In-Flight Measurement of Human Response Characteristics

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A general review is presented of documented flight research programs in which data have been obtained for the measurement of human pilot response characteristics. The techniques for obtaining and analyzing the in-flight measured data are described. Salient features such as forcing function input, display characteristics, and vehicle dynamics are summarized and discussed. With this perspective, a recent program conducted by Cornell Aeronautical Laboratory, Inc. is reported in which the Air Force variable stability T-33 was used to obtain human pilot response characteristics for a compensatory roll tracking task. Details of the experimental equipment, design of the experiment, and the resulting describing function representation of the human pilot are presented.

Nomenclature

K = general gain constant
K_c = controlled element gain constant
K_p = pilot gain constant
s = Laplace operator
T = general time constant
T_I = general lag constant
T_L = general lead constant
Y_c = controlled element transfer function
Y_p = pilot transfer characteristic
δ_A = aileron position
δ_{AS} = aileron stick position
τ = time delay
ϕ = bank angle
Φ_{ic} = system input, pilot output cross-power spectrum
Φ_{ii} = system input, power spectrum
$\Phi_{i\epsilon}$ = system input, system error cross-power spectrum
$\Phi_{i\phi}$ = system input, system output cross-power spectrum

Introduction

FOR the past decade the Air Force has conducted a continuing program for the analytical investigation of handling qualities of piloted aircraft. One of the most promising concepts developed under this program has been the analysis of the closed-loop pilot-vehicle situation by using control engineering methods. This analysis method requires a suitable model of pilot dynamic characteristics. One form of the pilot model is composed of a generalized describing function and "adjustment rules" which specify how to "set" the parameters of the generalized describing function to approximate human behavior for a particular control situation. The parameters consist of pilot gain, reaction time delay (transport lag) and equalizing characteristics (usually a first-order lead and lag combination). The adjustment rules specify the form of the equalizing characteristics, phase margin range, and some properties of the crossover frequency.

A typical describing function representation of the human pilot is

$$Y_p = K_p e^{-j\omega\tau} [(T_L j\omega + 1)/(T_I j\omega + 1)] \quad (1)$$

where K_p = pilot gain, τ = reaction time delay, T_L = lead time constant, and T_I = lag time constant.

By using the pilot model as an element in a closed-loop analytical evaluation, the control engineer is able to approximate pilot-vehicle stability and performance and thereby to estimate handling qualities. Theoretical analyses can be made to synthesize proposed augmentation systems and to predict the control situations and ranges of parameters for simulator investigations of the systems.

Existing pilot models have been obtained experimentally through ground-based simulations of single-loop, compensatory tracking tasks. Application of these models has been made to multiple-loop situations with reasonable success. However, the implications of the in-flight situation have not been fully understood. Additional investigation of them is required.

Human response characteristics can readily be measured during simulation and flight test studies. The signals necessary for data reduction can be obtained from a closed-loop tracking task during which the normal system performance measures, such as rms error and pilot opinion rating, may be obtained.

In this paper some aspects of the specific problem of in-flight measurement of human response characteristics are discussed. A review of previous programs is presented to illustrate the requirements for such investigative programs: the form of the tracking task, the mechanization, the implementation problems involved. The second part of this paper deals with a recent program conducted with the Air Force variable stability T-33 operated by the Cornell Aeronautical Laboratory (CAL). Detailed discussions of the experiment design, the equipment and the resulting describing function representation of the human pilot are presented.

Use and Value of In-Flight Measurements

The discussion here is concerned with three aspects of human response characteristics: the pilot model, methods of simulation, and the application of pilot models to handling qualities work.

1. Pilot Model Refinement and Validation

The quasi-linear mathematical description of the dynamic response characteristics of the human pilot has undergone continuous, detailed modification and refinement. This ef-

Presented as Paper 67-240 at the AIAA Flight Test, Simulation and Support Conference, Cocoa Beach, Fla., February 6–8, 1967; submitted May 12, 1967; revision received Feb. 27, 1968.
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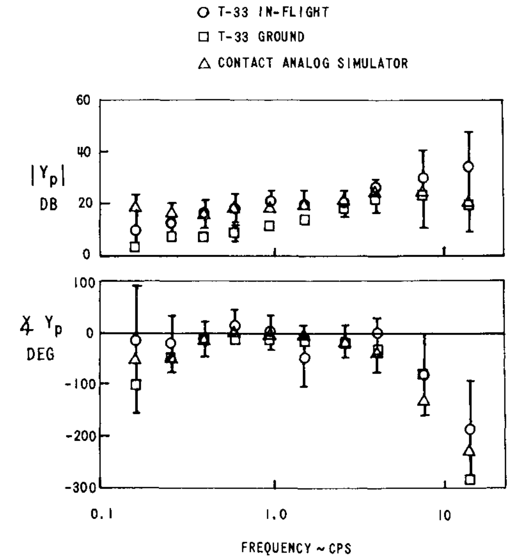


Fig. 1 Comparison of in-flight and ground-based pilot describing function data.[2]

fort has been made principally by Systems Technology Inc., and has resulted in the present analytical/verbal describing function model.[1] This model has evolved through a comprehensive series of carefully conducted ground-based experiments with simple controlled elements. The effects of the in-flight situation and more complex aircraft dynamics on the pilot model are not fully understood or verified and additional investigation of these factors is being conducted. It appears from past data that the characteristic form of the pilot model is not significantly changed by the in-flight environment. However, subtle variations and modifications to the pilot model "adjustment" rules are expected.

2. Simulator and Simulation Techniques

In-flight measured human response data are being used to determine the validity of ground-based simulator and simulation techniques in a study being performed at the NASA Flight Research Center. The hypothesis is that a more valid simulation results when the describing function for the pilot in the ground-based simulator matches his dynamic characteristics in flight for the control task of interest. Figure 1, taken from Ref. 2, shows a comparison of human describing functions obtained with the Air Force variable stability T-33 in flight and as a ground-based simulator with a normal instrument panel, and with a second ground-based simulator with a contact analog display. This figure shows one comparison of the many possible conditions which can be investigated and compared. Other comparisons can be made such as display evaluations, pilot variations, and differences of piloting technique that occur between ground simulation and flight, by using human response measurements.

The matrix of simulation experiments to be performed in a research study can be delimited through theoretical analysis by using the pilot model. These analyses can also point out control situations of particular interest (possible instabilities) and be used to establish ranges of controlled element parameters pertinent to the control situations that are found to need comprehensive study.

3. Handling Qualities

The application of pilot models to the analysis of stability and control for the manual closed-loop situation is well documented and in widespread use (see Bibliography). Pilot-vehicle analyses have been made of control problems in launch vehicle operation, carrier approach, and other piloting tasks to determine parameters for vehicle handling qualities. The availability of in-flight human response data can aid in the refinement and the validation of handling qualities parameters, and it may be helpful in the more general sense of explaining anomalous flight test data.

Additional factors used as measures of handling qualities are pilot opinion rating and workload. The Air Force is currently funding a contract to determine the correlation between pilot opinion rating and the dominant characteristics of the pilot describing function. Workload limits, when defined as the maximum capability of the human pilot, can be expressed in terms of pilot dynamic characteristics. However, these limits may be difficult to obtain in flight if they are also the limit of control.[3]

Discussion of In-Flight Measurement

Ground, fixed-base measurement of human pilot describing functions is normally accomplished for a single-axis compensatory tracking task with a random or random-appearing forcing function. The display is usually a cathode ray tube (CRT) with a bar or dot representation of the error signal. Attempting to duplicate these measures in flight with a full six-degree-of-freedom aircraft presents a number of technical challenges. Documented literature presents some of these challenges and states how they were met. Of primary interest are three independent research efforts conducted over the same time period (1956–1958). These efforts will be identified by the organization performing the research effort and the specific vehicle involved. They are the CAL F-94,[4,5] the Princeton Navion,[6] and the NASA TV-2.[7] Some recent in-flight experiments by NASA with an F-104B[8] will also be discussed. These experiments are summarized in Table 1.

1. Tracking Task

For the in-flight situation, the tracking task can be implemented on a cockpit display or by visually sighting the horizon. The natural horizon was tracked visually with the CAL F-94 and the NASA TV-2. The pilot in the CAL F-94 was instructed to track the horizon using a fixed sight mounted on the nose of the airplane and to maintain level flight in the presence of artificially generated pitch disturbances introduced through the elevator. The NASA pilots tracked the horizon in a similar manner and, in a separate series of experiments, by reference to a gyro horizon indicator. Displacement and rotation of the horizon bar from a line etched on the face of the display corresponded to pitch and roll attitude of the airplane.

The Princeton Navion aircraft had a 5-in. CRT on which a "target spot" and a "horizon line" moved about. They represented the pilot's "inside-out" view of the target aircraft and the horizon in a simulated air-to-air gunnery situation. The target spot moved in accordance with the sum of "noise" input signals and the output of three attitude gyros sensing the Navion aircraft's changes in orientation. The horizon line was controlled in tilt and position by the same gyros. Instructions were to track continuously, as closely as possible, consistent with the limitations of a Navion aircraft.

Cockpit controls were the normal center stick and rudder pedals in the F-94 and TV-2 aircraft, and wheel and rudder pedals in the Navion. The vehicle dynamics (controlled elements) were the natural modes of motion for the Princeton Navion and the NASA TV-2. The CAL F-94 utilized a variable stability system. The primary mode of motion controlled was the longitudinal short period dynamics mode.

All of the aforementioned vehicles utilized actual aircraft motion in harmony with the tracking task. However, it is of interest to measure pilot describing functions in flight for a task without motion cues, to separate and determine environment effects on the pilot model. This has been accomplished

Table 1 Summary of in-flight human response measurement experiments

AUTHORS	FORCING FUNCTION	DISPLAY	CONTROLLED ELEMENT	DATA RECORDED & DESCRIBING FUNCTION OBTAINED
EAKIN & CAMPBELL REF. 5 CAL F-94	"KNOWN, REPEATABLE AND UNPREDICTABLE (BY THE PILOT) DISTURBANCE" INJECTED DIRECTLY TO THE AIRPLANE CONTROL SURFACE (ELEVATOR)	TRACK NATURAL HORIZON WITH AIRCRAFT GUNSIGHT	LONGITUDINAL SHORT PERIOD CASE ζ_{SP} ω_{SP}(RAD/SEC) 1 .54 1.66 2 .71 2.45 3 .75 4.79	RECORD: g - NORMAL ACCELERATION F - STICK FORCE N - NOISE INPUT COMPUTE CROSS-SPECTRAL DENSITY RATIO Φ_{FN}/Φ_{gN}
SECKEL, HALL, McRUER & WEIR REF. 6 PRINCETON NAVION	WHITE NOISE THROUGH THIRD-ORDER LOW PASS FILTER AT A CORNER FREQUENCY OF 1 RAD/SEC INJECTED AT THE DISPLAY AFTER SUMMATION WITH THE OUTPUT.	SIMULATED AIR-TO-AIR GUNNERY WITH "TARGET SPOT" & "HORIZON LINE" ON 5 INCH CRT. SAME INSTRUMENT USED FOR GROUND-BASED AND IN-FLIGHT EXPERIMENTS.	LONGITUDINAL: PHUGOID: $\zeta_p = .05$, $\omega_p = .206$ RAD/SEC SHORT PERIOD: $\zeta_{SP} = .73$, $\omega_{SP} = 3.6$ RAD/SEC LATERAL-DIRECTIONAL: DUTCH ROLL: $\zeta_d = .14$, $\omega_d = 2.68$ RAD/SEC SPIRAL: $1/T_s = .012$ PER SEC ROLL: $1/T_R = -6.77$ PER SEC	RECORD: i - INPUT SIGNAL e - TRACKING ERROR c - PILOT OUTPUT COMPUTE CROSS-SPECTRAL DENSITY RATIO $\Phi_{ic}/\Phi_{i\epsilon}$
KUEHNEL REF. 7 NASA TV-2	SUM OF 12 SINUSOIDS WITH AMPLITUDE ATTENUATED WITH INCREASING FREQUENCY. SIGNAL INJECTED INTO THE CONTROL SYSTEMS.	GYRO HORIZON INDICATOR USED IN FLIGHT AND GROUND SIMULATIONS. NATURAL HORIZON ALSO TRACKED IN FLIGHT (SEPARATELY) AS WELL AS ONE "BLINDFOLD" EXPERIMENT.	LONGITUDINAL DYNAMICS: 10,000 FT 150 KNOTS / 20,000 FT 250 KNOTS ω_{sp}(RAD/SEC) 1.79 2.97 ζ_{SP} 0.66 0.63 K_A 1.00 1.59 T_A 1.00 0.65 $\frac{\Theta}{\delta_e} = \frac{K_A(Ts+1)}{T_A s\left(\frac{s^2}{\omega_{SP}^2} + \frac{2\zeta_{SP}}{\omega_{SP}} s + 1\right)}$	RECORD: i - INPUT SIGNAL e - TRACKING ERROR c - PILOT OUTPUT COMPUTE CROSS-SPECTRAL DENSITY RATIO $\Phi_{\epsilon c}/\Phi_{\epsilon\epsilon}$
SADOFF & DOLKAS REF. 8 F-104B	SUM OF 4 SINUSOIDS WITH AMPLITUDE-FREQUENCY CHARACTERISTICS AMP. FREQ. (RAD/SEC) 1 14.4 .28 2 6.3 .74 3 2.0 1.15 4 1.0 1.6	SCOPE DISPLAY AND CONTROLLER WITH UNIT GAIN DYNAMICS TO THE DISPLAY	$Y_c = \frac{K_c(Ts+1)}{\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta}{\omega_n} s + 1\right)}$ CASE A B K_c 13 13 T 1 1 ω_n (RAD/SEC) 4 6 ζ .06 .04	
THIS PAPER; CURRENT PROGRAM	SUM OF 10 SINUSOIDS: REL. AMP. FREQ. (RAD/SEC) 1 1 0.157 2 1 0.262 3 1 0.393 4 1 0.603 5 1 0.969 6 1 1.492 7 0.1 2.539 8 0.1 4.032 9 0.1 7.566 10 0.1 13.797	LEAR ALL-ATTITUDE INDICATOR	ROLL MODE: K/s; K = 50 (DEG/SEC)/INCH $\frac{K}{s\left(s-\frac{1}{T}\right)}$; K = 120 (DEG/SEC)^2/INCH T = 1 SEC	RECORD: i - INPUT SIGNAL e - TRACKING ERROR, DISPLAYED BANK ANGLE c - PILOT OUTPUT, AILERON STICK, IN. ϕ - AIRPLANE BANK ANGLE, DEG COMPUTE CROSS SPECTRAL DENSITY RATIO $\Phi_{ic}/\Phi_{i\epsilon}$
		LEAR ALL-ATTITUDE INDICATOR, AIRSPEED, ALTITUDE, RATE OF CLIMB	A-2 AND A-2* GROUND $\frac{K}{s\left(s+\frac{1}{T}\right)}$; K = 60 (DEG/SEC)^2/INCH T = 0.35 SEC A-2 AND A-2* FLIGHT $\frac{K}{s\left(s+\frac{1}{T}\right)}$; K = 45 (DEG/SEC)^2/INCH T = 0.35 SEC	

for 0-g and 1-g flight in an F-104B aircraft.[8] The details of this display and the controls were not given in Ref. 8, but the controlled element was a very lightly damped longitudinal short-period mode.

2. Random-Appearing Forcing Function

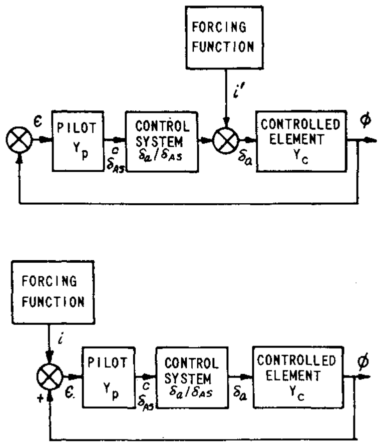
To provide a tracking task that will assure closed-loop compensatory control, which is required for the measurement schemes of interest, the pilot must be provided with a random or random-appearing forcing function. Simple periodic functions are normally quickly learned by the subject and his mode of control changes to a programmed open-loop form. Discrete tasks also become programmed maneuvers and do not permit valid computation of the dynamic response of the human operator for many control situations of interest.

Methods for mechanizing this random forcing function in previous investigations were varied. For the CAL F-94 program, the random noise generator consisted of "a light source, a turntable with crumpled tinfoil mounted on it, a lead sulfide phototube pickup, and associated circuitry. The phototube sensed the light reflected from the tinfoil mounted on the rotating turntable." Although no spectral analysis of the output of this device is given in the report, it gave a "known, repeatable and unpredictable (by the pilot) disturbance" during each evaluation run.

The noise generating device used in the NASA TV-2 used mechanical cams that were machined to provide a spectrum composed of a combination of 12 discrete sinusoids. Four disturbance programs resulted from using two sets of cams with each set run at two speeds. Repeatability was only fair because of difficulties with speed regulation of the cam drive motor. Power spectral densities of the four input signals show that the frequencies are roughly equally spaced and the amplitudes attenuated with increasing frequency.

The forcing function signal for the Princeton Navion was white noise, derived from a gas tube, filtered by a low-pass filter with a cutoff of 18 db/octave at a corner frequency of 1 rad/sec. For the NASA F-104B, the random-appearing input signal consisted of a sum of four sinusoids with amplitude attenuation as frequency increased. The device used for generation of this signal was not specified in Ref. 8.

If given a display tracking task and the means for generating a random-appearing signal, then one must decide at what point in the control loop to inject this signal. The two locations that are readily accessible to the experiment designer are shown in Fig. 2. The forcing function was injected directly into the airplane control surfaces (elevators) for the



a) Forcing function injected at the control surface

b) Forcing function injected at the display

Fig. 2 Tracking task disturbance input.

CAL F-94 and NASA TV-2 as shown in Fig. 2a. The control sticks for both aircraft were irreversible, hence they were not driven by the forcing function. The commanded task was to hold zero attitude variations, or straight and level flight, in both pitch and roll.

The second method of disturbance signal injection is to sum the noise signal and actual airframe attitude, and display this sum as an "error" signal as shown in Fig. 2b. The pilot then attempts to null the error in a compensatory tracking situation. One advantage of this method is that it permits the computation of the open-loop pilot vehicle combination Y_pY_c.

The Princeton Navion simulated an air-to-air gunnery situation wherein vertical and horizontal disturbance signals were fed into the "dot" representation for the target aircraft. The disturbance of the dot then represented the "command" for the pilot. However, a "horizon line" which represented the pilot's inside-out view of the distant horizon provided the pilot with a pursuit-like display. His instructions for tracking as given in Ref. 6 were rather vague on this point. The pilot controlled both longitudinal and lateral axes with the conventional wheel control, and refrained from using rudder control. All experiments were performed in nonturbulent air to minimize the effects of unknown gust disturbances.

3. Data Recording and Reduction

The data for the CAL F-94 experiments were recorded using onboard oscillographs, and then manually read and transferred to punched cards for digital computer processing. The computer calculated cross-power spectral densities between stick force and noise input signals and between normal acceleration and noise input signals. The ratio of these cross-power densities was then defined to be the describing function for the pilot.

During tracking runs with the Princeton Navion, the longitudinal and lateral "noise" inputs, the corresponding attitude error signals, and the elevator and aileron control positions were telemetered to the ground where time histories were tape recorded. These data tapes were then analyzed on the Franklin Institute machine. This machine, an analog device, computed the cross spectrum of the input forcing function and operator output and the cross spectrum of the input forcing function and the error signals. Again, the ratio of the cross spectra defines the pilot describing function.

The NASA TV-2 was fully instrumented with both an onboard oscillograph and a NASA 10-channel telemetry system. The telemetered data were recorded on magnetic tape. These data were analyzed with the NASA analog cross-spectrum analyzer. The power spectral density data were taken only at the frequencies at which a power peak occurred in the input spectrum of each individual sample. The ratio of the cross-power spectral density of the pilot's output and error signal to the power spectral density of the pilot's input (error) signal was defined to be the pilot's describing function. A comparison of the measured describing functions of the latter two cases shows that unless the cross spectrum is taken with respect to the input signal when there is pilot-injected noise in the system, the ratio will not be a correct estimate of the pilot's describing function.[9,10]

As discussed previously, the requirements for in-flight measurement of human response data are readily satisfied for practically all current flight test data systems. The fundamental concepts of in-flight measurements have changed little since the original effort in the 1956–1958 time period, but analysis methods and equipment have improved tremendously. An in-flight measurement task is readily implemented in a flight test program; it may be part of a normal stability and control series.

The background information which has thus far been reviewed has been applied in a recent program that used the USAF variable stability T-33. The T-33 was used as both a ground-based simulator and in actual flight to obtain data on three pilots controlling a compensatory roll task. This program‡ is discussed in the remainder of this article and the general block diagram applicable to it is shown in Fig. 3.

T-33 Experimental Equipment

1. Variable Stability System

The variable stability system is called a response-feedback system because the responses of the airplane are sensed by the angle-of-attack vane, the sideslip probe, and the gyros. These signals and their appropriate derivatives are modified by adjustable gains and summed in appropriate amplifiers according to the aerodynamic surface they are to control. The adjustable gains are the ones that must be determined and set to accomplish a given simulation.

For the lateral-directional case, these gains are determined with the aid of a digital computer program. Twelve independent model constants (such as ω_d, ζ_d, ω_ϕ, ζ_ϕ, etc.) are specified and the program will solve for the required gains with compensation of the variable stability system dynamics taken into account. For the longitudinal case, the problem is less demanding and the gains are determined directly by stability derivative matching, except for the lift term over which there is no automatic control.

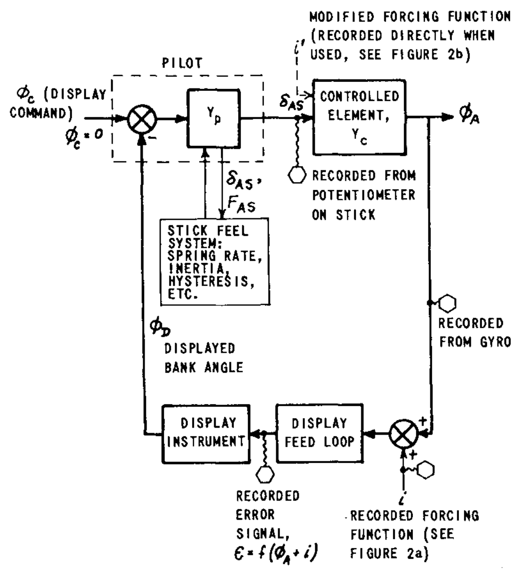


Fig. 3 Experiment general block diagram.

‡ This research was performed for AFFDL, WPAFB under Contract AF33(615)-3605 by CAL and is reported in AFFDL-TR-67-30.

For a configuration that is to be simulated both on the ground and in the air, the stability system gains are modified by compliance factors for the loaded and unloaded aerodynamic surfaces. Thus, the gains used on the ground are not exactly those used in the air.

The feel systems, which provide artificial feel for the cockpit controls, are irreversible hydraulic servo systems which use either cockpit control deflection or force as the inputs. The elevator stick feel and rudder pedal feel systems use flow control valves and the aileron stick feel system uses a pressure control valve.

Ideally, the aileron feel system operates a pure spring wherein the spring rate is chosen by setting a potentiometer. However, the hydraulic strut has considerable friction which results in an unacceptably large breakout force. To reduce the breakout force, two techniques have been used. One is to minimize the actuator friction. The other is to incorporate positive force feedback as depicted in Fig. 4 to provide a driving signal within the breakout force band to reduce the breakout force.[11] A hysteresis loop of aileron stick position is shown in Fig. 5. Here it is seen that the aileron stick gradient is 2.5 lb/in. and that if breakout force is defined as one-half the width of the hysteresis loop, then it is $\frac{3}{4}$ lb.

2. Ground-Based Simulator

Whenever the T-33 is used as a ground-based simulator, it is connected with an analog computer which simulates a set of limited six-degree-of-freedom equations of motion. These equations are valid over a limited speed and altitude range, that is, the equations represent a specific, preselected flight condition; in this case, 23,000 ft altitude and 250 knots indicated airspeed.

For ground-based simulator studies with the T-33, one must decide whether to include the dynamics of the simulated vehicle in the equations of motion which are on the analog computer, or to implement normal T-33 equations of motion on the analog, and use the variable stability equipment in the airplane to obtain the characteristics to be simulated. In the first instance, only the cockpit instruments and artificial feel systems of the T-33 are used. In the second instance, the cockpit instruments, artificial feel systems, and the response-feedback, variable stability system are used. If ground and flight comparisons are to be made, it is more effective to use the complete variable stability system of the T-33 in the ground-based simulation because then the variable stability system will be included in both the in-flight and ground-based simulations. In this program the T-33 variable stability system augmented the analog computer equations in obtaining the ground-based simulations of the A-2 and A-2* configurations. For the K/s and $K/s(s - 1/T)$ configurations the variable stability equipment in the T-33 was not used, as these configurations were simulated directly on the analog computer.

When the variable stability system is used in conjunction with the analog computer, the inputs to the system are vane angle of attack, probe angle of sideslip, and body-axis angular rates and accelerations. The vane and probe angles are true

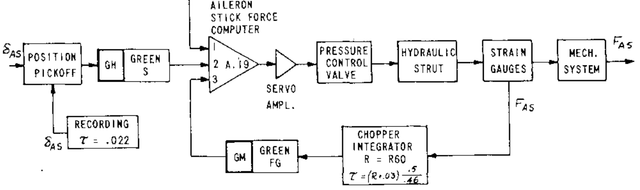


Fig. 4 Aileron stick feel system block diagram.

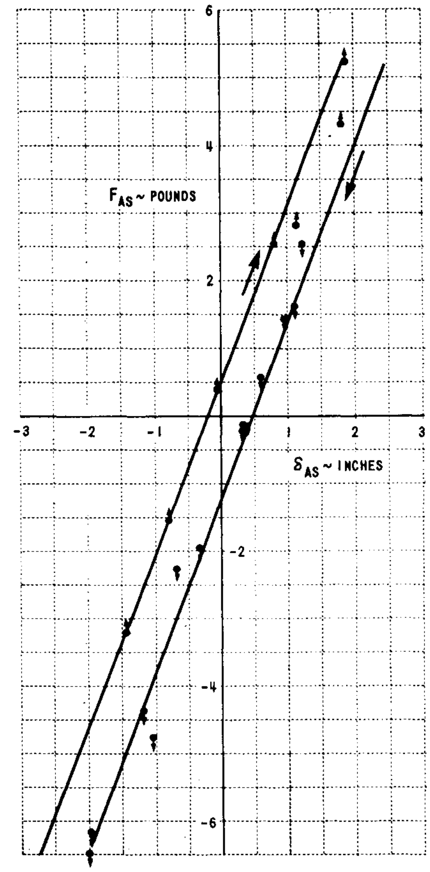


Fig. 5 Hysteresis loop of aileron stick force vs aileron stick position.

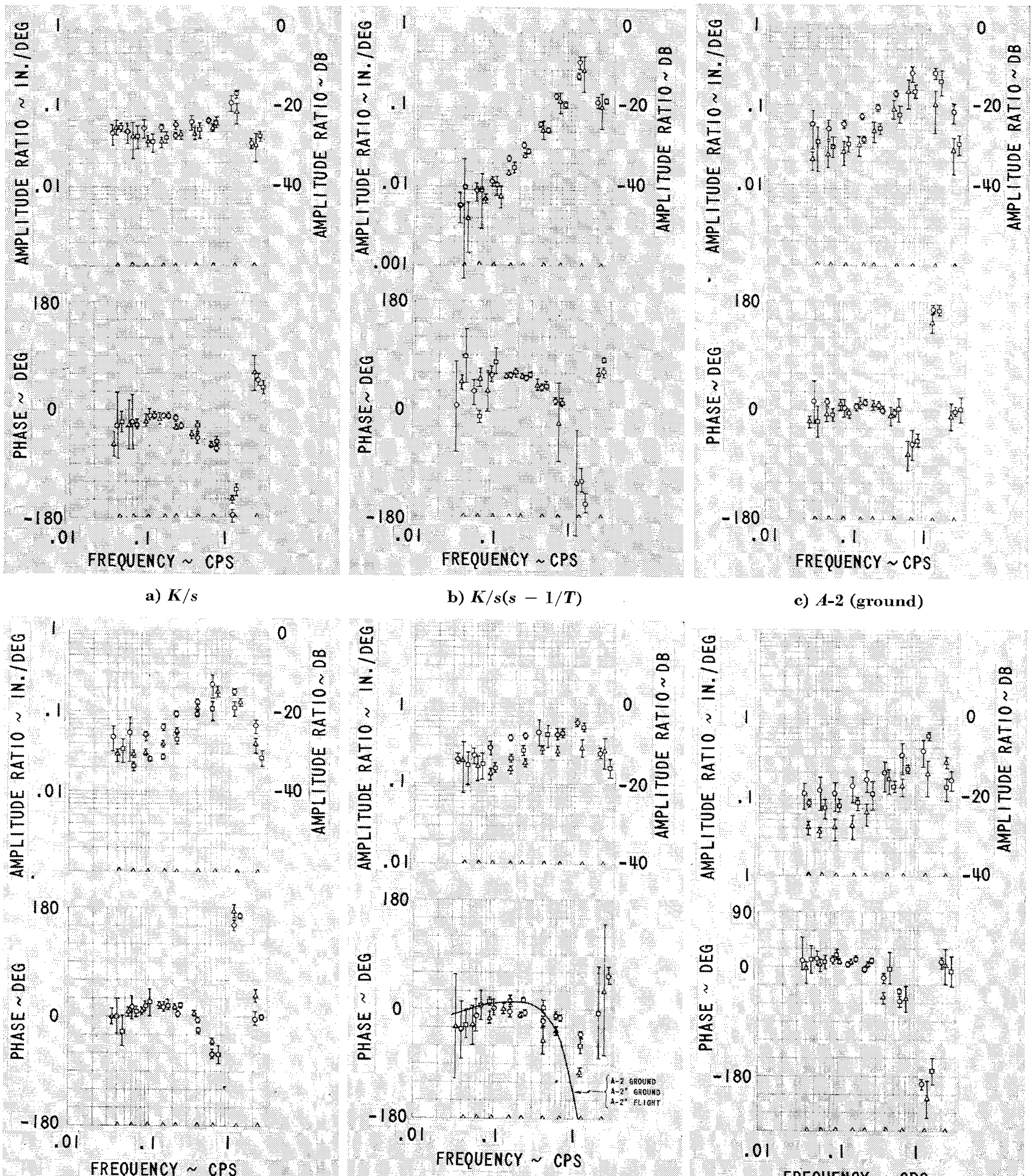
angles, computed from the equations of motion, and corrected for the characteristics of the vane and probe which are on the airplane. The inputs to the analog computer are the positions of the aerodynamic control surfaces of the T-33 and throttle position.

The instruments that were used during the experiment depended upon the configuration. For the simple controlled elements, only the roll display of the Lear all-attitude indicator was operable. The Lear indicator displayed pitch, roll, sideslip, and yaw rate.

Design of Experiment

The design of the experiment is very straightforward. The essentials are that three pilots participated in the program and three different controlled elements or dynamic conditions were flown in the ground simulator, and one of these was flown in real flight for two different methods of introducing the task. The task was always compensatory roll tracking. One of the two ways in which the tracking task was introduced was to put the error signal directly onto the roll axis of the ball attitude indicator, corresponding to Fig. 2b. The other way was to drive the ailerons, thereby causing the airplane to respond in roll, as shown in Fig. 2a. In the ground-based simulator, there is no perceptible difference between these configurations because the pilot is aware of the tracking error only through the roll motion of the attitude indicator. However, in flight there is a very definite difference; in one case the pilot *must* watch the attitude indicator to see the tracking error and the motion of the airplane proper is due only to his inputs, and in the other case he may fly "heads up" since he can see and feel the tracking error from the motion of the airplane.

The pilot task for each configuration was to maintain zero bank angle. The forcing function was one which appears



a) K/s b) $K/s(s - 1/T)$ c) A-2 (ground)

d) A-2* (ground) e) A-2 (flight) f) A-2* (flight)

Fig. 6 Pilot transfer characteristic with specified controlled element. Legend: frequency location sheared slightly for clarity: ○ Pilot A; □ Pilot B; △ Pilot C; standard deviation shown on plots; (this refers to carets on figures) frequency for which data are shown.

random to the pilot but actually it is the sum of ten sine waves. No frequency is a harmonic of any other frequency. Relatively speaking, the first six of these frequencies are at an amplitude of one, and the highest four frequencies are at an amplitude of one tenth. The maximum bank angle excursions seen by the pilot were plus and minus 8°. The input was produced by NASA-FRC on a digital computer and recorded on FM tape through a digital to analog converter.

The two simple controlled elements that were flown only on the ground simulator were operational only in the roll mode. One of these configurations was a pure integrator K/s and the other was divergent, $K/s(s - 1/T)$, with one pole at the origin and a second pole in the right-half plane, $1/T = 1$. The controlled element that was flown both on the ground and in the air had very nearly the longitudinal and lateral-directional dynamics of the normal T-33. For the

K/s and $K/s(s - 1/T)$ configurations there were no longitudinal dynamics. For the other two configurations, longitudinal dynamics were simulated on the ground to make the ground and in-flight experiments as comparable as possible. The constants for these configurations are given in Table 1.

The K/s and $K/s(s - 1/T)$ configurations each represented a roll mode and the input to the analog computer was aileron stick position. For the divergent roll mode $K/s(s - 1/T)$ the tracking task required complete attention of the pilot if he were to avoid losing control.

The actual design of the experiment is shown in Table 2, which indicates the number of times each pilot was to fly each controlled element. The A-2 designation represents the configuration wherein the roll disturbance input was introduced through the ailerons. The A-2* designation represents the same configuration but indicates that the tracking task error signal was introduced through the attitude indicator only. It is noted that, except for configuration A-2, Pilot A flew considerably more runs on each configuration than either of the other pilots. The purpose for this emphasis on one pilot is to obtain sufficient data to ascertain trends in a pilot's variability. The other pilots are included to determine the trends of interpilot and intrapilot variability.

Each data run for each pilot consisted of 4 min of tracking in roll. The data which were recorded included the tracking task signal (i), the input to the pilot (ϵ), the pilot's output in terms of aileron stick motion (c), and the actual roll motion of the airplane (ϕ). Sufficient data were obtained to compute cross spectra from which describing functions for the pilot and controlled element can be determined. These data were recorded on an FM tape recorder and additional data were recorded with a 50-channel oscillograph.

The input forcing function tape was played back through a Pemco FM tape playback unit in the T-33. For the simple controlled elements and the A-2* configurations, the forcing function signal was displayed directly on the roll attitude indicator. For the A-2 configurations, the function was applied through the ailerons and therefore the FM tape used was a recording of a modified sum of ten sine waves. The modification was to precompensate the signal for the bank angle per aileron deflection transfer function so that the tracking task which the pilots saw was the same for all configurations.

Computation and Validation

The digital computer program used to analyze the data was adapted from an autocorrelation, power spectral density program already in use at CAL for determining the correlations and spectral densities of random signals. However, the input for this series of experiments has only ten discrete frequencies in it and the ratios of the appropriate cross-spectral densities are required at only these ten frequencies. The program was established to compute the ratios only at the ten

Table 2 Experiment design

Controlled element, Y_c		Design Pilot A	Design Pilot B	Design Pilot C	Obtained Pilot A	Obtained Pilot B	Obtained Pilot C
K/s	IF[a]	...	...	...	...	...	...
	GB[b]	10	3	3	10	3	3
$\frac{K}{s}\left(s - \frac{1}{T}\right)$	IF	...	...	...	...	...	...
	GB	10	3	3	10	3	3
A-2[c]	IF	10	10	10	8	10	10
	GB	10	10	10	3	10	8
A-2*[c]	IF	10	3	3	10	3	3
	GB	10	3	3	10	3	3

[a] T-33 in flight.
[b] T-33 ground-based simulator.
[c] A-2 and A-2* are identical except for the method used to inject the disturbance input.

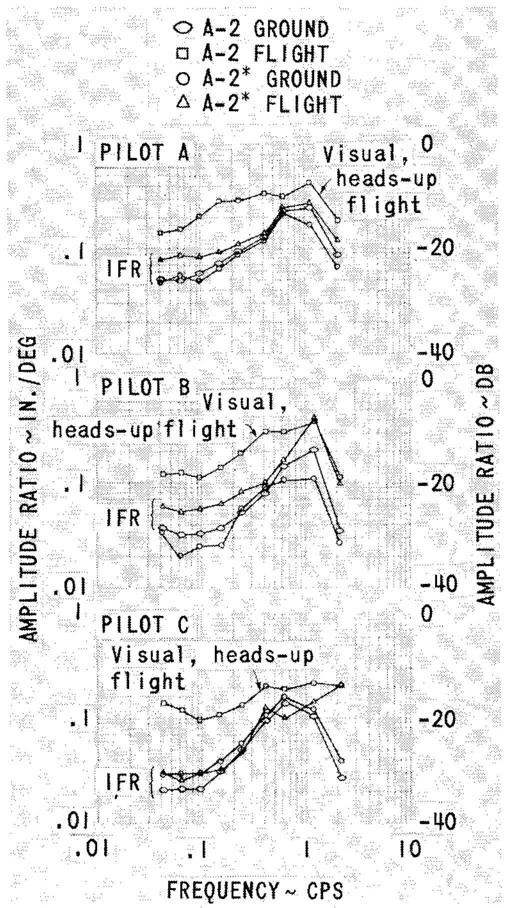


Fig. 7 Comparison of flight and ground pilot transfer characteristic $|Y_p|$ data adjusted to common K_c.

pertinent frequencies of the input signal. To be certain that the ten frequencies are matched from run to run (because there could be variation in tape playback speed or tape record speed, etc.) the spectral density of the input signal was computed for each run. Then the digital computer searched the input spectral density to determine the actual ten frequencies at which the desired ratios should be computed. This feature was found to be very necessary.

This computer program has been verified in several ways, among which was a comparison of results obtained by CAL and the Franklin Institute Laboratory data reduction for eight runs of this program. The program requires 12 min per run on an IBM 7044 or 8.5 min per run on an IBM 7090 (for a spectral window of 0.005 cps) for determining Φ_{ii}, $\Phi_{i\epsilon}$, Φ_{ic}, $\Phi_{i\phi}$, Y_p, Y_c, and Y_pY_c.

1. Verification of Controlled Element

Verification of a configuration that is being simulated is a many-faceted task that can be treated in only a general manner here. Other than having an experienced pilot check the simulator in a gross way, there are two general approaches for verifying a configuration. One is to analyze a special response by a least-squares technique to obtain stability derivatives. The special response record is one for which all modes of the airplane responses are excited for either the longitudinal or the lateral-directional case. The other verification technique is to identify modal constants from records of airplane or simulator responses to step, pulse, and doublet inputs. Determination of the modal constants is, at present, the most often used technique.

Other methods of response matching are to obtain airplane response records to specific inputs and then to compute on a digital computer what the responses should be for these same specific inputs. A one-to-one correspondence of the actual with the computed responses constitutes verification. In addition to these techniques, in this experiment the transfer function of the controlled element was computed, whenever possible, from the closed-loop data that was recorded for each tracking run. Good agreement was obtained among the verification procedures used.

Discussion of Results

The pilot transfer characteristics which were measured in the current program are presented in Figs. 6a–6f. It can be noted from these figures that Pilot A operates at a higher gain than do the other two pilots, except with the divergent configuration $K/s\ (s - 1/T)$ for which all three pilots are very nearly the same. In comparing the A-2 and A-2* ground results with the A-2 and A-2* flight results, one must recall that the gain of the controlled element differs between ground and flight and make allowance for this difference in gain. One means of doing this is to make the comparisons in terms of $|K_cK_p|$ which is legitimate because these configurations are very easy to fly and it is expected that the only adjustment the pilot makes is in his gain. The adjusted comparison is shown in Fig. 7. If the comparison is made in this way, then it is seen in a very general way that the instrument flight configurations, A-2 ground and A-2* ground and flight, all result in approximately the same individual transfer characteristic for each pilot. However, for the heads-up A-2 flight configuration, each pilot increases his gain by a multiplicative factor of between two and three for frequencies below 0.5 cps. A possible reason for such a change in gain is the more complete field of information available from the combined visual scene and harmonized motion of the airplane. For the heads-up A-2 flight configuration the pilots were aided in resolving bank angle errors by four horizontal grease paint lines on the windscreen. Except for the A-2 flight case all of the other configurations were flown by reference to the attitude indicator and for the A-2* flight case the motion of the airplane is in harmony with the pilot's inputs but not necessarily in harmony with the motion presented on the attitude indicator.

Summary and Conclusion

The measurement program described herein has presented the dynamic response characteristics of a human pilot while performing a compensatory roll tracking task both in flight and in a ground-based simulator. Subject pilots performed the tracking task in flight by observation of the natural horizon when the aircraft was disturbed by aileron inputs and by observation of the attitude director indicator when the artificial horizon was perturbed by an input forcing function signal.

Measurements of the pilot transfer characteristics show good agreement for ground and flight experiments when tracking with the attitude director indicator. These data also compare favorably with the existing pilot models which were obtained with ground-based simulations. The data for the horizon tracking situation show a different characteristic which may be attributed to the additional visual and vestibular cues available.

The fundamental concepts for in-flight measurement of human response characteristics have changed little since the original efforts in the 1956–1958 time period. However, considerable advances have been made in general analysis and modeling techniques and in the quality of equipment for data recording and analysis. The addition of human response measurement capability to existing and future flight test programs is highly recommended and can be readily implemented. The data acquisition equipment and magnetic tape recorders exist for practically all flight test data systems. The task may be part of a normal stability and control test series.

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