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MANUAL AND AUTOMATIC FLIGHT CONTROL DURING SEVERE TURBULENCE PENETRATION

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16. Abstract

An analytical and experimental investigation of possible contributing factors in jet aircraft turbulence upsets was conducted. Major contributing factors identified included autopilot and display deficiencies, the large aircraft inertia and associated long response time, and excessive pilot workload.

An integrated flight and thrust energy management director system was synthesized. The system was incorporated in a moving-base simulation and evaluated using highly experienced airline pilots. The evaluation included comparison of pilot workload and flight performance during severe turbulence penetration utilizing four control/display concepts:

- Manual control with conventional full panel display.
- Conventional autopilot (A/P-A) with conventional full panel display.
- Improved autopilot (A/P-B) with conventional full panel display plus thrust director display.
- Longitudinal flight director with conventional full panel display plus thrust director display.

Simulation results show improved performance, reduced pilot workload, and a pilot preference for the autopilot system controlling to the flight director command and manual control of thrust following the trim thrust director.

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SYMBOLS

Values are given first in U.S. Customary Units followed by SI units. The measurements and calculations were made in U.S. Customary Units.

a_T	Tangential acceleration
$a_{x_{FP}}$	Perturbation inertial acceleration along axis aligned with the aircraft flight path, positive forward
a_z	Perturbation inertial acceleration along axis perpendicular to aircraft flight path, positive downward
ADI	Attitude Director Indicator
ATC	Air Traffic Control
ATR	Air Transport Rating
C_D	Coefficient of drag
C_L	Coefficient of lift
C_{L_α}	$\partial C_L/\partial\alpha$
CAS	Calibrated airspeed
dB	Decibel
D	Total drag
EPR	Engine pressure ratio
FD_C	Flight director for control column input
FD_T	Flight director for throttle input
g	Gravitational constant
h	Perturbed altitude
HSI	Horizontal Situation Indicator
IAS	Indicated airspeed
IFR	Instrument flight rules
IVSI	Instantaneous vertical speed indicator

kg	Kilogram
kt	Knot, nautical mile per hour
K_{p_i}	Pilot gain in the feedback loop particularized by i
KIAS	Indicated airspeed in knots
m	Unit of length, meter
M	Mach
M_{DF}	Design dive limit Mach
M_{MO}	Maximum operating limit Mach
M_u	Aircraft pitching moment due to speed perturbation
n_z	Total acceleration along aircraft z axis due to gravity and aircraft perturbation
N	Unit of force, Newton
R	Radius
R/C	Rate of climb
s	Laplace operator, $s = \sigma \pm j\omega$
S	Wing area
T	Thrust
TAS	True airspeed
T_i	Time constant of the real root for the numerator particularized by i = h, u, θ, etc.
u	Perturbation inertial velocity along the flight path
u_g	Horizontal component of the air mass gust velocity
V	Total velocity or speed
V_C	Calibrated velocity or speed
V_{DF}	Design dive limit velocity or speed
V_E	Equivalent velocity or speed
V_{MO}	Maximum operating limit velocity or speed
V_2	Initial climb speed following takeoff

w_g	Vertical component of the air mass gust velocity
W	Weight
x	Sum of aerodynamic forces along x stability axis divided by the vehicle mass
x_i	$\partial x/\partial i$ where $i = u, w, \alpha,$ or δ
Y_{p_θ}	Transfer function for pilot when controlling pitch attitude
z	Sum of aerodynamic forces along z stability axis divided by vehicle mass
Z_i	$\partial Z/\partial i$ where $i = u, w, \alpha,$ or δ
α	Perturbation angle of attack
α_T	Trim angle of attack
γ	Flight path angle relative to the horizontal
γ_p	Potential flight path angle related to instantaneous inertial acceleration perturbation
δ_j	Control deflection specialized by j = c, e, T, TL
Δ	Denominator of the open-loop airframe transfer function; also used to denote perturbation in motion quantities
θ	Pitch angle relative to the horizontal
ρ	Density of air
σ	Real part of the Laplace operator
σ_i	Root mean square of motion quantity particularized by $i = \theta, \dot{h}, u, a_z$
$j\omega$	Imaginary part of the Laplace operator
ω_j	Undamped natural frequency of the second-order mode particularized by the subscript

Subscripts

c	Control column
e	Elevator
FD	Flight director
p	Phugoid
SP	Short period
T	Thrust
TL	Throttle lever

Notes

Dot over quantities (e.g., $\dot{\theta}$) indicates derivative with respect to time

Primed quantity (e.g., T'_{p_2}) denotes root of closed-loop system

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SUMMARY

The primary purposes of this analytical and experimental program were to increase understanding of the fundamental control problems involved in turbulence penetration and upsets and to develop flight director and autopilot design guidelines to minimize gust input tendencies. The turbulence upset of concern is that associated with IFR flight conditions rather than clear air turbulence (CAT).

Standard operating procedures under normal and severe turbulence conditions are reviewed. It is concluded that a major potential contributing factor in turbulence upset is inadequate attitude and thrust management references which require an iterative process by the pilot to establish trim attitude and flight path. The combination of a required change in aircraft speed and piloting technique during turbulence penetration, huge aircraft inertia and low thrust-to-weight ratios, possible conflicting motion cues, and severe environment with possible physiological and psychological degradation further complicate the situation.

A new turbulence penetration system concept is synthesized. This system consists of a flight director indicator for loose control of attitude and airspeed via elevator and a trim director indicator for manual thrust setting to achieve an airspeed and flight path selected by the pilot. The director system computes the trim attitude and thrust reference based upon the selected airspeed and flight path and the current aircraft energy state. The attitude and airspeed director also provides the basic reference signal for an improved autopilot turbulence mode. The system was incorporated in a moving-base simulation and evaluated by highly experienced airline pilots. The simulation involved a realistic duplication of a jumbo jet aircraft and a navigational task involving normal air traffic control procedures. Severe random turbulence imbedded with large discrete wind shears were input to simulate turbulence penetration. The simulation was used to compare performance and pilot workload with the improved turbulence penetration director and autopilot system against that with the conventional display and autopilot.

In general, it was found that the improved longitudinal autopilot mode together with display of computed attitude and thrust trim references provided the best performance and lowest workload and met with enthusiastic pilot support.

INTRODUCTION

Turbulence upset is generally considered as a temporary loss of control brought about by severe turbulence encounters. It can, however, range from a sudden loss of several thousand feet of altitude with some passenger and/or crew injuries to a major catastrophe including loss of life and possibly complete loss of the aircraft. The severe turbulence of concern here is that associated with IFR flight conditions rather than clear air turbulence (CAT). Over the past few years the occurrence of such turbulence-induced upsets has decreased markedly within the continental United States. This is largely due to improved weather monitoring, reporting, and communication systems, both ground-based and airborne (pilot reports), which permit avoiding areas of severe turbulence. However, upsets continue to be encountered outside the U.S. and especially over the oceans where there are few weather reporting stations and a sparsity of air traffic. In fact, the most recent incidents have occurred during transoceanic flights. A new investigation of jet transport "upsets" has therefore been undertaken because the occasional but continuing occurrence indicates the problem was not completely "solved" in past analysis and simulation.

The core of our approach is recognition that upsets are basically a poorly understood closed-loop pilot/display/aircraft procedural and control problem, sometimes aggravated to the point of loss of control by severe turbulence. Even without (or with slight) turbulence, upset-like excursions have been observed on flight recorder traces and are blamed on poor pilot/aircraft stability (Ref. 1). But, before jumping on the pilot, it should be noted that at least two recent "incidents" occurred while on autopilot (Refs. 2 and 3).

In light of these occurrences and perhaps especially pertinent to the new generation of transports entering service, it was felt that a fresh view, unencumbered by the urgency usually associated with a post-accident investigation and involving application of updated pilot/display/aircraft techniques, might provide new insight to the "problem." With this groundwork, the specific objectives of this research were to:

- Increase understanding of the fundamental control problems involved in turbulence penetration and upsets.
- Determine if "loose" attitude control (the presently recommended manual or automatic piloting procedure) always prevents upsets assuming reasonable atmospheric inputs.
- Determine the proper definition of "loose" attitude control.
- Investigate strategies and/or cues the pilot can use to establish proper "loose" attitude control and to disregard distracting "secondary" motions.
- Develop flight director and autopilot design guidelines to:
  - minimize gust upset tendencies
  - provide aircraft motions in harmony with normal pilot expectations
  - minimize unsafe aircraft excursions
  - maintain satisfactory ride qualities
- Validate the concepts in a moving-base piloted simulation.

The accomplishment of the first four objectives has been documented in Ref. 4. This included a critical review of past investigations, simulations, etc., to eliminate from consideration those specific mechanical shortcomings already overcome (e.g., for new aircraft), and to probe for possible remaining soft spots. Recurring dynamic control aspects were identified which have not been adequately explained or considered in past investigations. For example, past studies concentrated on upsets initiated in high altitude cruise flight under severe random turbulence, yet:

- The majority of upsets occur in low to moderate altitude climb or descent (Table 1).
- The actual "upset" is usually preceded by significant changes in aircraft trim energy state.

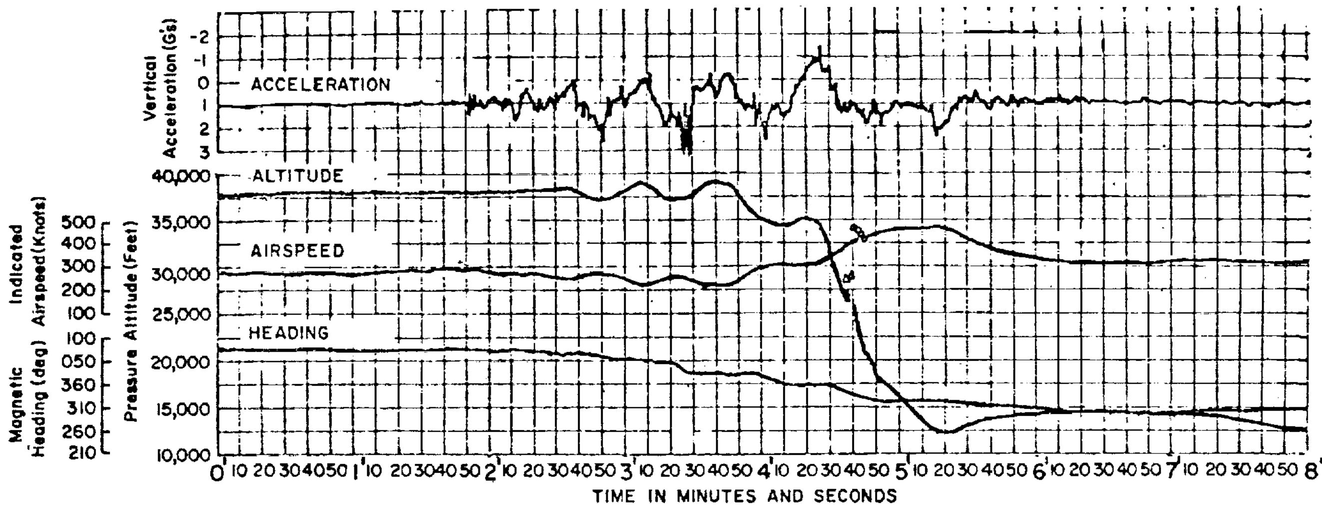
- The flight traces often reflect one or more cycles of large phugoid-type motions prior to loss of control (Fig. 1).

These recurring aspects led initially to a review of the basic stability of an aeroelastic aircraft during sudden encounter with large discrete vertical gusts, to a search for large, discrete, high shear gradient disturbances, and a review of piloting techniques including a dynamic analysis of

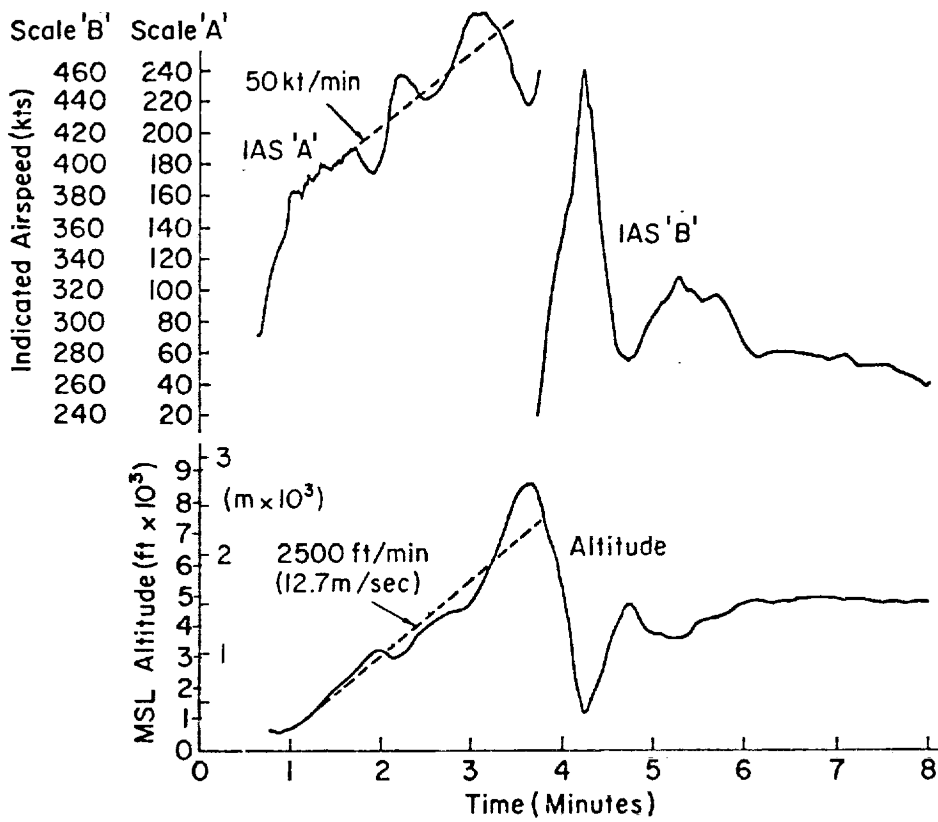
TABLE 1. TYPICAL UPSET SCENARIO
(Ref. 4)

DATE	LOCATION	AIRCRAFT	PHASE	CLEARANCE	h	V	h LOSS	TURBULENCE
1961	Lisbon	B	Climb	IFR	6,000 ft	?	6,000 ft	Light/Moderate
1963	Miami	A	Climb	IFR	17,500	270 kt	17,500	Severe
1963	O'Neill	A	Climb	IFR	37,000	250	26,000	Severe
1963	Washington, D. C.	B	Climb	IFR	4,000	280	2,700	Severe
1963	Houston	B	Climb	IFR	19,000	260	13,000	Severe
1963	Quebec	B	Climb	IFR	6,000	?	6,000	Light
1964	New Orleans	B	Climb	IFR	7,000	250	7,000	Moderate/Severe
1964	Formosa	B	Cruise	IFR	37,000	?	17,500	Heavy
1967	Caribbean	D	Cruise	IFR	30,000	?	11,000	Severe
1968	Detroit	E	Climb	IFR	4,500	270	7,500	Severe
1970	Nantucket	F	Climb	IFR	26,000	280	4,000	Moderate

the closed-loop control task when following the recommended technique of "loose" attitude control. The results presented in Ref. 4 strongly supported the suspicion that poor pilot/display/vehicle stability was a root cause. This immediately raised the specter of aircraft static stability (short period), but this was not found to be a significant factor. Rather, the problem appeared to lie with speed stability characteristics and path control difficulties, i.e., energy management. With today's jumbo jets having



a) Flight Recorder Trace from Flt. 746,
O'Neill, Nebraska, 12 July 1963
(Ref. 5)



b) Flight Recorder Trace from
Detroit, Michigan, 1968
(Ref. 6)

Figure 1. Typical Flight Traces

huge inertias, low thrust-to-weight ratios, and very low drag, the pilot must continually be operating several minutes ahead of his aircraft. He must avoid situations requiring rapid changes in speed or large attitude excursions which result in exchanging vehicle kinetic energy for potential energy and vice versa. "Loose" attitude control should prevent upsets, providing the disturbance does not induce sudden large airspeed deviations. However, large horizontal gusts such as obtained in frontal wind shear activity are a reality, and therefore large airspeed deviations can be expected and will cause the pilot to adjust either attitude or thrust (or both). No satisfactory strategy or cues were found to enable the pilot to judge proper "loose" attitude control or energy management using current displays. Quite the contrary, it appeared that current attitude and thrust references are inadequate and contribute to the control problem which can lead to upset.

A continuing search of the literature uncovered several items which provide additional support for some of the conclusions of Ref. 4. The first was an incident which occurred while the aircraft was under control of an attitude hold autopilot. Figure 2 verbally summarizes the event (described in Ref. 2). While this may or may not be considered an actual upset, it certainly is a "near miss" and demonstrates that attitude control alone is not sufficient to prevent, and could contribute to, an upset by overpowering the normal aircraft speed stability and allowing speed to decay.

Another bit of support was found in a recently published flight testing handbook (Ref. 7). The advice for accomplishing thunderstorm penetration as an adjunct to testing for effect of inclement weather and flight conditions on jet engine performance, etc., is:

> "During thunderstorm penetrations, the attitude control technique should be used primarily, but not exclusively.
>
> Tempered corrections in airspeed and altitude should be made as necessary; but not to the extent that an over-control results....
>
> Attempting to fly pure attitude control on the other hand will result in large airspeed excursions and possible 'upset.'
>
> The best technique in large subsonic aircraft is to concentrate primarily on attitude control while maintaining airspeed within predetermined limits by varying altitude, attitude and power as necessary."

Aircraft IFR/Climbing/On Autopilot/300 kt IAS

"crossing FL 270: captain started to decrease speed to 250 kt and increase R/C

at FL 280: 265 kt

- moderate to severe turbulence
- attitude reference decreased (to accelerate to 275 kt penetration speed)
- speed actually decreased; R/C showed 2500 fpm (12.7 m/sec) climb
- attitude reference decreased further
- speed continued to fall rapidly

230 kt

- stall warning/AFCS cutoff
- pilots pushed control column forward
- aircraft broke into clear air

Speed regained through altitude loss:

"Autopilot successfully countered

4-5000 fpm (20-25 m/sec) 'updrafts'
6-7000 fpm (30-35 m/sec) 'downdrafts'

but permitted 35 kt speed loss and necessitated manual takeover"

Figure 2. Summary of Severe Turbulence Penetration While on Autopilot

A discussion of additional standard operating procedures is contained as a part of the next section. For many reasons this discussion relates to the new generation of jumbo jet aircraft and, for convenience, is particularized to a specific aircraft denoted as "Aircraft F" due to our previous report (Ref. 4). This aircraft was selected as the subject vehicle for the synthesis and simulation program since it is considered typical of jumbo jet characteristics and, most important, a complete data package was available from a previous NASA simulation. The section entitled "Review of the Problem" also reviews the previously mentioned energy management problem.

A new turbulence penetration system concept is synthesized in the section entitled "Improved Turbulence Penetration System." This system consists of a flight director indicator for loose control of attitude and airspeed via elevator and a director indicator for manual thrust setting to achieve a desired flight path. The attitude and airspeed director also provides the basic reference signal for an improved autopilot turbulence mode.

The section entitled "Simulation" is devoted to a description of the simulation program run at the NASA Ames Research Center. This involved a realistic simulation of cockpit layout and Air Traffic Control procedures as well as of the aircraft and its systems.

The results of the simulation are presented in the section entitled "Results" and include statistical analysis of aircraft excursions during periods of severe random and discrete encounters, time histories of representative segments of the simulated flight, and pilot evaluations and ratings of resulting flight safety and performance.

The final section presents conclusions and recommendations for design of autopilot and flight director systems applicable to the severe turbulence environment. In general, it was found that an improved longitudinal autopilot mode together with display of computed attitude and thrust references provided the best performance and met with enthusiastic pilot support. The use of an attitude flight director, per se, was found to increase pilot workload because of the increase in number of instruments to interpret and assimilate. In addition, lack of pilot response to the director during the time periods required for him to scan, read, and interpret the panel in the severe jostle environment often resulted in buildup of large director commands. When he returned attention to the director, he would not follow these large commands.

REVIEW OF THE PROBLEM

It was indicated previously that a large percentage of upsets have occurred prior to establishing high altitude cruise conditions. In this section we shall briefly review standard operating procedures for initial and en-route climb. These will be compared with turbulence penetration standard operating procedures and "rules of thumb" which evolved from previous studies (circa 1964) and are currently practiced. Attention is focused on overall energy management aspects which were determined in Ref. 4 to be the major problems.

One of the major end items of this research program is a validation of improved turbulence flight mode display and autopilot concepts in a moving-base piloted simulation at the NASA Ames Research Center. For a realistic simulation of conditions surrounding, and possibly influencing, turbulence upset, it was necessary to include a continuous variation of aerodynamic coefficients over a significant portion of the flight envelope, incorporate nonlinear aerodynamics effects, engine-thrust dynamics, etc. As a result of a recent large-scale simulation program the necessary data, programs, etc., for Aircraft F were on file at NASA ARC. Therefore, this aircraft, one of the new generation of jumbo jets, was selected as the subject vehicle for all further systems analysis, synthesis and simulation.

Standard Operating Procedures — En-Route Climb

The flight envelope and nominal climb profile for Aircraft F is shown in Fig. 3. The envelope is bounded at high speed by the maximum operating limit (V_{MO}, M_{MO}) and design dive limit (V_{DF}, M_{DF}). The low-speed boundary is the stall speed which varies with aircraft weight, flap settings, etc. The 200 kt equivalent velocity boundary shown is conservative for stall but does represent the severe buffet region. The nominal climb profile is identified by the dotted line. Climb is generally divided into several segments. The first two involve flight in the immediate vicinity of the airport, i.e.,

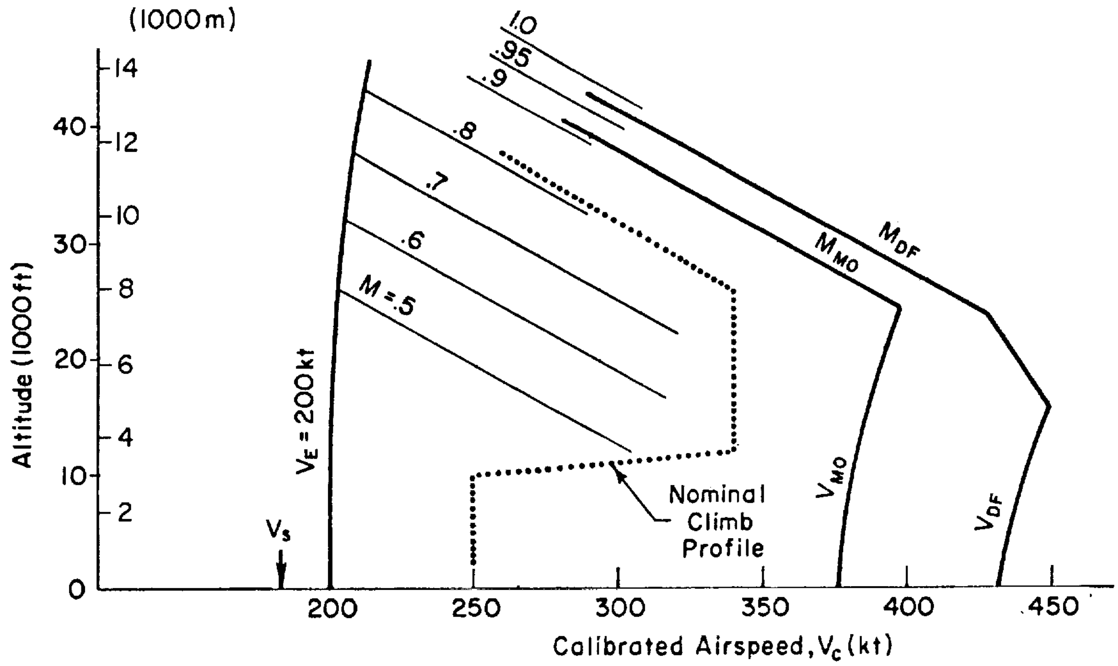


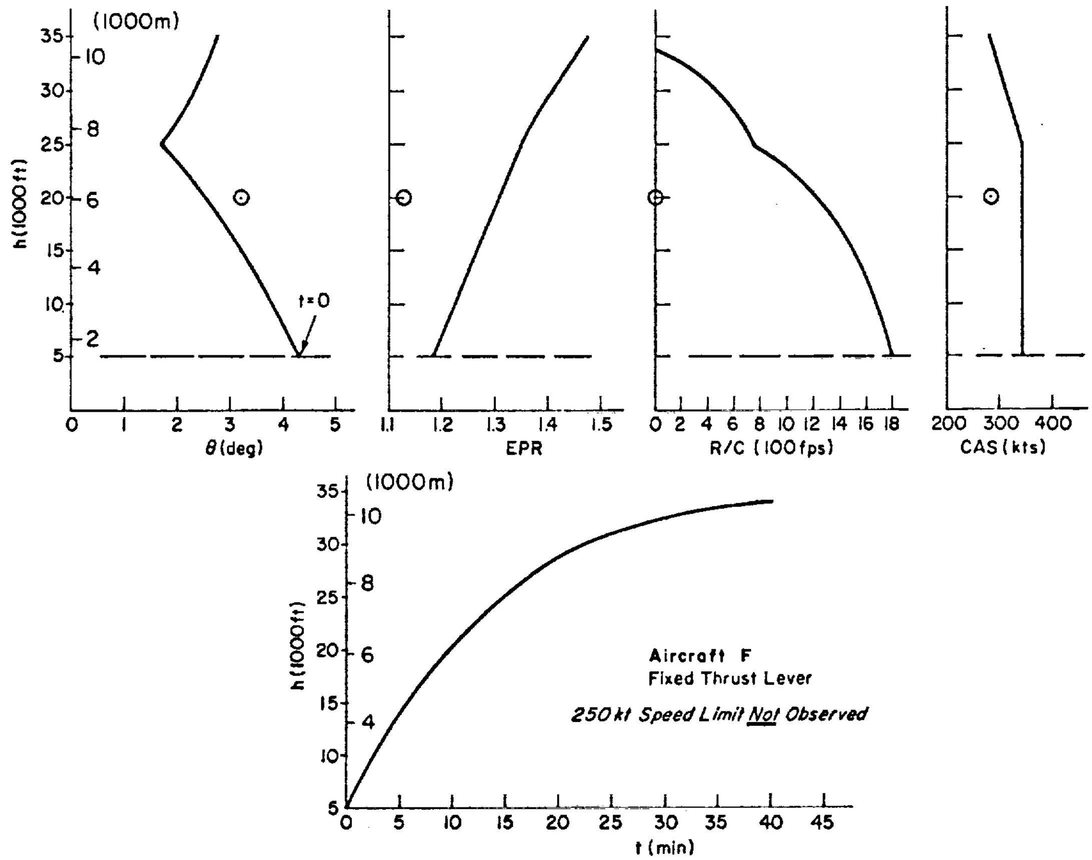
Figure 3. Aircraft F Flight Envelope and
Nominal Climb Profile

noise abatement and initial climb departure. Following these, the aircraft is under an FAA-imposed speed limit of 250 kt to 10,000 ft (3048 m). Above 10,000 ft (3048 m) the path and speed may be selected based upon tradeoff of operational cost and other pertinent considerations.

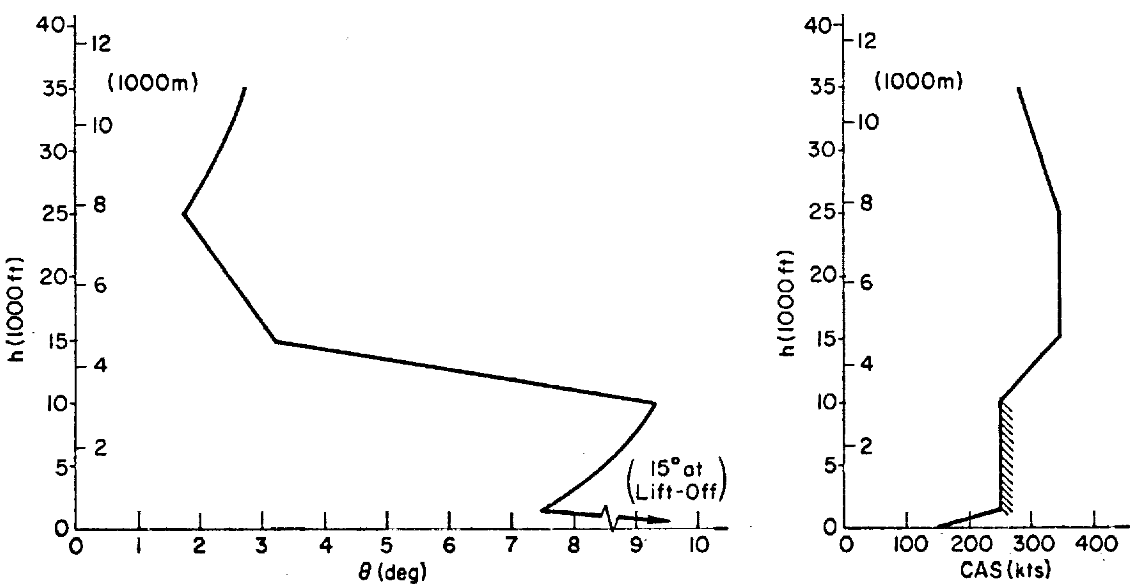
Throughout climb the basic flight reference is constant indicated (or calibrated) airspeed or Mach. The segments are flown at constant thrust setting. In changing from one segment to another, large thrust changes may be required to achieve target speeds and flight path. Since these aircraft operate near minimum drag where there is no well-defined thrust setting for desired rate of climb and speed, a rule-of-thumb EPR setting is used for each segment and the attitude adjusted to achieve the desired airspeed.

Unfortunately, engine EPR is not a precise reference for thrust since a given setting will provide different thrust at different speeds, altitudes, engine states, etc. Large variations in aircraft weight also affect the thrust required which further mitigates against reliance on "canned" EPR settings. Thus, following the preselected EPR setting, performance instruments (IAS, IVSI, and h) are observed for indications of the desired change. If these do not occur, further EPR adjustment is required and the process is repeated until the desired stable flight path is achieved. A waiting period is inherent between EPR (and attitude) adjustments to allow the aircraft to stabilize. To compound matters further, time lags between throttle movement, EPR change, and thrust change are generally quite large.

In the process of establishing the desired climb/thrust/airspeed relationship, pitch attitude, also adjusted iteratively, is the primary means of controlling the desired flight path (rate of climb or descent). Once the trim thrust and flight vector are set, any further speed deviation is controlled with small attitude correction. Like EPR, "canned" attitude references are not possible because trim attitude varies with altitude, atmospheric conditions, and aircraft weight. The changes in attitude are shown in Fig. 4a for Aircraft F during a nominal climb (340 KIAS), but without observing the 250 kt speed limit below 10,000 ft (3048 m) altitude. It is readily apparent that attitude, thrust (EPR), and flight path (R/C) indications all vary significantly throughout the climb. Furthermore, the change in trim attitude reverses at 25,000 ft (7620 m) altitude where constant Mach becomes the reference. The circled points at 20,000 ft (6096 m) identify trim attitude and thrust for level flight at the recommended turbulence penetration speed of 280 KIAS. Thus, if the pilot were to elect to level off and reduce speed for penetration, a significant (approximately 15%) change in thrust level must be made but the attitude is increased only about 0.7 deg. This attitude change may border on the readability of the attitude indicator in buffet or heavy turbulence. [If the pilot were to elect to hold θ constant (at the climb attitude) and only reduce thrust to achieve the 280 KIAS penetration speed, the rate of climb would change from +914 fpm (4.5 m/sec) ($\gamma = +1.06^{\circ}$) to −695 fpm (3.5 m/sec) ($\gamma = -0.94^{\circ}$).]



a) Nominal Climb Speed Limit Not Observed



b) Effect of Speed Limit on Trim Attitude

Figure 4. Variation of Trim Display Values During Climb

When the low altitude speed limit is taken into account, the change in trim attitude with speed and altitude is much greater, as shown in Fig. 4b. Pressure ratio and climb rate have not been calculated for this case, and the acceleration from 250 KIAS to 340 KIAS has been arbitrarily assumed to consume 5000 ft (1524 m) of altitude. The major point of these figures is to indicate the severe fluctuations in trim attitude during nominal climbs and the difficulty a pilot might encounter in estimating the required trim attitude for continued climb or level-off with a change in speed for penetration. Similar difficulty would ensue with thrust lever estimation.

The normal climb procedures and problems may thus be summarized as:

- Basic flight reference is airspeed:
  - 250 kt IAS speed limit up to 10,000 ft (3048 m).
  - climb, descend at constant IAS (or Mach at high altitude)
  - flight segments are flown at constant thrust (whenever possible)
- Large thrust changes may be required between climb and level-off with iterative adjustments of attitude and thrust until desired airspeed and zero rate of climb are established.
- Constant IAS, changes in gross weight, etc., then result in continuously changing pitch attitude for equilibrium climb.
- IAS deviation is used as attitude change reference — watch rate of speed change.
- There is no adequate engine parameter for thrust lever reference.

Turbulence Penetration Standard Operating Procedures

When flight through severe turbulence cannot be avoided and sufficient warning permits, it is generally recommended that level flight be established at an altitude and airspeed which provide adequate weight-dependent margin for the avoidance of high-speed buffet, stall, excessive load factors, etc. Unfortunately, outside the continential U. S. there is a high probability that the severe turbulence encounter will come as a surprise. If already in a stabilized climb condition, the pilot may or may not choose to level off. Due to the urgency of the situation he might be expected to utilize the rule-of-thumb penetration speed shown in Table 2. As indicated previously, this SOP was developed as a result of the rash of upsets prior to 1964 and is still applied to the new jumbo jets.

Whether or not the proper penetration trim conditions are established prior to the encounter, the "loose" attitude control technique of Table 2 is recommended while within severe turbulence. The basic premise of this technique is to do nothing except smoothly apply elevator and aileron control to restrict attitude deviations from the pre-encounter trim attitude. This technique increases the path (phugoid) damping and does not aggravate the control task by disturbing the basic aircraft trim. It thus maximizes the probability of successful penetration providing the disturbances are not so severe as to cause "extreme" airspeed variation.

Unfortunately, there are several shortcomings with this operating procedure. First, the pilot is supposed to instantly relegate the primary reference (IAS) of many thousand flight hours to a secondary role and to control to a "reference" attitude. If, due to a surprise turbulence encounter, the attitude is severely disturbed and the pilot's short-term memory is degraded, the "reference" attitude recalled may be considerably in error and result in speed buildup or bleedoff. If in a climb (intended or otherwise) the "reference" attitude selected may improve with time or may become more in error. For best results, the pilot should utilize an adjustable attitude reference to avoid such problems. However, training manuals warn against this practice and recommend the pilot "memorize" various "safe" reference attitudes.

Second, if thrust is varied (either to correct for an initial off-penetration airspeed or to counter "extreme" airspeed variations during the encounter), the trim airspeed/attitude/flight path is additionally disturbed, the previous attitude reference is no longer valid, and there is no way to establish the new trim relationship except by trial and error. If the engines are podded under the wing, any alteration of thrust will introduce an additional pitch mistrim.

TABLE 2

COMPARATIVE STANDARD OPERATING PROCEDURES

	NOMINAL CLIMB	PENETRATION
AIRSPEED	Basic flight reference Depart airport at V_2 250 kt speed limit below 10,000 ft 340 kt to 0.82 M above 10,000 ft	Ideal penetration varies with gross weight and altitude Rule of thumb: 280 kt IAS; $h < 33,000$ ft (All weights) 0.8 M $h > 33,000$ ft Do not chase airspeed
ATTITUDE	Continuously changing with IAS, Mach, W, h, etc. Adjust attitude to minimize rate of change of speed	Attitude is primary reference Maintain wings level and desired pitch attitude Do not use sudden large control inputs
ALTITUDE	Meet assigned altitude/airways schedule	Allow to vary — do not chase Sacrifice altitude to maintain attitude and speed
THRUST	Large thrust changes may be required between climb segments Iterative adjustments may be required to achieve specific climb schedule since there is no precise engine parameter for thrust lever reference	Continuous ignition on Make initial thrust setting for target speed Change thrust only in case of extreme airspeed variation

Thus, lack of adequate references for either attitude or thrust management is a basic problem. If the pilot is once forced to alter thrust and/or attitude to correct for unsafe airspeed excursions, then airspeed must continue to be relied upon to reestablish equilibrium flight. It then becomes a matter of definition as to whether the pilot is "chasing airspeed."

Finally, it was concluded in Ref. 4 that headwind or tailwind shear may be the strong contributor to past upsets. This is based on a conflict between the two primary cues (attitude and airspeed) in the presence of such disturbances and because wind shear is fully reflected as indicated airspeed deviations which may then induce the pilot to "chase" airspeed via attitude or throttle or both. A sudden and large increase in headwind would also contribute to the "pitch-up in updraft" reported in several of the actual upsets. This reasoning has been recently corroborated by a report (Ref. 8) that the upset shown in Fig. 1b was triggered by flight through a strong weather front shear which rapidly shifted a 40 kt tailwind to a 40 kt headwind. However, the pilots described the disturbance as a "sudden strong updraft with uncontrollable pitch to 18 deg nose-up."

Aircraft Control and Performance Related Factors

It has been pointed out thus far that the upset problem may center about the low-frequency vehicle characteristics. This includes the static attitude control problem, speed-to-attitude sensitivity, flight path stability, and thrust/weight ratio. These parameters are further identified by examining typical longitudinal control characteristics.

Three handling quality parameters are of particular interest. One is the time constant for airspeed change due to attitude change (T_{θ_1}). Another is the magnitude of airspeed change for step attitude change ($-gT_{\theta_1}$). The third is the flight path change due to attitude change (T_{θ_1}/T_{h_1}). Values of these parameters at the two flight conditions are shown below. Note that a velocity change of 25 to 30 kt is obtained per degree of pitch attitude change and is achieved in about 1.3 to 1.5 minutes. Thus, imprecise control of attitude due to any cause (selection of improper attitude reference, inadequate resolution of display, pilot inattention, etc.) will result in appreciable wander in airspeed.

h	ft (m)	10,000 (3048)	26,000 (7925)
V	kt	250	280
T_{θ_1}	sec	77	91
gT_{θ_1}	kt/deg	25.2	30.2
T_{θ_1}/T_{h_1}	—	−0.51	0.0764

For a positive increase in attitude, positive values of T_{θ_1}/T_{h_1} indicate the flight path angle will increase (frontside operation) while negative values indicate the flight path will decrease, i.e., the aircraft will actually descend (backside operation). The latter requires adjustment of thrust to stabilize the flight path divergence. Note here that the aircraft is on the backside at the 10,000 ft case selected and is very nearly so for the 26,000 ft case. This proximity led to a check of the frontside-backside boundary for two aircraft weights representative of initial climb. The results are plotted in Fig. 5 for level, 1 g flight. This shows that the more heavily loaded aircraft are indeed on the backside during the initial climb phases and, more important, can be on the backside when at the recommended turbulence penetration speed at altitudes above 20,000 ft (6096 m).

The three circled points in the region between the two front-backside curves of Fig. 5 represent conditions at which "upset-like" incidents have recently occurred with Aircraft F. The conditions surrounding each are summarized in Table 3. The aircraft was in a slight climb in Cases I and II and was at, or near, recommended penetration speed in Cases II and III just prior to the sudden flight path perturbations. In Incident I the pilot had reduced thrust and was in the process of slowing the aircraft to the recommended penetration speed when the sudden loss of altitude occurred. It should also be noted that the autopilot was "on" and in "turbulence" mode during this incident.

TABLE 3

RECENT UPSET "INCIDENTS" INVOLVING AIRCRAFT F

INCIDENT	DATE	PHASE	WEATHER	h	V	Δh	TURBULENCE	NOTES
I	Nov. 1970	Climb 300 fpm (1.52 m/sec)	IFR	26,000 (7925 m)	340 kt → 280 kt	− 4000 (1219 m)	Moderate	Initially on turbulence mode (AFCS) Pilot reduced power to achieve penetration speed (Ref. 3)
II	Feb. 1971	Climb 50 fpm (.254 m/sec)	IFR	33,200 (10,119 m)	270 kt	+ 750 (229 m) − 1350 (−411.5 m)	Severe	At penetration V Initiated turn at 1.25 deg/sec (.0436 rad/sec) Lost 10 kt in speed (5.15 m/sec) Started losing altitude Divergent h (oscillatory) (Ref. 9)
III	June 1971	?	IFR	30,000 (9144 m)	280 kt	− 2000 (609.6 m)	?	At penetration V Developed divergent phugoid — steep dive (Ref. 10)

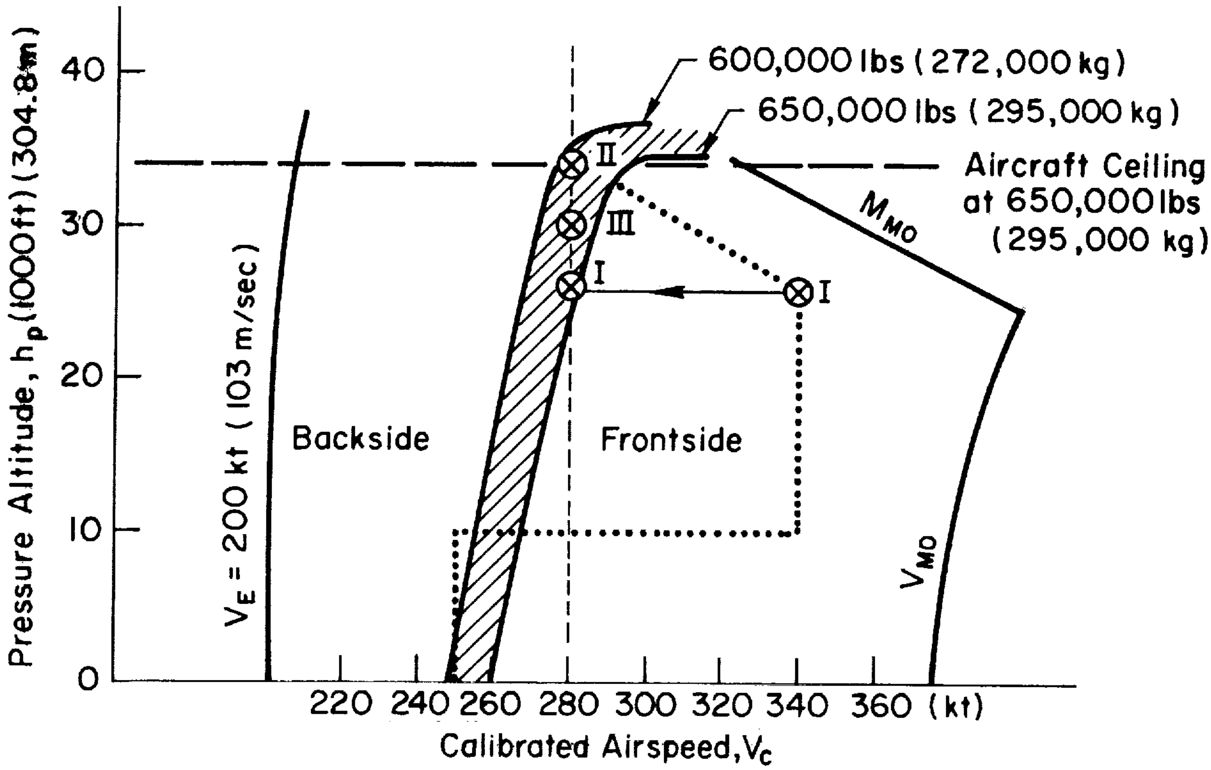


Figure 5. Approximate Frontside-Backside Boundaries; Level, 1 g Flight; Thrust Effects Included

It may be purely coincidental that all three incidents lie between the two front-backside boundaries calculated here since the actual aircraft weight is not known for Cases II or III. It is known that the Case I aircraft was at a gross weight of approximately 600,000 lb (272,000 kg). In any event, it is quite apparent that the rule-of-thumb penetration speed may not be very appropriate for the higher gross weight aircraft during climb or early cruise.

The effect of significant disturbances or maneuvers when near backside at such altitudes is shown in Fig. 6. Trim points for the nominal 340 KIAS climb and 280 KIAS level flight at 26,000 ft (7925 m) and 600,000 lb (272,000 kg) gross weight are indicated. A +0.25 g incremental load factor or a −30 kt wind shear, when at the 280 KIAS penetration condition, places the aircraft on the backside. Such changes are readily encountered in

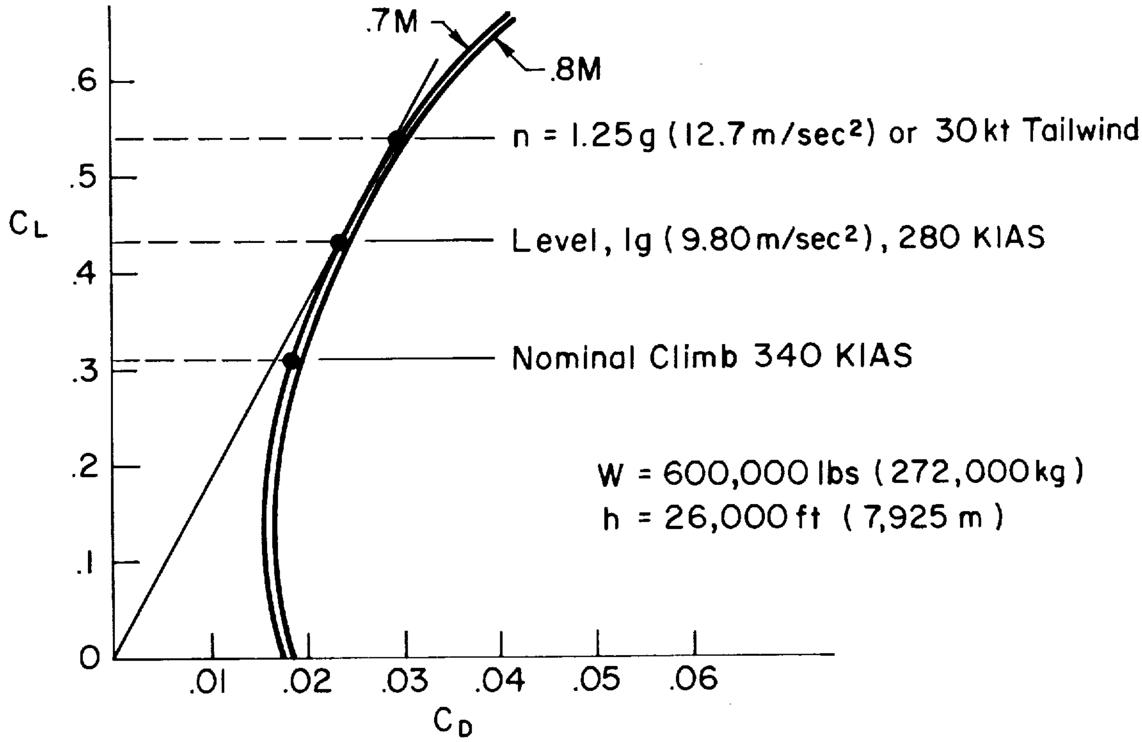


Figure 6. Trim C_L vs. C_D, Aircraft F

severe turbulence and may lend further significance to the location of the three "incidents" in Fig. 5.

One final aspect of concern is the Aircraft F airspeed response to throttle. At 0.7 M and 26,000 ft (7925 m) an early model aircraft has a full thrust capability of about 50,400 lb (224,190 N). Of this, 31,500 lb (140,119 N) is required to maintain level flight, so a positive increment of only 19,000 lb (84,516 N) is available to accelerate or combat disturbance effects. If the aircraft gross weight is 650,000 lb (295,000 kg), the maximum acceleration capability is 0.029 g or 0.56 kt/sec^2 and requires full forward throttle motion (roughly 38% of the lever movement available). Thus, massive changes in thrust must be applied for appreciable time periods to change airspeed via thrust only. On the other hand, it requires only a 1.7 deg flight path change to produce a gravity acceleration equivalent to application of 19,000 lb thrust.

Current Autopilot Turbulence Modes

The recent generation of jet transports (737, 747, DC-10, L-1011, etc.) make extensive use of automatic flight control systems for climb and cruise flight phases. Longitudinally, in addition to pitch attitude hold, these systems provide flight path control (IAS, M, h capture and hold) via the elevator and automatic stabilizer trim. Laterally, roll attitude and heading hold are provided. When turbulence is encountered, a turbulence control mode can be selected which automatically disengages all path control and autotrim modes and reverts the control to attitude hold at reduced attitude feedback gains. Longitudinally, the reference attitude will be that which existed at the time of turbulence mode engagement. This reference can then be altered manually by means of an adjustment knob or a control column command mode. A simple schematic of the lateral and longitudinal turbulence autopilot modes for Aircraft F is shown in Appendix A. The attitude-loop gain is usually reduced about a factor of two from the nominal gain. Throttles are manually set.

This attitude hold turbulence mode relieves the pilot of the actual aircraft stabilization task and under most situations will perform a superior attitude stabilization job because turbulence does not degrade its memory or attitude sensing capability. The pilot can, therefore, concentrate on monitoring autopilot operation, monitoring and interpreting the various instruments, etc. However, in the event of large discrete horizontal disturbances, the autopilot will dutifully minimize attitude deviations and hence actually <u>delay</u> recovery from unsafe airspeed deviation. An example is the previously cited event described in Fig. 2. Thus, at best, this partially automatic, partially manual turbulence control operation relieves the pilot of actual elevator control manipulation to regulate against attitude excursions, but it retains the problem of the pilot maintaining compatible attitude and thrust references for the desired penetration speed and flight path. At worst, the pilot may disengage the autopilot and take over manually when large speed deviations are encountered. It, therefore, appears that an improved turbulence mode is needed which will not suffer these shortcomings and in which the necessity for pilot takeover is minimized.

Summary

Piloting of jet aircraft is a demanding task even under normal conditions. The huge inertias, low thrust-to-weight ratios, and operation at near minimum drag require the pilot to be continually operating 2 to 3 minutes ahead of his aircraft. He must also avoid situations requiring rapid changes in speed or large attitude excursions which result in exchanging vehicle kinetic energy for potential energy and vice versa. Since the use of available power is relatively ineffective in changing airspeed (due to low thrust/weight) and it is undesirable to use large attitude excursions to change speed, the pilot has little regulation capability against horizontal gusts and shears.

The task is complicated by inadequate attitude and thrust management references and as such requires an iterative process to obtain trim attitude. Once trim is established, airspeed becomes the primary reference, and deviations from the desired speed determine needed change in the trim pitch attitude. For constant airspeed climb the pitch attitude steadily decreases with increasing altitude. When turbulence is encountered, the recommended practice is to fly "loose" attitude and to not "chase" airspeed. However, in case of extreme airspeed variation, thrust changes are permissible and may be required. The combination of changing the priority of motion quantities (airspeed versus attitude), poor attitude and thrust references, possible conflicting motion cues, and severe environment with possible physiological and psychological degradation appears to render the recommended turbulence penetration piloting technique marginal. The major problem is a lack of adequate attitude and thrust references from which to obtain timely, precise flight condition changes. This situation could be changed with the aid of improved energy management displays and autopilot modes.

IMPROVED TURBULENCE PENETRATION SYSTEM

This section presents an improved longitudinal display and control system for turbulence penetration. The basic guidelines established early in the study are shown in Fig. 7. The key to accomplishment of these goals is to provide attitude and thrust required references for any selected flight condition. This approach also facilitates attitude, speed, and flight path control, i.e., energy management.

In this section a functional description of such an energy management system is presented. The longitudinal axis is of prime interest. It is comprised of a control column (elevator) and thrust flight director display and a compatible autopilot axis operating through the elevator surface. The lateral display and autopilot axis are conventional elements and are not discussed. The basic mechanizational approach for the longitudinal display and autopilot was developed early in the program (Ref. 4). Detailed system synthesis has been reported in Ref. 11.

Overall System Concept

A simplified flow diagram for the computational functions is presented in Fig. 8. Operational procedure is consistent with both normal and turbulence penetration procedures. The pilot selects the desired airspeed and flight path (rate of climb/descent) and then follows his director displays to achieve and maintain the selected flight condition or to verify proper operation of the autopilot.

As indicated previously, one of the key elements is derivation of the pitch trim attitude reference for the current or selected aircraft state. This is obtained by summing trim angle of attack and the desired flight path angle ($\theta_{Ref} = \alpha_T + \gamma_{SEL}$). Trim angle of attack is continuously computed based on the relationship

$$\alpha_T = \frac{W}{(1/2)\rho\, V_{SEL}^2 S\, C_{L_\alpha}}$$

- Minimize control upset tendencies in the presence of severe random turbulence and large imbedded wind shear

- Provide harmonious display and aircraft motion, e.g.,
  - director commands consistent with normal and turbulence penetration standard operating procedures
  - director display consistent with other status information

- Provide elevator and thrust responses that result in aircraft motions with respect to the relative air mass and inertial space that
  - minimize unsafe aircraft state vector excursions
  - maintain satisfactory ride qualities

- Provide compatible flight director and autopilot operation through utilization of the same basic references and feedback loop structures to
  - ease pilot monitoring function
  - enhance pilot confidence (and acceptance) of its proper functioning

- Permit utilization during all phases of constant speed flight (climb, descent, level) to
  - provide change in trim speed and/or path at anytime
  - provide smooth transition with minimum delay in stabilizing at near trim

Figure 7. Basic System Guidelines

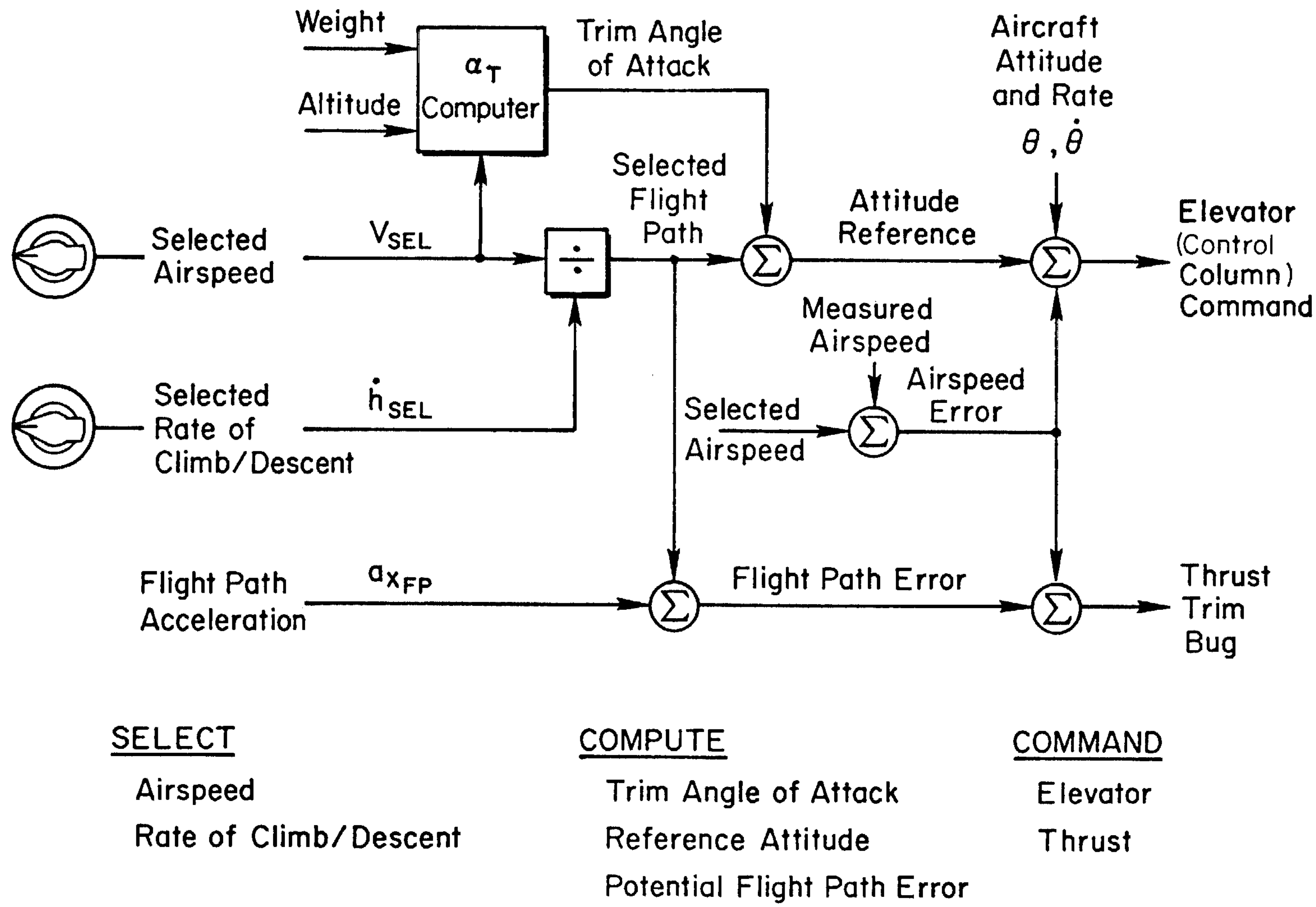


Figure 8. Longitudinal Autopilot-Director System

where velocity (airspeed) is selected by the pilot, aircraft weight may be obtained as a function of fuel flow, and aircraft lift curve slope information may be stored in the computer as a function of configuration. The desired flight path is obtained from the pilot selected rate-of-climb/descent and airspeed, i.e., $\gamma_{SEL} \doteq \dot{h}_{SEL}/V_{SEL}$. Since rate of climb/descent has more direct bearing on the piloting function than does flight path angle, the former is directly selected by the pilot. The pilot also directly selects a desired indicated airspeed which is then converted in the computer to the true airspeed select shown in the above equations.

Again in keeping with standard operating procedures, attitude control or regulation in the presence of gust disturbances is the primary function of the elevator axis. However, the attitude error feedback is tempered by a low gain feedback of airspeed error. The latter provides automatic correction for large airspeed deviations (e.g., due to wind shear) without resulting in "airspeed chasing." The airspeed feedback is lagged to reduce the high frequency gust content and to avoid ballooning when a different airspeed is selected. Additional logic is included in the airspeed error feedback (discussed later) to give greater weight for recovery from low airspeed deviation then to high airspeed reduction. This requires a tradeoff between airspeed recovery (stall avoidance) and altitude excursion; however, maintenance of assigned altitude has the lower priority in severe turbulence standard operating procedure.

The purpose of the thrust director is to aid the pilot in setting trim thrust for any selected rate of climb/descent and airspeed. If preparation for turbulence penetration is initiated during climb, it may be desirable to level off as well as change airspeed. On the other hand, after entering the turbulence it may be desirable to change altitude to escape from prolonged exposure. In the event of large discrete gust encounter, the thrust director also calls for thrust changes to overcome airspeed excursions and hence works in consort with the control column director.

It was pointed out in Section II that thrust is relatively ineffective in changing airspeed. This means that the director cannot be used by the pilot in a closed-loop compensatory-control fashion. Rather, he can only make discrete adjustments to the power and wait for things to develop. This method of operation is probably more desirable from the standpoint of pilot workload and passenger anxiety.

Several thrust director concepts were studied at NASA Langley (Ref. 12) for energy management under conditions of no turbulence. One of these, the potential flight path director, was further developed in the preceding effort (Ref. 4) for application in severe turbulence and wind shear environments. This director is based on the approximate equation for equilibrium flight path:

$$\frac{T - D}{W} = \frac{\dot{u}}{g} + \sin\gamma = \frac{a_{XFP}}{g}$$

The motion quantities $\dot{u}$ and γ are obtainable from sensors in the inertial navigation systems now used in many jet transports. The quantity a_{XFP} is the inertial acceleration of the aircraft along the instantaneous flight path (γ) as influenced by changes in thrust, drag, or external disturbances and is called the potential flight path (γ_p). Potential being referred to the condition when $\dot{u} = 0$. It is a measure of the energy excess or deficiency relative to maintaining level unaccelerated flight. It, therefore, is a direct measure of thrust required. If positive, the potential is to climb; if negative, the potential is to descend.

Unfortunately, this measure is inertial and will cause reverse sensing. For example, wind shear associated with turbulence. A sudden tailwind could cause positive inertial acceleration $D << T$, hence γ_p positive, but reduce the relative airspeed to the point of aircraft stall. Thus, airspeed error is also included in the thrust director to maintain the correct throttle sense, depending upon whether γ_p changes are caused by external disturbances or throttle changes. This also provides a direct throttle command for the pilot when he makes a change in the selected airspeed.

A key factor in the concept is simultaneous use of the attitude control (via flight director or equivalent autopilot mode) to maintain constant airspeed (or, at high altitude, constant Mach). Thus, any change in current kinetic energy (i.e., ΔT) will be transformed into potential energy (flight path change) at the same airspeed. To prevent the two directors from commanding opposing responses to any reference airspeed changes, airspeed feedback must be supplied to both directors.

The functioning of the complete system (θ_{ref} and T_{ref}) is such that when both displays are centered or nulled the aircraft will be at or on the way to the selected rate of climb and the selected airspeed.

The combined use of airmass and inertial sensed data also provides the capability of smoothing the airmass data in an unstable (turbulent) airmass environment. With proper equalization in each feedback (again see Ref. 4), the combination can be complementary filtered to better reject the higher frequency random turbulence signal content and enhance the low frequency relative motion between aircraft and airmass.

It should be noted that the constant airspeed, potential flight path mechanization employed here is most accurate for flight path changes involving leveling off from climb or descent or for initiating relatively short duration climbs or descents. As discussed in Ref. 4, for constant indicated airspeed and constant flight path climb, an aircraft has a finite inertial acceleration (since true speed is increasing). Unless a Mach and temperature correction term is incorporated to modify the acceleration feedback in Fig. 8, the flight path angle will actually decrease as the climb progresses. However, the error due to omission of the term is not large, i.e., for a constant 300 IAS climb from sea level to 15,000 ft (4572 m), the terminal flight path error is 15%. The error increases slightly at higher altitudes and decreases at lower airspeeds but, in general, is not significant since it is not necessary to maintain a prescribed climb or descent flight path angle during en route operations. Thus, this simplified director system should be of value during all phases of flight.

The command outputs of Fig. 8 are suitable for totally manual flight control via a director display or the elevator command can be utilized as the input to the autopilot servo. In the latter case the attitude director display then becomes the pilot's means of montioring autopilot performance. It will be noted later that there are minor differences in feedback gains and equalization between the flight director and autopilot modes because of certain "pilot centered" requirements (Ref. 13).

Autopilot Mode

A more detailed block diagram of the improved turbulence penetration autopilot is shown in Fig. 9. The gains and time constants were established via the system synthesis and preliminary simulation of Ref. 11. That simulation indicated the desirability of the nonlinear gain and logic shown in the airspeed feedback. Greater weight (higher feedback gain) is employed when the airspeed is less than V_{SEL}. However, to prevent excessive altitude excursion in the process of correcting for airspeed deviation, airspeed feedback gain is also reduced by a rate-of-climb/descent logic $f(\dot{h})$ whenever $\dot{h}$ exceeds ±3000 fpm and a limiter is employed to prevent command of more than 5 deg attitude change due to airspeed error. A 4 sec lag is employed for smoothing of the random turbulence. This time constant was found to provide adequate smoothing in a cruise airspeed control and display for a KC-135 (Ref. 14).

The V_{SEL} input or command also must be rate limited or smoothed to prevent a large attitude (and altitude) deviation from being introduced whenever the reference speed is changed. This is especially noticeable when it is desired to change speed at a constant altitude. A 20 sec lag was found to be satisfactory in the simulation.

Director Displays

Attitude Director

The attitude director (Fig. 10) has essentially the same mechanization as the autopilot, except the effective system dynamics are tailored to meet specific pilot-centered requirements for manual control (Ref. 13), i.e., the feedback gain ratios are selected to provide controlled element dynamics which are K/s-like in the desired crossover frequency region. To assure "loose attitude" control no matter how tightly the pilot actually attempts to close the director loop, column position is also fed back to the director. This feedback must be both lagged to avoid high-frequency

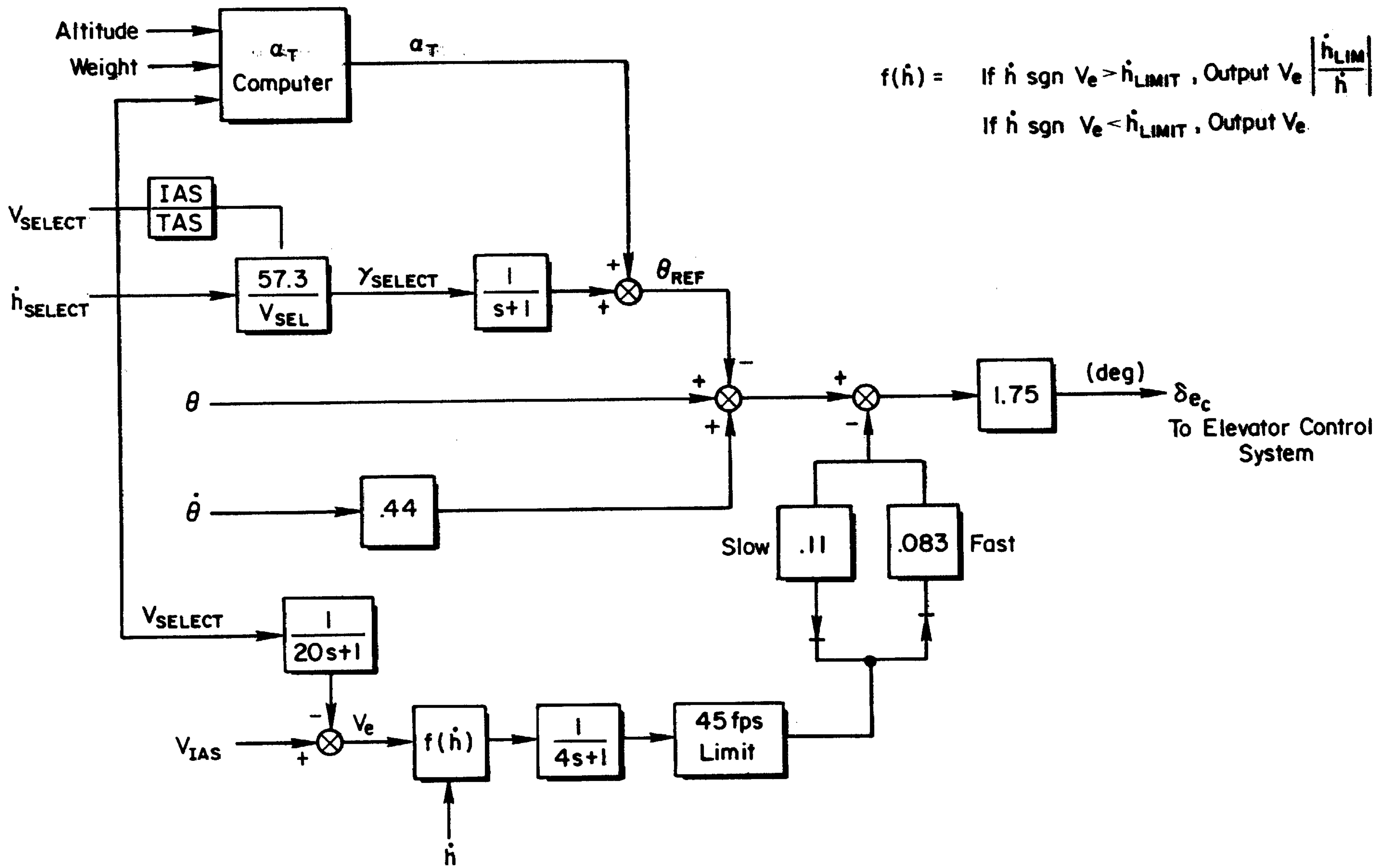


Figure 9. Block Diagram of Improved Pitch Autopilot

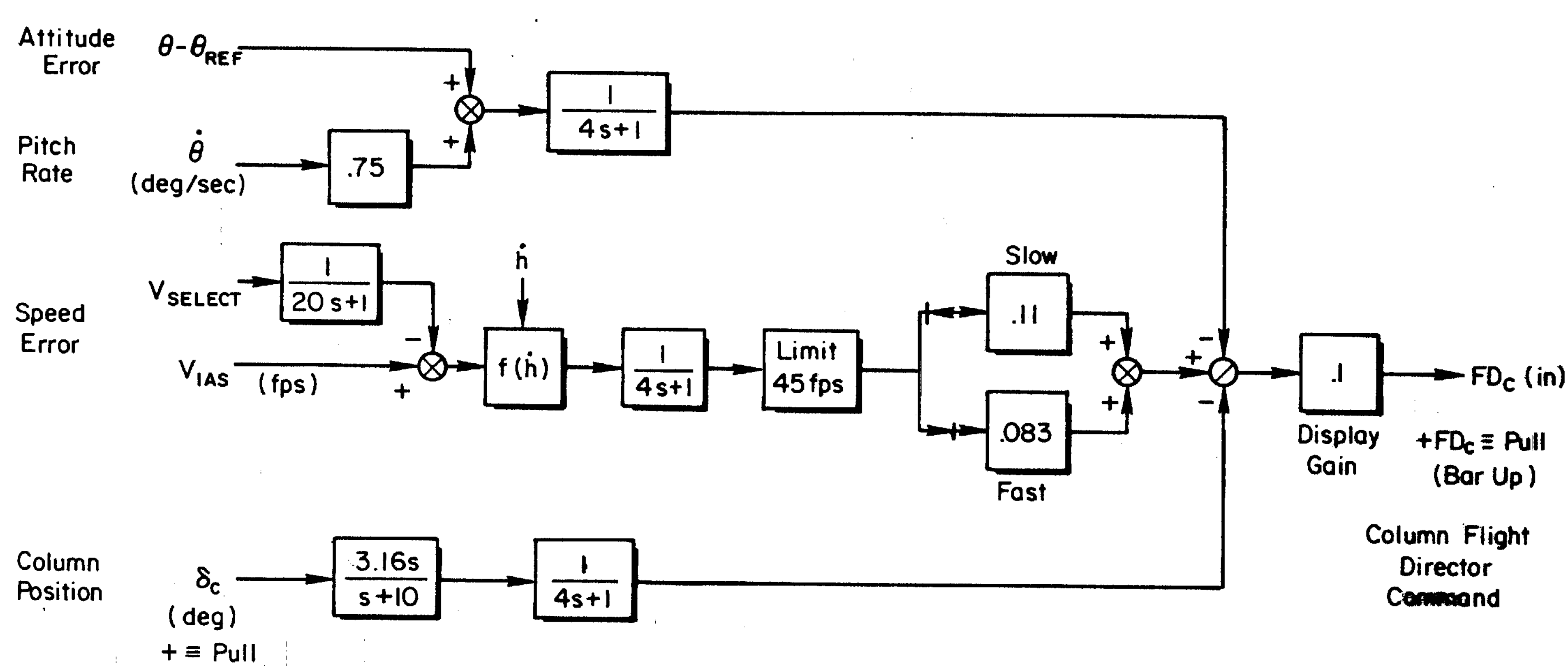


Figure 10. Block Diagram of Column Flight Director

command bar motions due to pilot remnant and washed out to avoid standoffs when column trim position is changed.

The resulting command to the pilot is presented via the pitch flight director bar on the ADI in the conventional sense, i.e., bar up, pull back. With the bar in the null position the vehicle follows the prescribed guidance law. When in the autopilot mode, a null or near null flight director display indicates correct autopilot functioning.

Thrust Director

The thrust director block diagram is shown in Fig. 11. Since thrust can be utilized to change speed independently of aircraft attitude or rate-of-climb, it is neither necessary nor desirable to include the speed error feedback gain change logic, signal limiting, etc., as required for the attitude director. The 20 sec lag on V_{SEL} is also unnecessary. It is necessary, however, to heavily damp the response feedbacks (V_{IAS} and a_{xFP}) to attenuate undesirable high frequency random turbulence influence on the director display.

Combined Display

One possible mechanization of the combined attitude and thrust display is shown in Fig. 12. The attitude (column) director bar is the same as for the conventional ADI. The thrust director is presented as a "trim bug" displacement on the right side of the ADI. Positive (up) displacement indicates potential to climb (excess airspeed or power) and requires thrust reduction to recenter the trim bug. The longitudinal situation depicted in Fig. 12 is an aircraft nose up disturbance from a trim descent with no airspeed error. Thus, the display calls for the pilot to "push" the nose down via the control column and not alter the thrust setting.

Similar director "commands" for step gust from eight directions are shown in Fig. 13. This figure is adapted from Soderlind's Ref. 15 discussion of display discrepancies induced by such gusts. However, in Ref. 15 only the aircraft initial short period response was considered rather than the accompanying (and resulting) flight path response. The

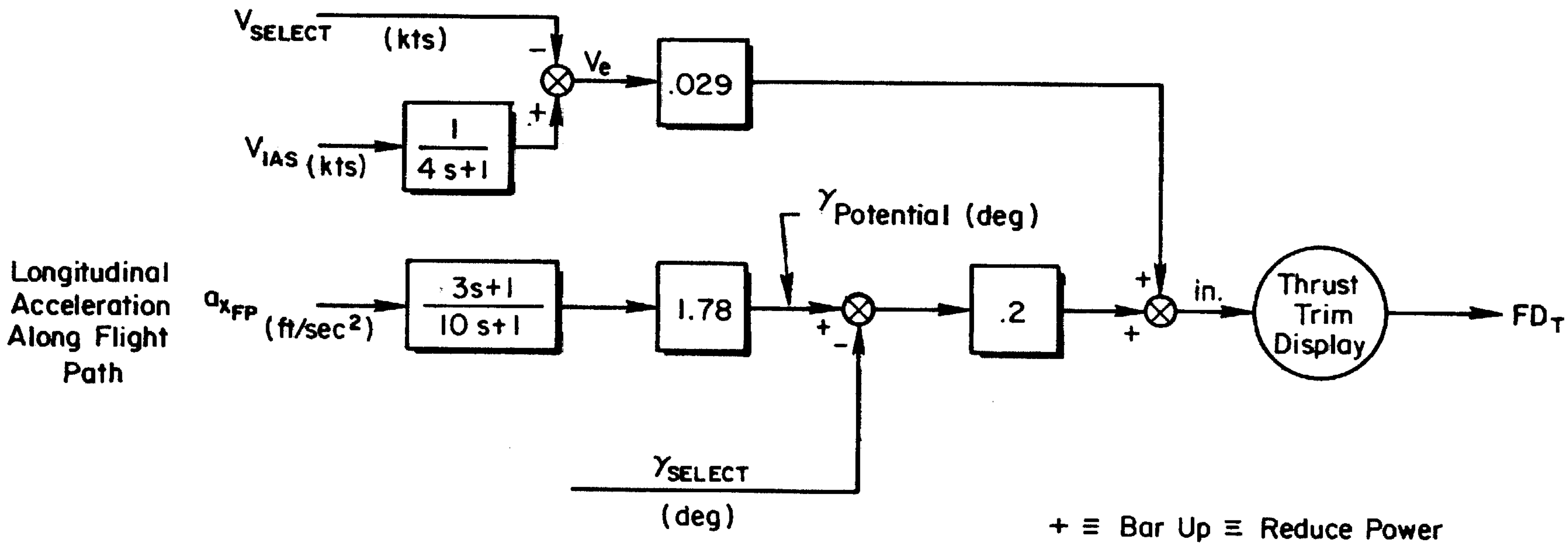


Figure 11. Block Diagram of Thrust Director

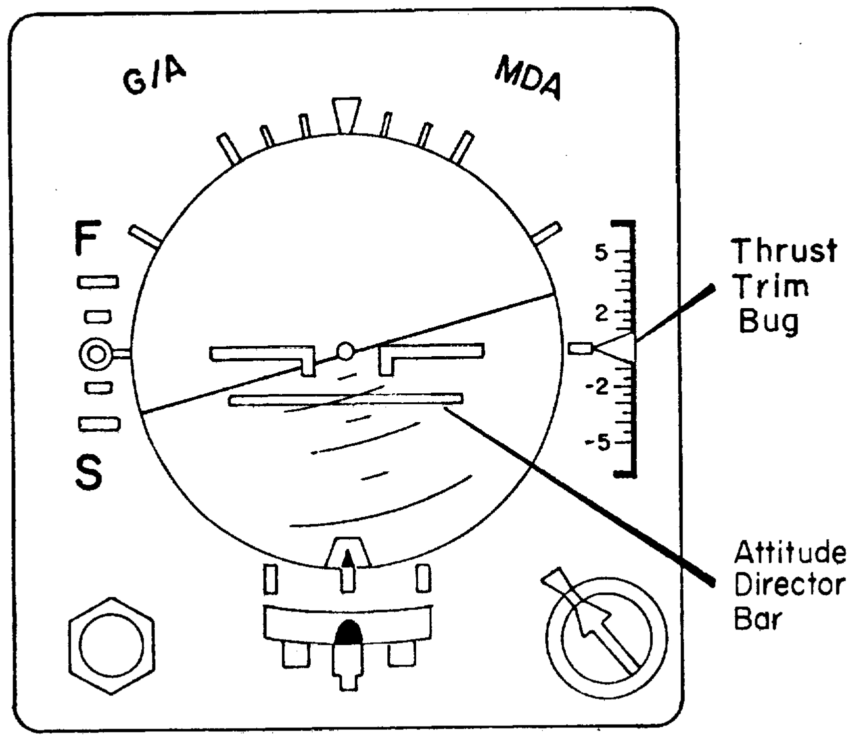
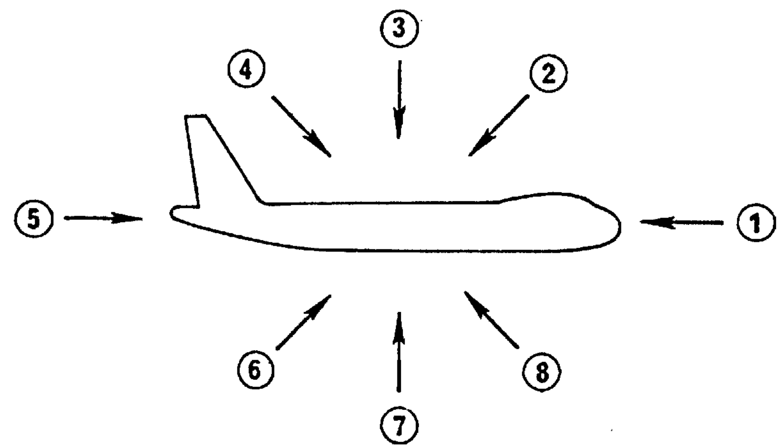


Figure 12. Attitude and Thrust Director Display



COMMAND RESPONSE

DRAFT DIRECTION	AIRPLANE'S RESPONSE	ATTITUDE INDICATOR	ALTIMETER INDICATOR	VERTICAL SPEED INDICATOR	AIRSPEED INDICATOR	LOAD FACTOR CHANGE	ATTITUDE DIRECTOR	THRUST DIRECTOR
1	Pitches Up Starts climb	Push	Push	Push	[Pull]	Push	Pull/Push	Reduce
2	Pitches Up Delayed climb	Push	—	Push	[Pull]	—	Push	Reduce
3	Pitches Up Descends	Push	[Pull]	[Pull]	—	[Pull]	Push	Add
4	Pitches Up Descends	Push	[Pull]	[Pull]	Push	[Pull]	Push	Add
5	Pitches Down Starts descent	Pull	Pull	Pull	[Push]	Pull	Push/Pull	Add
6	Pitches Down Delayed descent	Pull	—	Pull	[Push]	—	Pull	Add
7	Pitches Down Climbs	Pull	[Push]	[Push]	—	[Push]	Pull	Reduce
8	Pitches Down Climbs	Pull	[Push]	[Push]	Pull	[Push]	Pull	Reduce

Figure 13. Input "Commanded" By Cockpit Indicators

aircraft response indicated in Fig. 13 reflects that which would be observed* for some 5 seconds, e.g., the time it might take the pilot to scan all instruments in a severe turbulence environment and decide what action to take. As in Ref. 15, the boxed commands would result in inappropriate control inputs.

Several conclusions can be drawn from Fig. 13. Firstly, the attitude indicator only indicates the proper corrective input for the short period pitch disturbance. The airspeed indicator, which reflects one aspect of the aircraft energy state, is almost always in disagreement with the attitude indicator and with the vertical speed indicator (which reflects the second aspect of aircraft energy state). The addition of the two director instruments resolves the apparent conflicts. Whenever the IVSI and IAS disagree, the thrust director commands the proper actions. Whenever the attitude indicator† and IAS disagree, the attitude indicator and director are in agreement and the attitude director commands proper action. Whenever the attitude and IAS agree, both the attitude and thrust directors reinforce the command response for the quickest, safest recovery. Thus, the director system may be seen to meet a portion of the requirements set forth in Fig. 7, i.e., to

- Provide harmonious display and aircraft motion
- Minimize unsafe aircraft state vector excursions
- Ease pilot monitoring of autopilot operation

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*Appendix A, Figs. A-1 to A-8.

†Note that an indication of aircraft attitude relative to the ADI horizon line is also available at all times and hence the ADI simultaneously presents attitude and attitude command information.

SIMULATION

An evaluation of the improved turbulence autopilot and flight director concepts was conducted at the NASA Ames Research Center. The purpose of the simulation was to assess pilot-aircraft system performance utilizing conventional and the improved control-display systems in a realistic, albeit severe, operational situation. In addition to a detailed dynamic representation of the aircraft, engine, and control system, emphasis was placed on duplicating the physical representation of the cockpit layout and normal air traffic control (ATC) route procedures.

The simulation was conducted on the S-16 moving base transport simulator. This is a three-degree-of-freedom (pitch, roll, heave) motion base cab complete with a full complement of transport aircraft instrumentation, controls, and engine noise simulation. No visual attachment was used since the task is concerned with up-and-away flight under IFR conditions. Aircraft F dynamic characteristics and cockpit layout were simulated as closely as possible.

This section presents an overview of the complete simulation, including the simulator itself, the ATC scenarios, and the pilot subjects. Additional details of the simulation are provided in the various appendices and in Refs. 16 and 17.

Aircraft Dynamics

The simulation included the standard six degree-of-freedom nonlinear aerodynamic characteristics, nonlinear engine and thrust characteristics, control system dynamics, etc. It had previously been employed for checkout of the Flight Simulator for Advanced Aircraft (FSAA) and, therefore, had been validated against actual flight performance throughout the aircraft envelope. The simulation was thus capable of duplicating total aircraft operations and performance from takeoff through climb, cruise, descent, landing, and landing roll-out. However, some modifications and simplifications were made to the XDS Sigma 8 version to fit this large simulation on the core-restricted EAI-8400 computer used with the S-16 cab. These changes included removal of the landing gear model, flap- and gear-down aerodynamics, and engine reverse thrust model.

Instrument Panel

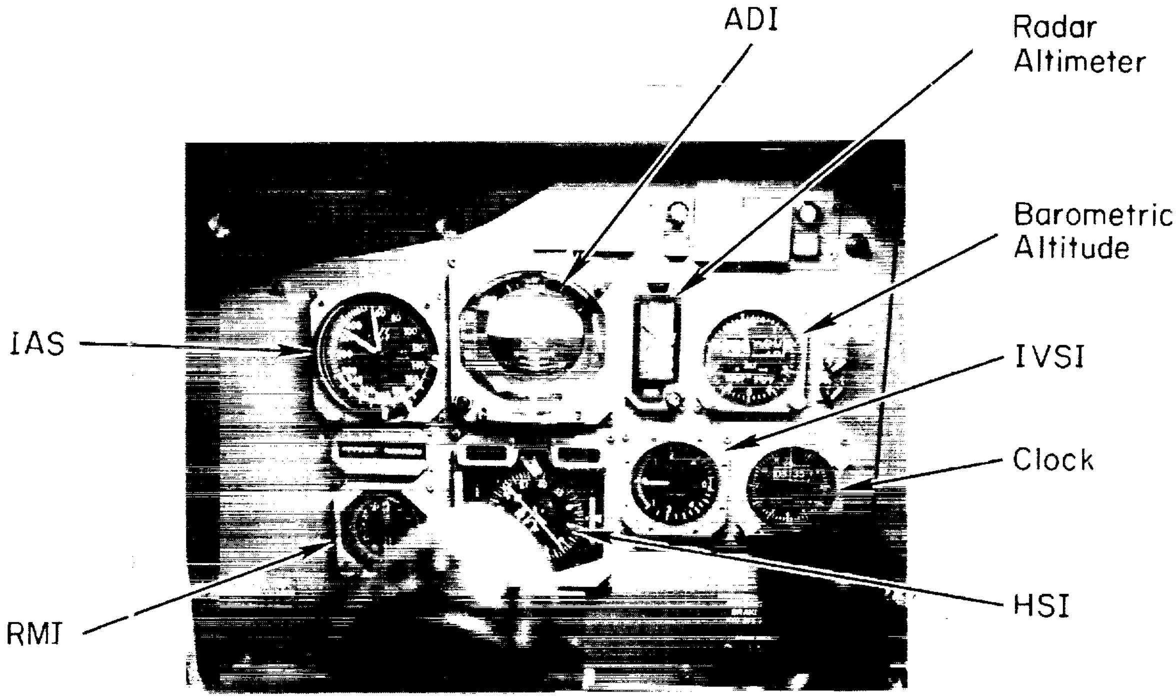
The test subject occupied the left seat. The right seat was occupied by a test engineer who performed many of the duties of a first officer.

The left seat panel of the S-16 cab was similar to the current Aircraft F cockpit. For example, an American Airlines configuration is shown in Fig. 14 and a photograph of the simulator front panel is shown in Fig. 15. The center console including the autopilot/flight director control panel is shown in Fig. 16. For reference, the instruments are identified in Fig. 17. The autopilot/flight-director select panel allowed selection by the experimenter of the conventional Aircraft F autopilot (A/P-A), the experimental autopilot (A/P-B), or the turbulence flight director system. As indicated previously, the conventional autopilot (A/P-A) turbulence mode is a "loose" attitude-hold system with all gains set at half their normal values and attitude reference set manually by an attitude control knob. Block diagrams for this system are presented in Appendix B. The longitudinal axis of Autopilot B is as defined in Fig. 9. The lateral axis of Autopilot B is the same as for Autopilot A.

The turbulence flight director display utilized a Sperry HZ-6B Attitude Director Indicator (ADI) with the column and thrust error indicators as shown in Figs. 12 and 17. The rate of climb and airspeed select panel is also shown in Figs. 15 and 17. These displays and their controls were located in available panel spaces with no attempt at optimizing pilot scan.

Disturbance Inputs

Two types of disturbances were used to simulate a severe atmospheric turbulence encounter. These were a random gust component and a discrete gust component that could be introduced independently or in combination. Random turbulence with zero mean was simulated by passing digital white



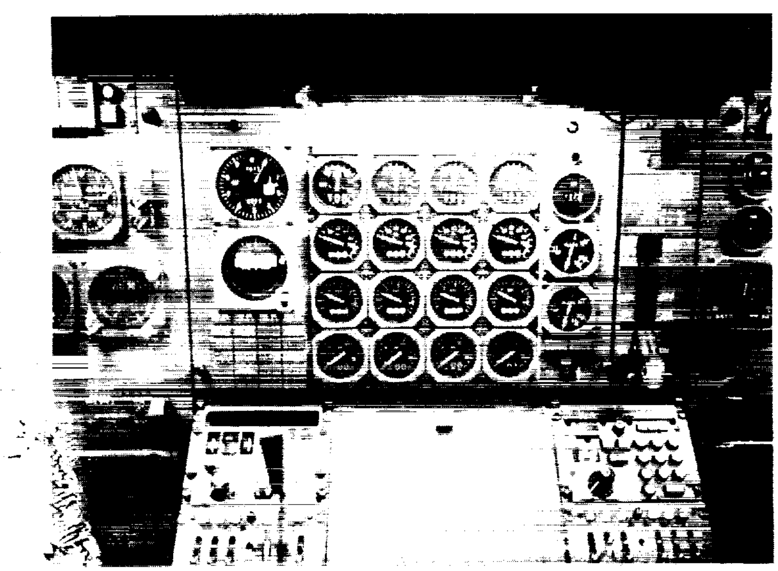


Figure 14. Instrumentation Layout of Aircraft F, American Airlines

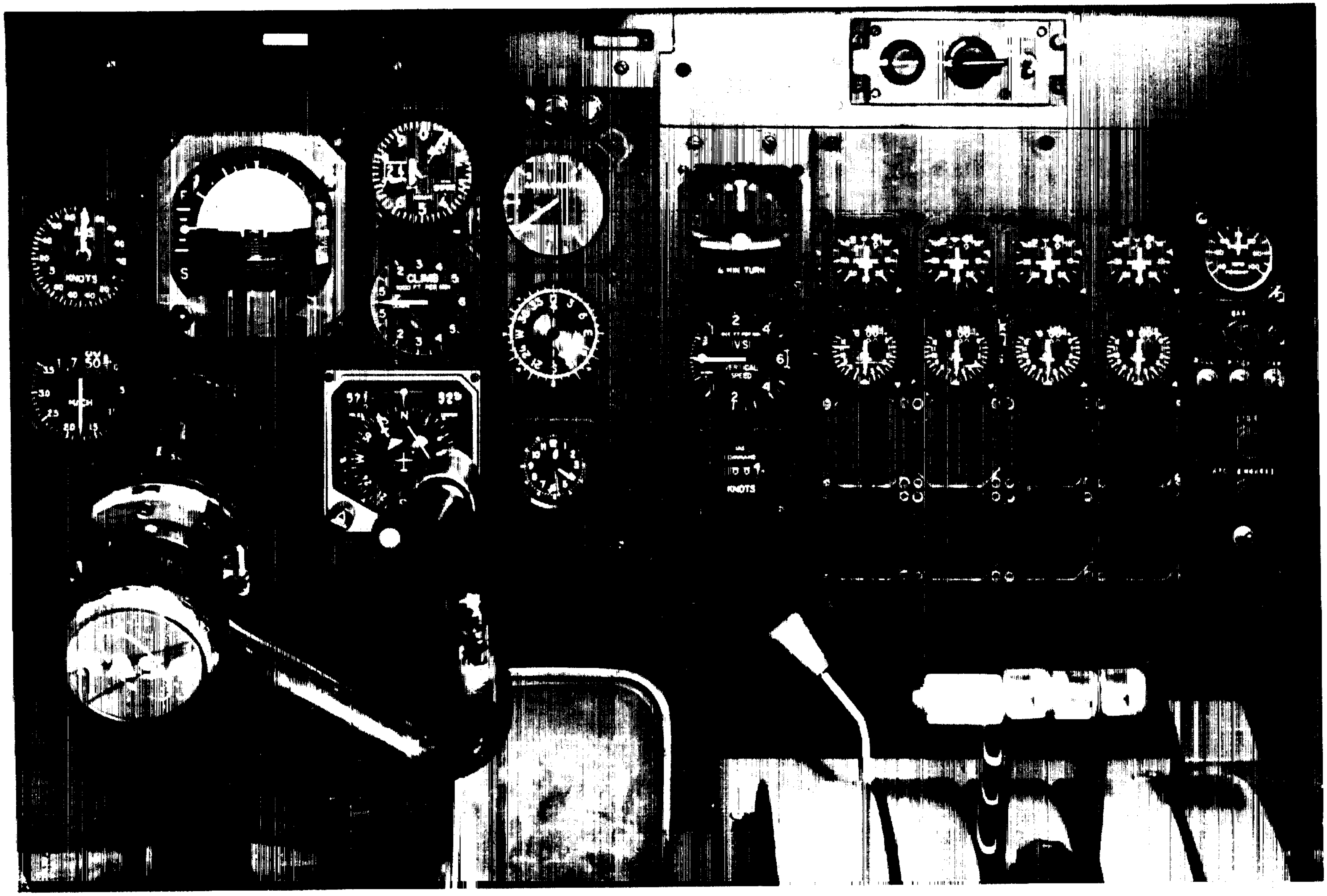


Figure 15. Simulator Front Panel of Aircraft F, American Airlines

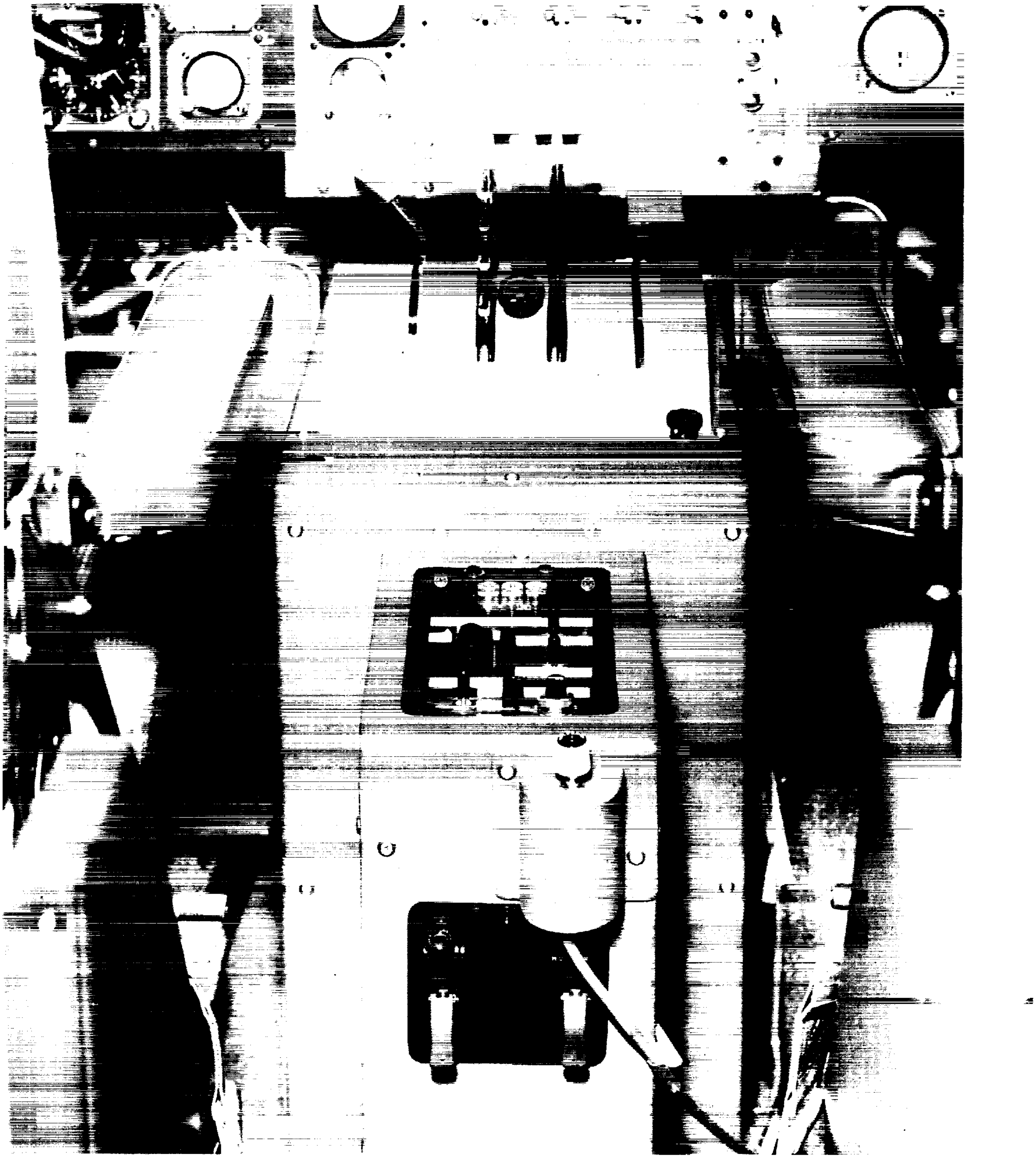


Figure 16. Center Console with Autopilot/Flight Director Control Panel

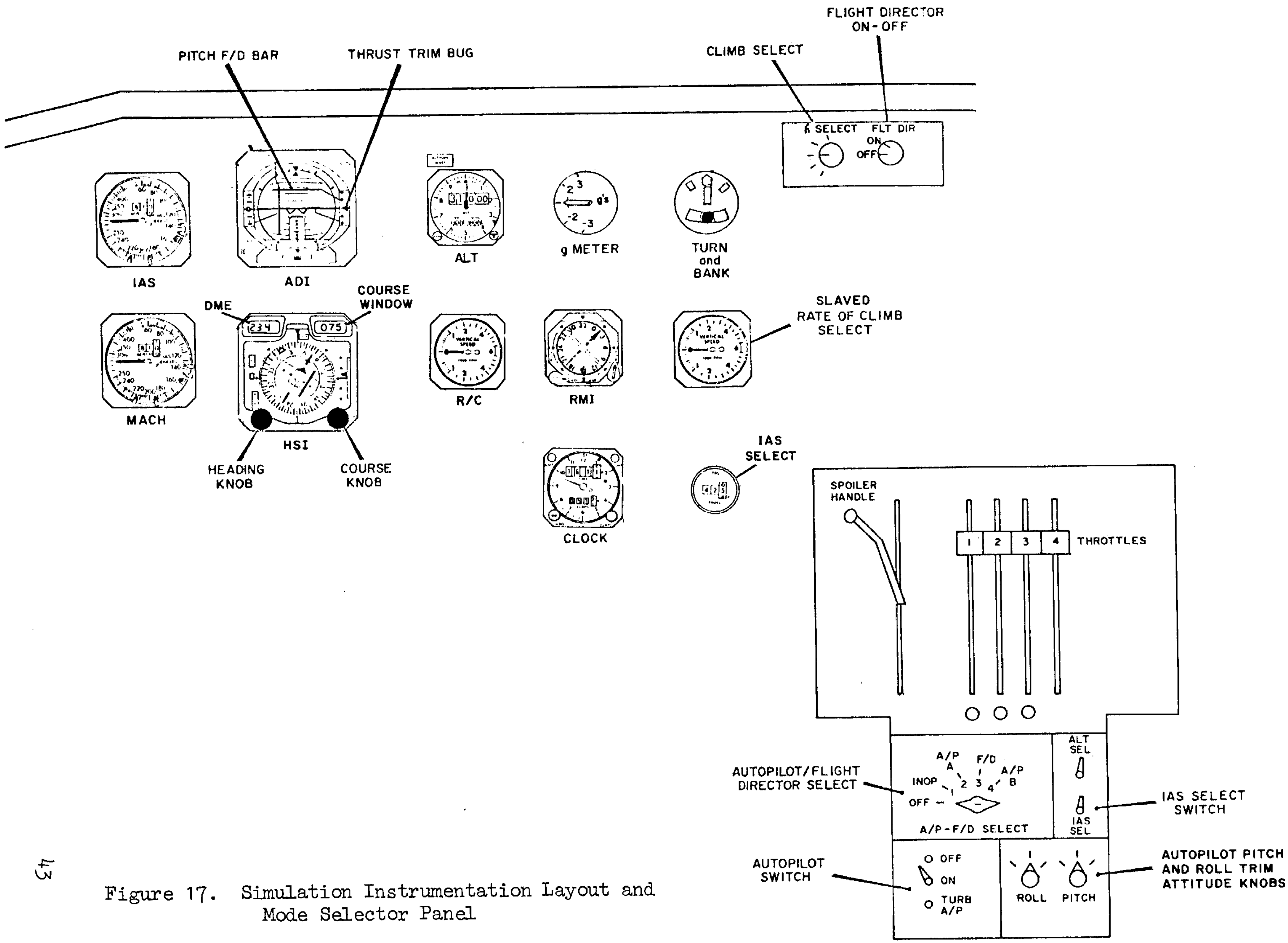


Figure 17. Simulation Instrumentation Layout and Mode Selector Panel

noise through a first order lag. Three such random signals were generated in inertial axes, appropriately transformed, and then fed into the u, v, and w body axes of the aircraft. Two second time constants were used on the u and v inputs and one second on the w input. The rms magnitude of these inputs could be varied from zero to twenty ft/sec by the experimenter.

Large discrete shears were simulated by a 40 ft/sec/sec ramp input to a maximum of 75 to 100 ft/sec. These could be introduced by the experimenter from each of the eight directions indicated in Fig. 13. The vertical shear was washed out with a time constant of 20 sec to simplify simulation and scenario aspects.

At appropriate times in the simulation scenario, the random turbulence was increased to maximum levels, held steady for periods of up to one minute, and then gradually decreased. The large discrete shears were introduced during most but not all of these periods of severe random turbulence to simulate flight through frontal activity. To show the compatibility of real and simulated gust disturbances, a comparison of simulated and actual aircraft normal acceleration traces is shown in Fig. 18.

Motion Drive

The S-16 cab provides pitch, roll, and heave motion as indicated in Table 4. The roll, pitch, and heave accelerations generated within the aircraft equations of motion are transformed for commands to the drive

TABLE 4

DYNAMIC CHARACTERISTICS OF S-16 MOTION SYSTEM

Motions Generated:	Displacement	Acceleration	Velocity	Frequency at 30° Phase Lag
Roll	±9 deg	4.7 rad/sec^2	.22 rad/sec	.5 Hz
Pitch	+14 deg −6 deg	4.7 rad/sec^2	.22 rad/sec	.5 Hz
Heave (Vertical)	24 in.	±1.0 g (from ambient)	—	.5 Hz

Drive: Hydraulic Servo (three linear actuators operated differentially or synchronized)

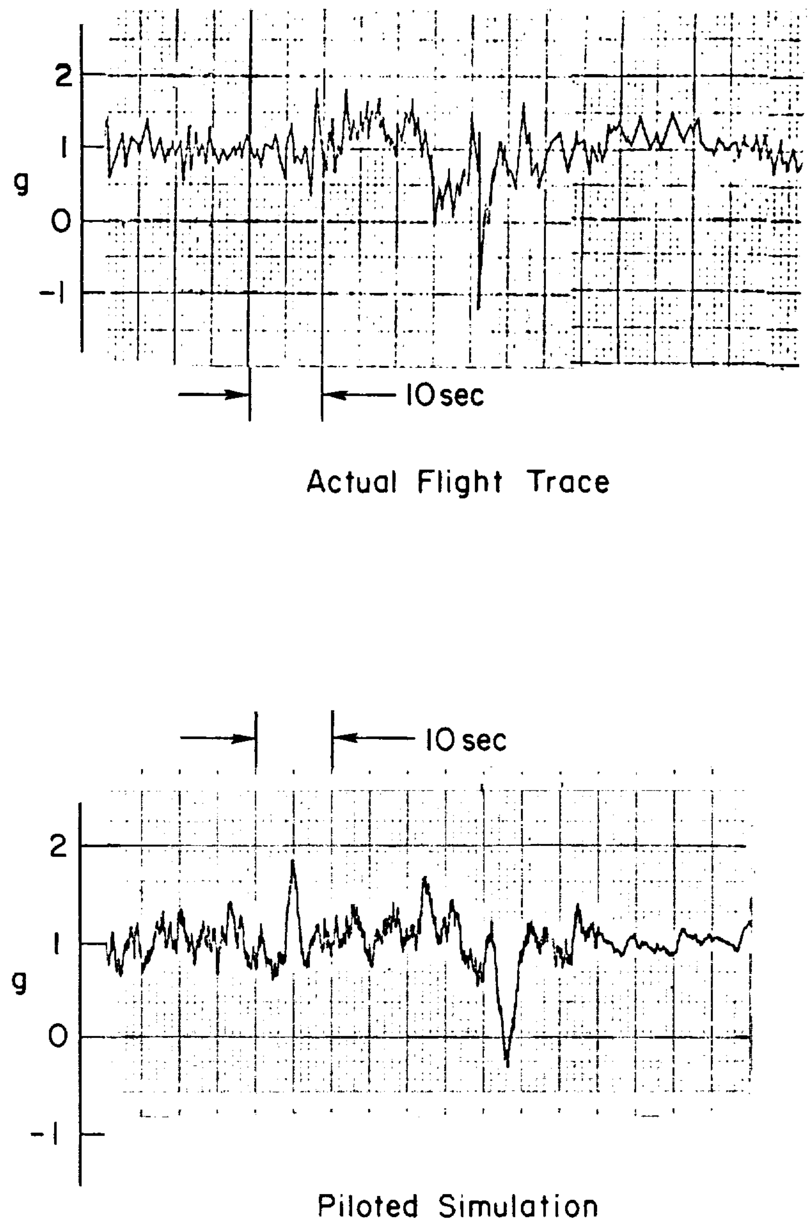


Figure 18. Comparison of Normal Accelerations Obtained in Severe Turbulence with Aircraft F, Simulation vs. Actual Flight

servos. Since the purpose of the motion was to simulate the high frequency jostle of severe turbulence, motion washout was not utilized and the servos could be momentarily driven into their stops. The end result was a very jarring, noisy ride, qualitatively assessed by experienced pilots as very realistic of the cockpit environment in severe turbulence.

Scenario

The evaluations were accomplished using a realistic ATC environment and route structure. This is detailed in Appendix C. The principal flight profile used covered the route from Los Angeles to Sacramento as shown in Appendix C, Fig. C-1. During the first segment of the flight the pilot executed a standard instrument departure from LAX. He was then radar vectored by ATC around thunderstorms and given various altitude changes throughout the trip. Pilot workload was controlled by varying the complexity of ATC clearances and timing of turbulence encounters. High workload situations were induced during some periods of extreme turbulence to accentuate differences between the various control/display concepts. Standard navigational equipment, including functioning VOR, RMI, and DME displays, allowed the pilots to use normal navigational procedures.

The flight profile was flown utilizing the following control/display configurations (but not necessarily in the sequence given):

- Manual control with conventional full panel display
- Conventional autopilot (A/P-A) with conventional full panel display
- Improved autopilot (A/P-B) with conventional full panel display plus thrust director display
- Longitudinal flight director with conventional full panel display plus thrust director display

At the conclusion of each run the pilots were required to rate overall performance achieved, safety margins, and pilot workload. Since none of the pilots were experienced at giving pilot ratings, a special rating scale was devised which is a modification of the common Cooper-Harper scale used for handling quality research. The modified scale is given in Fig. 19 and is seen to be cast entirely in terms of safety margin, performance, and workload. Aircraft handling characteristics, per se, were not a factor in the ratings. All of the pilots qualified in Aircraft F agreed that this aircraft is extremely well behaved and handles as well or better than other jet aircraft in heavy turbulence.

Subject Pilots

All of the subject pilots were exceptionally well qualified for the evaluations. All are high flight time airline captains. A brief summary table of pilot background is given in Table 5. Since airline training is now heavily oriented toward the simulator, there were no problems with pilot acceptance of the simulation as an effective representation of the "real world." In fact, most considered this simulation to be more realistic than their regular training simulator.

TABLE 5

PILOT BACKGROUND SUMMARY

PILOT	TOTAL HOURS AND RATINGS	DESCRIPTION OF DUTIES
A	22500 ATR	Captain, Aircraft F, for major U. S. airline. Also current on other jet transports. Has approximately 2500 hr in Aircraft F. Served as instructor pilot for 6 years.
B	33000 ATR	Retired Captain, Aircraft F. (Retired 3 months before simulation.) 2400 hr in Aircraft F. Was with major U. S. airline for 37 years.
C	12000 ATR	FAA Flight Inspector assigned to major U. S. airline. Principal duties are to give Aircraft F rating rides and 6 month instrument checks. Gave 97 Aircraft F rating rides last year.
D	15000 ATR	Aircraft F instructor pilot for major U. S. airline. Check pilot for 16 years.
E	16700 ATR	Captain, Aircraft A, for major U. S. airline.

SAFETY MARGINS	TASK PERFORMANCE AND PILOT WORKLOAD	RATING
Clearly adequate	Desired performance obtained with low pilot workload	1
Clearly adequate	Desired performance obtained with modest pilot workload	2
Clearly adequate	Desired performance obtained with acceptable pilot workload	3
Clearly adequate	Desired performance not obtainable or requires unacceptable pilot workload	4
Adequate	Adequate performance obtained with high pilot workload	5
Marginal	Adequate performance requires excessive pilot workload	6
Inadequate	Adequate performance not obtain-able with tolerable pilot workload	7
Inadequate	High pilot workload required to maintain control	8
Inadequate	Extreme pilot workload required to maintain control	9
None	Loss of control inevitable	10

Figure 19. Task Performance and Pilot Workload Rating

RESULTS

Results of the simulation were documented via strip charts, x-y plots of the aircraft flight path, on-line computation of aircraft rms motion responses, and pilot qualitative assessment. These data were analyzed to determine the aircraft and energy control technique and/or strategy employed by each pilot with each of the four control/display systems, and to assess comparative performances, workloads, etc. Results were also compared to time traces of actual aircraft severe turbulence encounters.

This section presents first the assessment of piloting technique and presents typical strip chart recordings of pilot/aircraft response to various severe disturbance inputs. This is followed by a comparison of rms aircraft response motions observed with use of each control/display system and a summary of pilot assessment of flight safety and workoad evaluations.

It should be noted at the outset that the scenarios and disturbances used in this simulation were not "canned." Each flight involved a real time interaction between the subject pilot and the simulation air traffic controller. The severe turbulence encounters were purposely varied from flight to flight to prevent pilot anticipation of the disturbance. As a result, one cannot directly compare performance or response between runs or flights. Each turbulence encounter was a unique situation. In some instances pilot inputs immediately preceding the disturbance actually reinforced the aircraft response and near upsets were observed. Because of this, differences in rms response measures must be fairly large to be significant.

Typical System Utilization and Aircraft Response

Manual Control with Full Panel Display

Current airline procedures dictate that pilots control attitude in a "loose" manner while flying in moderate to severe turbulence. All of the test subjects used in the simulation indicated that this is indeed standard practice. However, analysis of strip chart recordings indicates an apparent tightening rather than loosening of attitude control in the presence of severe turbulence. An illustration is shown in Fig. 20. In this trace the aircraft was initially in a constant speed descent (approximately 330 kt and 1400 ft/min). The pilot attempted to slow to the 280 kt penetration speed upon encountering turbulence. The random turbulence was slowly built up to an rms level of 20 ft/sec and then three large discrete gusts (direction 8 reversed to direction 4 and then reversed again to direction 8) were superimposed. It may be observed in the control column (δ_c) trace that the pilot steadily increased the magnitude of his inputs as the random turbulence level increased. As a result, amplitude of the α and n_z oscillations also increase.

An apparent tightening of control is most noticeable in the n_z trace immediately following the second disturbance 8 input. Here the envelope of n_z excursions diverges for several cycles, damps suddenly (possibly due to fortuitous phasing of a single control column deflection), immediately returns to large amplitude, and then slowly converges to a lower level. During this same time period pitch attitude excursions remain smaller than for the rest of the strip chart. The n_z divergence is due to the pilot driving the aircraft short period unstable in the attempt to restrain θ excursions. This can be demonstrated with the aid of a closed-loop attitude control survey plot (Fig. 21). The transfer function for the pilot and airframe at this flight condition is shown in the upper left of Fig. 21. Here the pilot is assumed to be described by a gain and time delay but no lead, i.e.,

$$Y_{p_\theta} = K_{p_\theta} e^{-.31s} \doteq K_{p_\theta} \frac{(s - 13)^2}{(s + 13)^2}$$

The range of attitude closure required to analytically reproduce the short period divergence observed in Fig. 20 is shown in both root locus and Bode form in Fig. 21. The relatively good match between the actual instability frequency and the analytical model indicates the pilot is indeed not generating a lead. Furthermore, the range of pilot gain necessary to provide the short period divergence-convergence observed is only on the order of 2 dB. This is not the type of closure which would normally be expected of the pilot. Generally, he would adopt a lead in the vicinity of crossover which would provide greater phase margin and reduce system sensitivity to his gain. One possible explanation is that vision degradation in the severe jostle environment and attendant increase in time required to scan instruments and assimilate information has reduced or eliminated his capability to generate lead. This tendency for increased short period oscillation was greater following combined severe random turbulence and a large discrete gust for all pilots flying manual control in this experiment. Thus, what appears on the time traces to be an increase in gain could just as well be due to loss of lead generation capability or a combination of the two.

The general excursions and responses shown in Fig. 20, i.e., the divergent short period, peak vertical acceleration excursions, and peak rate-of-climb or descent, compare favorably with an actual Aircraft F turbulence encounter shown in Fig. 22. Additionally, a tendency of the pilot/vehicle system to exhibit a phugoid type oscillation in heavy turbulence has been noted previously (e.g., Fig. 1). This was also experienced in the simulation during high workload situations even without a large discrete gust disturbance. For example, Fig. 23 shows a distinct phugoid oscillation as the pilot is slowing from 250 to 230* kt and, at the same time, performing a complicated holding pattern entry at the Saratoga intersection. The 50-60 second period phugoid oscillation is very distinct in the attitude and rate-of-climb but not the airspeed trace. At this flight condition the aircraft is on the backside of the thrust required curve (see Fig. 5). The normal "frontside" piloting technique (control of sink rate with pitch attitude) results in the oscillatory $\dot{h}$ trace and a divergent airspeed bleedoff unless thrust is also employed to stabilize airspeed. In this instance his throttle activity was initially insufficient to prevent airspeed bleedoff which decreased to 200 kt before he added power. The airspeed then dipped below 200 kt before he took more drastic action in lowering the nose to maintain essentially constant pitch attitude and

*ATC regulations require holding patterns to be flown at 230 kt or less.

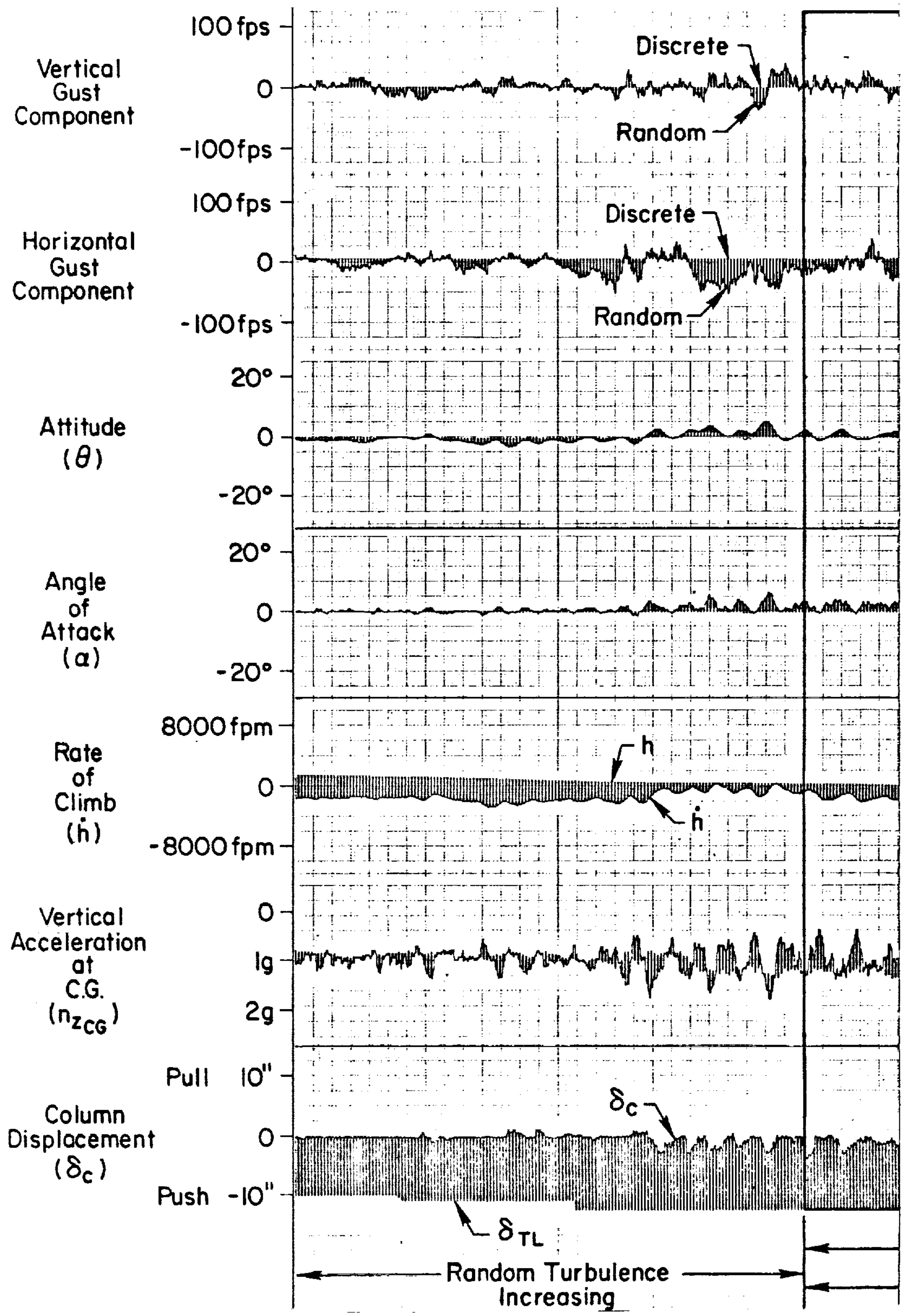


Figure 20. Illustration of Attitude Oscillations During Manual Control

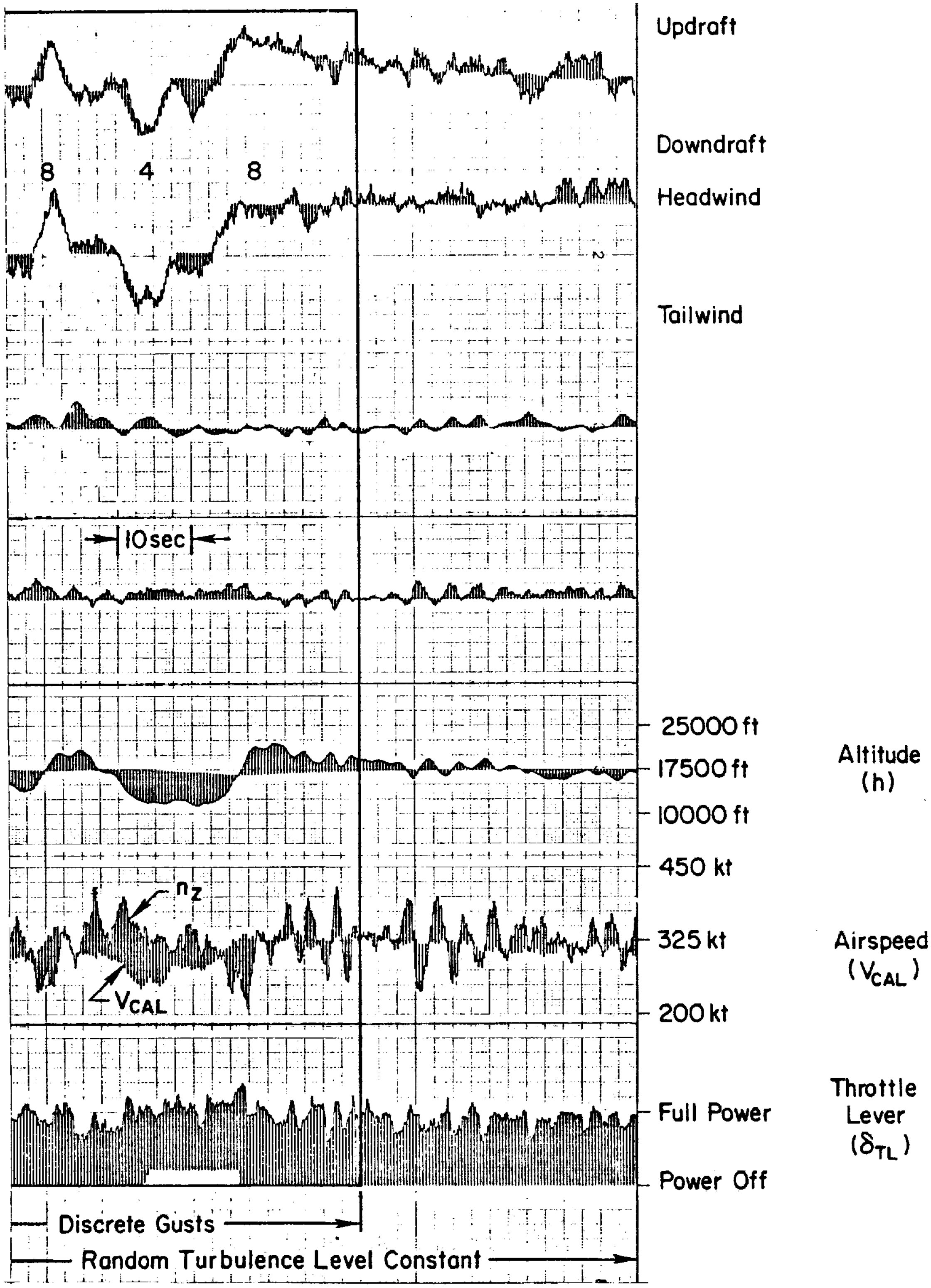


Figure 20. Continued.

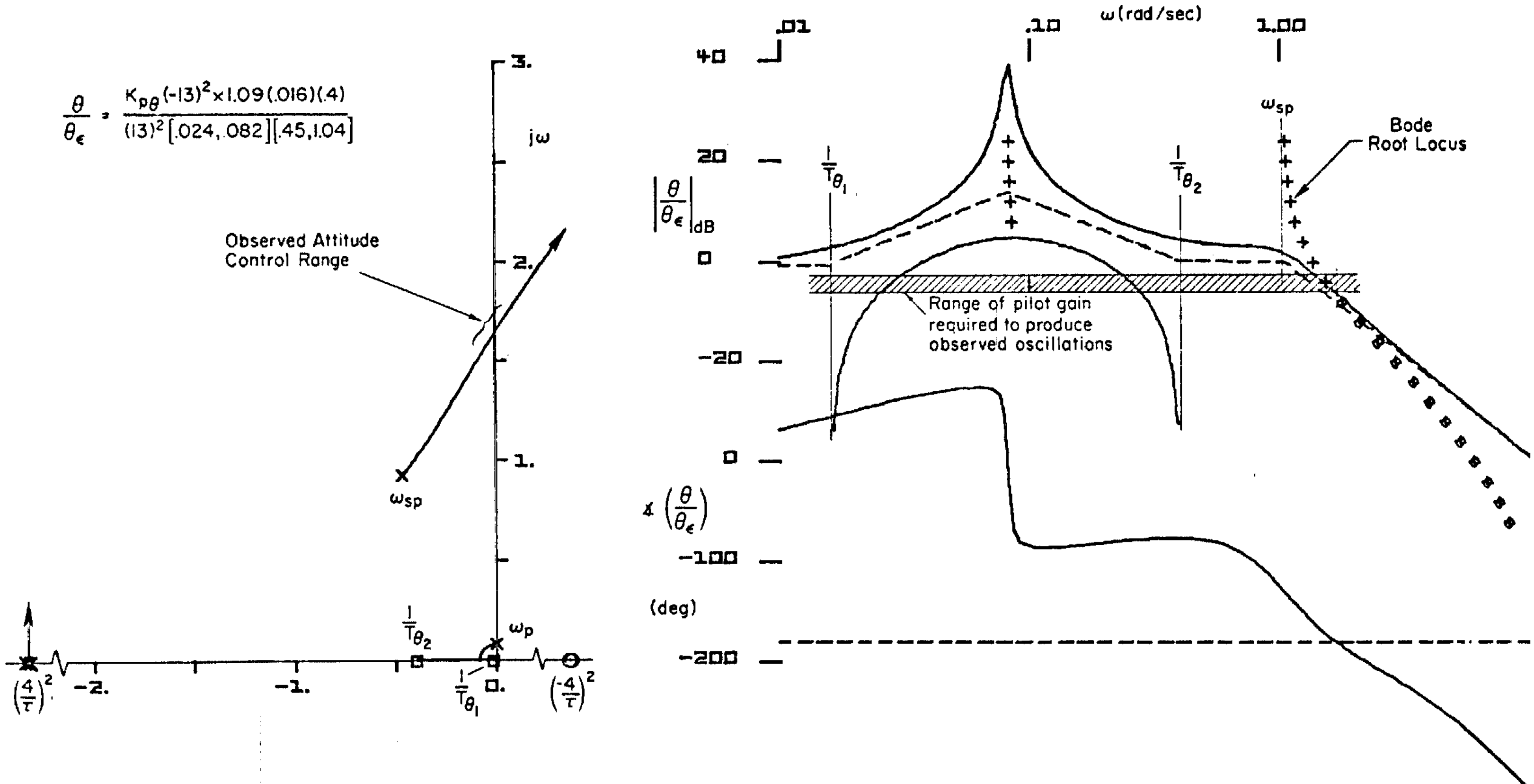


Figure 21. Piloted Closure of Attitude Loop (h = 20,000; M = 0.5)

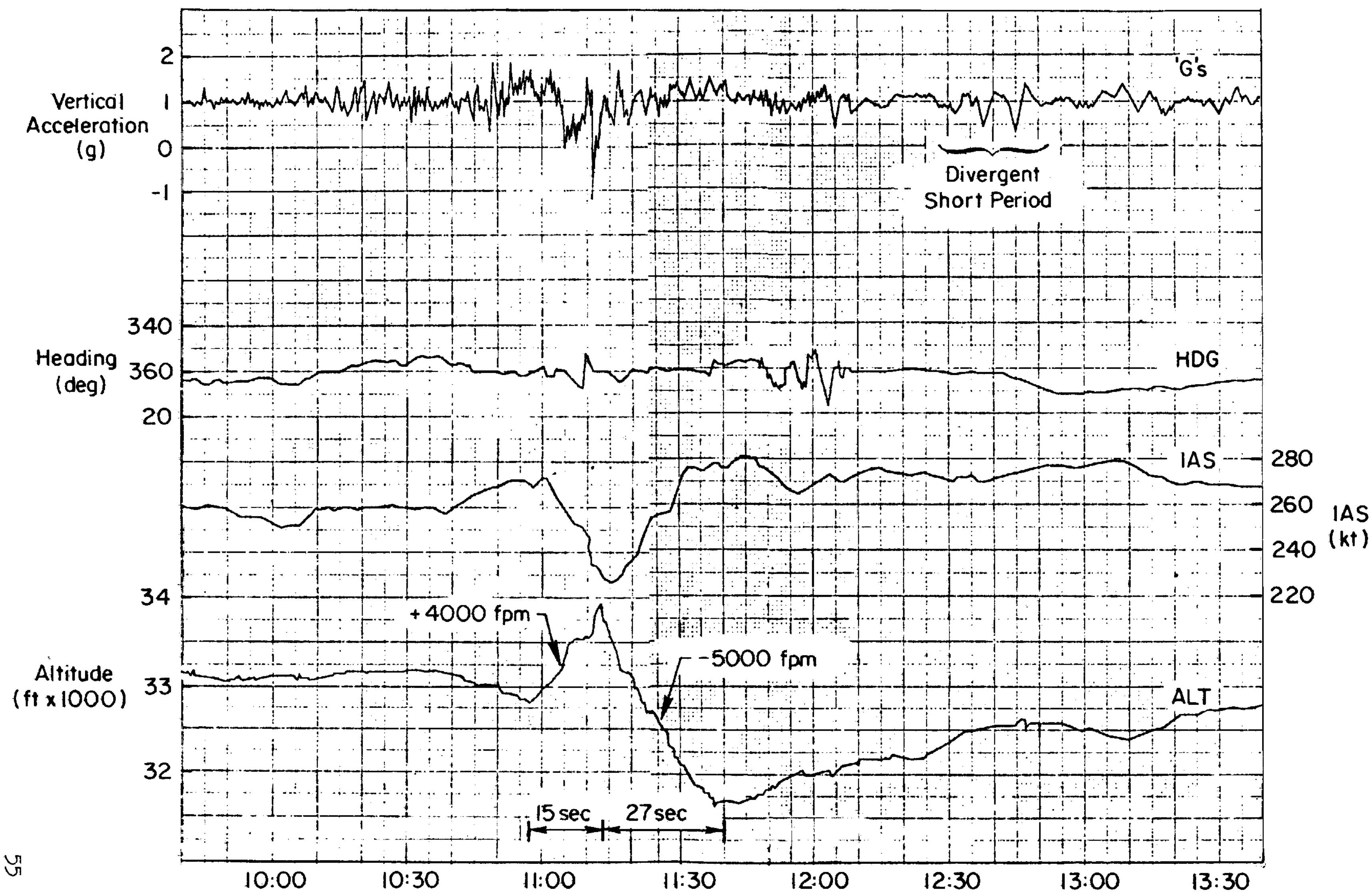


Figure 22. Aircraft F, Actual Flight Traces (Ref. 9)

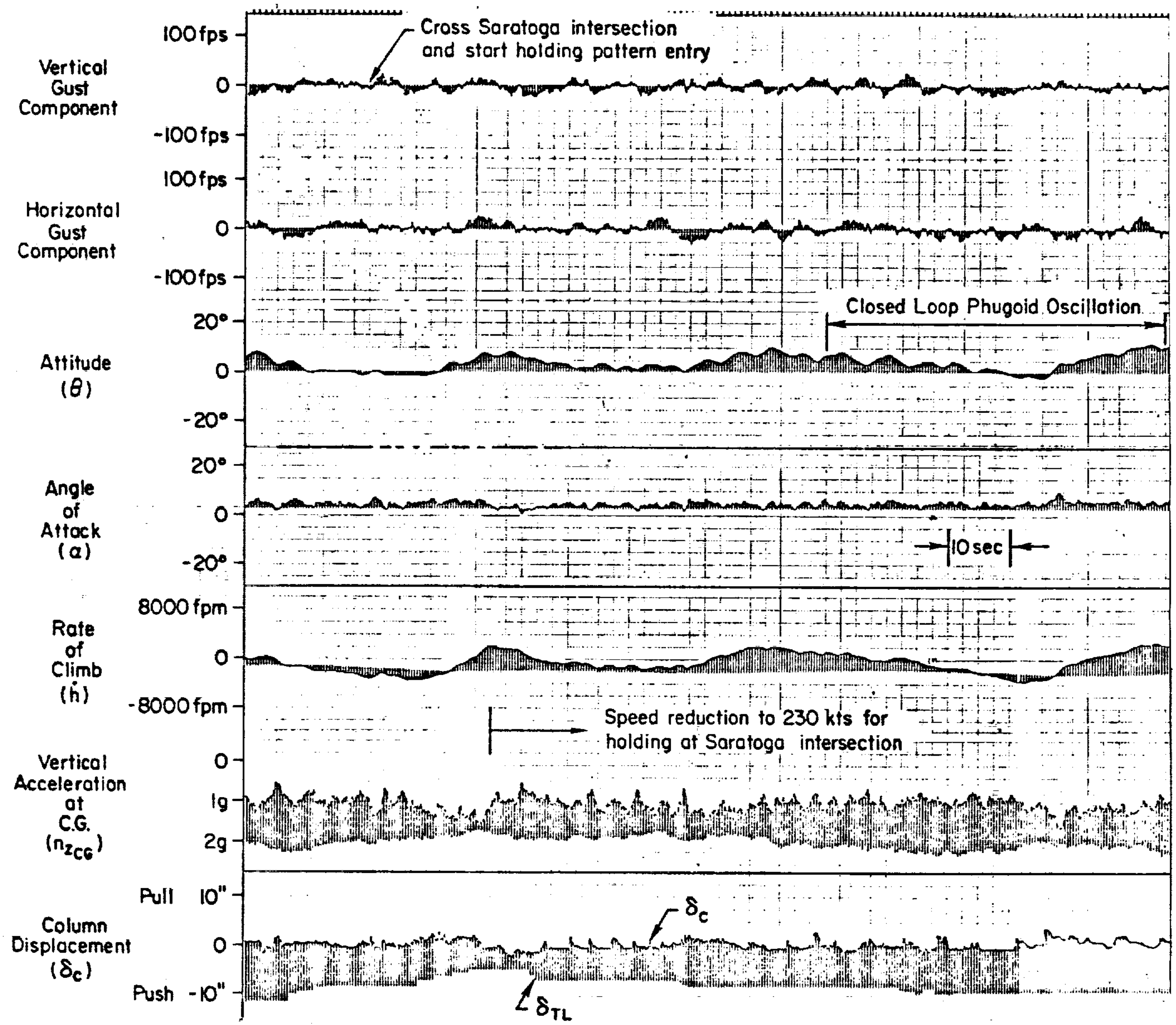


Figure 23. Example of Closed-Loop Phugoid Oscillation

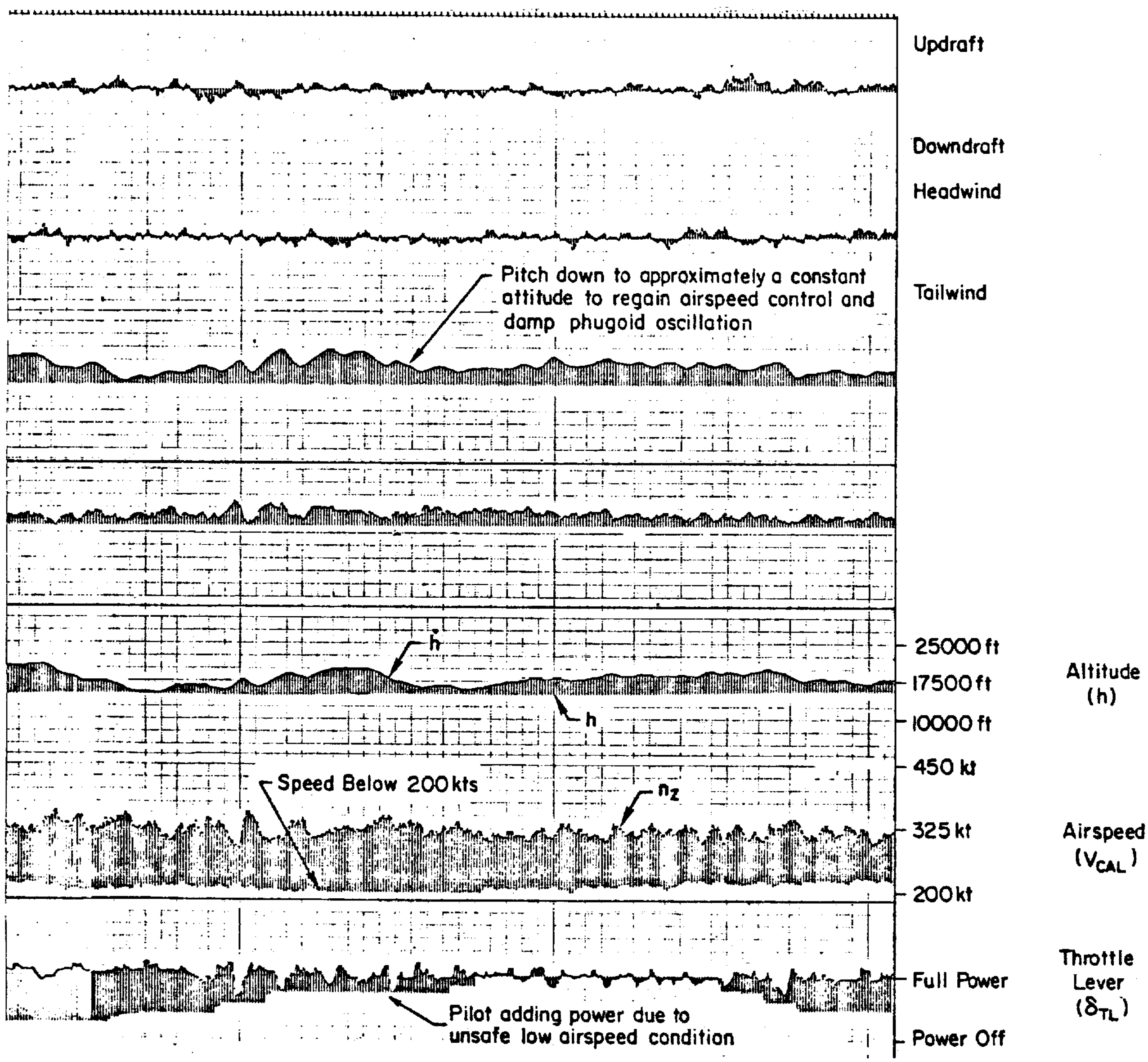


Figure 23. Continued.

adding full power. This "backside" operation coupled with the holding pattern navigational task created such a high workload that the pilot could no longer cope with large discrete disturbances. In such instances attempts to maintain aircraft lateral-directional control to the prescribed track resulted in excessive altitude and airspeed excursions and attempts to control the latter required abandonment of pattern turns. This portion of the simulation is considered to validate the concern expressed previously (Figs. 5 and 6) regarding backside operation in severe turbulence.

In summary, the simulation time traces show that all pilots tended to tighten rather than loosen attitude control and/or lose their lead generating capability when in severe turbulence and thus aggravate the aircraft short period mode normal acceleration excursions. All of the pilots that were given the backside control task were near workload saturation and allowed airspeed bleedoff to near stall conditions.

Autopilot A

Autopilot A is the standard aircraft system in which the attitude loop gains are reduced by one half in the turbulence mode. However, few of the pilots used this turbulence mode. Instead they generally left the autopilot in the higher gain, normal attitude hold mode and introduced frequent, small adjustments in pitch-attitude trim-reference to regulate rate of climb/descent. This was accompanied by infrequent, large step changes in thrust. An example is shown in Fig. 24.

Comparison of the time traces of Fig. 20 and 24 indicates much smoother (less oscillatory) control of pitch attitude provided by the autopilot (Fig. 24) and, with the exception of the single large vertical acceleration spike, a general reduction in rms acceleration at the aircraft c.g. The discrete step changes in pitch attitude reflect the autopilot responding to pilot change of the pitch trim knob. The large n_z spike is an artifact of the discrete gust combination employed. This is a 3-7-3, i.e., a downdraft (75 fps in and out) followed by an updraft (75 fps in and out) and then a downdraft (approximately 85 fps) which is slowly washed out. The vertical acceleration spike is primarily due to the aircraft basic aerodynamic response to a large downdraft (Z_{w_g}) coupled with a simultaneous nose down pitch trim command (by the pilot). The latter completely overpowered the normal aircraft nose up weathervane response to a downdraft. The situation was compounded by an almost simultaneous thrust reduction. The end result is a sudden rate-of-climb reversal from +3500 to almost −6000 fpm. The pilot then responded 5 to 10 seconds later with step increases in thrust and trim reference change to return the aircraft to level flight. However, the altitude loss is about 1200 ft.

The above was a fortuitous event insofar as upset simulation is concerned. This total incident, including the time to arrest the descent, is remarkably similar to the actual flight perturbation of Fig. 22! A key point is that the pilot appeared to regulate aircraft rate-of-climb with pitch attitude (definitely not recommended practice in severe turbulence), thereby reinforcing the influence of a vertical gust and providing a near input.

It might be reiterated that the pilots considered the simulation to be a realistic representation of the jarring ride produced by severe turbulence in which it is difficult to see the instruments and to manipulate throttles and the control column.

Autopilot B

For this experimental system the pilot selects the desired penetration airspeed and rate of climb/descent. The autopilot computer then determines the appropriate trim attitude reference, automatically controls the aircraft to this reference and displays the thrust setting required of the pilot to accomplish the desired flight condition. Although the thrust command was originally conceived as a flight director, it was found that the pilots would not respond to the "higher" frequency command movements for fear of overheating or damaging the engines. The method of operation adopted was to observe the thrust indication to ascertain longer term aircraft energy state trends during severe turbulence encounters and to adjust thrust to the indicator only after sustained deviation had been observed. Thus, the command function was renamed a "thrust trim bug."

An example of control in severe vertical gusts is shown in Fig. 25. The gust sequence is the same as in Fig. 24 for Autopilot A; however, the

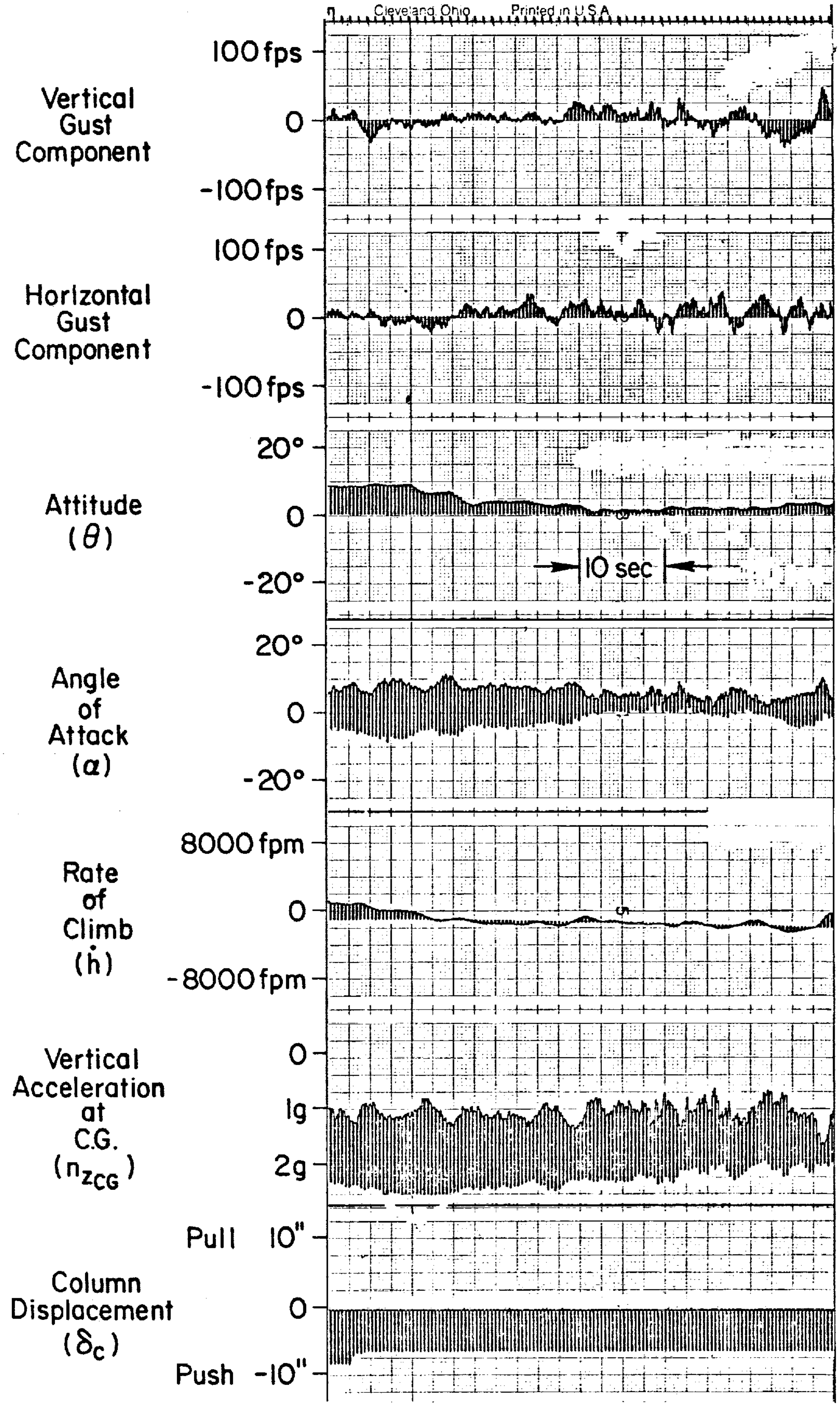


Figure 24. Pilot Technique with Autopilot A

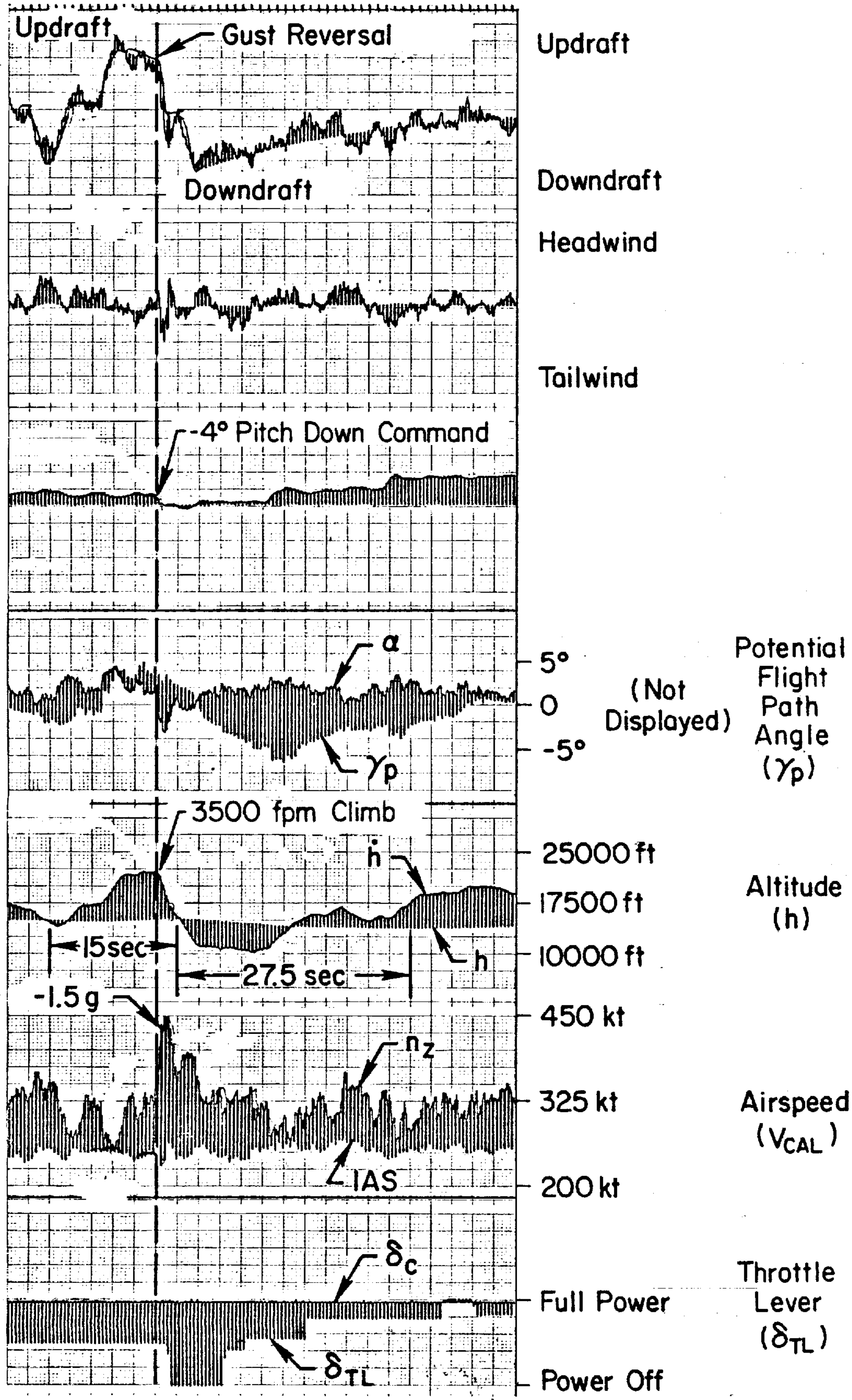


Figure 24. Continued.

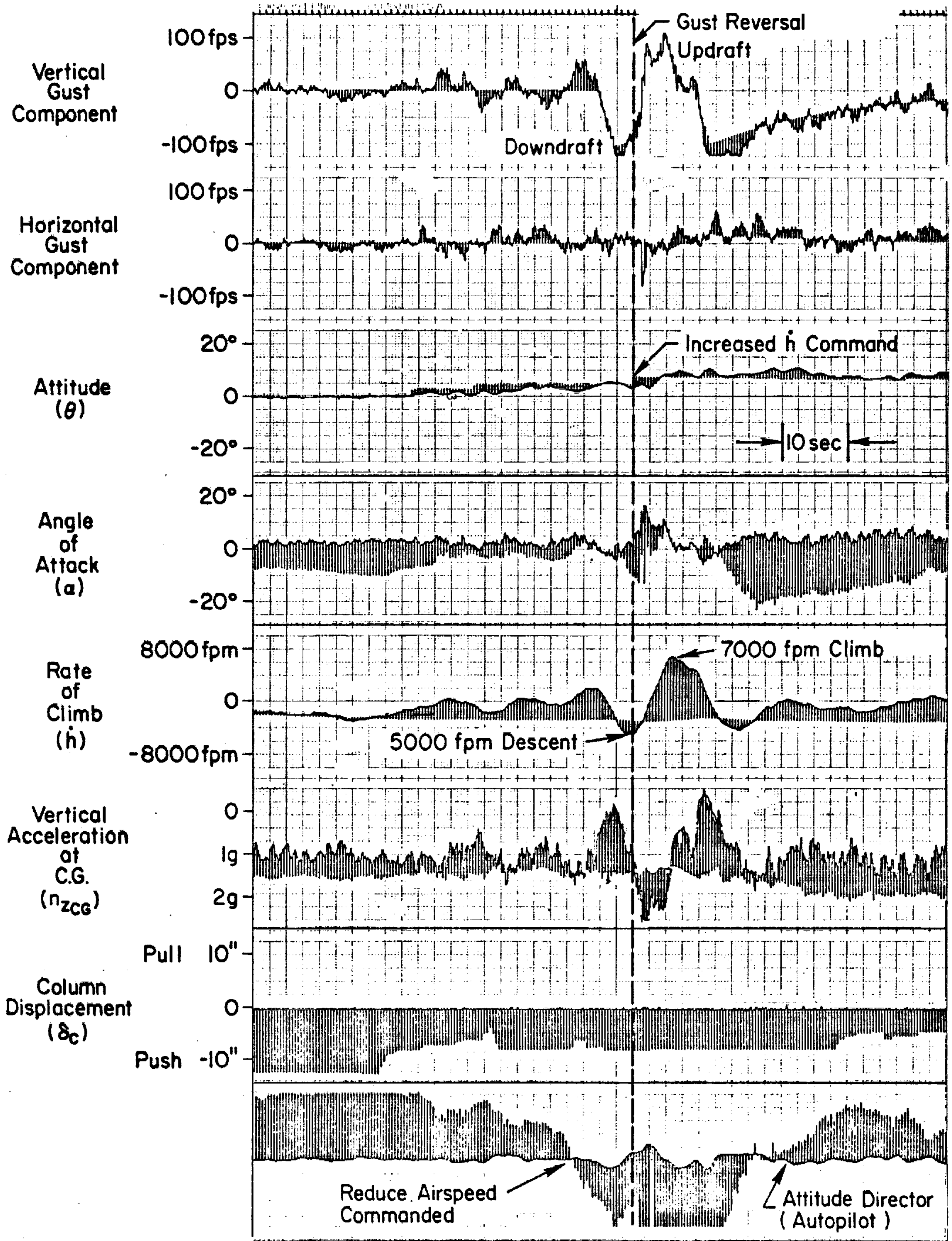


Figure 25. Response of Autopilot B to Large Vertical Gusts

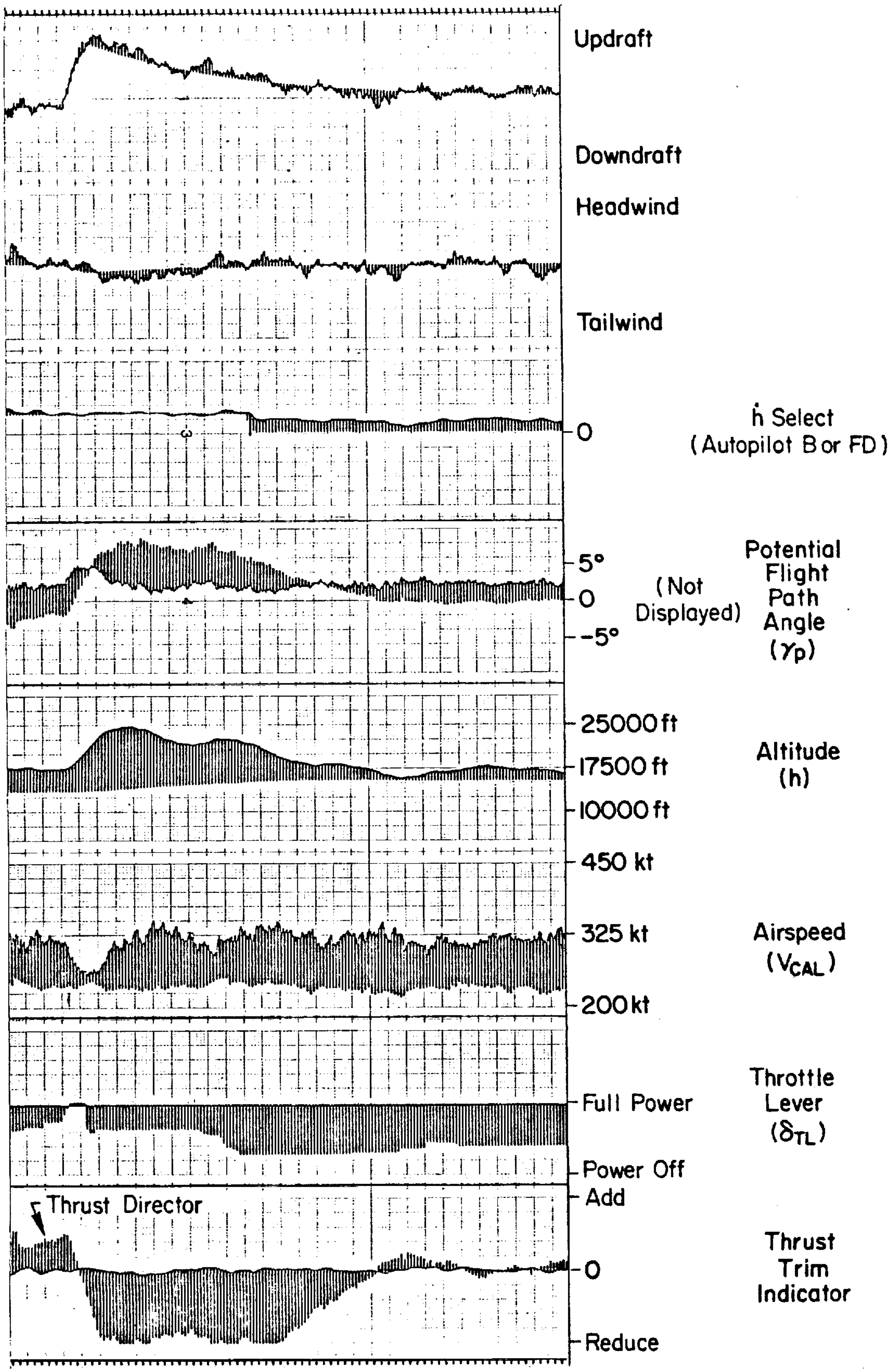


Figure 25. Continued.

discrete disturbances are greater (125 fps down and 100 fps up). The rate of climb command track (channel 3, $\dot{h}$ select) indicates that the pilot again was actively adjusting the command to maintain the desired flight path irregardless of the turbulence and discrete gusts. And again he reinforced the vertical gust by commanding a rate of climb just as an updraft was encountered. The combined updraft and commanded climb resulted in a reversal from −5000 fpm to almost +7000 fpm. The following downdraft forced a −4000 fpm descent. Because these high rates of climb/descent were of short duration (10 sec or less), the altitude excursions were less than ±500 ft. The large vertical acceleration peaks are again the basic aircraft Z_{w_g} response.

In this encounter the pitch attitude excursions are slightly larger than obtained with Autopilot A because of the low gain airspeed error feedback into attitude command. However, the airspeed and random vertical acceleration deviations are noticeably less than with Autopilot A. Specifically, with Autopilot A the desired 230 kt airspeed dipped to 200 kt or below and then varied as high as about 270 kt. With Autopilot B, the aircraft was initially at 280 kt and the command of 230 kt was inserted during the discrete gust encounter. The system smoothly transitioned to 230 kt and held this speed within ±5 kt.

Pilot use of the thrust trim indicator is also apparent in Fig. 25. Initially it was indicating the need for a power increase to which he responded. When the pilot selected a reduction in reference airspeed, the thrust trim indicator immediately called for a thrust reduction. However, the pilot did not respond to this — most probably because of the severe gusts being encountered at that time. Shortly thereafter he resumed following the trim thrust command and rapidly achieved the desired trim. The difference in use of thrust between Figs. 24 and 25 is quite striking.

The ability of the system to smoothly and rapidly guide the pilot and autopilot to the selected airspeed and flight path conditions in the presence of severe disturbances is demonstrated in these traces. All the pilots felt that the capability of being able to make an aggressive response to airspeed excursions when necessary and to fly a loose throttle response during other portions of the flight was a very desirable feature of Autopilot B. These comments would indicate that it is better to allow the pilot to select a throttle loop closure frequency than to force a lower closure frequency via heavy display filtering or control position feedbacks.

While one of the chief benefits of Autopilot B is the ability to provide some measure of airspeed control in the presence of moderate-to-severe turbulence, this benefit could become a detriment in the presence of very large horizontal gusts. Even though the airspeed-to-attitude feedback gain is very low, it was considered that large gusts could cause unacceptable pitching due to this feedback reinforcing the basic aircraft pitch moment, M_u. To investigate this possibility, a rapid 1-5-1 gust sequence (headwind-tailwind-headwind) was included in the simulation scenario although the physical reality of such a disturbance is highly questionable. A single shift from headwind to tailwind or vice-versa can be readily encountered in frontal shear activity. However, if a triplet disturbance could ever be encountered and if its wavelength were tuned to the aircraft response time, it might provide the possibility of initiating an upset. Therefore, the triplet shown in Fig. 26 was introduced. This involves a 75 fps headwind shifted to a 75 fps tailwind and then returned to 75 fps headwind (essentially 90 kt changes in airspeed) with random disturbances of up to 50 fps superimposed upon these discrete gusts. Channel 3 of Fig. 26 shows the peak attitude excursions to be +5 deg (the airspeed error command limit) and −4 deg. However, the accompanying vertical accelerations are relatively mild (approximately ±0.5 g). Some of the smoothing may be credited to pilot use of thrust in response to the thrust director. The pilot did not hesitate to use full throttle travel and did so in a very timely manner as directed by the trim thrust display.

Flight Director

Two attitude (elevator) flight director control laws were tested. Flight Director 1 was described in Fig. 9 and had essentially the same feedback structure and gains as Autopilot B; however, it did not compare favorably with Autopilot B because of the increase in pilot workload required to crosscheck and assimilate the additional information with

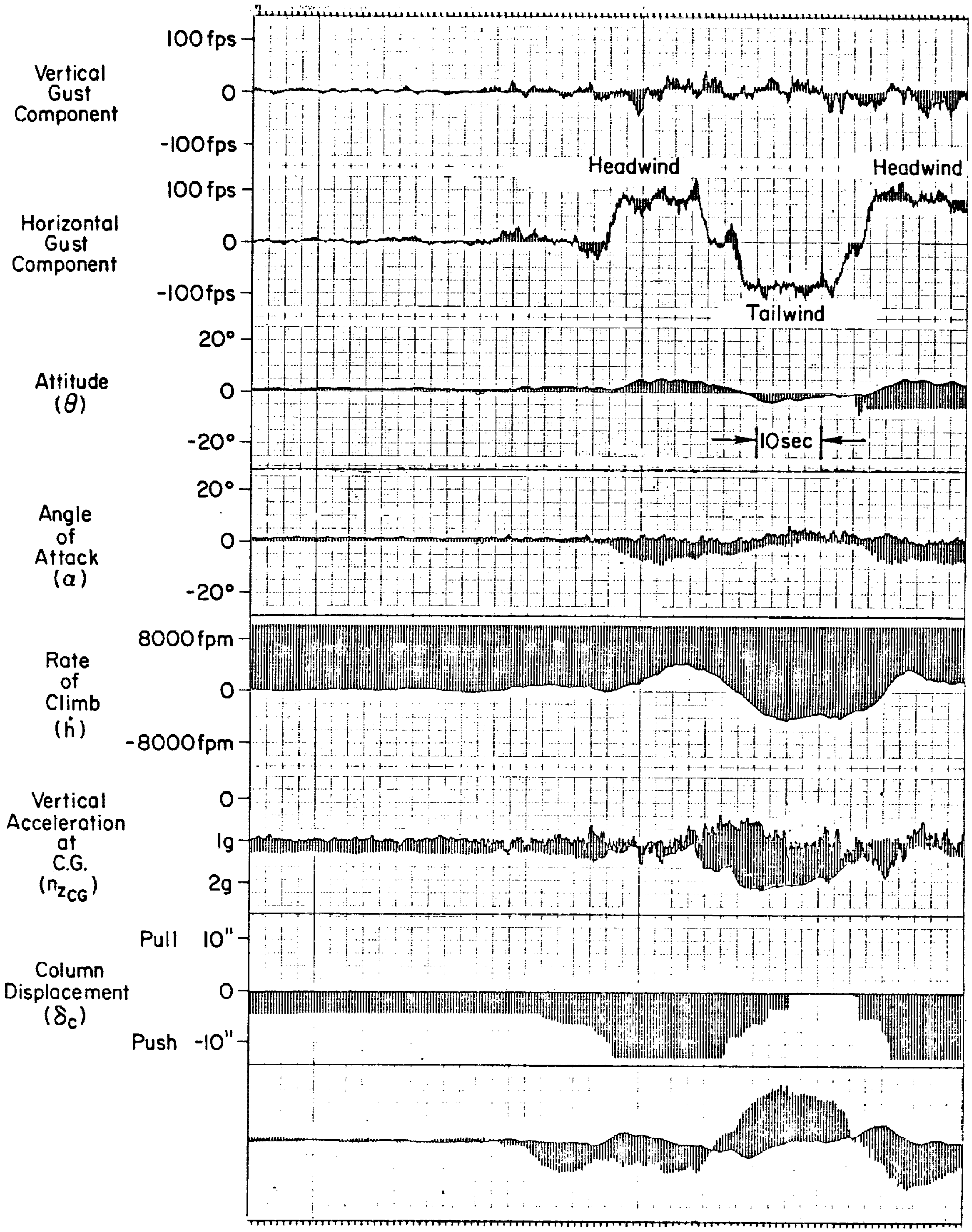


Figure 26. Response of Autopilot B and Pilot to Large Horizontal Gusts

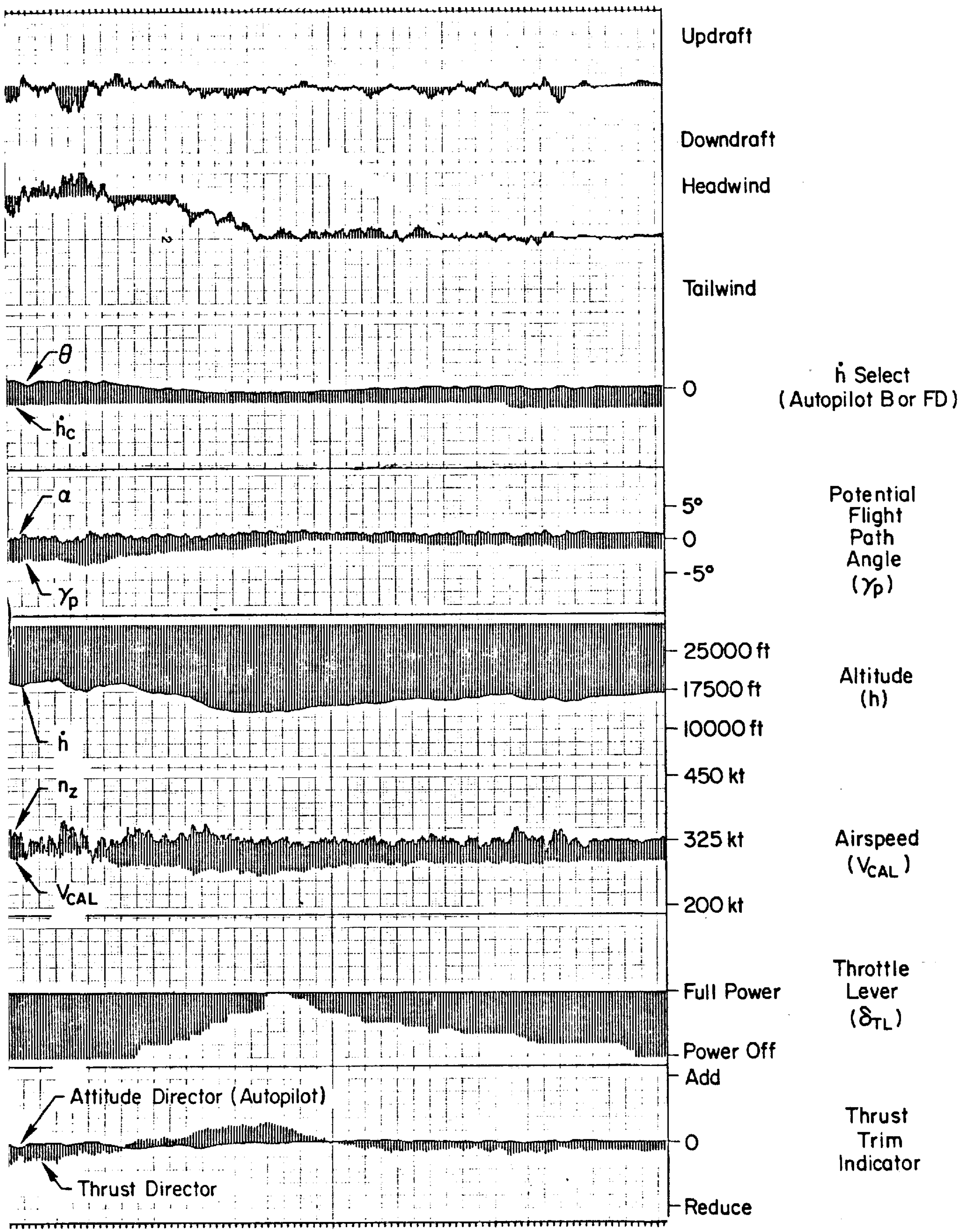


Figure 26. Continued.

the conventional panel instruments. Pilots did not like to follow computed information in severe turbulence without checking raw data and validating the display. During the time required to scan and read the various instruments the aircraft would deviate from the desired attitude and airspeed. When attention was returned to the flight director, the director bar would be commanding a large input. The pilots objected to the large maneuver commands and time histories indicated they generally were not following the command bar on Flight Director 1. This result may have been influenced by pilot training. Emphasis is currently placed on avoiding over-reliance (or tunneling) on flight director displays.

An alternate display (Flight Director 2) was incorporated and evaluated by one pilot. This "director" was simplified to display only computed pitch attitude reference (trim) for the selected speed and flight path (attitude rate). It did not contain attitude, airspeed, or control column feedback. The reference was displayed directly on the ADI director bar. The resulting steady reference apparently reduced the amount of instrument crosschecking required. The single pilot indicated this plus the thrust trim reference to be much more desirable for manual control than the more complicated attitude director.

Summary

Time histories of the simulation responses compare very closely with avialable flight traces of actual disturbance encounters with the aircraft. The pilots considered the simulation to be a realistic representation of the severe, jarring ride produced by severe turbulence. They further considered the simulation to be a realistic representation of line operation flight tasks and cockpit workload.

The ATC scenario used was designed to make the pilot slow to 230 kt prior to reaching the Saratoga intersection. All of the pilots that attempted this maneuver undershot 230 kt and went below 200 kt with manual control and with Autopilot A. The time required to recover from the speed overshoot and to settle on 230 kt was from 35 sec to 2 min. In each case the problem was centered about trying to find the proper trim pitch attitude and trim power in turbulence. Perhaps the most important aspect of Autopilot B is the ability to achieve the right combination of pitch attitude and power during transitions in speed and altitude without iterations by the pilot. This is vividly illustrated in Fig. 25, where it is seen that the pilot was able to slow to his holding speed of 230 kt in the presence of the large discrete and severe random disturbances without undershoots or appreciable transients. As noted above, all attempts to do this under manual control or with Autopilot A resulted in speed excursions under 200 kt and dangerously near the stall boundary. Had the aircraft been hit with a large tailwind gust during these excursions below 200 kt, an upset may have been induced. However, with Autopilot B, excursions to the limit of performance never occurred, and thus adequate speed margins were always available for tailwind or vertical gusts.

A flight director version of Autopilot B was found to be unacceptable by the pilots since the column director command did not have face validity and it added to the already high scan requirements and hence to the overall workload.

Performance Evaluation

RMS Responses

During the periods of encounter with a discrete gust, rms values of 15 vehicle motions, display variables, and control actions were computed on-line. This computation was triggered by the random turbulence level exceeding 15 fps. Typically, the discrete gust followed within 5 sec, was maintained for 30 to 40 sec and then removed, and then 5 to 10 seconds later the random turbulence was turned down below 15 fps. The rms measures were computed during this total period (approximately 1 min.). Pitch attitude, airspeed, rate of climb/descent, and normal acceleration excursions provide the best measures of system performance. The data presented here represent the average for four of the five line pilots. Data for the fifth pilot are not included because he assisted in refining the simulation scenario and finalizing the gust levels, flight director gains, etc. He therefore was more familiar with the scenario, the control configurations being examined, and, most important, the technical goals of the program.

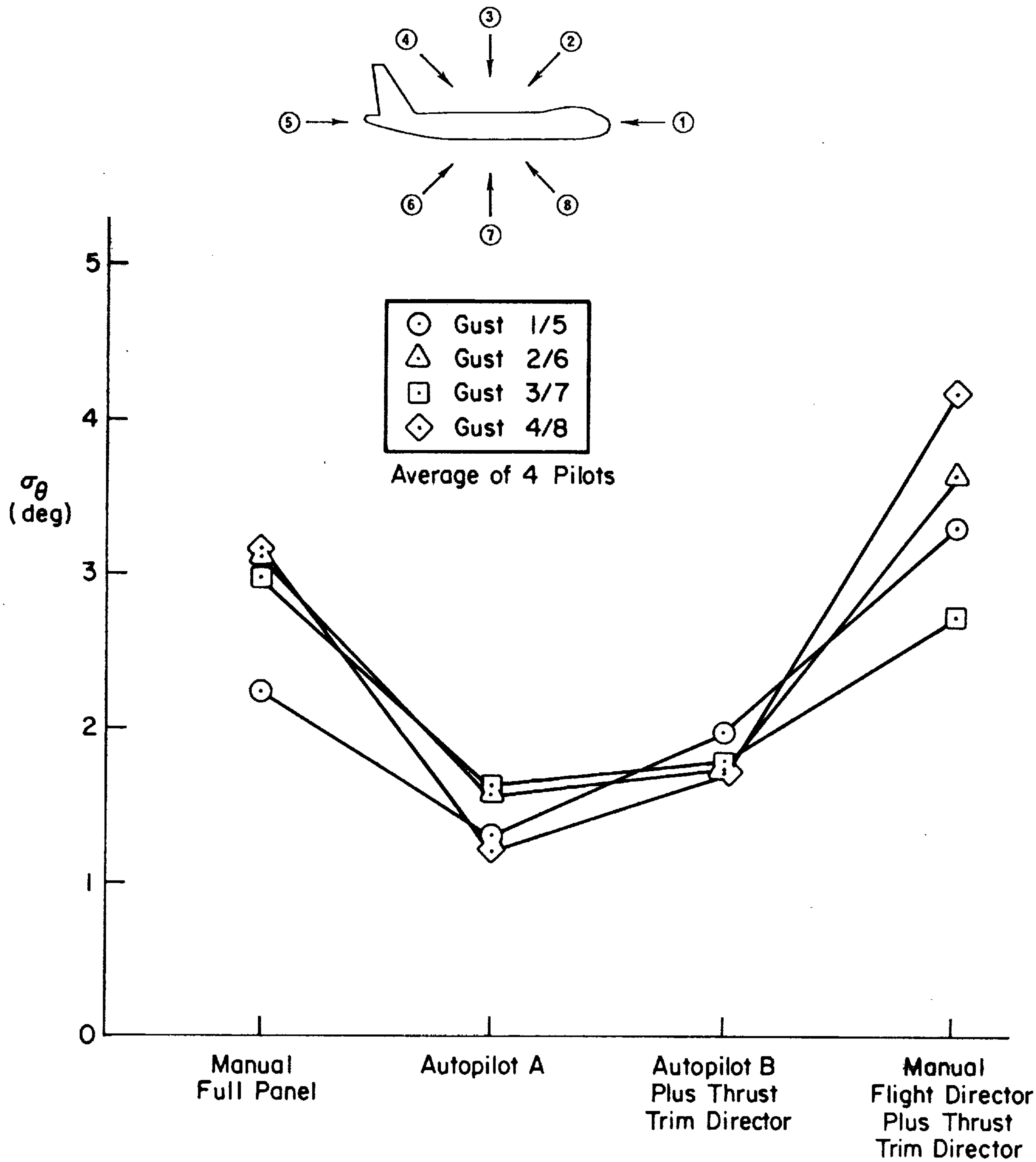


Figure 27. Pitch Attitude Excursions for Manual and Automatic Control Modes

Figure 27 shows the average pitch attitude dispersions for the four primary control systems tested. Individual gust directions are indicated so that the most crucial condition can be identified. The obvious result is that Autopilots A and B had much smaller attitude excursions than the manual modes. Autopilot A had slightly lower excursions than Autopilot B. This is partly due to the pilots using the high gain (no turbulence) attitude hold mode with Autopilot A, while Autopilot B employed the lower attitude gains appropriate for turbulence penetration, and partly because of the airspeed error feedback to attitude command in Autopilot B. There also is little difference in attitude excursions with direction of the discrete gust when the autopilots are engaged.

In manual control there is a slight difference in attitude excursion between use of the conventional full panel display and the addition of the turbulence flight director (attitude and thrust). Some increase in excursion is to be expected because of the airspeed feedback in the flight director control law and this indeed appears to account for the change in attitude excursions with gust direction. The significant difference in rms excursion between the flight director and Autopilot B results (the autopilot and flight director control laws are essentially the same) probably reflects the difference between continuous control (autopilot) and intermittent control (manual). The latter is due to periodic interruption of manual control to the flight director display in order to scan the instrument panel and validate the information being presented by the flight director.

RMS rate of climb/descent excursions are shown in Fig. 28. Note that gust 4/8 always produced the highest excursions in $\dot{h}$ and gust 2/6 the smallest. There is little difference in performance between the various autopilots and displays with the exception of the single deviation for the flight director and the 1/5 (headwind, tailwind gust). This could be due in part to insufficient pilot training and experience with the flight director. It also could indicate need for review of the flight director control law and nonlinear logic.

Figure 29 presents the rms airspeed excursions for each system. Again there is essentially no difference between the manual full panel, manual

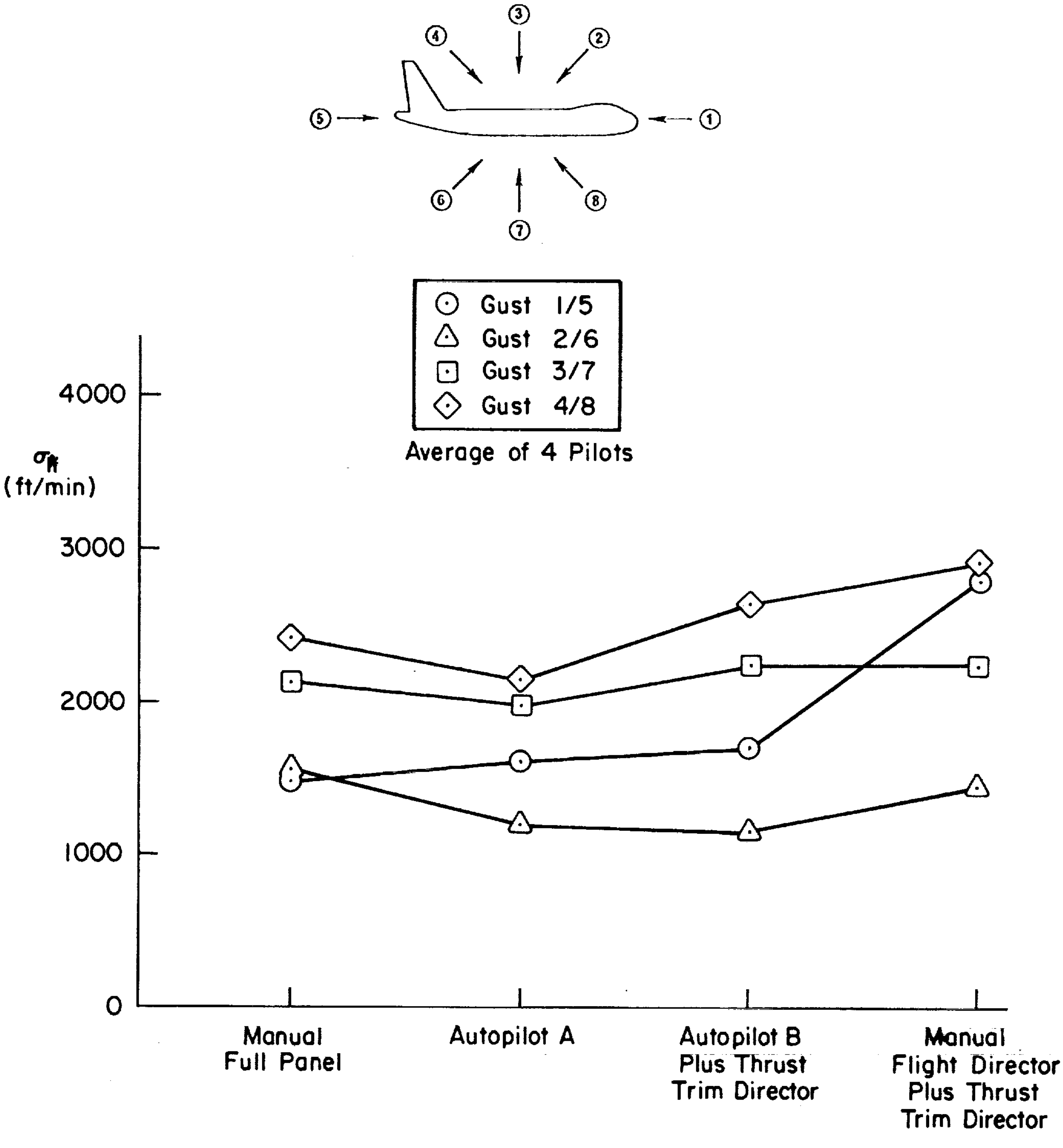


Figure 28. Rate of Climb/Descent Excursions for Manual and Automatic Control Modes

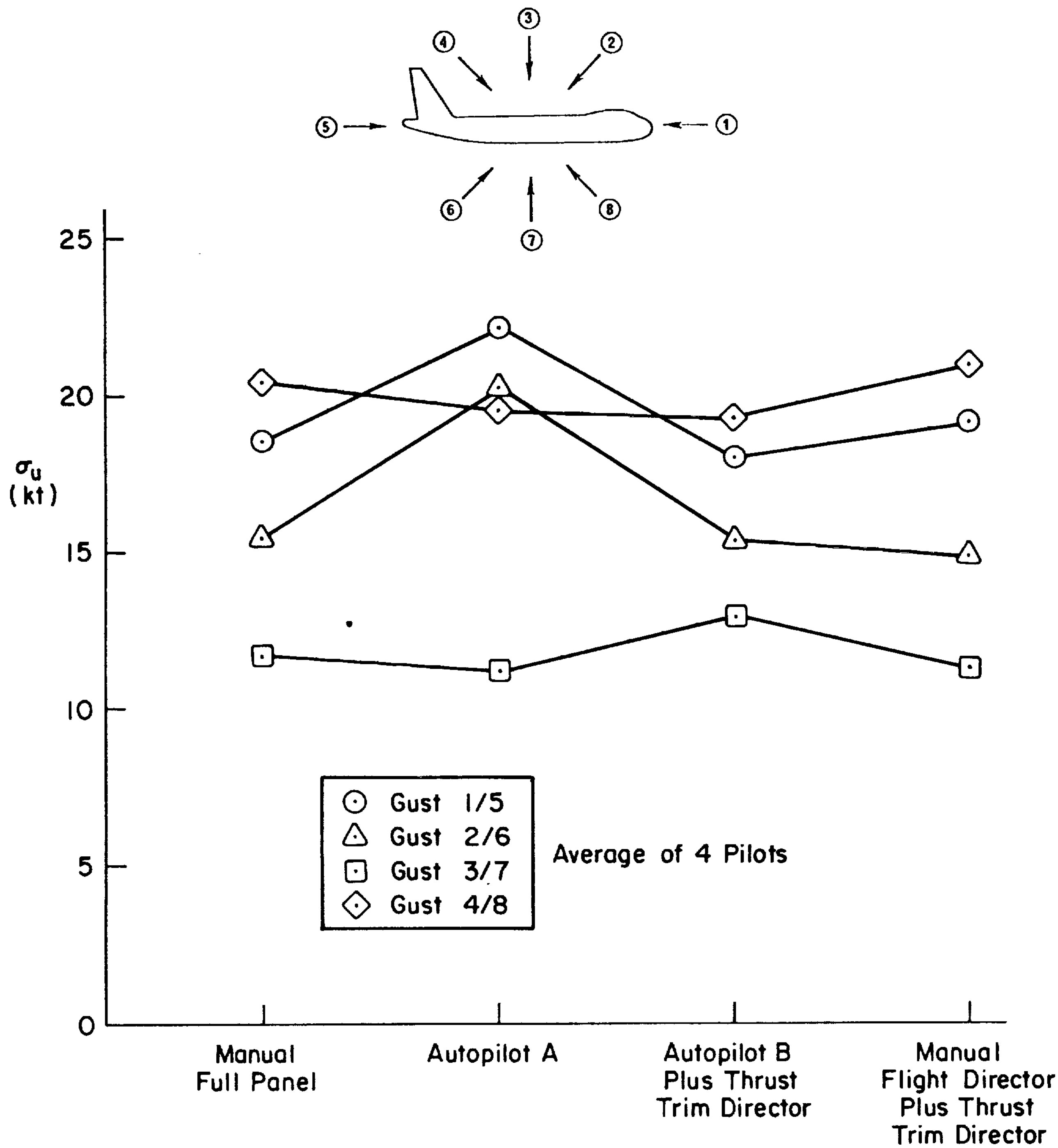


Figure 29. Airspeed Excursions for Manual and Automatic Control Modes

flight director, and Autopilot B performance. For Autopilot A there is a significant shift in airspeed deviation with the headwind-tailwind (1/5) and the 2/6 quartering gust (headwind from above, tailwind from below). This is due to the lack of airspeed feedback of any kind and the fairly tight attitude control system which completely overpowers the basic aircraft speed stabilizing tendencies.

Perhaps one of the more meaningful differences between manual and autopilot control in the severe turbulence simulated is reflected in Fig. 30. The rms normal acceleration at three fuselage locations (cockpit, c.g., and rear passenger door) are shown. For either autopilot system the rms normal acceleration is essentially the same throughout the length of the aircraft. There also is no significant difference between the autopilots. However, for manual control there is a 50 percent increase in normal acceleration between the front and rear of the aircraft. This difference between manual and autopilot control performance is consistent with that observed for pitch attitude excursions and is due to the greater pitch attitude weathervaning permitted in piloted control. The center of pitch rotation in response to a vertical gust is approximately one fuselage length ahead of the aircraft. If the aircraft is allowed complete freedom to weathervane, the tangential (vertical) acceleration at the rear will therefore be twice that at the nose ($a_T = R\omega = R\dot{\theta}$). Under "loose" manual control the increment is held to 50 percent increase. However, control by autopilot essentially eliminates pitch weathervaning and converts the gust disturbance into almost pure heave motion. This indicates loose attitude control is not desirable from a passenger ride comfort and safety standpoint.

Pilot Rating

At the completion of each simulation session each pilot rated the task performance and workload in accordance with the Fig. 19 rating sheet. The average pilot rating obtained for each of the four control configurations is shown in Fig. 31. The maximum variation about the average is shown by the vertical line through each point. In general, the workload was so high during the severe turbulence encounters that all piloting functions

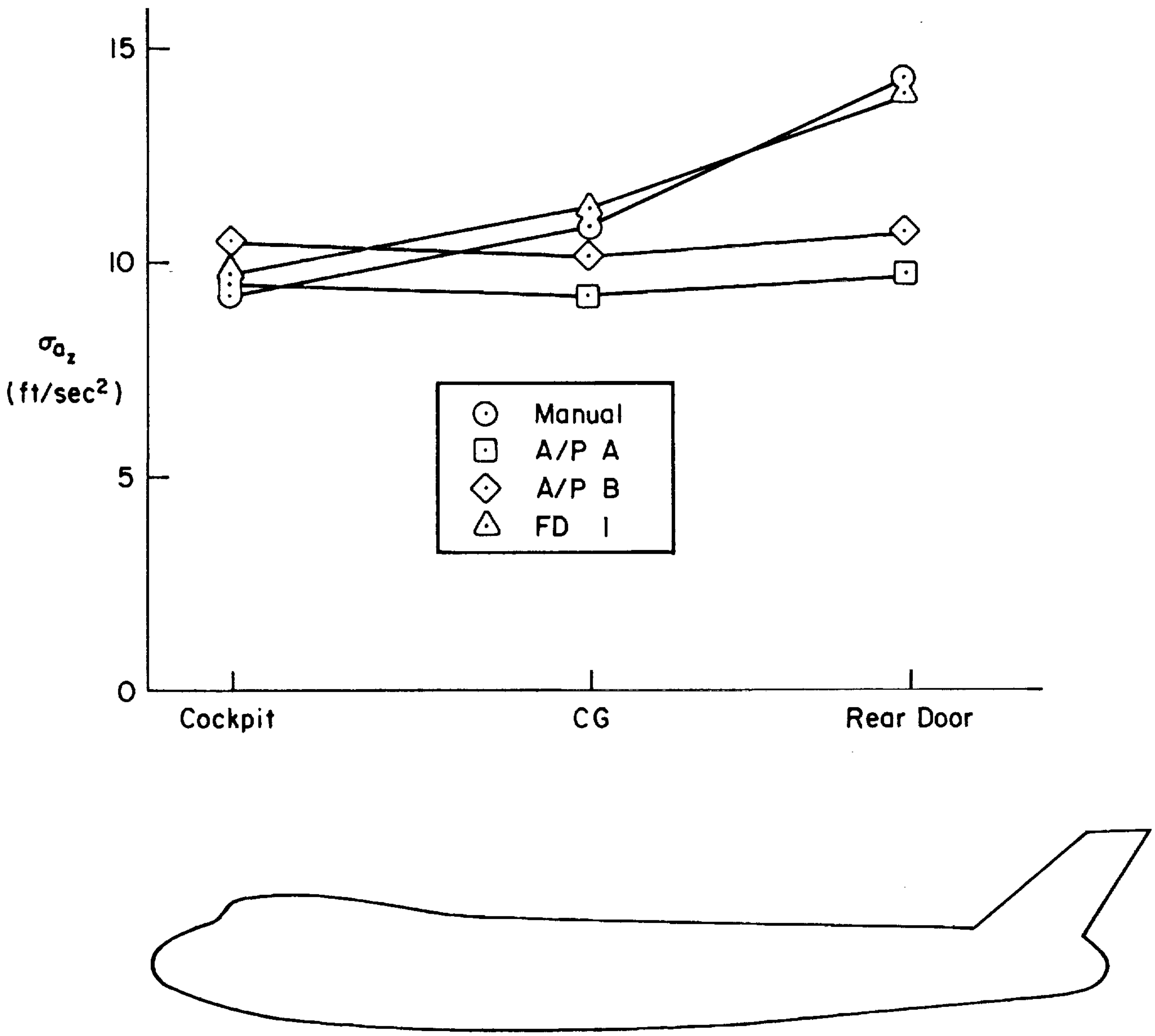


Figure 30. Difference in RMS Normal Acceleration Excursions with Fuselage Station for Manual and Automatic Control Modes

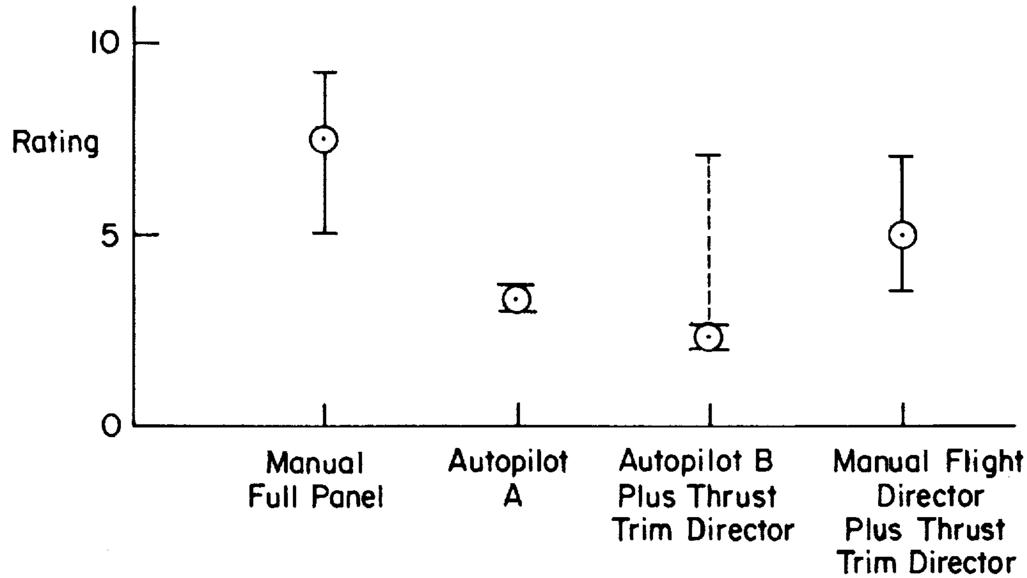


Figure 31. Average Pilot Ratings for Each System

(navigation, path, and speed control) could not be accomplished without aids. Specific comments are as follows.

Manual, full panel display. — The ratings given by all pilots except one were in the range of 7-8.5, indicating inadequate safety margin with high to extreme pilot workload to maintain control. One rated it a 5, indicating adequate safety margin but high workload. This pilot was not as experienced with Aircraft F as the other pilots.

Autopilot A. — This system was rated between 3 and 3.5 (clearly adequate safety margins but pilot workload borderlined between acceptable and unacceptable.

Autopilot B plus thrust trim director. — All but one of the pilots rated this system between 2 and 2.5 (clearly adequate safety margins with desired performance obtained with modest to acceptable pilot workload). One pilot rated it a 7 due to recollection of overly severe pitch attitude excursions. Subsequent analysis of his strip chart recordings indicated less pitch activity than with Autopilot A which he rated a 3.5. Therefore, during the post-simulation debriefing he apparently recalled aircraft motion from some other element of the simulation. The erroneous rating is indicated with a dashed line.

Flight plus thrust trim director. — Ratings for this display ranged from 3.5 to 7. The thrust trim director was considered very desirable. In all instances this display was marked down for "safety margin or workload" reasons largely due to the attitude flight director. Some objected to the tendency to visually "tunnel" on the attitude director to the exclusion of the complete instrument panel crosscheck scan. On the other hand, while the scan was being accomplished the attitude director error could become large. Subsequent response to the director command would result in a larger than desired control input.

The one pilot given the computed trim pitch attitude reference in place of the attitude director (but with the Thrust Trim Director) rated it a 2.5.

Summary

In the opinion of the highly experienced line-pilot subjects the overall task was very realistic of severe turbulence penetration and attendant aircraft control problems. Maneuvers closely bordering on upsets were observed during the simulation. These invariably were chance occurrences resulting from an inappropriate pilot input (control column or autopilot trim command) coinciding with a discrete gust of appreciable vertical component. The pilot input was generally based upon a prior decision to alter the aircraft flight vector without knowledge of the impending disturbance. The combined tailwind-downdraft or headwind-updraft were the most difficult shear disturbances to handle.

The quantitative parameters often used as measures of system performance (e.g., rms u, $\dot{h}$, θ, a_z) failed, for the most part, to discriminate between the systems and tasks investigated in this simulation. The single significant variation observed was between manual and autopilot regulation of pitch attitude and normal acceleration (at aft section of the aircraft). Manual control resulted in larger rms θ excursions and hence significantly larger a_z excursions in the aft cabin area. This is considered to be due to the more imprecise attitude control by the pilots and indicates loose attitude control is not desirable in the presence of large vertical gust components.

The new autopilot-director concept (Autopilot B) and the conventional (high gain) attitude hold autopilot (Autopilot A) provided essentially the same quantitative results. However, the new autopilot-director was preferred by all pilots because of the considerable decrease in workload it afforded. In particular, the Thrust Trim Director and Autopilot B allowed the pilots to make rapid, precise changes in aircraft trim either prior to or during severe turbulence encounters. This system was considered to provide an improved energy management technique for all phases of flight.

Overall manual control performance was not improved using the attitude and thrust trim directors as compared with the conventional full panel display. Overall pilot ratings of safety margin and workload slightly favored the director type display primarily because of the Thrust Trim Director feature. The attitude director was not considered desirable for manual control because the pilots either tended to "tunnel" on this one instrument (to the neglect of others) or it increased the panel scan and information collation workload by adding another instrument. The attitude director was desired in conjunction with Autopilot B since it provided a direct monitor of proper autopilot functioning. A limited trial indicated a simple display of computed reference pitch attitude (together with thrust trim) to be preferable for manual control.

CONCLUSIONS AND RECOMMENDATIONS

This analysis and simulation program provides evidence that some severe turbulence jet upset problems are related to closed-loop pilot/aircraft/display problems. This situation most readily occurs when the aircraft is changing energy state (e.g., slowing down and leveling off as required by standard operating procedures) prior to severe turbulence penetration. Due to the large inertia, low drag, and low thrust/weight ratio at high speed of modern jet aircraft, there often is insufficient time to achieve a new trim state before the severe turbulence is encountered. This is especially true in the case of surprise encounter. Due to a lack of direct display references, pilots must estimate and iterate on the attitude and thrust settings which will achieve the desired trim flight condition.

In this simulation, which presented realistic aircraft characteristics and pilot workload tasks, no dangerous situations were observed when the vehicle was subjected to only severe random turbulence (zero mean). Several near upsets were obtained, however, when large wind shear was superimposed on the severe random turbulence. Some of these closely matched recorded traces of actual flight incidents. The most critical gust from a safety/control ambiguity standpoint was found to be a quartering tailwind/downdraft. Based upon these results and pilot assessment, it was concluded that the simulation was representative of actual flight and aircraft control problems and that the large wind shears employed were, in fact, realistic. It would appear from this that the large shear gusts may be a major factor in jet aircraft upset.

Standard operating procedure for turbulence penetration calls for "loose" attitude hold in either manual or autopilot control modes. The problem with loose attitude control is that it allows considerable sharp weathervaning of the aircraft in response to vertical wind shear disturbances. Since the aircraft center of rotation for vertical gust inputs is generally one or more fuselage lengths ahead of the aircraft, this weathervaning produces a significant increase in vertical acceleration between the front and rear of the aircraft. Thus the ride is much more severe in the rear of the aircraft. Tight attitude control prevents this weathervaning and reduces vertical accelerations throughout the aircraft but also completely overpowers the normal aircraft speed stability and allows excessive airspeed excursions (to near stall) when large tailwind shear components are encountered. Thus a combination of tight attitude and loose airspeed control appears more appropriate to safe penetration and good ride qualities. This is best accomplished by autopilot since with manual control the system delays (including scanning) do not allow desired attitude and airspeed regulation.

Results of this simulation indicate pilots increase their gain (tighten rather than loosen control) and/or lose the ability to provide anticipation when in a severe random turbulence environment. Unfortunately, this makes the aircraft short-period mode more oscillatory and increases the rms vertical acceleration with attendant degradation in ride qualities. This together with the high workload (and stress) and the pilot's reluctance to let large attitude excursions develop under any circumstance generally leads to excessive airspeed deviations and many near-stall situations.

Based on the results of this program future turbulence penetration systems should:

- Compute and display trim attitude and thrust references for pilot selected airspeed and flight path (via rate of climb).

- Be based on an autopilot system rather than a longitudinal flight director system.

- Provide <u>autopilot</u> modes utilizing a mix of normal gain attitude and low gain airspeed feedbacks to control to the computed attitude reference.

- Display to the pilot the error between the trim attitude reference and the combined autopilot attitude-airspeed feedback so he can directly monitor autopilot and computer functioning.

- Incorporate feedback gain logic which gives greater weight to low airspeed flight situations and limits attitude excursions.

- Display to the pilot the error between the trim thrust reference and a combined feedback of aircraft longitudinal (inertial) acceleration and velocity relative to the local air mass (airspeed).

This form of thrust-required computation and display provides a direct indication of potential or future flight path. It also properly accounts for thrust commands initiated by the pilot (due to new airspeed select) or those that occur as a result of horizontal discrete gusts. With appropriate complementary filtering this system smooths air mass fluctuations and minimizes erroneous thrust commands that can result from rare but possible combinations of gust inputs and aircraft responses.

The simulation time available for this program only allowed a cursory investigation of the new display and autopilot system. Additional time would be required to optimize system gains, filters, logic, etc. However, even in its current state, the pilots were all very enthusiastic about the autopilot as it significantly reduced their workload and inspired confidence that they were using the best possible strategy to maximize safety margins (by reducing excursions) in a confusing and potentially dangerous situation.

Although the system was devised for a specific flight mode — turbulence penetration — simulation results indicate the concept to be very useful in all phases of flight (in both turbulent or calm air). The system not only provides a direct payoff in decreased pilot workload and improved penetration safety but also potential indirect payoff due to increased efficiency in aircraft energy management (e.g., increased engine life and fuel economy).

It is recommended that investigation of the improved director and autopilot system be continued with additional pilot subjects to further:

- Optimize the autopilot logic, gains, and filtering.
- Explore applicability in all flight phases under both calm and turbulent conditions.
- Explore possible energy management payoffs.

APPENDIX A

AIRCRAFT F OPEN-LOOP GUST RESPONSES

This appendix presents time responses of the open-loop vehicle motions to Gusts 1, 2, 3, and 4. Gusts 5, 6, 7, and 8 are the reciprocals and hence the responses are opposite. Two flight conditions are represented to show the change in vehicle responses. Figures A-1 to A-4 are for a low speed, low altitude climbing flight condition, i.e., 250 kt at 10,000 ft. Figures A-5 to A-8 are for a higher altitude and speed condition, i.e., 280 kt at 26,000 ft in level flight. Both conditions utilize a 600,000 lb aircraft. The second condition was also chosen since one reported upset (Ref. 3) occurred at this "recommended" turbulence penetration speed and flight path.

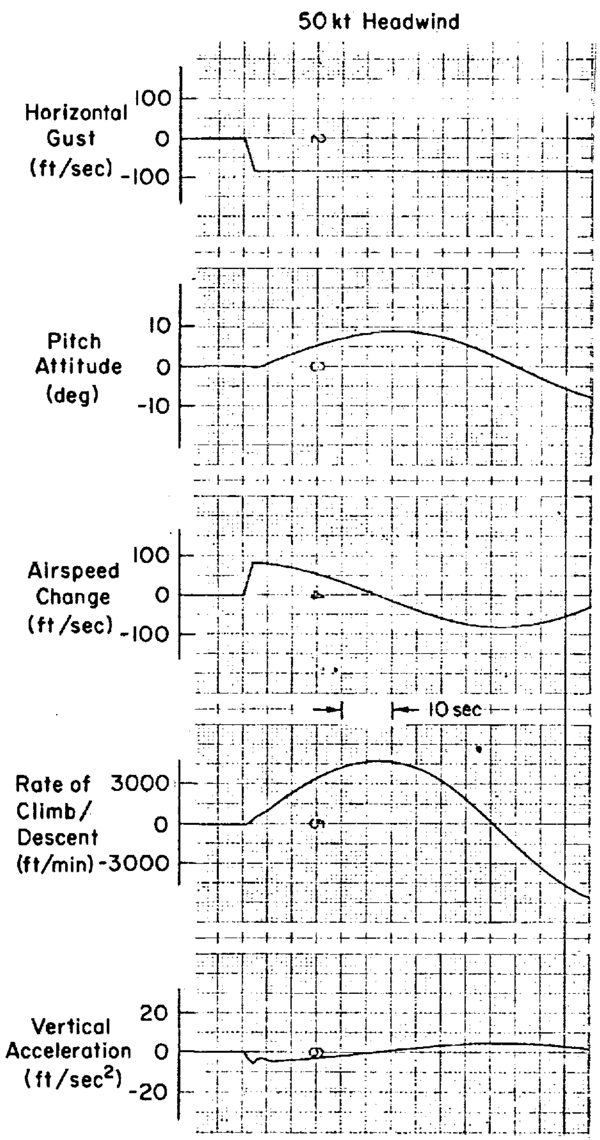


Figure A-1. Open-loop gust responses; Gust 1; 250 kt at 10,000 ft (3048 m); $\gamma_0 = 5$ deg.

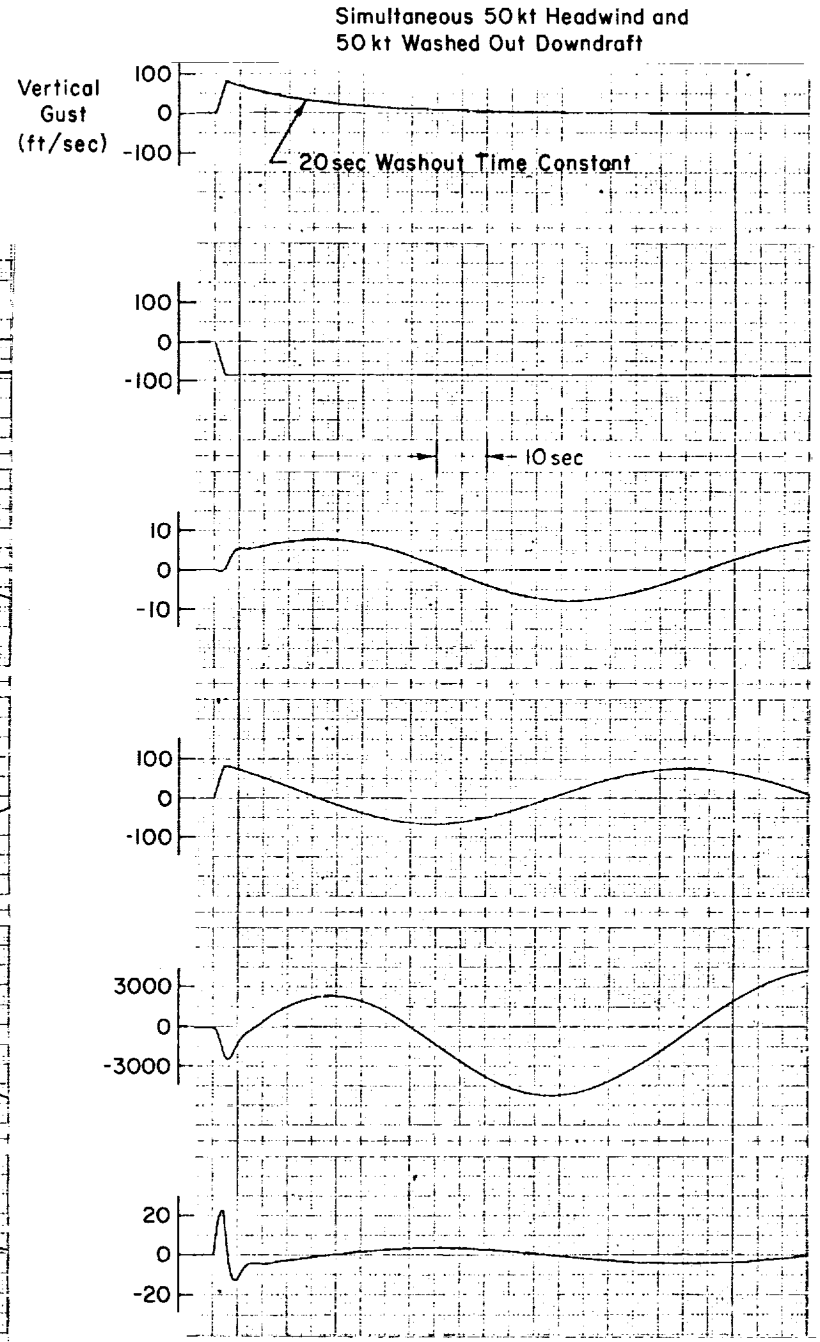


Figure A-2. Open-loop gust responses; Gust 2; 250 kt at 10,000 ft (3048 m); $\gamma_0 = 5$ deg.

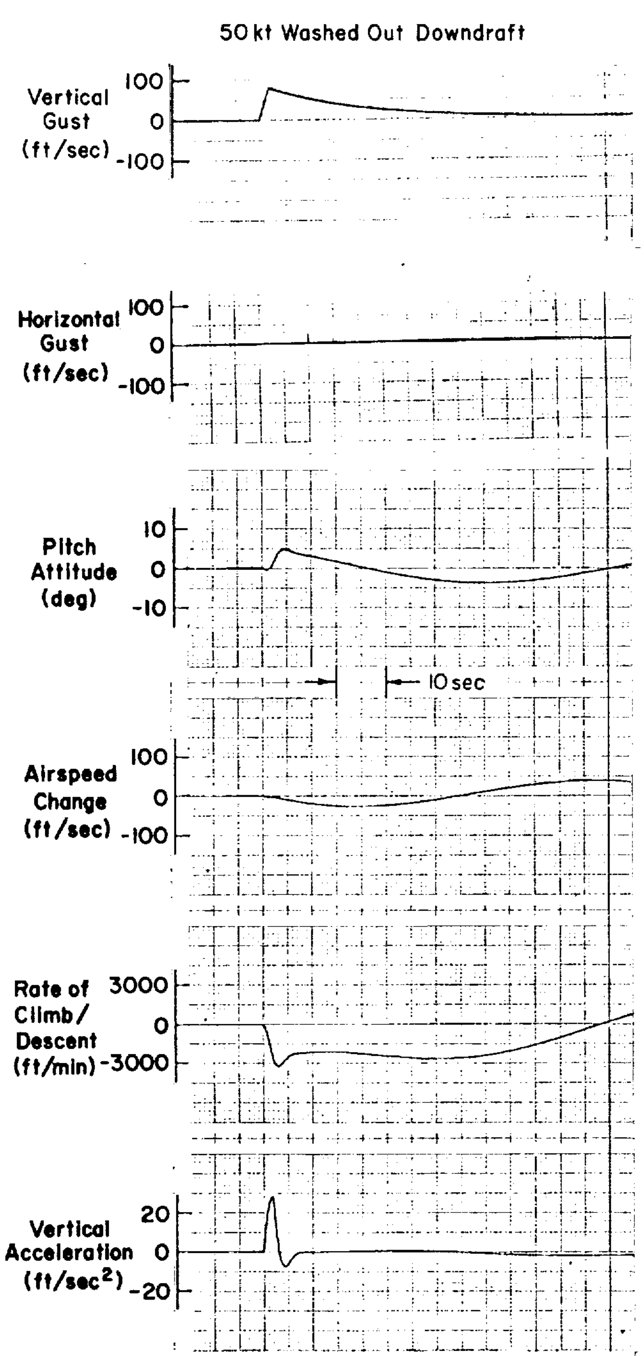


Figure A-3. Open-loop gust response; Gust 3; 250 kt at 10,000 ft (3048 m); $\gamma_o = 5$ deg.

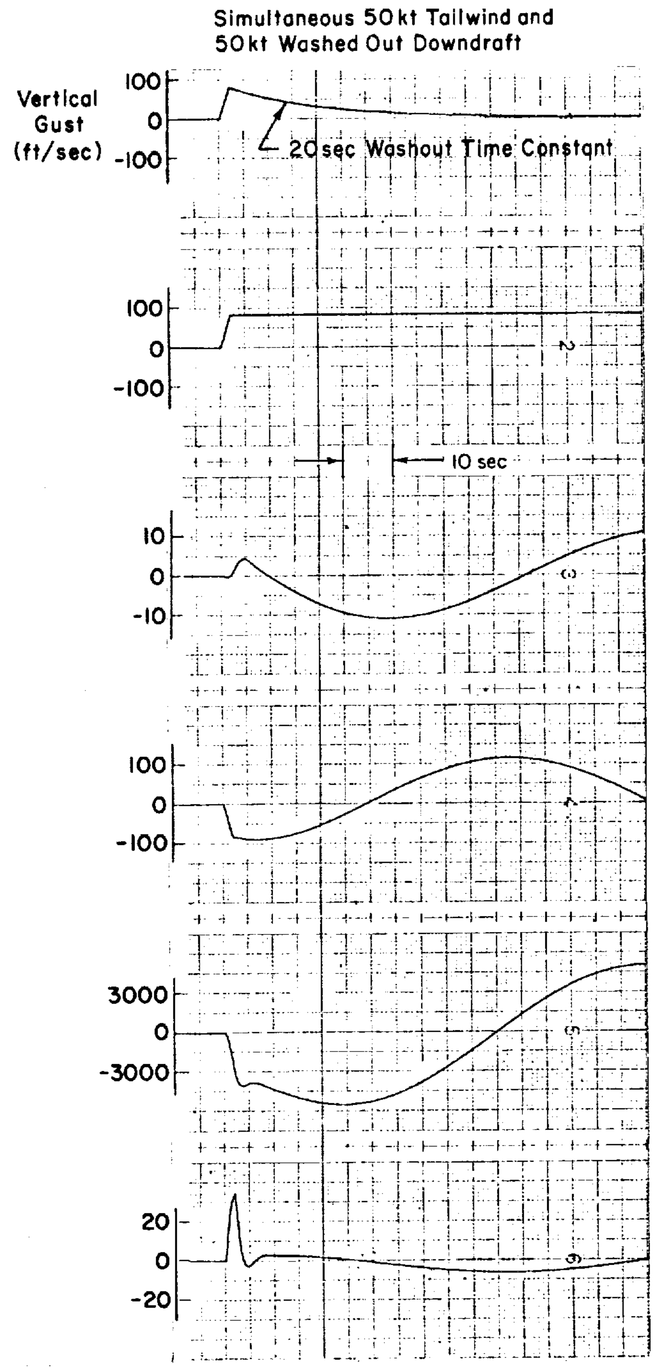


Figure A-4. Open-loop gust response; Gust 4; 250 kt at 10,000 ft (3048 m); $\gamma_o = 5$ deg.

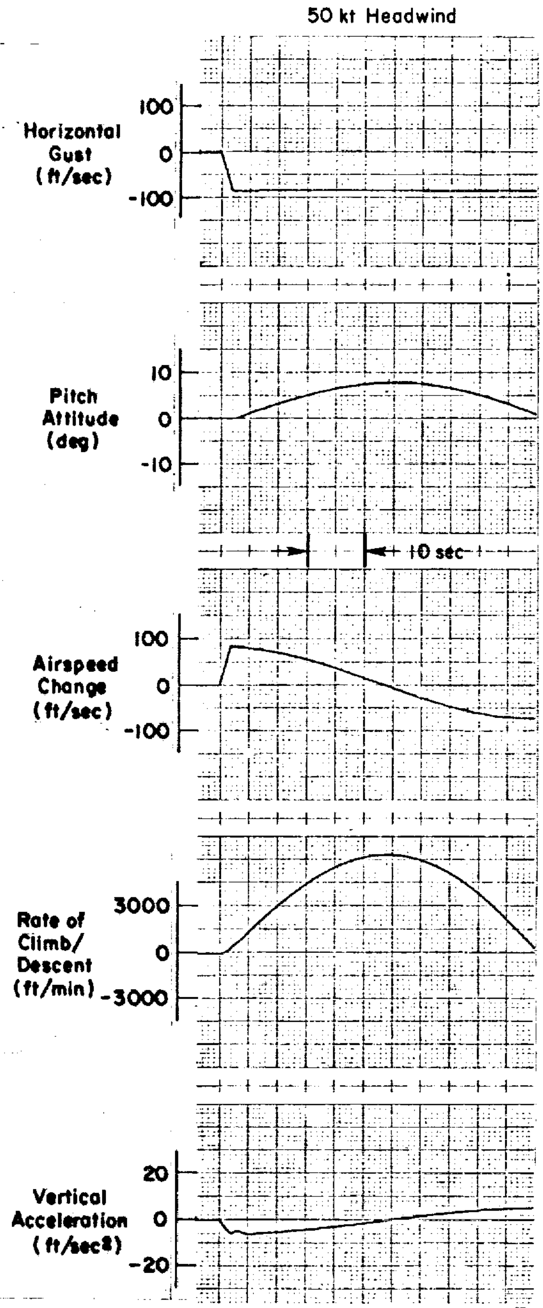


Figure A-5. Open-loop gust response; Gust 1; 280 kt at 26,000 ft (7924 m); γ_o = 0 deg.

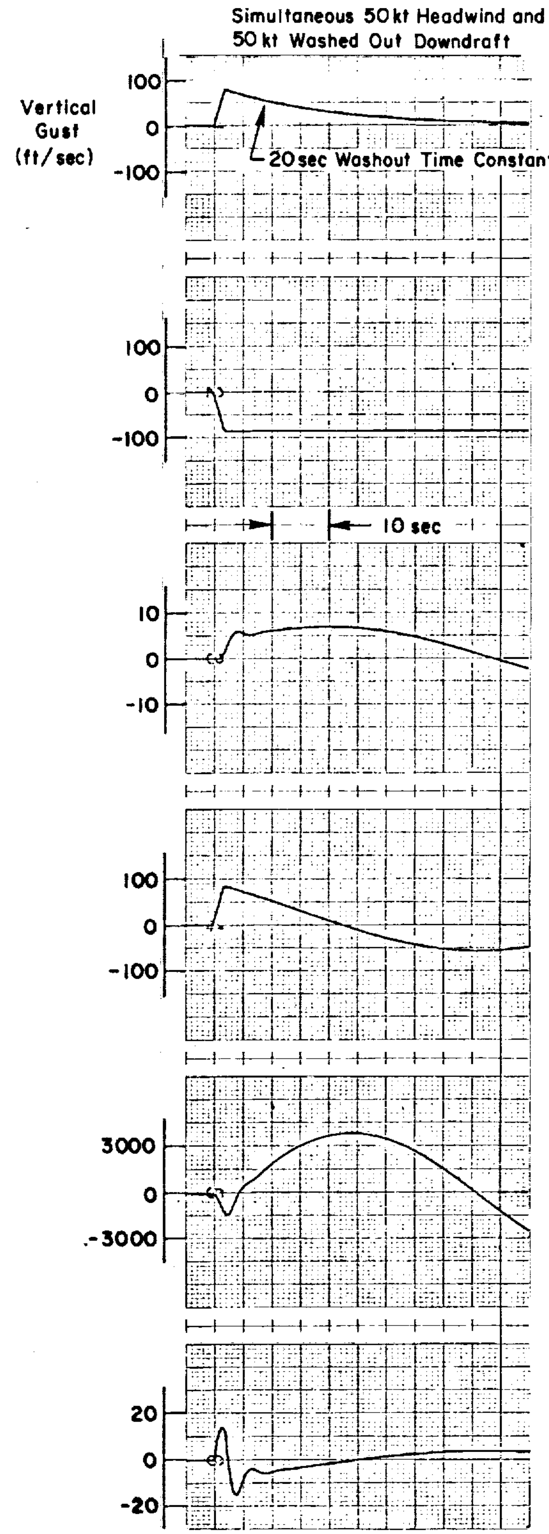


Figure A-6. Open-loop gust response; Gust 2; 280 kt at 26,000 ft (7924 m); γ_o = 0 deg.

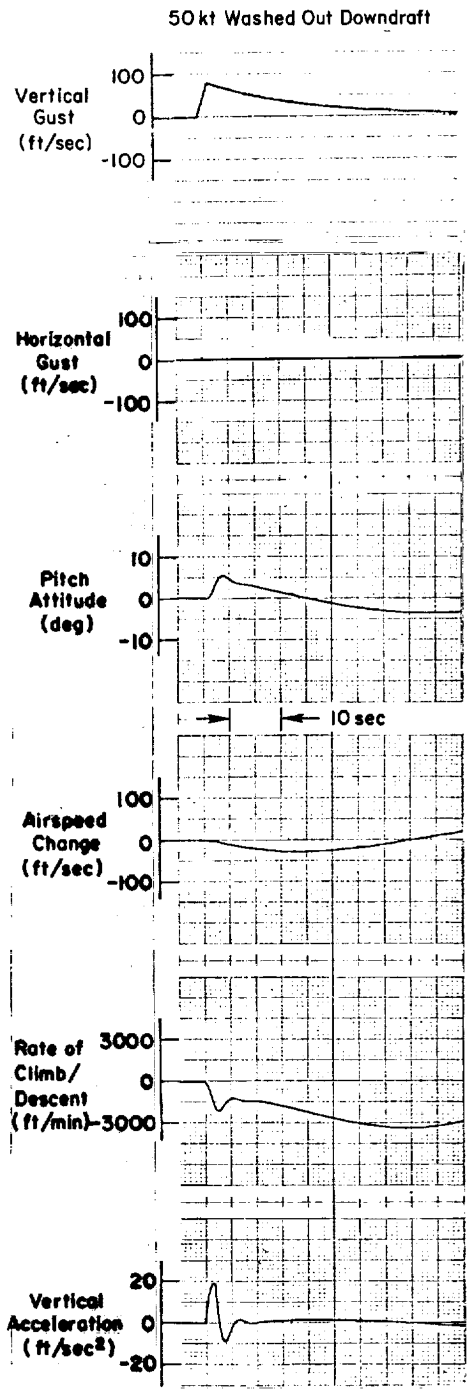


Figure A-7. Open-loop gust response; Gust 3; 280 kt at 26,000 ft (7924 m); γ_o = 0 deg.

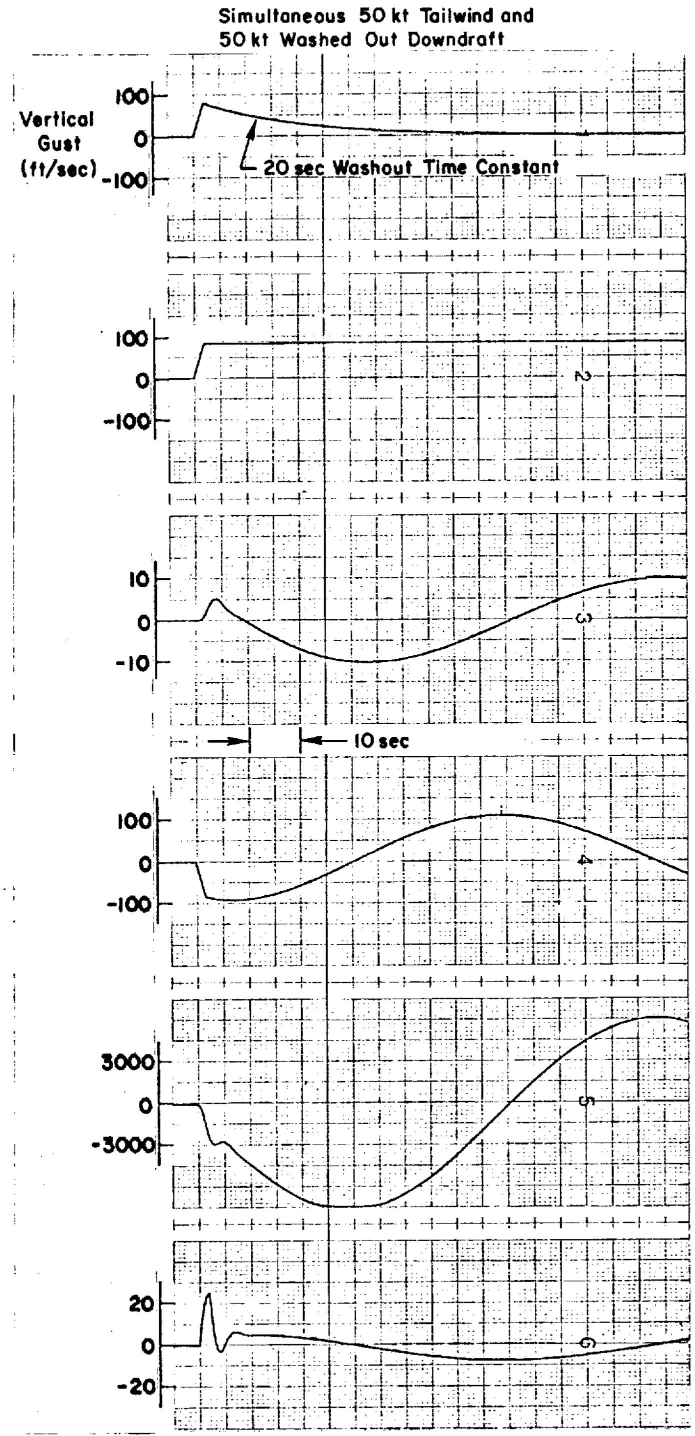


Figure A-8. Open-loop gust response; Gust 4; 280 kt at 26,000 ft (7924 m); γ_o = 0 deg.

APPENDIX B

AIRCRAFT F AUTOPILOT

Information for the autopilot configuration of Aircraft F was obtained from Ref. 16. The functions mechanized for simulation are summarized below.

Longitudinal

The basic longitudinal system is an attitude hold mode* in which changes to the reference pitch attitude are made manually via an attitude select knob on the control console. A block diagram is shown in Fig. B-1. Washed out pitch rate is used to provide damping. The pitch rate feedback is also lagged to attenuate high frequency structural mode. Roll attitude cross-feed is utilized to maintain level flight in steady turns. In turbulence the pilot is recommended to use the "turb" mode which reduces all gains by one half. Typical closed loop responses to a step θ_c are shown in Fig. B-2 for the normal system gain and the turbulence mode gain. It is readily apparent that there is little difference in response between the two.

Lateral

The basic lateral autopilot block diagram is shown in Fig. B-3. This system has both heading and bank angle command capability. In normal operation, turns to a new heading are achieved by setting the heading bug on the HSI to the desired heading. In turbulence mode the heading hold is disengaged leaving only the bank angle command. The roll angle command is rate limited to provide smooth, safe response to commands. Again, in the turbulence mode all feedback gains are reduced by one half.

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*Additional longitudinal autopilot modes (e.g., altitude hold, airspeed hold) are not used in flight through turbulence and hence were not mechanized.

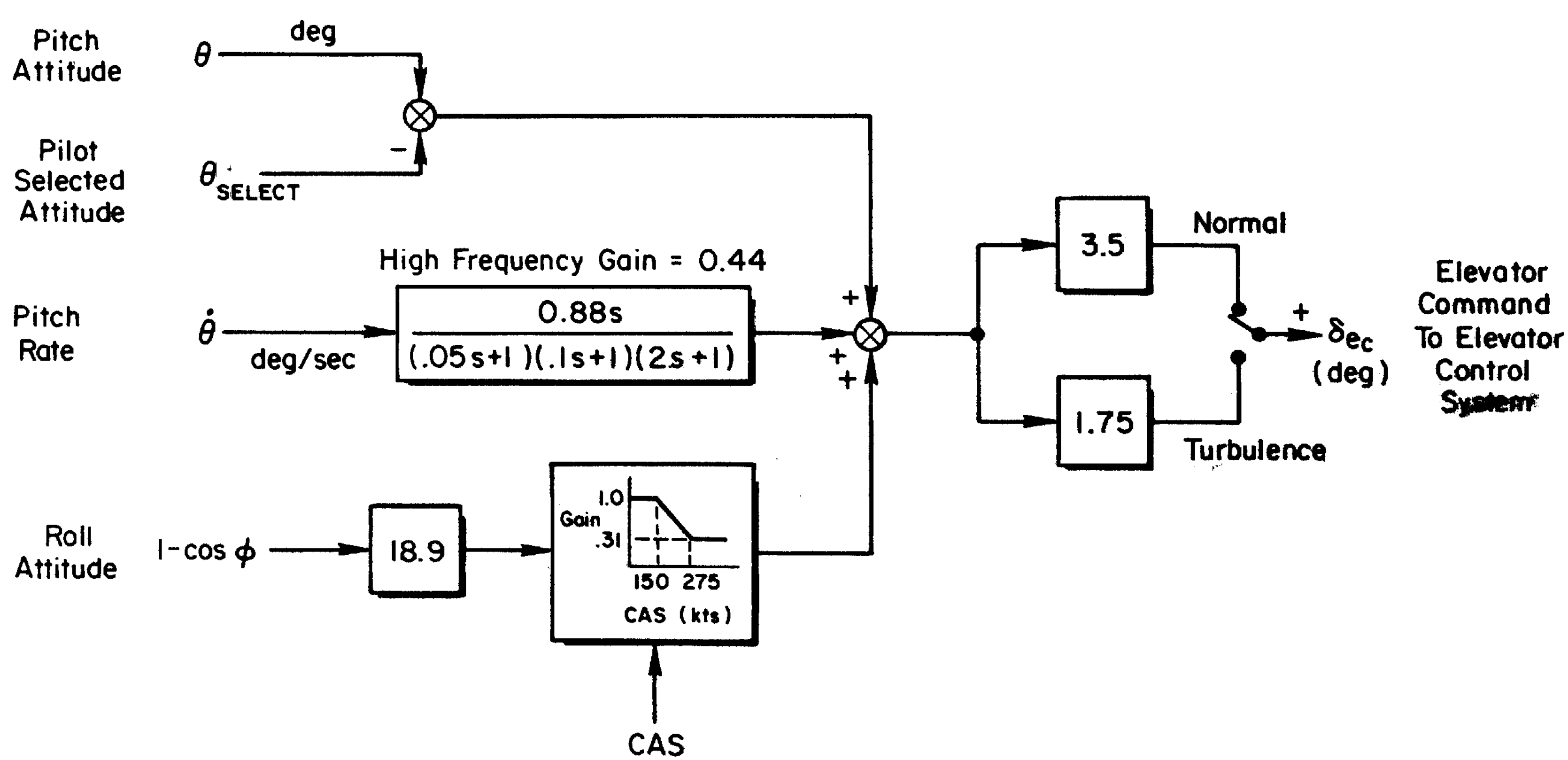
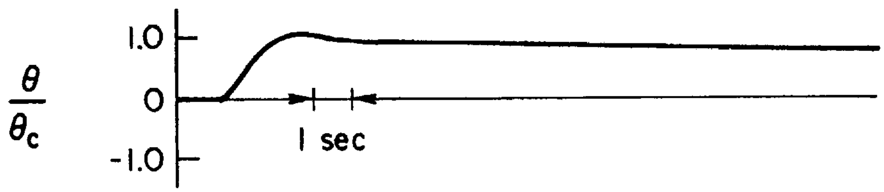
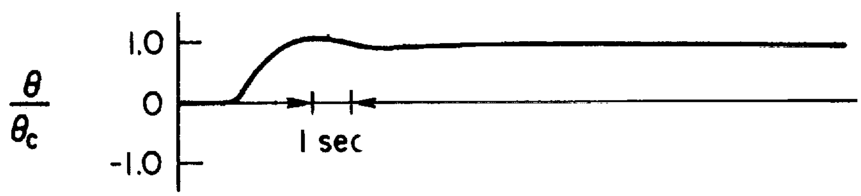


Figure B-1. Block Diagram of Aircraft F Longitudinal Autopilot (Autopilot A)



a) Normal Gain $K_\theta = 3.5 \frac{\text{deg } \delta_e}{\text{deg } \theta}$



b) Turbulence Gain $K_\theta = 1.75$

Figure B-2. Attitude/Attitude Command Time History for Autopilot A

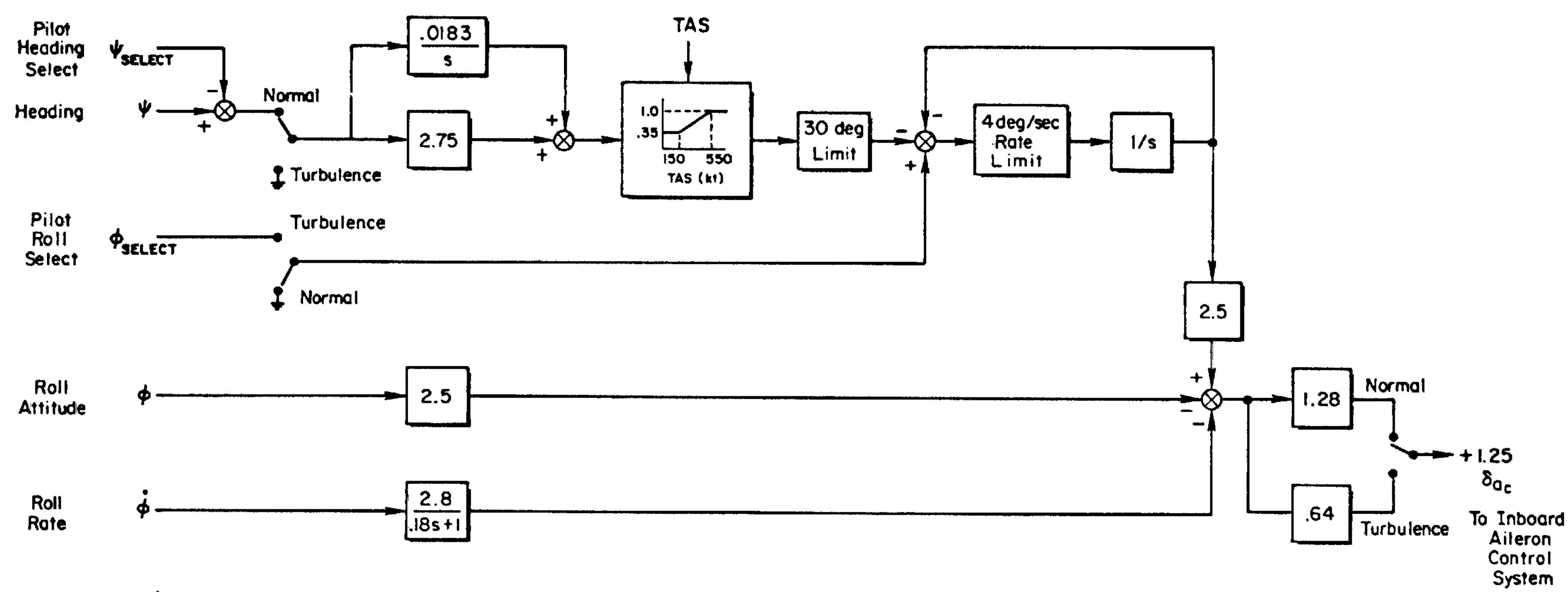


Figure B-3. Block Diagram of Aircraft F Roll Autopilot

APPENDIX C

SIMULATION SCENARIO

In order to set up a realistic scenario, two flights were devised. The first "trip" was from Los Angeles to Tucson and was primarily for pilot familiarization. Once the pilots were satisfied that they had attained the necessary proficiency level with the director displays, console layout, etc., they were given a break and then started on Trip No. 2 from Los Angeles to Sacramento. Standard Jeppesen en-route charts, instrument departure and arrival plates, and approach plates were supplied to the pilots. Navigation was accomplished using computed VOR information presented on the HSI and on an RMI display. DME information was available for the Number 1 VOR receiver (HSI). Aircraft position was available at the computer console on an x-y plotter, enabling one of the test engineers to give "radar vectors" and to monitor performance.

The simulated task was run with a complement of three people. Their functions are summarized in Table 1.

TABLE C-1. FUNCTIONS OF SIMULATION PERSONNEL

PILOT	COCKPIT ENGINEER	COMPUTER ENGINEER
Fly the task Evaluate each of the autopilots and the flight director Evaluate realism of the simulation	Act as copilot – Copy clearances – Tune radio – Set reference airspeed – Set reference rate of climb/descent Take notes on pilot commentary Answer questions	Act as ATC controller – Issue clearances – Give radar vectors – Give weather problems Monitor strip chart output Input random and discrete gusts at appropriate time and flight condition

The flight used for evaluation of the tested autopilots and the turbulence flight director was from Los Angeles to Sacramento (see x-y plotter overlay in Fig. C-1). This was picked because it involved sufficiently complex departure and arrival procedures and was about the right length (1 hour). Before departure, the pilots were given a weather briefing for lines of thunderstorms along the route with moderate to, at times, severe turbulence. The IFR clearance read as follows: "You are cleared to the Sacramento Airport via the Gorman Three departure, Avenal transition, Victor 137 Salinas, Victor 25 San Francisco direct Concord, Concord One arrival. Maintain Flight Level 240." Since no visual cockpit display was available for VFR flight, the problem was initiated at 2000 ft, climbing at runway heading. The "Gorman Three departure" is a standard IFR procedure out of LAX.

Early in the program the pilots flew the entire route four times (manual, Autopilots A and B, and flight director). However, this was found to be too time consuming so the flight was broken up into three segments. These are shown along with descriptions of the finalized scenario in Figs. C-2, C-3, and C-4. In these figures the notes in rectangular boxes indicate the gust environment input by the test engineer. The notes in "clouds" indicate the ATC clearances "radioed" to the pilot. Most of the evaluations were done on Segment 2 and 3. These two are discussed in detail in the following paragraphs.

Segment 2 (Fig. C-3)

The first discrete gust (Combination 4/8/4) occurs shortly after level off from a climb to 26,000 ft. Each of the other possible discrete gust combinations are given during the remainder of Segment 2 in level flight. In each case the random turbulence is turned up to an rms values of 20 ft/sec before the discrete gust inputs and then returned to 4 ft/sec, thereby simulating a "patch of turbulence."

Segment 3 (Fig. C-4)

This segment was initialized at 33,000 ft and with a clearance to descend to 22,000 ft by the Salinas VOR (55 miles). The turbulence was completely removed to encourage a high-speed descent (near barber pole). When it was apparent that a steady-state descent was established, the turbulence was quickly increased to an rms level of 20 ft/sec and a horizontal discrete gust sequence executed. The rationale was to cause the indicated airspeed to exceed maximum Mach (barber pole) thereby putting the pilot in a position where simple loose attitude control at constant power resulted in exceedance of a safety boundary. Thus, it was possible to evaluate the pilots' manual response (reduce power, increase pitch attitude, etc.) against the response with autopilot and flight director aids.

The segment between Santa Cruz Intersection and Saratoga Intersection was used to obtain statistical data for normal flying in light turbulence (rms control activity, altitude, attitude, etc.).

The holding pattern at Saratoga Intersection was designed to increase the pilot workload to maximize the probability of inappropriate pilot response to two discrete gust sequences. As shown in Fig. C-4, the holding pattern involves a rather complex entry procedure in addition to having to retune radios (set SJC on the No. 1 VOR), adjust the course selector, and figure out reciprocals. The random turbulence was increased at the first crossing of the holding fix.

After several turns in the holding pattern, the pilot was cleared direct to the Concord VOR and to descend to 12,000 ft. During the descent a 4/8/4 gust combination was given to complete the series of gusts.

All the pilots agreed that they became totally absorbed in the task and that the simulation scenario was very representative of a high workload situation.

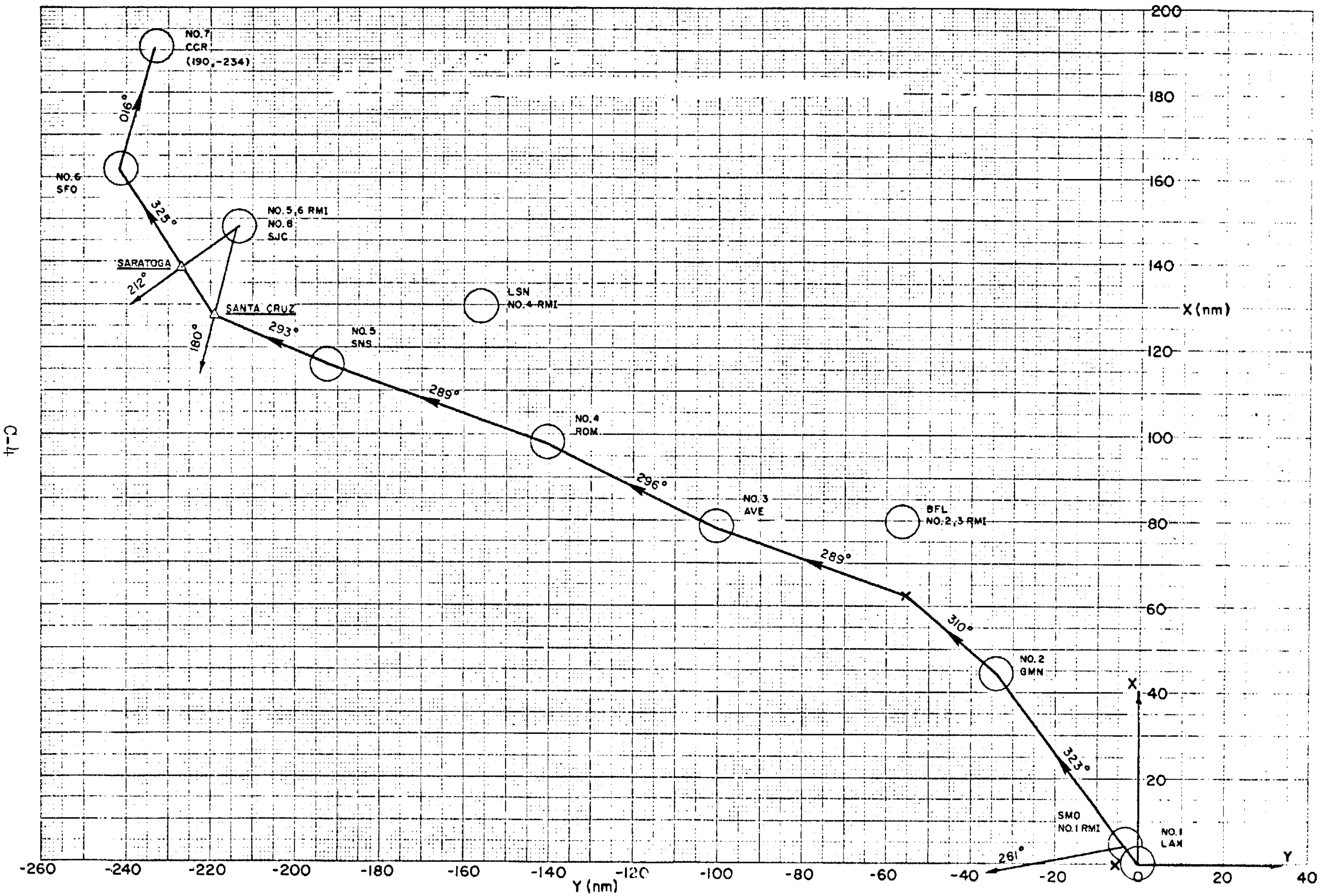


Figure C-1. x-y Plotter Overlay for Los Angeles-Sacramento Flight

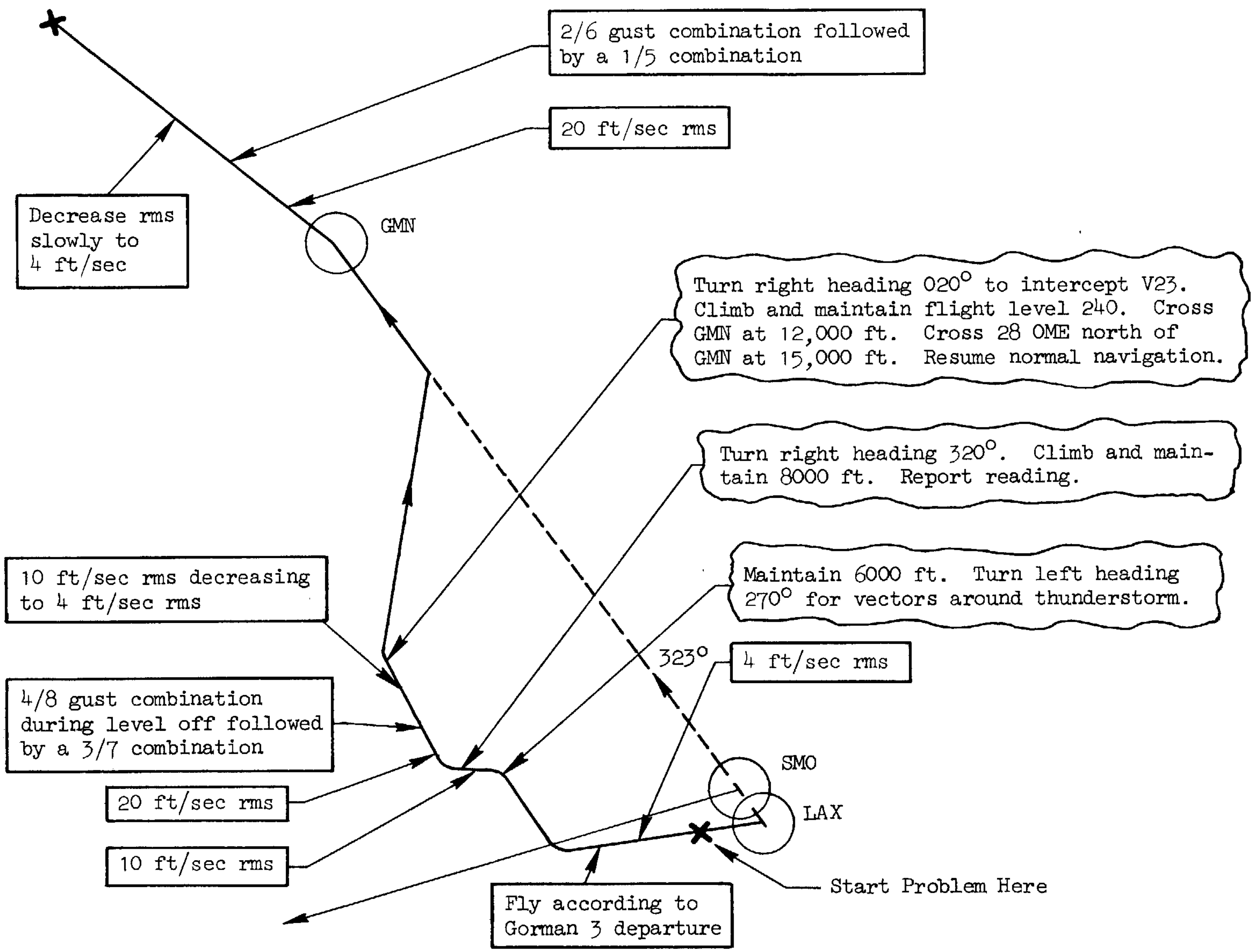


Figure C-2. Segment 1, LAX-SAC

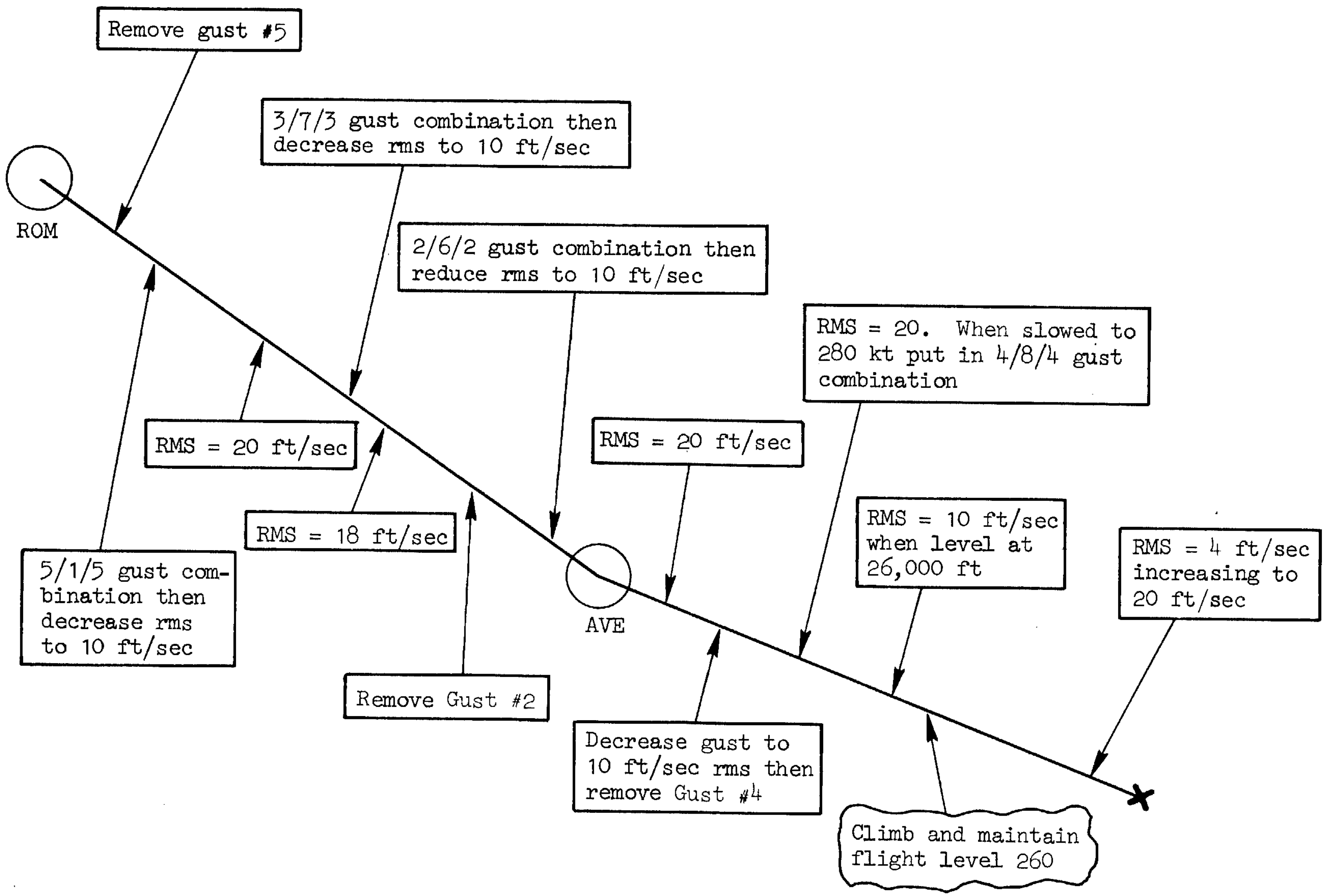


Figure C-3. Segment 2, LAX-SAC

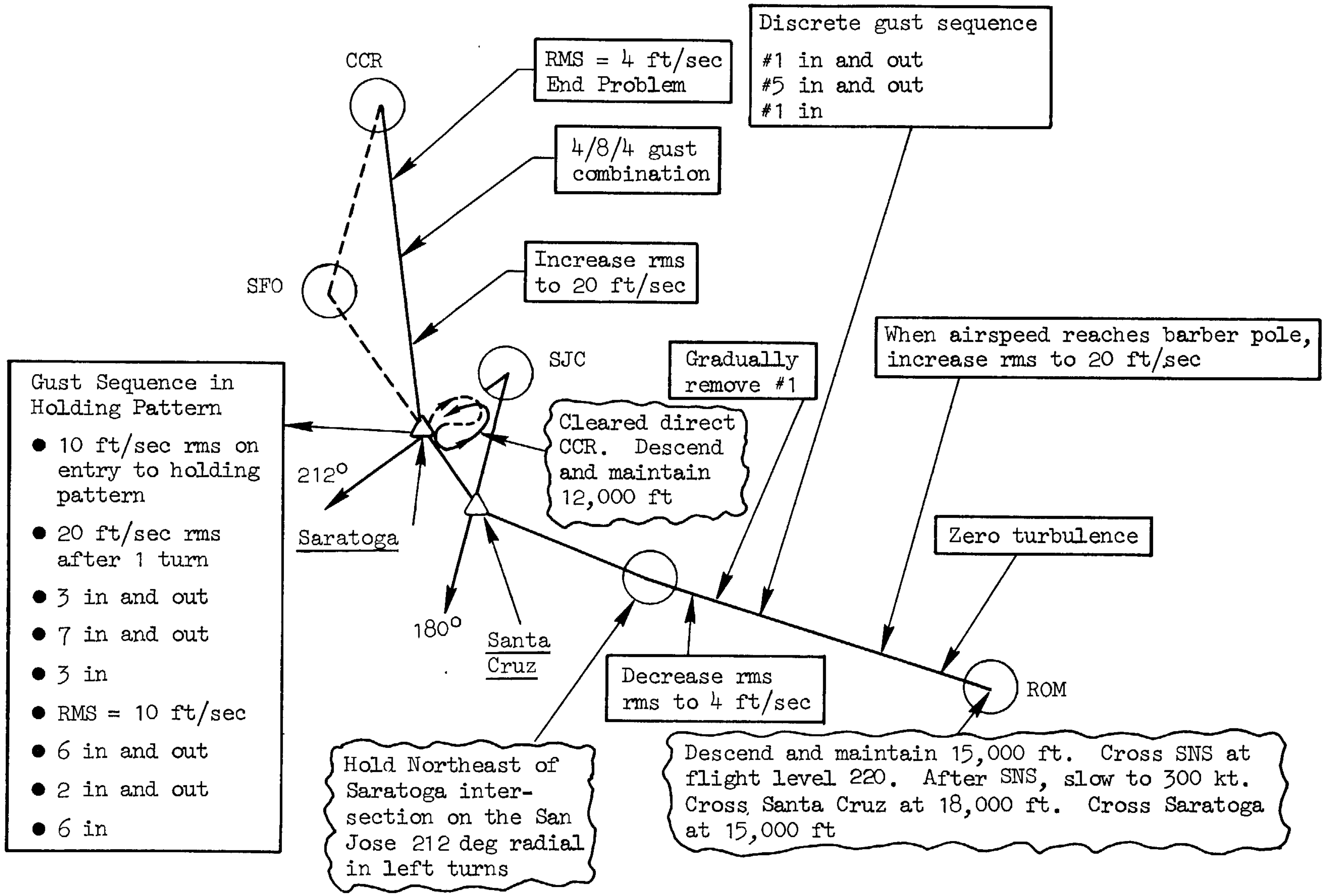


Figure C-4. Segment 3, LAX-SAC

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