PAPER Nr. : 71

DFVLR FLYING QUALITIES RESEARCH USING OPERATIONAL HELICOPTERS

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AUGUST 28 – 31, 1984 – THE HAGUE, THE NETHERLANDS

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Abstract

A flight test program has been conducted in the field of flying qualities research. The tests utilized the operational helicopters BO 105 and UH-1D of the DFVLR and the German Flight Test Center. The main advantage of operational helicopters is the reality of visual and motion cues for the pilot. The extensive flight tests had the objectives: (1) to assess the demands of missions, (2) to derive qualified flight test tasks, (3) to determine criteria for task performance evaluation, and(4) to establish anchorpoints for an examination of validity of simulator results. An overview of the DFVLR test activities is presented. Exemplary results for each objective are shown. A definition of agility demands for missions and a task performance evaluation approach for 'dolphin' and 'slalom' are discussed.

NOMENCLATURE

ΔF	evaluation area, m×sec
n_z	normal load factor, g
p	roll rate, deg/sec
q	pitch rate, deg/sec
$\|p\|^2$	power density of roll rate, deg^2/sec^2
$\|q\|^2$	power density of pitch rate, deg^2/sec^2
t	time, sec
x,y,z	directions of flight test course, m
δ_o	collective pitch input
δ_x	longitudinal control input
Θ	pitch attitude, deg
Φ	roll attitude, deg
σ	standard deviation
ATTHeS	Advanced Technology Testing Helicopter System
NOE	Nap-of-the-Earth

indices

e	error signal
c	command signal

1. INTRODUCTION

The optimization of the handling qualities with regard to a mission is an essential premise to achieve a desired mission effectivity for a helicopter system. It must be recognized that the mission to be performed by a helicopter can have a substantial effect on the required handling qualities. An universal formulation of handling qualities criteria is no more acceptable. An evaluation and specification of handling qualities have to be made in relation to a mission or, in more detail, to mission elements. Definition and quantification of parameters like performance, integrity of structure and system reliability can be derived directly from operational demands and compliance can be checked by appropriate technical test approaches. In contrast to these, flying qualities are a term of the overall system. They describe the quality of the interaction of technical system elements, and of the human pilot in the flight task. As a consequence it is difficult to specify flying qualities and their compliance in the terminology of engineers. To evaluate and define flying qualities, the pilot is of central meaning in the test loop. As a result of the expanded operational range of helicopters, the demands for the overall system have been increased. Therefore the system concept must make full use of pilot capabilities. On the other hand, an overloading of the pilot yields a rapid degrading of mission performance.

In this situation it is one of the most essential questions to the flight mechanical research, to supply mission related criteria for an evaluation of helicopter flight dynamics. The urgency can be underlined by the necessary revirement of the helicopter handling qualities specification MIL-H-8501 A, which is initiated [1]. Learnt from the experience with existing specifications modern criteria have to meet the requirements not to be restrictive against the technological development of helicopter systems. Their structure should allow to incorporate future missions. For all phases of a helicopter development the criteria have to guarantee:

- formulation of requirements for the helicopter system, derived from the mission,
- guide for the system design, and
- method for helicopter certification.

In this paper the specific problems of helicopter flight testing in the area of flying qalities research are dealt with. With an ongoing longterm program, the "Institut für Flugmechanik" of the DFVLR is making a contribution to a solution of the problems mentioned above. Extensive flight tests have been conducted in order to obtain a collection of data with adequate validation.

2. DEMANDS ON FLIGHT TEST TECHNIQUES

2.1 General aspects

Flying qualities criteria formulation can be approached in two different ways:

- task performance evaluation, and
- handling qualities criteria.

The advantage of an evaluation by task performance parameters is the possibility to check directly the defined demands during the certification phase. The mission related definition of the evaluation parameters yields good flexibility to suit new defined missions and improved technologies. Presupposition of a task performance evaluation approach is an identification or -more extensive- a standardization of the flight test tasks, representative for the missions. Defficiencies may result during the design phase, when the flight vehicle or sufficient valid modelling of the flight-dynamics does not exist.

In contrast, the applicability of handling qualities criteria is possible in all development phases of a helicopter system. The main disadvantage of these criteria is the high expense for their establishment, because they have necessarily to be formulated in a comprehensive and generally accepted way. Due to new missions or technologies there is the risk, that these criteria have to be updated. Both evaluation approaches complement one another, so both have their field of application.

In the approach to develop a data base for flying qualities, the evaluations of the test pilots are the essential scale for a quantitative classification of handling qualities parameters. As pilots are involved, it is necessary to have realistic conditions. So flying qualities research especially requests for the use of test facilities:

- operational helicopters,
- in-flight simulators, and
- ground based simulators.

The different application areas exploit the advantages of the individual facilities (*Fig.1*). Ground based and in-flight simulators are qualified for investigations to establish handling qualities criteria which require specific variations of system dynamic characteristics. A detailed discussion of the use of in-flight simulators is presented in [2]. The operational helicopters are prefered for tests, if high fidelity of reality is required. In the DFVLR extensive flight tests with operational helicopters were conducted with the objectives:

- to assess the demands of new missions,
- to derive representative flight test tasks from mission elements,
- to define parameters for task performance evaluation, and
- to establish anchorpoints for an examination of the validity of simulator test results.

The following provides an overview of these tests, and the specific demands on test procedures. Their verification is discussed in connection with exemplary results. More detailed descriptions of the specific tests and results have been published in [3,4,5]. Two test helicopters were used for the tests (*Fig. 2*):

- BO 105 of the DFVLR, and
- UH-1D of the German Flight Test Center in Manching.

2.2 Demands on Test Procedures

Particularly the complexity of tests for flying qualities investigations results from the different elements involved in the closed loop system. In general, the individual influences of the elements must be strongly taken into consideration for the lay-out of a test procedure in respect to the test objectives. *Figure 3* gives a rough impression of the organization of the main loop elements. The flight task is the frame including all loop elements and their interrelations. The task instructions together with all the information of the environment and the vehicle response will be transformed in a control strategy by the pilot. Going through the loop yields the task performance of the overall system. All the elements and factors effect the test results especially if they react upon the pilot. The tolerances of factors with not desired influences have to be limited by the establishment of the test conditions. On the other hand the acquisition of data of all elements with variations is a self-evident test premise. The measurement of vehicle response and control input signals can be realized with acceptable accuracy. The acquisition of all the data from environment, scenario, or pilot state is a most complicated and risky attempt.

Flying qualities are the response characteristics of a vehicle and its control system to put the pilot in the position to perform desired maneuvers or a mission with the vehicle. The pilot is only a single element in the loop but he has a central significance for the success of a test. He needs clear instructions how to perform the flight task and good information about vehicle response, environment and task scenario. He is the qualifying element in the loop and his evaluations and comments are the requisite for interpretation and quantification of flying qualities. In the DFVLR tests a modified Cooper-Harper rating system was used. The pilots were asked to rate with respect to vehicle characteristics, task performance and pilot stress. Using this rating system yields redundant information about reasons of rating values. In addition, the pilots had to give comments relating to specific vehicle response characteristics and to the factors which influence the stress rating. To reduce the influence of pilot individuality, a minimum of three pilots were involved in the different tests.

3. ASSESSMENT OF MISSION DEMANDS

Especially missions of today contain elements which require high precision in the low speed region or high agility in the middle and high speed region. In cooperation with the user representative maneuvers were chosen by the DFVLR and combined in two test missions (*Table 1 and 2*). Mission A primarily consisted of low speed or hover elements and in addition two NOE segments. The altitude over ground was defined with a maximum of 100 ft. The mission B was flown up to an altitude of 400 ft with more emphasis on high speed. The separation of the missions into different elements makes it possible to analyse as well the data of specific maneuvers as the data of the whole mission. Additional maneuvers can be added or results already obtained can be replaced by results from further tests. This procedure seems to be important as long as the listed mission elements are in discussion.

1	Hover
2	Takeoff
3	NOE–Flight
4	Quickstop (Frontwind)
5	Hover
6	Hover Turn anticlockwise
7	Hover Turn clockwise
8	Bobup, Bobdown
9	Sidestep left, Bobup to 100 ft
10	Precision Hover, Bobdown
11	Sidestep right
12	Forward and Rearward Hover
13	Acceleration to Vmax
14	NOE–Flight with Vmax
15	Quickstop (Tailwind)

Table 1. Mission A

1	Hover and Takeoff
2	Acceleration, Noe–Flight, Quickstop
3	Bobup, Bobdown
4	Sidesteps
5	Hover Turn
6	Rearward Hover
7	NOE–Flight, G–Turns
8	U–Turns
9	Wingover
10	Dive

Table 2. Mission B

The tests were conducted on a special low level flight area of the German Test Center to achieve realistic test conditions. The two test helicopters were utilized in these tests. The test vehicles are characterized by extreme differences in engine power and flight dynamics behaviour corresponding to the different types of rotor systems. For this reason the helicopter types were chosen for the tests.

As an example of the obtained test results the agility required for the missions is discussed. Agility demands of a mission can be described by the geodetic accelerations. The histograms of both missions are compared in *Figure 4*. Here the accelerations are defined in an earth fixed reference system that turns with the helicopter azimuth angle. The "geodetic" accelerations described in this way give a better impression of the actual flight state without it beeing necessary to know the terrain and flight direction. The higher demands result from the mission B. This aspect is particularly pointed out by the y-acceleration histogram. The maximum accelerations in the three axes were flown in the mission elements characterizing the middle and high speed NOE.

Transforming the agility demands into the helicopter system gives an assessment of the required helicopter dynamics. The pilots control the requested geodetic accelerations by variation of thrust vector in direction and magnitude. This means, the pilots command the necessary speed changes -or really position changes- through use of attitude control, and set aside a thrust adaption with collective pitch. However, the extreme attitudes highly correlated with geodetic accelerations cannot mark the helicopter agility capability. An additional aspect for flying close to the ground and using the terrain as cover is the time needed to command an attitude change. The ratio of attitude rate and attitude illustrates the aggressivenes of the pilot/helicopter closed loop system in a high agility flight task. *Figure 5* shows the maximum pitch- and roll rate drawn via peak to peak of the attitudes for two representative pilots. Only mission elements with high agility demands are inserted in the diagrams, which are the NOE-segments and the acceleration maneuver for mission A, and the NOE-segments, the u-turn, and the wingover maneuver for mission B. In the pitch diagram the values for the wingover maneuvers are omitted, because the pitch attitudes were measured between 65 and 85 deg (peak to peak) with maximum rates similar to those of the other segments. The envelopes describe the region of ratios for both missions. The asymptotic slopes can be interpreted as general boundaries for the rates set by the pilots. They are for maximum roll rate ±40 degrees and for maximum pitch rate between +25 and -17 degrees. The lower rates for the helicopter 2 show the lower agility capability of the helicopter.

4. FLIGHT TEST TASKS

For the investigation of task performance evaluation and handling qualities criteria the complexity of the flight task has to be decreased. On one side the flight test task must fully represent the demands of the mission element which shall be examined. But in opposition to meet this requirement of good reality the task has to be simplified for the pilot. Clear task conditions will reduce his bandwidth of individual variations of task performance and control strategy. For the analysis in respect to helicopter dynamic characteristics the influences of helicopter system in three axes should be separated. Starting with the NOE-mission segments two types of flight test tasks were abstracted with the idea to divide the NOE in a task with only x- and y-position changes and a task with x- and z-position changes. With close reference to the agility demands of mission elements the evaluation tasks were defined. The level of congruence of the rate power spectra indicates the fidelity of the flight test task.

Dolphin task: The dolphin task characterizes the NOE in the x,z - plane (*Fig. 6*). A course was built with two obstacles with a height of 15 m to put the pilots into a realistic situation -as much as possible. The distance between the obstacles was 350 m. The centerline of the course was marked on the ground to facilitate the heading for the pilots. The pilots were instructed to traverse the course while minimizing the time and altitude over the obstacles. The altitude of entering and finishing the course was 5 m and the pilots had to align the helicopters on the 5 m altitude between the obstacles if possible. The speed was defined in the test conditions and had to be flown at the beginning, between the obstacles and at the end of the course.

Slalom task: The slalom task -a task in the x,y-plane- was defined as equivalent to the dolphin (*Fig. 7*). The course had two 10 m high obstacles placed 350 m apart. The obstacles were alternatively off-set 10 m from the centerline. The task for the pilots was to fly around the obstacles in an altitude of 10 m and to minimize the time and lateral displacement from the obstacles. The pilots started the course holding the centerline track as long as possible until committed to turn right to fly around the first obstacle. They had to track the centerline between the obstacles if possible and repeat the turn to the left around the second obstacle.

In addition, a slalom task was adopted from the NASA [6]. Six 300 m ground markers formed the course as shown in *Figure 8*. In the lateral direction they were separated by 80 m. The course was flown in an altitude of 100 ft. The pilots were instructed to traverse the course while treating the markers like poles in a ski-slalom.

5. TASK PERFORMANCE EVALUATION

An evaluation of task performance for the dolphin can be defined by the evaluation area that combines the time and height of exposure over the obstacles. *Figure 9* illustrates the definition of this parameter. The evaluation area parameter correlates significantly with the pilot ratings obtained in the tests. Accordingly the pilots commented the time and height of exposure as influence factor for the degradation of rating if the value of evaluation area was higher than 13 m×sec. Boundaries are drawn in the diagram which recommend an evaluation with the combination of the parameters evaluation area and control activity. The pilots chose a control strategy characterized by a combination of the controls: longitudinal and collective. The combination of both depends on the individual pilot. Here the control activity parameter is defined as the average of the standard deviations of both controls measured in percent of full throw. The scatter of some pilot ratings in *Figure 9* is due to other parameters influencing the pilot workload. With higher levels of pitch attitude, the workload of pilots increases because high attitudes (peak to peak over 40 deg) render the orientation of the pilots in the course more difficult. However, the pilots mentioned acceleration levels over 1.6 g (peak to peak) as a reason of their workload in the comments. High pitch attitudes and accelerations result from primary use of longitudinal control in flying the course.

To assess more detailed the influence of differences in control combinations on task performance in the dolphin, additional control strategy tests were conducted. The pilots had to fly the course with three control strategies using

- longitudinal control,
- combination of longitudinal and collective pitch control, and
- primarily collective pitch control.

Figure 10 shows the evaluation area and pilot ratings over the ratio of both control inputs. The minimum of the evaluation area parameter points out that the best adaptation of control strategy is with emphasis of collective. Certainly the minimum of pilot ratings is shifted to a control strategy with use of both controls in a same portion. The pilot comments can clear up this discrepancy. In the case of collective control strategy the problems with system coupling and with collective control dynamics were mainly mentioned. The summarized pilot comments distinctly indicate the fields for necessary improvements of system characteristics in respect to pitch due to collective coupling and bandwidth of collective control. The pilots commented the high ratings in the only longitudinal control strategy configurations with exposure time/height, high bank angles and accelerations task performance factors.

In general the slalom task shall be performed with main use of lateral control inputs. The collective control has to be used for compensation of thrust changes. In an ideal steady turning flight the analytical relation between the bank angle and the normal load factor can be expressed as $nz=1/\cos \phi$. This function has to be extended for dynamical turns with additional terms describing kinematic properties. But assuming that the steady state values of pitch and bank angle are near zero this function can also be taken as an ideal reference in the slalom. Two main influences substantially stand for deviations from the reference. If the agility capability of a helicopter is too low for the task, the pilot will add the use of tail rotor control yielding a sideslip to support the turns. The roll-to-pitch and roll-to-heave coupling inherent in the helicopter system must be compensated by the pilot. Remaining system responses in pitch and heave result in a change of normal load factor. In *Figure 11* crossplots of roll angle and normal load factor are shown together with typical pilot ratings. The width of scatter from the reference curve correlates very well with the pilot evaluations. This diagram can be recommended for task performance evaluation for a slalom task. To be sure, boundaries between acceptable and unacceptable (pilot rating=6.5) have to be verified by additional tests.

6. VALIDATION OF SIMULATOR TEST RESULTS

Simulator facilities have deficits in respect to the modelling of the visual and motion cues, the environment, the scenario, and the helicopter dynamics. All these factors can influence the evaluation of pilots and result in incorrect conclusions for flying qualities evaluation. Pre-tests with the fly-by-wire helicopter (BO 105 ATTHeS) in the basis configuration yield a rating degradation of about 2 points in comparison to the operational BO 105. Reasons are the lower confidence of the pilots in the system and the special situation of test pilots (seat position, interaction of test and safety pilot). To prove the validity of simulator results anchorpoints must be established with operational helicopters in the same flight task. One criterion for fidelity is the extent to which the simulator induces the same control strategy and task performance as does the actual vehicle. *Figure 12* gives an impression of the spread between the operational and fly-by-wire BO 105-S3 (basis for BO 105 ATTHeS) for the slalom task B. For the BO 105-S3 the clear phases of zero bank angle between the slalom poles are missing.

In simulation tests -in-flight and ground based- the test pilots need extensive training time to adapt their control strategy to the test configuration and the task. For both, the training phase and the fidelity of task performance in comparison to an actual vehicle, a quick-look method is helpful to control the test online. For the slalom a score factor was computed (*Fig. 13*). The ratio of the standard deviations of the defined command track signal and the divergence of actual track have an asymtotic slope in the training phase. The score factor should be nearly constant during the evaluation runs and of the same value as for the operational helicopter.

7. CONCLUDING REMARKS

At the beginning of the paper two different approaches of flying qualities criteria are discussed: (1) task performance evaluation, and (2) handling qualities criteria. The need for viable flying qualities data base includes the use of operational helicopters with the objectives:

- to assess mission demands,
- to define flight test tasks,
- to define task performance evaluation, and
- to verify simulator test results.

Extensive flight tests have been conducted in the DFVLR to obtain data with adequate validation and to contribute to a solution of these questions.

From the presented test results the following general aspects and conclusions can be stated:

- The agility demands of middle and high speed NOE-mission elements are described by the ratio of maximum rates and peak to peak of attitudes.
- 'Slalom' and 'Dolphin' are defined as representative flight test tasks for the NOE mission elements
- A task performance evaluation for the 'dolphin' can be defined by the exposure area. The control strategy combining the longitudinal and collective control additionally influences the task performance. With emphasis on the use of collective control yields the better task performance.
- For 'slalom' task performance evaluation a diagram including bank angle and normal load factor is recommended.
- To avoid a high degradation of pilot ratings in simulator tests an examination of obtained task performance is necessary. For the slalom a score factor is proposed.

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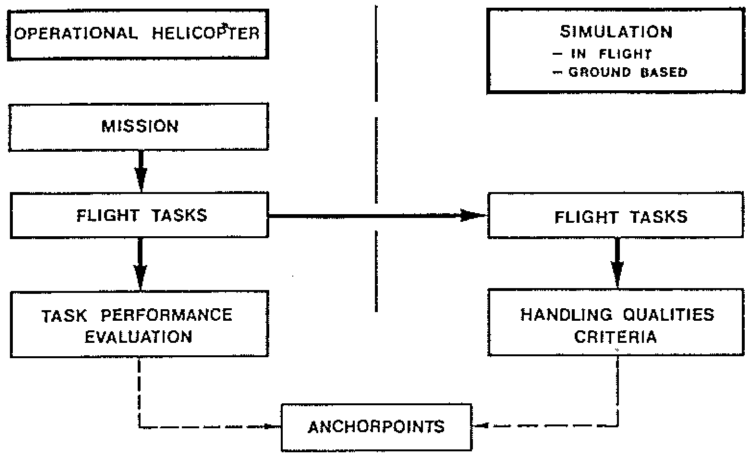

Figure 1. Use of Test Facilities for Flying Qualities Data Base

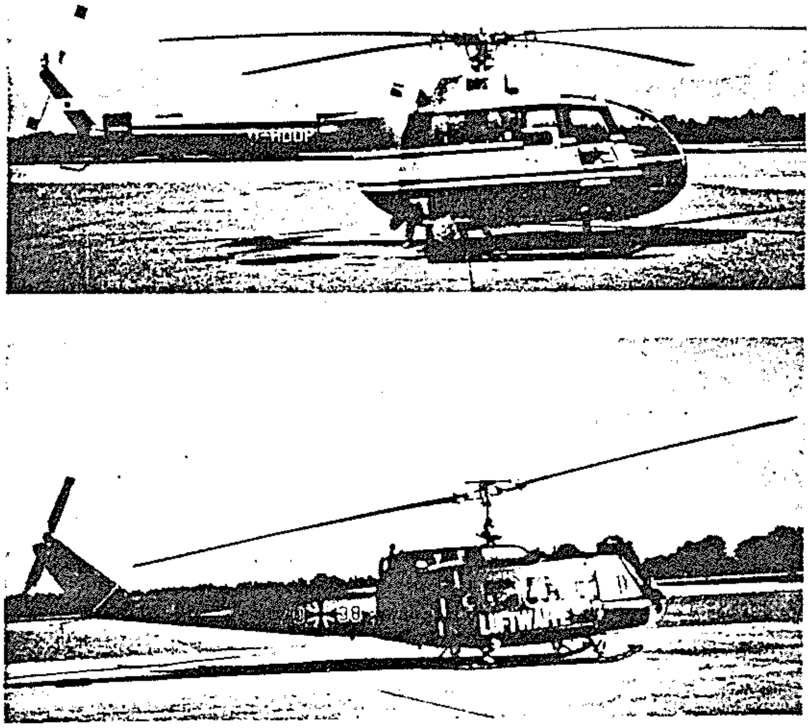

Figure 2. Test Helicopters

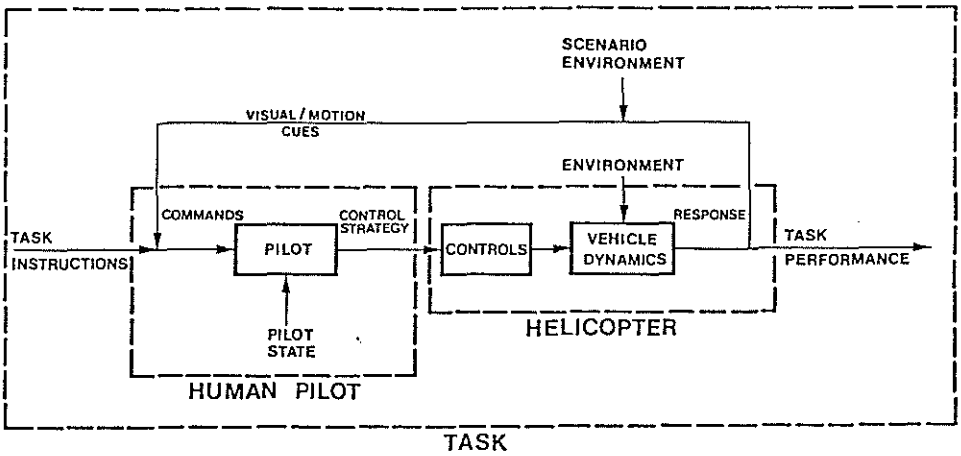

Figure 3. Block Diagram of Pilot-Vehicle-Task System

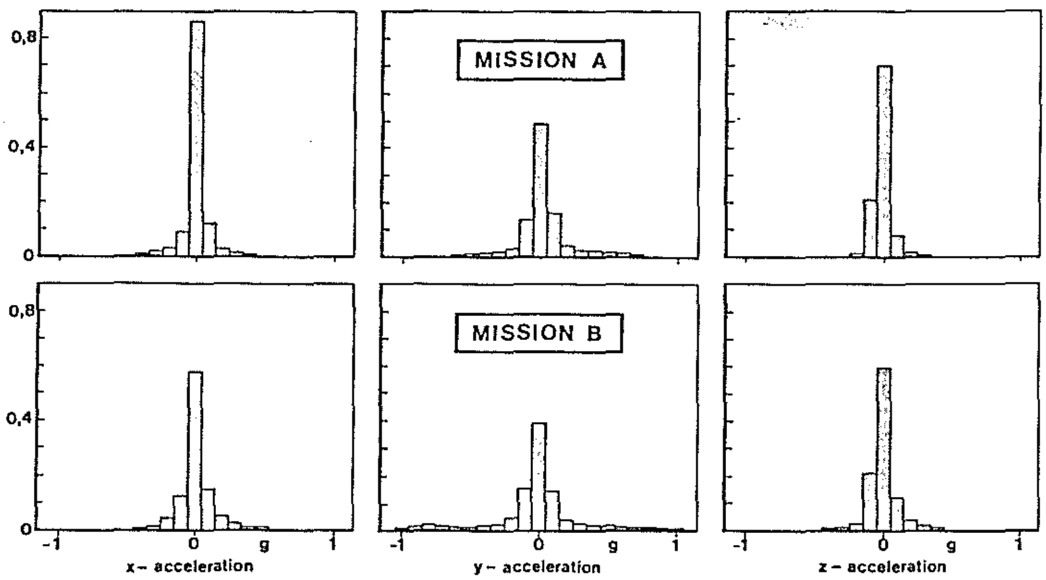

Figure 4. Relative Distribution of 'Geodetic Acceleration'

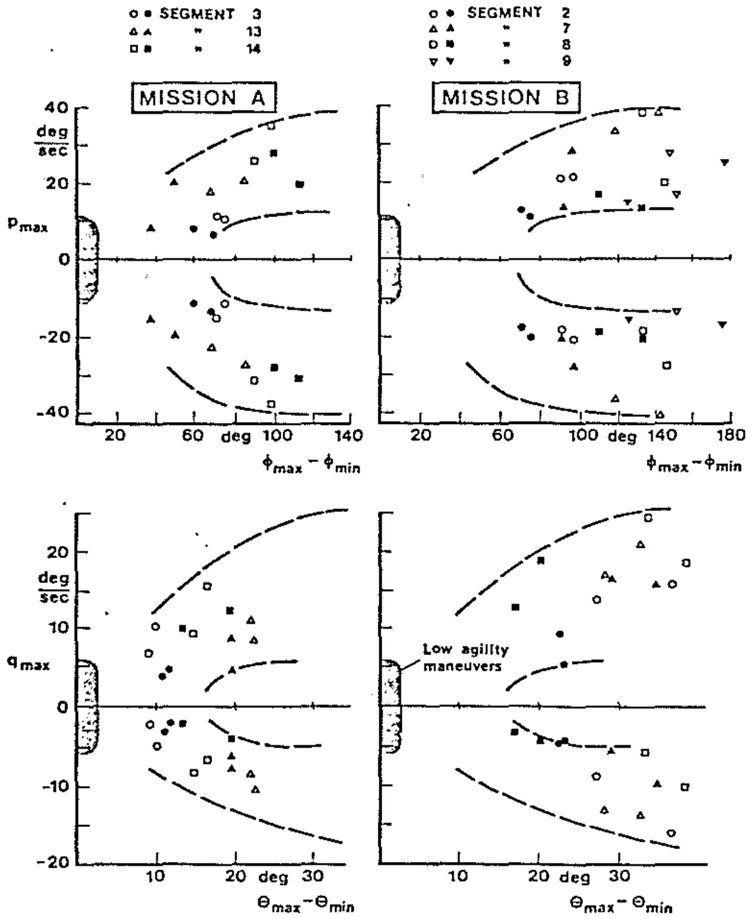

Figure 5. Rates and Attitudes for High Agility Mission Elements (○ Helicopter 1 ● Helicopter 2)

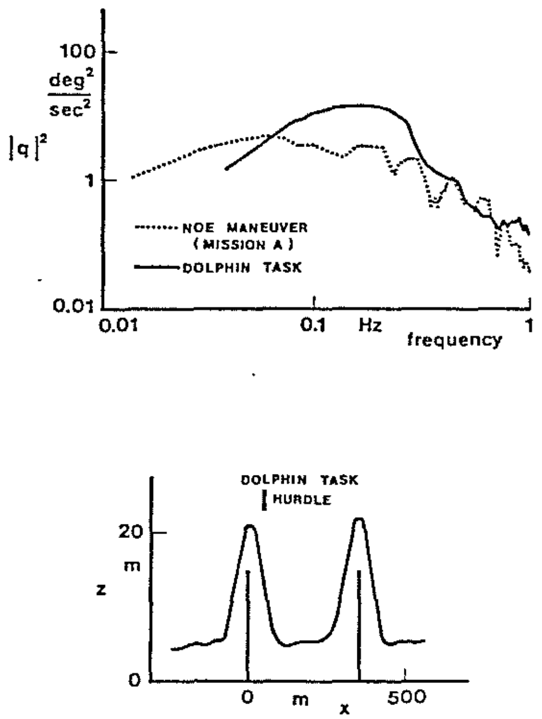

Figure 6. Dolphin Flight Task

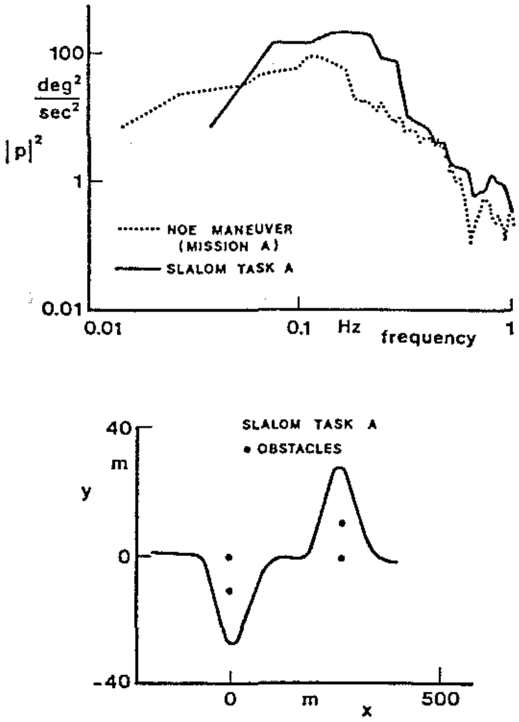

Figure 7. Slalom Flight
Task A

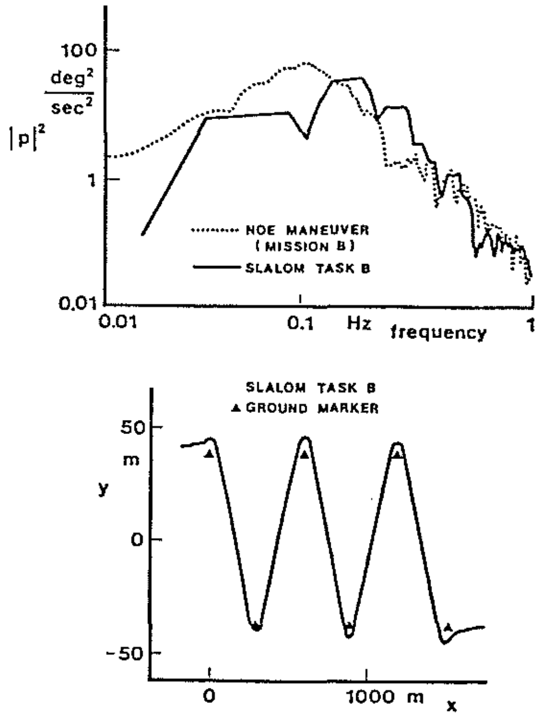

Figure 8. Slalom Flight
Task B

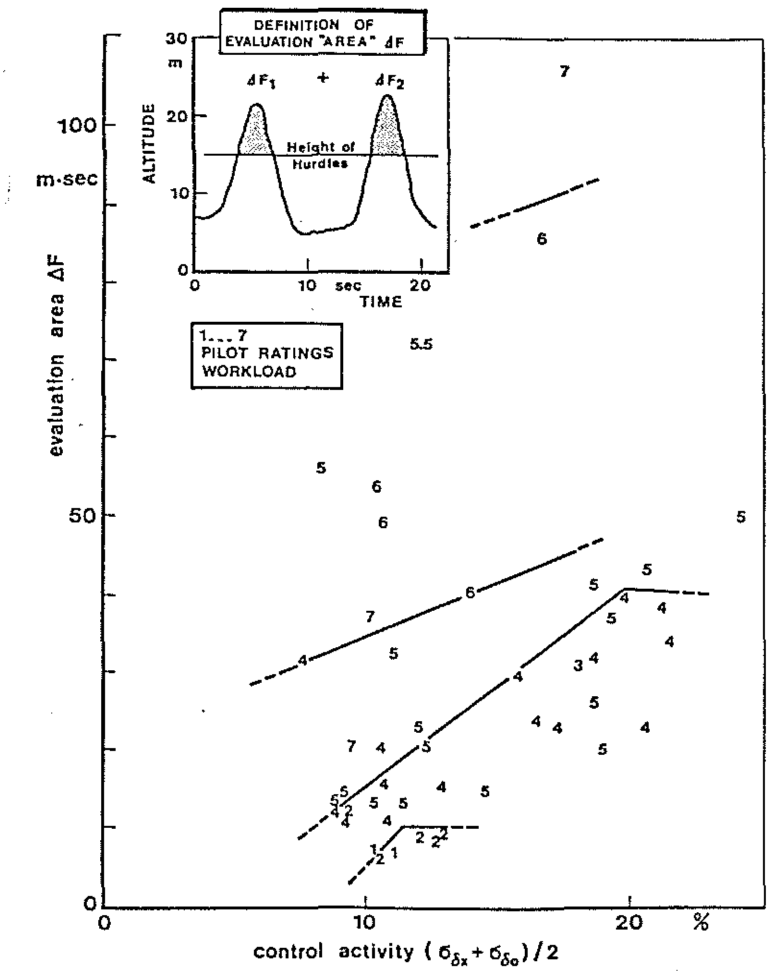

Figure 9. Task Performance
Evaluation - Dolphin

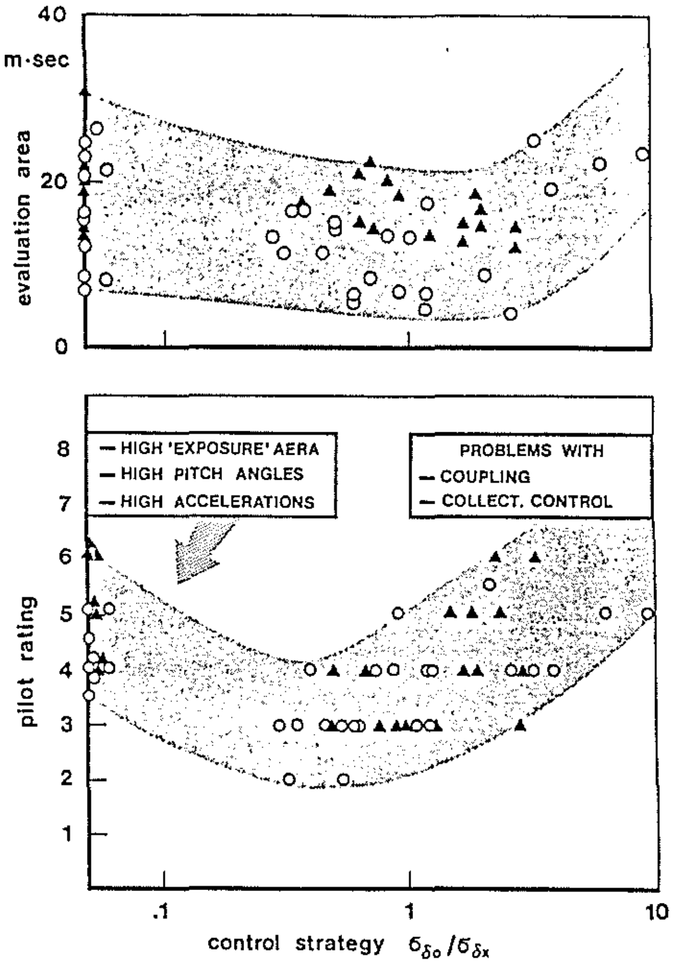

Figure 10. Effect of Control Strategy on
Task Performance Evaluation
(○ Helicopter 1
▲ Helicopter 2)

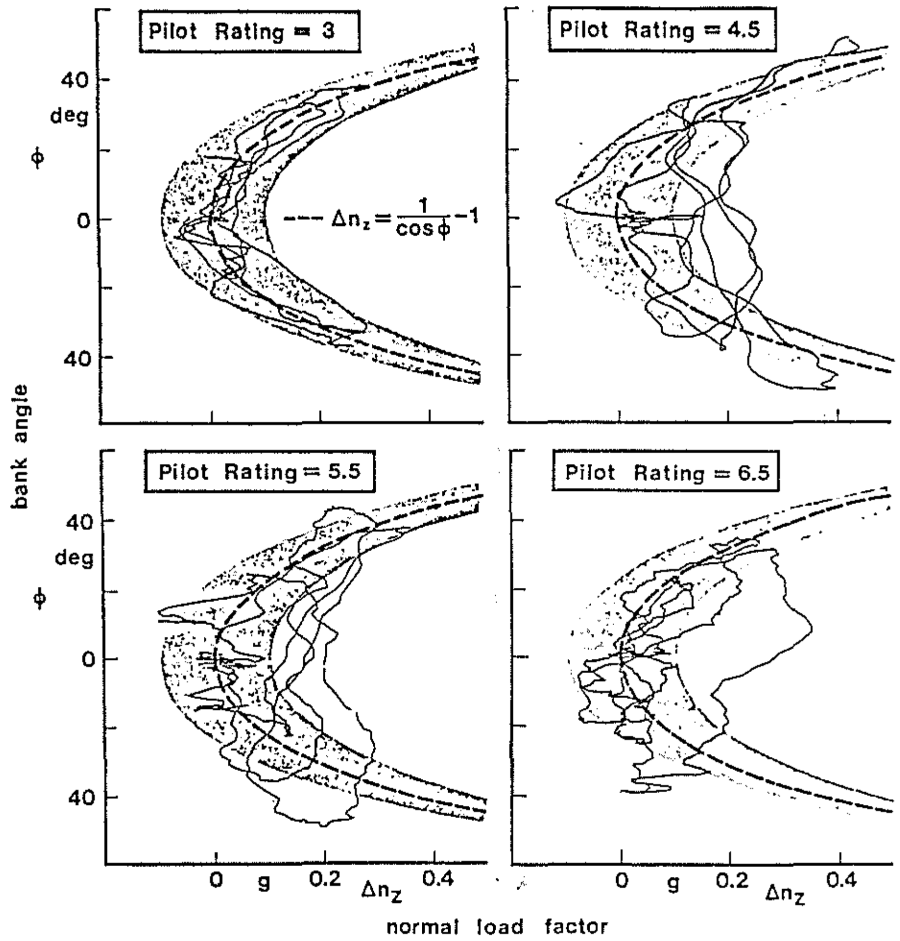

Figure 11. Task Performance Evaluation - Slalom

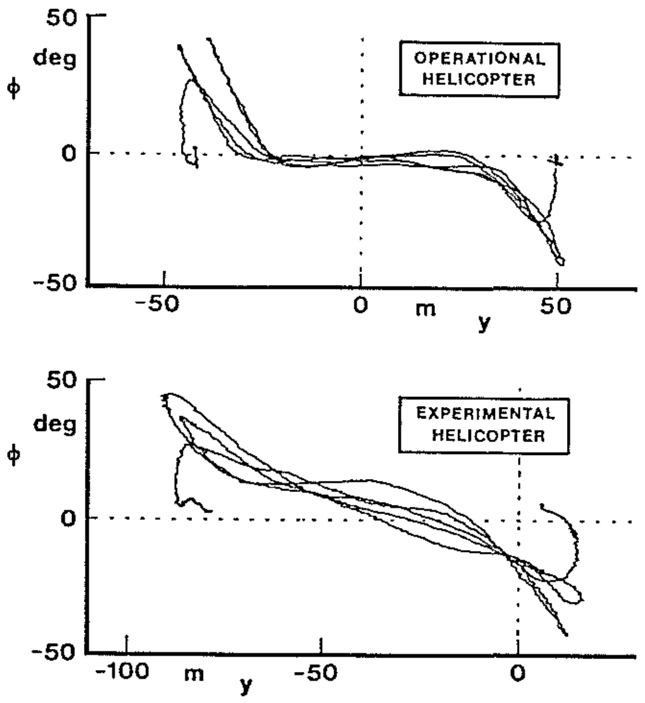

Figure 12. Task Performance for Operational and Experimental Helicopter

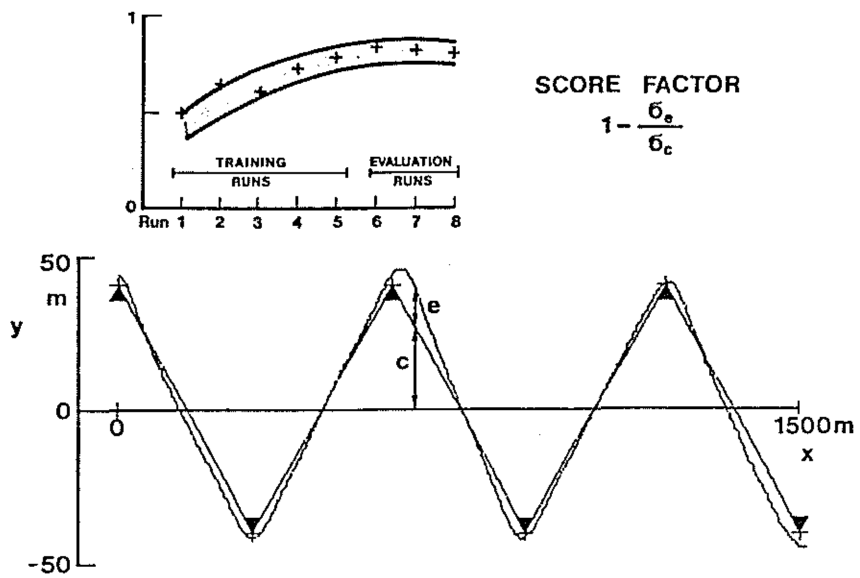

Figure 13. Definition of Score Factor