N75 19151

IN-FLIGHT MEASURED HUMAN PILOT DESCRIBING FUNCTION AND REMNANT FOR PITCH ATTITUDE CONTROL

H.A. Mooij

National Aerospace Laboratory
Amsterdam, The Netherlands

ABSTRACT

Flight tests have been performed with a variable pitch-rate-command/attitude-hold flight control system in a Beechcraft Queen Air-80 aircraft. Some results of in-flight measured runs for two pilots controlling typical "easy" and "difficult" dynamics are presented together with the initial results of the same tracking experiment performed on a ground-based flight simulator. Results are compared with results of other investigators using fixed-base flight simulators.

1 INTRODUCTION

Twenty-five years of pilot modeling have passed since Tustin's initial efforts to describe the human controller and still there are good reasons for expanding the available knowledge, even for the most simple control situations such as single loop compensatory tracking.

The reason here, for performing some experiments in this area is the involvement in a program aimed at the formulation of design criteria for electrical primary flight control systems for transport aircraft. Longitudinal systems are studied and especially the approach and landing flight phases are considered. Pitch-rate-command/attitude-hold systems form the basis of all flight-control system mechanizations presently under study.

In the experimental phases of this particular research program, piloted moving base flight simulation plays an important role. Because it is planned to incorporate a compensatory tracking task experiment in the handling qualities evaluation program (to gain more insight into pilot ratings and commentary), hard- and software has been prepared to measure pilot dynamics and pilot-aircraft system performance.

At the moment a pilot-vehicle system analysis study is performed for the prediction of total system behaviour; results of this study will be used to indicate ranges of parameters for the aircraft/flight control system combination which are worthwhile to be covered during piloted flight simulation. For this study we needed Analytical Verbal Describing Function Model (AVDFM) rules (Ref. 1) which are applicable to real pilots, normal piloting effect (rather than optimized behaviour after considerable practice) controlling the (simulated) aircraft with the type of manipulator which is typical for electrical flight control systems for advanced designs, which is a displacement side-stick controller with some viscous damping.

Relatively little systematic work has been reported on the correlation of flight and ground-simulator studies as far as pilot describing functions, remnant and pilot-aircraft system performance is concerned in order to determine the accuracy with which simulator studies of control problems can be extrapolated to the flight environment. On the subject of pilot's remnant no in-flight measured data could be traced in the literature.

A limited in-flight as well as moving/fixed base flight-simulation study of three dynamical configurations with three pilots has been performed. The results of these experiments have given basic information on models to be used in system analysis studies as well as more insight into the correlation of in-flight and ground based measured data.

After a short description of the experiment, some of the final results of the in-flight experiment are presented in this paper. Initial results of the measurements of the ground-based flight simulator counterpart of the in-flight experiment, which ended just two weeks ago, will be presented as well.

2 THE EXPERIMENT

The task was single axis compensatory pitch-attitude tracking with a small amplitude disturbance input. The random appearing forcing function was injected at the display. This "still air" task seems applicable for the study of pitch-attitude-stabilized aircraft.

(Although the longitudinal control task for approach and landing is typically multiloop, several investigators have shown that pilot dynamics of the pitch attitude inner loop in this multiloop situation are quite similar to the pilot dynamics for the single-loop attitude tracking task, e.g. reference 5).

The forcing function should ideally have a power spectral density representative of the task under study, which is landing approach for transport type aircraft. However to be able to correlate results with those of many fixed-base experiments a rectangular spectrum formed by 10 sine waves with an effective bandwidth (6 sine waves) of 1.5 rad/sec has been used. The control system, display and manipulator were the same for flight- and ground experiments. Below a short out-line of the equipment used, is presented.

<u>Vehicle</u>: <u>flight</u> :
- Beechcraft Queen Air Model-80
- Speeds 130 KIAS
- Normal acceleration characterized by the first order zero*) of the pitch attitude-to elevator deflection transfer function: value 1.26 sec^{-1}
- Roll control by safety-pilot.

<u>ground</u> :
- 3-degrees of freedom, Moving Base Flight Simulator of the Delft University of Technology, also used "fixed-base".
- Pitch attitude motion identical to flight situation (no wash-out)
- Normal acceleration characterized by the first order zero, see above Wash-out, second order, with a time constant of 2 secs

<u>Control system</u> : Prefilter-Model-Following mechanization for a pitch-rate-command/attitude-hold system;

<u>Controlled element (CE)</u>: General form $Y_c = \dfrac{K_c(S+1/T_c)}{S(S^2+2\zeta_c\omega_c S+\omega_c^2)}$

Parameters $1/T_c$ and ω_c selectable

---

*) Short-period approximation.

Dynamics used:

CE No.	$1/T_c$ sec^{-1}	ω_c rad sec^{-1}
1	1.5	4
2	0.6	4
3	0.6	0.8

$\zeta_c = 0.7$

<u>Display</u> : CRT (0.75 meter distance to the pilots eye)
Root-mean-square amplitude of forcing function: 1 cm

<u>Manipulator</u> : NLR-side-stick controller; gradient 2.5 kgcm/degree
Stick sensitivity near optimum for each Controlled Element.

3 DATA PRESENTATION

Fourier analysis of the recorded data has been performed on a Hewlett Packard 5450 A Fourier Analyzer. Run length was 200 secs and the data sampling rate was 10. Computed results are averages of 5 runs for each pilot-controlled element combination.

A least squares fitting procedure was used to determine the parameters of a mathematical model approximating the measured describing functions near cross-over frequency. Data weighting according to the frequency separation with respect to the cross-over frequency has been applied.

The derived numerical results for the pilots who controlled both "easy" and "difficult" dynamics during the in-flight experiments are presented in table form. Only the describing function data for CE-3 are in graphical form because this is possibly the most interesting controlled element tested.

4 DISCUSSION OF RESULTS

<u>Flight</u>

For the in-flight experiment the standard deviation for data averaged over 5 runs as indicated in figure 1 and 2 for the system and human controller describing function is small. Minus 20 dB/dec slope for the amplitude ratio of the system describing function is measured in the region of cross-over.

Table 1, presenting cross-over frequencies and phase margins shows for pilot A, CE-1 a regressed situation. As indicated in table 2 high scores (score = 1 - variance of the error divided by variance of the forcing function) for "easy" dynamics relative to those for CE-3 have been measured. This table shows also that error-related relative remnant $(\rho^2_{a_e})$ is always higher than or equal to output-related relative remnant $(\rho^2_{a_o})$.

Regarding pilot models (table 3) the interesting observation can be made that near equal (-high)-values for the lead time constant have been obtained (table 3) and identical values for the effective time delay for control of CE-3.

When observing the in-flight measured input injected remnant, figure 3, for pilot B, or nearly flat spectrum up to 4 rad/sec is measured for the "easy dynamics" situation CE-2. The results for the CE-3 however indicate a -20 dB/dec slope over the same frequency band. The data above $\omega = 4$ rad/sec should be disregarded because a neuro-muscular/manipulater mode existed around 5.7 rad/sec.

The probability density function of the pilot's output (Fig. 4) clearly illustrates the regressed situation of pilot A, CE-1, (peak-at-zero); for the CE-3 situation this pilot shows less bimodal character than pilot B.

A comparison of these results for pilot dynamics with the predictions of the AVDFM of reference 1, shows (table 4) lag (lead) equalization (CE-2) by the pilot as expected from the AVDFM "rules" with the location of the break frequency $(1/T_I)$ in such a way that a long stretch of -20 dB/dec for the open loop system will exist. The cross-over frequencies measured, 3 respectively 1.8 rad/sec, are 60 °/o below the values of 5 respectively 3 rad/sec for K_c and K_c/S^2-forms as indicated by the AVDFM. However, the controlled statement form actually existing during the experiment differs from the simple expressions mentioned above. An additional 90° phase lag exists for CE-2 while an increased phase lag (in excess of 180°) exists for $\omega > 2$ rad/sec for CE-3.

Comparison of flight results with ground-simulator results

Moving-base experiments yielded higher cross-over frequencies and lower phase margins than comparable fixed-base experiments for the same pilot with an "easy" controlled element, pilot A, CE-1 x). [A comparison for pilot B, CE-2, is not possible because for the moving-base situation too few practice runs were included.]
For CE-3 no appreciable changes in cross-over frequency and phase margin can be observed when comparing moving- and fixed-base results.

Approximately 30 °/o increase in the $1 - \sigma$ value for the error can be observed when going from the moving-base to the fixed-base situation; this is also measured for the easy dynamics. This trend correlates well with the commentary of the pilots, stating that the task was easier when performed with motion. The score fore moving-base was always higher than either flight or fixed-base.

Trend in the output-related relative remnant shows a reverse in the relative numbers when comparing the easy and difficult dynamics; for the easy dynamics the relative remnant decreases when going from the MB to FB-situation while the inverse holds for the difficult dynamics.

Excluding the regressed control situation in-flight for pilot A, CE-1, good correspondence exists between in-flight and ground-based measured pilot-vehicle system performance.

The relation of moving-base and fixed-base simulator results show that motion cues have a definite effect on pilot's tracking behaviour.

Comparison with previous results

With respect to the in-flight results, no direct comparison of system performance with previous results is possible due to the lack of data in the literature.

A similar in-flight and ground-based study by Seckel and others, reference 2, presents no pilot-aircraft system data.

More recent in-flight data have been reported by Newell and Smith in reference 3; pilot-aircraft system data for a forcing function bandwidth of 1.5 rad/sec are given but the task here was a roll-tracking task. For the A-2+ configuration of this reference, a cross-over frequency of 1.8 rad/sec and a phase margin of 50 degrees were obtained for pilot A and B (Pilot C showed "regressed" control characteristics). A fitting of a simple mathematical model indicated a lead time constant of 2.3 seconds.

---

x) This same observation could be made from the data of another pilot participating in the ground-simulator program. (Pilot C, table 1).

In reference 2 and 3 no remnant data are presented.

Table 5 presents correlation of the current FB results with data of reference 4 and 5 (fixed-base also). In reference 4, data originally from NASA TND-2067 are presented (p.244) for high ω_c dynamics which are suited for a comparison with the current CE-2 dynamics. The estimate for system cross-over frequency (3.3 rad/sec) from data at lower frequencies reported herein seems on the optimistic side. The phase curve of the reference coincides completely with the current measured phase curve at lower frequencies. A phase margin of 35 degrees (as predicted in the reference) leads to a newly estimated cross-over of 3 rad/sec.
This agrees very well with the current measured 2.8 rad/sec (phase margin 40 degrees for CE-2.

In reference 5 results for a single axis experiment are presented which can be used for comparison with the current low ω_c dynamics (CE-3). The measured pilot-aircraft system describing functions for this experiment are presented however in reference 6.
The cross-over frequencies of 2.4/2.7 reported herein for two pilots corresponds to very low phase margins of 12 and 0 degrees respectively. Taking the liberty to question the correctness of the amplitude scaling in this case, a new estimate for the cross-over frequency can be made. Taking the lowest phase margin reported in the current program as well as in the experiments described in the literature for tasks where low frequency lead is generated, namely 20 degrees, a value of 2 rad/sec for both pilots results. Again this correlates very well with the results described here.

To summarise, the following can be said:

- The predictions of pilot's equalisation (form and location of break points) and his effective time delay by the AVDFM (1965 status) holds for the in-flight pitch attitude tracking situation.

- The flight data correlate very well with results obtained during the ground-based experiment. Characteristic for "easy dynamics" are cross-over frequencies of 3.0 to 3.2 rad/sec with a phase margin of 20 to 30 degrees for flight and moving-base simulation conditions. Fixed-base, somewhat lower cross-over frequencies with higher phase margings have been measured.
  For control of the "difficult dynamics" cross-over frequencies of 1,8 to 2,0 rad/sec with phase margin 20 to 35 degrees are measured.

5 REFERENCES

1. McRuer, D.T. Jex, H.R.	A review of quasi-linear pilot models. IEEE Transactions on Human Factors in Electronics. Vol. HFE 8, number 3, September 1967.
2. Seckel, E. Hall, I.A. McRuer, D.T. Weir, D.H.	Human pilot dynamic response in flight and simulator. WADC Technical Report 57-520, 1958.
3. Newell, F.D. Smith, H.J.	Human transfer characteristics in flight and ground simulation for a roll tracking task. NASA TND-5007, 1969.
4. Sadoff, M. Dolkas, C.B.	Acceleration stress effects on pilot performance and dynamic response. Second Annual NASA-University Conference on Manual Control, NASA SP-128, 1966.
5. Stapleford, R.L. Craig, S.J. Tennant, J.A.	Measurement of pilot describing functions in single controller multiloop tasks. NASA CR-1238, 1969.
6. Weir, D.H. McRuer, D.T.	Pilot dynamics for instrument approach tasks: full panel multiloop and flight director operations. NASA CR-2019, 1972.

CE	Pilot	ω_c (rad/sec)			φ_m (degrees)		
		FLT	MB	FB	FLT	MB	FB
1	A	1.3	3.2	2.5	80	30	65
	C	-	3.0	2.5	-	20	45
2	B	3.0	2.5	2.8	30	45	40
3	A	1.8	2.0	2.0	35	35	20
	B	1.8	2.0	2.0	20	35	25

Table 1 Cross-over frequency ω_c and phase margin φ_m.

FLT = in-flight MB = moving-base simulator FB = fixed-base simulator

CE	Pilot	σ-error			Score			relative remnant $\rho^2_{a_c}$		
		FLT ')	MB ")	FB "')	FLT	MB	FB	FLT ($\rho^2_{a_e}$)	MB	FB
1	A	0.54	1.9	2.5	0.71	0.78	0.73	0.84 (0.93)	0.87	0.73
2	B	0.48	1.9	2.8	0.77	0.79	0.69	0.70 (0.70)	0.90	0.75
3	A	0.77	4.1	5.2	0.40	0.58	0.40	0.20 (0.63)	0.35	0.58
	B	0.85	3.5	4.7	0.27	0.62	0.49	0.50 (0.66)	0.40	0.48

Table 2 Performance measures and relative remnant. ') cm display
") and "') Volts

CE	Pilot	K_p deg/cm display	T_I	T_L	τ_e
			sec		
1	A	5.5	1.1	0.8	0.28
2	B	6.0	1.4	0.7	0.26
3	A	0.6	0.1	4.7	0.38
	B	0.6	0.05	4.3	0.38

$$Y_p = K_p \frac{(T_L j\omega+1)}{(T_I j\omega+1)} e^{-\tau_e j\omega}$$

Table 3 Model for pilot's describing function (FLT)

Form controlled element near cross-over frequency				
CE-2		CE-3		
K_c (based on amplitude ratio; phase lag $\approx -90^\circ$)		K_c/S^2 (very good approximation for amplitude ratio; phase lag exceeds -180° for $\omega > 2$ rad/sec)		
AVDFM	This study Pilot B	AVDFM	This study Pilot A	Pilot B
Lag(-lead)	Lag(-lead)	Low freq.lead	Low freq.lead	Low freq.lead
$1/T_I \approx 1/T_c = 0.6$	$1/T_I = 0.7$	$1/T_L \ll \omega_c = 1.8$	$1/T_L = 0.21$	$1/T_L = 0.22$
$(\tau_o = 0.33)$ $\tau_e = 0.22$	$\tau_e = 0.26$	$(\tau_o = 0.50)$ $\tau_e = 0.38$	$\tau_e = 0.38$	$\tau_e = 0.38$

Table 4 Correlation with pilot dynamics predicted by the AVDFM of reference 1. ω_i = forcing function bandwidth. $(\tau_e = \tau_o - 0.07\,\omega_i)$

Source	Pilot	Controlled Element $1/T_o$ sec^{-1}	ω_o rad/sec	ζ_o	ω_i rad/sec	ω_c rad/sec	φ_m deg.	$\rho^2_{a_c}$
Ref.4	A	0.4	3.35	0.53	1.5	3.3 1)	34 1)	-
This study (FB)	A	1.5	4.0	0.70	1.5	2.5	65	0.73
	B	0.6	4.0	0.70		2.8	40	0.75
Ref. 5	A	0.6	0.8	0.4	1.0	2.4 2)	small	0.30
	B					2.7 2)	small	0.36
This study (FB)	A	0.6	0.8	0.7	1.5	2.0	20	0.58
	B					2.0	25	0.48

1) Estimated from system describing function data at lower frequencies.
2) Estimated as indicated in reference 6.

Table 5 Correlation with previous results, fixed-base.

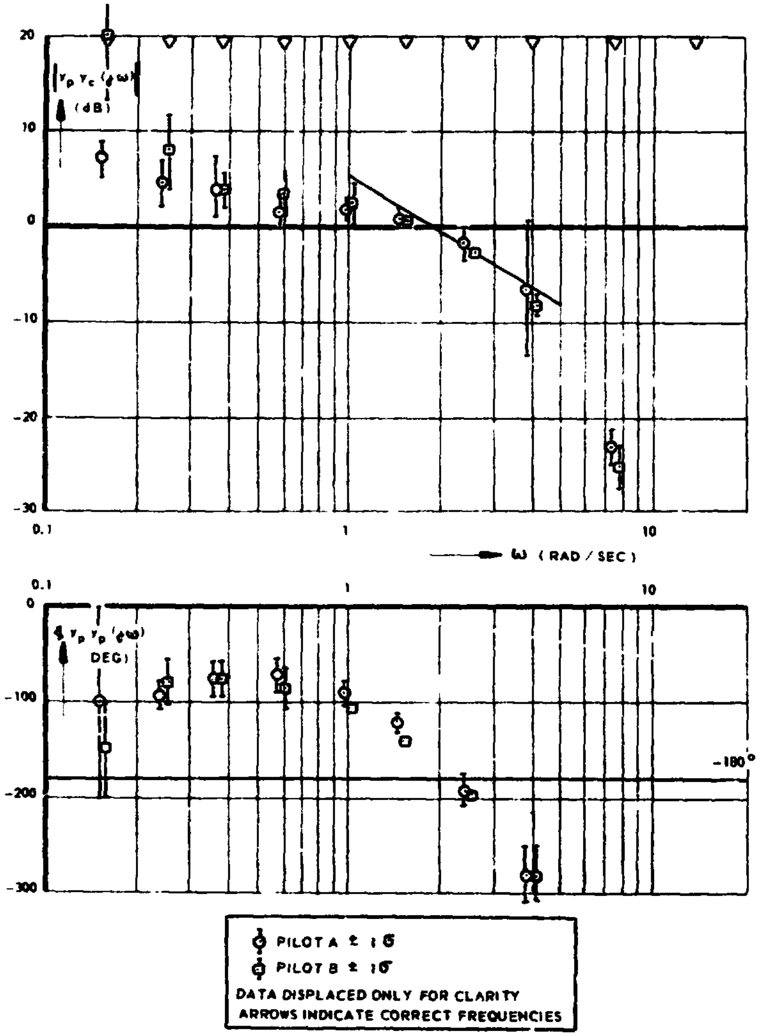

FIG 1. SYSTEM DESCRIBING FUNCTION CE-3 (FLIGHT)

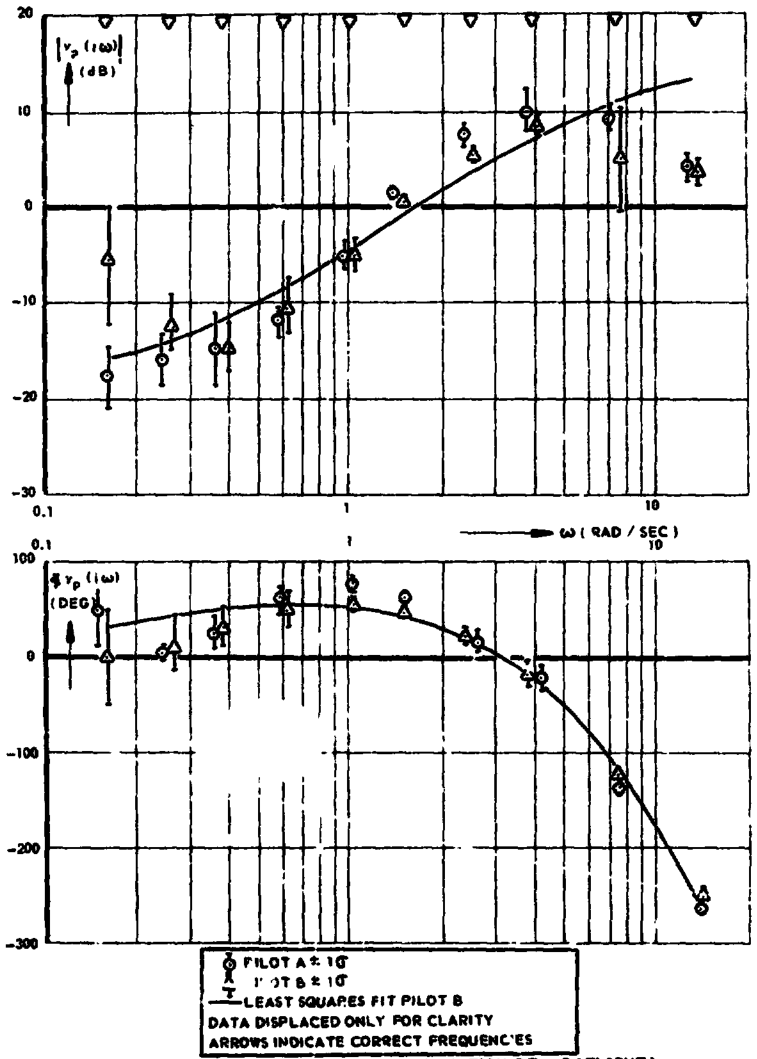

FIG. 2 HUMAN PILOT DESCRIBING FUNCTION CE - 3 (FLIGHT)

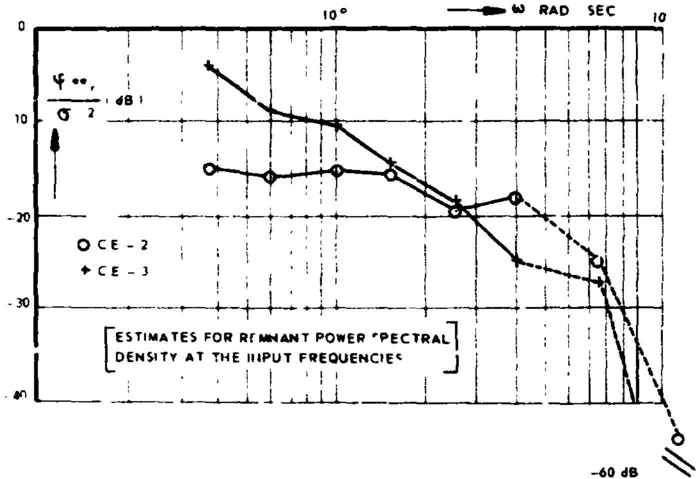

FIG 3 OUTPUT INJECTED REMNANT, PILOT B (FLIGHT)

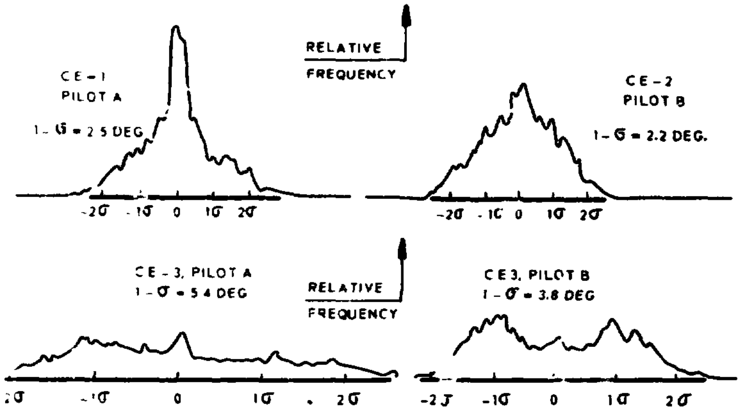

FIG 4 PROBABILITY (FLIGHT) DENSITY FUNCTION OF THE PILOT OUTPUT