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A STUDY OF ROLL RESPONSE REQUIRED IN A LOW ALTITUDE SLALOM TASK

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Abstract

A helicopter in-flight simulation was conducted to investigate the influence of roll sensitivity, roll damping, and roll-to-pitch coupling on the evaluation of handling qualities. The flight test task for the test pilots was to fly a slalom track set up with poles on the ground. The altitude of 100 ft and the airspeed of 60 kts had to be maintained fairly constant. The slalom task represents evidently the roll response demands of an NOE flight. The experiment utilized the variation capability of the DFVLR BO 105-S3 helicopter equipped with a fly-by-wire control system. The research helicopter, the flight test set up and the test procedure are described.

Results are shown in terms of Cooper-Harper ratings and pilot comments. They are compared with existing criteria requirements and recommendations of previous studies. These results yield the suggestion of a higher level of roll sensitivity and damping in comparison to the current criteria. In addition, approaches for task performance evaluation are discussed and correlated with the test data.

NOMENCLATURE

f	frequency, Hz
L_p	roll damping, 1/sec
$L_{\delta y}$	roll control sensitivity, rad/sec^2/inch
N	numerator
NOE	Nap-of-the-Earth
n_z	normal load factor, g
PR	Cooper-Harper pilot rating
p	roll rate, deg/sec (rad/sec)
q	pitch rate, deg/sec (rad/sec)
T_1	lag time constant, sec
T_2	lead time contant, sec
t	time, sec
V_x, V_y	control gains
V_{xy}, V_{yx}	control crossgearing gains
V_s	gain for control step input

x, y	position in relation to course, m
Δ	determinant of characteristic equation
Δ_ϕ	net roll angle change, deg
δ_x	pitch stick input, % (inch)
δ_y	roll stick input, % (inch)
η_x	pitch control actuator input, %
η_y	roll control actuator input, %
σ_c	standard deviation of command signal
σ_e	standard deviation of error signal
ϕ	roll angle, deg

1. INTRODUCTION

It is well accepted that the need exists to establish a viable data base which can be used to define the requirements for helicopter flying qualities. This has become more obvious with the effort to revise the military handling qualities specification for rotary-wing aircraft MIL-H-8501 [1, 2] and with the many helicopter projects being in the phase of planning. The purpose of this paper is to describe flight tests which have been conducted and evaluated with the objective to make a reasonable contribution to the mentioned requests. The high number of data gaps asks for coordinated efforts of all the institutes with potential in this area of endeavor. A coordination of the activities is necessary to guarantee that the efforts are supplementary and the results are comparable.

The flight tests adressed in this paper were conducted as a part of a research program of the DFVLR Institute of Flight Mechanics consisting of analytical studies and flight experiments. The flight test studies include the use of operational helicopters and the in-flight simulator ATTHeS (Advanced Technology Testing Helicopter System) [3, 4]. The studies commenced with an investigation for the assessment of the demands of new missions, the derivation of flight test tasks being representative for selected mission elements, and the evaluation of task performance and pilot workload in specific NOE flight test tasks [5, 6]. To meet the requested coordination, cooperations exist with RAE and esspecially with US-ARMY/NASA including the mutual participation of pilots and engineers in the flight tests.

If handling qualities are those vehicle response characteristics which impact the pilot's ability to perform a demanded flight task or a mission then we must accept to quantify handling qualities in close relation to the mission or, more detailed, to specific flight tasks. This important interrelation between missions and required handling qualities has been stated and discussed in some previous papers [2, 7, 8]. Historically, requirements for helicopter handling qualities have not been very closely tied to individual flight tasks. Especially emphasis has to be placed on requirements dealing with the low altitude phases of todays helicopter missions. In the DFVLR study with the objective to assess mission demands and to derive representative flight test tasks, a slalom task was found which represents evidently the demands of lateral maneuvering in the NOE (Nap-of-the-Earth). This slalom task was used for these tests. It is essentially similar to a slalom track used for US-ARMY/NASA experiments [9].

Fundamental helicopter stability and control characteristics, such as control sensitivity, damping, and cross-coupling vary widely with the type of rotor system and can be influenced significantly with the installed control system. At NASA both, the influence of rotor design parameters and of various levels of control augmentation was examined [10, 11]. It is of particular interest to determine the effect of these characteristics on the handling qualities evaluation during the performance of low altitude flying like NOE, which requires a well adapted combination of response characteristics. In addition, the allowable reduction of handling qualities has to be examined for the failure situations of augmentation systems. Consequently not only satisfactory characteristics have to be identified. The degradation of characteristics with an only acceptable and unacceptable evaluation has to be considered.

To address these needs, an in-flight simulation experiment was conducted specifically dealing with the effects of roll control sensitivity and roll damping for NOE operation. For the experiment the DFVLR BO 105 equipped with a fly-by-wire control system was utilized. The great advantage of the BO 105 helicopter for in-flight simulation is the high inherent control power, which enables a broad variation of vehicle characteristics that is an important aspect of handling qualities studies.

2. DESCRIPTION OF EXPERIMENT

2.1 RESEARCH HELICOPTER

The research helicopter (Figure 1) corresponds in all essential components to the serial helicopter MBB BO 105 with the exception of the control system [4]. The modified system requires a two-man crew consisting of a safety and an evaluation pilot for simulation flights. The cockpit has been modified by moving the safety pilot's station to the left hand back seat and the evaluation pilot's station to a center front seat. This modification allows single pilot evaluations while still giving the safety pilot a good outside visibility and visual contact with the evaluation pilot's control activity. The safety pilot is provided with a direct link to the helicopter controls through the standard mechanical/hydraulic control system. The evaluation pilot's station is equipped with conventional pedals, stick, and pitch. However, these controls are electrically linked to the helicopter controls.

The fly-by-wire system is a simplex, full-authority system. When the evaluation pilot station is engaged, the actuators operate in an electrohydraulic mode with mechanical feedback to the safety pilot's controllers. A schematic diagram of the control system is shown in Figure 2. The helicopter can be flown in three modes: (1) the 1:1 fly-by-wire mode, (2) the fly-by-wire mode with an additional control system as variable stability or variable control helicopter, and (3) the fly-by-wire disengaged mode where the safety pilot has exclusive control. The fly-by-wire system can be disengaged by both pilots and a safety system using limitations for the mast moment and lag moment. In addition, the safety pilot can override the fly-by-wire system by applying a specified force to the appropiate controller.

For this flight experiment the variable control capability was used to realize the configurations which should be evaluated. For further handling qualities studies with a variable stability capability a model following control system was designed and tested in a simulator experiment [12].

2.2 TEST MATRIX

With respect to the main objective of the experiment to evaluate the effect of roll response variation in a low level slalom task a variation of roll control sensitivity and roll damping were investigated. Starting with the characteristics of the basic BO 105 in a 60 knot forward flight condition ($L_{\delta y}$= 2.22 rad/sec^2/inch, L_p= 7.6 1/sec) the roll control sensitivity was reduced in steps of 1/4 and the roll damping was altered in steps of 1/3 of the basic helicopter. The range of control sensitivity and damping covered in the experiment is shown in Figure 3. Also shown are the requirements of the V/STOL specification MIL-F-83300 [13] and recommended boundaries of two previous studies [9, 14]. The ref. 14 requirements are determined for only satisfactory characteristics based on data records from mission tests. The pilot's workload has not been taken into account. The ref. 9 recommendations are derived from data recorded in a slalom that was essentially similar. The tests were flown with the V/STOLAND variable stability helicopter which is a modified UH-1H helicopter. The teetering rotor system has only allowed a variation of roll control sensitivity up to 1 rad/sec^2/inch. The discrepancy between the recommendations of the two references and additonally, the satisfactory ratings for the basic BO 105 examined in a previous DFVLR study [6] has initiated the experiment with the aim to get an extended data base.

The altered roll characteristics were realized with an analogue feedforward device installed in the fly-by-wire control loop of the evaluation pilot. The control sensitivity was varied with a variation of the gain. The altered influence of roll damping was achieved with a lag time constant whereas a lead time was chosen to cancel a first order L_p time constant inherent in the basic helicopter. An approximate roll axis response transfer function can be expressed by:

$$\frac{N^p_{\delta y}}{\Delta} = \frac{L_{\delta y}}{s + L_p} \cdot V_y \frac{T_2\ s + 1}{T_1\ s + 1} \quad .$$

The pitch axis response was altered in harmony with the roll axis. Figure 4 shows the installed analogue network in a block diagram.

To reduce the effects of roll/pitch crosscoupling for all configurations a crossgearing of the controls was implemented which abates the initial response coupling. An additional device was used to enable accurate step inputs for the longitudinal and lateral controls. Figure 5 shows the verification of the initial response decoupling. For about two seconds the influence of roll to pitch coupling can be treated as negligible. To get an impression of the range of roll damping and roll sensitivity, step responses for extreme configurations are shown in Figure 6. Both diagram represent time histories recorded in flight.

2.3 EVALUATION TASK AND TEST APPROACH

The flight experiment was conducted at the German Forces Flight Test Center at Manching. Four test pilots, all of whom had considerable flight test experience and helicopter time, were involved in the tests (RAE-Bedford, NASA-Ames, and DFVLR-Braunschweig).

A slalom ground track was set up, which respresents the NOE demands on the helicopter roll response characteristies [5]. It also has been used previously in DFVLR experiments with operational helicopters [6]. In addition, it is essentially similar to a track used in the US-Army/NASA in-flight simulation study [9]. Six 300 m ground poles formed the course along a marked centerline shown in Figure 7. In lateral direction they were separated by 80 m. The task was flown with a 60 knot airspeed and 100 feet height which is defined as the minimum height for the helicopter in the fly-by-wire mode. The pilots were instructed to follow the ground track, minimize the lateral displacements from the poles, and maintain the airspeed within ± 6 kts and the height within ± 10 ft. All tests were flown in good visibility and calm wind conditions (± 30^{o} front wind, max 6 kts).

The flight tests consist of several training runs followed by a series of two or three evaluation runs for each pilot/configuration combination. The training phase allowed the pilot to familiarize himself with the test configuration and to adapt his control strategy. The progress in task performance was monitored on-line in the ground station. To support the decision for starting the evaluation runs a score factor was computed as the ratio of the standard deviations of the commanded ground track (σ_c) and the deviation from the ground track (σ_e) (see fig. 7). In the training phase the score factor has revealed an asymptotic slope and has stayed nearly constant during the test runs. The scatter in the factor depends on the difficulty of the flight task and the qualification of the vehicle characteristics to perform the task.

Providing the test engineer an on-line information about the achieved task performance and the learning curve of the pilot has an essential benefit to the test approach in the field of handling qualities research. Test runs in the learning phase of pilots can be avoided which would yield incorrect ratings and comments of the pilots with respect to the vehicle configuration and the task. It must be recognized that this aspect has accounted for many problems with the analysis of test data. Additionally the test pilots have been aware of the situation to achieve the demanded task performance and they have not responded to more difficult characteristics by reducing the task performance.

2.4 DATA ACQUISITION

Data acquisition was provided by telemetry to the ground station for the on-board measured data. Variables recorded included control positions, actuator control positions, attitudes, rates, accelerations, airspeed data, and radio altitude. A laser tracking system on the ground yielded the helicopter position data relative to the slalom course. On-board and position data were digitized on-line and were time synchronized in the ground station with a sampling frequency of 20 Hz for the evaluation test and 100 Hz for the verification step input tests. In this format the data were available for on-line monitoring and data accuracy checks, and post-flight analysis. A more detailed description of the DFVLR data acquisition technique is given in [15].

For each configuration the pilots had to answer a questionnaire which included an overall Cooper-Harper rating and ratings for pilot's workload and task performance to obtain redundancy in the rating information. A commentary checklist was used for the pilots to comment on the roll response characteristics like preciseness, sensitivity, and damping, on the coupling responses, and on other influences effecting pilots workload and task performance.

3. DISCUSSION OF RESULTS

3.1 DAMPING, SENSITIVITY, AND COUPLING

In the following discussion, the ratings and comments of the pilots are used to illustrate the trends of evaluation for the varied vehicle characteristics. The individual pilot ratings are shown in Figure 8. With the decoupling, an improvement of about one rating point can be noticed. These evaluations underline the influence of coupling on the pilot workload. In this experiment the gain of the roll/pitch coupling was reduced by the control crossgearing. A more precise examination has to take into account the frequency-dependant characteristic of coupling. Consequently it must be recognized that the coupling influence on handling qualities requirements have to be explored more detailed in further experiments. Related to the altered damping and sensitivity a trend for an optimum combination of both is obvious. The pilot scatter for the individual ratings is between 1 to 2.5 rating points. Especially the scatter is increased with higher ratings, which may be affected also by the differences of the vehicle response on pilot control and turbulence inputs. Figure 9 exhibits the pilot ratings in regard to the range of score factors computed from the evaluation runs. The drawn envelopes make clear the consistent pilot behavior which is a necessary prerequisite for expressive handling qualities statements. Evidently one test pilot has flown the slalom course with higher agressiveness than the others. The occuring deterioration of task performance with ratings of more than five correlates with the used Cooper-Harper scale which specifies a step in the pilot decision tree from desired to adequate performance at this rating.

Figure 10 illustrates the region of satisfactory evaluated combinations of roll control sensitivity and roll damping. In comparison to the data of Corliss and Edenborough the present data are in closer proximity to the Edenborough NOE-criteria. The tests suggest that pilots prefer a level of sensitivity between $L_{\delta y} = 1$ and 2 rad/sec/inch and a level of damping between $L_p = 4$ and about 9 sec^{-1}. The recommended level 2 boundary slope is nearly synchronous to the data of ref. 9. Missed data points with only unacceptable evaluations are a handicap to ensure the level 2 boundary. However, some convergence with the existing criteria established in the specifications like MIL-F-83300 exists for level 2 recommendations in the region of higher damping and low sensitivity and higher sensitivity and low damping. The criteria seem to require too low roll sensitivity and roll damping for a NOE flight. The pilot comments depict the same suggestion. Figure 11 summarizes the main pilot comments for some essential configurations. The pilot comments have high correlation with the pilot ratings and reflect implemented vehicle characteristics. Evidently it can be noticed that the pilots evaluated the coupling influence depending on the evaluation of the primary response characteristics. Having satisfactory roll characteristics, coupling is not so much a problem for the pilots than having worse evaluated damping/sensitivity configurations.

3.2 CONTROL STRATEGY AND TASK PERFORMANCE

In order to get an insight into the adaptation of piloting technique to the slalom task and to the altered vehicle response behavior the data recorded in the test were analyzed. The 300 m distance of the course poles is equivalent with a bank angle commanded with a frequency of about 0.1 Hz. Figure 12 shows representative autospectral density plots for roll attitude over the slalom course of one pilot. The curves point out a dominance in the spectral densities at the course frequency for all test configurations. The bandwidth differs evidently depending on the damping/sensitivity combination. The decrease of roll attitude density with frequencies above the course frequency correlates with the pilot evaluations. The pilots desire a smooth slope implying a fairly high roll response bandwidth in closing the loop, that means a vehicle capability which allows the pilots to react with rapid attitude changes in the slalom course. Simplifying the piloting technique in a slalom it can be described as closing the outer loop for the lateral displacements commanded by the poles of the course. The pilot matches the ground track commands with an inner loop using the helicopter roll capability to support the basic maneuver. For a handling qualities approach the more emphasized role of the pilot is to control and stabilize the roll attitude. This interpretation can also be stated using time history plots (see Figure 13). A well rated configuration yields peak roll rates up to 50 deg/sec nearby the slalom poles and clearly delimited phases with roll attitudes and roll rates near zero between the poles. The deterioration of the ratings correlates with higher control activity in all phases of the slalom, with higher control inputs up to full throws, with decreasing peak roll rates, and inaccuracies of ground track.

In general, two phases have to be distinguished in the slalom track task. In the large amplitude phase, the pilots desire a high ratio of roll rate and roll attitude, and a sensitive vehicle response. In the low amplitude phases, the pilots had to stabilize the vehicle after the turns. An adequate preciseness of response is required. Summarizing the closed loop behavior and its correlation with the pilot ratings and comments suggests a rate command-attitude hold system as the best adapted response type for this class of roll maneuvers.

3.3 TASK PERFORMANCE EVALUATION

In ref. 7 a concept for task performance evaluation is described. Based on the phase plane trajectories an effective task performance is expressed by the commanded net roll angle changes and the corresponding peak roll rates during these changes. Figure 14 shows the data of this experiment using the technique for the high amplitude phases. The diagram illustrates the agressiveness of the pilot/helicopter system which can be achieved with the implemented helicopter roll characteristics. The data points indicate bounds for the evaluation of task performance. The maximum peak roll rate required by the slalom task is 40 deg/sec for roll angle changes with more than 50 deg. Also a minimum roll rate capability of 25 deg/sec seems to be necessary to perform the slalom in a satisfactory manner. The region between about 25 deg and 50 deg commanded roll angle changes points to a linear relation of the desired ratio of peak roll rate and roll angle. The boundary for an acceptable evaluation is yielded by a parallel displacement to more moderate demands. It should be noted that the advantage in applying this approach and evaluation technique is to permit a rapid examination of flight data without the expense of complicated measurement equipment and data analysis technique. The concept includes the recognition of the flight task as an integral part of the man/vehicle system.

Another approach for task performance evaluation of a slalom task is proposed in ref. 3. In the approach it is assumed that a slalom task can be performed ideally using only roll attitude control. Then the relation of normal load factor and bank angle, being expressed as $n_z = 1/\cos \phi$, can be taken as reference for the task performance evaluation. Figure 15 shows crossplotted roll angle and normal load factor data for typical examples of recorded slalom runs together with the pilots' evaluations. Evaluation bounds can be drawn distinguishing the two mentioned phases of the task. Turning around the poles the pilots tolerated deviations from the reference of about 15 deg in the roll angle. A satisfactory and acceptable evaluation can be separated principally by the low amplitude roll angle phase between the poles that includes also the initiation and ending of the turns and characterizes essentially the transitory nature of the slalom task execution. An unacceptable evaluation is obtained if both phases are no more distinguishable and necessary maximum bank angles cannot be flown. Two main influences of the helicopter characteristics substantially stand for the deviations of test data from the reference curve and are consequently included in the evaluation approach. (1) If the roll sensitivity and preciseness are insufficient for the task, the pilots have to add sideslipping to support the turns mainly in the transition. (2) In general, the pilots compensate the helicopter inherent coupling response. Remaining coupling responses in pitch and heave are effecting the normal load factor.

4. CONCLUSIONS

This paper presents results of an in-flight simulation experiment in which the effects of broad varied roll sensitivity and roll damping and gain reduction of roll/pitch coupling were examined. The test configurations were evaluated on an NOE related slalom track at 60 kts. The data were analyzed with respect to existing criteria and recommendations of previous studies. In addition, the task performance of the pilot/helicopter system was examined and compared with approaches for task performance evaluation.

A test procedure was applied to increase the confidence in and to improve the accuracy of handling qualities experiment results. This procedure included an extended pilot questionnaire to achieve redundancy in pilot ratings and comments. The adaptation of pilots to the task and to the test configuration was checked with an on-line computed score factor.

Recommendations for the combination of roll sensitivity and roll damping can be stated for the NOE. A range of sensitivity between $L_\delta = 1$ and 2 rad/sec^2/inch and a damping between $L_p = 4$ and about 9 1/sec yields satisfactory evaluations. The derived level 1 and level 2 bounds agree with portions of criteria and previous studies, but show to be supplementary, too.

A pure gain reduction for roll/pitch coupling points out the evident influence of coupling on handling qualities. A more detailed study is planned at DFVLR using a frequency dependant characterization of coupling.

The amplitude and bandwidth of the roll angle are primarily characterizing the closure of the loop by the pilot. Phases of low amplitude and high amplitude modes can be distinguished. The correlation with the pilots evaluations suggests a rate command/attitude hold response system for this class of roll flight tasks.

The examined task performance approaches, based on the phase plane technique and on a bank angle-load factor relation, show a significant relation to the evaluations. Both approaches have been found to be feasible alternatives for helicopter examinations with the pilot in the loop. Their advantage is that they do not need complicated measurement equipment or analysis technique.

References

1) N.N., Helicopter Flying and Ground Handling Qualities; General Requirements for Military Specifications, MIL-H-8501 A, 1961.

2) Key, D.L., The Status of Military Helicopter Handling Qualities Criteria, AGARD-CP-333, 1982.

3) Pausder, H.-J., Sanders. K., DFVLR Flying Qualities Research Using Operational Helicopters, Paper presented at 10th European Rotorcraft Forum, 1984.

4) Gmelin, B., Bouwer. G., Hummes, D., DFVLR Helicopter In-Flight Simulator for Flying Qualities Research, Paper presented at 10th European Rotorcraft Forum, 1984.

5) Pausder, H.-J., et al., Flight Test Techniques for the Assessment of Helicopter Mission Demands, AIAA-83-2735, Paper presented at 2nd Flight Testing Conference, 1983.

6) Pausder, H.-J., Gerdes, R.M., Flight Tests for the Assessment of Task Performance and Control Activity, Vertica, Vol. 8, No. 1, 1984.

7) Heffley, R.K., Bourne, S.M., Helicopter Handling Requirements Based on Analysis of Flight Maneuvers, Paper presented at the 41st Annual AHS Forum, 1985.

8) Gmelin, B.L., Pausder, H.-J., Mission Requirements and Handling Qualities, in Helicopter Aerodynamics, AGARD-LS-139, 1985.

9) Corliss, L.D, Carico, G.D., A Preliminary Flight Investigation of Cross-Coupling and Lateral Damping for Nap-of-the-Earth Helicopter Operations, Paper presented at 37th Annual AHS Forum, 1981.

10) Talbot, P.D., et al., Effects of Rotor Parameter Variations on Handling Qualities of Unaugmented Helicopters in Simulated Terrain Flight, NASA TM 81190, 1980.

11) Chen, R.T.N., et al., A Piloted Simulator Study on Augmentation Systems to Improve Helicopter Flying Qualities in Terrain Flight, NASA TM 78571, 1979.

12) Hilbert, K.B., Bouwer, G., The Design of Model-Following Control System for Helicopters, AIAA-84-1941, Paper presented at AIAA Guidance and Control Conference, 1984.

13) N.N., Flying Qualities of Piloted V/STOL Aircraft; Military Specification, MIL-F-83300, 1970.

14) Edenborough, H.K., Wernicke, K.G., Control and Maneuver Requirements for Armed Helicopters, Paper presented at 20th Annual AHS Forum, 1964.

15) Holland, R., Zöllner, M., Real-Time Ground Analysis Systems, Paper presented at AGARD-Cranfield Flight Test Instrumentation Short Course, 1985.

Figure 1. ATTHeS Research Helicopter

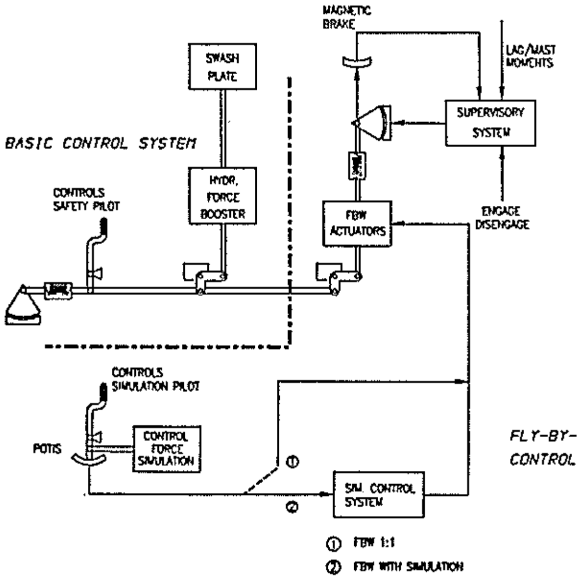


Figure 2. Schematic of Control System

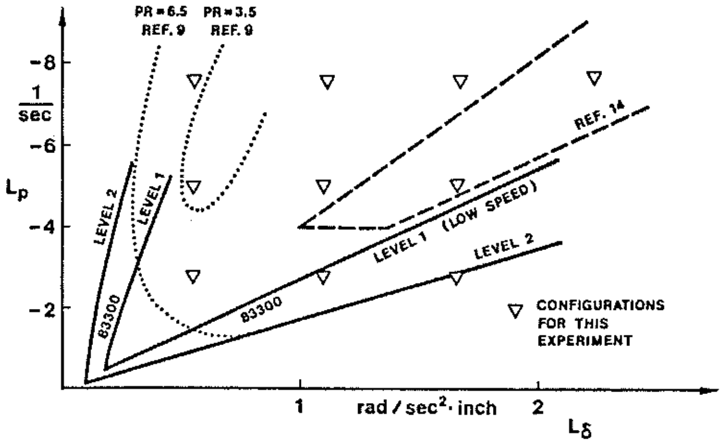


Figure 3. Test Matrix

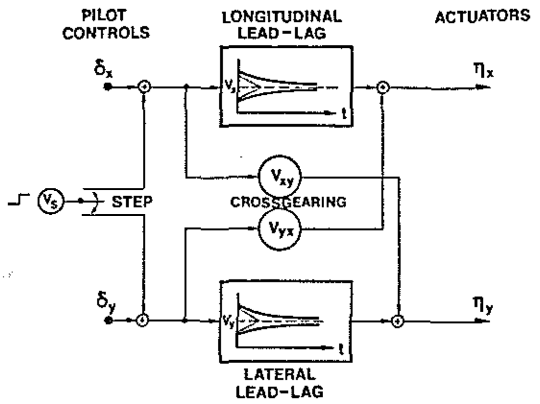


Figure 4.
Lead-Lag Network

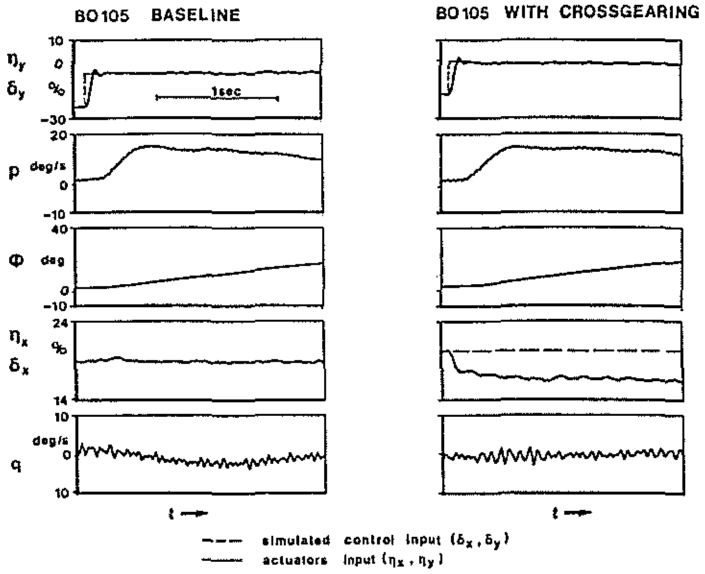


Figure 5. Influence of Control-Crossgearing

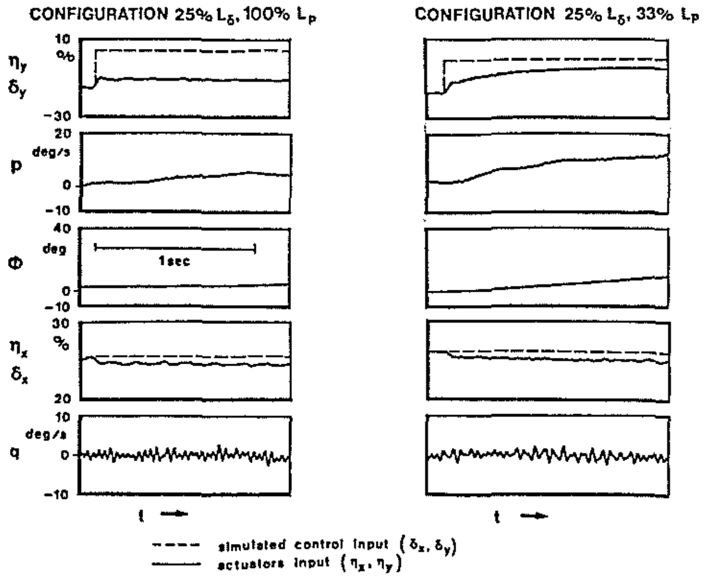


Figure 6. Configuration Verification

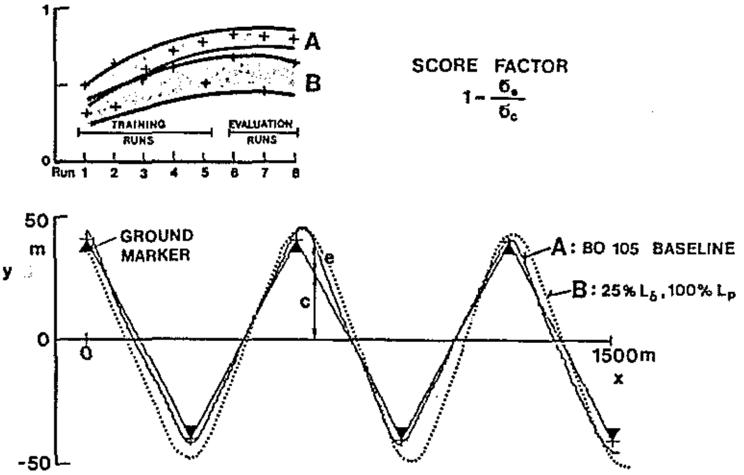


Figure 7.
Slalom Course

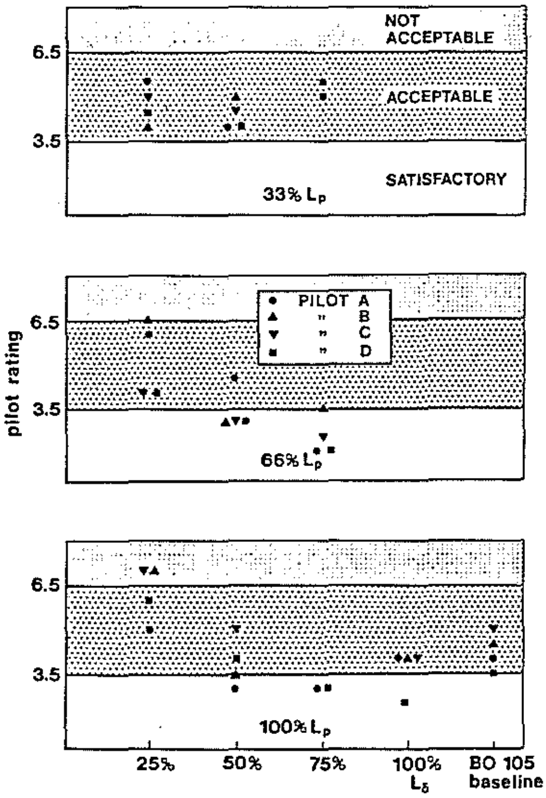


Figure 8.
Individual Pilot Ratings

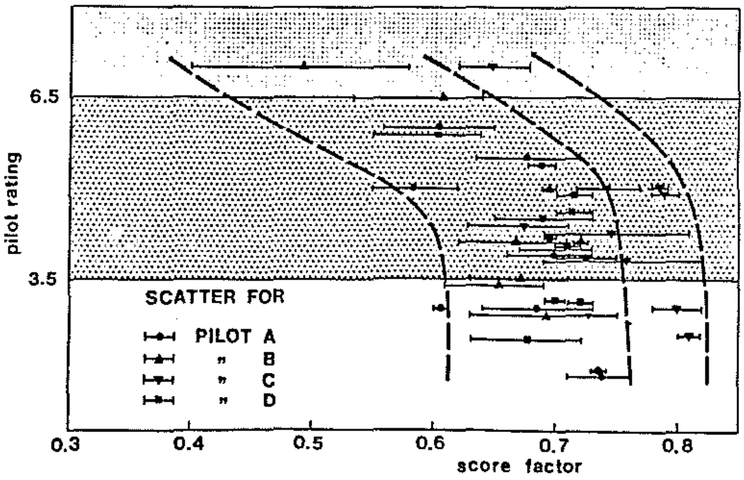


Figure 9. Trend of Score Factor

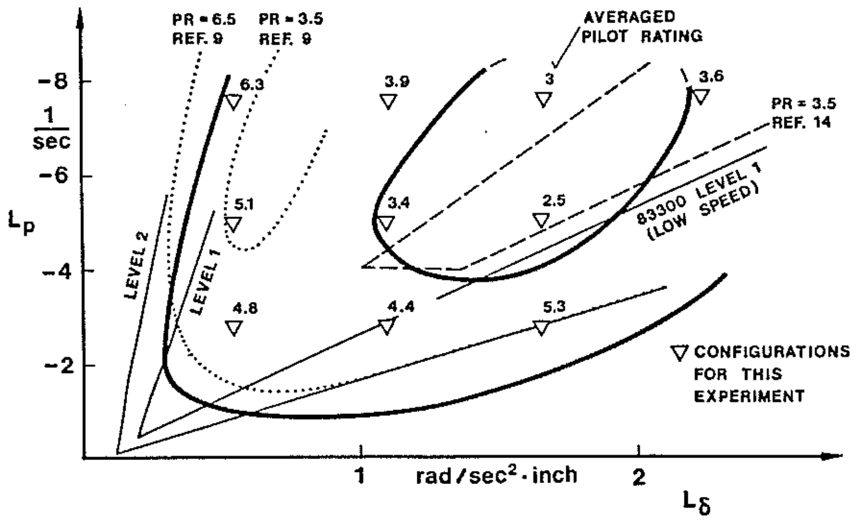


Figure 10. Pilot Rating Results for Slalom, 60 knots

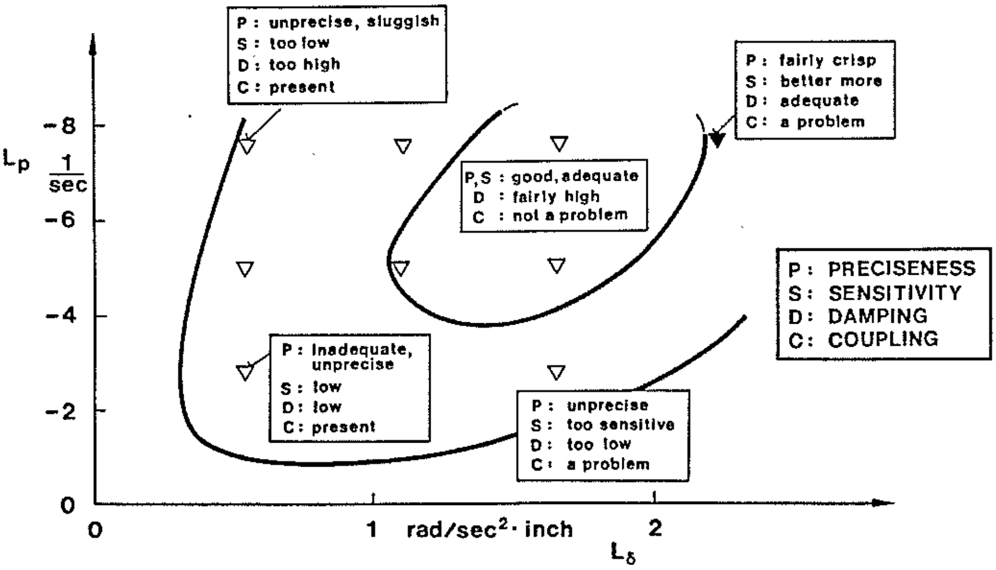


Figure 11. Summary of Pilot Comments

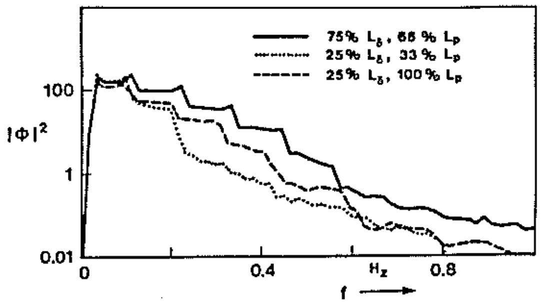


Figure 12. Typical Power Spectra of Roll Attitude

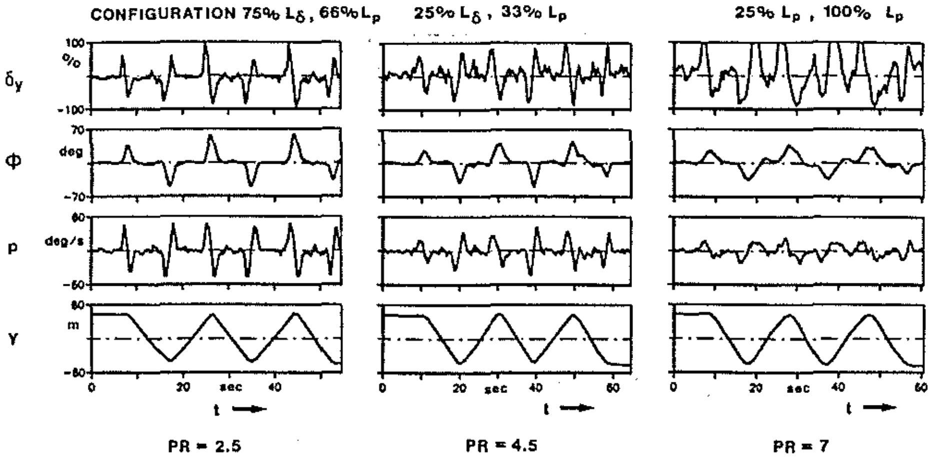
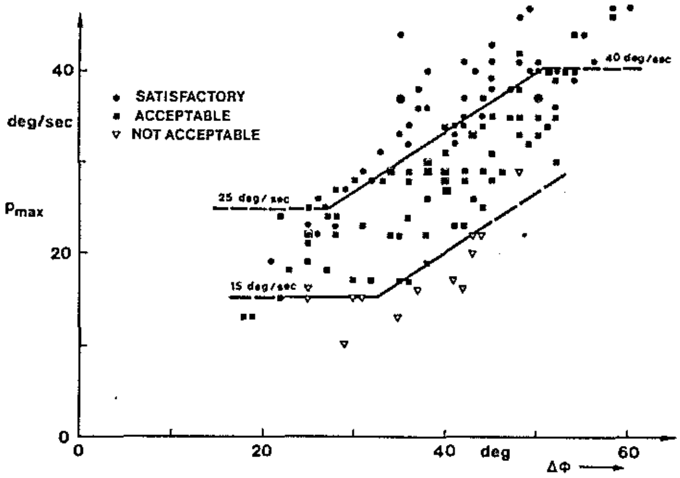


Figure 13. Typical Slalom Time Histories

Figure 14.
High Amplitude Task
Performance Evaluation
(Phase Plane Approach,
Ref. 7)



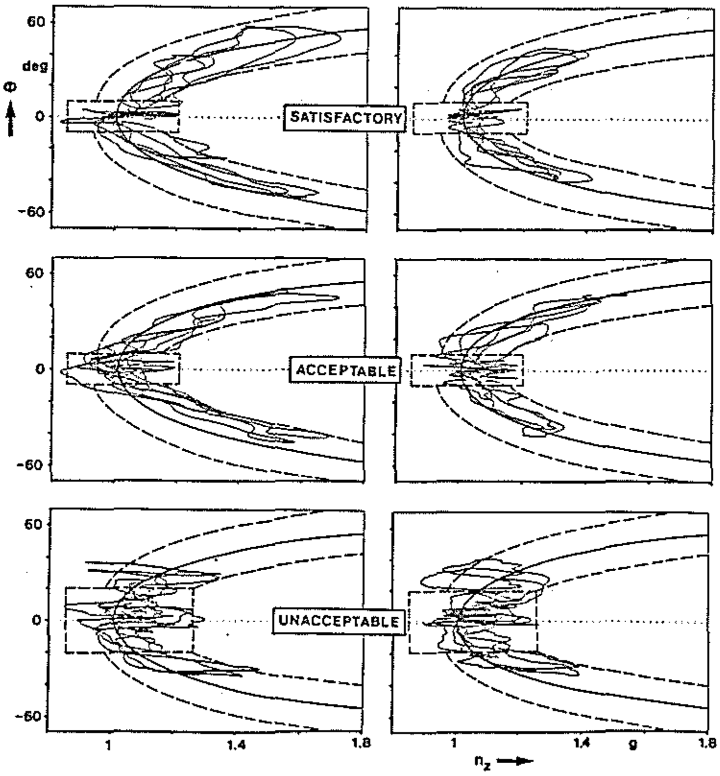


Figure 15.
Slalom Task Performance Based on
$n_z = 1/\cos\phi$ Reference