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THE EFFECTS OF PILOT STRESS FACTORS ON HANDLING QUALITY ASSESSMENTS DURING U.S./GERMAN HELICOPTER AGILITY FLIGHT TESTS

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SUMMARY

In a U.S./German cooperative program, flight tests were conducted with two helicopters to study and evaluate the effects of helicopter characteristics and pilot and task demands on performance in nap-of-the-Earth flight. Different, low-level slalom courses were set up and were flown by three pilots with different levels of flight experience. An extensive pilot rating questionnaire was used to obtain redundant information and to gain more insight into factors that influence pilot ratings.

The flight test setups and procedures are described, and the pilot ratings are summarized and interpreted in close connection with the analyzed test data. Pilot stress is briefly discussed. The influence of demands on the pilot, of the helicopter characteristics, and of other stress factors are outlined with particular emphasis on how these factors affect handling-qualities assessment.

INTRODUCTION

In the last few years, the operational spectrum of helicopters has been considerably expanded, in particular for military applications. At the same time, technological developments have made it possible to influence the flying characteristics of helicopters to a limited extent. This can be achieved by suitable design of the basic system or by the addition of subsystems.

Given this situation, the current military handling-qualities criteria specification, MIL-H-8501A, had many obvious deficiencies although it gave good guidance in its early years (ref. 1). There have been several attempts to revise the specification but either they were never completed or the proposed changes were not adopted. In order to overcome this situation, a new program has been initiated by the U.S. Army and Navy to update the helicopter specifications (ref. 2). The effort will include the development of a new specification structure as well as the incorporation of valid, available criteria and the existing data base. It is expected that significant shortcomings or complete voids will be found in the existing flying-qualities data base. Therefore, one main objective of flight mechanical investigations is to produce a data base adequate for deriving recommendations for flying-qualities requirements.

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As a consequence of the different demands resulting from the required military operations, mission orientation has to be taken into consideration in the investigations. Flying close to the ground in order to use the terrain as cover or to obtain superiority requires well-adapted flying qualities of the helicopter system and a good interaction of pilot and helicopter. Otherwise the pilot's workload will be too high or the mission performance will deteriorate.

In response to these needs, research programs in the field of helicopter handling qualities have been initiated by NASA and the U.S. Army and by DFVLR, the German Aerospace Research Establishment.

A joint NASA and U.S. Army research program consisting of analytical studies, ground-based simulations, and flight experiments has been under way at Ames Research Center. These studies commenced with an exploratory piloted-simulator investigation of the effects of large variations in rotor-system dynamics on nap-of-the-Earth (NOE) handling qualities. Forty-four combinations of rotor design parameters — such as flapping-hinge restraint, flapping-hinge offset, blade Lock number, and pitch-flap coupling — were applied to teetering, articulated, and hingeless rotor systems (ref. 3).

This was followed by another exploratory simulation that examined the use of various levels of control augmentation to improve terrain flight handling qualities. These consisted of simple control systems that provided interaxis decoupling as well as rate-command and attitude-command augmentation (ref. 4).

Ames Research Center's UH-1H variable stability and control research helicopter was used to investigate control augmentation and decoupling requirements for NOE flight (teetering-rotor case) and to correlate the results with piloted simulation. Eleven combinations of roll and pitch damping and pitch-roll cross-coupling were evaluated (ref. 5).

The effects of engine response time and helicopter vertical damping and collective control sensitivity were investigated on the Ames Vertical Motion Simulator. Special emphasis was placed on defining handling-quality requirements and helicopter limitations with respect to demanding NOE flying tasks such as quick stops and bob-up/bob-down maneuvers (ref. 6).

The relevant analytical and experimental activities of DFVLR, Institute for Flight Mechanics at Braunschweig, consist of programs for helicopter system identification from flight test data, tests on the DFVLR-Moving-Cockpit-Simulator, and flight tests for mission-oriented handling-qualities evaluation.

The efforts in system identification focused on the development and application of parameter identification methods to define and verify rigid-body mathematical models of helicopters in various speed regimes. DFVLR's BO 105 research helicopter was used to produce sufficient good quality flight test data. For the evaluation, the maximum likelihood method was utilized (ref. 7).

Theoretical studies of the closed-loop pilot/helicopter system led to simulation tests with the objective of improving the mathematical pilot model. Two helicopters were modeled and six pilots were involved in a compensatory tracking task. The determined pilot transfer functions yielded, compared to STI's (Systems Technology Incorporated) linear pilot model, a more optimal model consisting of two lead-lag terms for the low- and high-frequency ranges and the effective time delay (ref. 8).

In the field of handling-qualities evaluation, a procedure was developed at DFVLR that consists of the analysis, correlation, and combination of statistical parameters computed from flight test data. Flight test probrams were conducted using the BO 105 and UH-1D helicopters in different NOE-related tasks. The measured data and the pilot ratings were evaluated, taking task performance as well as pilot workload into account. For the flight tests, the Cooper-Harper rating scale was modified in order to detect specific influences on the pilot's evaluation. In addition, the influence of the pilot's control strategy on the task performance was analyzed (refs. 9-12).

With the objective of coordinating the efforts of NASA, the U.S. Army, and DFVLR, a memorandum of understanding (MOU) titled "Helicopter Flight Control" was signed by the two governments in 1979. In the last three years, complementary efforts were performed by the participants of the MOU and the results were exchanged.

Under this MOU, common NASA/U.S. Army/DFVLR flight tests were conducted, having as one objective the comparison of U.S. and German flight-test techniques. The main intention of this paper is to discuss factors that influence pilots' evaluations, as determined, during this program.

DESCRIPTION OF EXPERIMENTS

Approach

A slalom course was constructed for the NASA/U.S. Army studies of the effects of roll damping, roll sensitivity, and pitch/roll coupling on helicopter flying qualities for NOE operations. The experiments were conducted using the UH-1H V/STOLAND research helicopter (ref. 5). The course was flown at an airspeed of 60 knots at an altitude of 100 ft. The variation of the configuration parameters was limited by the capabilities of the teetering-rotor system.

At the DFVLR Institute of Flight Mechanics, slalom tests were performed with a BO 105 and a UH-1D helicopter. The objectives of the tests were the measurement and definition of task performance and control activity as evaluation parameters for a handling-qualities data base (ref. 11). The course consisted of two realistic obstacles. The tests were flown at an altitude of 30 ft at airspeeds from 40 to 100 knots.

As a part of the MOU, a cooperative flight test program was planned with the following objectives:

1. To verify the compatibility of U.S. and German slalom results

2. To determine the effect of flight task variation

3. To examine factors that influence pilot evaluations

The tests were performed in 1981 at the German Forces Flight Test Center. The test matrix is shown in table 1. Test configurations included

1. The duplicated NASA slalom

2. The DFVLR slalom

3. The NASA slalom flown at a reduced altitude of 30 ft to make it equivalent to the DFVLR slalom

For all configurations the airspeed was 60 knots. Two helicopters were used for the tests: (1) the BO 105 of the DFVLR, and (2) the UH-1D of the German Flight Test Center (fig. 1). Three pilots, all of whom had considerable flight test experience and helicopter time were involved in the tests (NASA Ames, DFVLR-Braunschweig, and Flight Test Center Manching). Each pilot flew both helicopters through all three evaluation courses.

Evaluation Courses

The NASA slalom course, essentially similar to the one used in the previous studies, was set up along a paved road in a parachute-drop area. Six 300-m ground markers formed the course, as shown in figure 2. In the lateral direction they were separated by 80 m. Additionally, two markers were used to indicate run-start and run-end.

The DFVLR course had two 10-m-high obstacles placed 350 m apart. The obstacles were alternatively offset 10 m from the centerline. The run-start and run-end were marked in a manner similar to that used on the NASA course. Both evaluation courses were symmetrical, thus making it possible to fly the courses in either direction, depending on the wind.

Data Acquisition

The data acquisition was provided by an analog magnetic tape recording in the ground station. Recorded variables included control inputs, attitudes, rates, accelerations, airspeed, altitude, torque, and rotor speed. The helicopter position data relative to the "poles" (obstacles) were measured by a laser position-tracking system and were recorded time-synchronized with the helicopter state and control data. To register these data in the helicopter and to transmit them to the ground, a programmable multipurpose instrumentation system was used. This made it possible to adapt quickly to the test technique (helicopter type, course, and direction of flight). The data were digitized on-line in the ground station and were available for data analysis. Sampling frequency was 20 Hz.

Tasks and Procedures

The basic flying task on the three evaluation courses was essentially the same: fly a specified ground track that minimizes the lateral displacement from the obstacles (poles), and maintain a constant indicated airspeed and radar altitude throughout the designated course. Ground speed varied with wind velocity.

For the two U.S. slalom courses, the pilot's task was to fly a series of alternating turns around the imaginary poles while holding airspeed at 60 knots and radar altitude at 100 ft in one case and 30 ft in the other. Three runs along both courses were made with each of the two helicopters.

For the DFVLR slalom course, the pilot's task was to enter the course on the centerline at 60 knots indicated airspeed and at a 30-ft radar altitude, then to hold the centerline track as long as possible until committed to turn right to start around the first obstacle, then return to the centerline and repeat the turn to the left around the second obstacle. Seven runs were made with each of the two helicopters.

Pilot Rating Systems

One objective of the program was to evaluate and compare the flight test techniques employed by the DFVLR and NASA. Therefore, for each evaluation run, the pilots were asked to provide pilot opinion ratings based on the systems used by both organizations.

NASA: For each configuration, the pilots were asked to give an overall Cooper-Harper handling-qualities rating and specific commentary relating to (1) roll control precision, sensitivity and damping, (2) interaxis coupling, (3) pitch and speed control, (4) height control, and (5) yaw control.

DFVLR: The DFVLR modified the Cooper-Harper rating system to adapt it better to mission-oriented handling-qualities assessments. Using this modified system, the evaluation pilots were asked to rate each configuration with respect to (1) aircraft characteristics, (2) task performance, and (3) pilot stress. Along with the rating for stress, the pilots were instructed to comment on the factors that influenced their rating.

DISCUSSION OF PILOT STRESS

Definition of Pilot Stress

In recent years there has been increased interest in the subject of human stress as it relates to well being and longevity. With the advent of more sophisticated aircraft and the space program, aerospace physiologists and psychologists have been studying the effects of pilot stress with the broad objective of improving the efficiency of cockpit workload. In the discussion of their pilot rating scale in reference 13, Cooper and Harper state that handling qualities include more than just stability and control characteristics, and that other factors influencing handling qualities are cockpit interface (e.g., displays, controls), the aircraft environment (e.g., weather conditions, visibility, turbulence), and pilot stress. They go on to state that these factors influence the closure of the pilot control loop and that their effects cannot be segregated.

The modified Cooper-Harper handling qualities rating scale used by the DFVLR in evaluating mission-oriented flying qualities contains a section pertaining to the evaluation of pilot stress in order to identify the significant pilot stress factors associated with the flying task. Reference 14 describes the use of this modified scale in a previous investigation.

At this point we must define what is meant by pilot stress. For the purpose of this discussion, pilot stress is defined simply as "physical and mental pressure resulting from cockpit workload." Cooper and Harper define workload as "the integrated physical and mental effort required to perform a specified piloting task." Factors contributing to pilot stress include the following:

1. Demands of the task
2. Aircraft response
3. Environmental conditions
4. Adequacy of information
5. Experience and skill

The cumulative effects of stress result in physical and mental fatigue that impairs judgment and flying skill. Thus the pilot's ability to process information, make decisions, and arrive at and execute the appropriate control strategy during handling-qualities evaluations is likewise diminished. It can be seen that the pilot's ability to make consistent assessments of handling qualities and assign pilot rating numbers can be significantly influenced by stress factors.

Stress Factors

The pilot stress factors listed above are briefly discussed in this section so that the reader will have a clearer understanding of these terms when they are presented in the results of this paper (fig. 3).

Demands of the task: Demanding tasks that require the evaluation pilot to fly complicated tracks involving rapid and precise maneuvering within specified limits can become very stressful. This is of particular significance when he is asked to perform the task repeatedly.

Aircraft response: Evaluating an aircraft that responds in an erratic or unpredictable manner and that demonstrates deficient flying qualities that require a significant degree of pilot compensation produces pilot stress. The degree of pilot stress is usually commensurate with the level of "aircraft characteristics" and "demands on the pilot" listed in the Cooper-Harper rating scale.

Environmental conditions. Environmental situations that contribute to pilot stress are (1) turbulence, wind shears, and crosswinds that upset aircraft attitude and drive it away from its intended track and (2) weather and lighting conditions that limit the pilot's vision and thus affect task-tracking performance.

Adequacy of information: The evaluation pilot must process a continuous flow of visual, audio, and kinesthetic information which he uses to perform the task and assess the adequacy of the aircraft for the mission. Pilot stress is increased when this information stream is deficient or degraded. For example, inadequate visual information from within (e.g., from the instrument panel) or outside (e.g., from the evaluation course) can increase pilot stress. Environmental conditions can be a factor in this case.

Experience and skill: Pilot stress is elevated to some degree by the difficulty of the task. An evaluation pilot whose flying background includes familiarity with the aircraft type and mission being tested will undergo less stress as a result of this experience and skill.

DISCUSSION OF RESULTS

In the discussion that follows, the ratings from the participating pilots are used to illustrate the influences of the different stress factors on pilot ratings. Also, flight test data are shown to provide an objective measure of the subjective ratings and comments.

Pilot Ratings and Comments

As mentioned in the previous section, the test pilots had to answer both a NASA questionnaire and a DFVLR questionnaire. The ratings are summarized in figure 4. Three different types of ratings are compared: (1) the overall ratings of the NASA questionnaire, (2) the ratings for pilot's stress, and (3) the ratings of task performance from the DFVLR questionnaire. An impression of the differences in the ratings depending on the pilots is given by the indicated spreads. As a consequence of the nonlinear characteristic of rating scales, an unweighted averaging of pilot ratings cannot be directly used. The average values noted in the rating summary are only intended to demonstrate the tendency of the ratings within the spreads.

In general, the test pilots evaluated the UH-1D well below the BO 105. This expected result reflects the lack of roll agility of the teetering-rotor system. The spread in all ratings is found to be higher for the UH-1D than for the BO 105, particularly in the case of the DFVLR course. This could very well be an example of the effects of a combination of stress factors: demands of the task as influenced by pilot experience and skill. The same tendency can be noted by comparing the spreads of ratings for the NASA and DFVLR slaloms. In addition, two pilots commented on the higher demands on the pilot/helicopter system of the DFVLR evaluation task. These pilots' statements are based on three factors: (1) a ground track demanding more pilot concentration, judgment, and skill, (2) lower altitude, and (3) real, rather than imaginary, obstacles.

For the BO 105, clear differences exist in the ratings of the pilots answering the specific evaluation questions, whereas the ratings for the UH-1D are quite consistent. In summarizing these evaluations it can be seen that in the case of the BO 105, overall ratings are identical with task performance ratings but they are about one rating number better than the stress ratings. It appears that a lack of rapid maneuverability response had the dominant effect on stress and task performance.

The pilot comments about the causes of the lower overall ratings and stress ratings can be summarized as follows: (1) the higher demands of the task; (2) low roll agility; (3) high pedal activity; (4) high roll/pitch coupling; and (5) problems in height control. The main helicopter characteristic required for a satisfactory performance of the slalom tasks and a low pilot stress is high roll agility. Additionally, the stress increases with pronounced coupling intensity that produces higher control activity in the secondary axes.

Flight Test Data

One pilot described the lower demands of the NASA tasks as follows: "The NASA slalom is a more coordinated flight maneuver." In figure 5, plots of both courses for one pilot flying the BO 105 are shown as an example. The requirement for the pilot to reenter the centerline after the obstacles makes it more difficult to fly the DFVLR course. The NASA course includes phases between the poles with only small variations in the roll angle. The differences in course demands are more obvious in the frequency domain (fig. 6). The power spectrum of the roll angle identifies generally a higher energy level and increased bandwidth demands for the DFVLR course. Roll rate and lateral stick input power spectra indicate particularly higher levels for this task.

As a consequence of the higher demand on roll agility and roll control activity, the DFVLR evaluation task seems to be the more realistic simulation of sideward motion in NOE flight. The influence of task variations is significant and has to be taken into consideration for the comparison of flight test results and evaluations.

For flying the tasks the pilots require, primarily, quick roll response. In their comments, they evaluated the roll agility of the BO 105 as good in general and that of the UH-1D as medium or low, especially for the DFVLR task. The missing roll agility is evident in the power spectra of figure 7. The roll angle and lateral stick spectra are quite similar for both helicopters and are determined primarily by the course dynamics. The main difference between the helicopters can be seen in the roll-rate diagram. A satisfactory evaluation can only be achieved with a helicopter system that allows quick changes in the roll motion and, consequently, precise roll control.

The lack of rapid maneuverability in the UH, which was not originally designed for this kind of high-agility mission, caused a decrease in the accuracy with which the course could be flown (fig. 8). The cross-plots of roll angle and lateral position point out a higher spread in the repeated S-turn maneuvers in the NASA task for the UH-1D. The maneuver phases with constant roll angle are not perceptible. The pilots flew these phases with a combination of roll and sideslip. Also, a comparison of the pedal inputs for both helicopters leads to this intensified coupling behavior of the closed loop pilot/UH-1D system. Increased pilot stress and degraded task performance can be deduced from this low-agility effect.

The roll/pitch coupling and the height-control precision are additional, and important, points of interest for the evaluation of helicopters related to slalom tasks. The responses of the test pilots point this out as a typical characteristic for single-rotor helicopters. Figure 9 shows this aspect in the power spectra of the pitch rate signal for the two helicopter systems. Correspondingly, the pilots mentioned degraded height-control precision as a result of pronounced pitch/heave coupling. Analysis of the pilot ratings indicates that the overall rating is more greatly influenced by the roll response, whereas the interaxis coupling influences the pilot stress in particular.

Other Stress Factors

Experience and skill: One of the three evaluation pilots had less total helicopter experience and relatively little time in the BO 105 as compared to the others. It was found that his ratings for stress were also higher than those of the two more experienced pilots. The pilot who had the most experience flying through the DFVLR course reported the lowest stress ratings. One main reason for this evaluation tendency is the training of the pilots to compensate for the coupling characteristics of the helicopter or to introduce closed-loop coupling. Figure 10 shows the interrelation of roll angle and load factor in the DFVLR task for the most experienced pilot (A) and the least experienced pilot (B). In a steady turning flight the analytical relation between roll angle and load factor can be expressed as $\Delta n_z = 1/\cos \phi$. This function has to be extended for dynamical turning with terms describing kinematic properties. The area of deviation from the steady flight curve function accounts for the precision of course performing.

Diverging load factors with high roll angles are mainly produced by the pitch rate. With low roll angles the load factor is strongly influenced by the sideslip. In their comments, pilot A described the coupling as existing but controllable, and pilot B considered the roll/pitch coupling and the height control to be the most pronounced problems of the hingeless rotor.

Environmental conditions: One of the evaluation pilots flew through all three courses on a day when the wind was quite gusty. Pilot rating data for that day were not used because the pilot complained of high stress in coping with the gust effects. Pilot ratings for all cases were one full rating number higher than similar runs repeated on a smooth day. An increase in pilot stress was also reported as a result of reduced visibility caused by low Sun angles, rain droplets on the windshield, and reflections.

Adequacy of information: An essential part of the piloting task was to hold airspeed and altitude constant. This required intermittent scanning of the airspeed indicator and radar altimeter. Pilot stress associated with this workload may become significant if these two instruments are poorly located. A specific aspect of the 100-ft tests was the change of the scale on the radar altimeter by a factor of 10 at this altitude. An altitude of 100 ft was difficult to hold with this radar altimeter, and the result was an increase in pilot stress.

CONCLUDING REMARKS

The need for a viable NOE handling-qualities data base requires the inclusion and comparison of data obtained from tests conducted under various conditions. The cooperatively conducted slalom tests reported here yield a well-defined measure of the different factors of pilot stress that influence pilot ratings. The following conclusions were reached:

1. The differentiated ratings, together with the additional pilot comments, facilitate the evaluation of test results. As a result of the redundant information, the reasons for rating deviations are obvious, including the secondary effects.

2. The test conditions have to be taken into consideration in a comparison of test results, because of their significant influence on pilot stress and task performance. Test conditions include (1) definition of task, (2) definition of environment, and (3) experience of test pilots.

3. Performing a slalom task with well-adapted track accuracy requires that the helicopter have high roll agility. This yields advantages for helicopters with adequate inherent moment-control capacity.

4. Increased interaxis coupling of the helicopter leads to an apparent rise in pilot stress. With regard to the high pilot workload in real missions, a minimum of coupling is recommended.

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TABLE 1.- TEST MATRIX

Test course	Altitude, ft	Number of course runs	
		BO 105	UH-1D
NASA slalom	100	3	3
NASA slalom	30	3	3
DFVLR slalom	30	7	7

Figure 1.- Test helicopters.

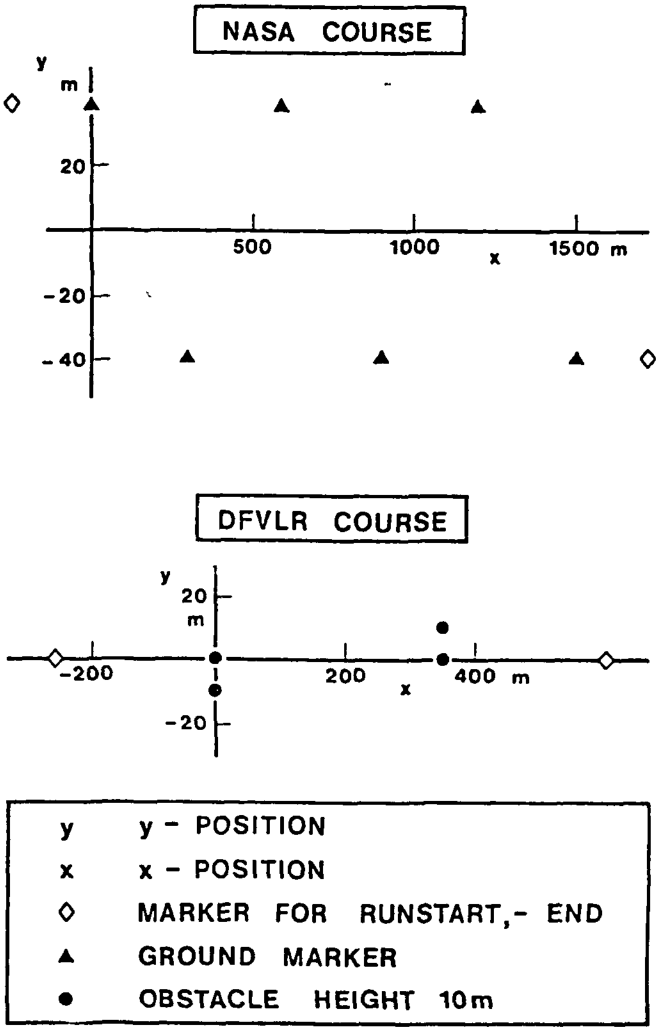

Figure 2.- Slalom courses.

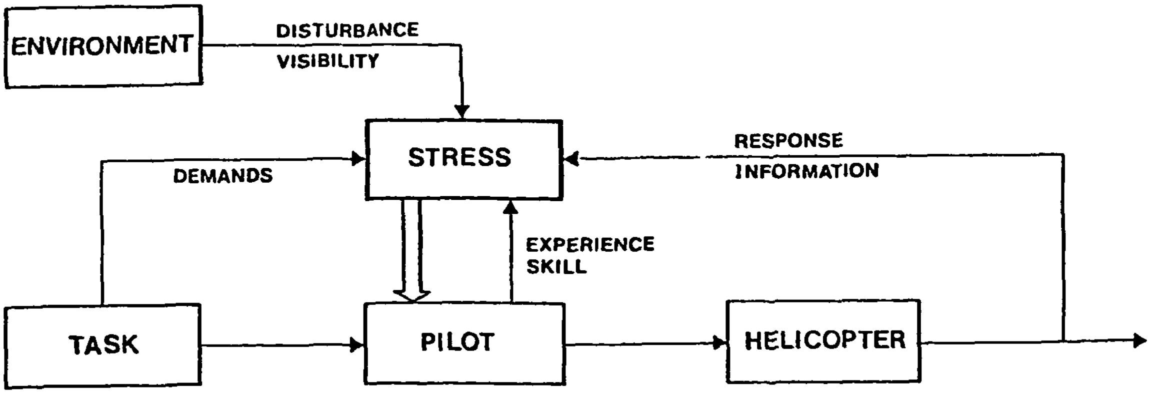

Figure 3.- Influences on pilot stress.

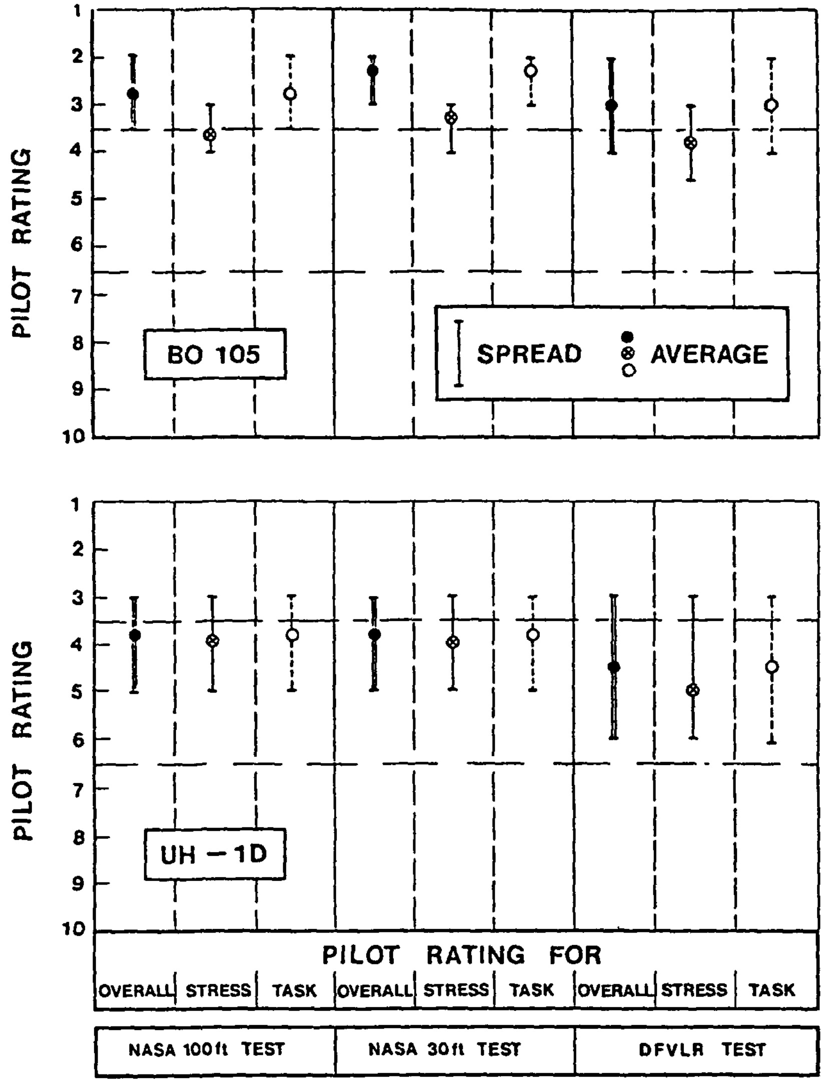

Figure 4.- Pilot rating summary.

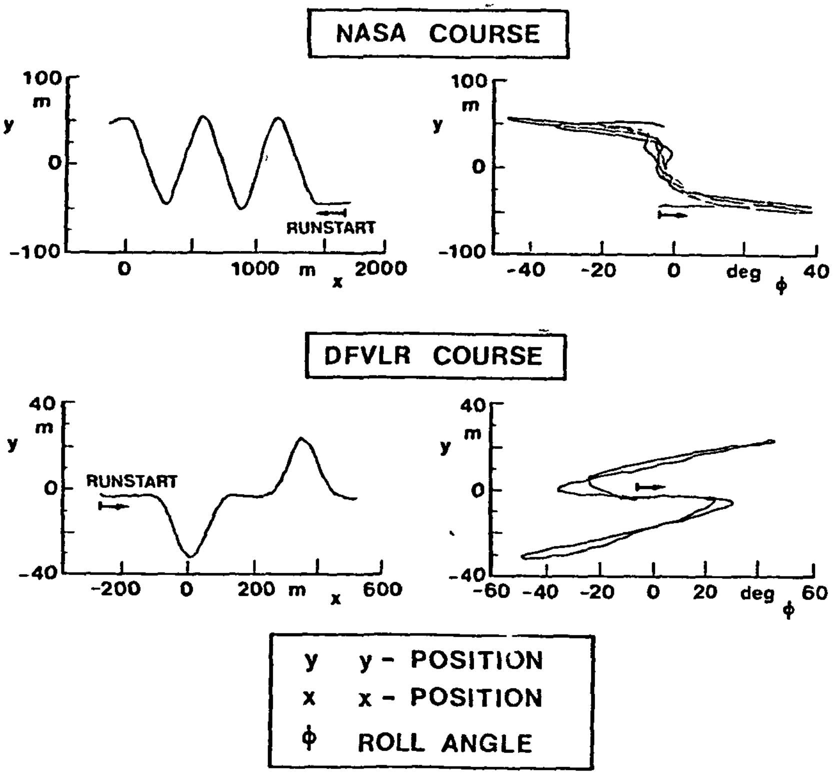

Figure 5.- Course characteristics (BO 105).

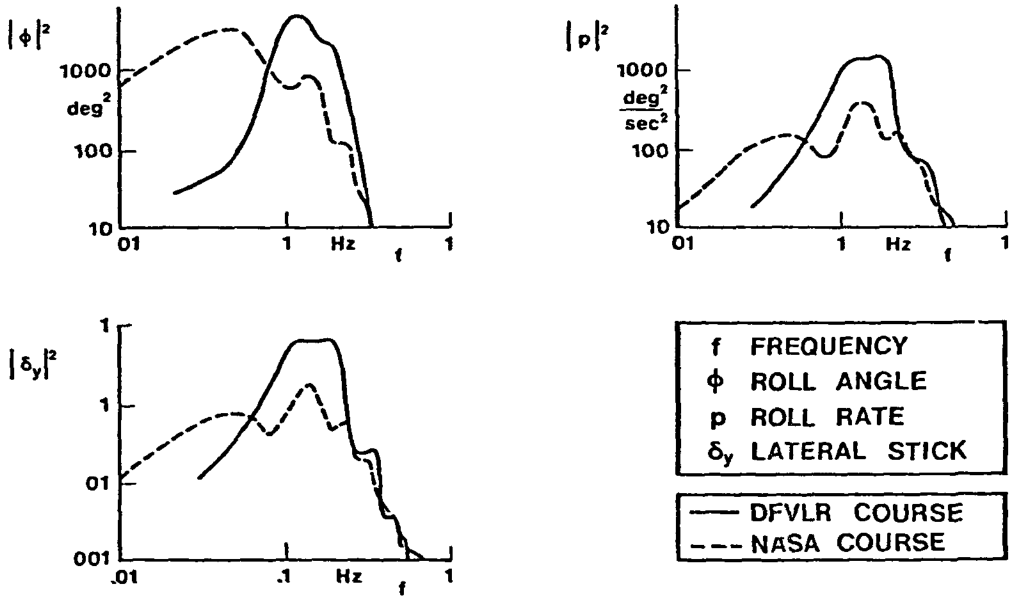

Figure 6.- Power spectra of main task variables (BO 105).

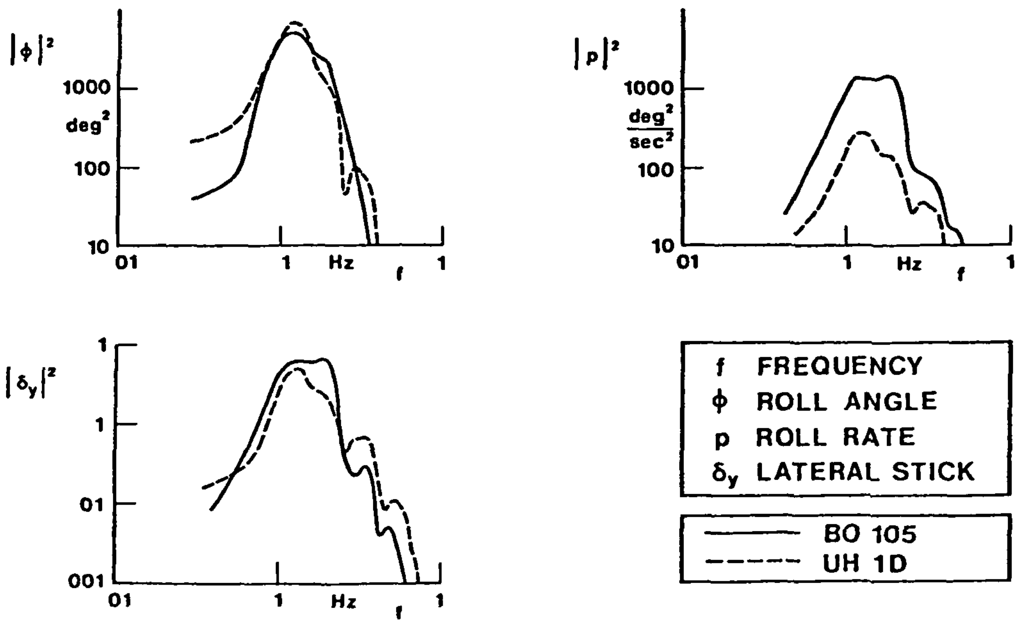

Figure 7.- Power spectra of roll agility parameters (DFVLR course).

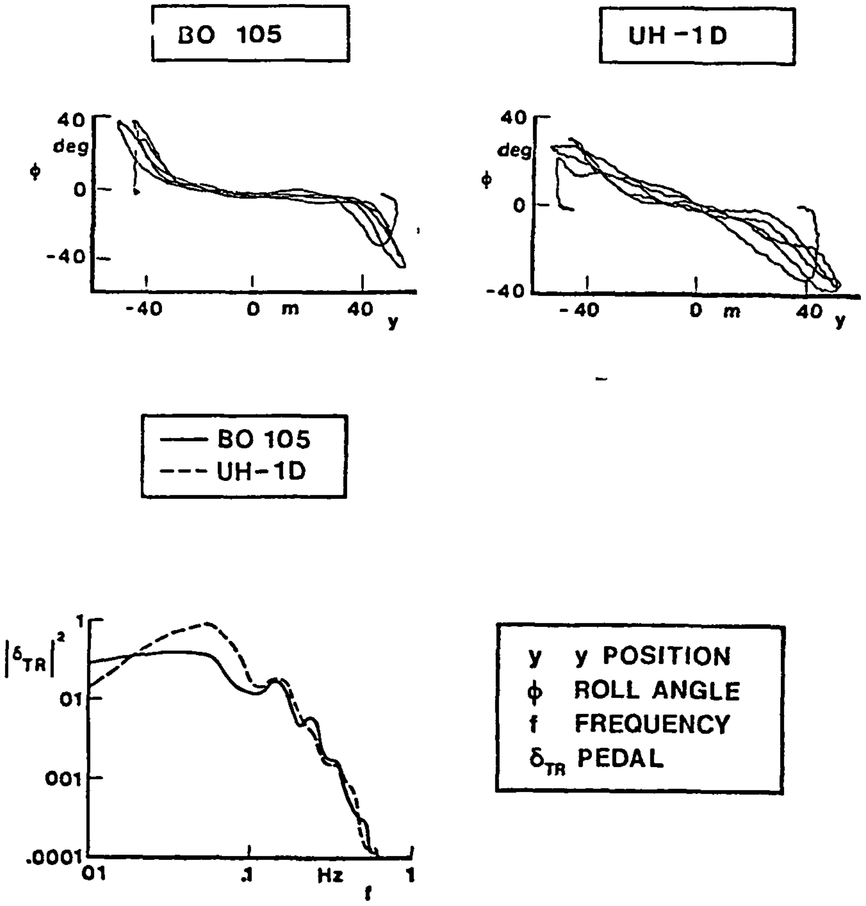

Figure 8.- Course accuracy (NASA course).

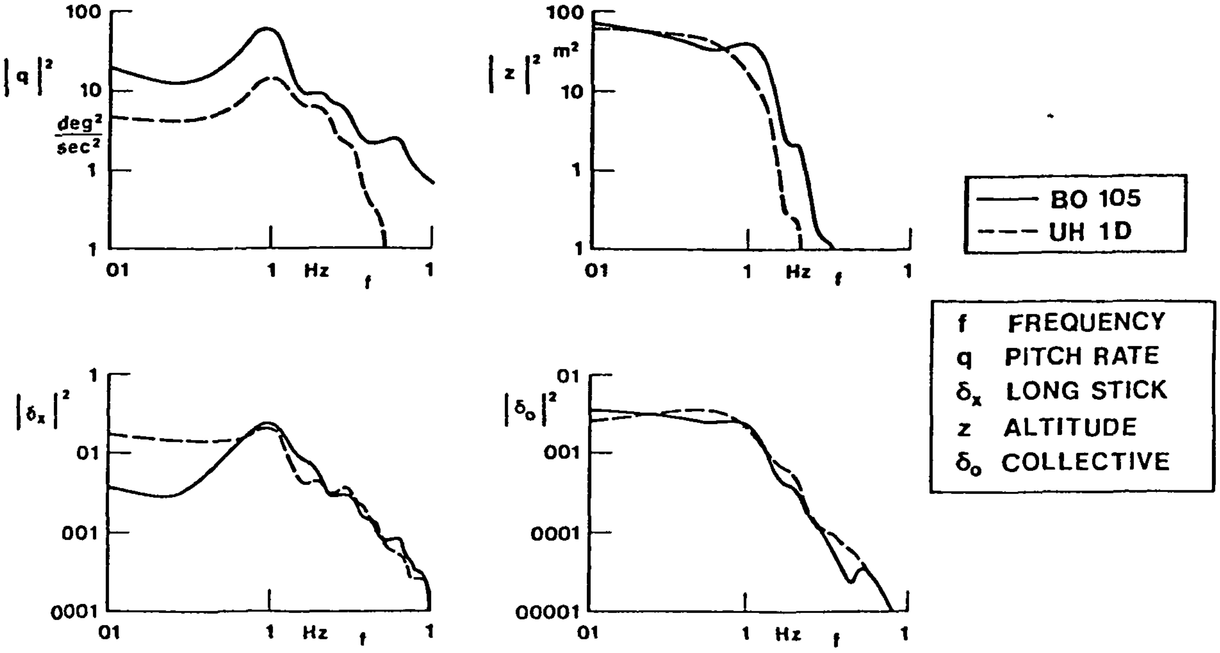

Figure 9.- Power spectra of coupling parameters (NASA course).

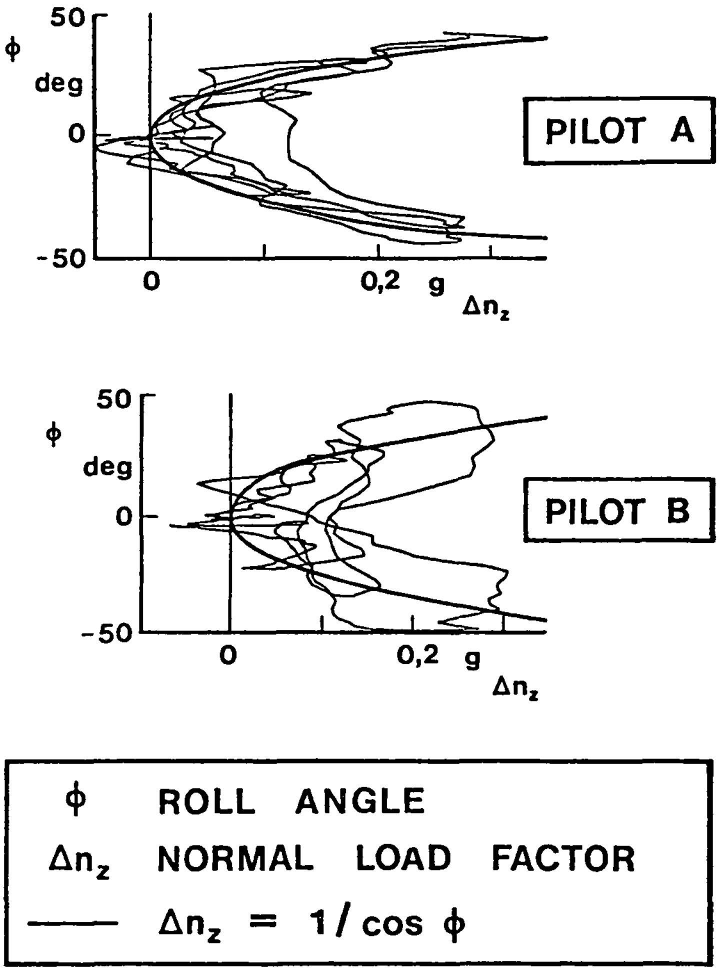

Figure 10.- Influence of pilot's experience on task performance.

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16 Abstract

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