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

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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 typic-
al "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, pilot-
ed moving base flight simulation plays an important role. Because it is
planned to incorporate a compensatory tracking task experiment in the hand-
ling 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

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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 Describ-
ing 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.

Vehicle: flight : - Beechcraft Queen Air Model-80

          - Speed: 130 KIAS

          - Normal acceleration characterized by the first order zero[m] of the pitch attitude-to elevator deflection transfer function: value 1.26 sec^{-1}

          - Roll control by safety-pilot.

     ground : - 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

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

Controlled element (CE): General form $Y_c = \dfrac{K_c(S+1/T_Q)}{S(S^2+2\zeta_Q\omega_Q S+\omega_Q^2)}$

Parameters $1/T_Q$ and ω_Q selectable

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m) Short-period approximation.

Dynamics used:

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

$\zeta_Q = 0.7$

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

Manipulator : 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

Flight

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, CB-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 CB-3 have been measured. This table shows also that error-related relative remnant $(\rho_{a_e}^2)$ is always higher than or equal to output-related relative remnant $(\rho_{a_o}^2)$.

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 CB-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 CB-2. The results for the CB-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/manipulator 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, CB-1, (peak-at-zero); for the CB-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) equalisation (CB-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 % 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 CB-2 while an increased phase lag (in excess of 180°) exists for $\omega > 2$ rad/sec for CB-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, CB-1[a]. [A comparison for pilot B, CB-2, is not possible because for the moving-base situation too few practice runs were included.] For CB-3 no appreciable changes in cross-over frequency and phase margin can be observed when comparing moving- and fixed-base results.

Approximately 30 % 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 for 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, CB-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.

a) 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_0 dynamics which are suited for a comparison with the current CB-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 at 3 rad/sec.
This agrees very well with the current measured 2.8 rad/sec (phase margin 40 degrees for CB-2.

In reference 5 results for a single axis experiment are presented which can be used for comparison with the current low ω_0 dynamics (CB-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 summarize, 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 margins 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.

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CB	Pilot	ω_0 (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_0 and phase margin φ_m.

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

CE	Pilot	σ-error			Score			relative remnant $\rho^2_{a_e}$		
		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
3	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
3	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°)		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
$1/T_I \approx 1/T_e \approx 0.6$	$1/T_I = 0.7$	$1/T_L \ll \omega_e = 1.8$	$1/T_L = 0.21$	$1/T_L = 0.22$
$(\tau_o = 0.33)$ $\tau_e = 0.22$	$\tau_e = 0.26$	$(\tau_o = 0.50)$ $\tau_e = 0.38$	$\tau_e = 0.38$	$\tau_e = 0.38$

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			ω_i	ω_c	φ_m	$\rho^2_{a_o}$
		$1/T_o$ sec^{-1}	ω_o rad/sec	τ_o	rad/sec	rad/sec	deg.	
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.
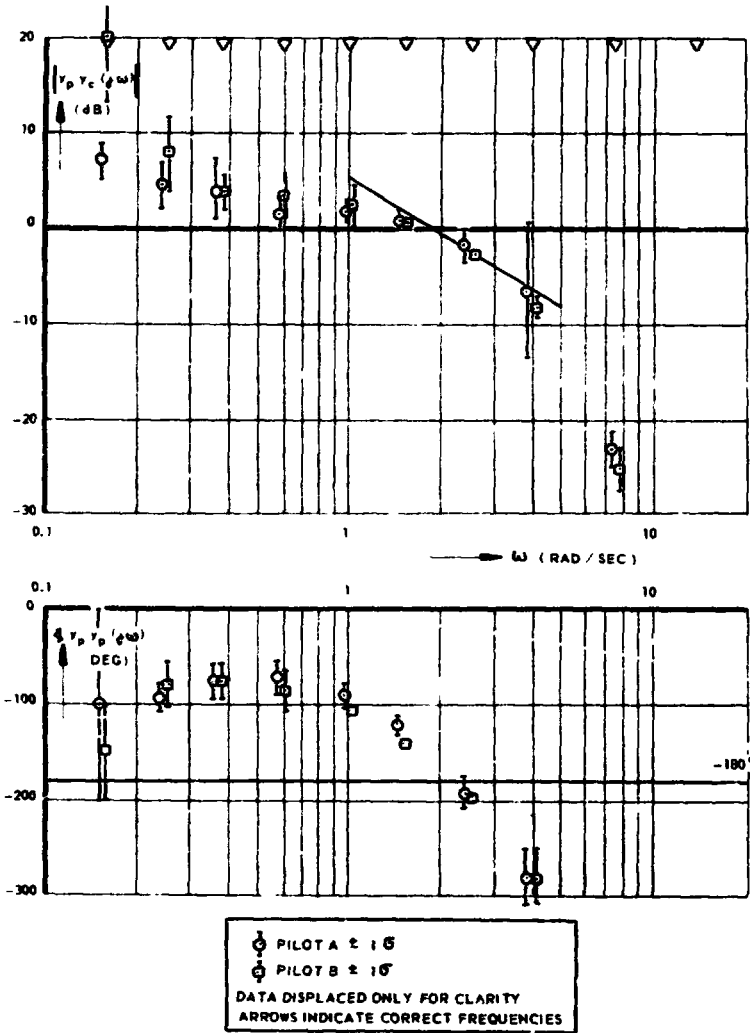
Table 5 Correlation with previous results, fixed-base.
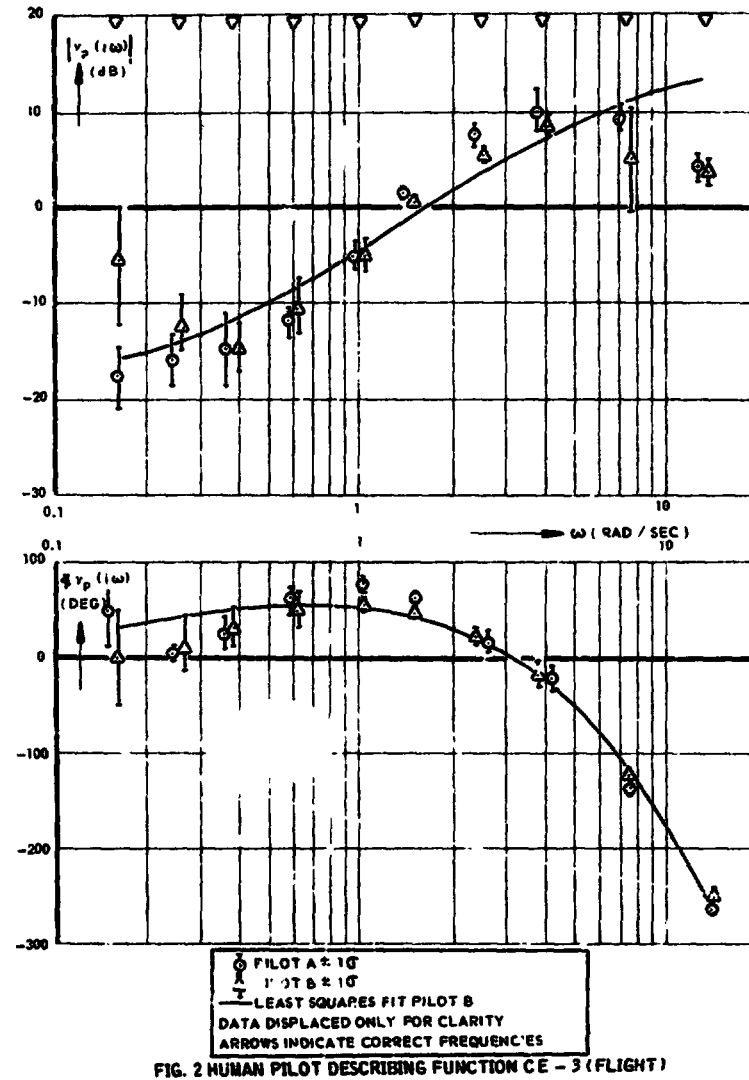
FIG 1. SYSTEM DESCRIBING FUNCTION C E – 3 (FLIGHT)

PILOT A ± 1σ
PILOT B ± 1σ
DATA DISPLACED ONLY FOR CLARITY
ARROWS INDICATE CORRECT FREQUENCIES

FIG. 2 HUMAN PILOT DESCRIBING FUNCTION C E – 3 (FLIGHT)

PILOT A ± 1σ
PILOT B ± 1σ
LEAST SQUARES FIT PILOT B
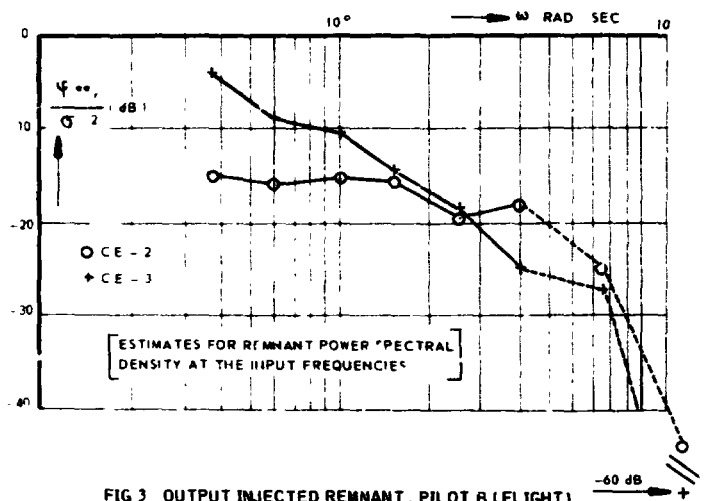DATA DISPLACED ONLY FOR CLARITY
ARROWS INDICATE CORRECT FREQUENCIES
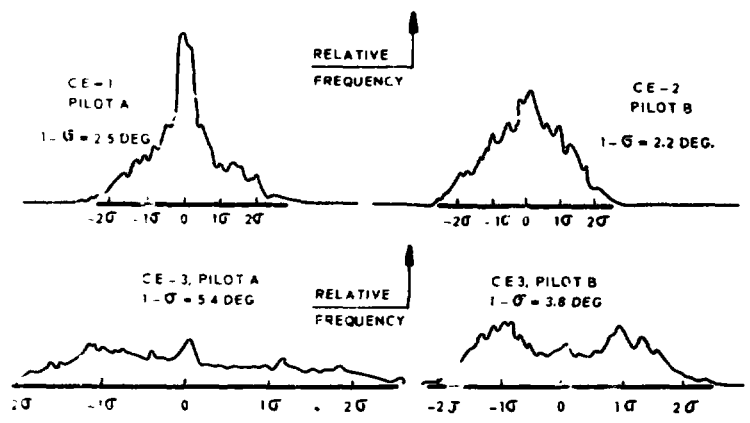
FIG 3 OUTPUT INJECTED REMNANT, PILOT B (FLIGHT)

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