UNIFIED RESULTS OF SEVERAL ANALYTICAL AND EXPERIMENTAL STUDIES OF HELICOPTER HANDLING QUALITIES IN VISUAL TERRAIN FLIGHT

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Abstract

A series of helicopter handling-qualities studies--analyses, piloted ground-based simulations, and a flight experiment--is described. The studies, conducted at Ames Research Center, were undertaken to investigate the effects of rotor design parameters, interaxis coupling, and various levels of stability and control augmentation on the flying qualities of helicopters performing low-level, terrain-flying tasks in visual meteorological conditions. Some unified results are presented, and the validity and limitations of the flying-qualities data obtained are interpreted. Selected results, related to various design parameters, provide guidelines for the preliminary design of rotor systems and aircraft augmentation systems.

Introduction

In recent years, the Army helicopter mission has placed considerable emphasis on terrain-flying tactics for purposes of survival and effectiveness in modern combat environments.[1] The terrain-flying tasks in these missions place strong demands on the agility and precision control capabilities of the helicopter and have raised questions concerning the flying qualities needed for such tasks and the means of achieving them. The existing flying-qualities specification for military helicopters, MIL-H-8501A, is a 1961 update of a 1951 document; it does not address specifically such present-day requirements of terrain flying.

To answer these flying-qualities questions, a joint NASA/Army research program was established at Ames Research Center. A series of analyses, piloted ground-based simulations, and flight experiments involving terrain-flying tasks and low-altitude tactical missions has been and is still being conducted. Studies and experiments designed to examine the effect of aircraft design parameters, interaxis coupling, and levels of stability and control augmentation on the flying qualities and man-machine performance of the low-level flying tasks in visual meteorological conditions were performed.[2-10] The influence of engine dynamics and excess power on these tasks was also examined.[11] In addition, research is in progress to investigate the effect of flight directors, vision aids, and side-stick controllers on performance of these terrain-flying missions in instrument meteorological or night conditions.[12,13]

The first visual terrain-flight experiment[2] was conducted on a fixed-based simulator to explore the effects on the handling characteristics of basic single-rotor helicopters of large variations in rotor design parameters, such as flapping-hinge offset, flapping-hinge restraint, blade inertia (or Lock number), and pitch-flap coupling. In the second ground-based simulation experiment, representative configurations from the first experiment were evaluated on a moving-base simulator [the Flight Simulator for Advanced Aircraft (FSAA)] to examine the effect of motion cues[3] and the effects of various levels of stability and control augmentation.[4] A more sophisticated stability and control augmentation system (SCAS) was also synthesized, using linear optimal control theory to meet a set of comprehensive performance criteria.[5] This system, designed expressly for a hingeless-rotor helicopter, was subsequently evaluated in the third piloted ground-simulator experiment on the FSAA.[6] A flight experiment[7] was conducted on the variable stability UH-1H/VSTOLAND helicopter[14] to verify some selected configurations from the first two ground experiments, to explore additional configuration variations, and to investigate the effect of field of view on helicopter flying qualities for nap-of-the-Earth (NOE) operations. To relate directly some of the results of these flying-qualities experiments to the design parameters of the helicopter, an analytical study[9,10] was conducted to develop a design rule for the selection of some primary rotor parameters to decouple the longitudinal and lateral motions of the helicopter.

The purposes of this paper are to consider this set of flying-qualities data for visual terrain-flying tasks in a unified framework, to interpret the validity and limitations of these data, and to relate the results directly, where possible, to design parameters, thus making them available as guidelines for use in the preliminary design of basic helicopters and their stability and control augmentation systems.

In what follows, we discuss the flying-qualities factors considered in designing the experiments, describe the conduct of the experiments, and discuss the main results and their design implications.

Factors Influencing Pilot-Vehicle Performance and Pilot Workload in Visual Terrain Flight

In terrain flight, especially in NOE flight, the pilot is often called upon to fly complicated and rapidly changing flight-path trajectories. These trajectories are generated, for example, from the need to avoid obstacles vertically or horizontally and to unmask and rapidly remask by accelerating and decelerating the aircraft vertically, longitudinally, or laterally. The quickness, ease, and precision with which the pilot is able to fly these trajectories are essential if mission performance is to be enhanced with a concomitant increase in endurance. Training, particularly in navigation skills, is of critical importance in NOE flight; however, the characteristics or qualities of the helicopter that permit the pilot to fly these complicated trajectories easily, precisely, and quickly are the key to safe and successful operation. These qualities or characteristics may be defined as "agility."

To fly these NOE trajectories quickly, the helicopter must be able to change rapidly the magnitude and direction of its velocity vector in space. It must, therefore, be able to rotate quickly the thrust vector of the main rotor and to change its magnitude to overcome drag and gravitational forces. Adequate control powers in pitch, roll, and yaw are therefore required to make possible the rapid rotation of thrust vector necessary to achieve the desired direction of the aircraft velocity vector; adequate thrust capability, installed power, and responsiveness of the engine/governor system are needed to meet the demand for rapid change in thrust magnitude.

To fly these complex NOE trajectories easily and precisely, the helicopter must possess satisfactory flying qualities. Thus, adequate damping in consonance with appropriate control sensitivity is needed in pitch, roll, yaw, and heave; interaxis cross-coupling must be minimized so that unnatural or complicated control coordination is not required; and adequate stability must be provided to damp out upsets owing to external wind/turbulence disturbances or to uncommanded control inputs from the pilot.

As a result of these requirements, there are many factors that influence helicopter agility: the basic performance capabilities of the aircraft and the engine/governor dynamic characteristics, as well as the flying qualities discussed above. The sequence of experiments described in the next section was designed to examine only the flying qualities while holding the performance factors and propulsion system characteristics constant. However, the effects of the latter two factors on the pilot-vehicle performance and pilot workload have also been examined recently at Ames.[11]

Design and Conduct of Experiments

The simulation models and experimental variables, the flight simulation facilities, the evaluation tasks, and the acquisition of the experimental data for this series of experiments (outlined in Table 1) are described in this section.

Helicopter Mathematical Model

The generic real-time helicopter simulation model (ARMCOP) developed at Ames for this series of piloted ground-simulation experiments[2-6] consists of five modules describing aerodynamic force and moment contributions of the main rotor, tail rotor, fuselage, vertical tail, and horizontal stabilizer. The main-rotor and tail-rotor modules are discussed in Ref. 15. The rotor model was derived from a linearly twisted rigid blade with an offset flapping hinge, a spring restraint about the flapping hinge, and pitch-flap coupling. For the first two experiments,[2-4] a common fuselate, tail rotor, and empennage with characteristics similar to those of an AH-1G helicopter were used; the main-rotor characteristics were varied. For the third experiment,[6] the generic mathematical model was configured to simulate a hingeless rotor helicopter with characteristics similar to those of a BO-105.

The ARMCOP model also includes a general form of SCAS (Fig. 1). The augmentation system employs a complete state feedback and a control mixing structure that facilitates implementation of control cross-feed[4,5] and control-quickening from each of the four cockpit control inputs. Also, the augmentation system gains may be programmed as functions of flight parameters such as airspeed. A limited attempt was made to validate the generic model, as discussed in Refs. 2 and 3.

Experiment Variables

The general objective of experiment I (Ref. 2) was to explore the effects on terrain-flight flying qualities of large variations in four primary rotor design parameters: flapping-hinge offset, flapping-hinge restraint, blade Lock number, and pitch-flap coupling. Forty-four combinations of the four parameters, which cover the teetering, articulated, and hinged rotor system families, were configured in the generic mathematical model ARMCOP, using a common fuselage, tail rotor, and empennage. To investigate systematically both the major and interactive effects, these configurations were designed and related to three sets of flying qualities parameters: damping and control sensitivity in pitch and roll axes; pitch-roll cross-coupling owing to aircraft angular rate; and longitudinal static stability.

In experiment II (Ref. 4), the objective was to investigate the use of various levels of SCAS to improve the flying qualities in terrain flight. Five basic single-rotor helicopters – one teetering, two articulated, and two hingeless – which were found to have major deficiencies in experiment I were selected as baseline configurations. The major handling-qualities deficiencies included inadequate damping and sensitivity in pitch and roll; excess pitch-roll coupling; and excess pitch and yaw coupling resulting from collective input. The SCAS that were designed and evlauated included simple control augmentation systems (CAS) to decouple pitch and yaw responses caused by collective input and to quicken the pitch and roll control responses; rate-command-type SCAS, designed to optimize the sensitivity and damping and to decouple the pitch-roll caused by aircraft angular rate; and attitude-command-type SCAS. The general form of the augmentation system in the ARMCOP was used to configure the above types of SCAS.

The objective of experiment III (Ref. 6) was simply to conduct a comparative evaluation to determine the extent to which the handling qualities of a basic hingeless-rotor helicopter can be improved by incorporating a sophisticated SCAS designed on the basis of linear optimal control theory.[5] Again, the basic aircraft and the SCAS system were implemented on the ARMCOP model. The mechanization was done in such a way that two levels of augmentation could be evaluated: stability augmentation only, and complete stability and control augmentation.

Experiment IV, the in-flight simulation experiment, was conducted to investigate the effects of variations in roll damping, roll sensitivity, and pitch-roll cross-coupling on the helicopter flying qualities for NOE operations and to correlate the results with the ground-based experiments, I and II.

Flight Simulation Facility

A fixed-base simulator, in conjunction with a Redifon closed-circuit television system, was used in experiment I. The simulator consisted of a Bell UH-1A cabin section facing a shrouded screen and TV projector. The UH-1A control system was used with working hydraulics, bungee cords, and magnetic brake. A 1:400 scale terrain model was used in this simulation. The Ames Flight Simulator for Advanced Aircraft (FSAA), a six-degree-of-freedom moving-base simulator (Fig. 2), was used in experiments II and III. The pilot was again provided with conventional pedals, cyclic stick, and collective controls, and a basic set of flight instruments, as shown in Fig. 3. The visual scene was generated from the same terrain model used in experiment I; the scene was presented through the cab window on a color TV monitor with a collimating lens.

Experiment IV, the flight experiment,[7] was conducted on the NASA/Army variable-stability UH-1H helicopter, which incorporates a V/STOLAND avionics system. The V/STOLAND system, equipped with two digital flight computers, was designed for flight control, display, navigation, and guidance research. The flight control portion of the V/STOLAND system was used in this experiment. Each control channel uses a combination of a limited-authority (20% to 30%) series servo and a full-authority parallel servo. In the research mode, the left cyclic stick, controlled by the evaluation pilot, is mechanically disconnected from the right stick and operated in a fly-by-wire status. The safety pilot on the right retains control of the aircraft through the standard UH-1H cyclic and cockpit instruments. The fixed-based simulator facility used for experiment I can be tied directly to the V/STOLAND hardware and was used in software development and checkout for this flight experiment.

Evaluation Tasks

Experiment I comprised three tasks: the longitudinal dolphin task – flying over a sequence of barriers (hurdles) placed at irregular intervals; a lateral task – flying a slalom course of trees spaced similar to the barriers in a straight line; and a combined longitudinal and lateral-directional task – flying a course of barriers combined with trees placed down the centerline of the barriers. Only the combination course (Fig. 4) was used in experiments II and III. A slightly different scaling was used in experiment I; it resulted in somewhat larger trees (75 ft instead of 50 ft), larger barriers (50 ft instead of 33 ft), and a correspondingly longer spacing between barriers (700 to 1400 ft). The pilots were given instructions to fly as low as possible and as fast as possible through the courses, banking alternately left and right around the trees and dropping down between the barriers. The tasks started at a trimmed, level-flight initial conditions of 40 knots at about 100 ft AGL for experiment I (60 knots for Exp. II, and 100 knots at 500 ft AGL for Exp. III). Minimum vertical obstacle clearance was limited to about 17 ft by a device designed to protect the television camera optics from inadvertent impact with the model terrain. Generally, each pilot was allowed a limited number of runs with a standard configuration at the beginning of his simulation test period in order to allow him to become reaccustomed to the simulator and task. Wind and turbulence were not introduced in these tasks.

For the flight experiment (Exp. IV), the task was to fly through a prescribed slalom course over a runway at the NASA Flight System Research Facility at Crows Landing, California (Fig. 5). The pilots were asked to fly through the course while maintaining speed and altitude constant at 60 knots and 100 ft AGL, respectively. Most of the evaluations were conducted in calm-air conditions or with winds below 10 knots at directions of no more than 40° to the centerline of the course runway.

Data Acquisition

Data collected from these experiments were of two types: 1) Cooper-Harper Pilot Ratings[16] and verbal comments recorded at the conclusion of each evaluation; and 2) time histories of helicopter trajectories, motion variables, and control usage for real-time monitoring and for postflight analysis. Two pilots participated in experiment I and completed a total of 172 evaluations. A total of 127 evaluations were achieved in experiment II by three participating pilots. In experiment III, two pilots completed a total of 21 NOE evaluations in addition to evaluations for tasks other than terrain flight. A total of 150 evaluations were achieved by four participating pilots in experiment IV.

Results and Discussions

The results of this series of experiments are combined and grouped in terms of major factors influencing the flying qualities of the helicopter in visual terrain flight. For this paper, only the Cooper-Harper Pilot Rating (CHPR) data will be used to quantify the flying-qualities results; other experimental data pertaining to the pilot comments and the task performance will not be discussed. The latter have been discussed elsewhere[2-10] in the results of each individual experiment.

Sensitivity and Damping in Pitch and Roll

The combined effects of control sensitivity and damping were expected to have a significant influence on NOE flying qualities, since they determine the short-term characteristics of the pitch and roll responses to cockpit cyclic controls. However, taking together all the pilot ratings for this series of experiments, the results indicate that the relationship of the sensitivity and damping in pitch and roll alone is not a predominant factor for the tasks evaluated. Other factors, such as yaw damping, pitch-roll coupling caused by aircraft angular rate, and collective input couplings to pitch and yaw also were found to be important.

Figure 6 shows the results of the pilot rating data for configurations with low yaw damping ($N_r = -1.2\ \text{sec}^{-1}$) and a low level of pitch-roll coupling caused by aircraft angular rate ($|L_q/L_p| < 0.3$). Most of the configurations covering a wide range of sensitivity and damping combinations in roll received ratings of acceptable (CHPR < 6.5) for the lateral task. In terms of the change in roll attitude at the end of 1 sec in response to an inch-step input in the lateral stick, $\Delta\phi_1$, these configurations extend from about 4° to 30°. It is noted, however, that the extreme low sensitivity and low damping combinations were found to be unacceptable. These configurations were brought into the region of "clearly acceptable" ratings in experiment II by increasing the damping and sensitivity to a level of $L_p = -5\ \text{sec}^{-1}$ and $L_{\delta a} = 1.4\ \text{rad/sec}^2/\text{in}$, respectively (and with slight augmentation in yaw damping from $N_r = -1.2$ to $-1.6\ \text{sec}^{-1}$).

Increasing the yaw damping to a high value ($N_r = -3.5\ \text{sec}^{-1}$) while reducing the pitch-roll coupling owing to angular rate to near zero improved the pilot rating considerably, as shown in Fig. 7. Nevertheless, the improvement for the low sensitivity and low damping combinations was insufficient to achieve a rating better than marginally acceptable. Limitations of in-flight simulation capabilities hindered the exploration of a wider range of sensitivity and damping combinations in experiment IV. Based on this set of data, as well as on the pilot commentary, it appears that there is a level of sensitivity and damping combination below which a precise roll control may not be achieved without a tendency to overcontrol or to develop pilot-induced oscillations. The data also suggest that a minimum roll damping of about $-3\ \text{sec}^{-1}$ with $\Delta\phi_1$ from 4° to 30°/in in 1 sec results in clearly acceptable flying qualities.

The flight experiment (Exp. IV) did not examine the effect of sensitivity-damping combinations in pitch. However, based on the result of experiments I and II, a minimum pitch damping (M_q) of about $-1.5\ \text{sec}^{-1}$ with $\Delta\theta_1$ (which is the change in pitch attitude, at the end of 1 sec, in response to an inch-step input in longitudinal stick) in the range of 4°-25° may be appropriate for acceptable flying qualities for the longitudinal task.

Pitch-Roll Cross-Coupling Resulting from Aircraft Angular Rate

Unlike fixed-wing aircraft, for which pitch-roll coupling is rare except in high-angle-of-attack operations, helicopters generally exhibit undesirable pitch-roll coupling because of aircraft angular motion. For example, in response to a roll rate to the right, the tip-path plane (TPP) tilts to the left with respect to the rotor hub to provide desirable roll damping; however, the TPP response can also include tilt in the fore-aft direction which produces an undesirable pitching moment. This coupling characteristic, for a general configuration, is a result of combined effects of gyroscopic and aerodynamic moments acting on the rotor system.

The ratio of the roll moment resulting from pitch rate to the roll moment resulting from roll rate, L_q/L_p, for example, plays an important role in determining the roll-rate-to-pitch-rate ratio in the short-term aircraft response to a step input in the longitudinal stick; similarly, the ratio M_p/M_q determines the ratio of pitch rate to roll rate in the short-term response to a step input in the lateral stick. Figure 8 shows the variation of the pilot rating with L_q/L_p from experiments I, II, and III. For comparison purposes, the boundaries discussed in Ref. 17 are also shown in the figure. The boundaries indicate that if the value of the coupling parameter exceeds 0.3, ratings better than acceptable cannot be achieved. (Values greater than 0.5 imply unacceptable flying qualities.) In experiment I, adverse comments on this kind of coupling were made by the pilots when $|L_q/L_p|$ exceeded 0.25. In experiment II, improvement in the pilot rating from unacceptable or marginally acceptable to at least acceptable was achieved when the coupling was reduced or the damping was increased or both.

The results from experiment IV (Ref. 7) pertaining to the effect on pilot rating of the pitch-roll cross-coupling are shown in Fig. 9 for three levels of roll damping with sensitivity held constant. With pitch and roll sensitivities fixed, the pilot commented that the aircraft was a little oscillatory with low damping and sluggish with high damping. Increasing the cross-coupling ratio degraded significantly the pilot rating for the highest damping, but only slightly for the low- and medium-damping cases. In particular, when the most favorable combination of sensitivity and damping ($L_p = -4$, $L_{\delta a} = -0.55$, $\Delta\phi_1 = 6$) the degradation of flying qualities with cross-coupling was not as severe as observed in the simulation experiments.

Collective Input Coupling

The effects of collective input coupling to pitch and yaw were expressly examined in experiment II. Data pertaining to these effects can also be extracted from the results of experiment III. The benefit of reducing the collective input to yaw coupling was found to be dependent on the level of yaw damping. For a moderate yaw damping ($N_r = -1.6\ \text{sec}^{-1}$), an improvement of about one rating point was achieved in experiment II (see Fig. 10) by decoupling yaw to collective response. When the yaw damping was high ($N_r = -3.5\ \text{sec}^{-1}$) such as in some configurations examined in experiments III and IV, the results suggest that only a slight improvement is realized by this decoupling.

In the speed range flown for the evaluation tasks (40 to 80 knots), the coupling to pitch from the collective input became substantial for hingeless rotor or stiffened hinged-rotor configurations. Experiments I, II, and III indicate that this sort of coupling has a significant effect on the flying qualities. Figure 11 shows the effect on pilot rating of doubling and eliminating the collective input coupling to pitch ($M_{\delta c}$), and a combined effect of eliminating both pitch and yaw coupling for a hingeless-rotor helicopter examined in experiment II.

Type of Flight Control System

As shown in Table 1, two types of flight control systems in the pitch and roll axes were examined in this sequence of experiments: 1) a rate type (including the basic aircraft, considered in experiments I, II, and IV, and 2) an attitude type, examined in experiments II and III. Taking all the experiments together, the results do not indicate a clear preference by the pilots for either of the two types of control system for the tasks flown. This was reported previously in the results of experiment II and was further substantiated in experiments III and IV. Figure 12 shows the results for a pilot (pilot A) who participated in all four experiments.

It should be emphasized that the result is valid only for the tasks evaluated. The tasks were flown at an airspeed in the range of 40 to 80 knots. In this flight regime, the pilot can perform the precision flight-path control task equally well and with ease with either a properly designed rate-type or attitude-command-type control system in pitch and roll. This result should not be extrapolated, however, to include other NOE tasks such as precision hover over the ground in turbulence. For these other precision position control tasks near hover an attitude system or another type of control system, such as a velocity-command type, may be preferred to the angular rate-type system.[12]

Effect of Longitudinal Static Stability

Limited consideration was given in experiment I to investigating the effect of variations in longitudinal static stability with respect to angle of attack (M_w) using a δ_3 hinge. The effect of variations in longitudinal static stability with speed (M_u) was not investigated in this series of experiments, because the tasks evaluated in the ground simulations did not call for precise speed control. The result obtained from experiment I suggests that, for the demanding tasks evaluated, some longitudinal static instability with angle of attack, such as is the case for some hingeless-rotor helicopters in forward flight, appears acceptable. However, this result must be qualified somewhat because the tasks were flown in calm air. In turbulence, degraded flying qualities caused by static instability may be expected.

Design Guidelines

The experimental results clearly indicate that the interaxis coupling, such as pitch-roll cross-coupling and collective input coupling to pitch and yaw, and levels of sensitivity and damping are major factors influencing the flying qualities of the helicopter in terrain flight. Analytical studies were performed to relate some of the experimental results to the design parameters of the rotor system and aircraft augmentation systems; this was done to develop means of improving the flying qualities. Some results and lessons learned are discussed in the following paragraphs.

Elimination of Interaxis Coupling

Pitch-Roll Decoupling

A design rule[9,10] has been developed for the selection of the design parameters of the rotor systems to reduce the undesirable pitch-roll coupling caused by aircraft angular rate in pitch and roll. The basic idea of the design rule is to cancel perfectly in hover the inertia and aerodynamic factors that contribute to the steady-state coupling in rotor tip-path-plane (TPP) response to the aircraft angular rate in pitch and roll. In essence, the method is to "tune" the flapping frequency ratio, P

$$P = \left[1 + \frac{K_\beta}{I_\beta \Omega^2} + \frac{eM_\beta}{I_\beta} + \frac{\gamma K_1}{8}\left(1 - \frac{4}{3}\varepsilon\right)\right]^{\frac{1}{2}} \qquad (1)$$

to the decoupling flapping frequency ratio P_D given by

$$P_D = \left[1 + \frac{\frac{\gamma^2}{4}\left(\frac{1}{4} - \frac{\varepsilon}{3}\right)\left(\frac{1}{4} - \frac{2}{3}\varepsilon + \frac{\varepsilon^2}{2}\right)}{2\left(1 + \frac{eM_\beta}{I_\beta}\right)}\right]^{\frac{1}{2}} \qquad (2)$$

through use of a pitch-flap coupling δ_3 ($K_1 = \tan\delta_3$) or a flapping restraint K_β or both for a given hinge offset e. In Eqs. (1) and (2) above, γ is the Lock number of the rotor blade; ε is the ratio of e to rotor radius; Ω is the angular velocity of the rotor system; and M_β and I_β are, respectively, the blade mass moment and moment of inertia of the blade about the flapping hinge.

The values of pitch-flap coupling required to achieve pitch-roll decoupling are generally moderate, as shown in Fig. 13, even for extreme combinations of ε and K_β. They are effective in reducing the the coupling ratio L_q/L_p (and M_p/M_q) in hover and in forward flight (as shown in Fig. 14) and they result in well-behaved TPP transient response. Figure 15 shows an example of the TPP transient response to a unit change in roll rate (and pitch rate) at hover and at an advance ratio of 0.3 for a rotor with $\varepsilon = 0.05$, $\gamma = 12$, with and without the use of decoupling δ_3.

Decoupling pitch and roll caused by aircraft angular rate may also be achieved using feedback control, as was done in experiment II by feeding the pitch rate to lateral cyclic and roll rate to longitudinal cyclic control.

Decouplihg Collective to Yaw and Pitch

The yawing moment resulting from collective input, N_{δ_C}, which exists in all conventional single-rotor helicopters, should be eliminated, particularly when the yaw damping of the aircraft is low. The yaw coupling can be eliminated simply by cross-feeding collective to the pedals. The gain is a nonlinear function of airspeed, the shape of which is similar to the familiar power required curve.[4] Care must be exercised, however, in deriving the cross-feed gain, especially when small-perturbation derivatives are used. Control derivatives such as N_{δ_C} can be a strong function of the magnitude as well as direction of perturbations, as shown in Fib. 16. Modifications to the initial design were required in experiments II and III to accommodate this kind of nonlinearity.

Increased control power obtained through hinge offset or a stiffened flapping hinge produces a coupling in pitching moment caused by collective input, which increases with airspeed. This pitching moment can be eliminated simply by cross-feeding the collective to the longitudinal cyclic and scheduling the gain with airspeed. Again, care must be exercised in mechanizing the system so as not to introduce the undesirable effect of reducing the longitudinal static stability with speed.[17]

Selection of Sensitivity and Damping in Pitch, Roll, and Yaw

The wide range of acceptable sensitivity in pitch and roll axes, as exemplified in Figs. 6 and 7, makes it somewhat difficult to select this parameter in the preliminary design stage. However, a proper selection may be accomplished by judiciously relating the sensitivity requirement to the task demands: lower sensitivity for demands with smaller attitude excursions, higher for tasks demanding larger attitude excursions. For example, to clear the obstacles in a slalom course, the radius for banked turns must be smaller than one half of the spacing between two obstacles. The turn radius is a function of the speed of flight and the bank angle, as shown in Fig. 17. For a spacing of 1000 ft, as used in experiment IV, bank angles of about 30° or more are required if a speed of 60 knots is maintained. Had the task been flown at 80 knots or with the spacing reduced to 500 ft, the bank angle required would have been about 50° or more; the lower roll sensitivity of $\Delta\phi_1 = 4.5^\circ$, which received good pilot ratings (see Fig. 7), might have been down-rated for the more demanding task. In experiment II (Ref. 4), the design of the rate-type SCAS used $\Delta\theta_1 = 7.5^\circ$, $\Delta\phi_1 = 10^\circ$, and $\Delta\psi_1 = 7.5^\circ$, approximately, and in experiment III (Ref. 5) the sensitivity criterion used for the SCAS design was $3 \le \Delta\theta_1 \le 20^\circ$, $4 \le \Delta\phi_1 \le 20^\circ$, and $6 \le \Delta\psi_1 \le 23^\circ$ for pitch, roll, and yaw, respectively. The designs resulted in pilot ratings of satisfactory for the tasks flown.

The minimum acceptable damping required for the tasks considered in the experiments appears to be about $M_q = -1.5$ to -2 sec^{-1}, $L_p = -3$ to -4, and $N_r = -1.6$ to -2, respectively for pitch, roll and yaw. The pitch and roll damping may be obtained by appropriately choosing the design parameters of the rotor system such as flapping-hinge offset, flapping restraint, and Lock number.[2] A cursory survey indicates, however, that yaw damping may be inadequate for many production helicopters for terrain flight; an augmentation in yaw damping is thus desirable.

Attitude SCAS Design

A few combinations of the two major design parameters associated with the attitude command system in pitch and roll, namely the sensitivity in aircraft attitude, change per unit stick deflection, and the bandwidth, were examined in experiment II. As expected, these parameters had significant effect on the flying qualities for the tasks evaluated. The "optimized" sets of these two parameters for the pitch and roll axes, as shown in Table 2, provide a guide for future design of such SCAS systems.

Finally, it is of interest to note that for a hingeless-rotor helicopter, it has been found beneficial[5,6] to feed back pitch-rate and pitch-attitude signals to collective pitch in addition to the longitudinal cyclic pitch. Because the available pitching moment resulting from collective pitch increases with speed, the gains to collective pitch must be scheduled with airspeed accordingly; however, the gains to the cyclic pitch may be held constant, because of essentially constant control effectiveness with the cyclic pitch for the hingeless-rotor helicopter.

Conclusions

A series of analytical and experimental studies investigating the effect of rotor design parameters, interaxis coupling, and levels of stability and control augmentation on the flying qualities of the helicopter in visual terrain flight has been conducted. The evaluation tasks used in the experimental studies consisted of a longitudinal dolphin task, a lateral slalom task, and a combined longitudinal and later-directional task; all tasks were flown in the airspeed range of 40 to 80 knots. The following conclusions were reached:

1) Minimum levels of damping and sensitivity in pitch and roll are required to achieve clearly acceptable or better flying qualities (CHPR < 5). For damping, a minimum of about -3 sec^{-1} for roll and -1.5^{-1} for pitch are appropriate; for sensitivity – in terms of the change in attitude at the end of 1 sec following an inch-step input in cyclic stick – a minimum of about 4° for both pitch and roll is suggested for the tasks at the flight conditions noted.

2) To achieve satisfactory flying qualities, the absolute value of the ratio of roll moment caused by pitch rate to roll damping must be less than 0.35. This coupling ratio can be reduced to nearly zero using a design rule developed in this series of studies.

3) In forward flight, the large pitching moment resulting from collective input associated with rotors having a large flapping-hinge offset and a stiff flapping hinge can be detrimental to flying qualities in terrain flight. Significant improvement in pilot ratings has been achieved by cross-feeding longitudinal cyclic from collective input.

4) The coupling to yaw caused by collective input can be objectionable, especially when damping in yaw is low. Augmenting the yaw damping or cross-feeding collective input to the pedals to decouple the yawing moment substantially improves the pilot rating.

5) Properly designed, both rate-command and attitude-command SCAS made substantial improvements in terrain-flight flying qualities in otherwise unacceptable helicopter configurations; no evidence was found for a clear-cut preference for either type of augmentation for the tasks flown.

6) The design of attitude-type SCAS for hingeless-rotor or stiff-hinged-rotor helicopters should include the feedback of pitch rate and pitch attitude to collective pitch, as well as their feedback to the longitudinal cyclic pitch.

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Table 1. Summary of terrain flight experiments

Experiments	Objective	Tasks	Simulator	Rotor type	Control system type
I	To determine effect of large variations in rotor design parameters	Longitudinal vertical task Lateral slalom task Combined task	Fixed base (Ames S-19)	Teetering Articulated Hingeless	Basic helicopter (rate-type in pitch, roll, and yaw)
II	To assess effect of various levels of SCAS	Combined task	Moving base (Ames FSAA)	Teetering Articulated Hingeless	SCAS Input Decoupling Rate command Attitude command in pitch and roll
III	To evaluate a sophisticated SCAS for hingeless rotor helicopter	Combined task	Moving base (Ames FSAA)	Hingeless	SCAS Attitude and rate Stability augmentation Control augmentation
IV	To investigate roll damping, roll sensitivity, and pitch-roll cross-coupling and correlate results with Experiments I and II.	Prescribed lateral slalom course over a runway	In-flight (UH-1H/ VSTOLAND)	Teetering	Rate-type in pitch, roll, and yaw

Table 2. Partially optimized characteristics of attitude SCAS in pitch and roll.

	Pitch	Roll
Frequency and damping ratio		
ω_n, rad/sec	1.9 to 2.0	1.8 to 2.0
ζ	0.9 to 1.0	1 to 1.2
Attitude sensitivities		
$\Delta\theta/\delta_e$, deg/in	5 to 10	20 to 22
$\Delta\phi/\delta_a$, deg/in		

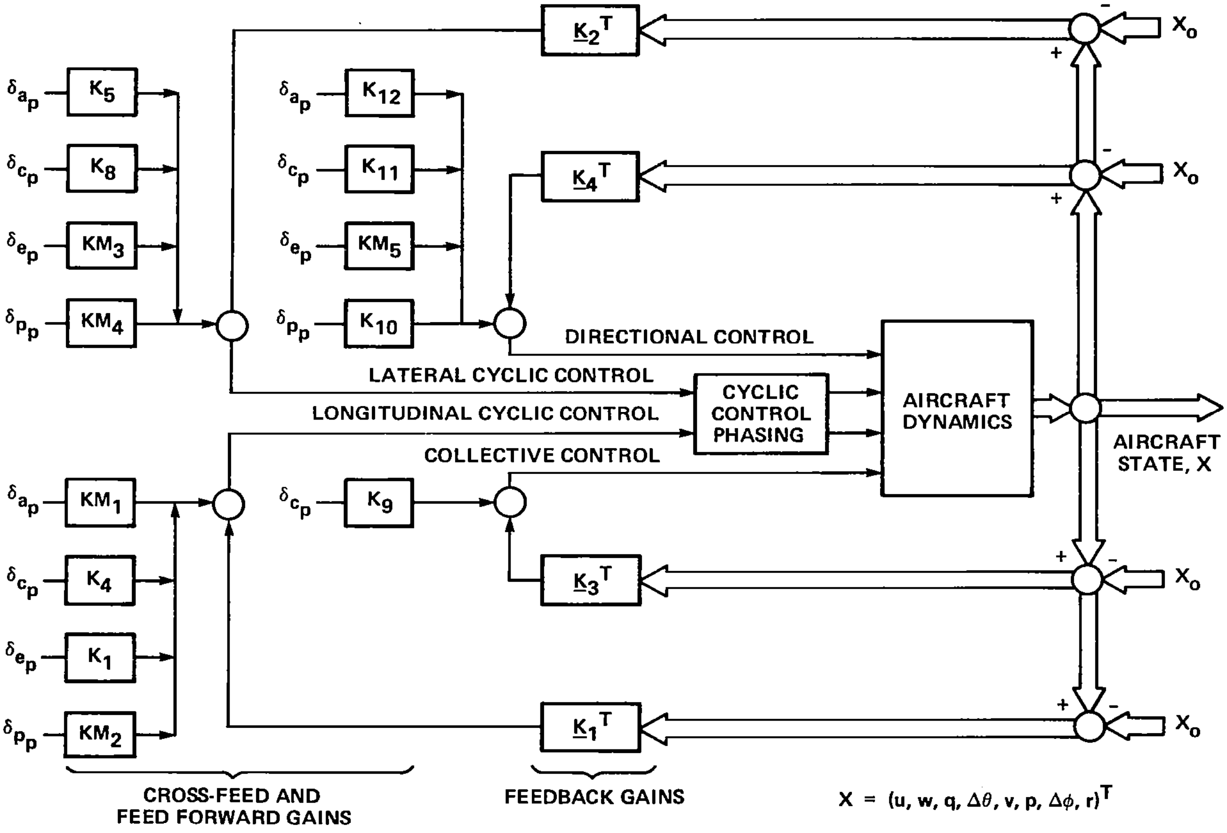

Fig. 1. General stability and control augmentation system structure of the ARMCOP model.

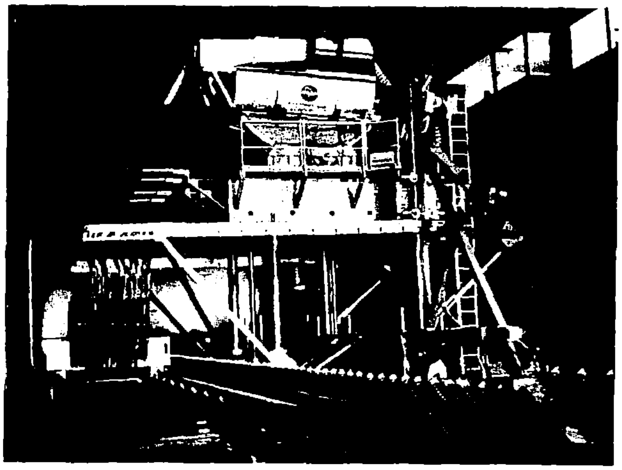

Fig. 2. The flight simulator for advanced aircraft.

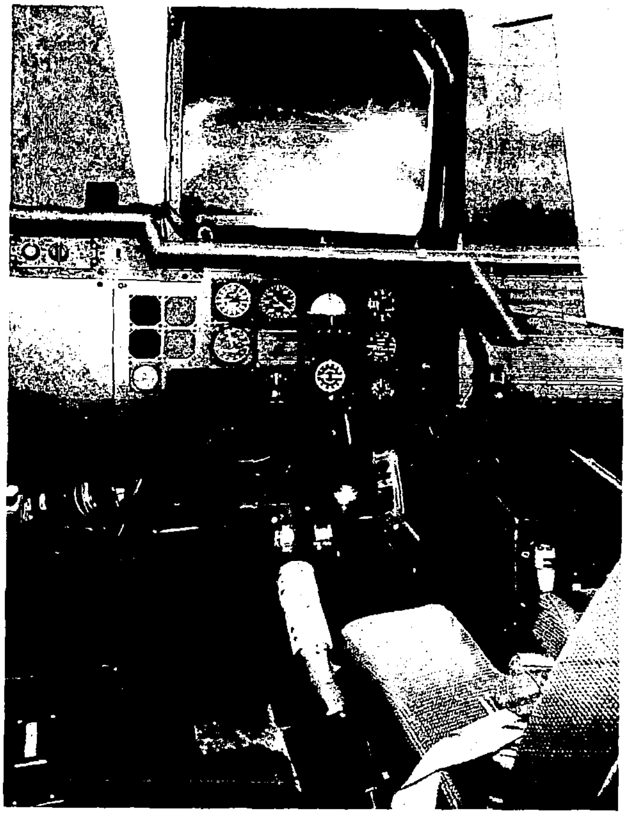

Fig. 3. Instrument configuration in simulator cab.

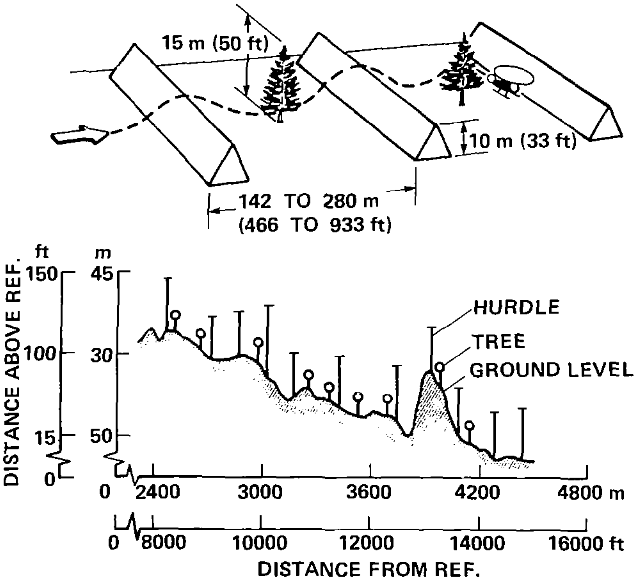

Fig. 4. Layout of nap-of-the-Earth terrain-avoidance obstacle course.

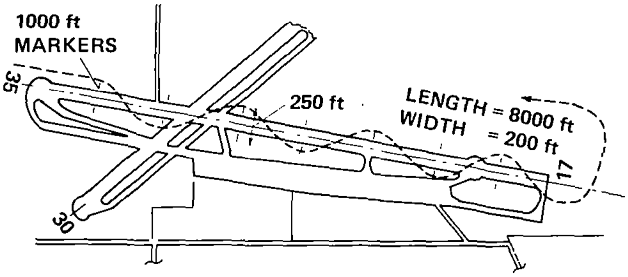

Fig. 5. Slalom-course task for the flight experiment (Crows Landing, Calif.).

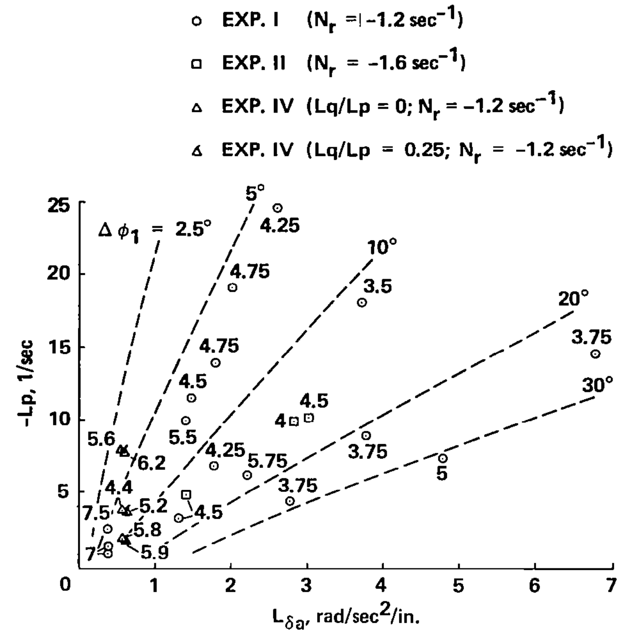

Fig. 6. Effect of roll damping and sensitivity on average pilot rating, $L_q/L_p < 0.3$; $N_r = -1.2\ \text{sec}^{-1}$.

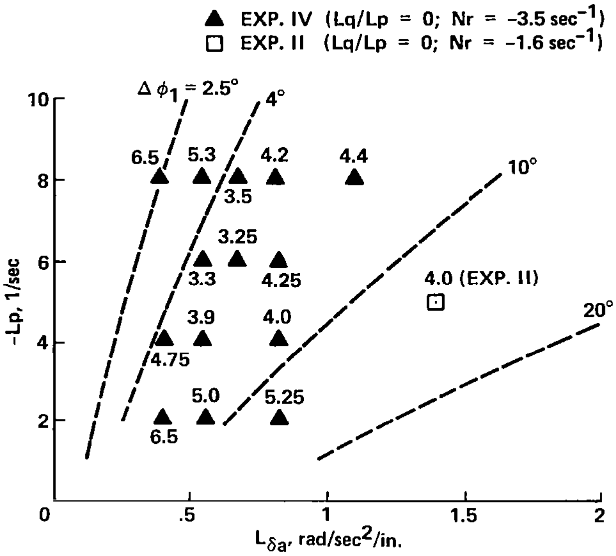

Fig. 7. Effect of roll damping and sensitivity on average pilot rating, $L_q/L_p = 0$; $N_r = -3.5\ \text{sec}^{-1}$.

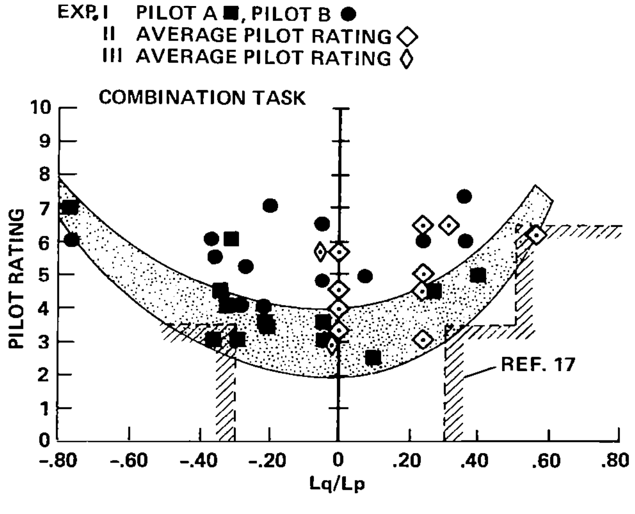

Fig 8. Pilot rating vs. L_q/L_p.

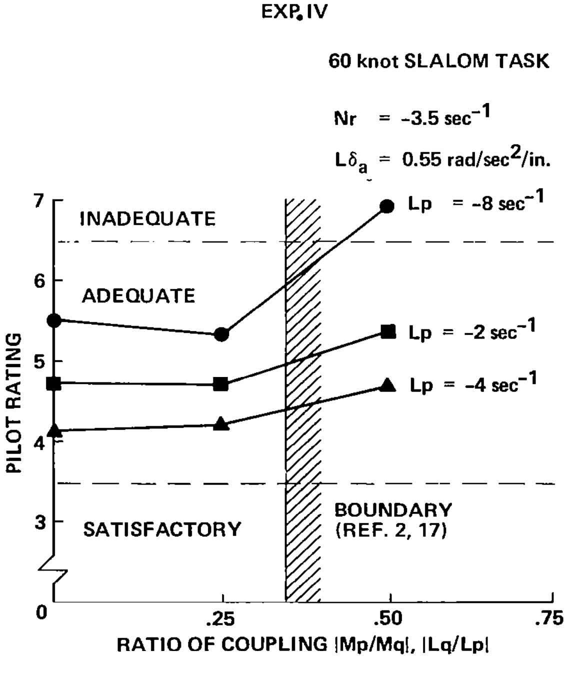

Fig. 9. Trends of pilot rating with ratio of coupling (from ref. 7).

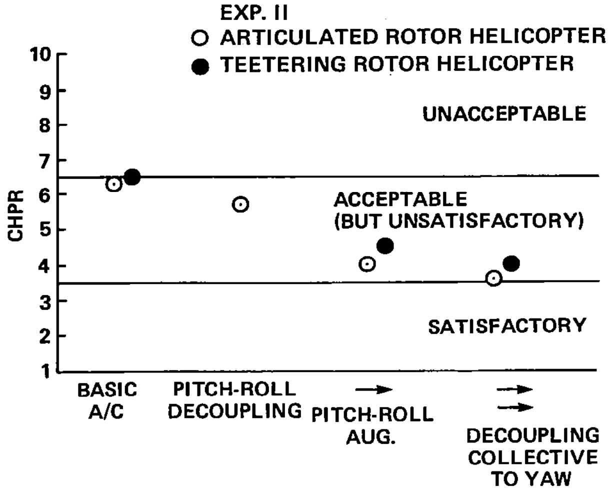

Fig. 10. Effect of pitch-roll coupling and yaw resulting from collective input on pilot rating.

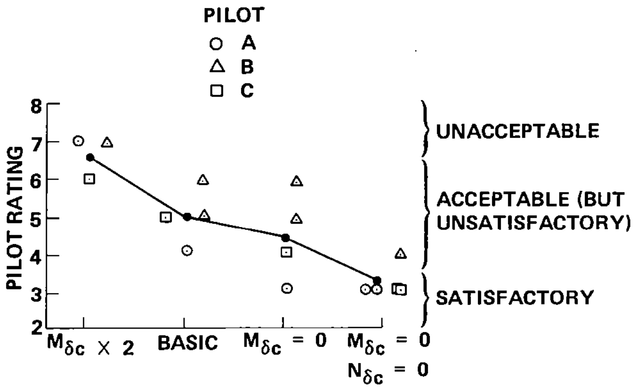

Fig. 11. Effect of pitch and yaw due to collective input on pilot rating, hingeless rotor, all pilots.

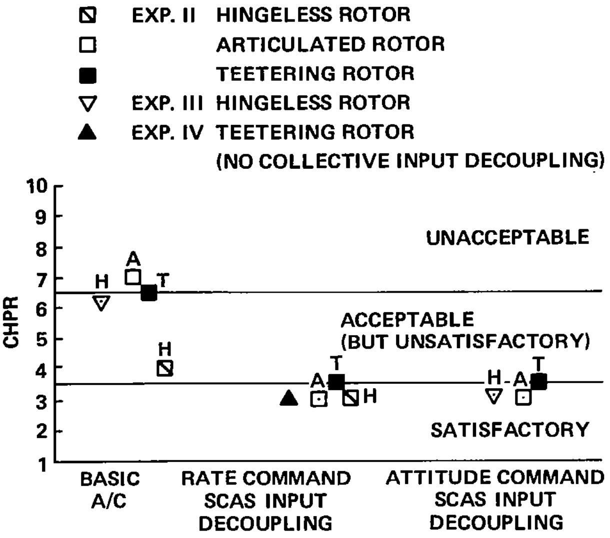

Fig. 12. Effect of SCAS mode on pilot rating, pilot A.

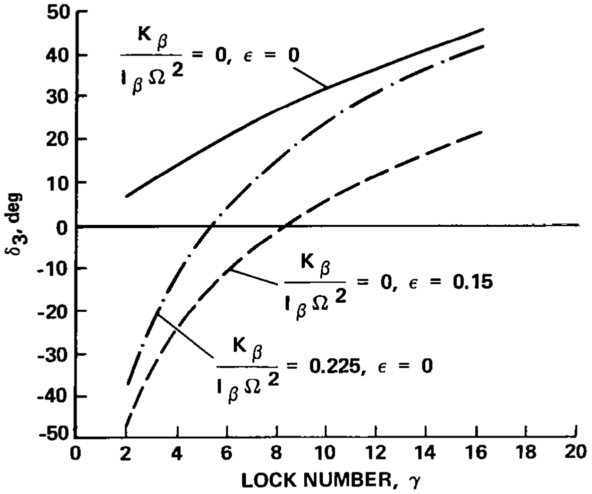

Fig. 13. Pitch-flap coupling required to decouple tip-path plane tilt for extreme values of flapping restraint and hinge offset.

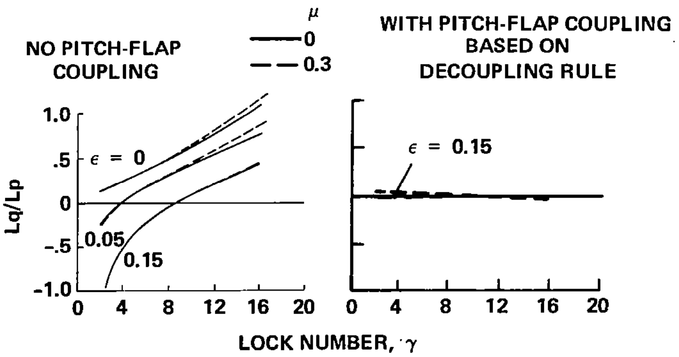

Fig. 14. Effect of decoupling rule on L_q/L_p.

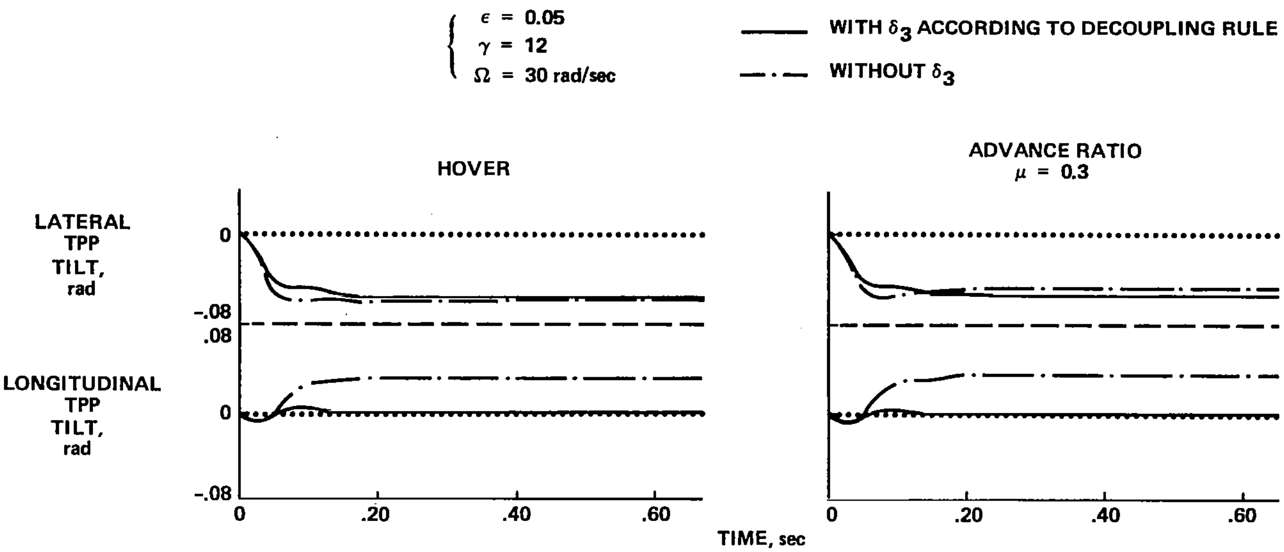

Fig. 15. Effect of decoupling rule on TPP transient response to 1 rad/sec step change in roll rate.

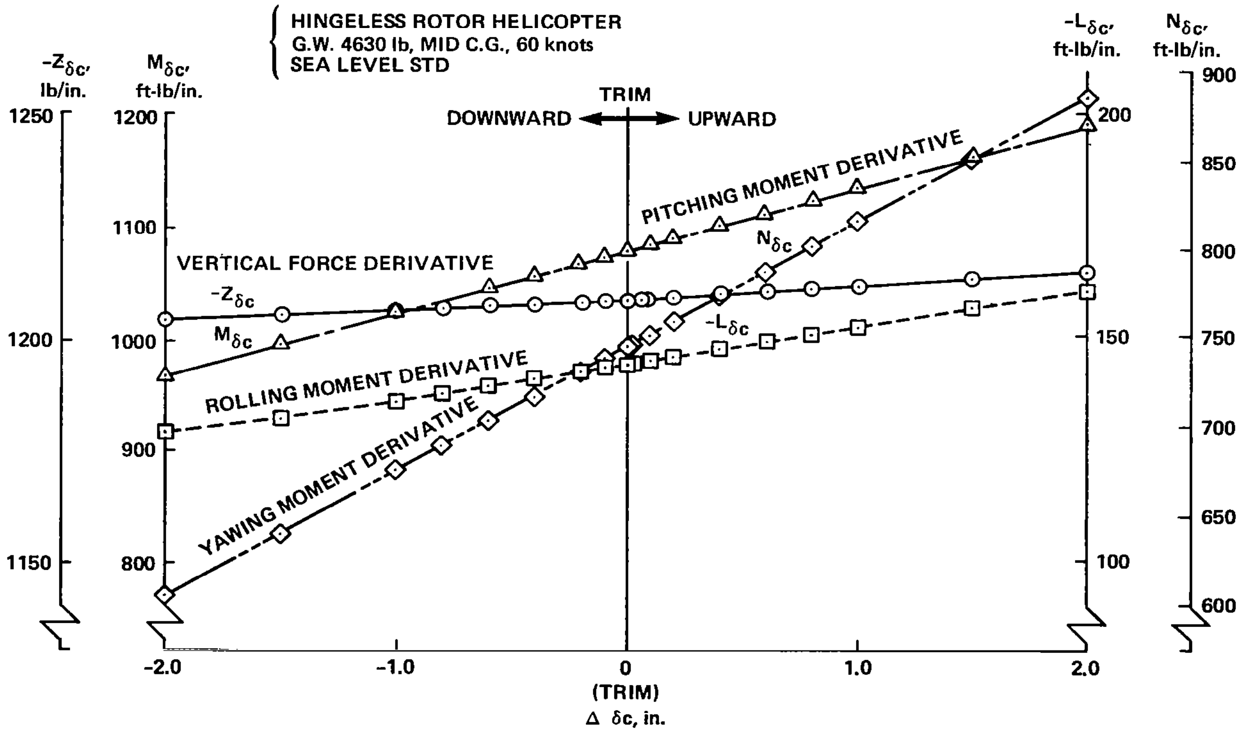

Fig. 16. Nonlinear effect of collective control derivatives.

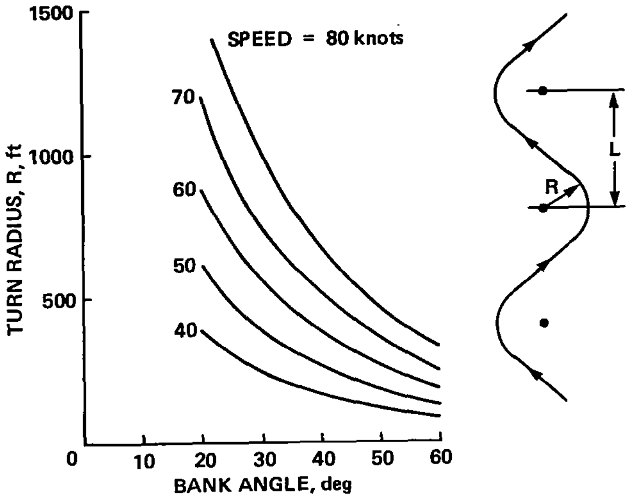

Fig. 17. Turn radius vs. bank angle in a slalom course.