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CORRELATION ASPECTS OF HELICOPTER FLIGHT MECHANICS AND PILOT BEHAVIOUR

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ABSTRACT

Simulation investigations using a moving base simulator to examine the correlations of helicopter dynamics and pilot behaviour for specified manoeuvers are presented. The tracking task simulation design of two helicopter configurations is described. Measured parameters including a subjective pilot rating are related.

Obtained results from spectral and statistical analysis demonstrate the interrelationships between task-performance precision, control activity and subjective pilot opinions. Correlation analysis suggest subdivision of pilot rating into a configuration dependent part connected with control activity and a pilot dependent part connected with tracking precision.

INTRODUCTION

The development of new helicopter systems is highly dependent on the requirements of specific operations and missions. To meet the requirements of these missions extensive theoretical and experimental investigations must be conducted for influencing the system concept in an early stage.Some aspects of these considerations are already treated in several papers [1, 2, 3, 4]. The current evaluation criteria, mainly on considerations of isolated helicopter parameters, are not sufficient for an overall system evaluation. These criteria will sometimes yield misleading results when applied to helicopters with advanced rotor systems.

The lack of information may be reduced by further improvement of existing criteria or by establishing new criteria. Especially, in the field of mission-oriented handling qualities an evaluation of the pilot-helicopter-system dynamics gives the possibility to integrate all subsystems with individual and sometimes undesirable characteristics. This overall rating requires the identification of correlations between helicopter performance and pilot behaviour. From this point of view operational evaluation methods will combine individual characteristics under the aspects of specified task conditions applicable in an early stage of development.

To examine correlations of helicopter dynamics and pilot behaviour for specified manoeuvers, in the DFVLR studies were conducted using a moving base ground simulator. The experiments were carried out using a rigid body six degrees of freedom (DOF) model. For a coordinated analysis, helicopter type and manoeuvers were varied under participation of several pilots.

OBJECTIVES AND SCOPE OF THE EXPERIMENTS

The main objectives of the experiments may be summarized to the determination of:

- pilot dynamics
- pilot adjusted dynamics of the system pilot-helicopter
- interrelationships between pilot opinion, pilot workload, pilot dynamics and helicopter dynamics.

Supposing that helicopter dynamics can be defined, a first step for solution of these problems is the measurement of parameters describing pilot behaviour. Thereby physical, psychological, physiological, and experimental effects can influence the humans relevant outputs [5]. Understanding pilot and helicopter as a closed loop system, the affecting variables may be subsummed under four categories as illustrated in Figure 1. The knowledge of these variables is essential for precision and validity of interpretations based on tasks.

The task variables comprise all system inputs and those system control elements, external to the pilot, entering directly into the pilot's control task. The display and controlled element dynamics induce the pilot's dynamics, because they must be adapted to provide the necessary loop stability. The environmental variables include factors as temperature, vibrations, accelerations, and noise. The procedural variables contain aspects of experimental arrangement, presentation of trials, briefing, and choice of pilots. Pilot's variables include the human characteristics belonging to the control task: training, motivation, physical conditions etc.

To obtain definite relationships between the various parameters it is necessary to keep these variables under control. Therefore simulation tests were chosen because of the substantially higher control of these variables. Limiting the studies on variation of specific task variables necessitates to keep the remaining variables constant. This allows to neglect their influence on interpretations.

The task for the current study was selected to minimize the error between commanded and actual pitch angle. This error was displayed on a cockpit-mounted TV-monitor (Figure 2). A simplified block diagram shows the inputs and outputs of this compensatory tracking task. Additionally the pilot had to stabilize the helicopter in the remaining axes. The experimental matrix included three different types of commanded pitch signals and two different helicopter models. For the investigations six pilots were available.

DESCRIPTION OF SIMULATION

Command Signals

The desirable characteristics of a forcing function composed of independent sine waves are specified as:

- random appearing to avoid learning effects
- extending over about two decades, including frequencies below 0,5 rad/s
- having a Gaussion amplitude distribution, so that methods of probability calculus may be used
- providing energy in and about the crossover range without disturbing the pilot's low frequency performance
- containing low frequency sine waves which are integral multiples of run length to minimize averaging error
- fitting to hardware components to avoid frequency resolution problems [6, 7, 8].

The forcing functions used for these experiments are enumerated in table 1 where m is the rounded number of periods per run, ω is the sine wave frequency, and A is the amplitude [9].

Models

The investigation included two helicopter configurations described by 6-DOF models. They represented light weight class helicopters with hingeless and see-saw rotors in cruise condition i.e. speed 170 km/h and altitude 1500 m. The control derivatives and eigenvalues show the different characteristics (Figure 3). Linearisation of equations of motion restrained deviation from trim position assuming small perturbations.

Simulator

For this study the facilities of the DFVLR moving cockpit simulator were used (Figure 4). The simulator consisted of an Alouette cabin section mounted on a moving base. A television system in front of the right screen provided a vision adapted to infinite by a Fresnel-lens. The pilot obtained the commanded signal by bright aircraft symbol, the reference by black tape. This view was the primary cue to the pilot. The aircraft symbol also provided the roll attitude like a virtual horizon. The range of the representable pitch angle was ± 20 degrees.

Motion cues were provided by the hydraulic moving system. Short time accelerations, smoothed by special wash-out filters, generated the impression of constant accelerations. The motion platform capabilities were ± 0,3 m lateral and vertical direction and ± 15 degrees in pitch and roll attitude.

Little reference was made to instruments in this task. Except of engine and power indications the instruments were functional. In the overall task was included to maintain heading, that means to make use of those cues provided by the vertical gyro. Thus the vehicle characteristics as a whole could be evaluated in a more realistic way.

Figure 5 shows the information flow in the simulation. The 6-DOF models were programmed on the digital simulation computer. In response to the simulation equations of motion the displayed signals, the moving base motion, and the instruments were commanded. Cycle time was 40 ms (25 Hz). A paper writer provided quick-look on selected parameters. The generation of forcing function and the storage of recorded data were carried out by a second digital computer.

Simulation Schedule

It was planned to perform the tasks for one pilot in one day to suspend individual long time performance oscillations. In a briefing the pilots were introduced into the simulation design and the objectives of the experiments. They were asked to minimize the displayed error explained as target tracking and to maintain course. The training period was finished when the score-factor, that means the quotient of error and forcing function variance, was stable.

Each recorded trial included five runs with a duration of 210 s in order to provide sufficient data for statistical analysis. For each run the helicopter initial flight condition was trimmed cruise flight. Special scales for rating of workload and helicopter characteristics were used to obtain pilot's opinion after each trial. The workload scale ranged from 0 to 10 asking for the pilot's efforts to minimize the displayed error and to perform the task. The simulated helicopters were rated for stability scaled in good, average and poor, and for control sensitivity scaled in high, average and poor [10].

OUTCOMINGS

For data analysis the following selected parameters were recorded:

- commanded pitch angle (forcing function)
- displayed error (pilot input)
- longitudinal stick movement (pilot output), and
- helicopter pitch angle (system output).

Figure 6 shows a 10 s section time histories of these parameters. The displayed error (pilot input) and helicopter pitch angle (system output) illustrates, that the pilot could not follow the commanded helicopter pitch angle signal at high frequencies. At lower frequencies the pilot's output has a phase lag in relation to the error.

To get further insight into the frequency contents a Fast Fourier Transformation of recorded data was performed. In Fig. 7 the error signal power spectra, computed at input frequencies, of both rotor systems and two forcing functions are depicted. The various pilots are marked by different symbols. In general for each configuration only a small error power exists at frequencies close to zero. The main pilot's activity lies within a medium frequency range around one rad/s, the bandwidth depends much more on the helicopter type than on the forcing function. For the helicopter B the error power bandwidth is wider at similar amplitudes, i.e. the error power of this helicopter is higher. At lower frequencies both systems are easy to control. The cutoff at approximately 2 rad/s results from the forcing functions amplitudes decreasing to a tenth.

In the same way pilot output power spectra are presented in Fig. 8. All configurations show a similar spectrum with a minimum near the phugoid mode frequency and decreasing power at the cutoff frequency. It is evident, that in comparison to helicopter B resonance and cutoff frequencies of helicopter A are higher. Total power, taken as the area between -3dB and an average curve, is higher for helicopter B for both signals. The increasing power in the medium frequency range relates to the reduced amplitude response of the vehicles. The overall shape of the pilot's output power spectrum depends more on the closed loop system than on the forcing function.

Fig. 9 shows the pilots frequency responses for both helicopters and signal 3. In the region of maximum error power there is a loss of pilot gain. For helicopter B the reduced magnitude extends over a larger frequency region than for helicopter A. The depicted frequency responses differ from that of the simple crossover model for human dynamic operations [5]. A better fit of the pilot model to the helicopter characteristics in the frequency range below 1 rad/s can be achieved by introducing additional lead-lag terms.

The obtained pilot ratings are presented in Fig. 10. Subjective pilot's opinions about their efforts to perform the overall task are rated up to 20 % higher than the efforts to minimize only pitch attitude error. For the same task comparison between ratings of helicopters yields a clear higher effort for helicopter B. That means, to fulfil this compensatory tracking task, pilots prefer good controllability instead of stability. In general, pilots found trials with signal 3 were easier to perform than with signal 1.

Interrelationships

The results of frequency analysis show spread for helicopters and for pilots in error and control power spectra density (Fig. 7, 8). In order to find connexions to these deviations in the time domain, statistical data were computed [11, 12]. The comparison of statistic parameters such as mean, mean crosses, deviation and variances with pilot ratings gives the impression that pilot ratings consist of two parts, a pilot related (PR_{Pil}) and a helicopter related, PR_{Konf}, part. To obtain further insight of these relationships a correlation analysis was performed. In Fig. 11 the correlation results to find the pilot related part are enumerated. To meet the .025 significance, all values below 71 are suppressed [13]. These results were found in three steps:

- first averaging the statistical parameters including signal correlations over the five runs of each trial,
- second correlating the averaged values over pilots,
- third averaging these correlation coefficients over configurations.

The values in Fig. 11 indicate a significant relationship between pilot rating and statistic parameters of the error. The pilot related part PR_{Pil} gives a value of task performance precision, because of close correlation between error variance and pilot rating. Other correlation coefficients give trivial relationships.

The correlation matrix to find the helicopter related part of the pilot rating is given in Fig. 12. In this case an analog method was used as before. But the averaged values were correlated over configurations and these correlation coefficients averaged over the pilots. Because of the correlation over the smaller number of configurations, here all values below .81 are suppressed to meet the same significance as before. The remaining coefficients show a relationship of pilot rating to the control variance. That means the helicopter related part, $PR_{Konf.}$, gives a value of the pilot's control activity.

In order to eliminate individual pilot influences the correlation coefficients were averaged over the pilots to provide helicopter related values, whereas the averaging over the configurations provided pilot related values. Correlation results give a rating portion primary dependent on the individual pilot and his adjusted tracking precision. The pilots cover different task variables by control activity.

SUMMARY AND CONCLUDING REMARKS

The experiments described in this paper were conducted to win more experience in the field of human behaviour measurements. In this first step a simulation test was designed and data analysis was developed. The presented results give some insight into relationships between measured data and subjective pilots opinions. Next step will be statistical approvement of these interrelationships by increasing the number of pilots and tasks. Then, based on more reliable results, existing evaluation criteria will be extended and refined considering special mission requirements.

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Signal 1

k	m	ωrad/s	A
1	5	0.1575	1.0
2	9	0.2620	1.0
3	13	0.3927	1.0
4	20	0.6019	1.0
5	32	0.9695	1.0
6	50	1.4923	1.0
7	85	2.5397	0.1
8	135	4.0338	0.1
9	253	7.5694	0.1
10	461	13.7979	0.1

Signal 2

k	m	ωrad/s	A
1	4	0.1164	-1.0
2	6	0.1745	1.0
3	10	0.2909	-1.0
4	15	0.4363	1.0
5	19	0.5818	-1.0
6	29	0.8727	1.0
7	44	0.3090	-1.0
8	58	1.7450	1.0
9	88	2.6180	-1.0
10	146	4.3680	0.2
11	219	6.5440	-0.2
12	292	8.7270	0.2
13	525	15.7100	-0.2
14	875	26.1800	0.2

Signal 3

k	m	ωrad/s	A
1	4	0.1227	1.0
2	5	0.1534	1.0
3	7	0.2148	1.0
4	9	0.2761	1.0
5	12	0.3682	1.0
6	15	0.4602	1.0
7	21	0.6136	1.0
8	28	0.8283	0.9
9	37	1.1040	0.63
10	47	1.4110	0.4
11	67	1.9940	0.23
12	83	2.4850	0.15
13	113	3.3750	0.11
14	144	4.2950	0.1
15	195	5.8290	0.1
16	251	7.5170	0.1
17	333	9.9710	0.1
18	421	12.5800	0.1
19	595	17.7900	0.1
20	759	22.7000	0.1

Table 1: Forcing Function Elements

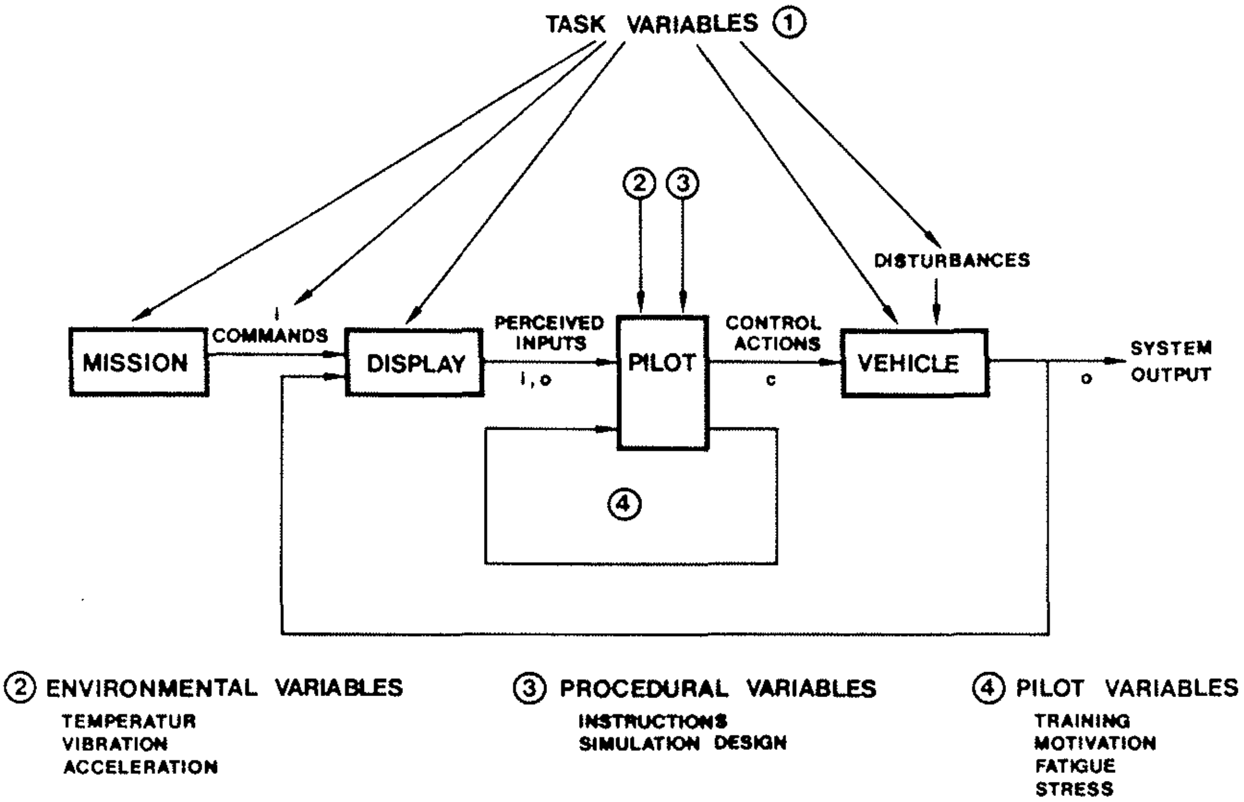

Figure 1: Variables, Affecting the Pilot-Vehicle System

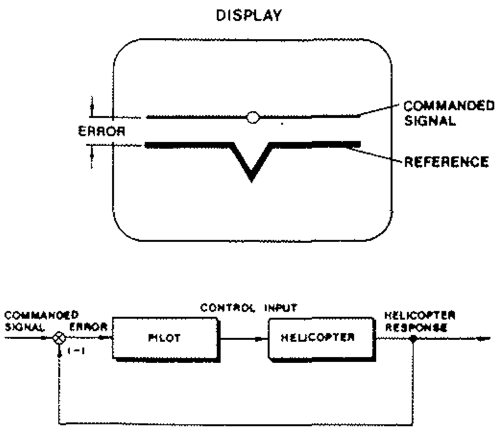

Figure 2: Compensatory Tracking Task

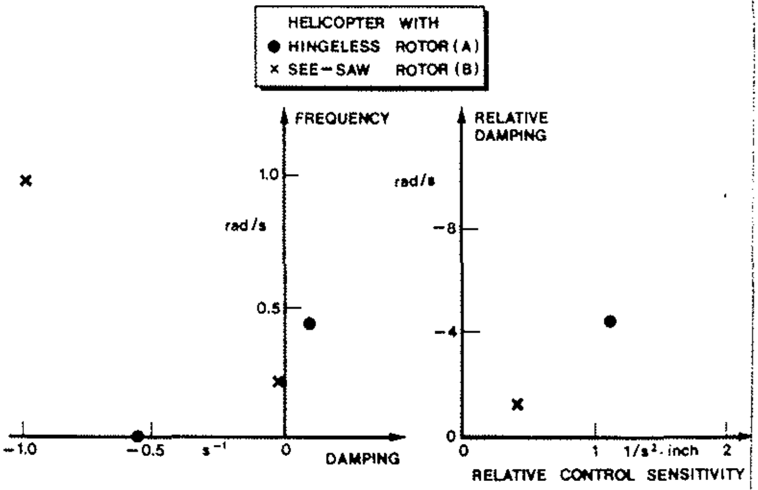

Figure 3: Simulated Helicopter Dynamic Characteristics

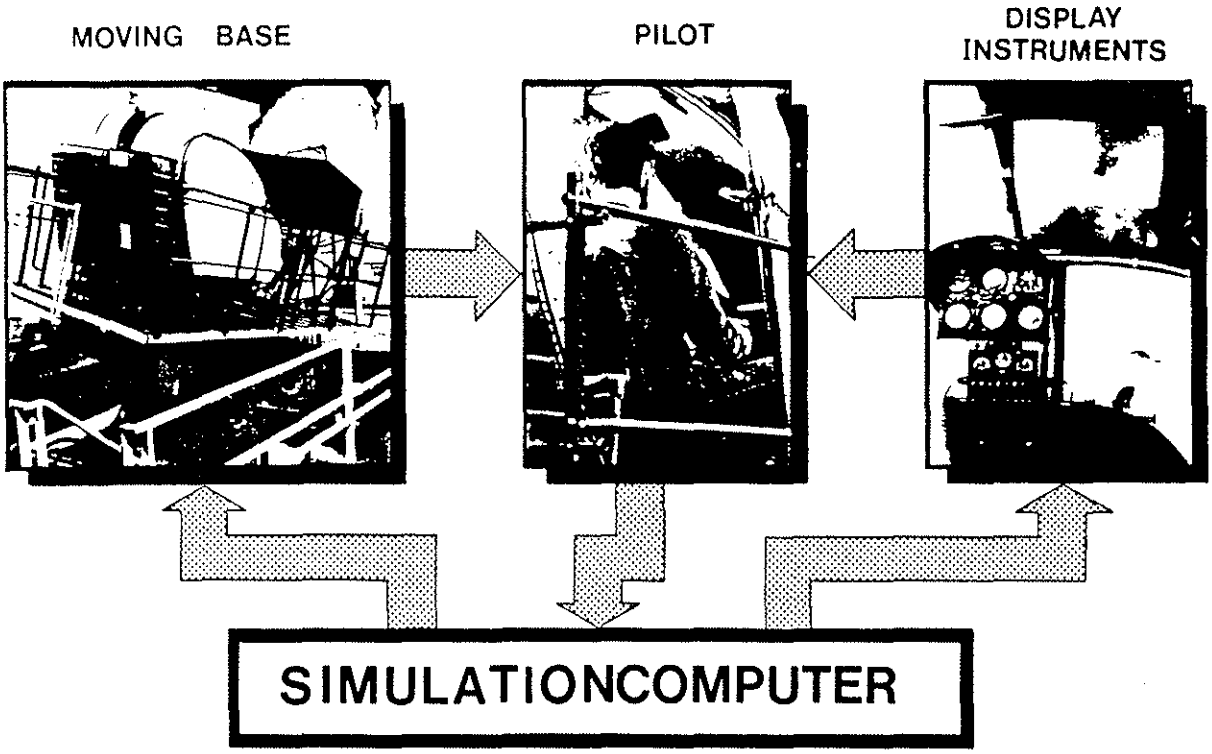

Figure 4: Simulation Components

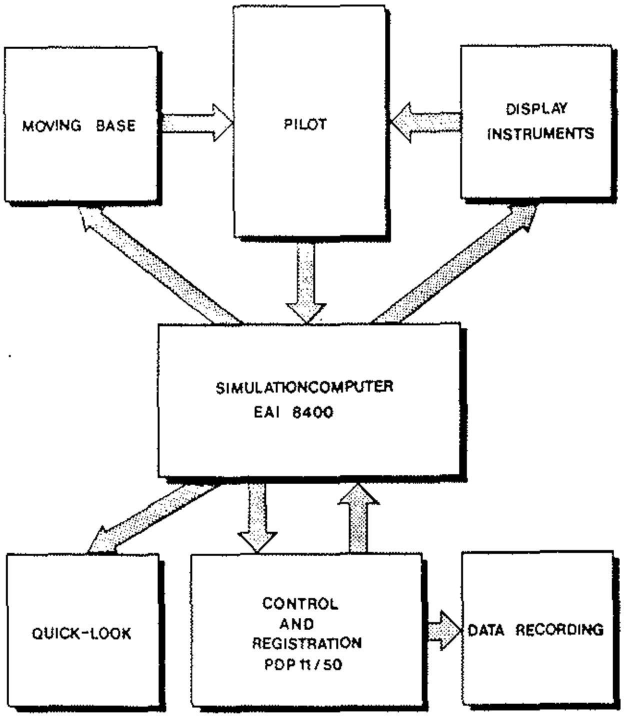

Figure 5: Simulation Scheme

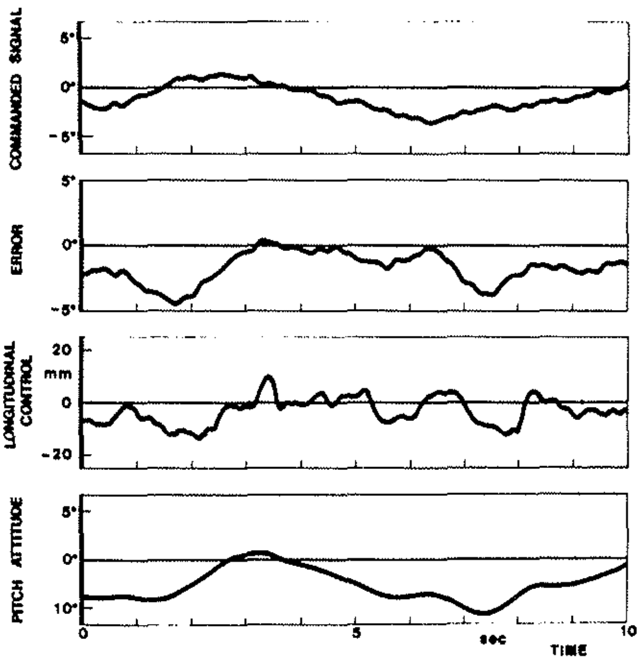

Figure 6: Time Histories

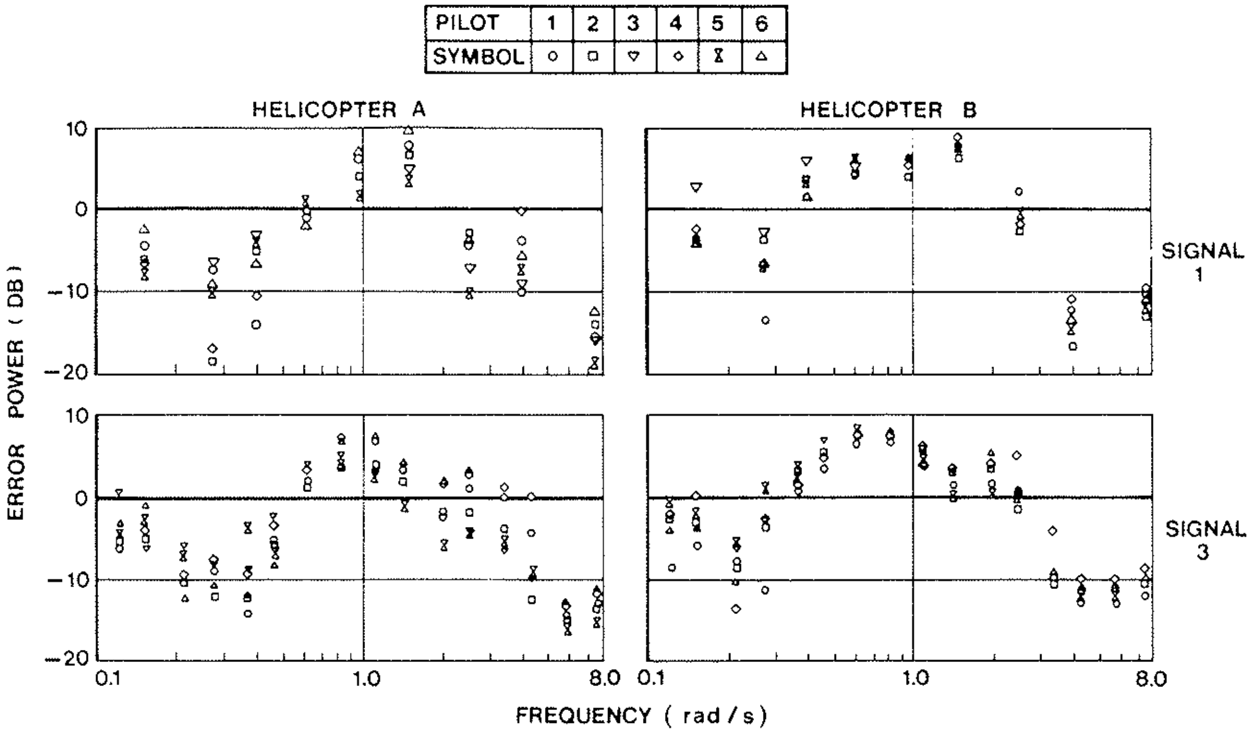

Figure 7: Error Power Spectral Density

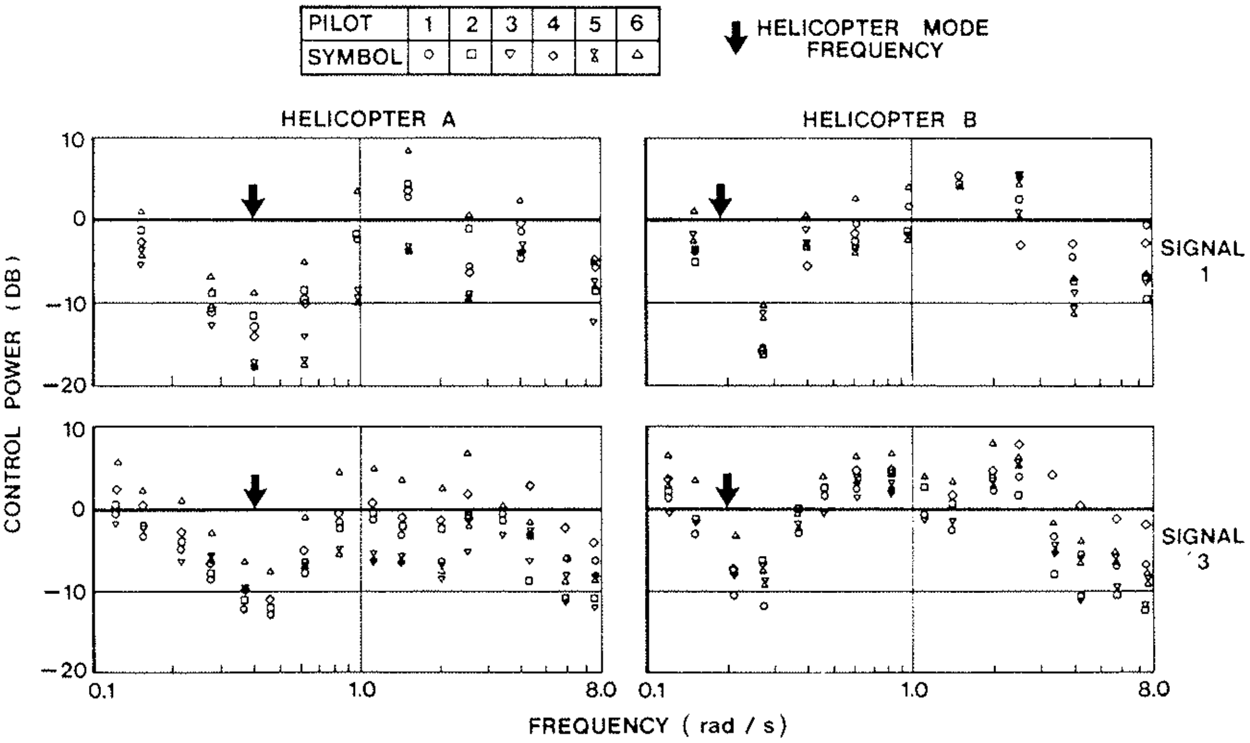

Figure 8: Control Power Spectral Density

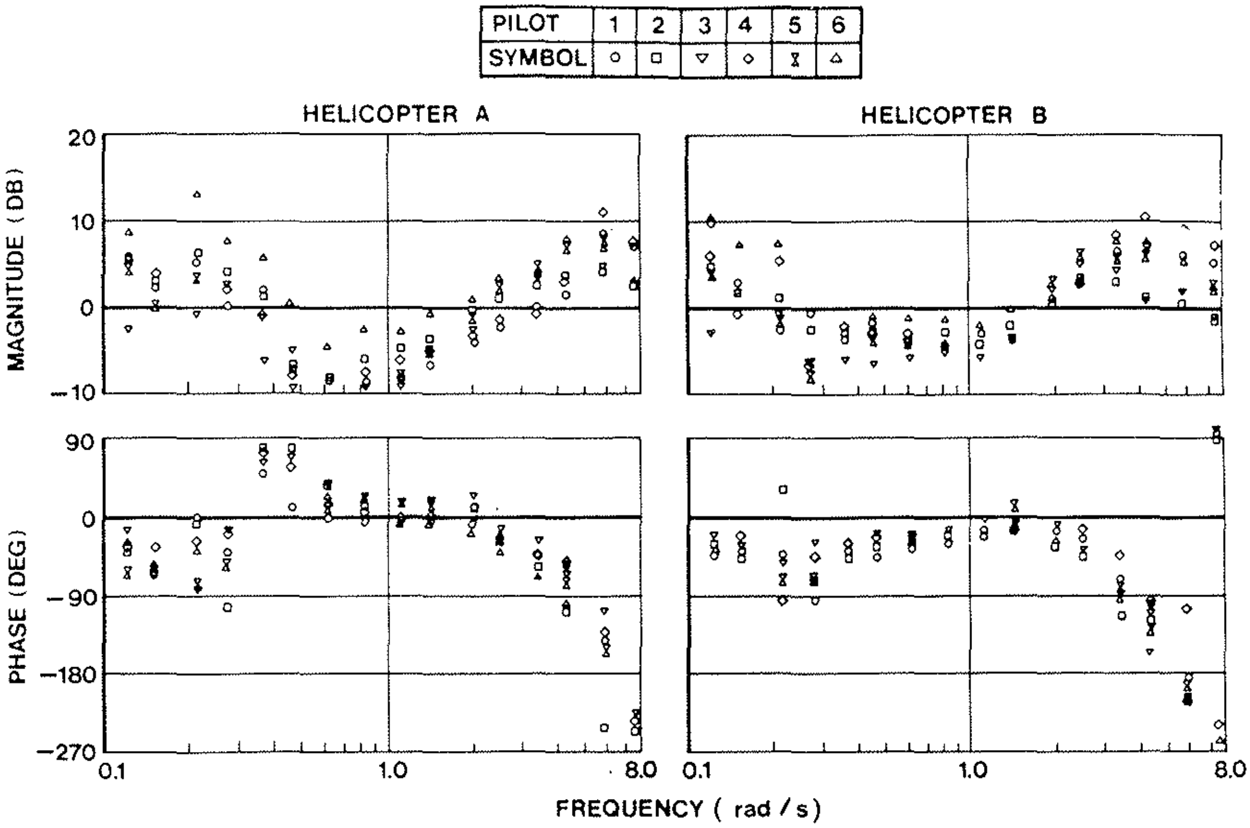

Figure 9: Pilot Frequency Response

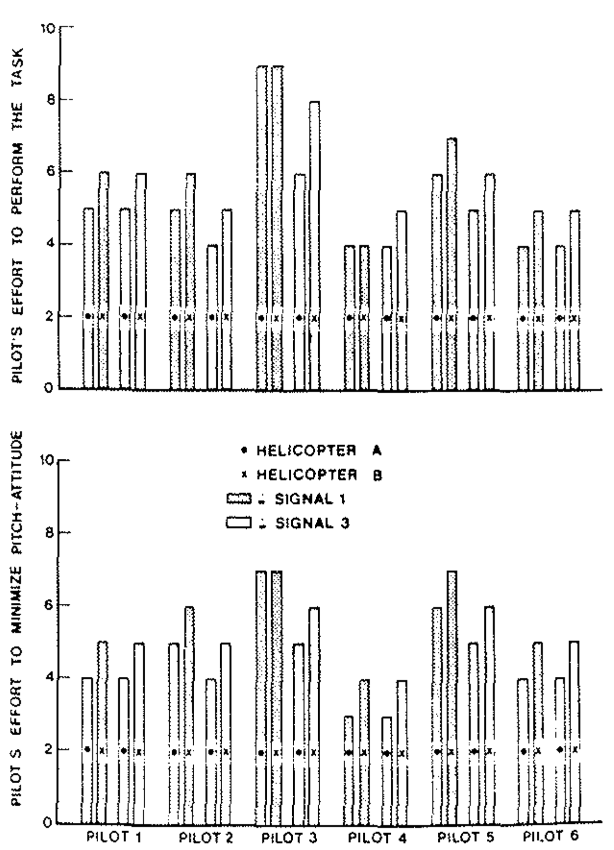

Figure 10: Pilot Rating

		SIGNAL c						SIGNAL o									SIGNAL e											
		PR	DEV	VAR	COR$_{cc}$	MC	CS	DEV	VAR	COR$_{oi}$	COR$_{oc}$	COR$_{oo}$	COR$_{oe}$	MC	REV	CS	MIN	MAX	MEAN	DEV	VAR	COR$_{ei}$	COR$_{ec}$	COR$_{eo}$	COR$_{ee}$	MC	REV	CS
	PR	1																										
SIGNAL c	DEV		1																									
	VAR		0.99	1																								
	COR$_{cc}$				1																							
	MC					1																						
	CS		0.86	0.83		0.84	1																					
SIGNAL o	DEV							1																				
	VAR							0.99	1																			
	COR$_{oi}$									1																		
	COR$_{oc}$										1																	
	COR$_{oo}$				1							1																
	COR$_{oe}$												1															
	MC		0.87											1														
	REV					0.81	0.81								1													
	CS		0.92	0.74												1												
SIGNAL e	MIN									0.91							1											
	MAX	0.85																1										
	MEAN																		1									
	DEV	0.93																0.94		1								
	VAR	0.94																0.95		1	1							
	COR$_{ei}$							0.87	0.83	0.81							0.74					1						
	COR$_{ec}$									0.88							0.81						1					
	COR$_{eo}$												1											1				
	COR$_{ee}$				1		0.75					1													1			
	MC									0.86							0.80									1		
	REV																										1	
	CS		0.74	0.65												0.81												1

Figure 11: Correlation Matrix, Average over Configurations

PR : Pilot Rating
DEV : Deviation
VAR : Variance
COR$_{xy}$: Correlation Coefficient
MC : Mean Crosses
REV : Reversals
CS : Crossing Slope

		SIGNAL c								SIGNAL o								SIGNAL e			
		PR	DEV	VAR	COR$_{ci}$	COR$_{cc}$	COR$_{co}$	COR$_{ce}$	MC	DEV	VAR	COR$_{oi}$	COR$_{oc}$	COR$_{oo}$	COR$_{oe}$	REV	CS	DEV	VAR	COR	MC
	PR	1																			
SIGNAL c	DEV	0.81	1																		
	VAR	0.81	1	1																	
	COR$_{ci}$				1																
	COR$_{cc}$					1															
	COR$_{co}$				0.93	0.8	1														
	COR$_{ce}$							1													
	MC				0.96		0.97		1												
SIGNAL o	DEV									1											
	VAR									1	1										
	COR$_{oi}$									0.89	0.9	1									
	COR$_{oc}$				0.93		1		0.97				1								
	COR$_{oo}$						0.8						0.8	1							
	COR$_{oe}$				0.94		0.9		0.95				0.9		1						
	REV				0.96		0.93		0.99				0.93		0.95	1					
	CS				0.96		0.93		0.97				0.93		0.96		1				
SIGNAL e	DEV																	1			
	VAR																	0.94	1		
	COR$_{ec}$							1	0.86	0.91	0.89				0.86	0.87	0.91			1	
	MC										0.95	0.91								0.82	1

Figure 12: Correlation Matrix, Average over Pilots