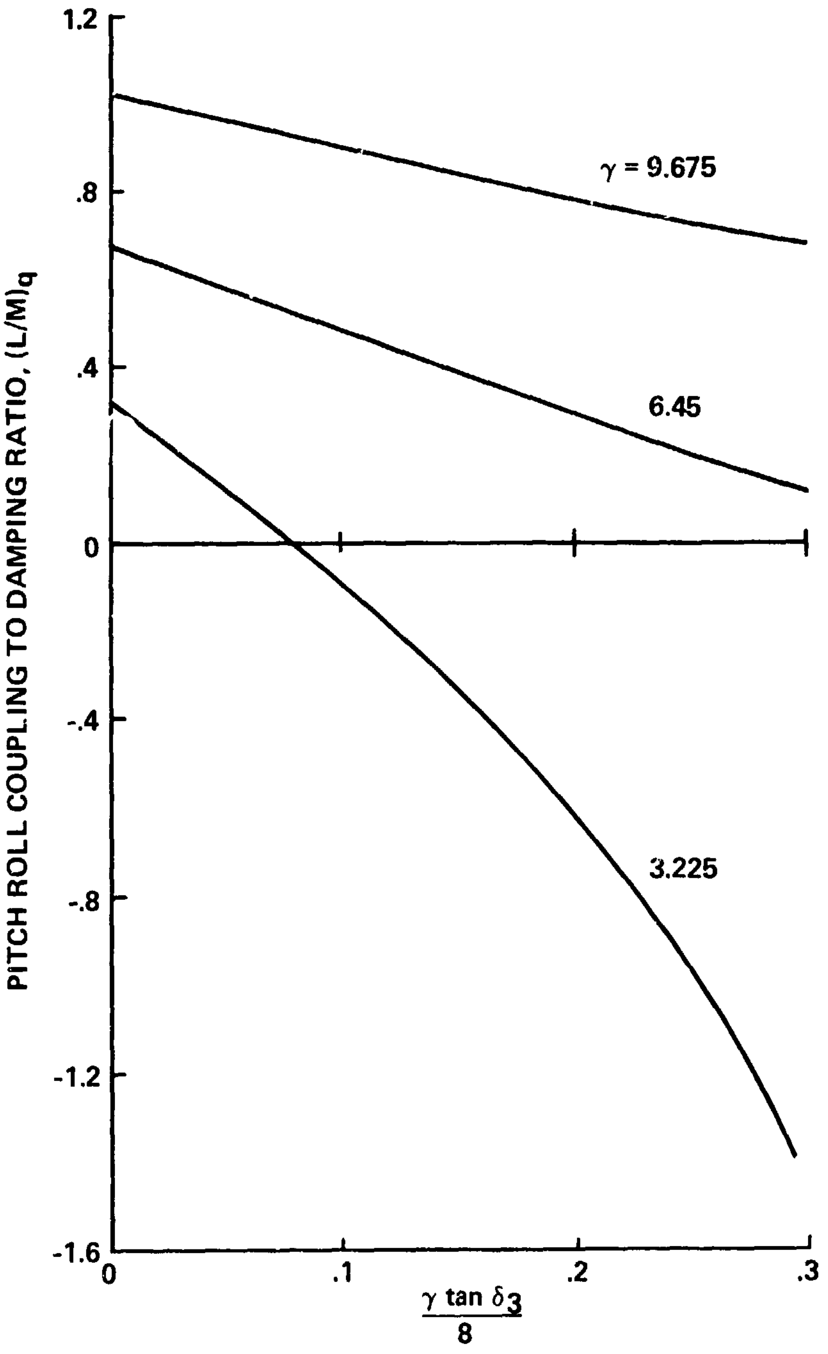
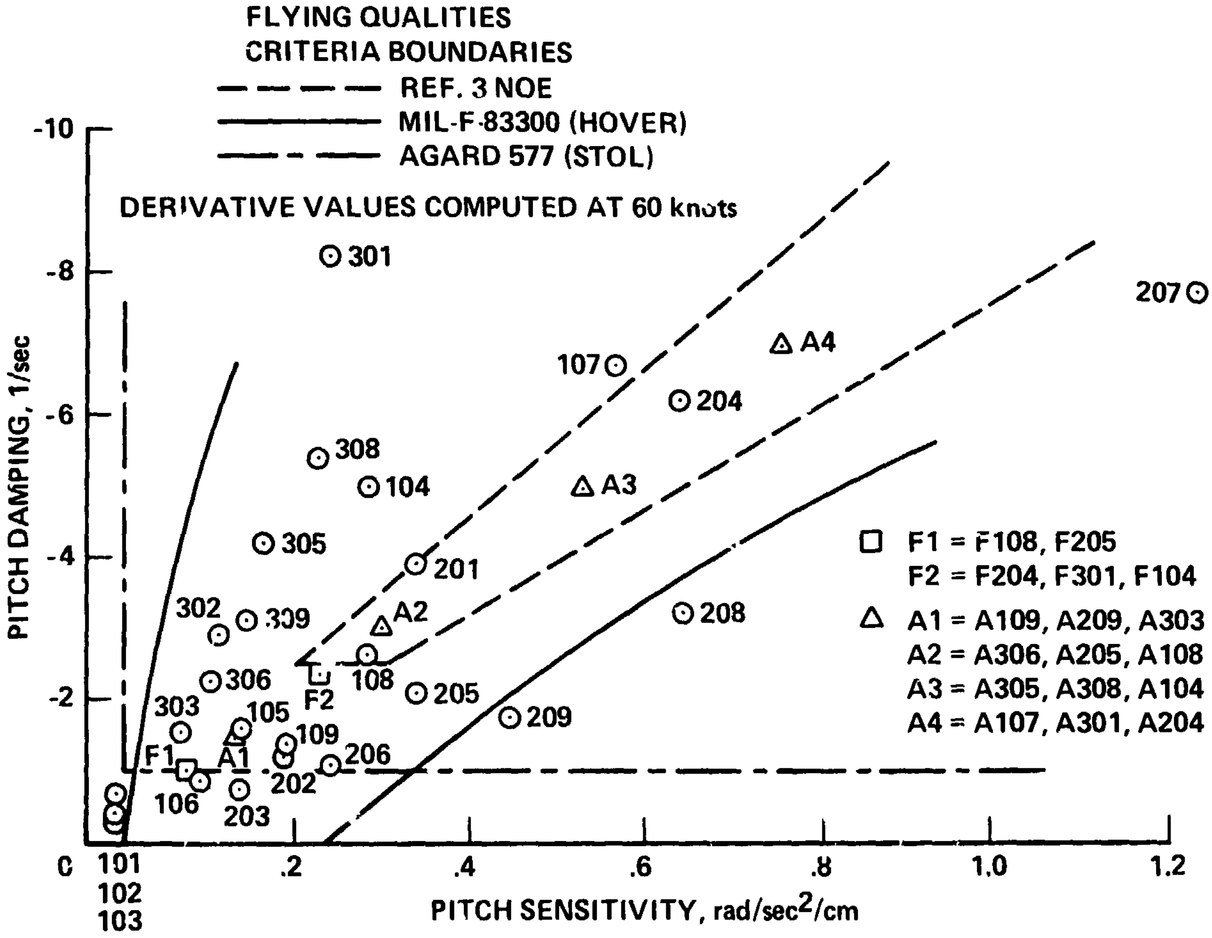
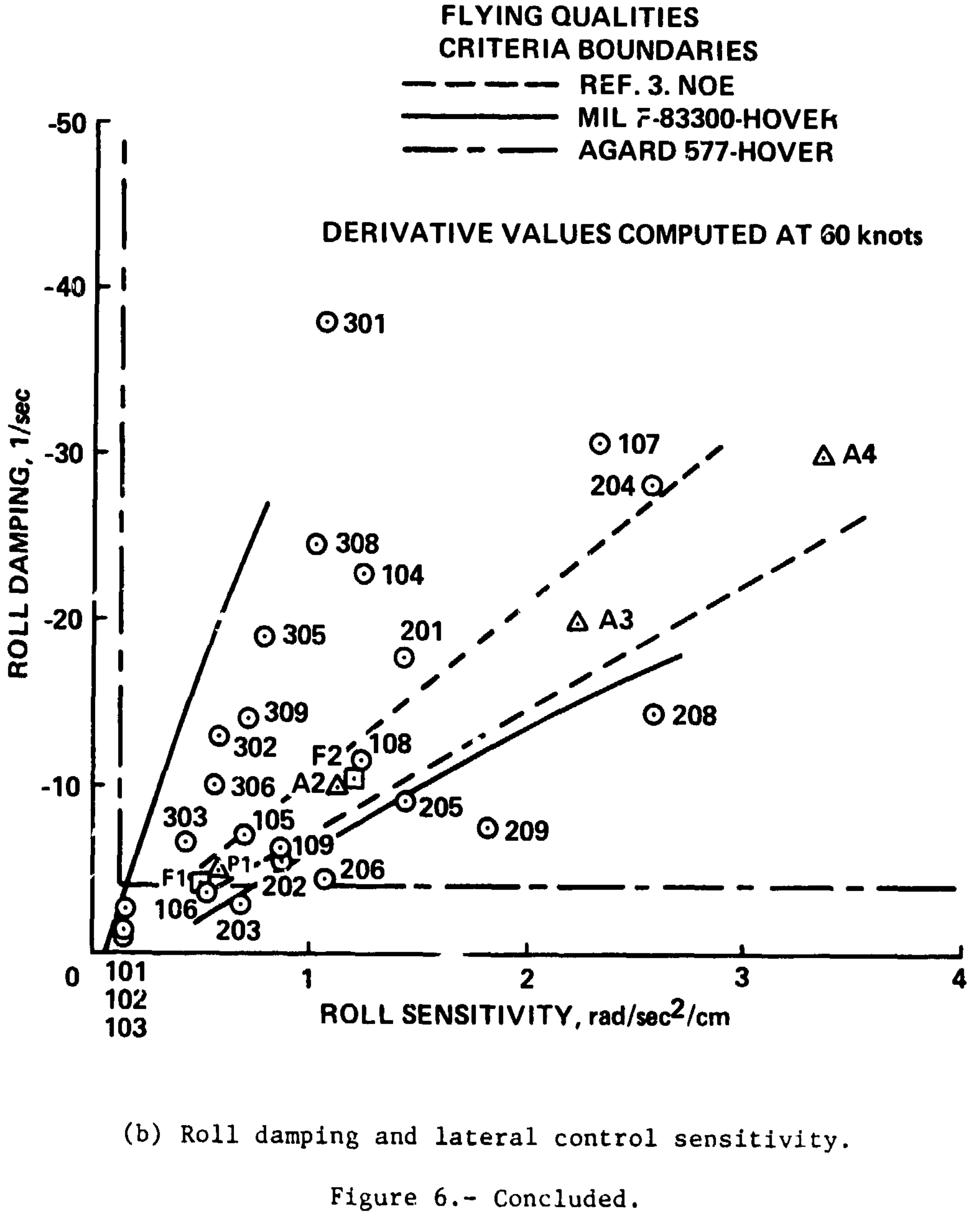


Figure 5.- Effecc of pitch-flap coupling on pitch-roll coupling at hover.



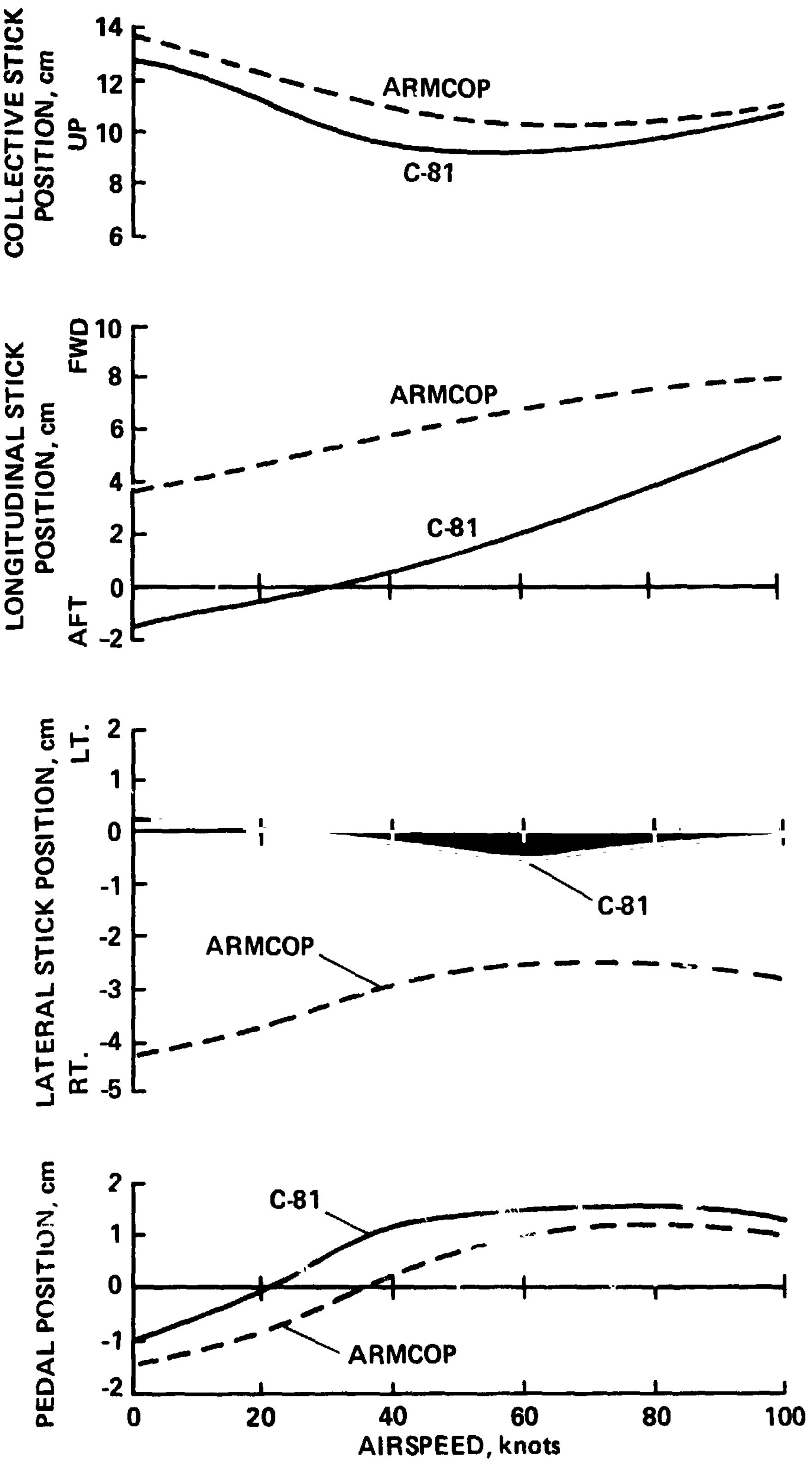
(a) Pitch damping and longitudinal control sensitivity.

Figure 6.- Test configuration values.



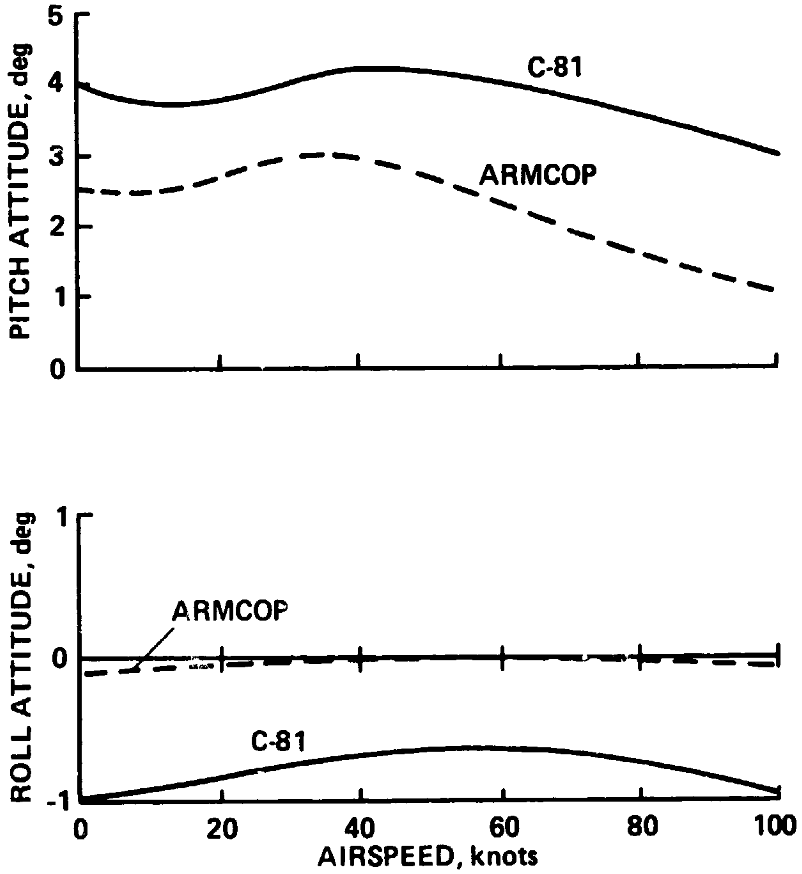
(b) Roll damping and lateral control sensitivity.

Figure 6.- Concluded.



(a) Trim control positions.

Figure 7.- Comparison of ARMCOP and C-81 models of UH-1H.



(b) Trim attitudes.

Figure 7.- Concluded.

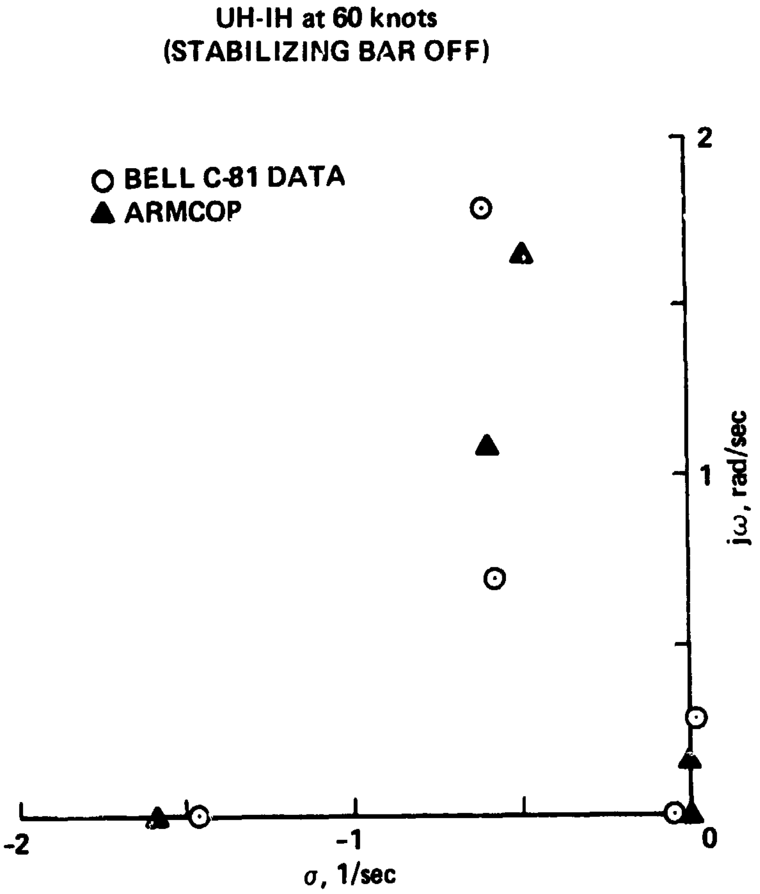
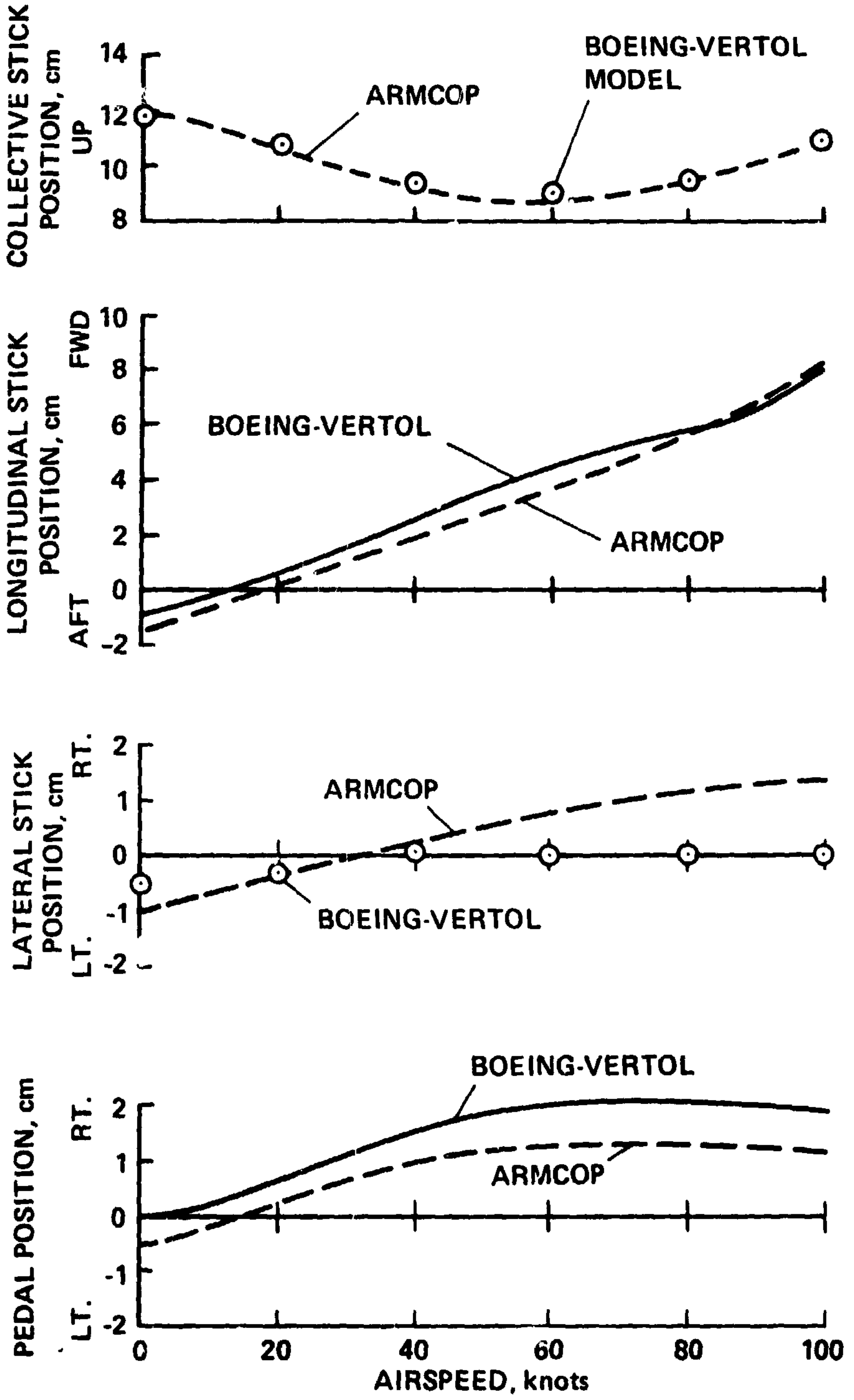
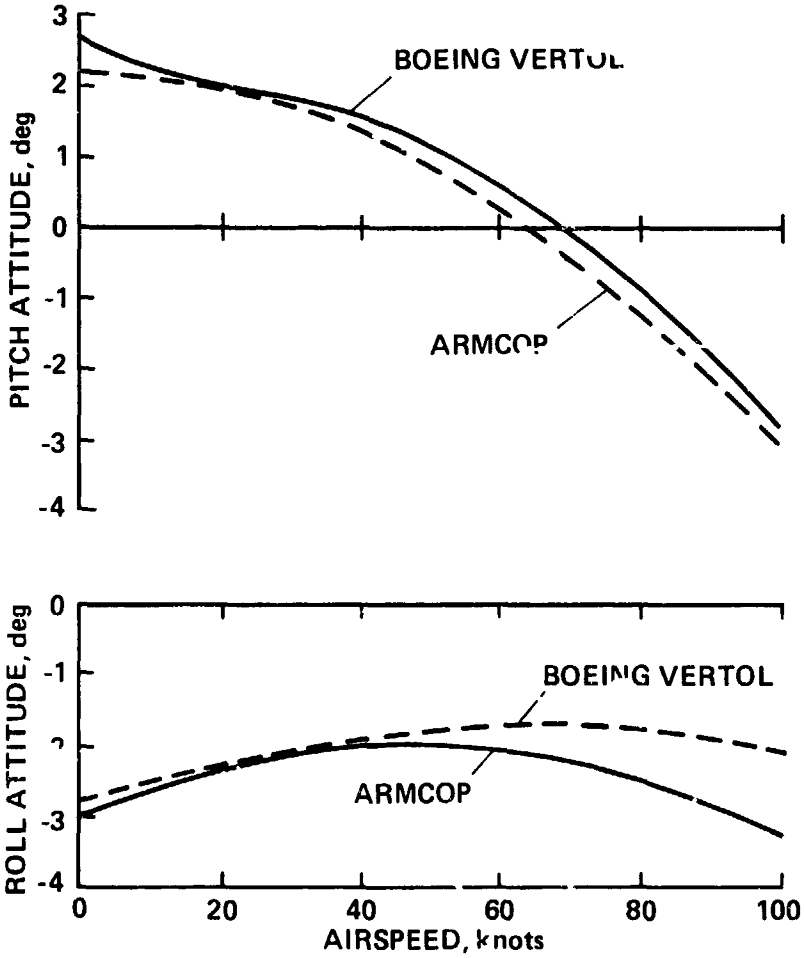


Figure 8.- A comparison of eigenvalues of rigid body modes of UH-1H obtained from C-81 and ARMCOP simulations.



(a) Trim control positions.

Figure 9.- Comparison of ARMCOP and Boeing-Vertol models of BO-105.



(b) Trim attitudes.

Figure 9.- Concluded.

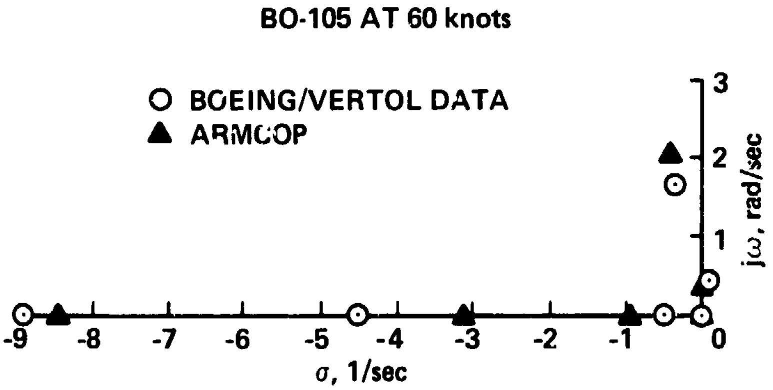


Figure 10.- A comparison of eigenvalues of rigid body modes of BO-105 obtained by ARMCOP and Vertol simulations.

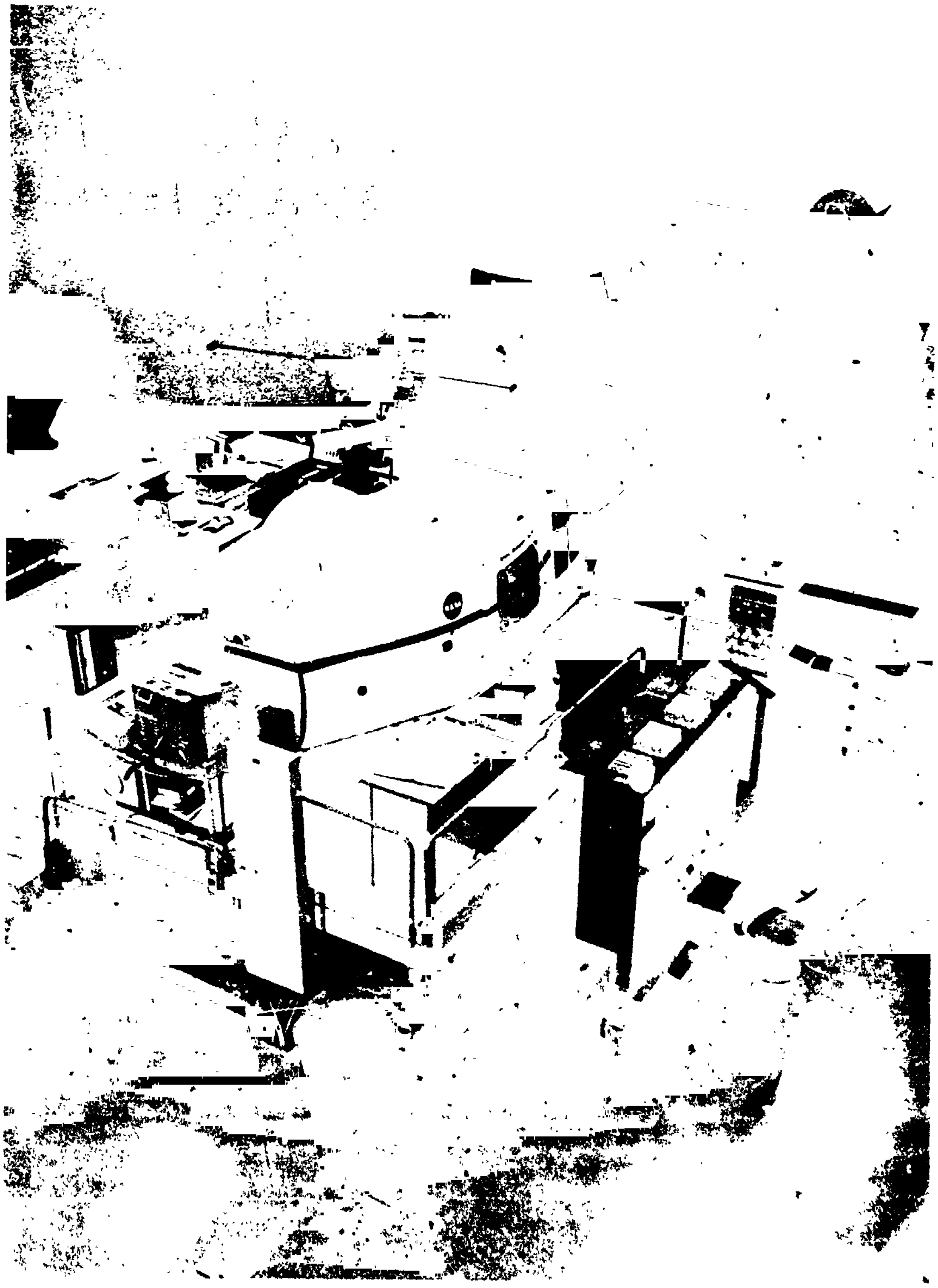


Figure 11.- Ames S-19 simulator.

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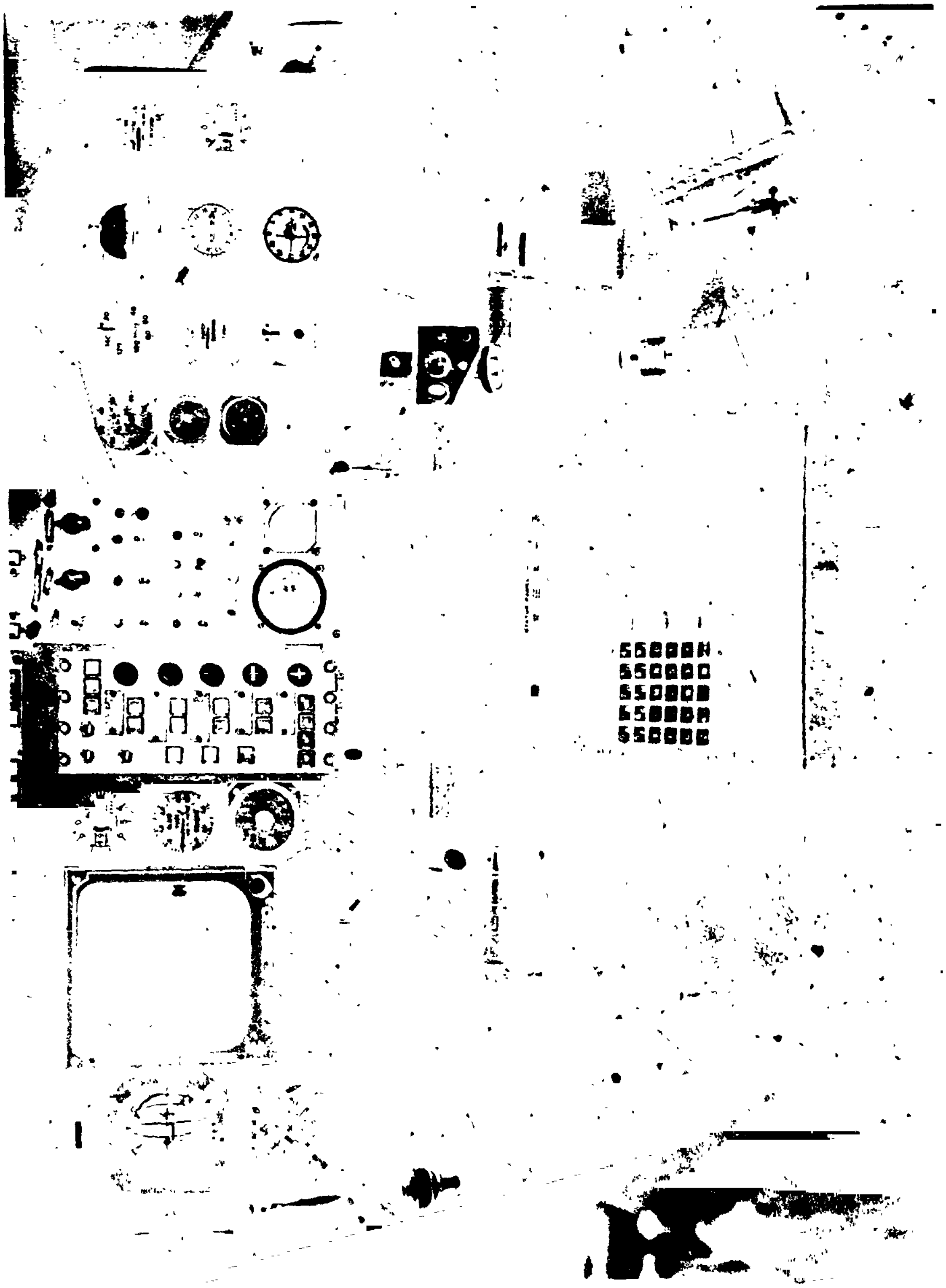

Figure 12.- Pilot's instrument panel — S-19 (right side).

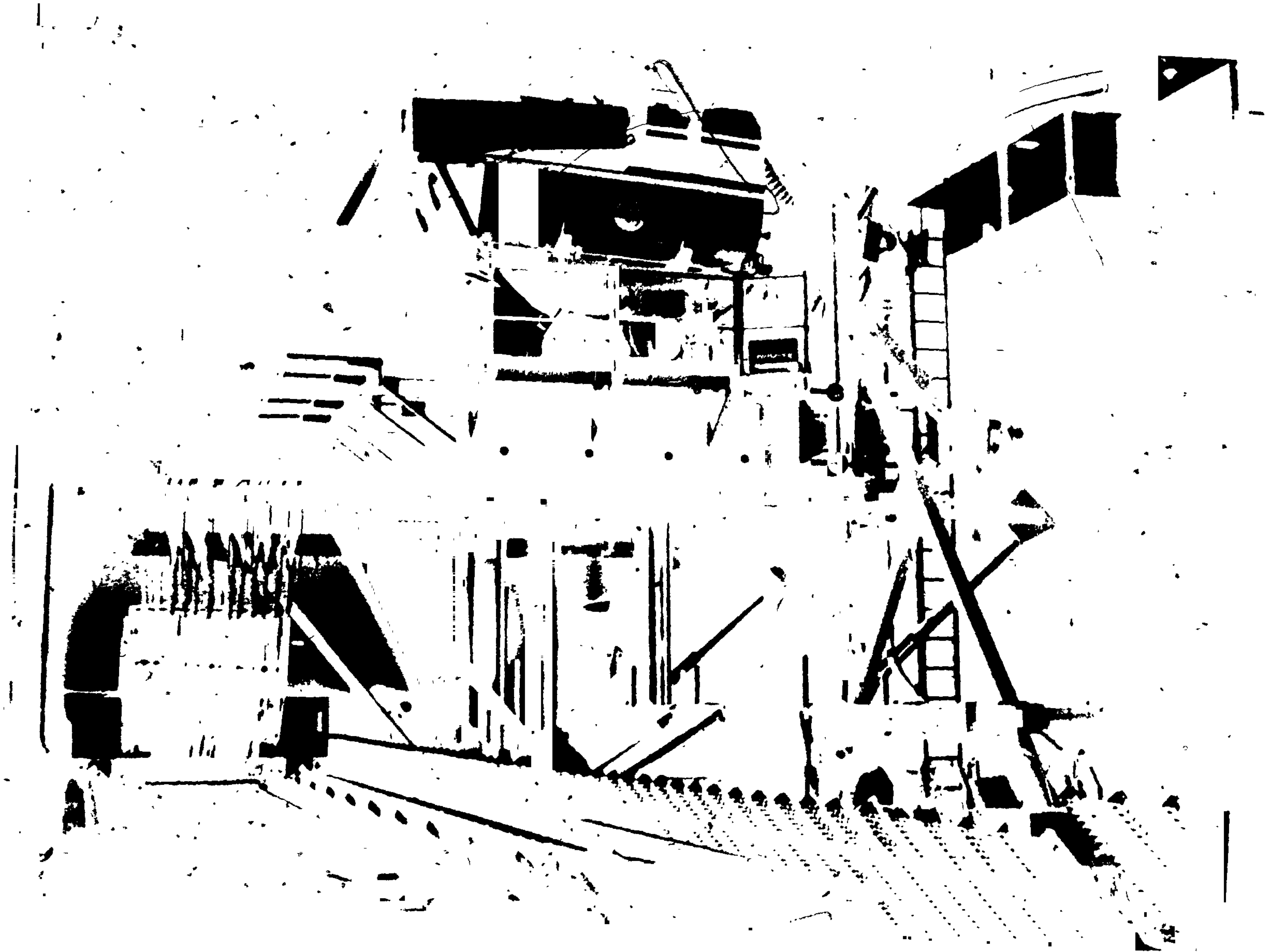

Figure 13.- Flight simulator for advanced aircraft.

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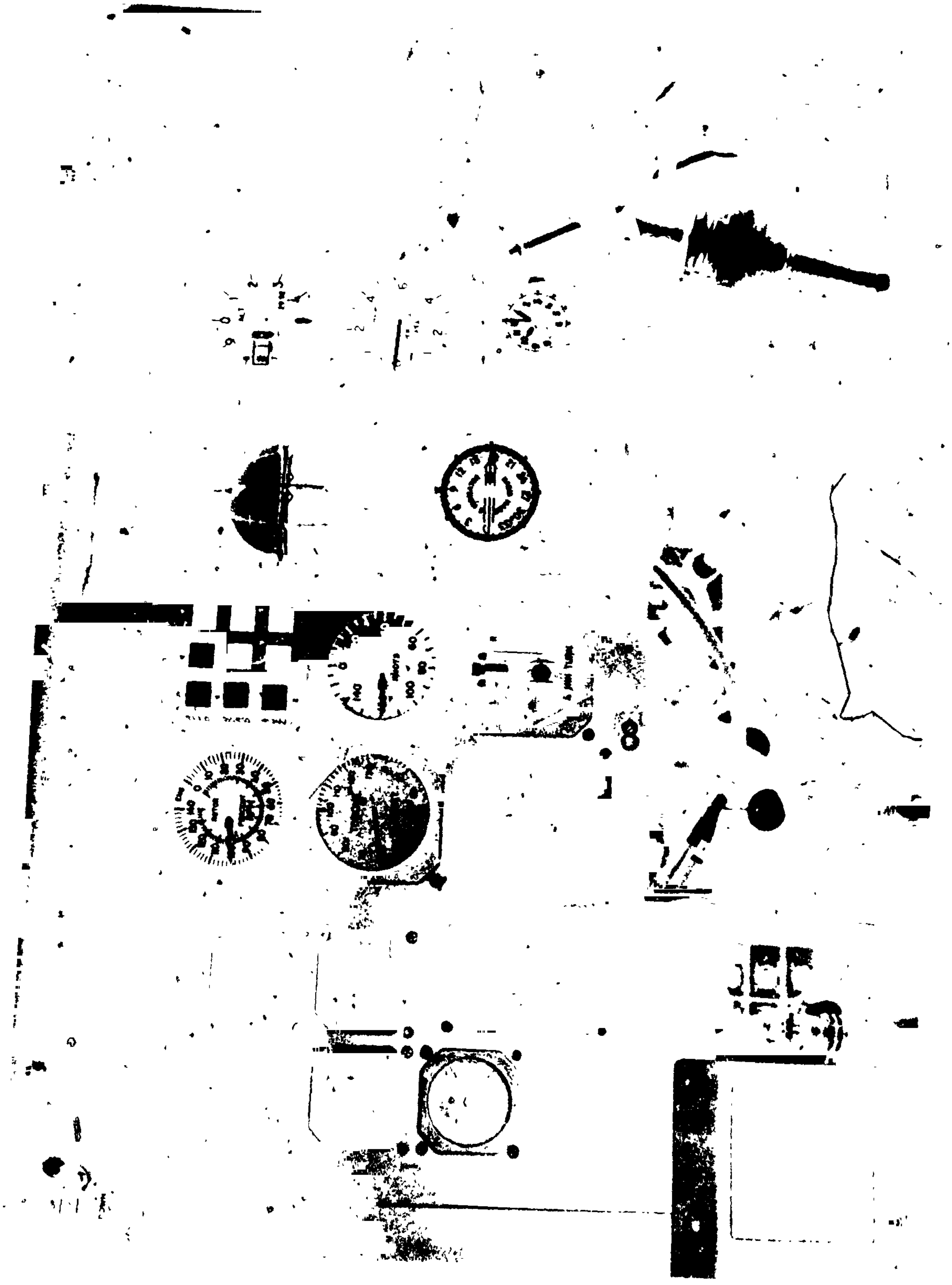

Figure 14.- Pilot's control console in FSAA cab.

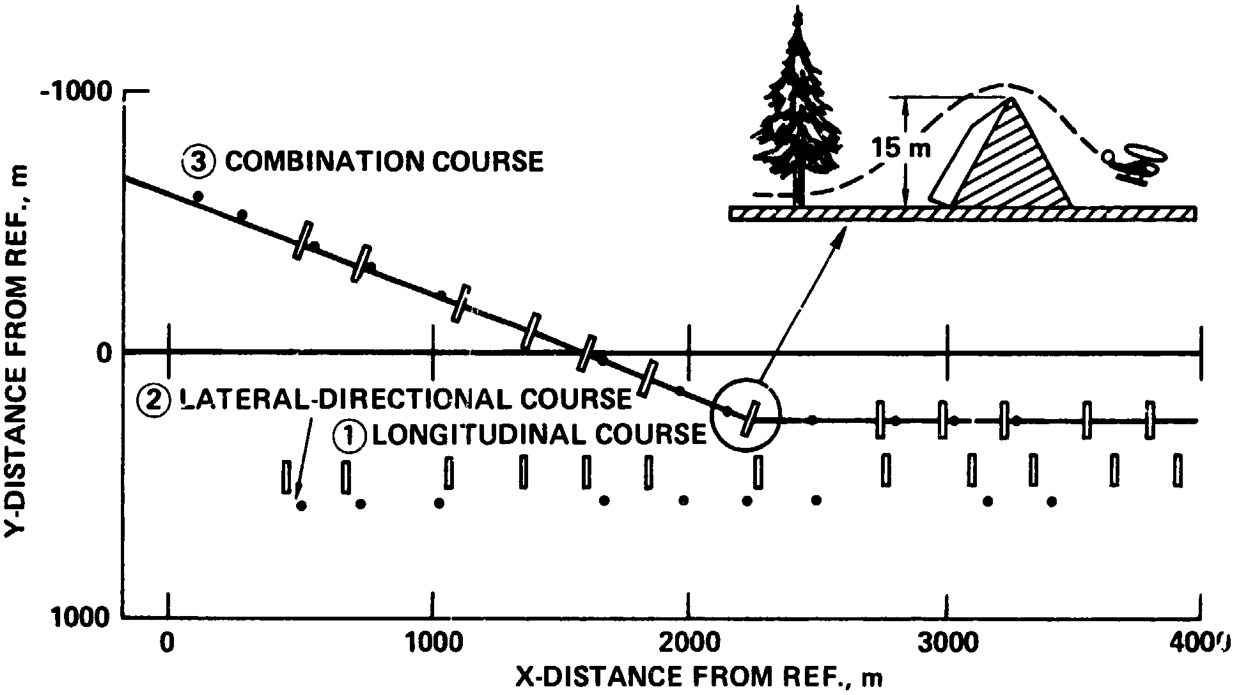

Figure 15.- Course layout, scale 1:600.

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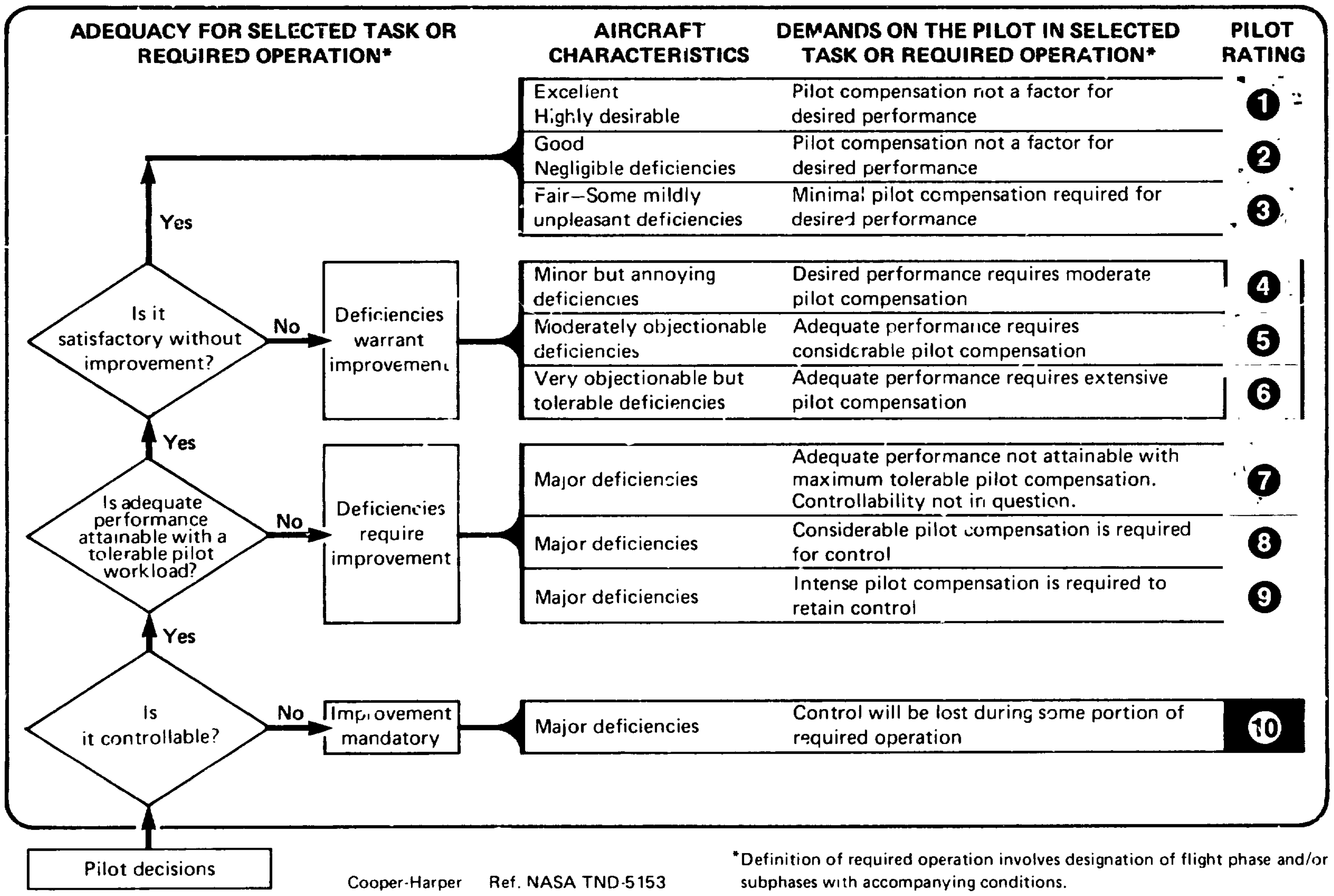
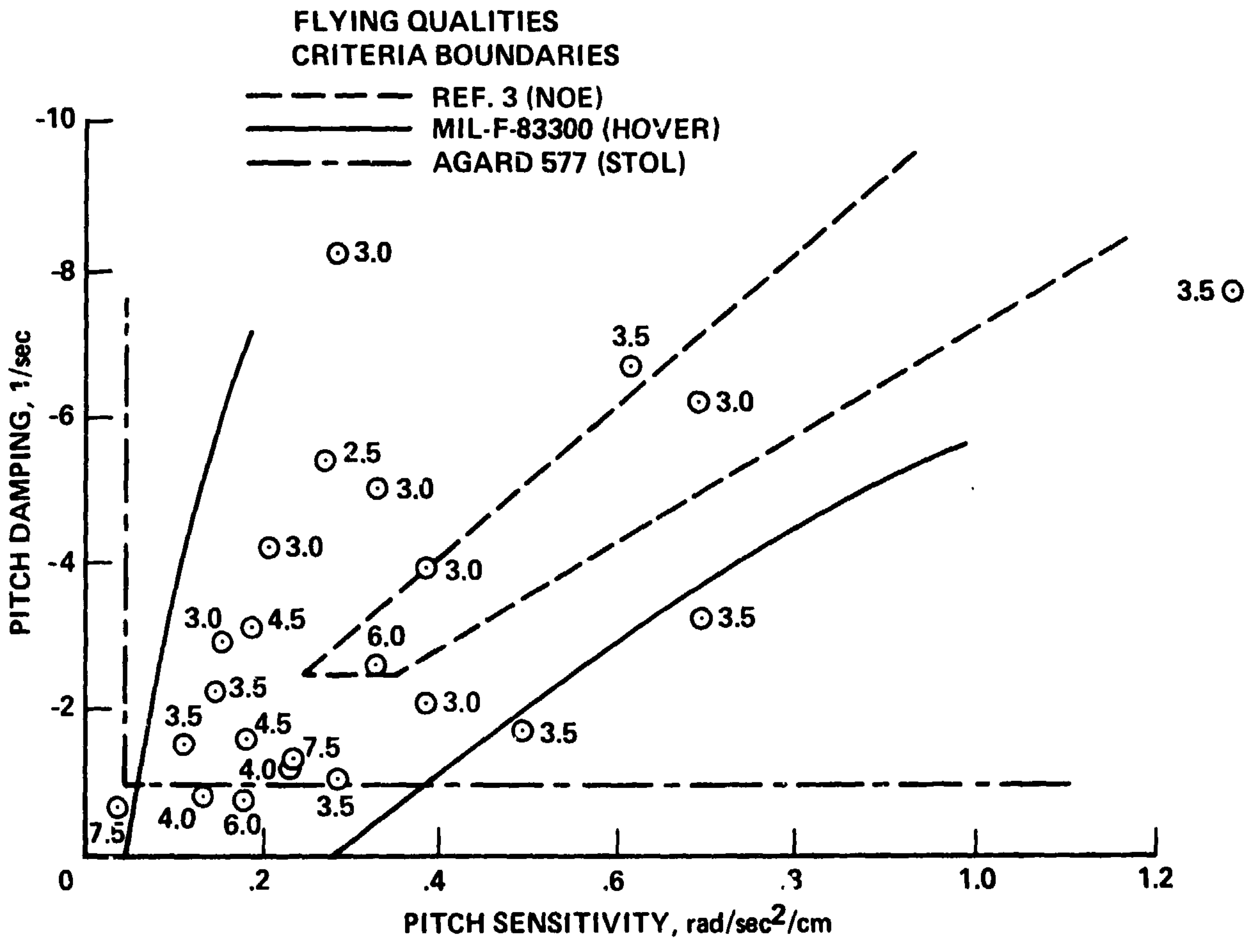
Figure 16.- Terrain model, 1:400 scale.



AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
Excellent Highly desirable	Pilot compensation not a factor for desired performance	❶
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	❷
Fair—Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	❸
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	❹
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	❺
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	❻
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question.	❼
Major deficiencies	Considerable pilot compensation is required for control	❽
Major deficiencies	Intense pilot compensation is required to retain control	❾
Major deficiencies	Control will be lost during some portion of required operation	❿

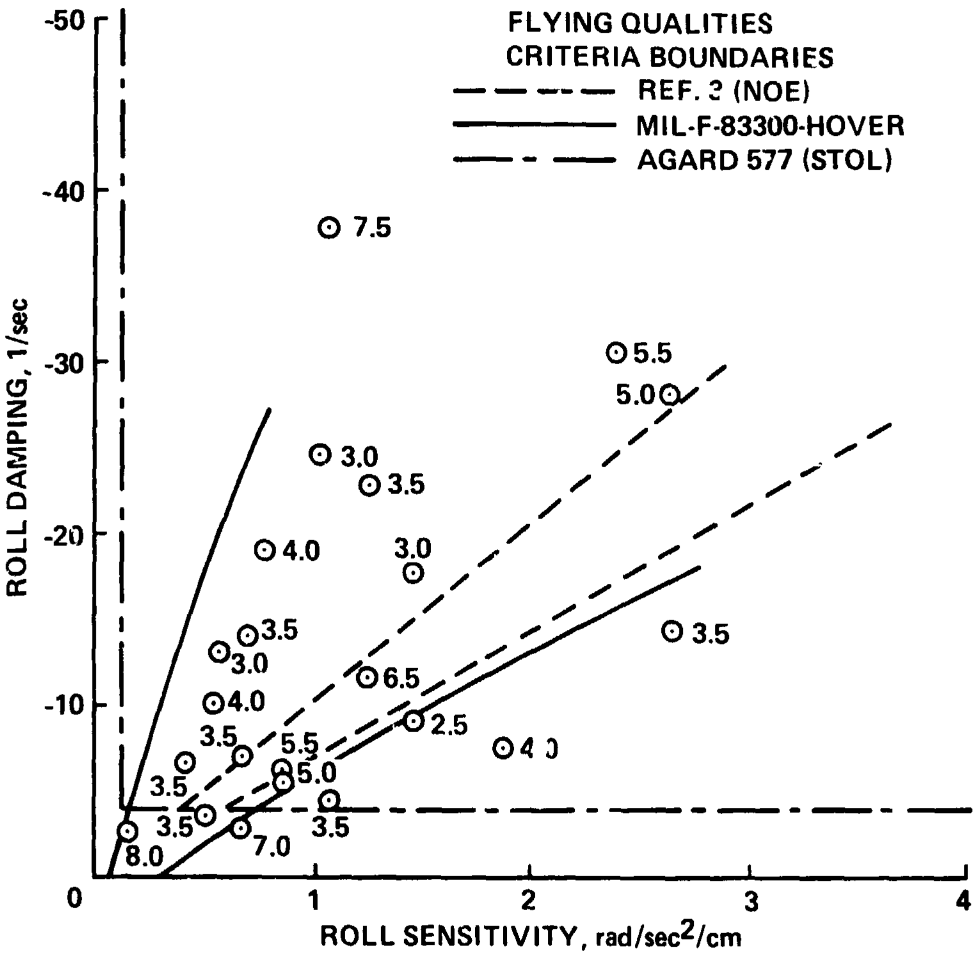
*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Figure 17.- Cooper-Harper handling qualities rating scale.



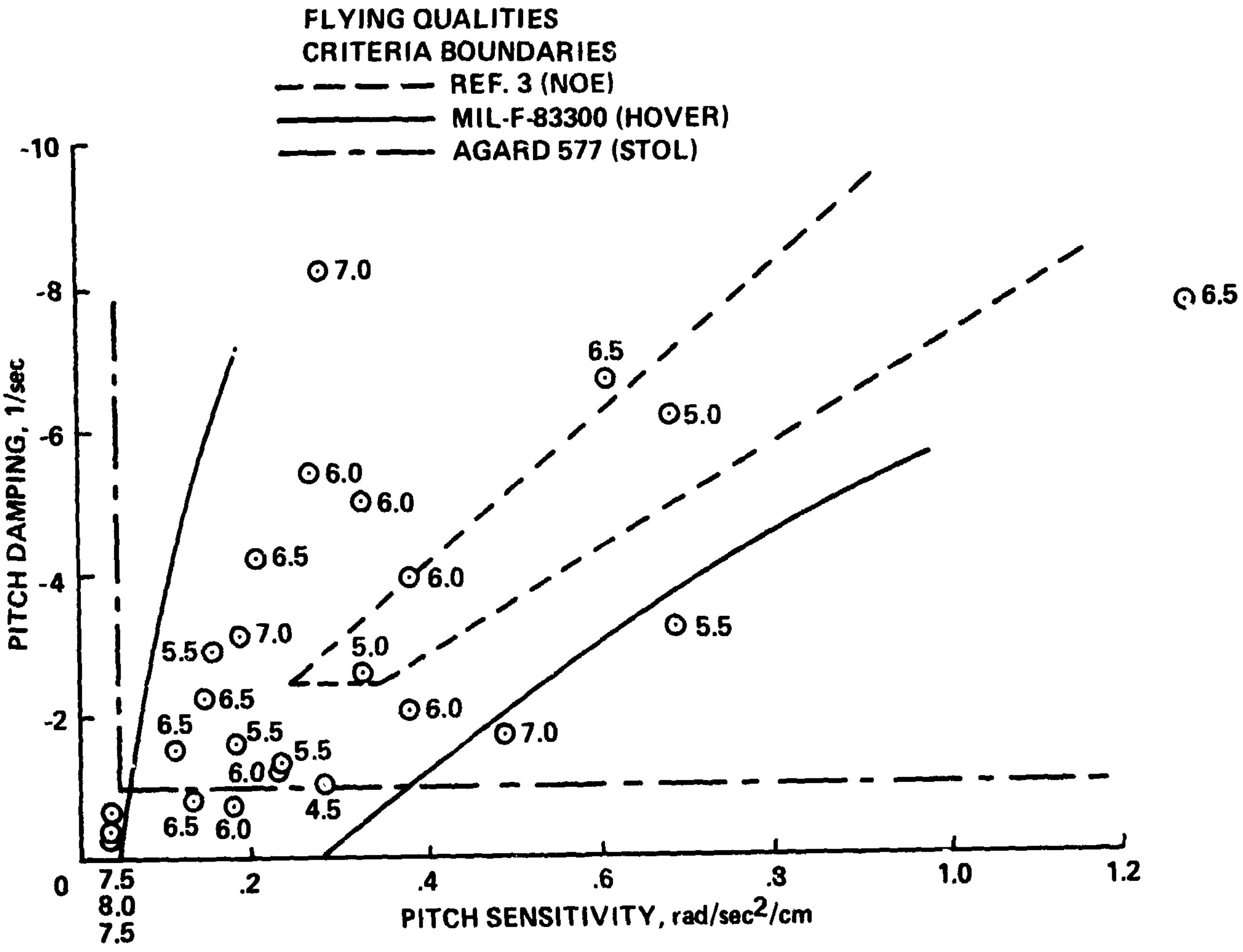
(a) Longitudinal-vertical task — pilot A.

Figure 18.- Pilot ratings.



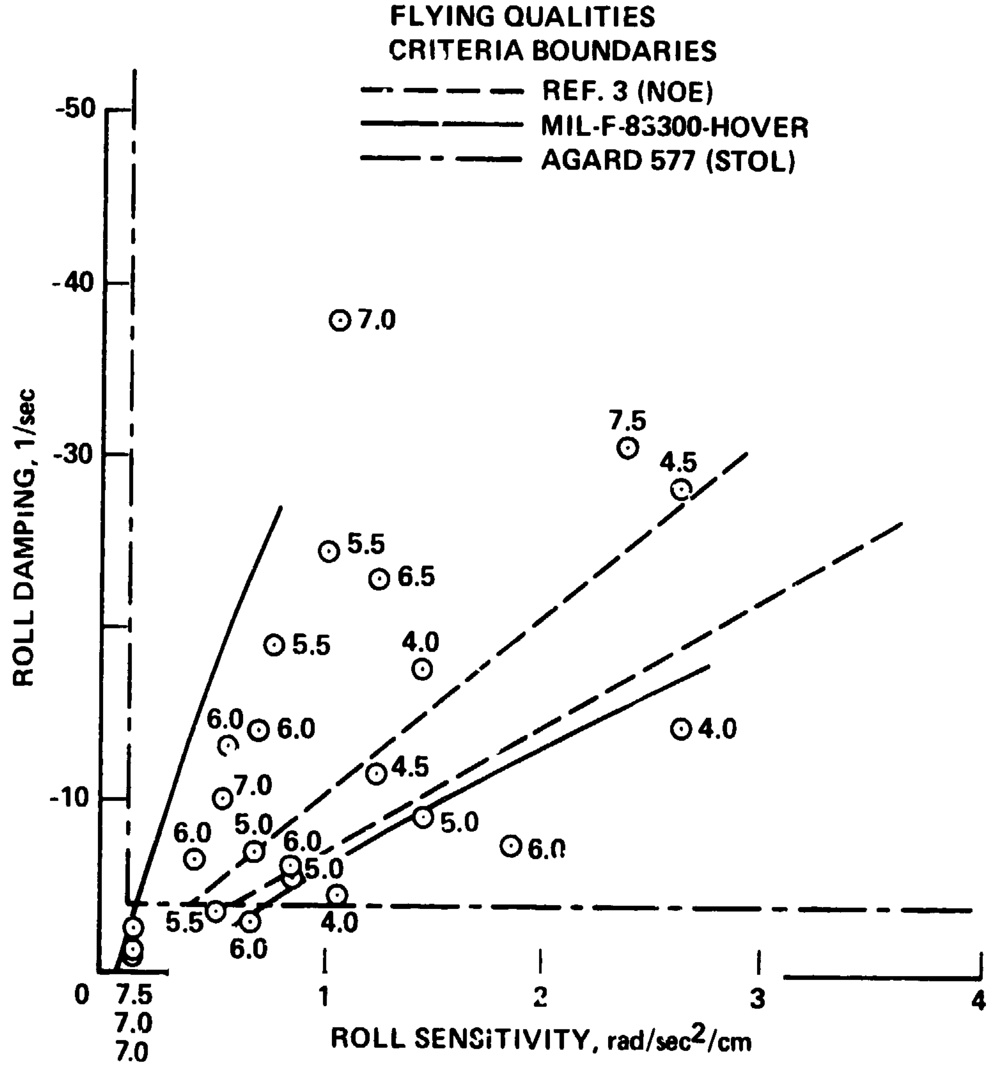
(b) Lateral-directional task — pilot A.

Figure 18.- Continued.



(c) Longitudinal-vertical task — pilot B.

Figure 18.- Continued.



(d) Lateral-directional task – pilot B.

Figure 18.- Concluded.

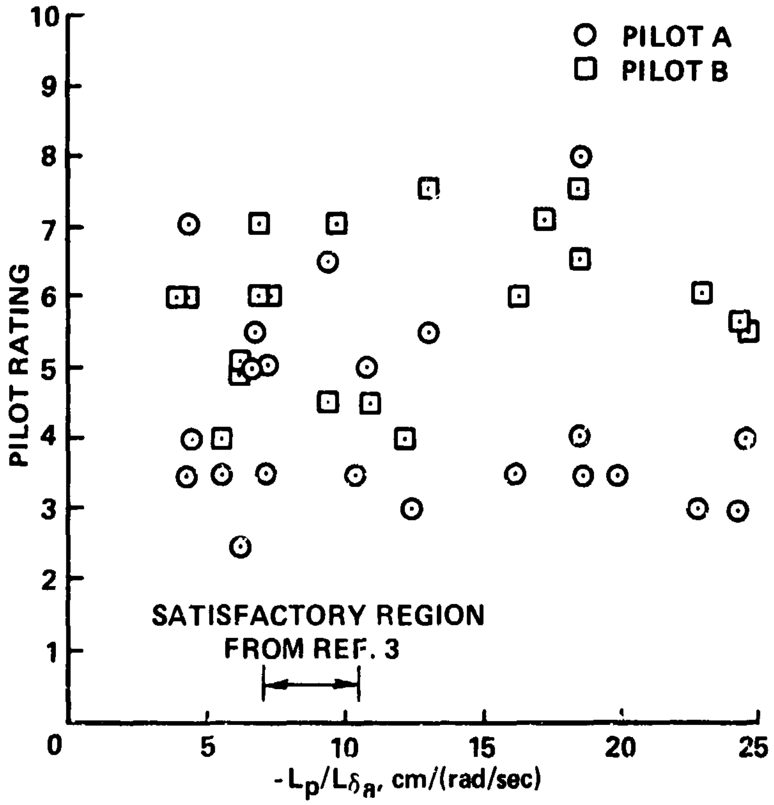


Figure 19.- Effect of ratio of roll damping to roll sensitivity on pilot opinion rating.

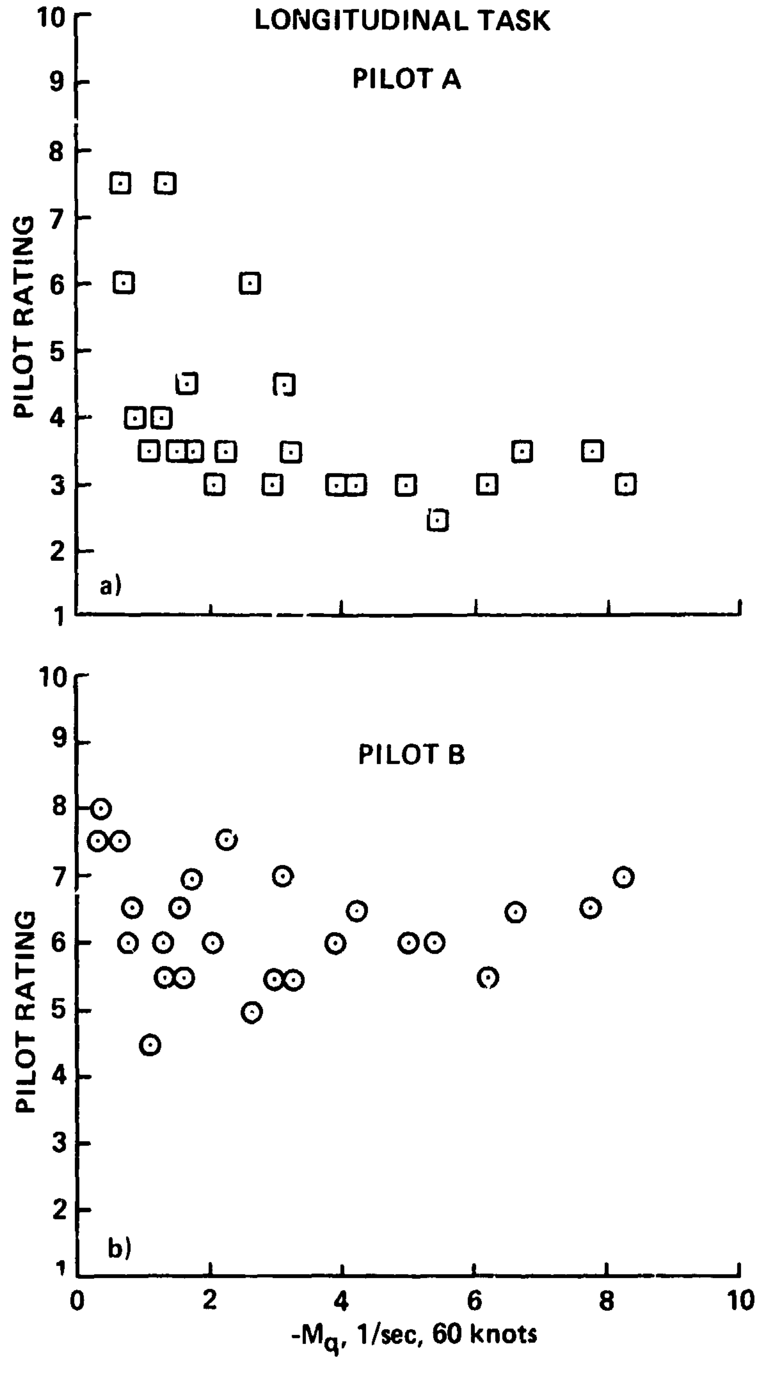


Figure 20.- Pilot rating vs pitch damping.

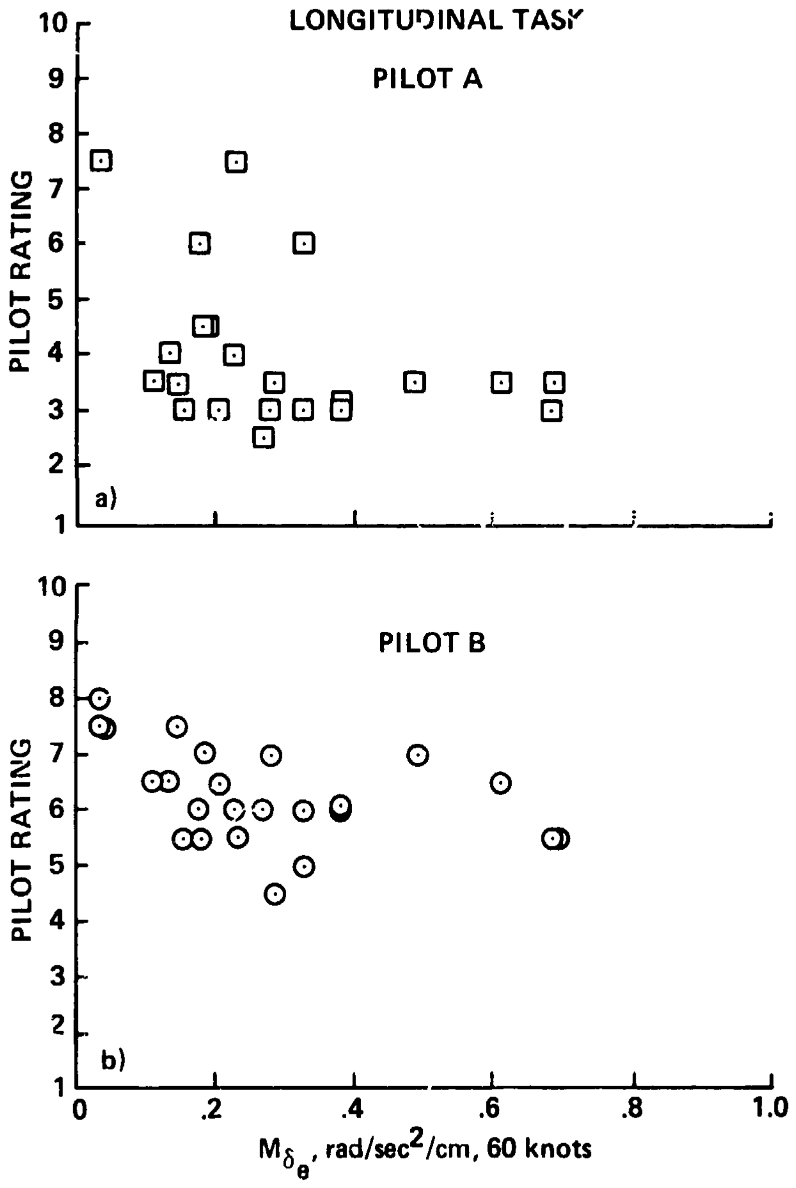


Figure 21.- Pilot rating vs pitch sensitivity.

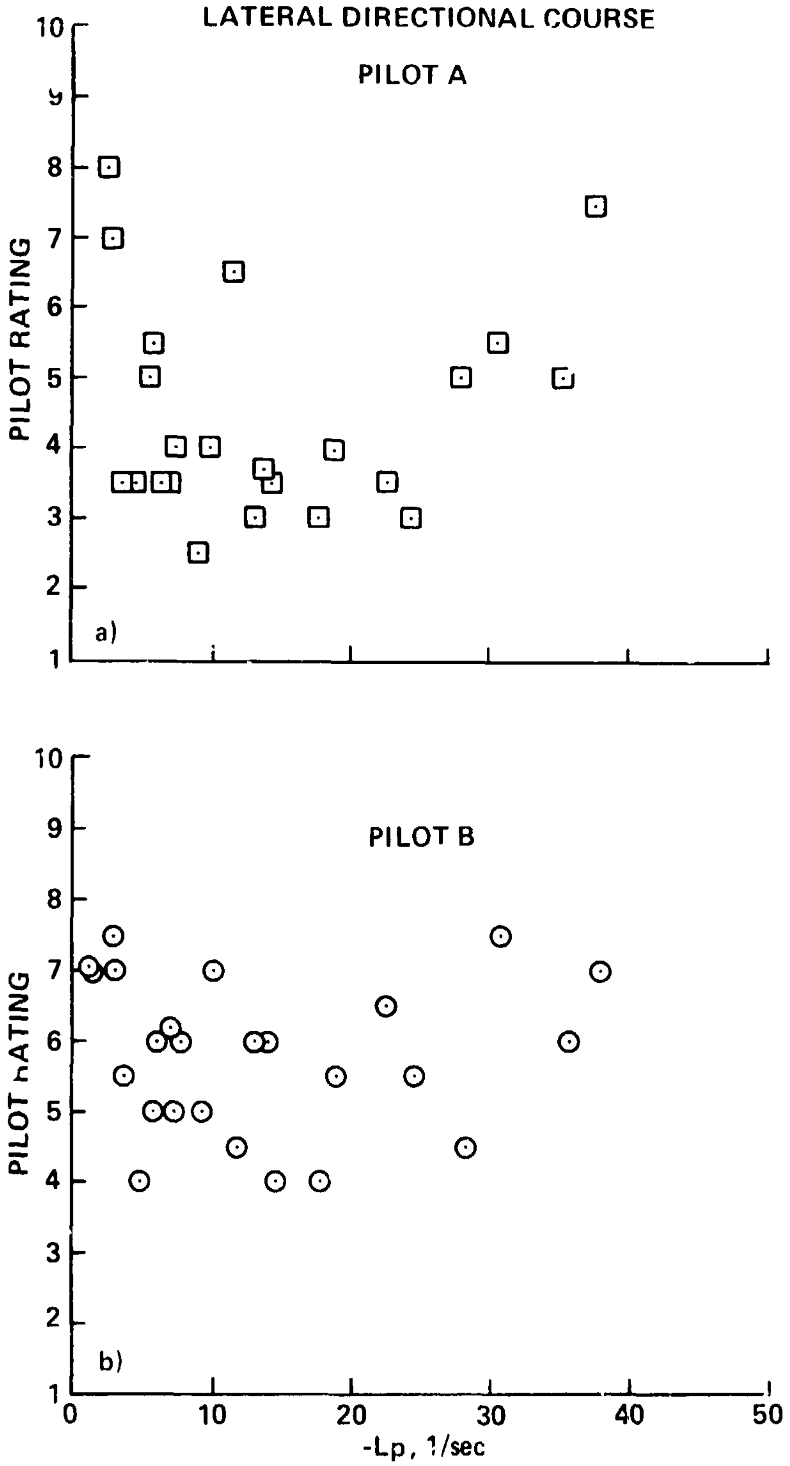


Figure 22.- Pilot rating vs roll damping.

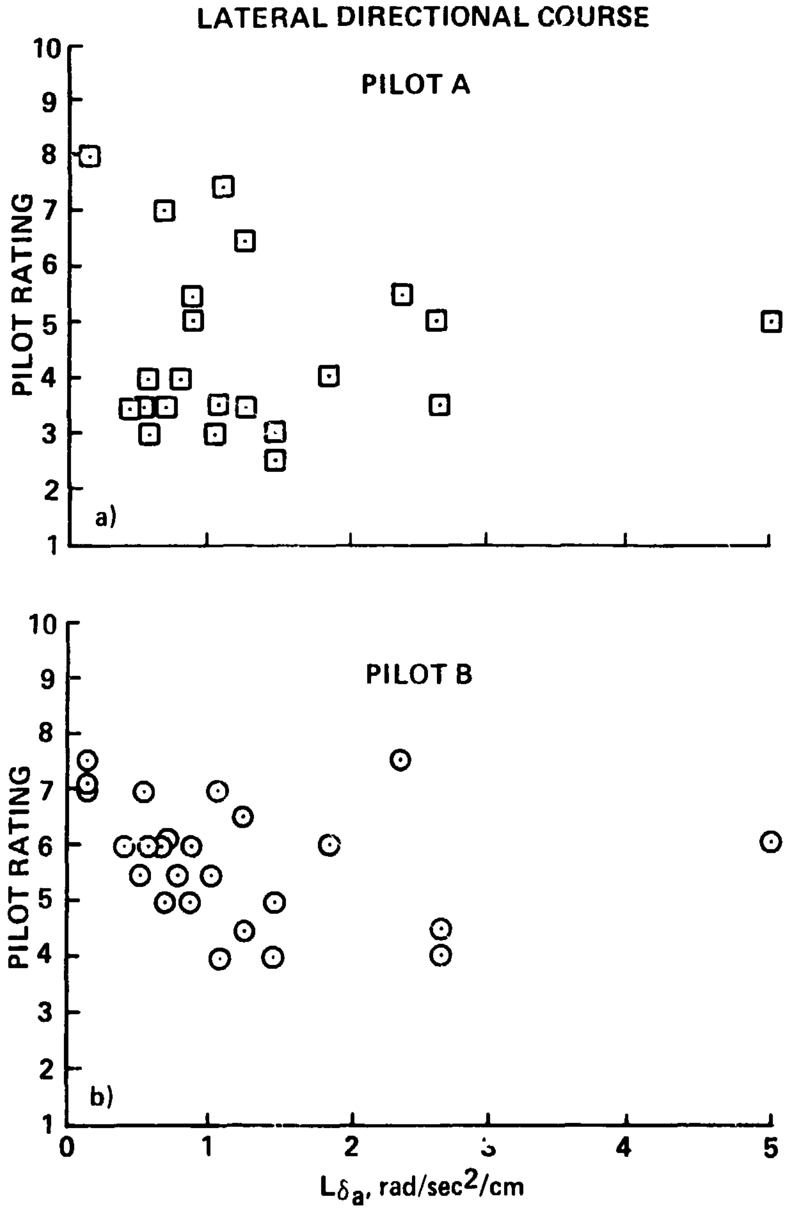


Figure 23.- Pilot rating vs roll sensitivity.

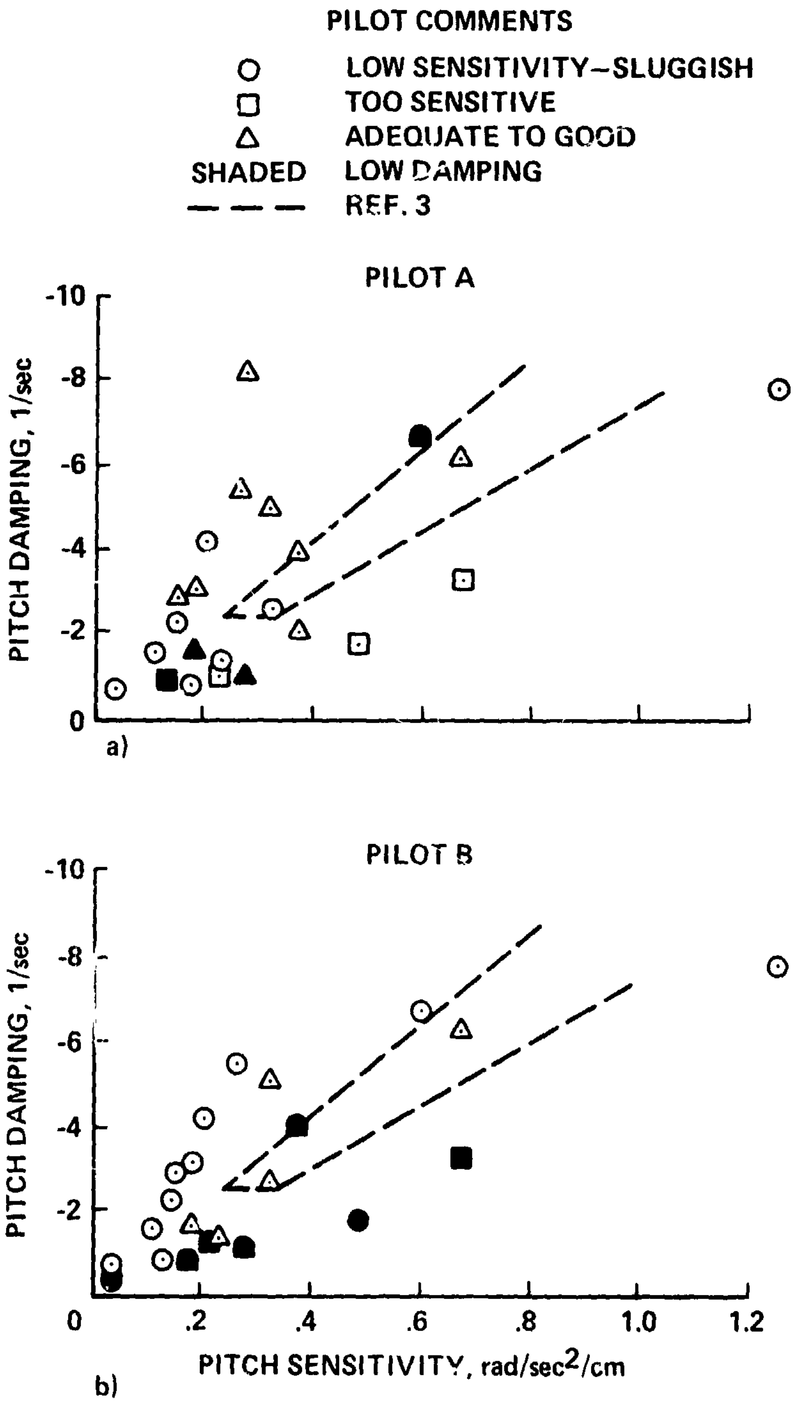


Figure 24.- Relationship between pilot comments and helicopter pitch damping and sensitivity.

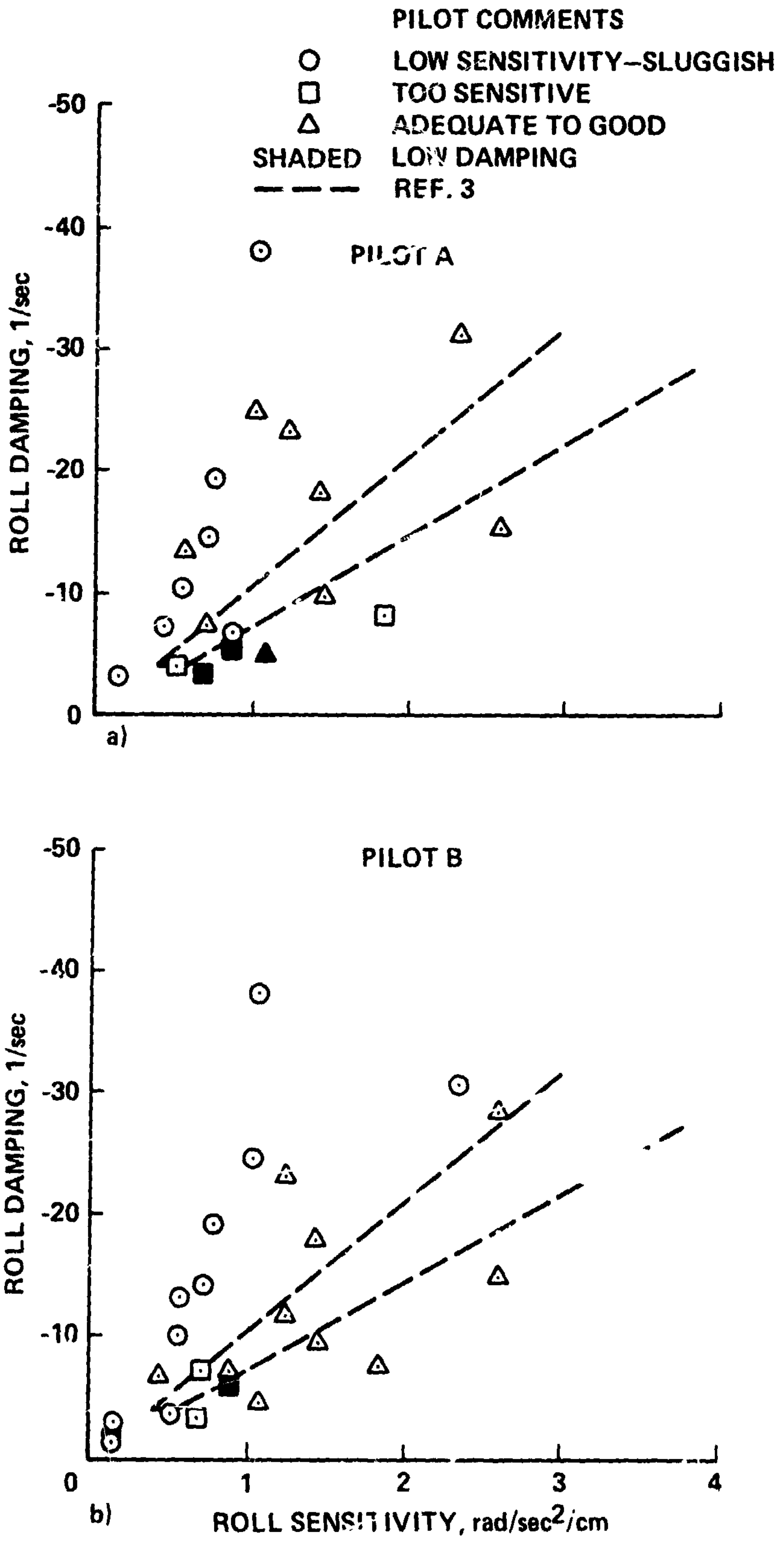


Figure 25.- Relationship between pilot comments and helicopter roll damping and sensitivity.

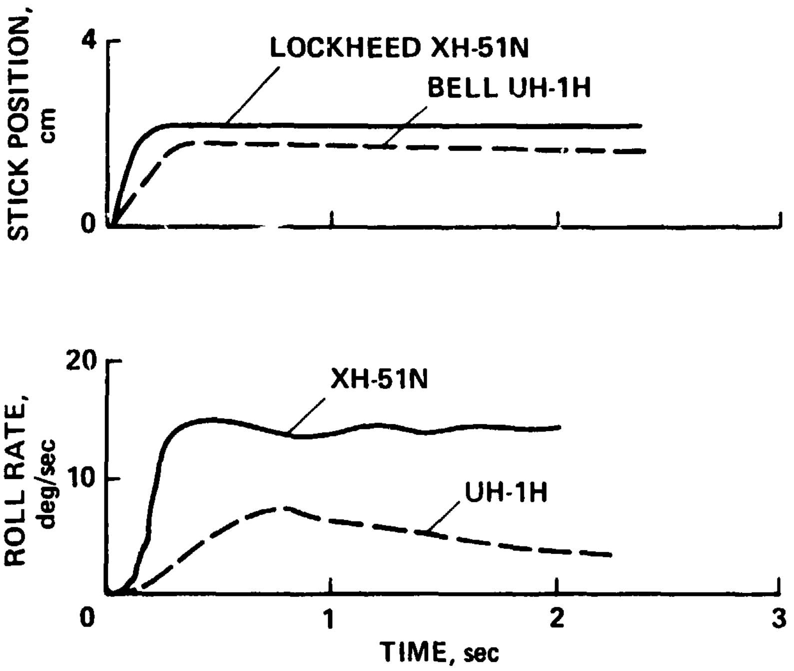


Figure 26.- Comparison of hingeless rotor and teetering rotor roll response in hover.

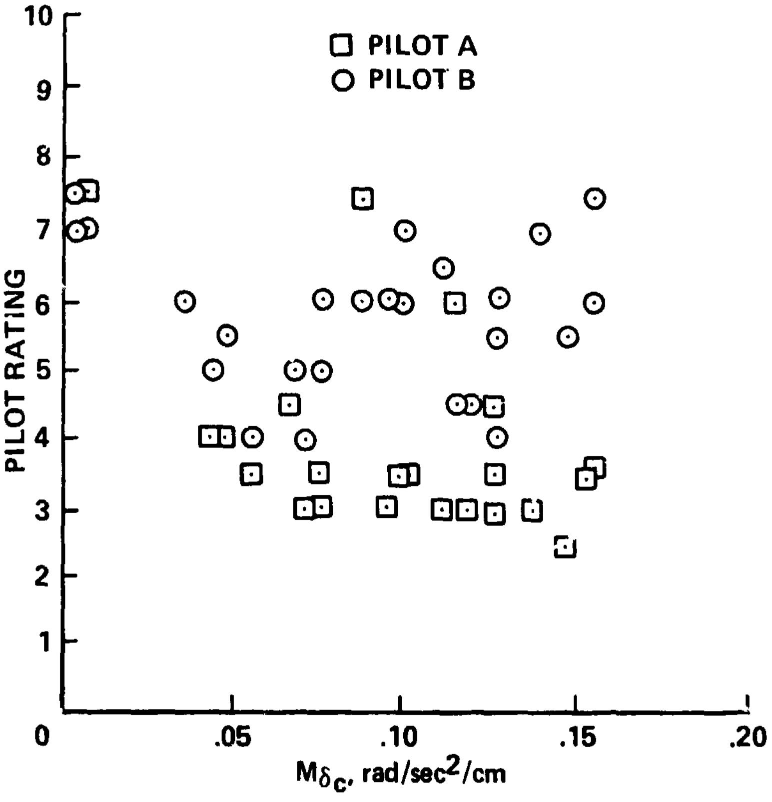


Figure 27.- Pilot rating vs pitch coupling due to collective control.

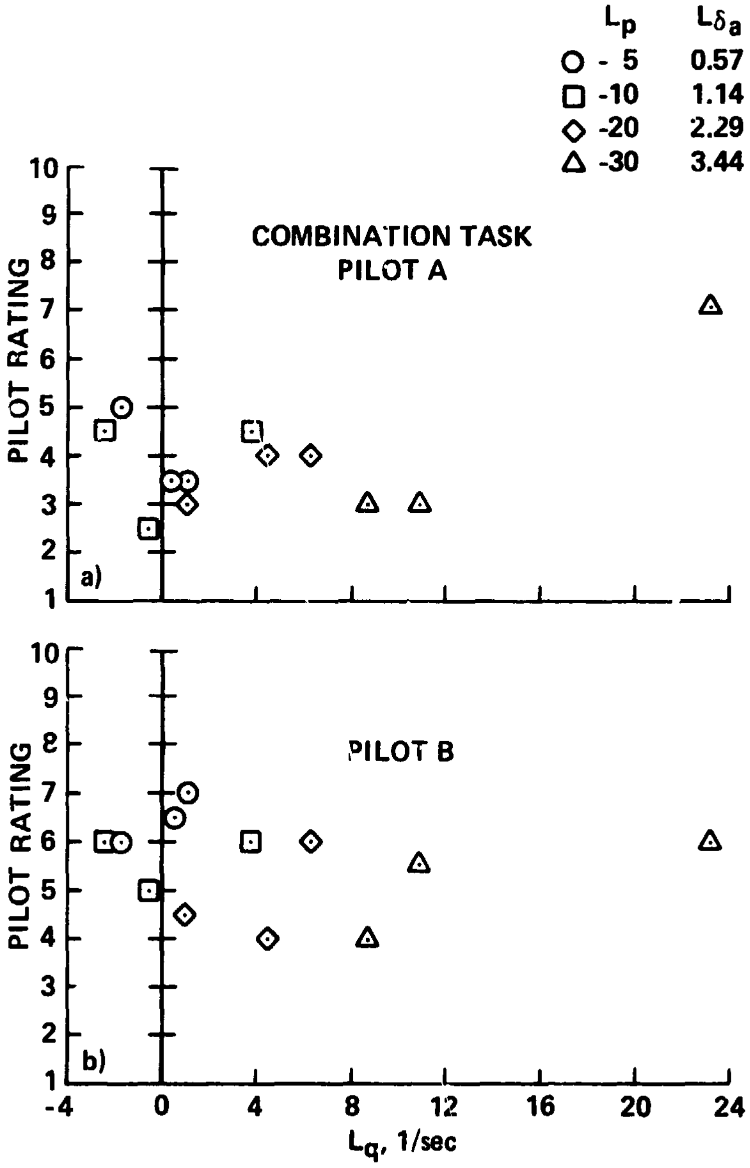


Figure 28.- Pilot rating vs roll coupling L_q.

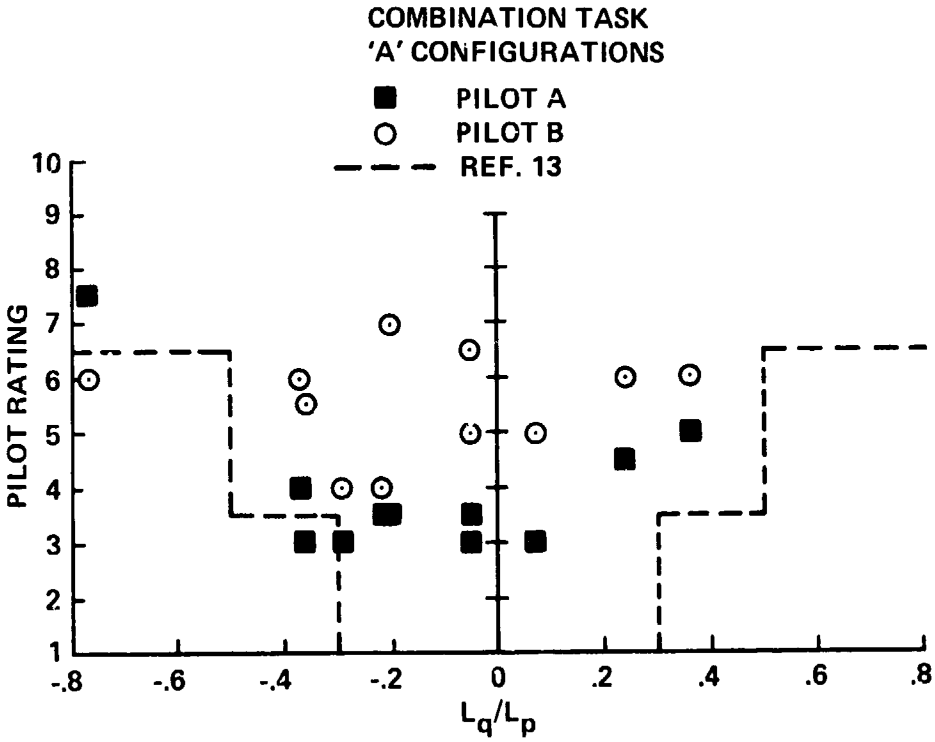


Figure 29.- Pilot rating vs coupling parameter (L_q/L_p).

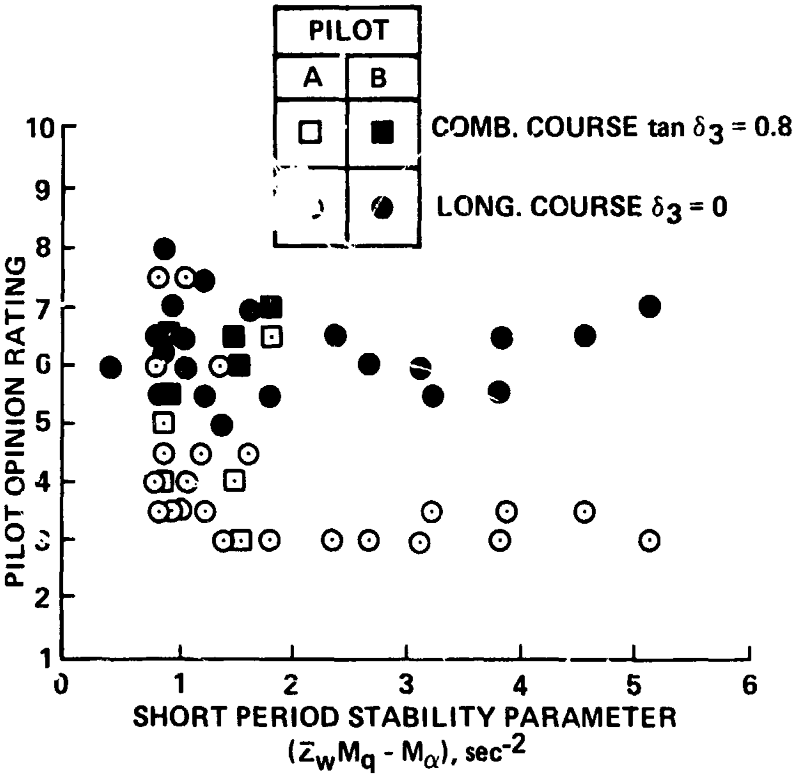


Figure 30.- Effect of short-period stability parameter on pilot opinion rating.

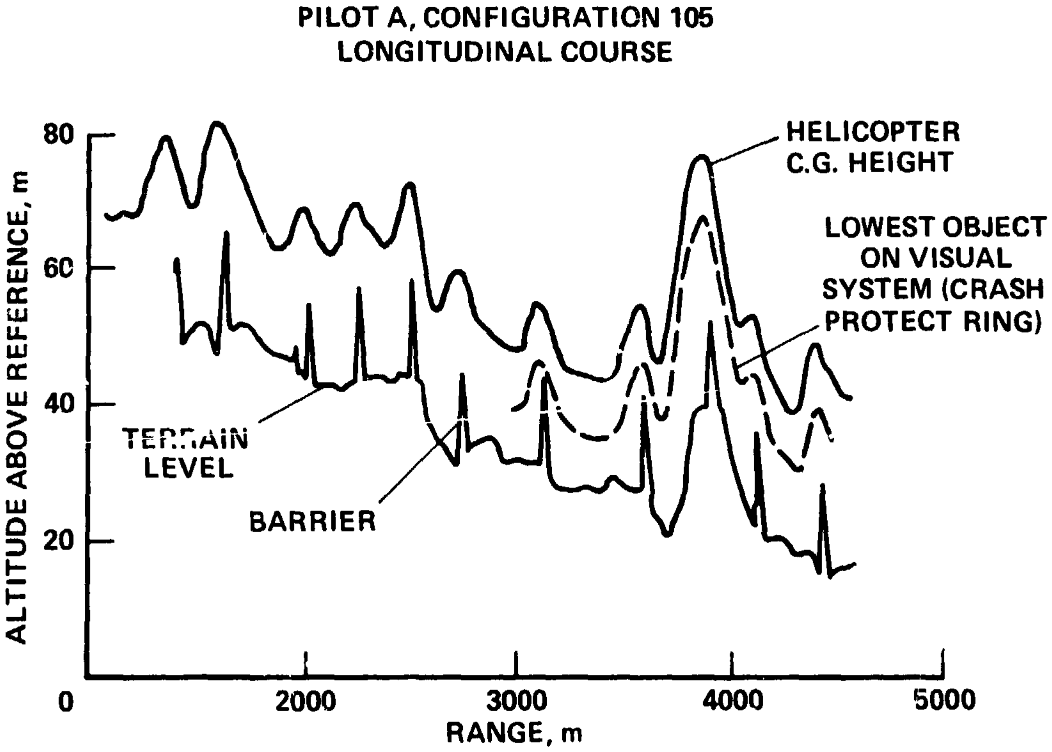


Figure 31.- Flightpath history of helicopter.

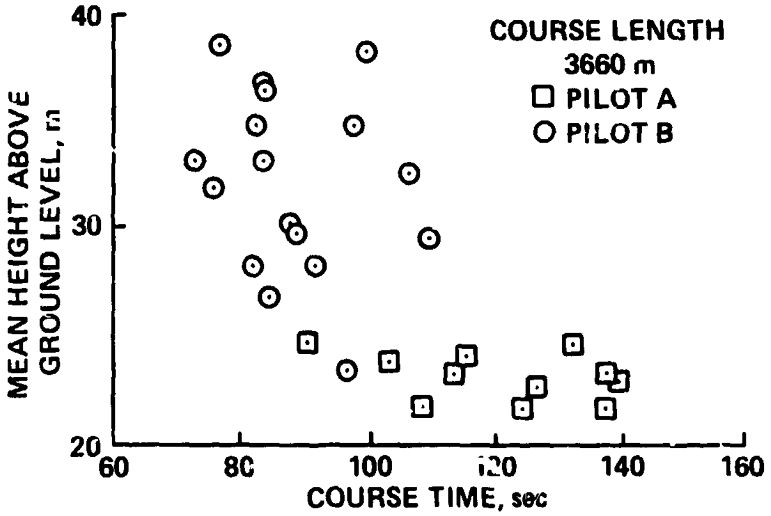


Figure 32.- Mean altitude AGL vs time to complete course — longitudinal-vertical task.

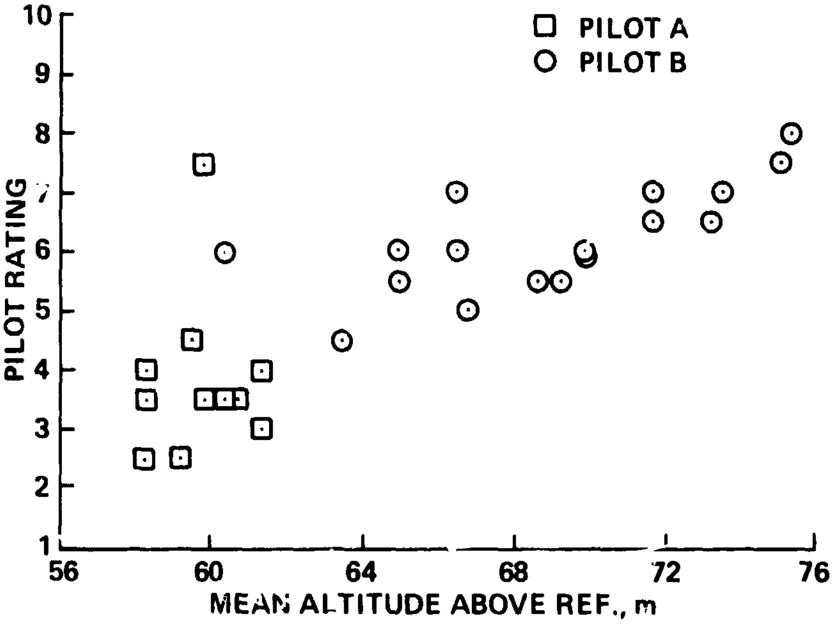
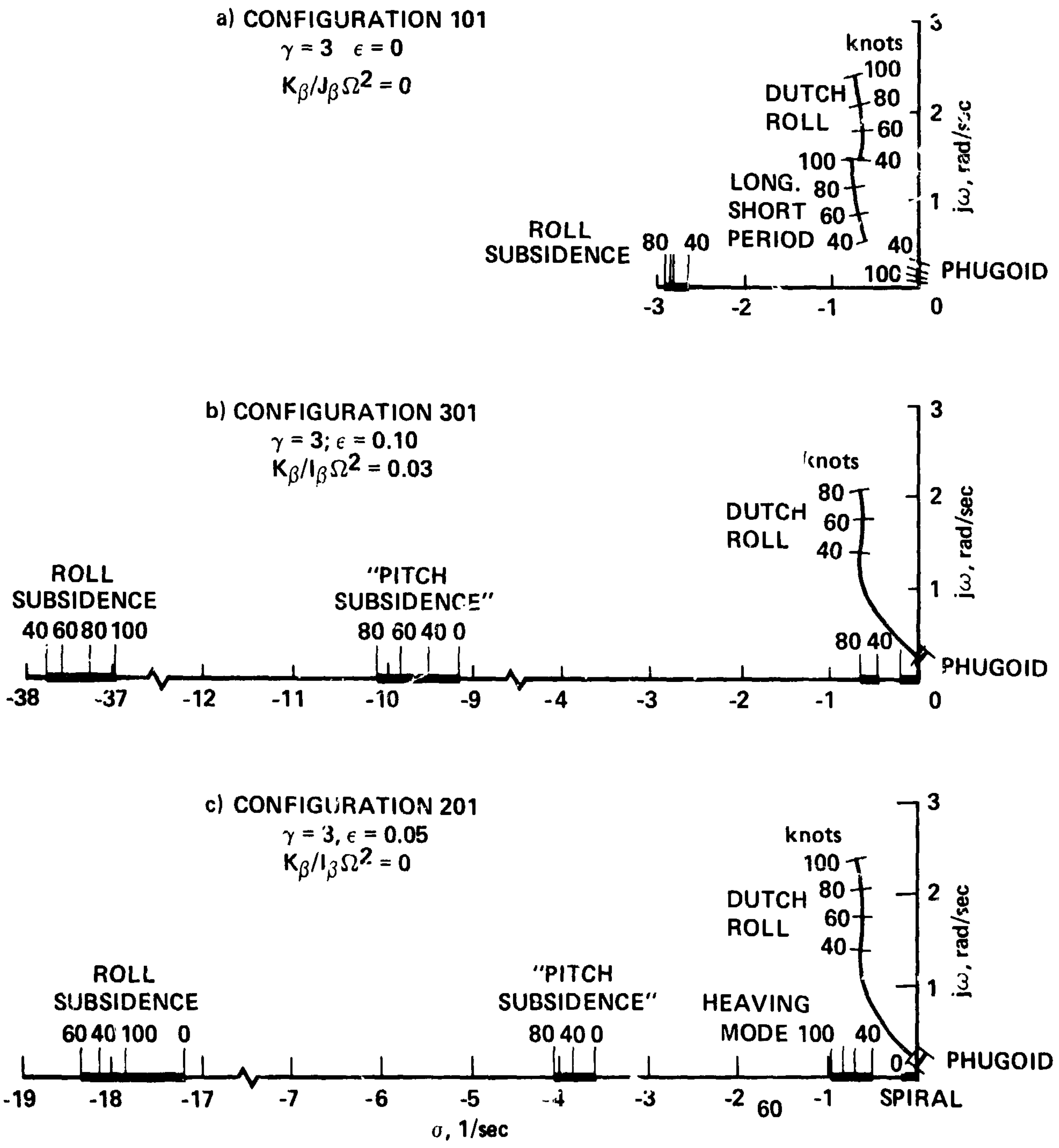


Figure 33.- Pilot rating vs mean altitude through longitudinal course.



a) CONFIGURATION 101
$\gamma = 3 \quad \epsilon = 0$
$K_\beta/J_\beta\Omega^2 = 0$

b) CONFIGURATION 301
$\gamma = 3; \epsilon = 0.10$
$K_\beta/I_\beta\Omega^2 = 0.03$

c) CONFIGURATION 201
$\gamma = 3, \epsilon = 0.05$
$K_\beta/I_\beta\Omega^2 = 0$

Figure 34.- Rigid body root loci.

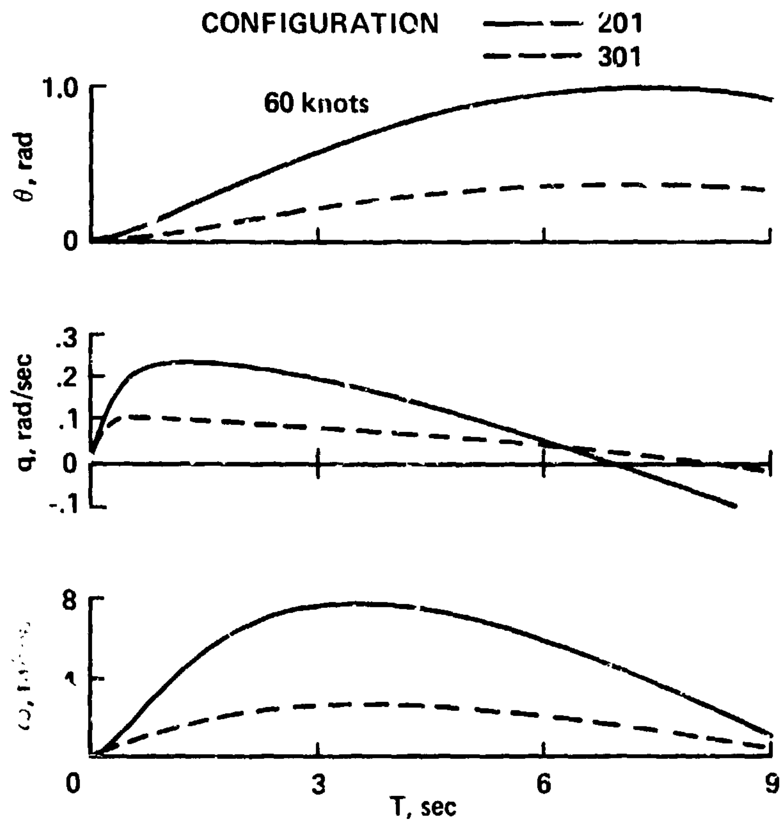


Figure 35. Aircraft response to a step δ_e input.

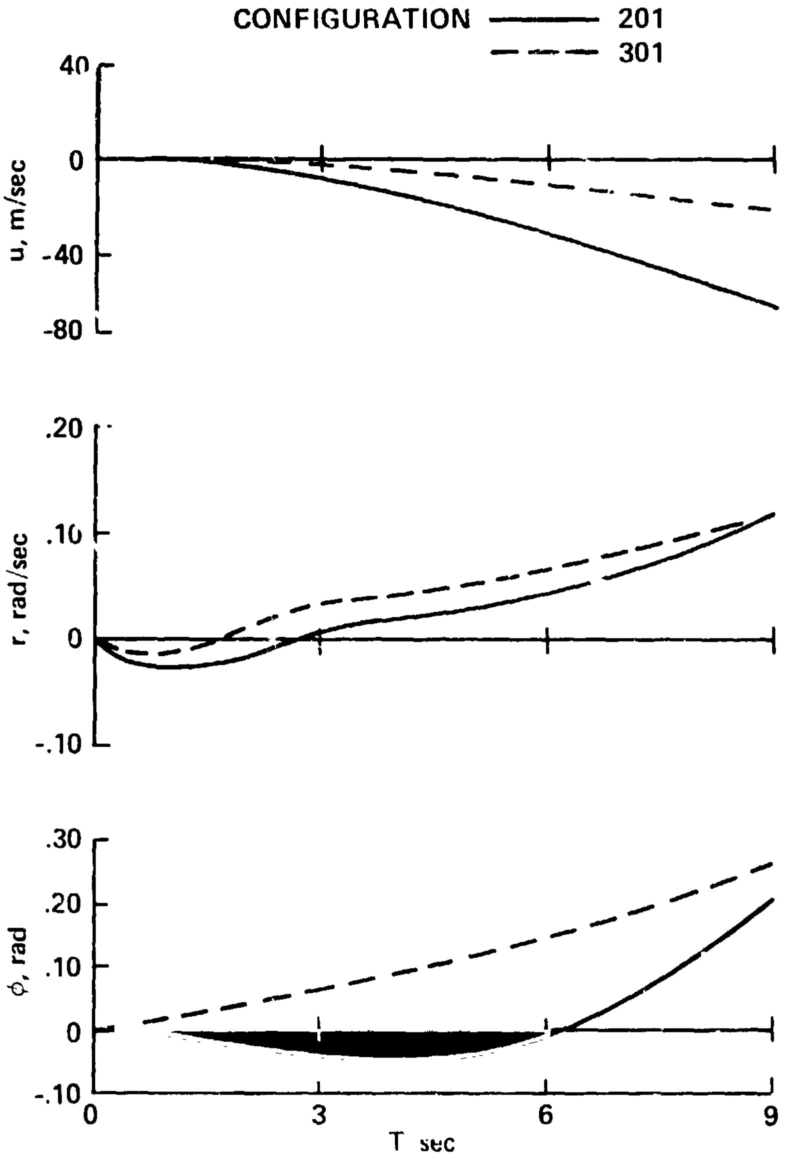


Figure 35.- Continued.

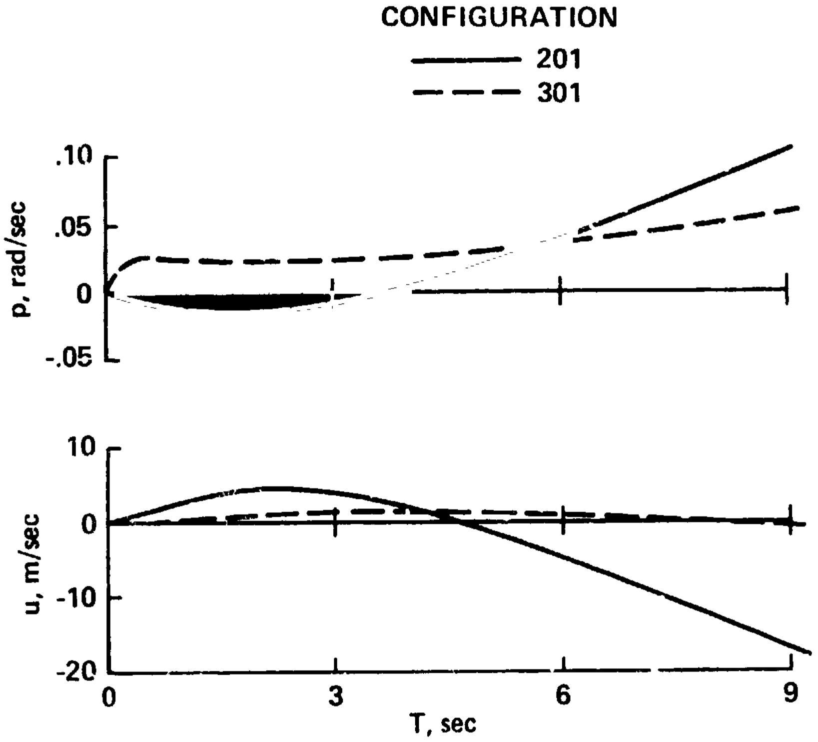


Figure 35.- Concluded.

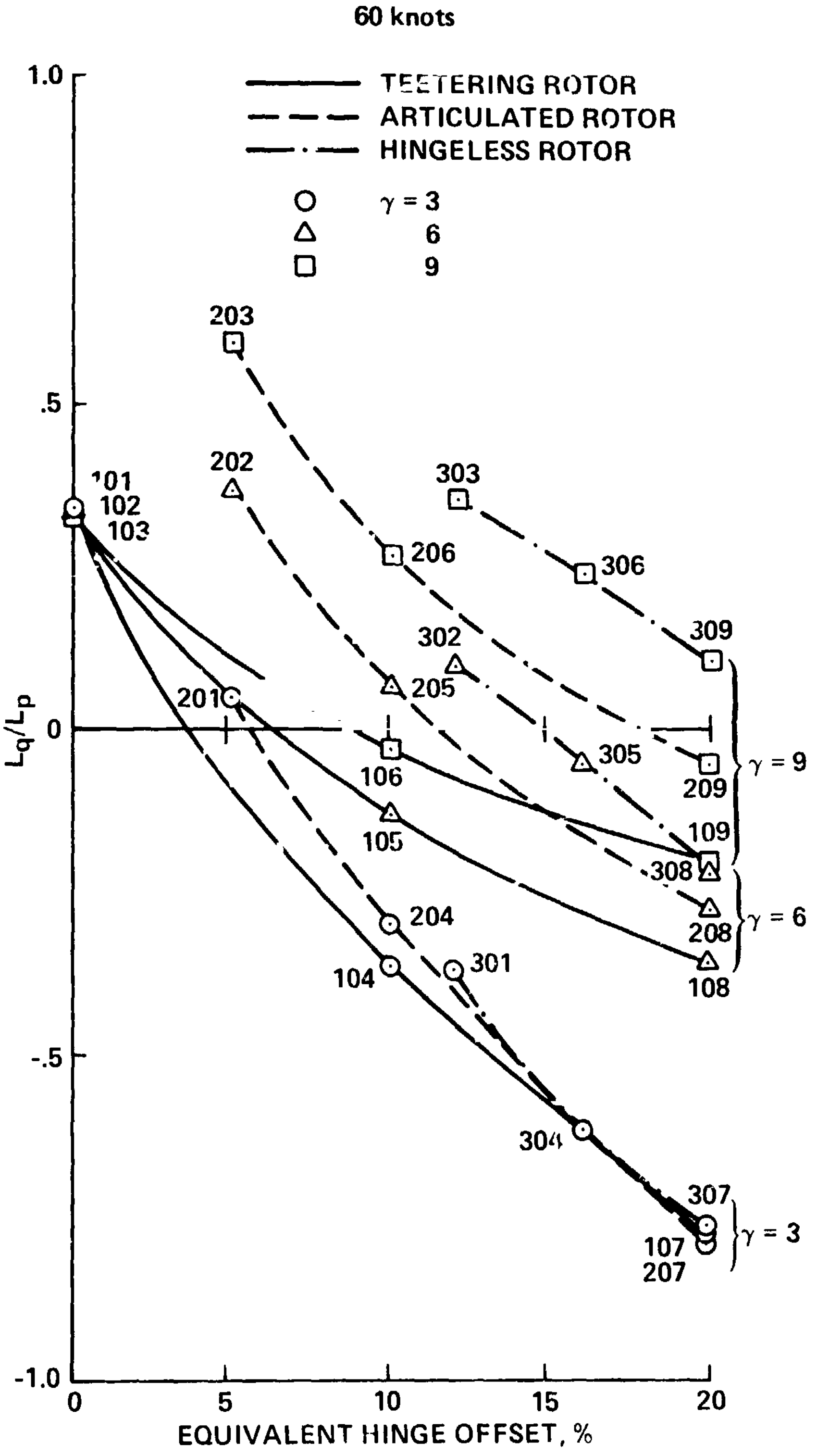


Figure 36.- Effect of rotor system parameters on L_q/L_p.

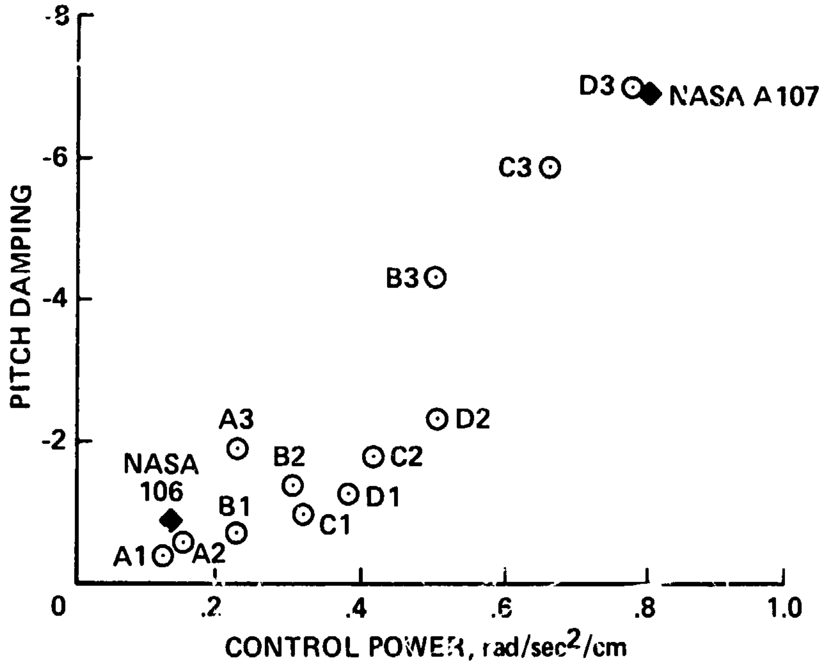


Figure 37.- Configurations tested in reference 15.

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16 Abstract

A coordinated analysis and ground simulator experiment was performed to investigate the effects on single rotor helicopter handling qualities of systematic variations in the main rotor hinge restraint, hub hinge offset, pitch-flap coupling, and blade Lock number. Teetering rotor, articulated rotor and hingeless rotor helicopters were evaluated by research pilots in special low-level flying tasks involving obstacle avoidance at 60-100 knots airspeed. The results of the experiment are in the form of pilot ratings, pilot commentary and some objective performance measures. Criteria for damping and sensitivity are reexamined when combined with the additional factors of cross-coupling due to pitch and roll rates, pitch coupling with collective pitch and longitudinal static stability. Ratings obtained with and without motion are compared.

Acceptable flying qualities were obtained within each rotor type by suitable adjustment of the hub parameters; however, pure teetering rotors were found to lack control power for the tasks. A limit for the coupling parameter $|L_q/L_p|$ of 0.35 is suggested.

17 Key Words (Suggested by Author(s))
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