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ROTORCRAFT PITCH-ROLL CROSS COUPLING EVALUATION FOR AGGRESSIVE TRACKING MANEUVERING

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SUMMARY

A research investigation has been conducted on the effects of pitch-due-to-roll and roll-due-to-pitch cross coupling on helicopter handling qualities while performing a forward flight (60 knots) roll axis tracking task. Conducted under the U.S./German Memorandum of Understanding for Cooperative Research in Helicopter Aeromechanics, this study involved complementary use of ground-based and in-flight simulation. Results show that the current time domain pitch-roll coupling limits are weakly supported for a tracking task, that frequency-domain criteria seem to offer a better or more comprehensive coverage, and that more data and analysis are needed to refine and define a comprehensive criteria.

1 INTRODUCTION

The ideal aircraft response to a pilot's control input is generally an uncoupled motion about a single axis. For a conventional helicopter, this would consist of heave from the collective, pitch from the longitudinal cyclic, roll from the lateral cyclic, and yaw from the pedals. When inter-axis coupling is present the pilot has to use a combination of control inputs to achieve a single axis response. *Table 1* [1] summarizes the sources of coupling for a single rotor helicopter. Depending on the severity of the inter-axis coupling, the ease and/or precision with which the pilot is able to control the aircraft's flight path may be degraded and hence the aircraft's handling qualities may be degraded.

The focus of the work described in this paper is pitch-due-to-roll and roll-due-to-pitch cross coupling. The two dominant pitch-roll cross coupling sources arise from what is commonly called control coupling and rate coupling. That is, pitching moments due to lateral cyclic ($M_{\delta y}$) or roll rate (M_p) and rolling moments due to longitudinal cyclic ($L_{\delta x}$) or pitch rate (L_q). In addition, there may be various combinations of both control and rate couplings. There have been a number of investigations into helicopter pitch-roll cross coupling [2 - 9]. Generation of criteria from these investigations has been somewhat less than desirable for a number of reasons, most of which can be attributed to the frequency dependent nature of the coupling which is illustrated in *Figure 1* (from reference 1). Due to this frequency dependency, unacceptable amounts of cross coupling are task dependent. For example, a pilot may be less tolerant of large amounts of coupling at high frequency for an aggressive precision task but may find the same amount acceptable for a non-aggressive low precision task. Ideally, criteria defining helicopter pitch-roll cross coupling limits to ensure satisfactory handling qualities should be dependent on the mission task to be performed and a function of not only the coupling amplitude but the frequency at which it occurs. Unfortunately, very little consistent and systematic data exists and/or the evaluation task has not been adequately characterized to support setting such limits.

An updated military rotorcraft handling qualities specification has been published and adopted by the U.S. Army Aviation and Troop Command as Aeronautical Design Standard - 33 (ADS-33C) [10]. Although ADS-33 is a U.S. specification, it is of international interest, and international studies have contributed to the data bases for the definition of some of the requirements. The ADS-33 is a mission-oriented specification, with different criteria limits depending on the mission task elements and the cueing available to the pilot. Minimum

RESPONSE / INPUT	PITCH	ROLL	YAW	CLIMB OR DESCENT
Longitudinal Stick	Pure (Prime)	1) Lateral flapping due to longitudinal stick 2) Lateral flapping due to pitch rate 3) Lateral flapping due to load factor	Negligible	Desired for vertical flight path control in forward flight
Lateral Stick	1) Longitudinal flapping due to lateral stick 2) Longitudinal flapping due to roll rate	Pure (Prime)	1) Undesired in hover, caused by directional stability 2) Desired for turn coordination and heading control in forward flight	Descent with bank angle at fixed power
Pedals	Negligible	1) Roll due to tail rotor thrust 2) Roll due to sideslip	Pure (Prime)	Undesired due to power changes in hover
Collective	1) Transient longitudinal flapping with load factor 2) Steady long. flapping due to climb and descent in forward flight caused by rotor flapping 3) Pitch due to change in horizontal tail lift	1) Transient lateral flapping with load factor 2) Steady lateral flapping with climb and descent 3) Sideslip induced by power change causes roll due to dihedral	Power change varies requirement for tail rotor thrust	Pure (Prime)

Table 1. Single rotor helicopter coupling sources (ref. 1)

requirements are established for control response types, and their characteristics are defined for comparison with the rotorcraft characteristics. This provides a quantitative assessment of the predicted Levels of rotorcraft handling qualities based upon flying qualities parameters. The Levels are related to the Cooper-Harper handling qualities rating (HQR) scale [11].

The ADS-33 pitch-roll cross coupling requirements are a time-domain criteria which considers the mission task and the coupling amplitude. The forward flight (> 45 knots) pitch-roll cross coupling criteria applies for the more aggressive mission task elements, i.e., ground attack, slalom, pull-up/push-over, assault landing, and air combat. The requirements are in terms of the ratio of peak offaxis response to the desired onaxis response, θ_{pk}/ϕ or ϕ_{pk}/θ, following an abrupt cyclic step input. The limits specified (see *Table 2*) shall not be exceeded for at least four seconds after the input is initiated and shall hold for control input magnitudes up to and including those required to perform the specified mission task elements. It should be noted that θ_{pk} (or ϕ_{pk}) is the maximum offaxis response occurring within the four seconds whereas, ϕ (or θ), is the onaxis response at four seconds.

PARAMETER	LEVEL 1	LEVEL 2
$\left\|\frac{\theta_{pk}}{\phi}\right\|_{\delta y}$ or $\left\|\frac{\phi_{pk}}{\theta}\right\|_{\delta x}$	±0.25	±0.60

Table 2. ADS-33C maximum values for pitch-to-roll and roll-to-pitch coupling

The current ADS-33 time-domain pitch-roll cross coupling criteria does not explicitly consider the aforementioned frequency dependency but only takes a gross cut by focusing on the response within the first four seconds. Some singular data points with the same off-to-onaxis coupling ratio but with the offaxis peak occurring at different times within the first four seconds, have shown variations in the handling qualities ratings for a slalom tracking task. In addition, the current ADS-33 cross coupling criteria specifies the same limits for both roll-due-to-pitch and pitch-due-to-roll. An evaluation of a BO 105 [12] has shown that quite different amounts of coupling exist for roll-due-to-pitch and pitch-due-to-roll and this suggests that further research is needed to determine if the limits really should be different.

As part of the U.S./German Memorandum of Understanding (MOU) for Cooperative Research in Helicopter Aeromechanics, the U.S. Aeroflightdynamics Directorate, Army Aviation and Troop Command and the

German Institute for Flight Mechanics, German Aerospace Establishment (DLR) have been performing research in handling qualities. The most recent topic for cooperation has been to investigate the effects from roll-due-to-pitch and pitch-due-to-roll cross coupling while performing a roll axis tracking task in forward flight (around 60 knots). The approach has been to make complementary use of the German in-flight simulator, the Advanced Technology Testing Helicopter System (ATTHeS), for the evaluation flight tests and the U.S. ground-based simulator to expand upon the variation of system configurations to aid in defining future flight test points. The objective of this work is to develop a refined helicopter pitch-roll cross coupling handling qualities criteria for aggressive forward flight maneuvering tasks.

This paper will provide some background in pitch-roll cross coupling dynamics, briefly review the existing data base, describe the approach used to develop a task involving the complementary use of the DLR ATTHeS in-flight simulator and the NASA-Ames ground-based simulator, and finally present the preliminary handling qualities results.

2 DISCUSSION OF EXISTING DATA

As previously mentioned, there have been a number investigations into helicopter pitch-roll cross coupling [2-9]. The four most recent of these will be discussed in some detail as they have formed the best sources for establishing pitch-roll cross coupling criteria in ADS-33 and therefore are particularly relevant to the current investigation.

In reference 6, a large variation in rotor system dynamic design parameters were investigated while performing nap-of-the-Earth (NOE) flight tasks on a fixed-base simulator. One range of rotor design parameters included the effects of pitch-roll cross coupling, i.e., pitching moment due to roll rate, (M_p), and rolling moment due to pitch rate, (L_q). Two pilots flew three courses; a longitudinal (or hurdles) course, a lateral-directional (or slalom) course, and a course consisting of a combination of these two. The pilots were instructed to fly as fast as possible and as low or close to the obstacles as possible. Published results were presented for the combination task and indicate that the handling qualities ratings given by the two pilots differed markedly. One pilot gave mostly HQR's of 3, 4, and 5 while the other pilot, who flew the course approximately ten knots faster and commented on adverse pitch-due-to-collective coupling, gave mostly 5's, 6's, and 7's. The results appear inconclusive but underline the dependency or influence of the task.

In reference 7, a helicopter in-flight simulation was conducted to investigate the effects of variation in roll damping, roll control sensitivity, and pitch-roll inter-axis coupling due to rate coupling during low-altitude maneuvering. The experiment utilized the NASA-Ames UH-1H helicopter in-flight simulator. Configurations evaluated included low to moderate onaxis damping (M_q = -2 1/sec, L_p = -2 to -8 1/sec, and N_r = -1.2 and -3.5 1/sec) and three levels of pitch-roll cross coupling. The cross coupling was described in terms of the ratios of L_q/L_p and M_p/M_q which were set equal to each other at 0, 0.25, and 0.50. The evaluation task was a series of s-turns around markers 1000 feet apart along the sides of a 200 feet wide runway. The pilots were instructed to maintain a reference altitude (about 100 ft.) and speed (60 knots). The results of this investigation were also somewhat inconclusive. It is speculated that there was some problems in the configuration models as the UH-1H manual mode was given the best ratings (HQR=3) by all of the pilots. Also, the evaluation task may have lacked the aggressiveness and precision to differentiate the coupling configurations. Autospectrum of the lateral cyclic control from flying the task indicates the dominant frequency band to be less than 1.5 rad/sec with some very small secondary peaks around 5 rad/sec when the coupling was increased from zero.

The reference 8 pitch-roll coupling investigation focused on hover and low speed tasks. It was conducted on the NASA-Ames Vertical Motion Simulator with the principal objective of determining the influence of varying task demands on cross coupling effects. Two tasks, a 100 foot sidestep and a 30 knot slalom, were each performed with two different levels of aggressiveness. The "easy" and "hard" slalom showed the task influences on the HQR's for all the configurations evaluated, i.e., the "hard" slalom was consistently rated one to one and half ratings worse than the "easy" slalom. Configurations included control and rate coupling with two different on-axis responses representative of a hingeless rotor and an articulated rotor. The configurations and handling qualities ratings were compared with recommended control and rate coupling limits from previous investigations [2 and 6] and with the current ADS-33 pitch-roll cross coupling limits (*Figure 2*). The results of these comparisons were mixed. That is, for some of the configuration and task combinations these recommended limits correlated well but for others they did not. In general, none of the recommended cross coupling limits were perfectly consistent measures for reliably correlating the degree of coupling with pilot opinion rating.

Reference 9 was an in-flight extension of the reference 8 investigation and therefore included the same general type of coupling configurations and tasks although the on-axis responses were limited by the in-flight simulator. The study was conducted using the NASA-Army CH-47B variable-stability helicopter at NASA-Ames. The in-flight experiment supported the VMS conclusions that the onaxis damping characteristics determine the impact of coupling and that increased damping causes increased sensitivity to the angular-rate coupling metric $|L_q/L_p|$. The control coupling results and recommendations were strongly dependent on the demands of the task. For the sidestep task, the results suggested that a maximum of approximately 30 degrees of control coupling be allowed for adequate handling qualities.

As is evident from the above discussion, the results from these pitch-roll cross coupling studies do not provide the necessary data base to establish definitive handling qualities criteria due to coupling. The ADS-33 pitch-roll cross coupling requirements were a cut at establishing coupling limits. These limits were made somewhat generous so as to minimize unnecessary complexity. However, even such loose criteria do force the designer to consider cross coupling, and the tester to evaluate and quantify the coupling and so are beneficial. None the less, as mission tasks become more demanding, and rotor designs tend toward greater stiffness for maximum agility, the need for precise criteria is apparent and underlines the emphasis for the current study.

3 GROUND-BASED AND AIRBORNE SIMULATIONS

This section will describe the ground-based and in-flight simulation facilities that were used for the pre-tests and the formal evaluations.

3.1 Ground-Based Flight Simulator

The piloted ground-based simulation was conducted on a NASA Ames fixed-base simulator. The cockpit had a single pilot seat mounted in the center of the cab and three image presentation "windows" to provide outside imagery. The visual imagery was generated using an Evans and Sutherland CT-5A Computer Image Generator (CIG). The CIG data base was carefully tailored to contain adequate macro-texture (i.e., large objects and lines on the ground) for the determination of the rotorcraft position and heading with a reasonable precision. The baseline stick-to-visual delay was 70 msec. A seat shaker provided vibration cueing to the pilot, with frequency and amplitude programmed as functions of airspeed, collective position, and lateral acceleration. Aural cueing was provided to the pilot by a WaveTech sound generator and cab-mounted speakers. Airspeed and rotor thrust were used to model aural fluctuations. Standard helicopter instruments and controllers were installed in the cockpit.

Mathematical models of the following items were programmed in the simulation host computer: (1) trim capability, (2) stability command and augmentation system (SCAS), (3) dynamics of the helicopter, and (4) ground effects. The SCAS was a stability-derivative model with known dynamics and no coupling [13], and the character of its response was easily manipulated by changing the stability derivatives. The flight control architecture and hence the implementation of the cross coupling was the same as in the in-flight simulator.

3.2 Airborne Flight Simulator ATTHeS

The DLR Institute for Flight Mechanics has developed a helicopter in-flight simulator. The Advanced Technology Testing Helicopter System (ATTHeS) is based on a BO 105 helicopter (*Figure 3*). The testbed is equipped with a full authority non redundant fly-by-wire (FBW) control system for the main rotor and fly-by-light (FBL) system for the tail rotor. The testbed requires a two-person crew consisting of a simulation pilot and a safety pilot. The safety pilot is equipped with the standard mechanical link to the rotor controls whereas, the simulation pilot's controllers are linked electrically/optically to the rotor controls. The FBW/L actuator inputs, which are commanded by the simulation pilot and/or the control system, are mechanically fed back to the safety pilot's controllers. In the simulation pilot's modes, the flight envelope of the testbed is restricted to not lower than 50 ft above the ground in hover and 100 ft in forward flight.

For in-flight simulation purposes, the most promising method of a control system design is to force the host helicopter to respond on the pilot's inputs as an explicitly calculated command model. The ATTHeS explicit model following control system (MFCS) design provides the airborne simulator with the demanded level of simulation flexibility. A detailed description of the ATTHeS in-flight simulation system is given in [14,15]. The capability of the ATTHeS simulator is described by a high quality of simulation fidelity up to a frequency of about 10 rad/sec in the roll axis. The level of decoupling which can be achieved with a decoupled command model is significantly lower than 10 percent of the onaxis response. For these tests, a control computer cycle time of 40 msec was realized. A generated subcycle one-fifth of the frame time allowed refreshing of the FBW/L actuator inputs in a lower time frame than the main cycle which was 16 msec for this study. The equivalent time delay for the overall system due to high order rotor effects, actuators dynamics, computational time and pilot input shaping was 100 to 110 msec in the roll axis and 150 to 160 msec in the pitch axis related to first-order rate command responses.

3.3 Development of Slalom Tracking Task

The objective of this study was to investigate the effects of pitch-due-to-roll and roll-due-to-pitch cross coupling from control inputs for a precision tracking task. To make complimentary use of the ground-based and in-flight simulator, a key was to develop an appropriate small amplitude precision tracking task that could be implemented on both simulators while considering the constraints of each. For the ground-based simulator, some of these constraints include a reduced field of view and visual resolution whereas, for the flight tests these include 100 feet minimum altitude. In addition, it was desired to keep the complexity of the task cueing to a reasonable level to minimize the building of exotic and expensive task cues. A modified slalom task with precise tracking phases through a set of gates was developed (*Figure 4*). This course layout included transition and precision tracking phases. The transition phases were intended to be a lower frequency disturbance with the main emphasis of the task being the higher frequency acquisition phase just prior to the gates, and the phase of tracking through the gates. The relative spacing between successive gates was established through the use of an inverse modeling technique [16] that considered the aircraft response, speed, bank angle, and the time to travel between the gates. The width of a gate (desired performance) was three meters. This course was initially developed and used for a cooperative bandwidth and time delay study [17] under the US/German MOU.

4 CROSS COUPLING MODELS

4.1 Onaxis Models

For this roll-pitch cross coupling investigation a decoupled rate command configuration in pitch and roll was selected as the baseline configuration which was consistently evaluated as a Level 1 configuration in the bandwidth and time delay study [17]. A rate of climb response and a sideslip command were implemented for the vertical and the directional axes and were kept constant. The responses to the pilot's inputs were decoupled except for the terms formulating the turn coordination and a pseudo altitude hold. *Figure 5* shows the selected rate command configuration together with the recommended Level boundaries. The onaxis roll and pitch responses are defined by the following transfer functions.

$$\frac{p_{on}}{\delta_y} = \frac{L_{\delta y}}{s+L_p} \quad \text{and} \quad \frac{q_{on}}{\delta_x} = \frac{M_{\delta x}}{s+M_q}$$

Where L_p = -8 rad/sec and M_q = -4 rad/sec, with no added time delay. The control sensitivities are defined with $L_{\delta y}$ = 0.143 rad/sec^2/% and $M_{\delta x}$ = 0.052 rad/sec^2/%.

4.2 Cross Coupling Models

A review of the two primary sources of pitch-roll cross coupling for single rotor helicopters may be illustrated using the following simple equations of motions.

$$\dot{p} = L_p\, p + L_q\, q + L_{\delta y}\, \delta_y + L_{\delta x}\, \delta_x$$

$$\dot{q} = M_p\, p + M_q\, q + M_{\delta y}\, \delta_y + M_{\delta x}\, \delta_x$$

These equations describe the dominant aircraft motions for lateral and longitudinal cyclic input and show the influences of the on-axis damping (M_q and L_p), the gyroscopic or rate coupling terms (M_p and L_q), and the control coupling terms ($M_{\delta y}$ and $L_{\delta x}$).

The implementation of the roll-to-pitch and pitch-to-roll cross coupling models is illustrated in the block diagram of *Figure 6*. The coupling responses are added to the onaxis responses which result in the following overall command responses in the pitch and roll axes:

$$q_{com} = \frac{M_{\delta x}}{s-M_q}\,\delta_x + \frac{M_{\delta y}}{s-M_{q,c}}\,\delta_y + \frac{M_p\, L_{\delta y}}{(s-M_{q,c})\,(s-L_p)}\,\delta_y$$

$$p_{com} = \frac{L_{\delta y}}{s-L_p}\,\delta_y + \frac{L_{\delta x}}{s-L_{p,c}}\,\delta_x + \frac{L_q\, M_{\delta x}}{(s-L_{p,c})\,(s-M_q)}\,\delta_x$$

The ratios of the coupling responses in relation to the onaxis responses are:

$$\frac{q_c}{p_{on}}\Big|_{\delta y} = \frac{M_{\delta y}\,(s-L_p)}{L_{\delta y}\,(s-M_{q,c})} + \frac{M_p}{s-M_{q,c}} \quad \text{and} \quad \frac{p_c}{q_{on}}\Big|_{\delta x} = \frac{L_{\delta x}\,(s-M_q)}{M_{\delta x}\,(s-L_{p,c})} + \frac{L_q}{s-L_{p,c}}$$

with the initial values (t=0)

$$\frac{q_c}{p_{on}}\Big|_{\delta y} = \frac{M_{\delta y}}{L_{\delta y}} \quad \text{and} \quad \frac{p_c}{q_{on}}\Big|_{\delta x} = \frac{L_{\delta x}}{M_{\delta x}}$$

and with the final values (t=∞)

$$\frac{q_c}{p_{on}}\Big|_{\delta y} = \frac{M_{\delta y}\, L_p}{M_{q,c}\, L_{\delta y}} - \frac{M_p}{M_{q,c}} \quad \text{and} \quad \frac{p_c}{q_{on}}\Big|_{\delta x} = \frac{L_{\delta x}\, M_q}{L_{p,c}\, M_{\delta x}} - \frac{L_q}{L_{p,c}}$$

This structure of the coupling models allows the realization of different pitch-roll cross coupling characteristics. When the parameters $M_{q,c} = M_q$ and $L_{p,c} = L_p$, the implemented cross coupling responses are close to the characteristics of a conventional helicopter. The parameters $M_{\delta y}$ and $L_{\delta x}$ define a control coupling response which is induced by the pilot control inputs. The parameters M_p and L_q define a rate coupling response which is induced by the onaxis rate in pitch and roll.

In addition, the objective of the study is to investigate a cross coupling behavior which simulates the coupling characteristics of an augmented helicopter with a feedback control system. In an augmented helicopter the pilot inputs and the onaxis rates initiate a coupling response which is reduced to or close to zero by the feedback system. This washed out characteristic in the offaxis response was realized in the tests by selecting the parameters M_p and L_q using the following equations. With the parameters $L_{p,c}$ and $M_{q,c}$, the dynamics of the washed out characteristics were varied.

$$M_p\, L_{\delta y} = L_p\, M_{\delta y} \quad \text{and} \quad L_q\, M_{\delta x} = M_q\, L_{\delta x}$$

Figure 7 illustrates the different types of cross coupling with step responses which have been tested: (1) control coupling, (2) rate coupling, (3) combined, control plus rate coupling, and (4) washed out coupling. The ratio of roll-to-pitch and pitch-to-roll control and rate coupling was defined close to the ratio of the BO 105 helicopter. In some complementary configurations which were performed in the ground-based simulator the influence of a variation of this coupling ratio was evaluated.

5 DESCRIPTION OF TESTS

5.1 Flight Tests

The flight tests were conducted at the German Forces Flight Test Center (WTD 61) in Manching. Nearly 30 flight hours were performed over an about two-week period. Four test pilots, one from DRA-Bedford, one from the U.S. Army, and two from WTD 61, were involved in the tests. All pilots were experienced test pilots. The U.S. Army pilot also participated in the ground-based simulation evaluations.

The following signals were measured in the flight tests: (1) position of the helicopter in relation to the ground track course, (2) pilot control inputs, (3) angular attitudes and rates, (4) accelerations, (5) airspeed, and (6) MFCS internal signals, like command to the actuators. Because of the limited space in the test helicopter, the tests had to be observed from the ground station. On two quick-look terminals, selected on-board signals were displayed. Additionally, the helicopter position data was displayed online in relation to the tracking gates to check the effects of training and task performance. When the test pilot had obtained a nearly constant task performance in the training phase for a given test configuration, two evaluation runs were performed. This test technique was used to ensure the pilot ratings and comments were based on a pilot that was well trained for the task and the configuration. For each configuration, the pilot had to fill-out a questionnaire and had to summarize his evaluation in a Cooper Harper handling qualities rating. The questions were related to task performance, pilot workload, and system response characteristics (onaxis and offaxis).

5.2 Ground-Based Simulation

The ground-based simulation was conducted at NASA Ames Research Center using an Interchangeable Cab (ICAB) for the Vertical Motion Simulator in a fixed-base mode. Over 80 evaluations were conducted during a two-week period with a NASA-Ames and a U.S. Army experimental test pilot. The visual scene was one that had been used for the reference 17 study with one modification. From comparison of both the reference 17 flight test results and subsequent ground-based evaluations, it was found that flying the simulator at 30 feet altitude the handling qualities ratings more closely match the flight test results flown at 100 feet. Therefore, for the pitch-roll cross coupling evaluations the "desired" and "adequate" altitude cues were lowered so that the reference altitude was 30 feet. For the ground-based simulation, the same gate-tracking information as implemented for in-flight simulation was available, i.e., helicopter position data relative to the tracking gates and a task performance metric that compared the helicopter track to an idealized ground track. This was used to assess pilot training and task performance. The pilot's flew each configuration numerous times before flying it at least two times for evaluation. For each evaluation, the pilot's answered a questionnaire and summarized his evaluation in a Cooper-Harper handling qualities rating.

To calibrate or anchor the results from the ground-based simulation relative to the flight test results, a range of control, rate, and washed-out coupling configurations evaluated in-flight were re-evaluated on the ground-base simulator. These were evaluated prior to expanding the variation of system configurations.

6 DISCUSSION OF RESULTS

6.1 Time Domain

The ADS-33 specifies the requirements for the roll-to-pitch and pitch-to-roll coupling in a time domain format. The ratio of the maximum offaxis attitude response within 4 sec to the onaxis attitude response at 4 sec after the pilot's input shall not exceed the limits of +-0.25 for Level 1 and +-0.60 for Level 2 handling qualities. *Figure 8* shows the test data for the control, rate, and combined coupling configurations in this format. Although there is a relatively large spread in the pilot ratings, the data demonstrate that the ADS criterion seems to be able to provide an appropriate format for the specification of the handling qualities. In addition, the data show nearly perfect consistency between ground-based and in-flight simulation. However, the test data recommend reduced values for the Level boundaries defined in the ADS-33. Configurations with a pitch offaxis to roll onaxis attitude amplitude ratio of about 0.1 and higher have been rated as handling qualities Level 2. The pilots commented on the amount of coupling which increased the pilot workload due to the pilot compensation necessary to achieve the desired task performance in the gate acquisition and tracking phases. The recommended reduction of the boundary values seems to be effected by the slalom tacking task which especially demands a well adapted short-term response.

The washed out coupling configurations represent a short term, high frequency phenomenon. A first selection of washed out coupling characteristics were evaluated in the flight tests. Complementary tests using the fixed-based simulator showed a high inconsistency in the pilot ratings and pilot comments compared with the flight test data. It is speculated that the lack of motion cueing negatively impacted the comparison between simulator and flight test results for the washed out coupling cases. The simulator tests seem to underpredict the influence of coupling and do not show the degradation of pilot evaluations with increasing washed out coupling amplitude. For the further discussion of the washed out coupling aspects only the flight test data are used. In *Figure 9* the data of the washed out coupling configurations are presented together with the data of the control coupling configurations using the ADS format. Only one test pilot evaluated these configurations in flight. This limited number of data does not allow a generalized conclusion but a tendency of the washed out coupling influences can be observed. The data significantly demonstrate that the time domain format is not suitable to cover the effect of this short term coupling response characteristic. Although the amplitudes of the washed out coupling configurations are very low compared to the control, rate, and combined coupling configurations, the pilot commented on the influence of the coupling responses with "increases in workload due to coupling", "objectionable multiaxis coupling", and "only adequate task performance and increased workload in the offaxis". Some attempts have been undertaken to use the data for a refinement of the time domain format (reduction of the 4 sec time to 1 sec, use of onaxis amplitude value at the time of the maximum offaxis amplitude, etc) which yielded no improvement in the consistency of the pilot evaluations.

For some Level 2 and Level 3 flight tests configurations, the pilots commented on the degrading influence of coupling on the onaxis roll response like "jerky tracking" or "jerky roll response due to cross coupling". In the flight tests and all previously discussed simulation test configurations, the ratio of roll-to-pitch and pitch-to-roll coupling amplitudes was defined based on the characteristics of the BO 105 helicopter. In hover the ratio of cross coupling in both directions is nearly one. In forward flight the BO 105 produces nearly three times higher roll rate due to pitch rate than pitch rate due to roll rate. This unbalanced amount of coupling is a typical helicopter characteristic in forward flight depending on the rotor system, the moments of inertia, and the airspeed. This aspect is described in more detail in [12]. In this study the two-axis rate coupling ratio is defined by

$$C \frac{M_p}{M_q} = \frac{L_q}{L_p}$$

To evaluate the influence of the coupling ratio in some more detail, rate coupling configurations with varied ratios were implemented in the fixed-based simulation and tests were conducted with one pilot. Ratios of C = -3 (basic rate coupling ratio), C = -1.8 (close to basic control coupling ratio), C = -1, and C = 0 (no pitch-to-roll coupling) were realized. The data in *Figure 10* demonstrate the influence of the coupling ratio. The ratings tend to degrade with a higher coupling ratio. This effect is not considered in the ADS criterion, which specifies individual but the same boundary values for roll-to-pitch and pitch-to-roll coupling. The test data indicate that a cross coupling criteria should combine both coupling directions in one format but for a final criteria definition more test data with broader variations are needed.

6.2 Pilot Control Strategy

An analysis of the pilots' control activity was performed to gain additional insight into the effects of changes in the cross coupling and the compensation on the pilots' control strategy while performing the slalom tracking task. *Figure 11* shows typical examples of pilot inputs crossplots. In the decoupled baseline configuration, the pilots have mainly used lateral control to fly the course which confirms that the slalom tracking course is essentially a single axis piloting task. Only a few excursions in the longitudinal control can be recognized. These were used for some mid-to-long-term corrections of the airspeed and the height. With an increasing amount of coupling, the pilots compensated for the coupling response with higher amplitudes in the longitudinal inputs. The "figure eight" characteristic of the lateral and longitudinal inputs points to a feedback related control strategy of the pilots which is in the fundamental characteristic and not depending on the type of coupling. A more feedforward related strategy would result in a more diagonally oriented control activity. This feedback compensation characteristic of the pilots' control could be verified by simulating the pilot as a pure gain feedback with a quite accurate matching of the measured flight data.

Figure 12 shows for the same test configurations the power spectra of the pilot stick inputs. In the decoupled baseline configuration spectrum, the phases of the slalom tracking task are marked. The phases (1) sequence of the gates, (2) transition from one gate to the next, (3) acquisition of the gates, and (4) tracking in the gates can be obviously separated in the control activity of the pilots. The lateral input spectra have briefly the same level of power in all phases for the Level 1 and Level 2 configurations. This demonstrates a nearly unchanged level of agression in the transition phases and an unchanged level of precision in the acquisition and tracking phases to meet the desired task performance. In Level 3 configurations the amplitudes and the frequencies of the lateral inputs were significantly reduced which affected the task performance in the course. With added amount of coupling, the activity in the longitudinal control was increased by the pilots in all phases of the task.

6.3 Frequency Domain

The pilots commented in the test questionnaires that the pilot ratings were primarily based on the gate acquisition and tracking phases. In these phases the influence of the cross coupling was most evident and highly complicate to be compensated. In the pilot input power spectrum of the decoupled baseline configuration in figure 12, the pilot's lateral input frequency in the gate acquisition is around 3.5 rad/sec and in the gate tracking up to a frequency of about 7 rad/sec. The bandwidth of the onaxis roll response is ω_{BW} = 3.46 rad/sec and the neutral frequency is ω_{180deg} = 7.45 rad/sec. Comparing the system frequencies with the pilots input frequencies, it can be stated that the pilots used the system bandwidth capability to perform the tracking task, at least in a Level 1 configuration.

For a high gain pilot tracking task, the pilot evaluations of the coupling influence on the handling qualities are more related to the short-term response. A frequency format seems to be more appropriate for a definition of the roll-to-pitch and pitch-to-roll cross coupling requirements. To illustrate this aspect, the pilot evaluations of the tested configurations are plotted against frequency related parameters in *Figure 13 to 15.* The amplitude ratios of the offaxis to the onaxis response roll-to-pitch and pitch-to-roll at a frequency of 3.5 rad/sec are used in the diagrams to check this premise. The 3.5 rad/sec frequency was picked because it is the roll axis bandwidth frequency and the gate acquisition frequency. The diagrams can only illustrate the tendency of handling qualities evaluation in a frequency format, for a more substantiated criteria format and verified requirements an extended data base is needed.

The figure 13 shows all the cofigurations of the control, rate, and combined coupling. The scatter in the pilot ratings exhibits at least the same quality of consistency compared with the one axis ADS format. In figure 14 the washed out coupling configurations realized in the flight tests are plotted against the control and rate coupling cases. The washed out ratings fit surprisingly well with the ratings for the other coupling cases. This plot especially underlines the potential of a frequency format for specifying the coupling influences in a tracking task. A frequency format can cover more adequately the different types of coupling representing a conventional and a highly augmented helicopter. Figure 15 shows the simulation data of the cases with a varied ratio of roll-to-pitch and pitch-to-roll coupling. The plotted data illustrate that this two-axis phenomenon can be appropiately matched by a two-axis format.

7 CONCLUDING REMARKS

A helicopter handling qualities study has been conducted to investigate the effect of different types of roll-to-pitch and pitch-to-roll coupling. The implemented coupling variation was based on a roll and pitch onaxis characteristic which was clearly evaluated as Level 1 handling qualities in a previously performed bandwidth study. The coupling investigation was conducted as a collaborative effort between the U.S. Army's Aeroflightdynamics Directorate (USAATCOM) and the German Institute for Flight Mechanics of DLR. A U.S. ground-based flight simulator and the German in-flight simulator ATTHeS were used in complement. The tests were performed in a slalom tracking task which was developed within the bandwidth study. The objective of this work is to develop a refined helicopter pitch-roll cross coupling handling qualities criteria for aggressive forward flight maneuvering tasks. The results of this cooperative research indicate:

- there are individual benefits of both ground-based and in-flight simulation which can be used in a complementary and time efficient manner,
- different characteristics of cross coupling have been considered:

(1) control, rate, and a combined (control plus rate) coupling representing more the behavior of a conventional helicopter,
(2) washed out coupling represents the behavior of an augmented helicopter, and
(3) a varied ratio of roll-to-pitch and pitch-to-roll coupling amount can represent different helicopters with different rotor systems,

- for the task evaluated, a time domain format for defining the coupling requirements as used in the ADS-33 shows some inconsistencies and cannot cover the coupling cases representing (1) a conventional helicopter and (2) an augmented helicopter in one format,
- for the task evaluated, a frequency based format seems to be more adequate to specify the initial response coupling characteristics, and
- a two axis format seems to be necessary to take into account the two-axis pitch-to-roll and roll-to-pitch coupling effects.

The generated data base allows first conclusions to be drawn for a refinement of the coupling requirements related to a tracking task. For a more substantiated and comprehensive definition of the requirements, an extension of the data base is needed. A second in-flight simulation test program with the ATTHeS testbed has been conducted mid of this year for covering a more complete set of coupling configurations.

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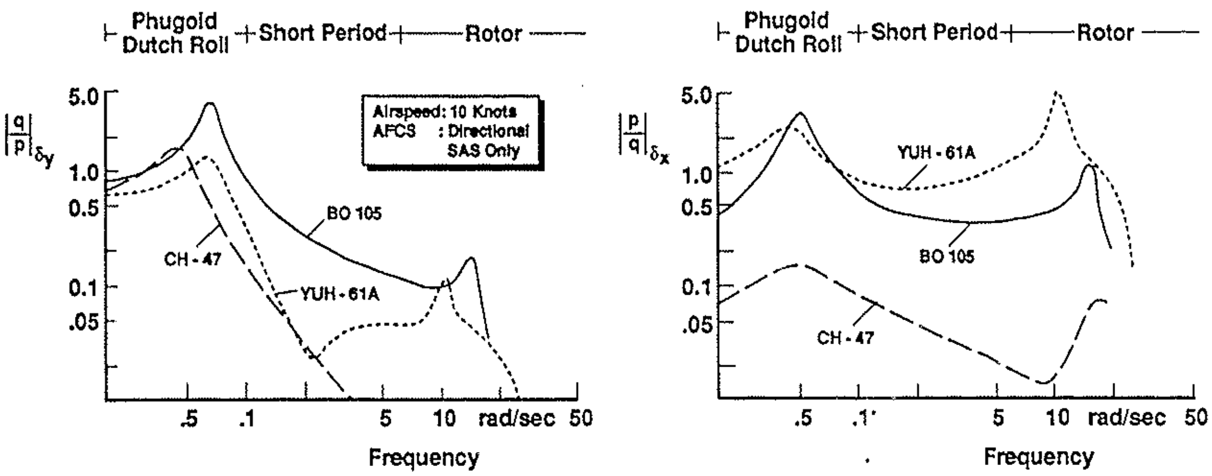
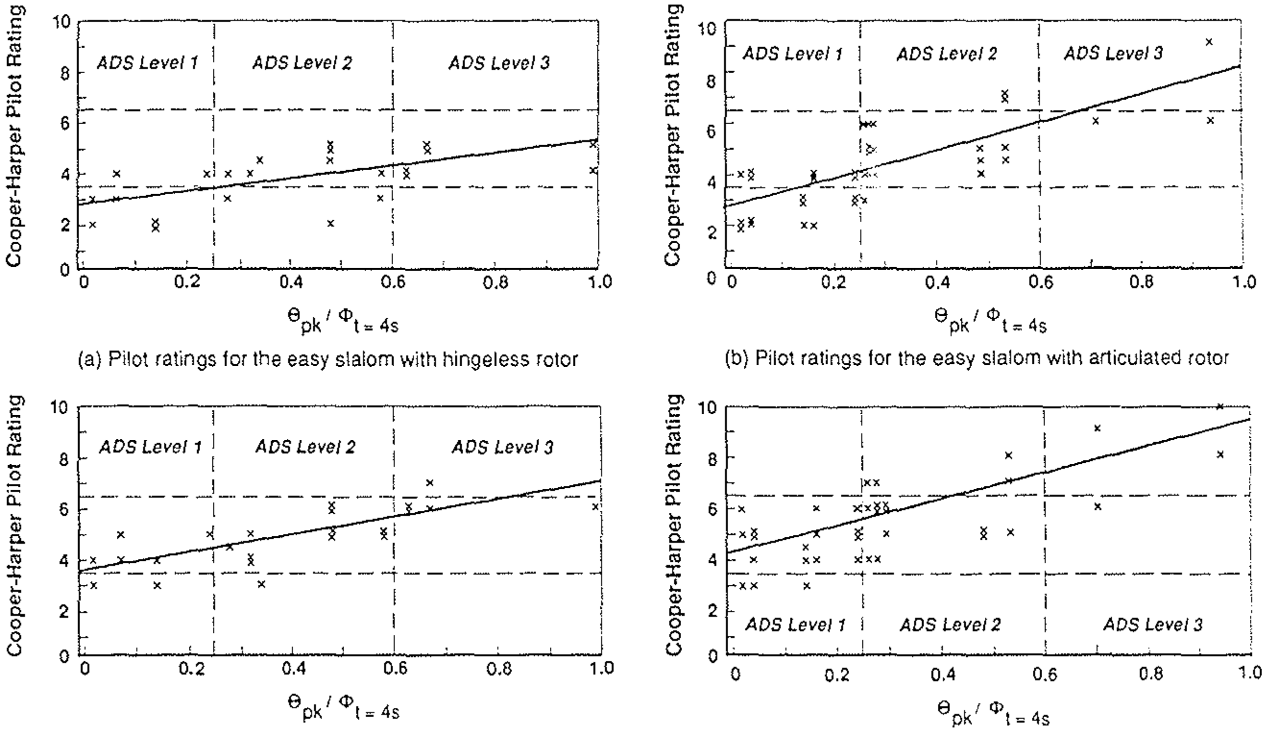


Figure 1. Frequency dependency of pitch-roll cross coupling (ref. 1)



(a) Pilot ratings for the easy slalom with hingeless rotor

(b) Pilot ratings for the easy slalom with articulated rotor

(c) Pilot ratings for the difficult slalom with hingeless rotor

(d) Pilot ratings for the difficult slalom with articulated rotor

Figure 2. Pilot ratings versus θ_{pk}/ϕ for an "easy" and "difficult" slalom (ref. 8)

Figure 3. DLR in-flight simulator ATTHeS

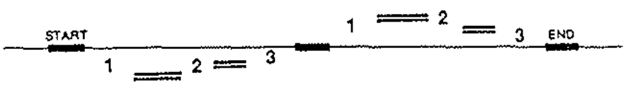


Figure 4.
Slalom tracking course
(times shown for 60 kts)

Gates :

3 sec
90 m/295 ft

5 sec
150 m/490 ft

Distances Between Gates
(x, y measured from previous gate)

1 (5 sec) x : 153m/500ft y : 10m/32ft

2 (3 sec) x : 92m/300ft y : 3.5m/12ft

3 (5 sec) x : 153m/500ft y : 6.5m/20ft

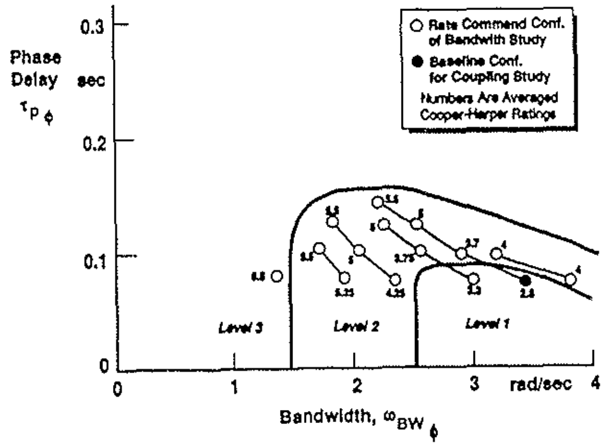


Figure 5. Baseline configuration

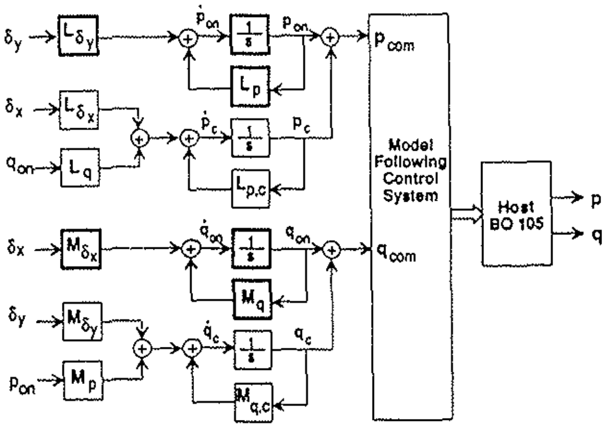


Figure 6. Models of pitch and roll axis

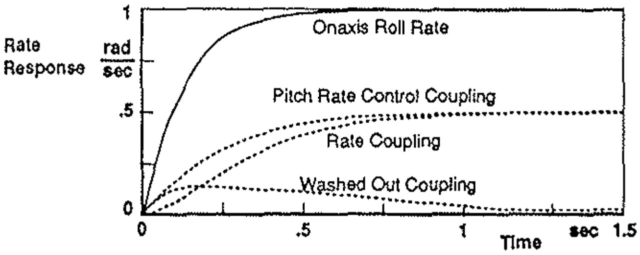
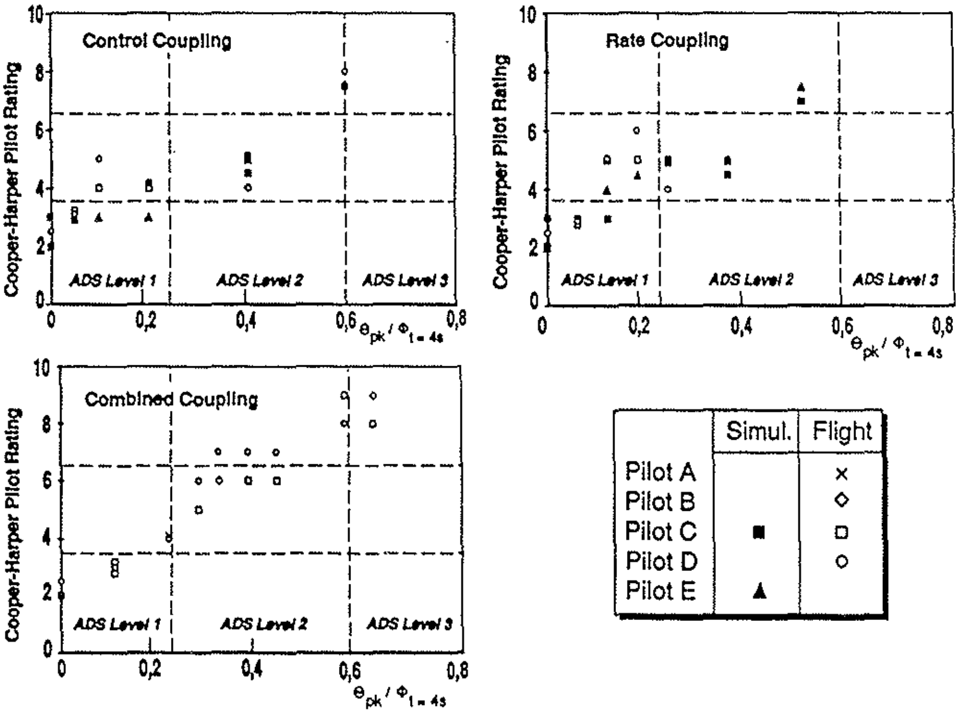


Figure 7.
Variation of coupling parameters

Control Coupling :	$\left\lvert \frac{L_p\, L_{\delta y}}{M_q\, M_{\delta y}} \right\rvert$	= 0.0 - 0.6	$\left\lvert \frac{M_q\, L_{\delta x}}{L_p\, M_{\delta x}} \right\rvert$	= 0.0 - 0.75
Rate Coupling :	$\left\lvert \frac{M_p}{M_q} \right\rvert$	= 0.0 - 0.625	$\left\lvert \frac{L_q}{L_p} \right\rvert$	= 0.0 - 1.875
Washed Out Coupling :	$\left\lvert \frac{M_{\delta y}}{L_{\delta y}} \right\rvert$	= 0.0 - 0.25	$\left\lvert \frac{L_{\delta x}}{M_{\delta x}} \right\rvert$	= 0.0 - 1.25
	$\lvert M_{q,c} \rvert$	= 2, 4, 6	$\lvert L_{p,c} \rvert$	= 4, 8, 12



	Simul.	Flight
Pilot A		×
Pilot B		◇
Pilot C	■	□
Pilot D		○
Pilot E	▲	

Figure 8. Pilot ratings versus θ_{pk} / ϕ for control, rate, and combined coupling

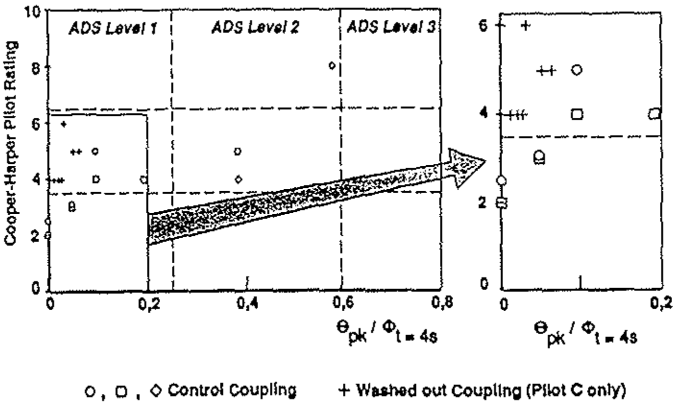


Figure 9. Pilot ratings versus θ_{pk} / ϕ for control and washed out coupling

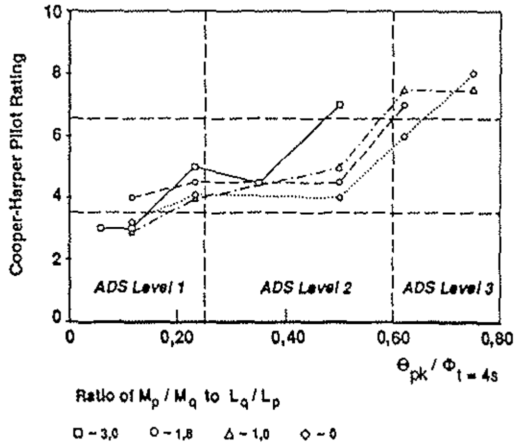


Figure 10. Pilot ratings verus θ_{pk} / ϕ for varied roll-to-pitch and pitch-to-roll ratios

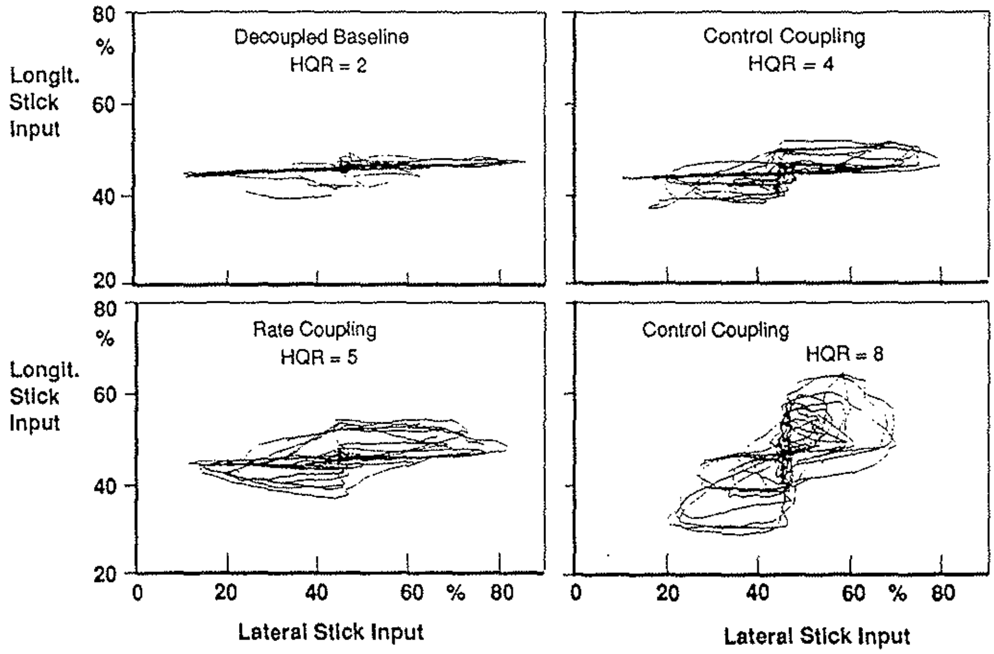


Figure 11. Pilot input crossplots

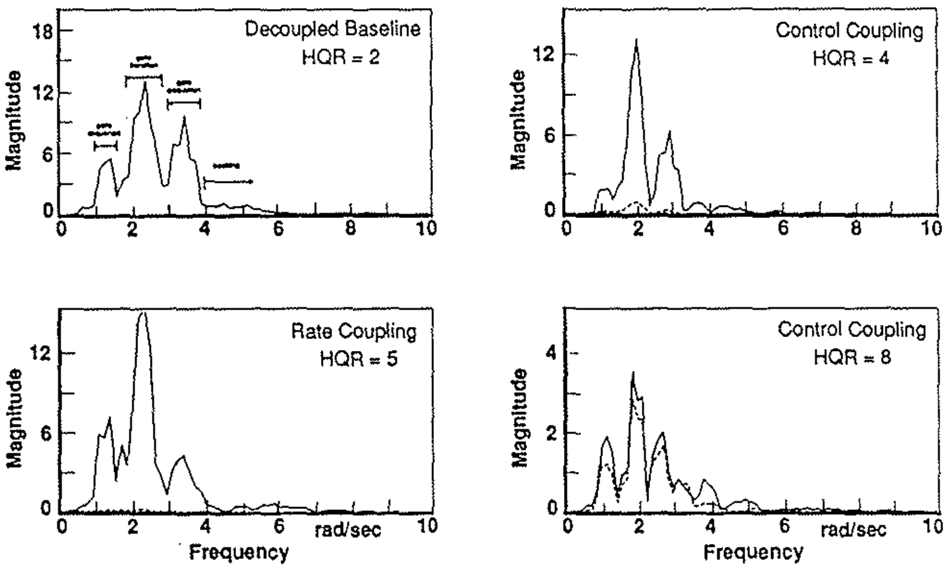


Figure 12. Pilot input power spectra

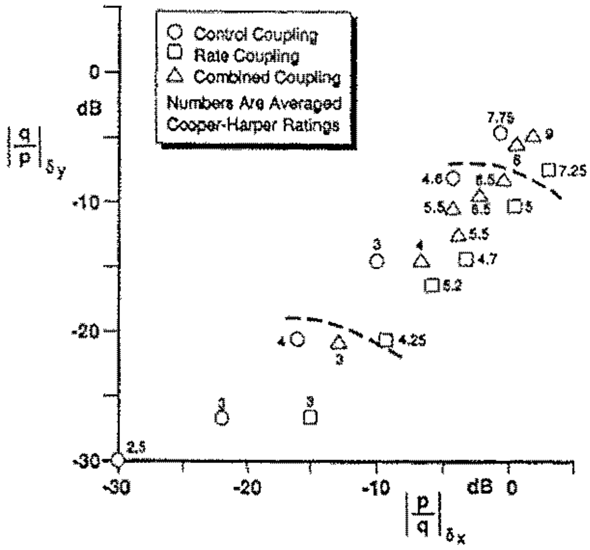


Figure 13. Coupling amplitudes at 3.5 rad/sec

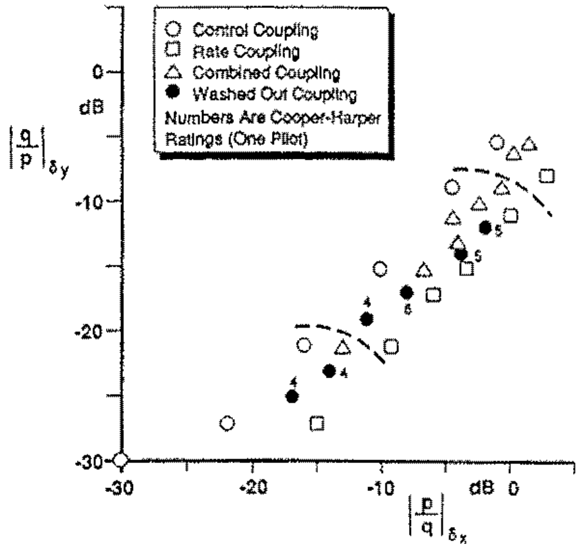


Figure 14. Coupling amplitudes at 3.5 rad/sec

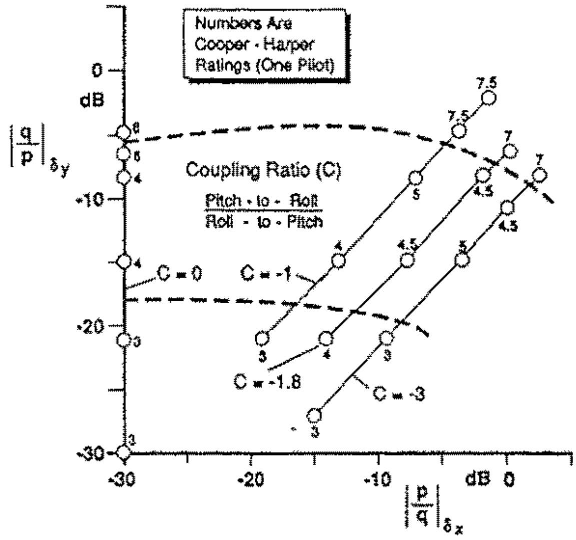


Figure 15. Coupling amplitudes at 3.5 rad/sec