SYSTEMS TECHNOLOGY, INC.

13766 SO. HAWTHORNE BOULEVARD • HAWTHORNE, CALIFORNIA 90250

Interim Technical Report No. 1003-2

TURBULENCE FLIGHT DIRECTOR ANALYSIS AND PRELIMINARY SIMULATION

June 1974

DRA

(NASA-CR-140487) TURBULENCE FLIGHT DIRECTOR ANALYSIS AND PRELIMINARY SIMULATION (Systems Technology, Inc.) 90 p HC $7.50 CSCL 01C

N74-33445

Unclas G3/02 17073

NASA CR-

TURBULENCE FLIGHT DIRECTOR ANALYSIS AND PRELIMINARY SIMULATION

By Donald E. Johnston and Richard H. Klein

June 1974

Prepared under Contract No. NASW-2118 by

SYSTEMS TECHNOLOGY, INC.
Hawthorne, California

for

Headquarters
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Turbulence Flight Director Analysis and Preliminary Simulation		5. Report Date June 1974
		6. Performing Organization Code
7. Author(s) Donald E. Johnston and Richard E. Klein		8. Performing Organization Report No. ITR-1003-2
9. Performing Organization Name and Address Systems Technology, Inc. 13766 South Hawthorne Boulevard Hawthorne, California 90250		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C.		13. Type of Report and Period Covered
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A control column and throttle flight director display system is synthesized for use during flight through severe turbulence. The column system is designed to minimize airspeed excursions without overdriving attitude. The throttle system is designed to augment the airspeed regulation and provide an indication of the trim thrust required for any desired flight path angle. Together they form an energy management system to provide harmonious display indications of current aircraft motions and required corrective action, minimize gust upset tendencies, minimize unsafe aircraft excursions, and maintain satisfactory ride qualities.

A preliminary fixed-base piloted simulation verified the analysis and provided a shakedown for a more sophisticated moving-base simulation to be accomplished next. This preliminary simulation utilized a flight scenario concept combining piloting tasks, random turbulence, and discrete gusts to create a high but realistic pilot workload conducive to pilot error and potential upset. The turbulence director (energy management) system significantly reduced pilot workload and minimized unsafe aircraft excursions.

17. Key Words	18. Distribution Statement		
Autopilot Flight director Turbulence penetration Energy management Jet upset			
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

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.

$a_{x_{FP}}$	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
A_u	Coefficient of the highest order term in the numerator polynomial of velocity perturbation due to elevator deflection
A_θ	Coefficient of the highest order term in the numerator polynomial of pitch attitude perturbation due to elevator deflection
C_D	Coefficient of drag
C_L	Coefficient of lift
CAS	Calibrated airspeed
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
G( )	Amplitude ratio of the real (σ) or imaginary ($j\omega$) part of the transfer function
G_i	Transfer function shaping of the feedback particularized by $i = a_x$, u, θ, etc.
h	Perturbed altitude
IAS	Indicated airspeed
IEPR	Indicated engine pressure ratio
IFR	Instrument flight rules
IVSI	Instantaneous vertical speed indicator
kg	Kilogram
kt	Knot, nautical mile per hour

K_i	Feedback gain particularized by $i = a_x$, u, θ, etc.
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
N	Unit of force, Newton
N_j^i	Numerator of the ith perturbation due to the jth forcing function; $i = a_x$, u, θ, etc.; $j = \delta_e$, δ_c, u_g, etc.
q	Dynamic pressure
R/C	Rate of climb
s	Laplace operator, $s = \sigma \pm j\omega$
SOP	Standard operating procedure
T	Thrust
T_E	Time constant of the engine first-order lag
T_{FD}	Time constant of the first-order shaping in the effective flight director feedback
T_i	Time constant of the real root for the numerator particularized by i = h, u, θ, etc.
T_{L_i}	Time constant of the first-order lag filter in the ith feedback
T_{p_1}, T_{p_2}	Time constants of the two real roots for a phugoid mode with greater than unity damping ratio
T_{WO}	Time constant of a first-order high-pass filter (or washout)
u	Perturbation inertial velocity along the flight path
u_a	Perturbation velocity along the flight path relative to the air mass
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
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
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
σ	Real part of the Laplace operator
$j\omega$	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

SECTION I

INTRODUCTION

Turbulence upset is a temporary loss of control brought about by severe turbulence encounters. It can result in sudden loss of several thousand feet of altitude, passenger and/or crew injuries or fatalities, aircraft structural damage, etc. 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 groundbased 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 "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 (Fig. 1). But, before jumping on the poor pilot, it should be noted that at least two recent "incidents" occurred while on autopilot (Refs. 2 and 3).

In light of this 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 analysis techniques, might provide new insight to the "problem." 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.

This interim report is devoted mainly to the fifth objective: synthesis of a turbulence penetration flight director and autopilot to:

- Minimize gust upset tendencies.

- Minimize unsafe aircraft state vector excursions.

- Maintain satisfactory ride qualities.

- Provide harmonious display and aircraft motions.

However, it also contains a review of and additional information regarding factors contributing to upsets. A later report will cover validation of the display and autopilot systems in a moving-base piloted simulation and establishment of design guidelines.

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).

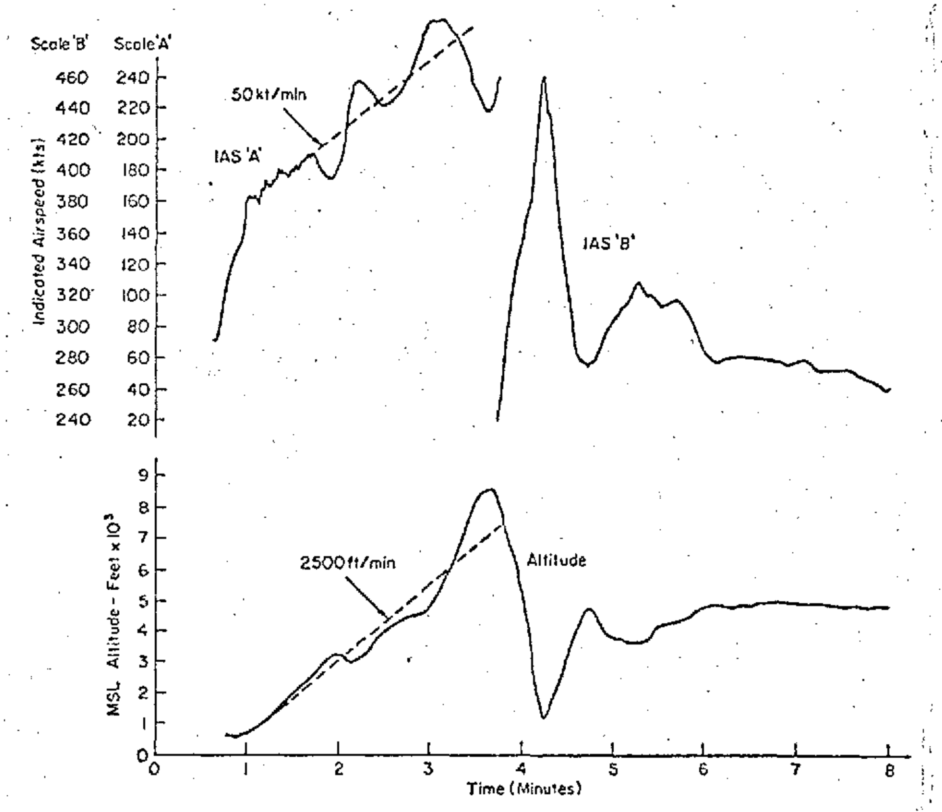
Thes recurring aspects led to a review of the basic stability of an aeroelastic aircraft during sudden encounter with large discrete vertical gusts,

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

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

to a search for large, discrete, high shear gradient disturbances, to a review of piloting techniques, and to a dynamic analysis of 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 is a root cause. This immediately raised the specter of aircraft static stability (short period), but this was found not 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 huge inertias, low thrust-to-weight ratios, and very low drag, the pilot must continually be operating 2-3 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 has uncovered several items which provide additional support for some of the conclusions of Ref. 4. The first is an incident which occurred while the aircraft was under control of an attitude hold autopilot. Figure 2 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 easily contribute to, an upset by overpowering the normal aircraft speed stability and allowing speed to decay.

Aircraft IFR/Climbing/On Autopilot/300 kt (154 m/sec) IAS

"crossing FL 270: captain started to decrease speed to 250 kt (124 m/sec) and increase R/C

at FL 280: 265 kt (136 m/sec)

- moderate to severe turbulence
- attitude reference decreased (to accelerate to 275 kt (142 m/sec) penetration speed)
- speed actually decreased; R/C showed 2500 fpm (12.7 m/sec)
- attitude reference decreased further
- speed continued to fall rapidly

230 kt (118 m/sec)

- 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 (18 m/sec) speed loss

and necessitated manual takeover"

Figure 2. Summary of Severe Turbulence Penetration While on Autopilot

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."

Discussion of additional incidents is contained as a part of Section II, in which some characteristics of Aircraft F are examined. This aircraft has been selected as the subject vehicle for this synthesis and simulation program. It is considered typical of jumbo jet characteristics and, most important, a complete data package for a previous NASA simulation is available. This previously mentioned energy management problem is also reviewed in some detail in Section II. A new turbulence penetration system concept is synthesized in Section III. This system consists of a flight director indicator for control of loose 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 results of a preliminary, three-degree-of-freedom simulation are presented in Section IV. The purpose of this simulation was to finalize system gains and some nonlinear logic aspects of the director system. Conclusions and recommendations are summarized in Section V.

SECTION II

REVIEW OF THE PROBLEM

It was indicated previously that a large percentage of upsets have occurred prior to establishing high attitude 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 to be 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 is 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 are on file at the 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.

A. 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 (103 m/sec) 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., noise abatement and initial climb departure. Following

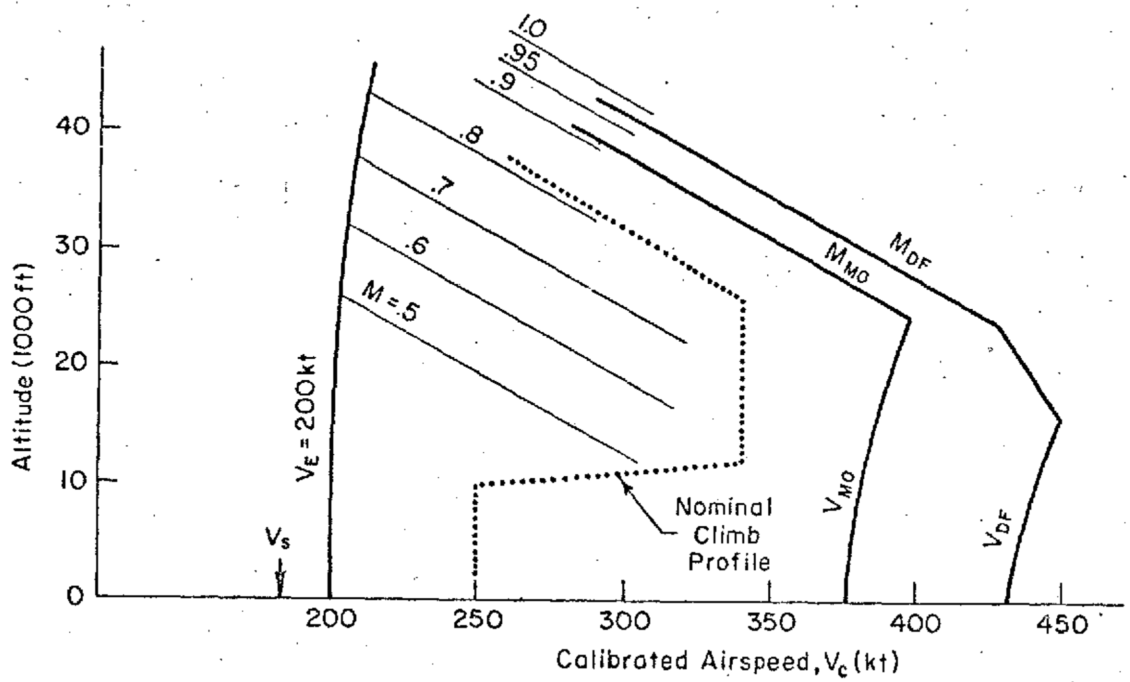


Figure 3. Aircraft F Flight Envelope and Nominal Climb Profile

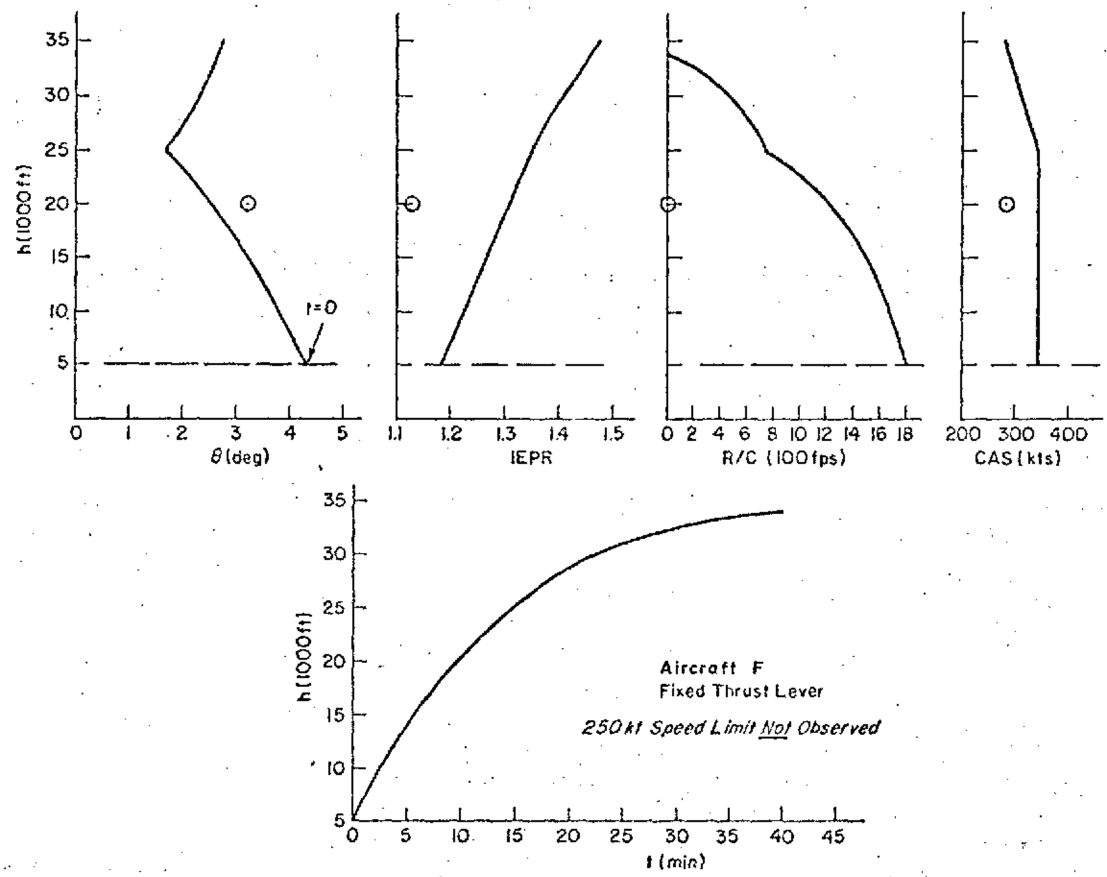
these, the aircraft is under an FAA-imposed speed limit of 250 kt (129 m/sec) to 10,000 ft (3048 m). Above 10,000 ft (3048 m) the path and speed may be selected based upon tradeoff of operational cost and other pertinent considerations.

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.

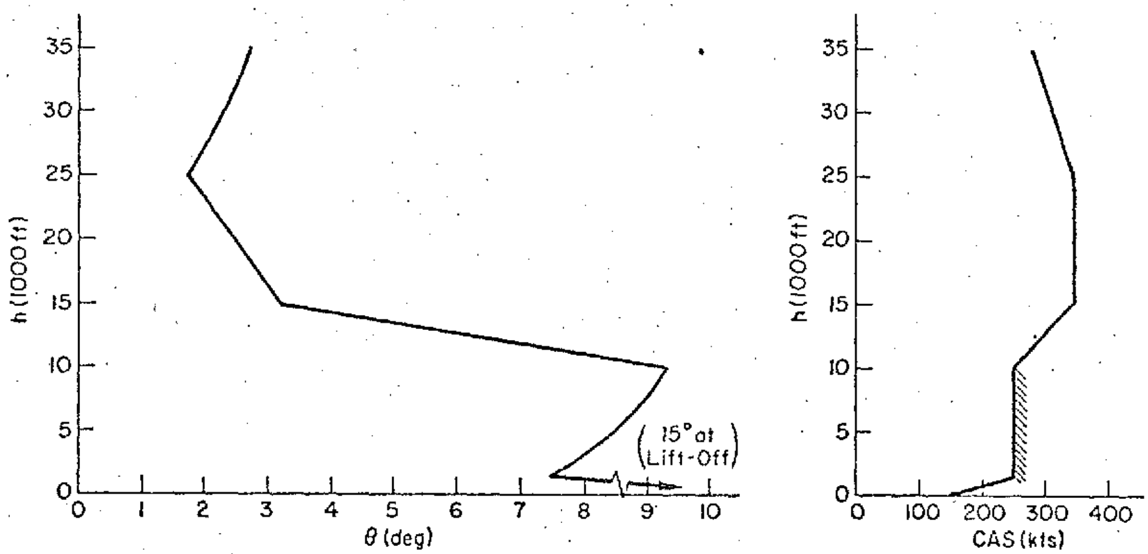
If these do not occur, further EPR adjustment is required and the process is repeated until the desired stable flight path is achieved. A waiting period is inherent between EPR (and attitude) adjustments to allow the aircraft to stabilize. To compound matters further, time lags between throttle movement, 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 to 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, 175 m/sec) but without observing the 250 kt (129 m/sec) speed limit below 10,000 ft (3048 m) altitude. It is readily apparent that attitude, thrust (IEPR), 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 (144 m/sec). 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 (144 m/sec) penetration speed, the rate of climb would change from +914 fpm (4.6 m/sec) ($\gamma = +1.06^{\circ}$) to −695 fpm (3.5 m/sec)($\gamma = -0.94^{\circ}$).]

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 (129 m/sec) to 340 KIAS (175 m/sec) 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



a) Nominal Climb Speed Limit Not Observed



b) Effect of Speed Limit on Trim θ

Figure 4. Variation of Trim Display Values During Climb

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 (129 m/sec) 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.

B. 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.

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
STABILIZER	Trim as necessary	Do not change trim

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.

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 to 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."

C. 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.

Stability derivatives and transfer function factors for two representative flight conditions are presented in Appendix A: 250 kt at 10,000 ft (129 m/sec; 3048 m) reflecting the low altitude speed limit case; and 280 kt at 26,000 ft (144 m/sec; 7925 m) reflecting an en-route climb turbulence penetration case. Three handling quality parameters are of particular interest at this point. 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

h	ft (m)	10,000 (3048)	26,000 (7925)
V	kt (m/sec)	250 (129)	280 (144)
T_{θ_1}	sec	77	91
gT_{θ_1}	$\frac{\text{kt}}{\text{deg}}$ $\frac{\text{(m/sec)}}{\text{deg}}$	25.2 (7.68)	30.2 (9.2)
T_{θ_1}/T_{h_1}	—	−0.51	0.0764

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.

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 two of the cases and was at, or near, recommended penetration speed in two just prior to the sudden flight path perturbations. In Incident I the pilot had reduced

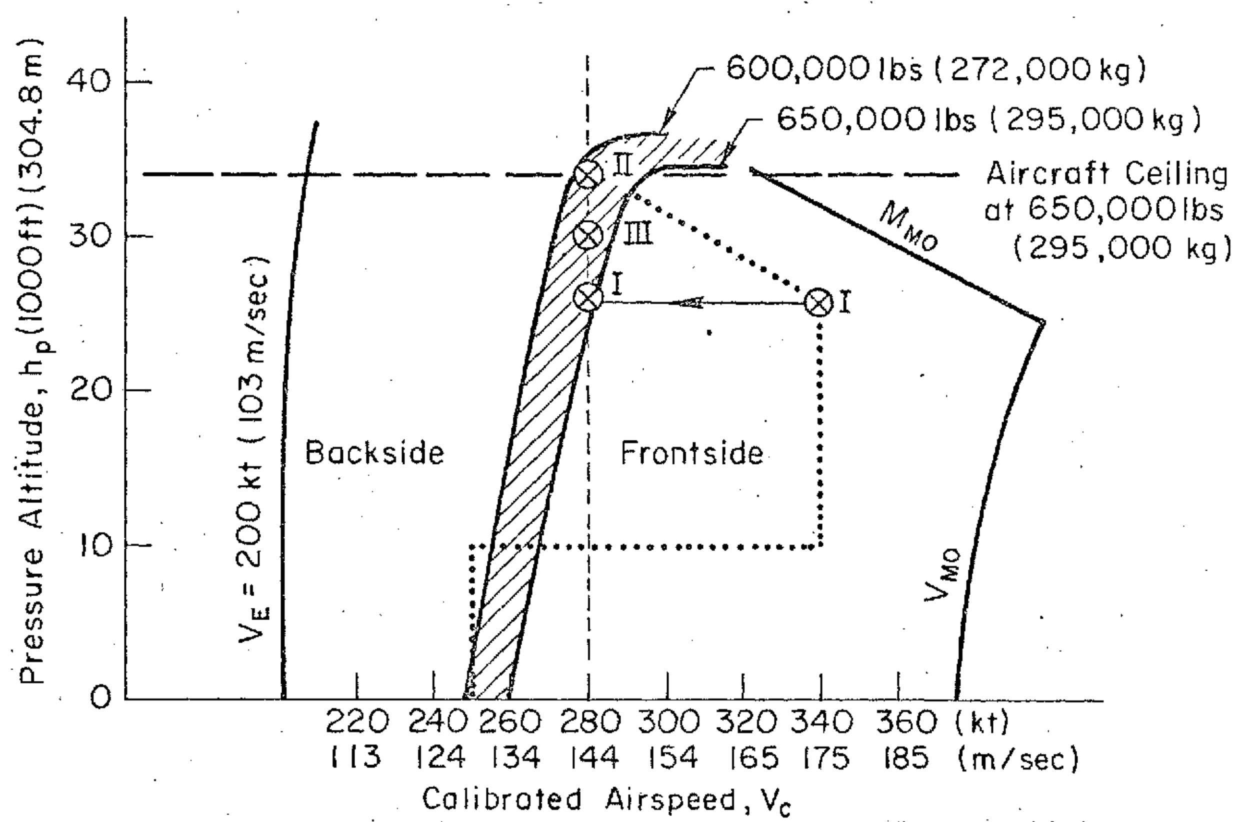


Figure 5. Approximate Frontside-Backside Boundaries; Level, 1 g Flight; Thrust Effects Included

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 (175 m/sec) ↓ 280 kt (144 m/sec)	− 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 (139 m)	+ 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 (144 m)	− 2000 (609.6 m)	?	At penetration V Developed divergent phugoid — steep dive (Ref. 10)

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.

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 (175 m/sec) climb and 280 KIAS (129 m/sec) level flight at 26,000 ft (7925 m) and 600,000 lb (272,000 kg) are indicated. A +0.25 g incremental load factor or a −30 kt wind shear when at the 280 KIAS penetration condition places the

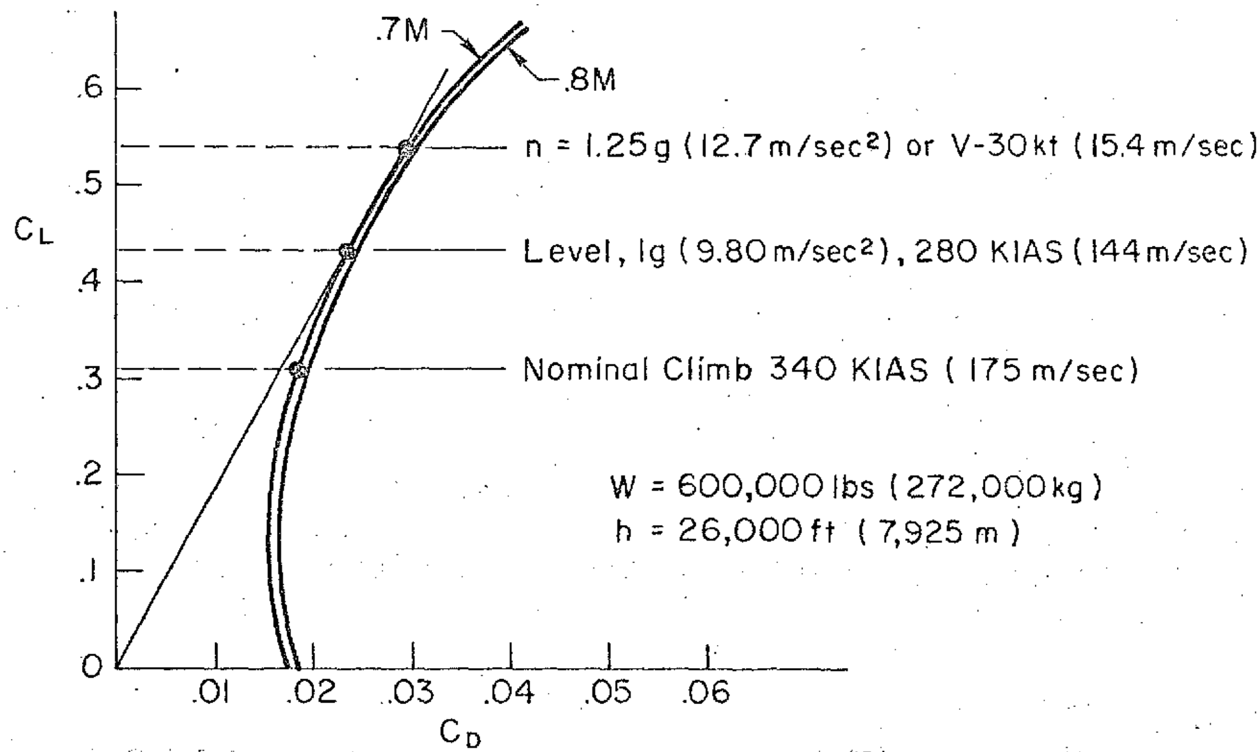


Figure 6. C_L vs. C_D, Aircraft F

aircraft on the backside. Such changes are readily encountered in 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) the 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 (0.29 m/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 2 deg flight path change to produce a gravity acceleration equivalent to application of 22,600 lb thrust.

D. SUMMARY

Piloting of jet aircraft is a demanding task even under normal conditions. A portion of the problem appears to lie with speed stability characteristics and path control difficulties, i.e., energy management. The huge inertias, low thrust-to-weight ratios, and operation at near minimum drag (therefore speed and path sensitivity to attitude deviation) requires the pilot to be continually operating 2 to 3 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. The task is complicated by inadequate attitude and thrust management references which require trim attitude to be obtained via an iterative process. Once trim is established, airspeed becomes the primary reference and deviations from the desired speed determine needed change in 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 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 appear to render the recommended turbulence penetration piloting technique marginal without the aid of improved energy management displays and/or autopilot modes.

SECTION III

TURBULENCE FLIGHT DIRECTOR SYNTHESIS

This section presents the detailed closed-loop analysis and synthesis of longitudinal control column and thrust flight director systems for turbulence penetration. The guidance and control related requirements are indicated in Fig. 7. A basic mechanizational concept (autopilot and flight director) meeting these goals was developed in the previous effort (Ref. 4). Additionally, consideration must be given to the pilot-centered requirements:

- Provide harmonious display and aircraft motions, e.g.:
  - director commands consistent with normal and turbulence piloting standard operating procedures.
  - director display consistent with other status information (low-frequency bar motions reflect path or speed deviations, mid-frequency motions reflect vehicle attitude deviations, and higher frequency content greatly attenuated).
- Provide flight director/vehicle dynamics that approximate a pure integration, K/s, over the frequency range of interest.

The next two subsections describe the system synthesis to meet the pilot-centered dynamic requirements. Attention will be focused first on the attitude director and then on the thrust director. Both will initially be synthesized for the nominal penetration flight condition of 280 kt (144 m/sec) at 26,000 ft (7925 m). The system dynamic characteristics will also be checked for the 250 kt; 10,000 ft (129 m/sec; 3048 m) case to determine sensitivity of the system to change in flight conditions.

A. CONTROL COLUMN FLIGHT DIRECTOR

1. Synthesis

While a specific definition of "loose" attitude control has not been found, it was determined in Ref. 4 that an attitude loop closure sufficient to damp airframe short-period excursions (i.e., nominal autopilot gain) resulted in a

- Minimize control upset tendencies in the presence of severe random turbulence with large imbedded wind shear.
- Command control column and thrust responses with respect to the relative air mass and inertial space which will:
  - minimize unsafe aircraft state vector excursions
  - maintain satisfactory ride qualities
- Permit utilization during all phases of constant speed flight (climb, descent, level)
  - provide change in trim speed and/or path at any time
  - provide smooth transition with minimum delay in stabilizing at new trim
- 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

Figure 7. Guidance and Control Related Requirements

harsh ride (high normal acceleration) in vertical gusts and extremely long airspeed recovery times for horizontal wind shears. Conversely, low attitude and high airspeed feedback gains resulted in large altitude excursions for nearly all disturbances. An acceptable compromise appeared to lie in a combination with both gains low which merely increased the airframe phugoid damping and provided an airspeed recovery time constant of approximately 15 to 20 sec. Therefore, these simple requirements serve as preliminary goals until they can be verified or modified in later piloted simulation.

A block diagram of the column director system is shown in Fig. 8. The display presented to the pilot is a column command, e.g., bar up; pull back. The vehicle follows a prescribed guidance law when the bar is maintained in the null position. Pitch attitude, θ, and airspeed relative to the air mass, u_a, are the primary feedbacks. Both are heavily lagged to attenuate display motion due to gust contributions in the frequency band above the flight path modes of interest here. Pitch rate (sensed or derived) feedback provides lead at airframe short-period frequencies to prevent degradation of short-period characteristics upon closure of the director loop. It will be noted that neither the u_a or θ feedbacks are washed out. This is conventionally

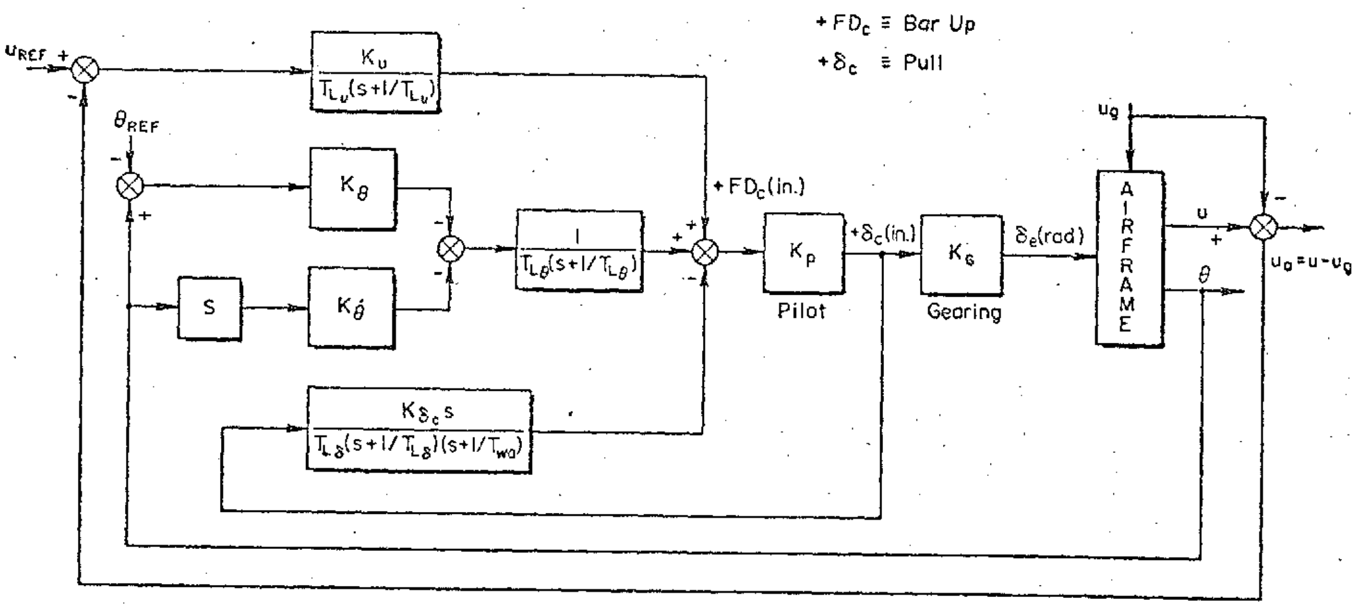


Figure 8. Block Diagram of Column Director System

done to prevent standoff errors between the two feedbacks. It is not necessary here because airspeed error is also fed back via the thrust director (discussed later) and any standoff calls for thrust or flight path adjustment. The third feedback in Fig. 8, control column displacement, δ_c, is utilized in a manner to decrease the gain of the innermost loop (display, pilot, and G_{δ_c}) and thereby force the "loose" effective control. This feedback is washed out to avoid display standoff or bias when control column trim position is changed. It is further lagged to avoid high-frequency command bar motions due to pilot remnant.

Note that altitude or rate of change of altitude is not a feedback. This is in keeping with the standard operating procedures for turbulence penetration, i.e., not chase altitude. Generally, proper regulation of attitude and airspeed will minimize altitude excursions and therefore these quantities are not of prime concern unless the aircraft is at very low altitude.

Flight director dynamics seen by the pilot thus reflect the combined dynamics of the vehicle and the three feedback loops, viz.,

$$\frac{FD_c}{\delta_e} = \frac{\dfrac{K_{\dot\theta}(s + K_\theta/K_{\dot\theta})}{T_{L\theta}(s + 1/T_{L\theta})}N^{\theta}_{\delta_e} + \dfrac{K_u N^{u}_{\delta_e}}{T_{L_u}(s + 1/T_{L_u})}}{\Delta} + \frac{\overbrace{(K_{\delta_c}/K_G)}^{K_{\delta_e}}s}{T_{L\delta}(s + 1/T_{L\delta})(s + 1/T_{wo})} \quad \frac{\text{in.}}{\text{rad}} \tag{1}$$

where $N^{\theta}_{\delta_e}$ and $N^{u}_{\delta_e}$ are the pitch and airspeed to elevator numerators and Δ is the airframe characteristic equation (denominator). The task is to adjust the feedbacks such that the guidance and control and pilot-centered requirements are satisfied.

In keeping with turbulence penetration SOP, pitch attitude is the primary controlled parameter which is biased as necessary to maintain the secondary parameter excursions (airspeed) within acceptable bounds. Figure 9 is a survey plot for a simple gain closure of the attitude loop about the basic airframe at the 280 kt; 26,000 ft (144 m/sec; 7925 m) flight condition. It will be noted that increasing gain, K_{p_θ}, drives the complex phugoid mode to the real ($-\sigma$) axis where it splits into two first-order modes, one of which

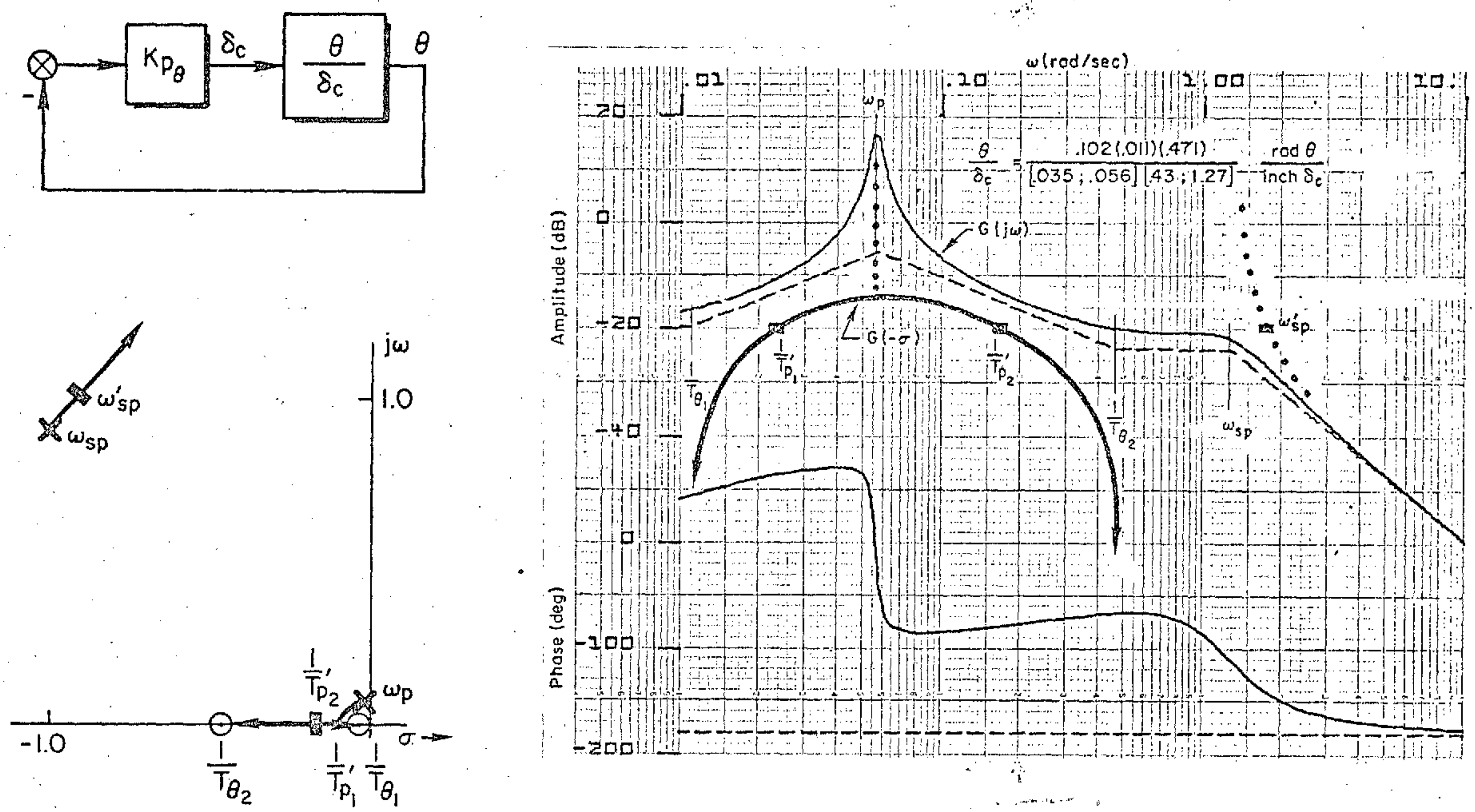


Figure 9. Attitude to Elevator Survey Plot

drives into the zero $1/T_{\theta_1}$ (speed mode) and the other into the zero $1/T_{\theta_2}$ (path mode). Thus, as the attitude loop gain is increased the closed-loop airspeed recovery time constant (T'_{p_1}) increases (undesirable) while the path time constant (T'_{p_2}) decreases (desirable). If the attitude loop gain is decreased to prevent the change in the airspeed mode, then low-frequency attitude control becomes imprecise (because $1/T_{\theta_1} \ll \omega_p$) and this can allow large airspeed error buildup (recall $u/\theta \doteq 30$ kt/seg) — also undesirable. It therefore is desirable to have $1/T_{\theta_1} \doteq \omega_p$. This is accomplished via proper ratioing of the u and θ components in Eq. 1. The effective zeros of these combined feedbacks are the roots of the ratio:

$$\frac{G_u N^{ua}_{\delta_e}}{G_\theta N^{\theta}_{\delta_e}} = \frac{K_u T_{L\theta} A_u (s + 1/T_{u_1})(s + 1/T_{L\theta})}{K_{\dot\theta} T_{L_u} A_\theta (s + 1/T_{\theta_1})(s + 1/T_{\theta_2})(s + 1/T_{L_u})(s + K_\theta/K_{\dot\theta})} = -1 \qquad (2)$$

A plot of the flight director zero migration (without the column feedback) is presented in Fig. 10. Here the filter lags $1/T_{L_\theta}$ and $1/T_{L_u}$ have been set at 0.25 rad/sec*, the pitch rate lead $K_\theta/K_{\dot\theta}$ set at 1.35 rad/sec, and the airframe

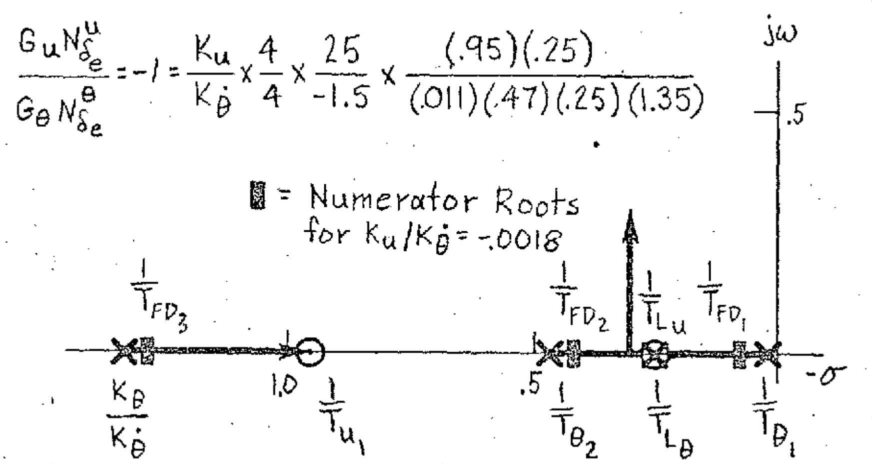


Figure 10. Plot of Flight Director Zero Migration with Varying Airspeed and Attitude Feedback Gain

*This filter lag was found to provide adequate gust smoothing in a cruise throttle airspeed control and display for a KC-135 (Ref. 11).

zeros $1/T_{\theta_1}$, $1/T_{\theta_2}$, and $1/T_{u_1}$ are obtained from Appendix A. The effective zeros $1/T_{FD_1}$, $1/T_{FD_2}$, and $1/T_{FD_3}$ are seen to vary with the gain ratio $K_u/K_{\dot{\theta}}$. Increasing K_u increases $1/T_{FD_1}$ (the apparent or effective speed zero), decreases $1/T_{FD_2}$ (the effective path zero) and decreases $1/T_{FD_3}$ (the effective lead equalization). Fortunately, the percentage change in $1/T_{FD_1}$ is greatest per unit gain change. It is not desirable to set the gain so high that $1/T_{FD_1}$ is greater than the airframe phugoid frequency since this results in overdriving attitude to effect speed control. When the gain ratio $K_u/K_{\dot{\theta}} = -0.0018$, the combined numerator is:

$$N_{\delta_e}^{(u+\theta)} = \frac{K_{\dot{\theta}} T_{L_u} A_\theta (s + .061)(s + .43)(s + 1.32)\cancel{(s + .25)}}{T_{L_\theta} T_{L_u} (s + .25)\cancel{(s + .25)}} \tag{3}$$

and the effective controlled element, without column feedback, is shown in Fig. 11. Note that $1/T_{FD_1}$ has been moved out to the phugoid frequency. Although the mid-frequency amplitude appears K/s-like, the display response at short-period frequencies has been attenuated 14 dB from the basic attitude response shown in Fig. 9. Consequently, the flight director will appear very sluggish and non-responsive to pilot control actions. An undesirably high pilot gain (large input) will be necessary to obtain a visual short-period indication of response to his control input. This then results in the pilot overdriving the system and excessive vehicle motion. Furthermore, the dropoff in amplitude and phase above 1 rad/sec indicates loop closures in this region will result in quite oscillatory response.

Addition of column feedback amplifies the high-frequency response of the display and prevents the pilot from overdriving vehicle attitude. The effective controlled element transfer function is:

$$\frac{FD_c}{\delta_e} = \frac{\dfrac{K_{\dot{\theta}} \cancel{T_{L_u}} A_\theta (s + .061)(s + .43)(s + 1.32)\cancel{(s + .25)}}{T_{L_\theta} \cancel{T_{L_u}} (s + .25)\cancel{(s + .25)}} + \dfrac{K_{\delta_e} s [\zeta_p ; \omega_p][\zeta_{sp} ; \omega_{sp}]}{T_{L_\delta}(s + 1/T_{L_\delta})(s + 1/T_{WO})}}{\underbrace{[\zeta_p ; \omega_p][\zeta_{sp} ; \omega_{sp}]}_{\Delta}} \tag{4}$$

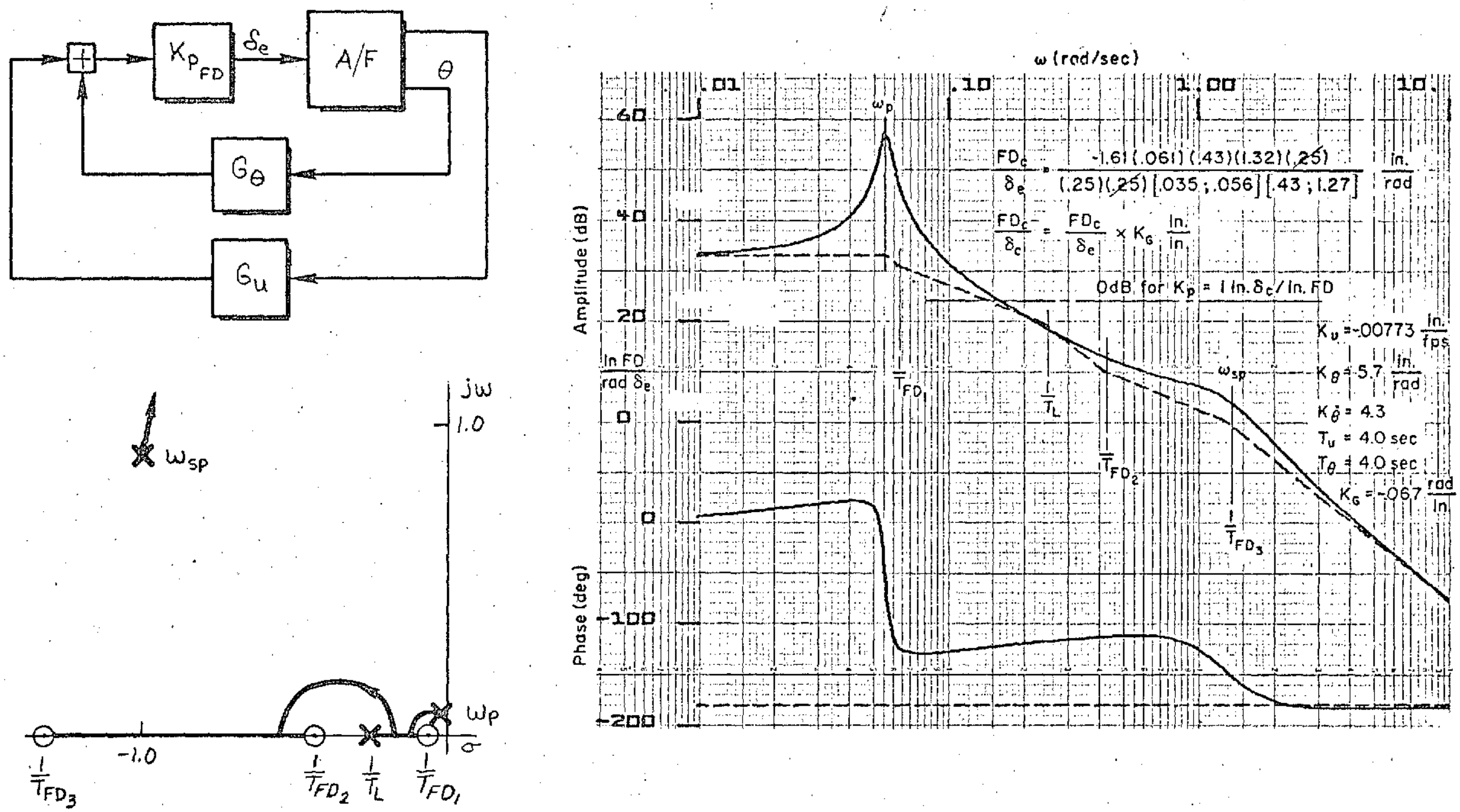


Figure 11. Effective Controlled Element Survey with Attitude and Airspeed Feedbacks Only

Again, the numerator is evaluated in a root locus plot, as sketched in Fig. 12. Here the column washout ($1/T_{WO}$) and filter ($1/T_{L_\delta}$) locations have been selected to attract the root emanating from ω_p. Note that if K_{δ_e} is infinite the gain ratio is zero, the numerator roots are those identified as (✖), and the flight director zeros are identically the same as the airframe poles plus the lags introduced in the feedbacks. Thus, pilot control to the flight director has no effect on the airframe since he is, in effect, controlling to null the control column. Decreasing the K_{δ_e} moves the numerator roots along the locus shown in Fig. 12. A gain ratio $K_{\dot{\theta}}/K_{\delta_e} = 0.25$ provides roots indicated by the solid rectangles (▮) and the complete column director transfer function is:

$$\frac{FD_c}{\delta_c} = \overbrace{-.067}^{K_G} \times \frac{K_{\delta_e}\cancel{T_{L_\theta}}\cancel{T_{L_u}}(\cancel{.25})(\cancel{.25})(.038)[.40\,;\,.125][.45\,;\,1.45]}{T_{L_\delta}\cancel{T_{L_\theta}}\cancel{T_{L_u}}(\cancel{.25})(\cancel{.25})(.25)(.1)[.035\,;\,.056][.43\,;\,1.27]} \tag{5}$$

The survey plot for this system is shown in Fig. 13. Note from Eq. 5 and Fig. 13 that the complete flight director numerator now contains two pairs of complex zeros with one pair near the phugoid and the other near the short-period modes. No matter how tightly the pilot closes the director loop, the

$$\frac{K_{\dot{\theta}}T_{L_u}T_{L_\delta}A_\theta(s+.061)(s+.43)(s+1.32)\cancel{(s+.25)}(s+1/T_{WO})(s+1/T_{L_\delta})}{K_{\delta_e}T_{L_\theta}T_{L_u}(s)(s+.25)\cancel{(s+.25)}[\zeta_p\,;\,\omega_p][\zeta_{sp}\,;\,\omega_{sp}]} = -1$$

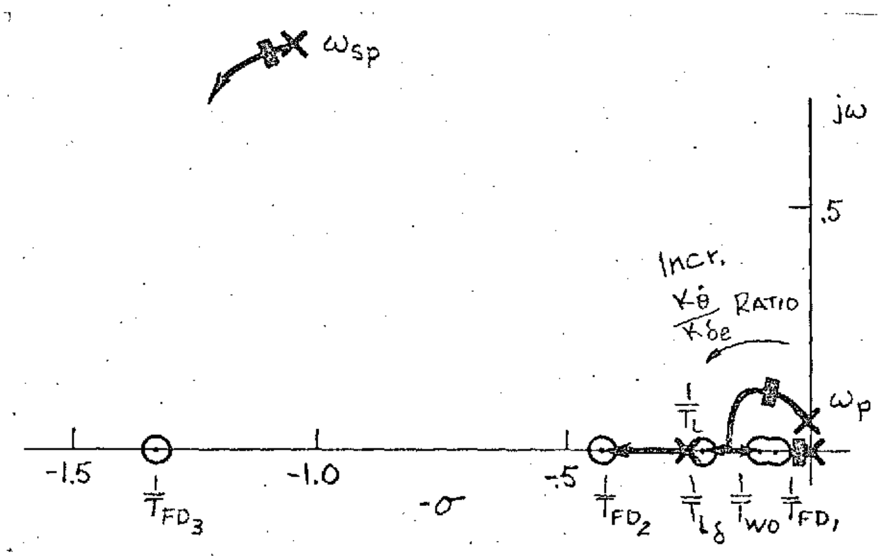


Figure 12. Influence of Column Feedback on Flight Director Zeros

$$\frac{FD_c}{\delta_c} = \frac{.3\cancel{(25)}^2(.038)[.41;.126][.45;1.46]}{\cancel{(25)}^2(.25)(.1)[.035;.056][.43;1.27]}$$

$K_u = -.00773$

$K_\theta = 5.73$

$K_{\dot\theta} = 4.3$

$K_{\delta_c} = 1.2 \ \frac{in.}{in.}$

$T_{L_\theta} = 4.0$

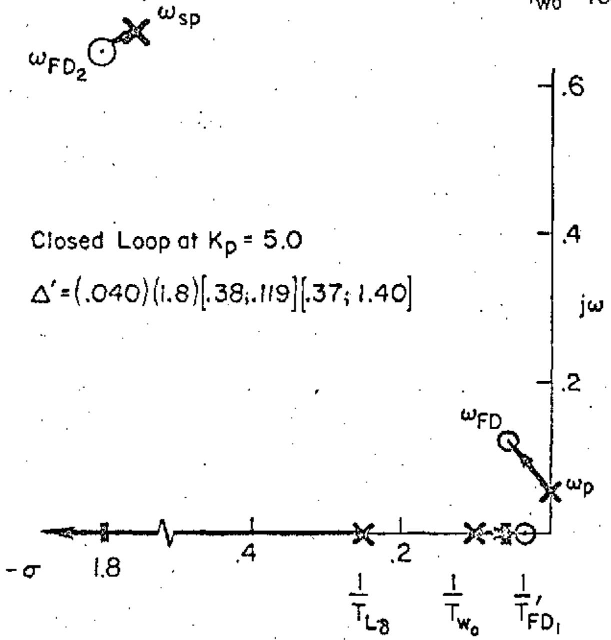
$T_{L_u} = 4.0$

$T_{L_\delta} = 4.0$

$T_{wo} = 10.0$

Closed Loop at $K_p = 5.0$

$\Delta' = (.040)(1.8)[.38;.119][.37;1.40]$



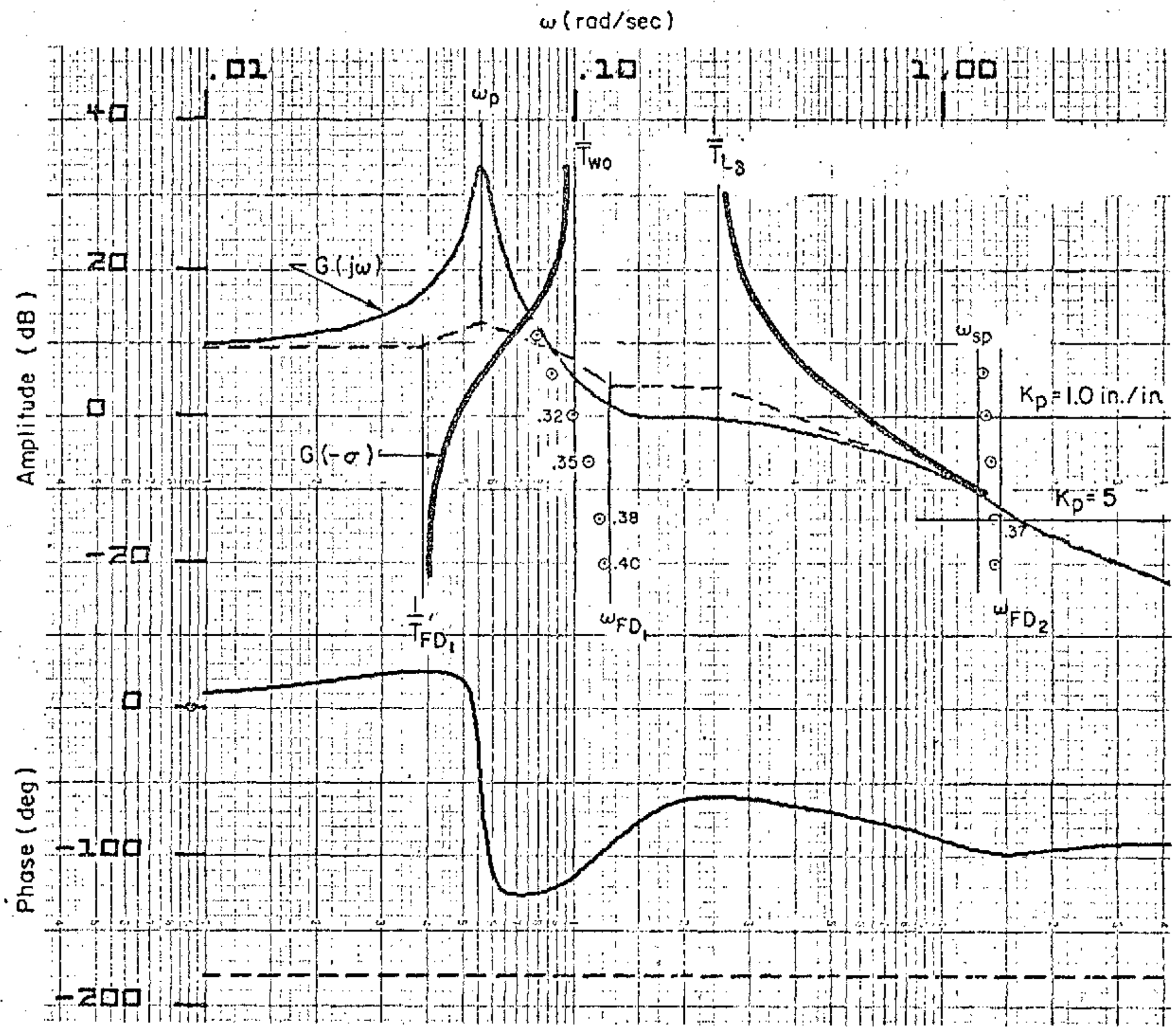


Figure 13. Director Response with Attitude, Airspeed, and Column Position Feedbacks and Equalizations

phugoid and short-period modes are driven into their respective counterpart zeros, and thus these modes cannot be overdamped or driven unstable. Figure 13 indicates that a pilot gain, $K_p = 5$ in./in., results in a crossover about 1.5 rad/sec, which is normally considered as "comfortable" for closed-loop compensatory control. This provides a closed-loop phugoid of $\omega_p' = 0.12$ rad/sec and $\zeta_p' = 0.38$ and a short-period $\zeta_{sp}' = 0.37$. This is exactly what would occur if the airframe-alone attitude loop of Fig. 9 was closed at about <u>0.1</u> rad/sec, i.e., very loosely. Decreasing the pilot gain a factor of five does not significantly change the closed-loop root positions (see Fig. 13).

The system gains and time constants are summarized in Fig. 13.

2. Closed-Loop Response

Time responses for recovery from large shear inputs using the flight director and an analog pilot are presented in Fig. 14. The assumed pilot gain, $K_p = 5$ in. δ_c/in. FD reflects the high gain line in Fig. 13. The airframe dynamics are for 280 kt at 26,000 ft. Discrete disturbance inputs reflecting the 8 directions of Fig. 15 were used. The gust magnitude is fixed at 85 ft/sec (26 m/sec) for both the vertical and horizontal components with an onset ramp of 2 sec. For quartering gusts (2, 4, 6, 8) this results in a gust magnitude of 119.5 ft/sec (36.4 m/sec). It should be pointed out that these are extremely large disturbances which, although possible (Ref. 12), are very rarely encountered. The vertical gust was washed out with a 20 sec time constant to avoid steady-state climb rates which tend to saturate the computer.

Figures 14a-14d present the closed-loop response of attitude (θ), airspeed (u_a), altitude (h), and vertical acceleration (a_z) to the gust inputs. (Open-loop airframe responses for the same inputs are presented in Appendix A for comparison.) Gusts from Directions 4 and 8 (Figs. 14a, A-4, and A-8) provide the greatest excursions in all motion quantities: attitude, airspeed, altitude, and vertical acceleration. The aircraft initially pitches up into the downdraft component (Gust 4) and then the director commands a pitch down to regain airspeed. This occurs at the expense of greater altitude loss than would be incurred if the initial attitude excursions were just returned to zero and held. Note that airspeed recovery is not initiated until after

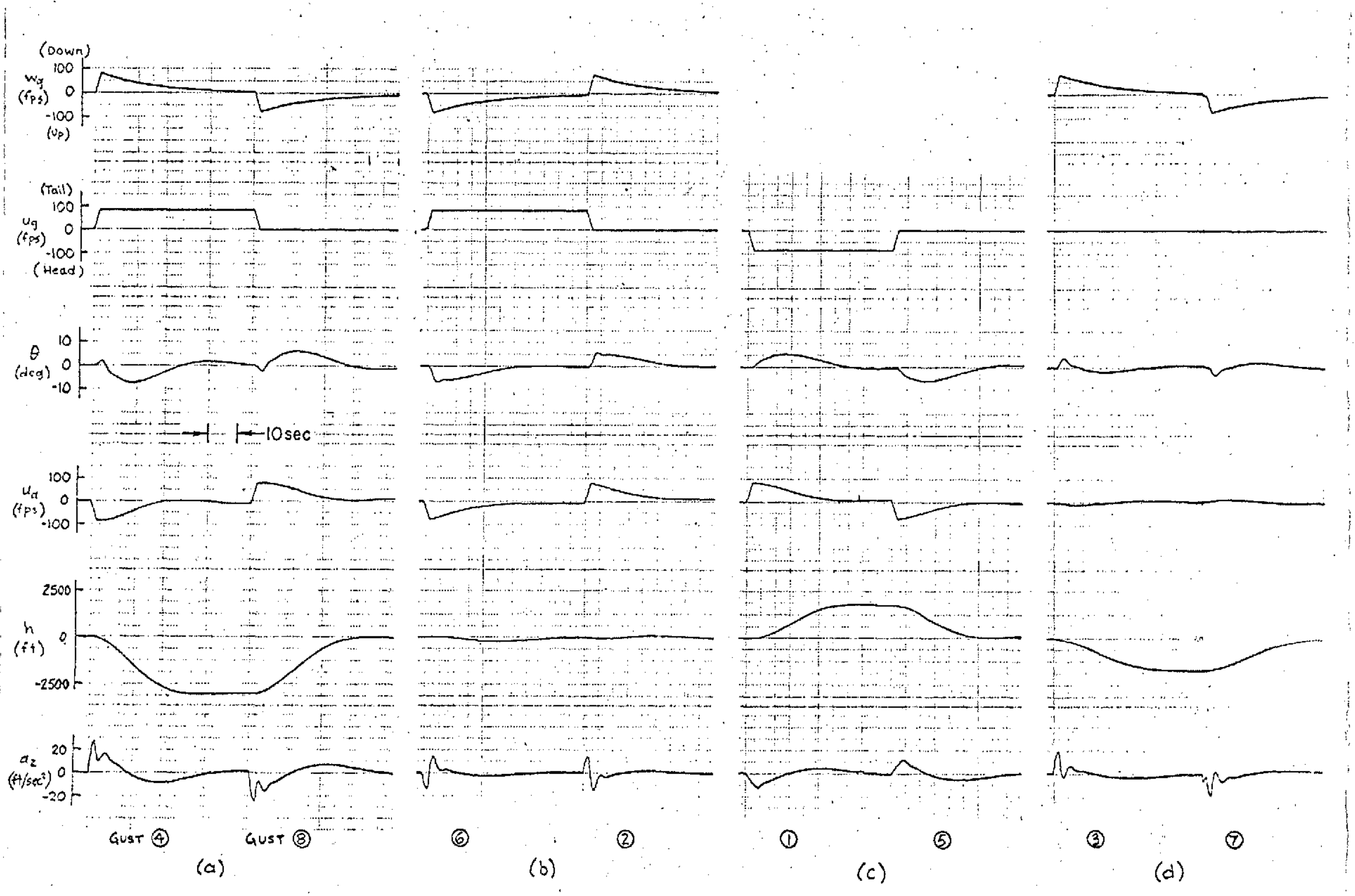


Figure 14. Time History of Vehicle Response to Gust with Elevator Director System Closed; $K_p = 5$

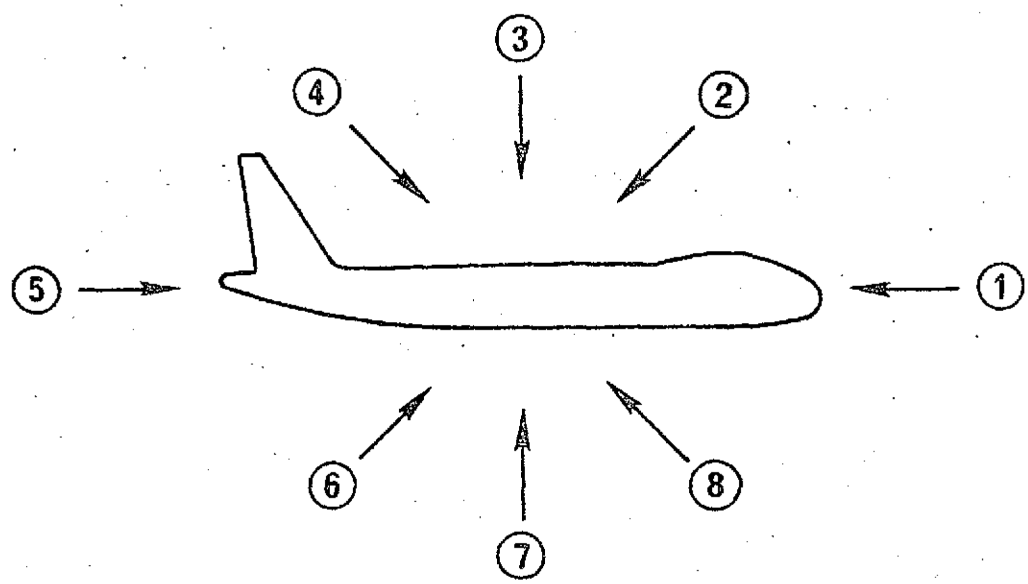


Figure 15. Directions of Discrete Disturbance Inputs

the aircraft has pitched down about two degrees. This results in a delay of several seconds before the pilot can be assured via the airspeed indicator needle that low airspeed has been arrested. The airspeed then exhibits a recovery time constant of approximately 10 sec which is well within the initial target response. Without the director, the pilot would have to recognize that the initial attitude deviation is in the opposite direction to that desired for airspeed recovery. Any delay on his part would result in even greater airspeed excursions which, together with the recovery time lags, could induce an overcontrol situation.

The initial spike in the vertical acceleration trace of Fig. 14a is a direct airframe response to the gust, i.e., $Z_u u_g + Z_w w_g$, and <u>cannot</u> be alleviated by a director system. In this case the two gust components are reinforcing and hence produce a large spike. However, during the commanded pullout to level flight, the induced vertical accelerations are less than 1/4 g (2.5 m/sec^2) which should be acceptable. Although not shown, elevator required for the maneuver is about ±2 deg which represents about ±1/8 in. (0.318 cm) of column displacement.

The next worst gusts from the standpoint of vertical acceleration are Numbers 6 and 2, i.e., updraft tailwind or downdraft headwind, see Fig. 14b. The sharp doublet form of the vertical acceleration should be quite uncomfortable or dangerous for passengers. In all other respects, the responses are rather mild. The attitude change necessary to regain airspeed opposes the vertical gust, hence the altitude change is minimized. The airspeed indication immediately assures the pilot that the control action is indeed correct and will result in recovery.

It is interesting to note that the Numbers 2 and 6 disturbance inputs are judged most confusing with the conventional IFR display and the loose attitude control (only) technique in Ref. 13 because all instruments (IAS, h, R/C) and the seat of pants (a_z) "command" corrective control action which is opposite to that "commanded" by the attitude indicator. However, these disturbances are <u>not</u> crucial from the standpoint of delayed pilot action, since the initial attitude excursion is in a direction to reduce the airspeed excursions.

The straight horizontal gusts (Numbers 5 and 1) produce nearly the same attitude and airspeed excursion as the previous gusts from the four quadrants. The main difference is the reduction in vertical acceleration.

In the last figure, it can be seen that the straight vertical gust produces the least excitation except for the initial a_z spike. The altitude change obtained is somewhat meaningless, since it is a function of the w_g washout time constant used in this simulation.

It should be mentioned that there may be slight differences between these simulation responses and those predicted by the small perturbation transfer functions. These are due to resolving the gust inputs into inertial coordinates in the simulation and utilizing a nonlinear airspeed-to-attitude gain. The latter is changed as a function of the sign of airspeed error. The stated gain ratio applies when airspeed is low, since it is critical to get airspeed back as soon as possible. When airspeed is high, the gain is reduced 25% to reduce the commanded attitude change.

Also, all the time responses were obtained with fixed throttle. Although the thrust has no short-period effect, it will increase the path mode damping and reduce the attitude excursions. The throttle director system is discussed later.

3. System Performance at Low Altitude

Thus far the analysis has been based on the vehicle characteristics for 280 kt (144 m/sec) level flight at 26,000 ft (7925 m). It was indicated in Section II (Fig. 5) that the 10,000 ft (3048 m) altitude and speed limited 250 kt (129 m/sec) condition might be more crucial, at least in terms of backside operation. Again, derivatives and transfer function factors for this condition are given in Appendix A. In addition to the negative $1/T_{h_1}$ and slightly decreased speed sensitivity to attitude change discussed in Section II, the data of Appendix A indicate this condition has a slowly divergent phugoid ($\zeta_p = -0.0036$). It will be shown in this subsection that these differences in flight condition and dynamic characteristics actually have negligible effect on the flight director dynamics and closed-loop response.

A Bode plot of the effective vehicle (FD_c/δ_c) at this lower altitude flight condition is shown in Fig. 16. Comparison of this plot with that of Fig. 13 indicates essentially no difference. This is further reflected in the time traces of Fig. 17. Comparing Fig. 17a with Fig. 14a, a somewhat higher initial vertical acceleration is obtained (due to larger $Z_w w_g$) and about 600 ft (183 m) less altitude is lost [since the true speed is 120 kt (62 m/sec) slower]. Pitch attitude change and airspeed recovery time are virtually identical. The remaining gusts 6 and 2, 5 and 1, and 7 and 3 are also nearly identical with those of Figs. 14a, 14c, and 14d, respectively. Therefore, it is concluded that the attitude director is quite insensitive to change in flight condition.

B. THRUST DIRECTOR

1. Synthesis

The purpose of the thrust director is to aid the pilot in setting trim thrust for any selected flight path and airspeed. If preparation for turbulence penetration is encountered during climb, it may be desired to level off as well as change airspeed (C_L is higher during climb and therefore there is greater danger of backside operation, stall, etc.). 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 disturbances the thrust director also calls for thrust changes to overcome airspeed excursions and hence works in consort with the control column director.

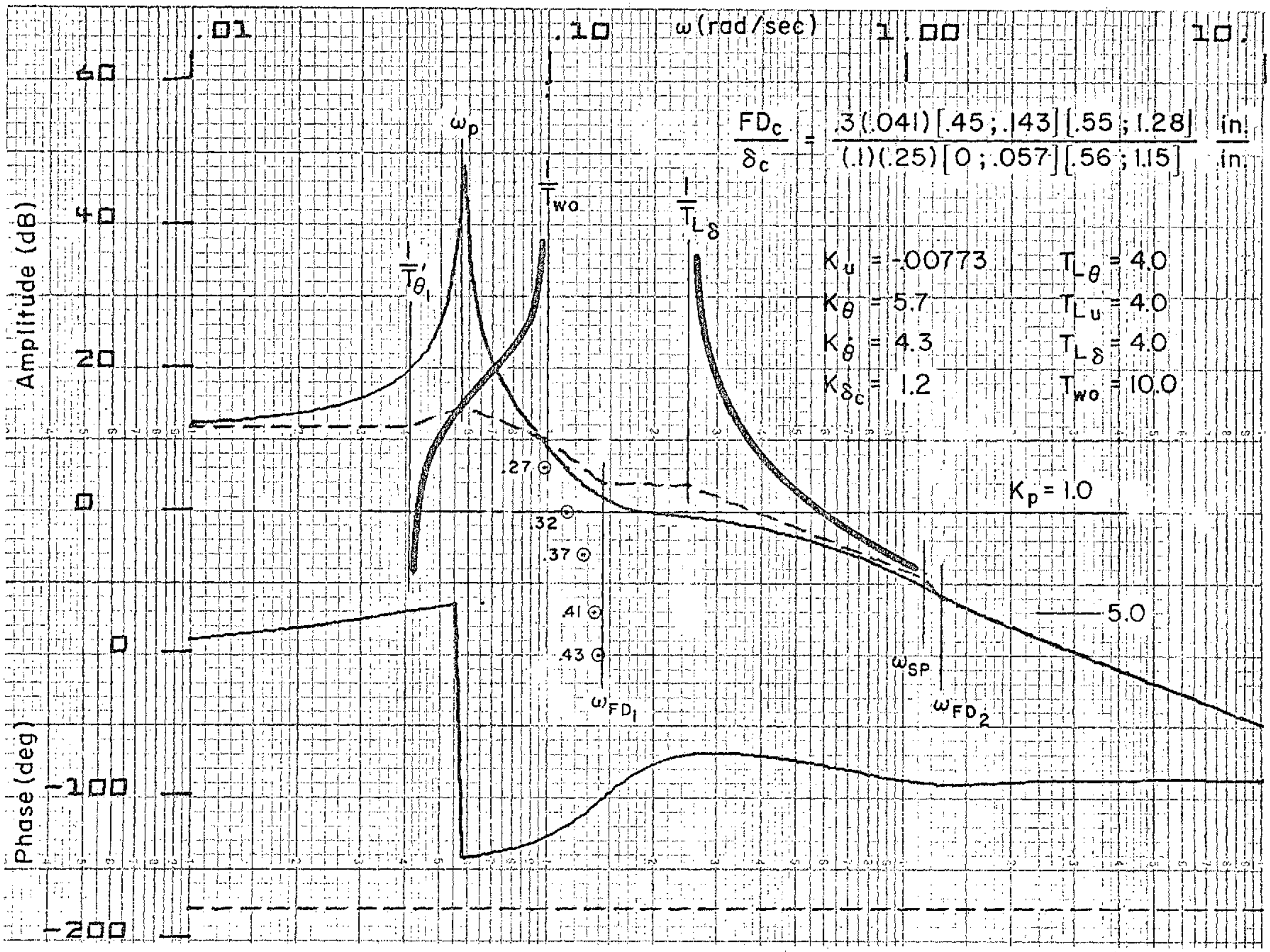


Figure 16. Elevator Director Frequency Response to Control Input, 250 kt (144 m/sec) at 10,000 ft (3048 m)

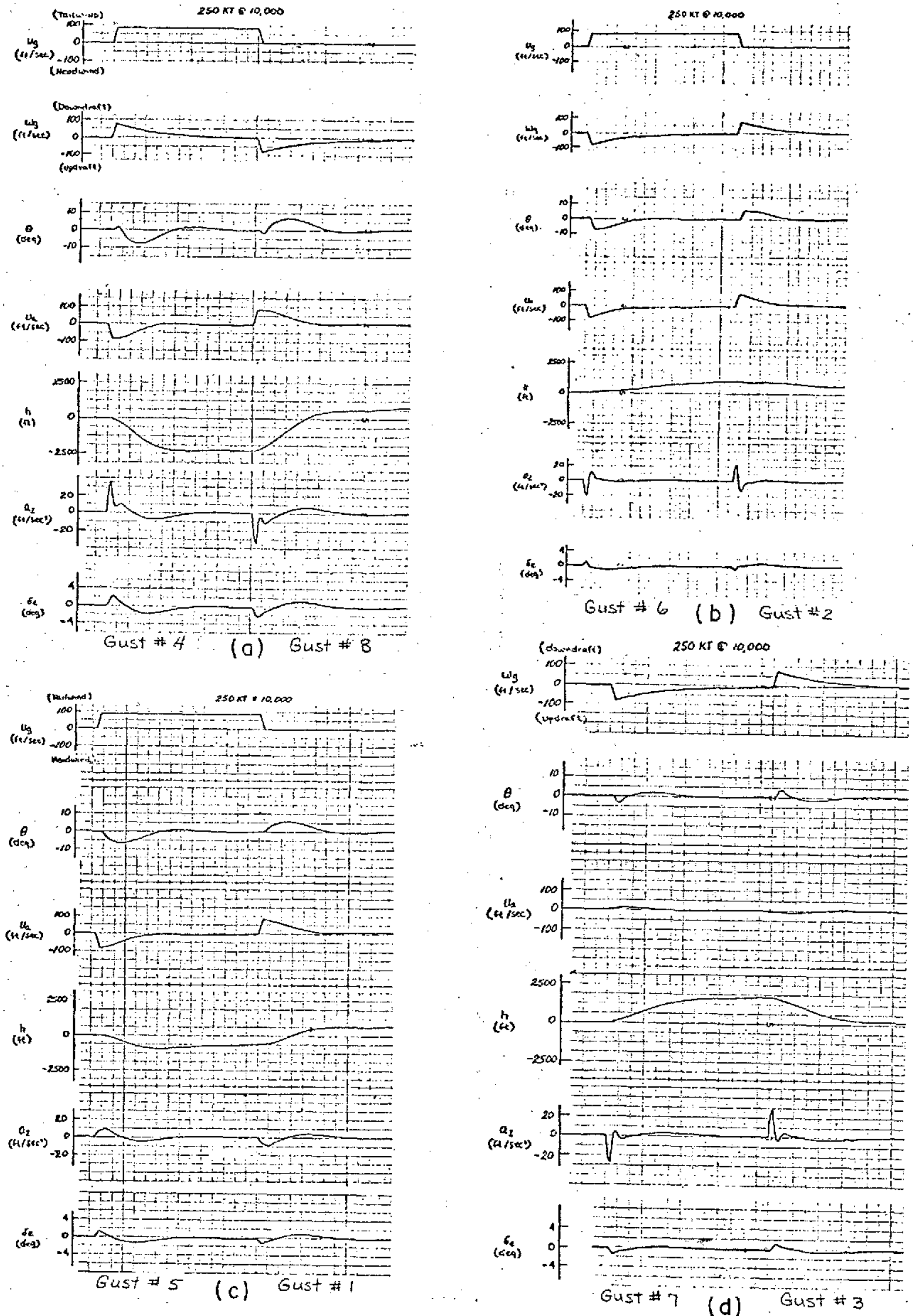


Figure 17. Time History of Vehicle Response to Gusts at 250 kt (144 m/sec) at 10,000 ft (3048 m) with Elevator Director System Closed, $K_p = 5$

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 consistent with the "no director" situation and more desirable from the pilot workload and passenger anxiety standpoint. Therefore, for the thrust director we will be more concerned with the guidance and control requirements than with the effective controlled element response and pilot closure characteristics, i.e., the pilot-centered requirements.

Several thrust director concepts were studied at NASA Langley (Ref. 14) 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 flight path:

$$\frac{T - D}{W} = \frac{\dot{u}}{g} + \sin\gamma = \frac{a_{x_{FP}}}{g} \tag{6}$$

The motion quantities $\dot{u}$ and γ are obtainable from sensors of the inertial navigation systems now used in many jet transports. The quantity $a_{x_{FP}}$ 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). A key factor in the concept is simultaneous use of the attitude-to-control-column flight director 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, the latter must be supplied to both directors.

A block diagram of the thrust director system is shown in Fig. 18. The engine dynamics are assumed to be a first-order lag with a time constant of 2 sec. The airspeed feedback shaping, G_u, also is assumed to be a first-order lag as in the column director system. As a starting point the airspeed loop is assumed to be the inner loop. Considering a severe turbulence environment, 50 kt airspeed error is selected to provide 1 inch of director displacement. Thus, K_{u_T} = 0.02 in./kt = 0.012 in./fps. Figure 19 indicates

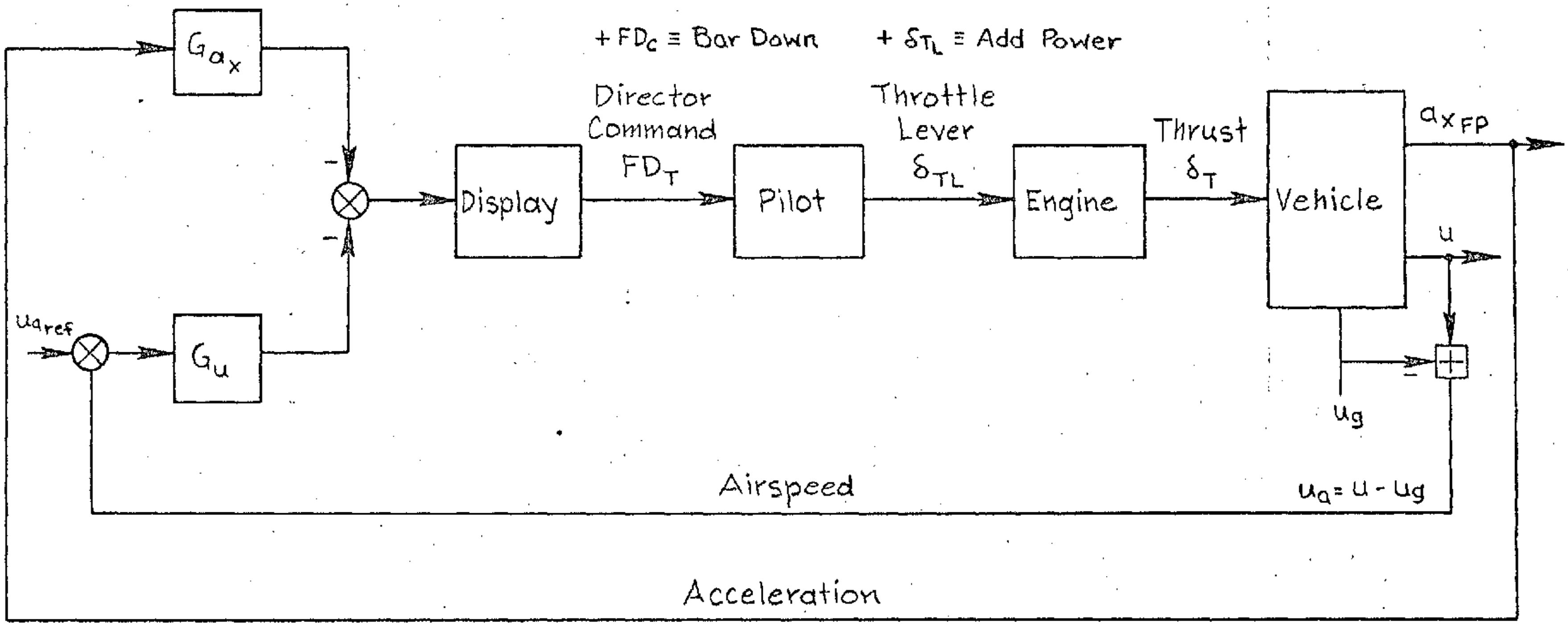


Figure 18. Generalized Thrust Director System

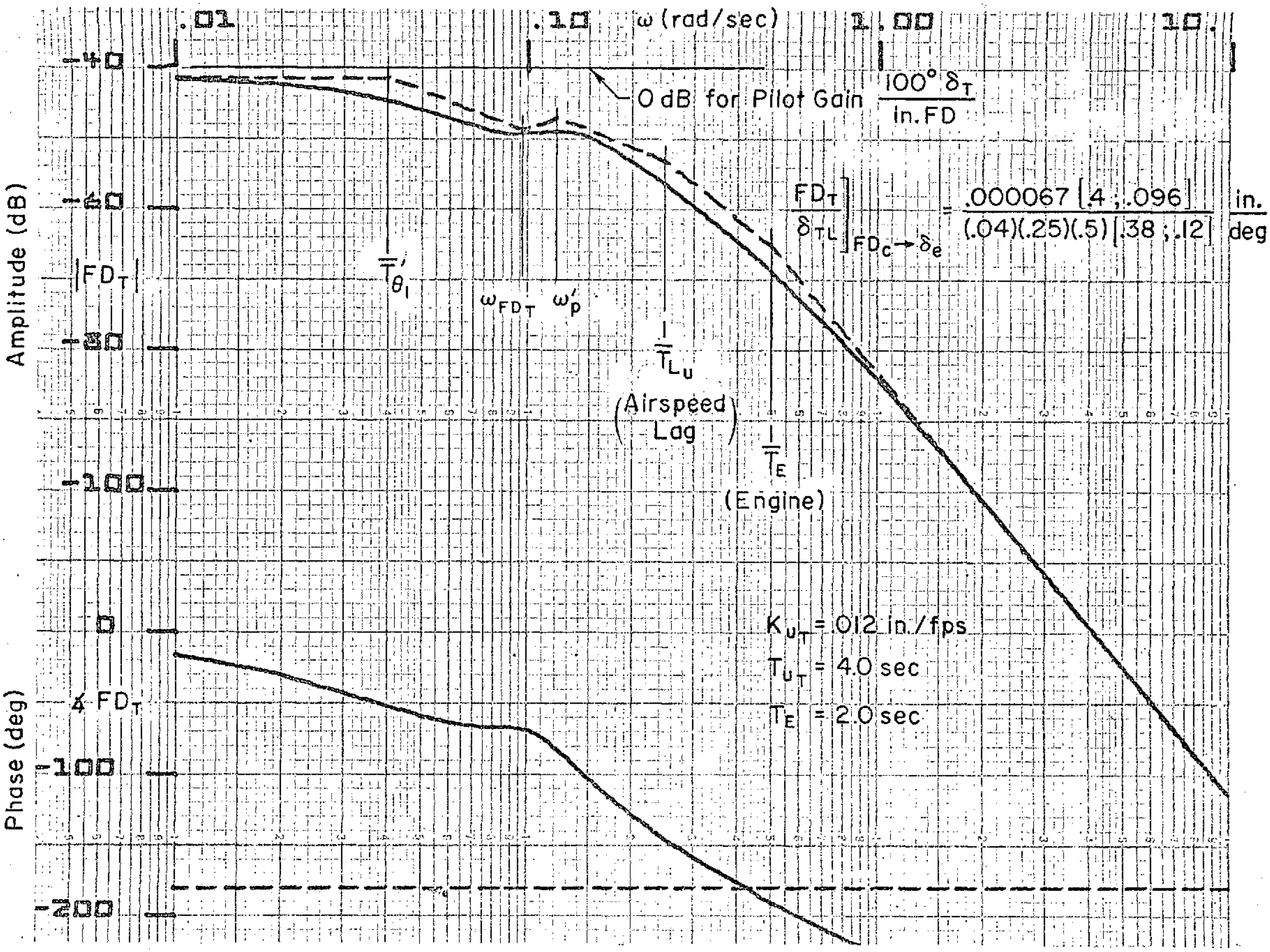


Figure 19. Thrust Director Effective Controlled Element with Lagged Airspeed Feedback Only, Column Director Loop Closed

the resulting director dynamics with only the lagged airspeed feedback but operating in conjunction with the column director system of Fig. 16 closed with a pilot gain $K_p = 5$. Note that full thrust lever (100°) per inch of director display does not cross the amplitude plot. Thus, precise closed-loop control of airspeed is not possible via thrust. This is caused by the low thrust/weight ratio of the aircraft, the limited throttle travel available (from trim), and the assumed display gain restrictions. Also, the effective controlled element (vehicle, engines, display) exhibits excessive phase lag at mid-to-high frequencies. For the director to be of benefit it therefore is desirable to increase the low-to-mid frequency gain and decrease the mid-to-high frequency phase lag. This is accomplished by adding the longitudinal acceleration feedback shown in Fig. 18.

The a_x gain selection is strongly influenced by vehicle gust sensitivity because the initial thrust director response to a horizontal gust will command a throttle application opposite to that required to return airspeed. This can be shown analytically by deriving the thrust director to u_g transfer function as shown below. Assume for simplicity that $\sin\gamma \doteq \gamma \doteq \theta$, then:

$$FD_T = G_u u_a + G_{a_x} a_x = \frac{K_u(u-u_g)}{\left(s+\frac{1}{T_u}\right)} + G_{a_x}(\dot{u} + g\theta)$$

$$= \frac{K_u + G_{a_x}\left(s+\frac{1}{T_u}\right)s}{\left(s+\frac{1}{T_u}\right)} u - \frac{K_u u_g}{\left(s+\frac{1}{T_u}\right)} + G_{a_x} g\theta \qquad (7)$$

For a disturbance due only to a horizontal gust:

$$\dot{u} + g\theta \doteq X_u u - X_u u_g$$

$$su - X_u u = -X_u u_g - g\theta$$

$$u = \frac{-X_u u_g - g\theta}{(s - X_u)}$$

and the feedback becomes:

$$G_u u_a + G_{a_x} a_x = \frac{K_u + G_{a_x}\left(s + \frac{1}{T_u}\right)s}{\left(s + \frac{1}{T_u}\right)}\left[\frac{-X_u u_g - g\theta}{(s - X_u)}\right] - \frac{K_u u_g}{\left(s + \frac{1}{T_u}\right)} + G_{a_x} g\theta$$

$$= \frac{-X_u G_{a_x} s\left[s + \left(\frac{1}{T_u} + \frac{K_u}{X_u G_{a_x}}\right)\right]}{\left(s + \frac{1}{T_u}\right)(s - X_u)}(u_g + g\theta) \tag{8}$$

$$\doteq \frac{-X_u G_{a_x} s\left[s + \frac{K_u}{X_u G_{a_x}}\right]}{\left(s + \frac{1}{T_u}\right)(s - X_u)}(u_g + g\theta)$$

The flight director response to a u_g is thus:

$$\frac{FD_T}{u_g} = \frac{X_u G_{a_x} s\left[s + \frac{K_u}{X_u G_{a_x}}\right]}{\left(s + \frac{1}{T_u}\right)(s - X_u)}\left(1 + g\frac{N_{u_g}^{\theta}}{\Delta}\right) \tag{9}$$

Since the derivative X_u is very small and negative, $K_u/X_u G_{a_x}$ is negative and the zero is non-minimum phase. This results in the initial director response to a u_g being of opposite sign to that desired and strongly influences the acceleration gain which can be utilized. For example, using a gain $K_{a_x} = 0.12$ in. FD/(ft/sec^2), a gain ratio $K_u/K_{a_x} = 0.1$, and assuming the elevator flight director loop is closed, gives the following transfer function:

$$\frac{FD_T}{u_g} \doteq \frac{-.00066\ s(s - 3.9)[s^2 + 2(.64)(.096)s + (.096)^2]}{(s + .04)(s + .25)[s^2 + 2(.38)(.12)s + (.12)^2]} \quad \frac{\text{in.}}{\text{ft/sec}} \tag{10}$$

The initial response (i.e., $s = \infty$) to a 50 kt (or 84.5 ft/sec) headwind gust is:

$$FD_T \doteq -.00066\ u_g = -.00066(-84.5) = +.05 \text{ in.} \tag{11}$$

The positive sign indicates a "down" bar, i.e., an "add power" command which is the wrong direction for a headwind. The command reverts to the correct sign after a period $t \doteq 1/3.9 \doteq 0.25$ sec. This relatively small displacement and time constant should not be troublesome but is undesirable. Increased accelerometer gains move the zero to lower frequency and increase the magnitude of the initial response. Thus, the reversal is larger and of longer duration.

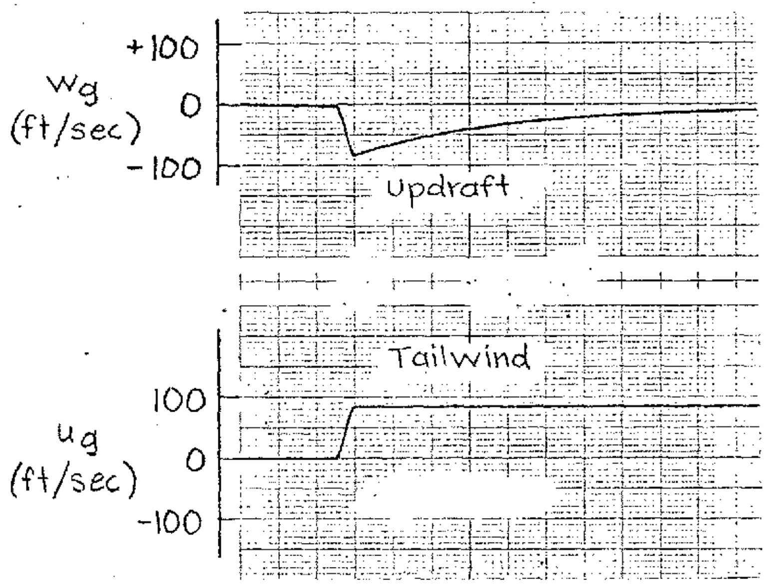
In most cases there is no problem for vertical gusts. For example, the a_x term in a 50 kt downdraft gust would move the bar the following distance:

$$FD_T = \underbrace{K_{a_x}(X_w w_g)}_{a_x \text{ due } w_g} = (.12)(.0231)(+85) = +.23 \text{ in.} \qquad (12)$$

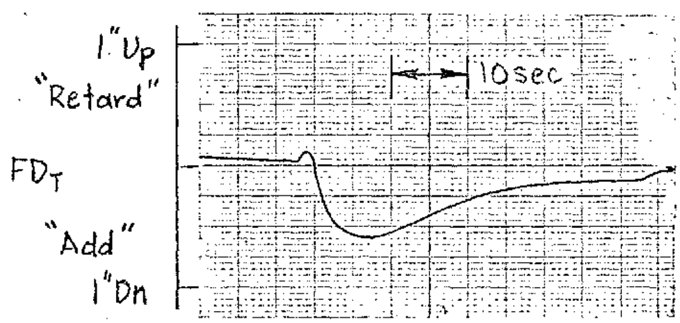
Although this is a significant movement, the command is to "add power" which is the correct sense for a downdraft.

Only in the case of Gusts Nos. 6 and 2 (Fig. 15) will the gust components command reinforce a wrong throttle movement. In this situation a tailwind updraft (No. 6), for example, will initially (due to a_x) command a "reduce power" due to the u_g component and a further "reduce power" due to w_g. For a step 70 kt gust from Directions 2 or 6, the u_g and w_g components of bar movement add up to a possible 0.28 in. of "reduce power" command initially. Since catching the low airspeed is assumed to be more important than stopping the ensuing rate of climb, we would not want to reduce power. However, it is unlikely the gust will be a true step. In a more realistic situation the gusts would have a finite rise time. Assuming 25 kt/sec for each component results in the time trace of thrust director response shown in Fig. 20. The reversal in director motion is less than 0.1 in. which would probably not be detectable by the pilot.

The effective controlled element transfer function for the throttle director using airspeed and longitudinal acceleration feedbacks is shown in Fig. 21. The low-frequency gain is increased approximately 4 dB from that obtained in Fig. 19 and the mid- to high-frequency gain is increased significantly. Unfortunately, the gain $K_{a_x} = 0.12$ in./fps provides a display displacement of only 0.067 in. per degree of potential flight path change.



GUST INPUT



THRUST DIRECTOR RESPONSE

Figure 20. Open Loop Thrust Director Response to Gust No. 6
$K_{a_x} = 0.12$, $K_u = 0.012$; Column Director Loop Closed

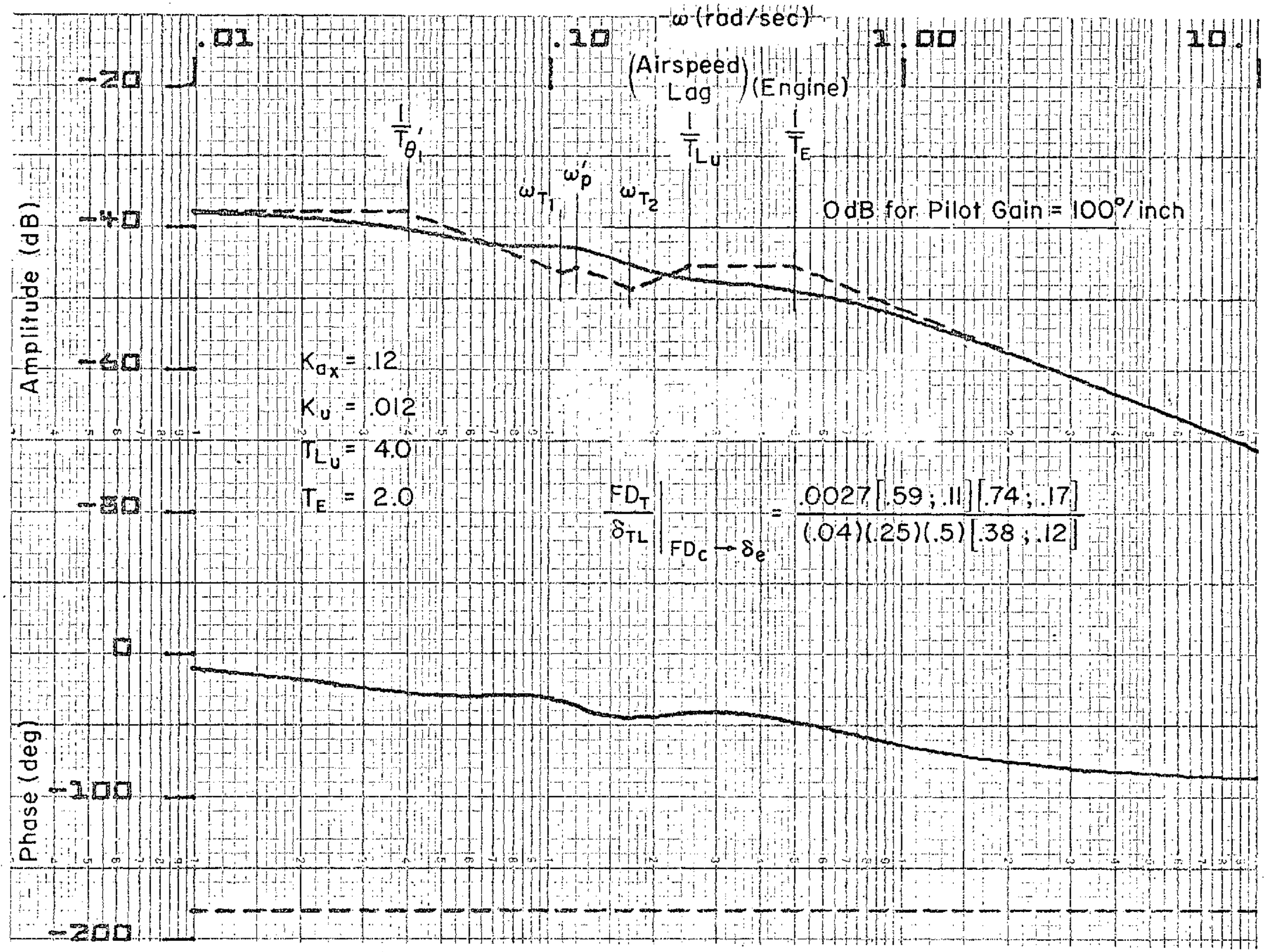
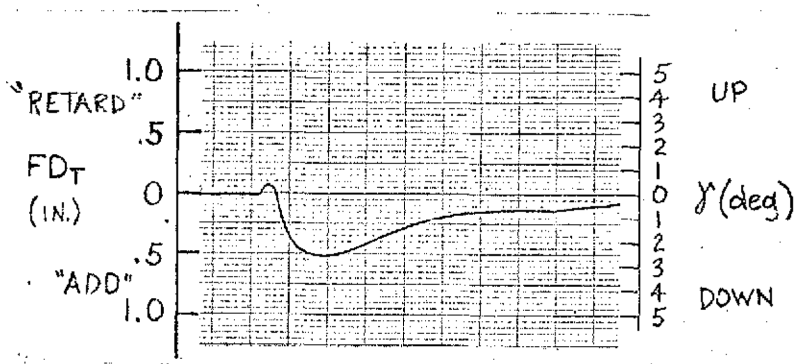


Figure 21. Preliminary Thrust Director Effective Controlled Element Response With Column Director Also Closed

To improve readability in a severe turbulence environment the display gain should be as high as possible. Since display panel space is at a premium, a gain of 1 in. per 5 deg will be assumed for this preliminary design phase. This requires a threefold increase in K_{a_X}. The adverse gust sensitivity noted above then becomes objectionable. The gust response can be reduced by lag-lead equalization of the acceleration feedback which attenuates the mid- and high-frequency gains of the total effective controlled element, FD_T/δ_T, but does not affect the K/s-like response in the region of pilot closure. Figure 22 shows the effective controlled element response for the throttle director system with lag-lead equalization of $(3s + 1)/(10s + 1)$. Note that the high-frequency gain is consistent with that of Fig. 12 and that the response is very K/s-like beyond 0.1 rad/sec. The thrust command transient in the presence of a gust from Direction 6 is shown below. The



gust magnitude is the same as employed in Fig. 20. The transient is shown in terms of thrust command and γ display perturbation to facilitate direct comparison with the Fig. 20 response. It is obvious that the lag-lead shaping has offset the larger initial reversal which should have resulted from the higher acceleration feedback gain. Again, this small initial adverse transient should not be objectionable or even noticeable in a severe random turbulence environment.

2. System Closed-Loop Response

It should be noted in Fig. 22 that the gain line for full (100 deg) thrust lever displacement per one inch director displacement gives a crossover on the amplitude plot at about 0.17 rad/sec. However, the actual lever travel

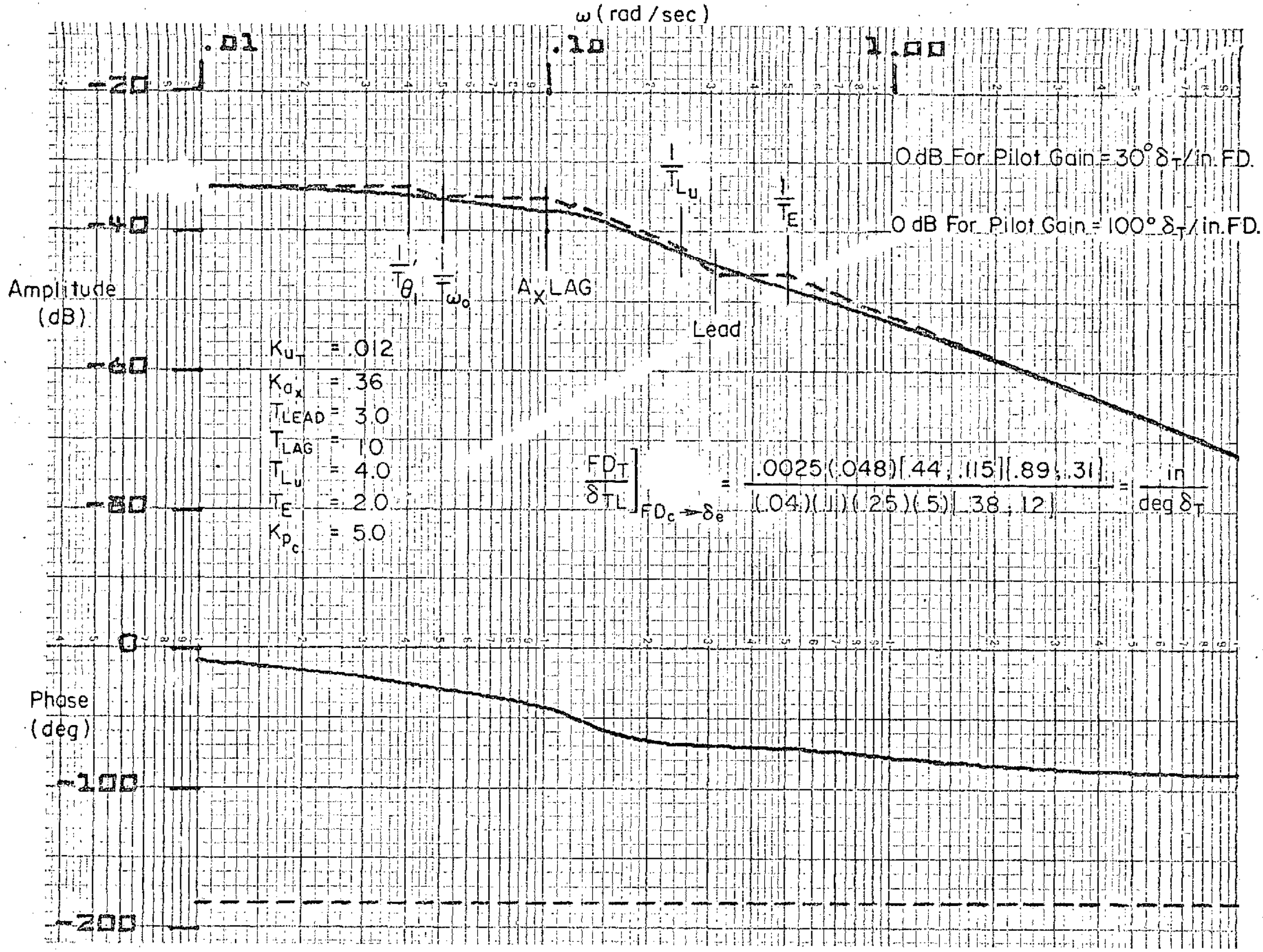


Figure 22. Thrust Director System Effective Controlled Element With Lag-Lead Compensation on a_X Feedback

available to the pilot will depend upon the trim flight condition. For Aircraft F at 280 kt and 26,000 ft level flight the usable thrust lever is approximately ±30 deg. This does not permit the gain line to cross the amplitude plot and therefore proportional closed-loop control of flight path with thrust is not always possible. Rather, the display response to a step throttle displacement may be a first-order lag. This can be seen in Fig. 23 in which manual control of flight path is accomplished via the thrust director but the column director loop is closed via the analog pilot (or autopilot) as in Subsection A-2, preceding. For this flight condition a 2-1/2 deg flight path increase requires nearly full power. Without any ability to overdrive the system (i.e., thrust limited), the response looks like a simple first-order lag with a 10 sec time constant. However, when leveling out, i.e., setting $\gamma_p = 0$, there is twice the incremental throttle capability, the gain line crosses the amplitude plot in Fig. 22, and the system response reflects well-damped second-order dynamics with a considerable improvement in response time. It is important to note in Fig. 23 the few number of thrust adjustments to transition from steady climb back to level trim conditions. Also note how well the director-guided vehicle (both column and thrust directors functioning) holds airspeed in the transition to climb, during climb, and in the level off. The maximum deviation is but 10 ft/sec (5.9 kt). The peak transient in normal acceleration, a_z, is about 0.18 g. Although this is not large in terms of severe turbulence penetration, it might be uncomfortable during maneuvers preparatory to the turbulence encounter. Thus, the pilot might voluntarily restrict system performance under normal conditions and not take full advantage of the director system capability unless the urgency of a situation should demand it.

The response of the complete system to a gust from Direction 4 is shown in Fig. 24. (Again, control via the thrust director in manual and an analog pilot or autopilot is used for control to the column director. Comparison of this response with that of Fig. 17 for column director only shows the complete system results in considerably less perturbation in a_z and θ and a somewhat faster airspeed recovery. Unfortunately, greater altitude loss was also incurred by the pilot anticipating thrust director motion and actually decreasing thrust too soon.

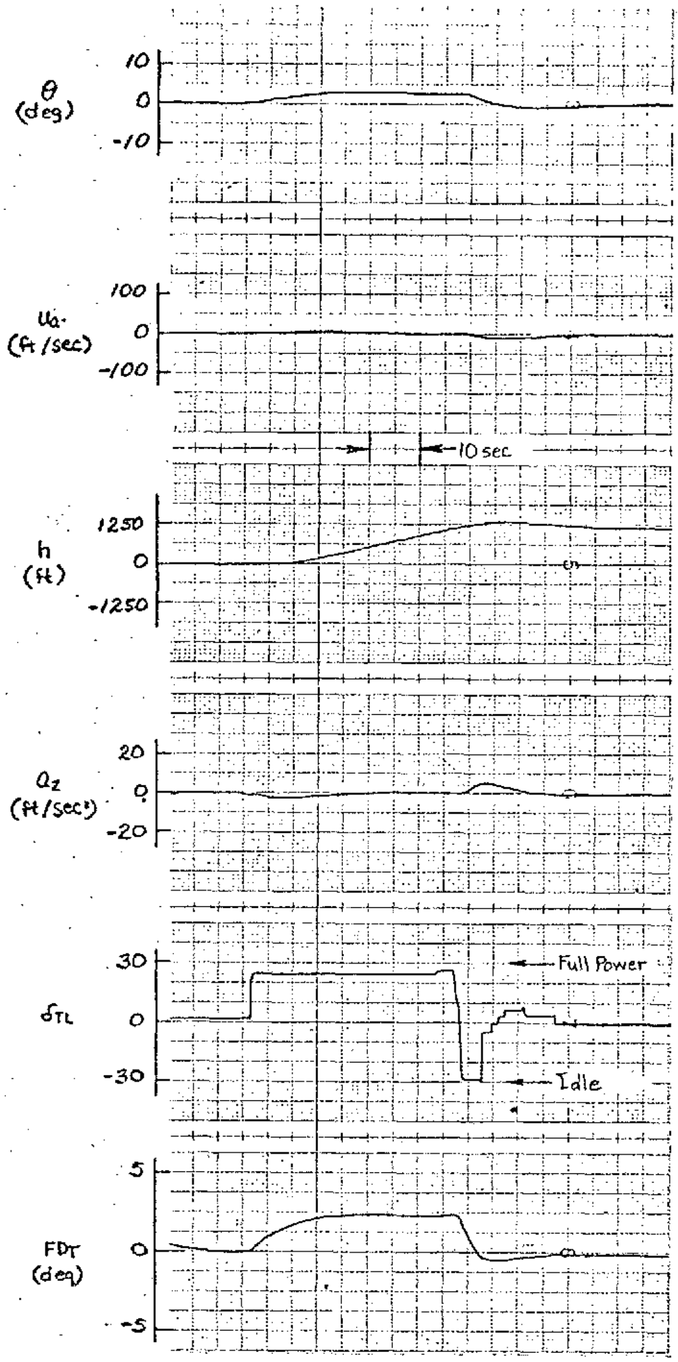


Figure 23. Thrust Director and Vehicle Response to Manual Throttle Input for 2-1/2 deg Climb and Level Out; 280 kt at 26,000 ft; Column Director Loop Closed Via Analog Pilot

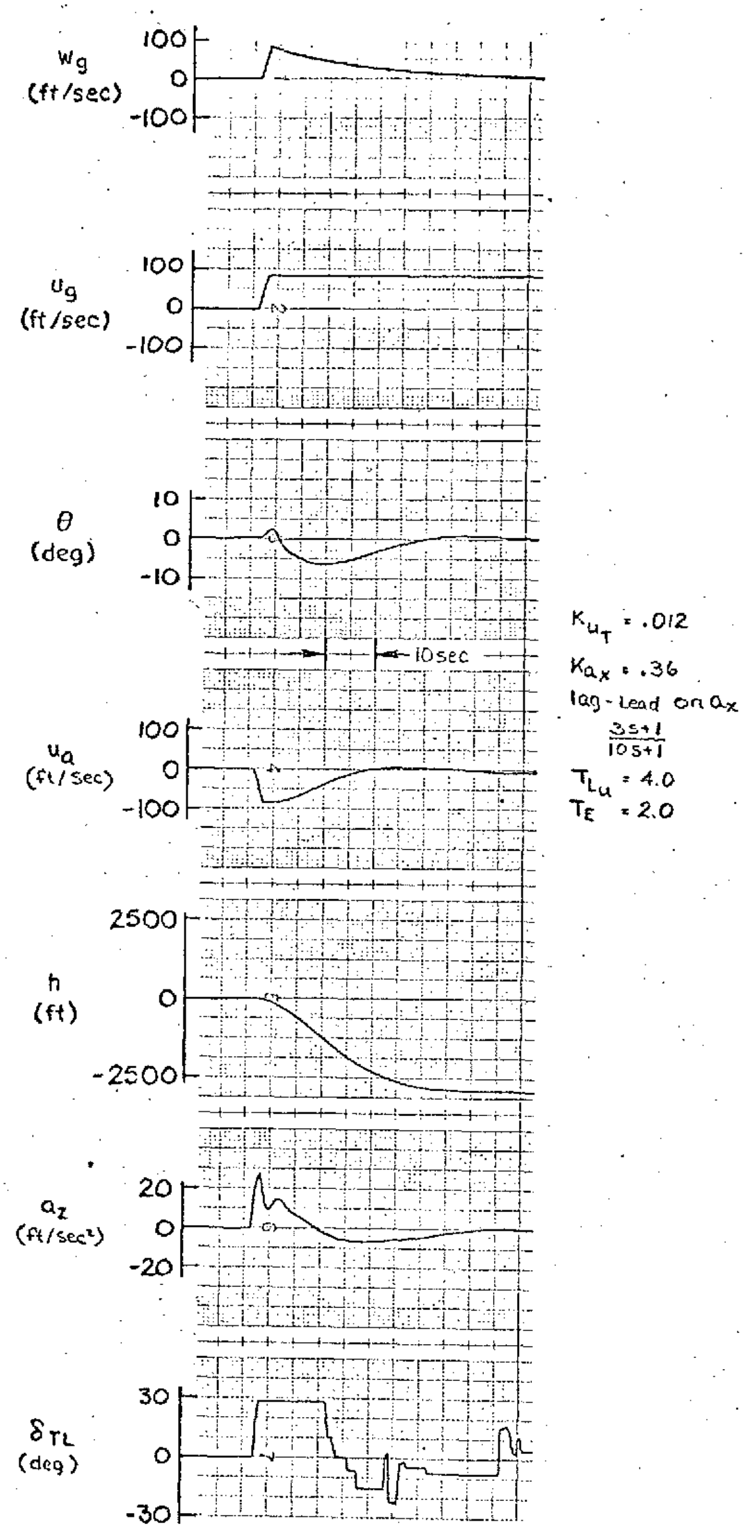


Figure 24. Closed-Loop Response to Gust 4 with Manual Control to Thrust Director, and Column Director Closed with Analog Pilot; 280 kt at 26,000 ft

3. System Performance at Low Altitude

Again the 250 kt, 10,000 ft case is used to determine the influence of change in flight condition. The main effect on the thrust director system is a 175% increase in X_{δ_T}, the thrust per unit throttle deflection. This nearly doubles the system gain and strongly influences the command response, i.e., the director is more responsive to throttle change. This can be seen from the amplitude ratio of the effective controlled element Bode shown in Fig. 25, Compared to Fig. 22 the dc gain is increased from 0.6 in./30 deg to 0.6 in./16.35 deg. The mid-frequency gain is also increased. Figure 26 shows the director response and vehicle motions for a 3 deg desired flight path change. Again, the thrust director loop is closed manually and the column director loop is closed via an analog pilot. It is apparent that the thrust director greatly aids in arriving at the trim thrust required for the desired flight path. The rapid thrust changes employed here actually resulted in path angle overshoot. In actual flight it is doubtful the pilot would employ such step-like thrust changes for fear of damaging the engines. It is more likely he would use a ramp-like throttle input. This would allow the director to follow the input more closely and hence prevent the overshoot in both commanded thrust and vehicle response.

With both director systems closed (control column with autopilot, thrust manually), the vehicle response to gust No. 4 is shown in Fig. 27. Compared to Fig. 24 there is no significant difference except that the throttle is reduced from full power sooner because of the much greater longitudinal acceleration at this flight condition. The main conclusions are therefore that the director systems will not require gain changes for moderate changes in the vehicle characteristics or dynamic pressure and an increase in thrust/weight ratio increases the usefulness of the throttle director system by reducing the lag between throttle displacement and vehicle response and thereby providing more direct control of the potential flight path, γ_p.

C. COMBINED DIRECTOR SYSTEMS

A block diagram of the combined column and throttle director system is presented in Fig. 28. In addition to the feedbacks developed in the preceding subsections, this figure indicates the means for inserting the trim commands,

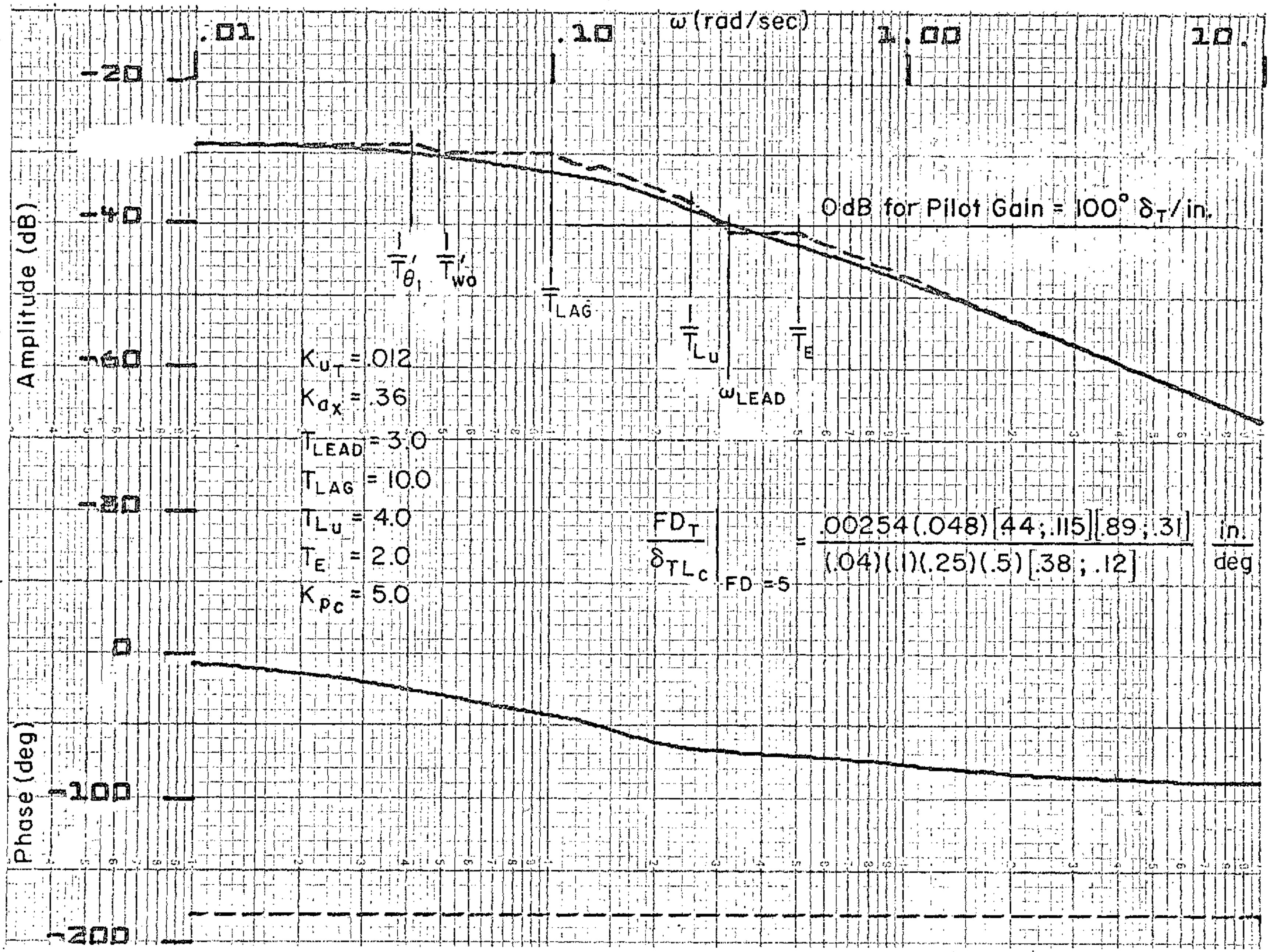


Figure 25. Thrust System Effective Controlled Element; 250 kt at 10,000 ft

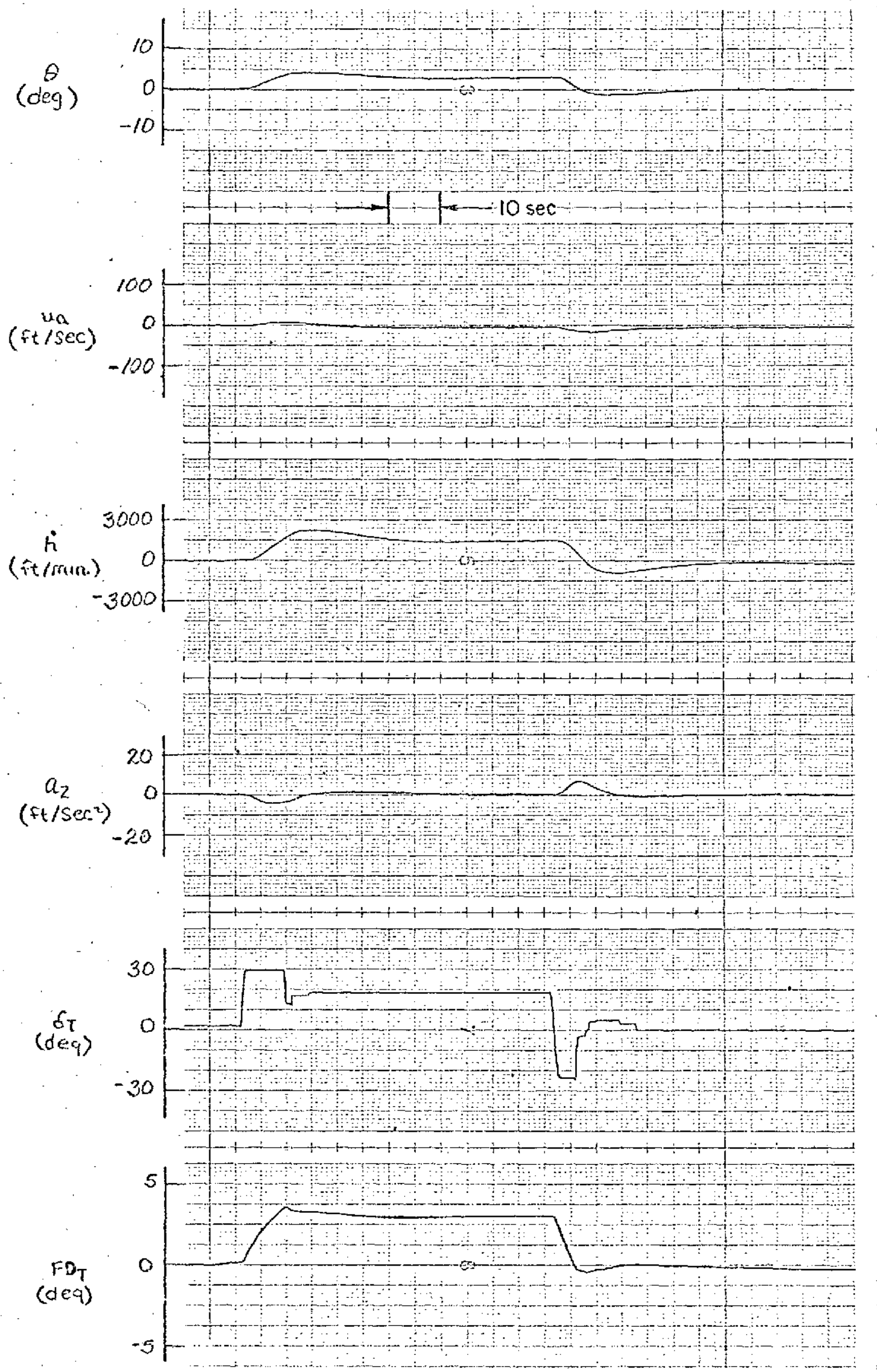


Figure 26. Thrust Director and Vehicle Response to Throttle Input for 3 deg Climb and Level Out; 250 kt at 10,000 ft, Column Director Loop Closed

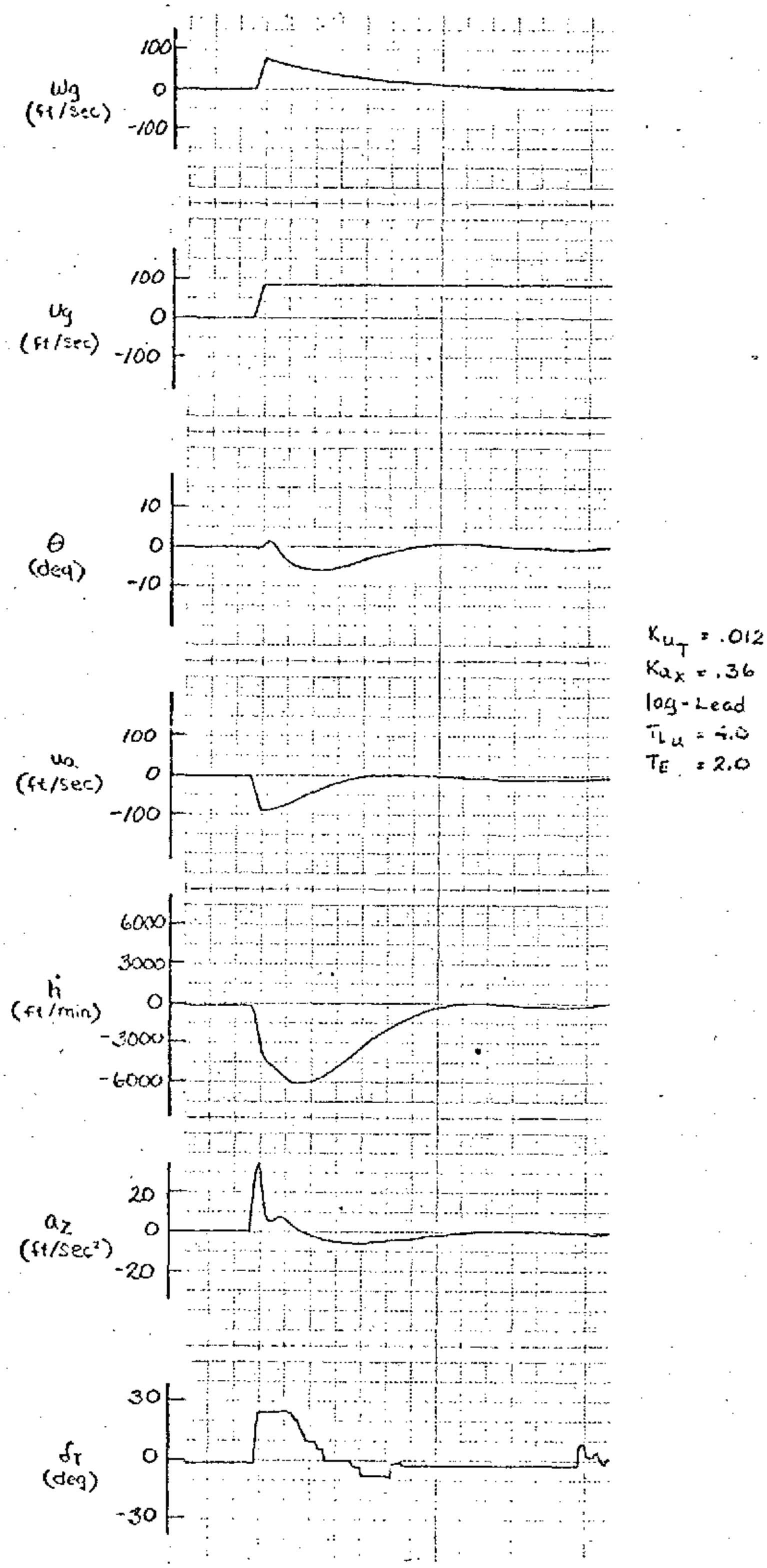


Figure 27. Closed Loop Vehicle Response to Gust 4; Manual Control to Thrust Director, Column Director Closed with Autopilot ($K_p = 5$); 250 kt at 10,000 ft

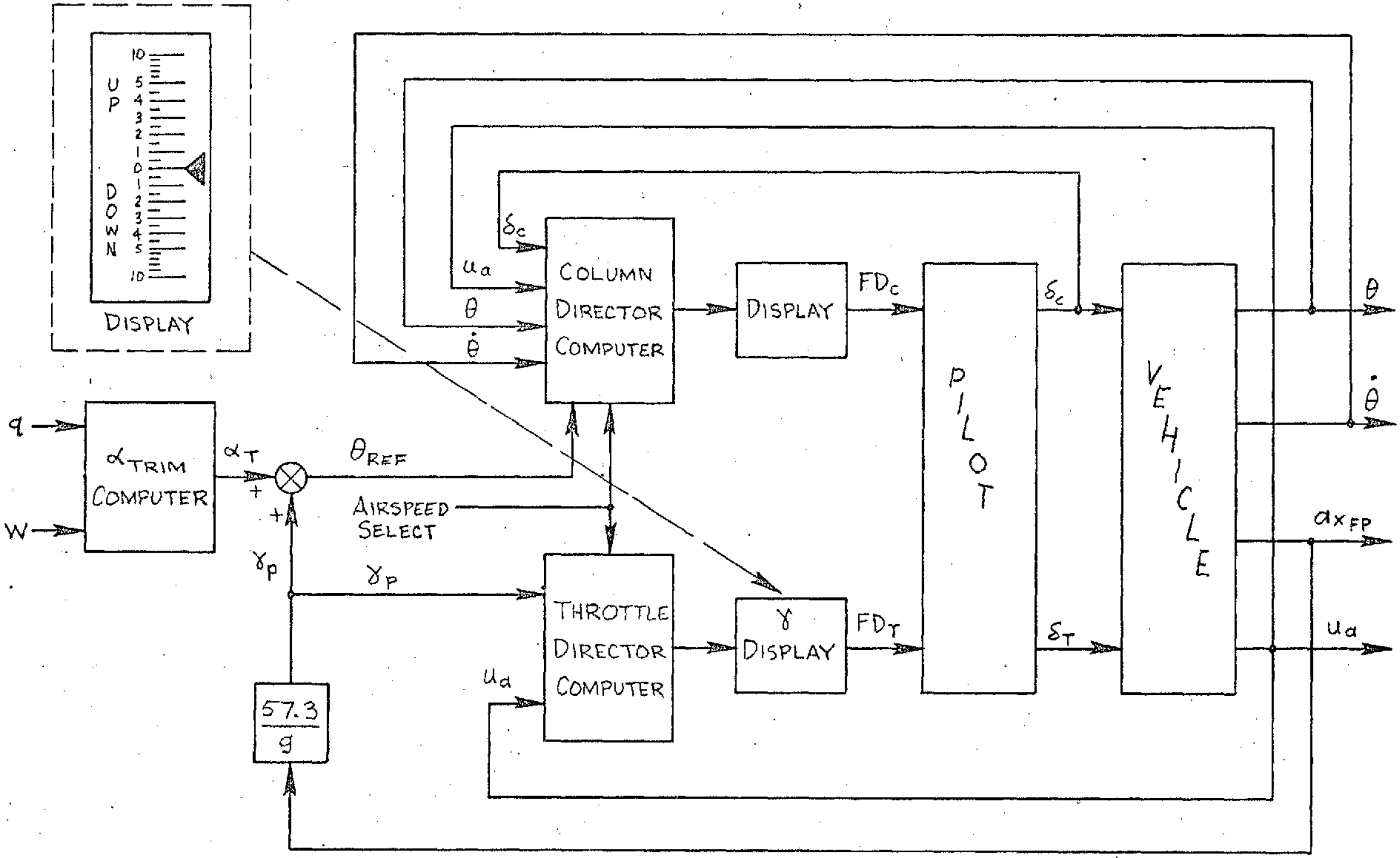


Figure 28. Block Diagram of Column and Throttle Director Systems

the computation of the reference pitch attitude, and a possible thrust director display format. The latter is scaled in degrees flight path angle with the "bug" reflecting the γ_p at all times. Thus, this display differs from the more common "zero reader" type director. A conventional attitude director display is used for the column director.

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. Unless a Mach and temperature correction term is incorporated to modify the acceleration feedback in Fig. 28 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, the terminal flight path error is 15%. If the initial flight path angle were 5.6 deg (3000 fpm) the path at 15,000 ft would be 4.75 deg, an error of 0.85 deg. 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.

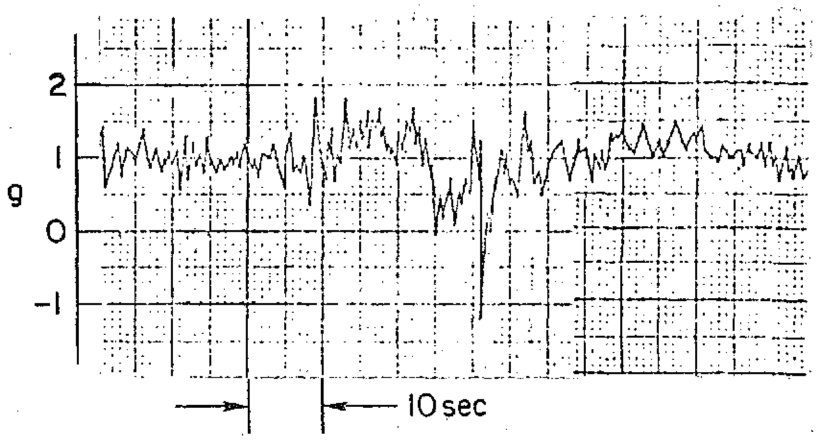
SECTION IV

PRELIMINARY PILOTED SIMULATION

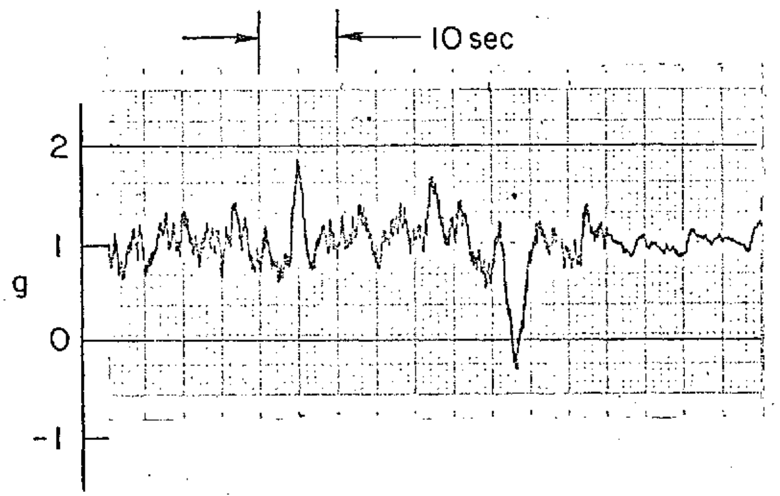
A three-degree-of-freedom fixed-base simulation was conducted as a preliminary test of the elevator and trim thrust director systems derived in Section III. The simulation was used to assess system gains and features, gust and turbulence models, and pilot workload with and without the director system. A 10-minute flight scenario required speed and flight path changes while negotiating light or severe random turbulence and the 8 discrete gusts (Fig. 15). The random u_g and w_g turbulence was obtained by passing white noise through a 2 sec lag. The rms g level was adjusted to about 0.25 g (2.5 m/sec^2) for the severe and less than 0.1 g (1.0 m/sec^2) for the light turbulence. This was found to be compatible with actual flight traces (see Fig. 29). The discrete gusts were the same as discussed in Section III. The scenario was flown with a conventional IFR display (raw data) and with column and thrust directors.

Because of equipment limitations it was not possible to simulate all functions of the flight director. For example, the reference airspeed could not be selected by the pilot and the small perturbations about a fixed flight condition did not require a change in pitch attitude reference. These were pre-set for the simulation and provided "fly-to" references whenever the directors were turned on.

This section contains a description of the simulation scenario and example time traces of the disturbance inputs, pilot control activity (column and throttle) and pertinent vehicle responses. Time traces are presented for flight with conventional IFR display (raw data) and with both directors on. Pertinent comments and suggestions of the engineer-pilot are presented regarding system performance and/or mechanization changes desired before initiating the formal, moving-base simulation.



Actual Flight Trace



Piloted Simulation

(Gust direction 4 and turbulence director off)

Figure 29. Comparison of Normal Accelerations Obtained in Severe Turbulence with Aircraft F, Simulation vs. Actual Flight

A. SCENARIO

Each flight began at 280 kt (144 m/sec) and 26,000 ft (7,925 m) and had the following scenario:

1. Accelerate 30 kt (15 m/sec) at constant altitude.
2. Climb at 1000 fpm (306 m/min) at constant airspeed.
3. Encounter random turbulence during climb. Starts light and goes to severe.
4. Turn on FD systems. Level off and slow down 30 kt (15 m/sec) to proper penetration speed.
5. Gust No. 6, 30 seconds after transition.
6. Fly out of turbulence, recover to straight and level.
7. Encounter severe random turbulence again.
8. Gust No. 2.
9. Fly out of turbulence. Turn off FD systems.
10. Accelerate 30 kt (15 m/sec) while level.
11. Descend at 1000 fpm (306 m/min) at constant airspeed.
12. Encounter severe random turbulence. Turn on FD systems. Slow 30 kt (15 m/sec) and level off.
13. Gust No. 8.
14. Light turbulence. Recover straight and level.
15. Severe random turbulence again. Gust No. 4.
16. Light turbulence. Gusts Nos. 1 and 5.
17. Recover straight and level.

In each case the scenario is started with the pilot flying basic IFR instruments. Also the horizon line of the ADI was offset several degrees so the pilot did not have a precise pitch attitude trim reference. This approximated the real climb situation as noted in Section II. For the no-director case the pilots were instructed to follow severe turbulence penetration recommendations (Ref. 4) to maintain:

- Loose attitude control, $\theta < \pm 10^{\circ}$
- Speed $< \pm 25$ kt (± 12.88 m/sec) but avoid low IAS
- Altitude $< \pm 1200$ ft (± 365.76 m)
- Rate of climb $< \pm 1400$ fpm (426.7 m/min

  Sacrifice to maintain θ and IAS
- Use thrust only in case of:
  - necessity to achieve penetration conditions.
  - extreme airspeed deviation

B. TIME HISTORIES

Time traces of the vehicle motions with and without the two directors are shown in Figs. 30-32 for Gusts Nos. 6 and 2, 8 and 4, and 1 and 5, respectively. The "a" and "b" portions compare the director-on with the no-director tasks. The scenario event sequence is identified at the top of the traces. The scenario for Figs. 30a and 30b is to set up the proper penetration condition upon encountering severe turbulence, i.e., Event 4: decrease speed 30 kt (15 m/sec) and level off, encounter Gust No. 6 (Event 5); fly out of turbulence, recover to straight and level (Event 6); encounter severe turbulence and discrete Gust No. 2 (Events 7 and 8); and fly out of turbulence (Event 9). The scenario events for Figs. 31 and 32 may be identified similarly.

Essentially all variables exhibit significant differences between the two cases. Attitude changes are more pronounced and decisive with the director system on. Director off, e.g., Figs. 31b and 32b, attitude is maintained almost constant even in the presence of the large discrete disturbances. Airspeed shows less wandering and is returned to the trim speed much sooner with the director. Throttle activity is significantly reduced with the director, i.e., number of changes, magnitude of change, and time duration from the trim thrust setting. The high thrust activity and small attitude changes when flying without the director indicates the pilot tended to use thrust rather than coordinated thrust and attitude for airspeed correction when flying basic IFR instruments. Column position also shows more activity in the raw data situation, which

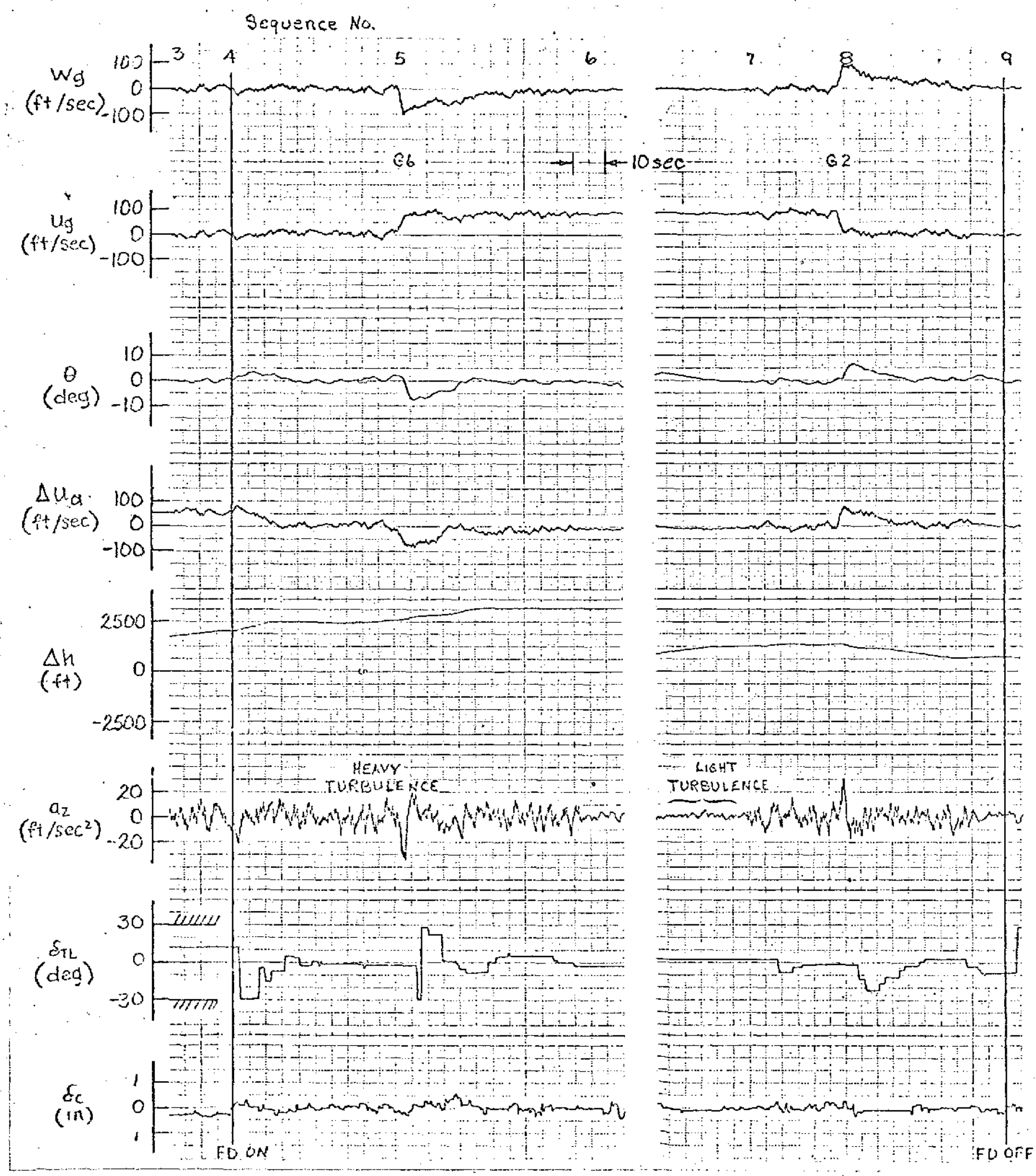


Figure 30. Simulation Time Histories for Gusts 6 and 2; 280 kt at 26,000 ft (144 m/sec at 7925 m)

a) With Turbulence Director On

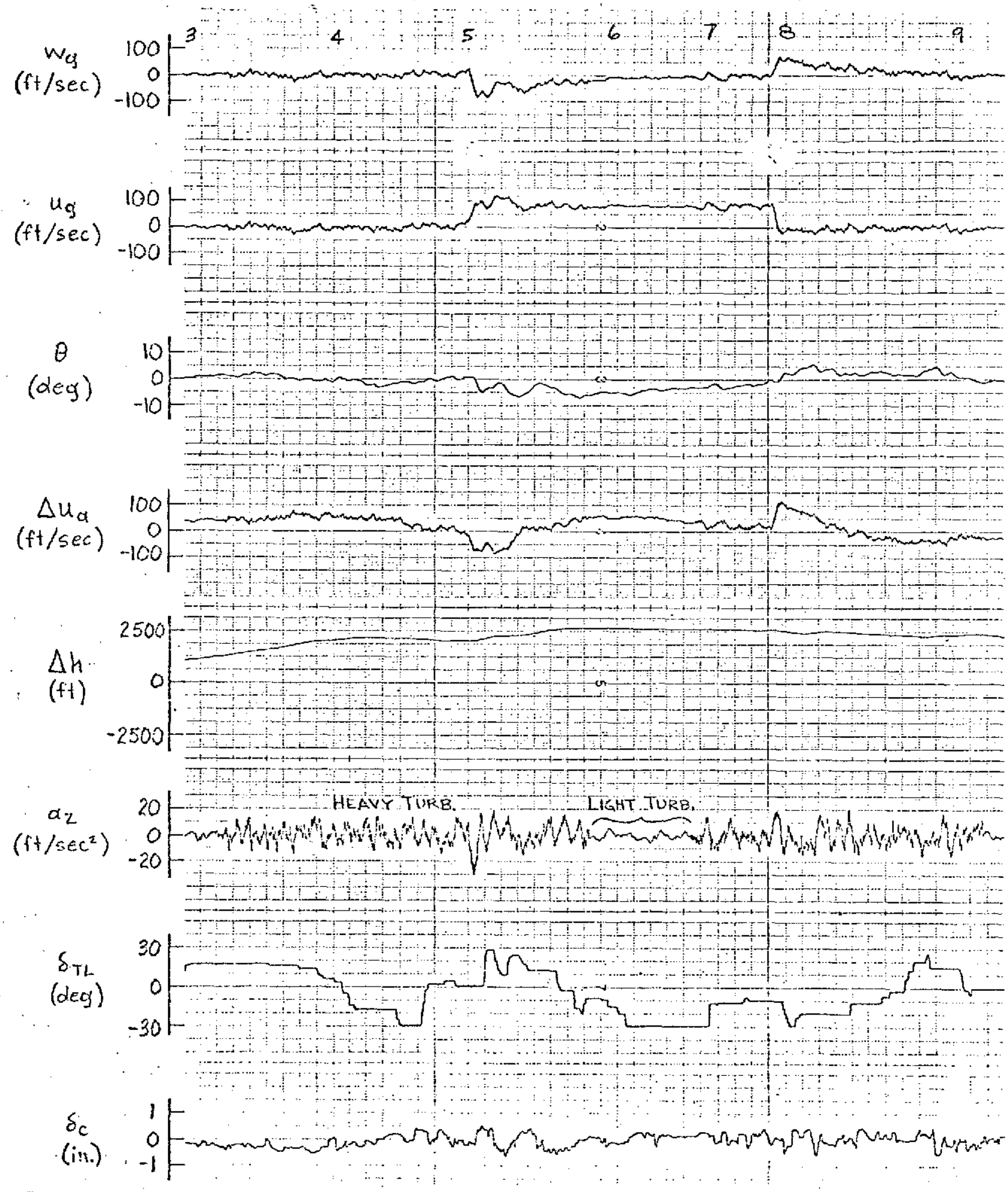


Figure 30. Concluded. (b) No Flight Director

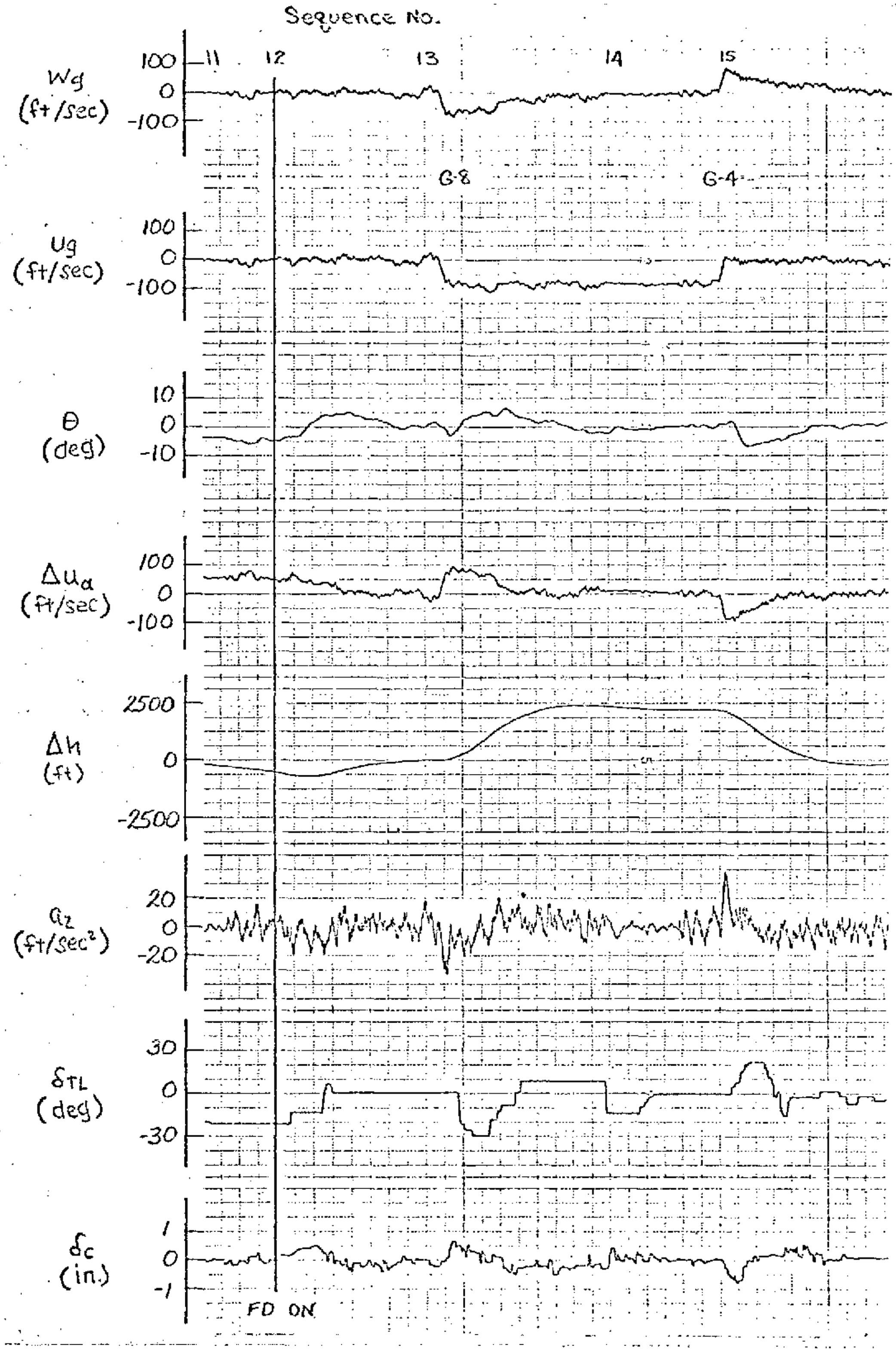


Figure 31. Simulation Time Histories for Gusts 8 and 4; 280 kt at 26,000 ft (144 m/sec at 7925 m)

a) With Turbulence Director On

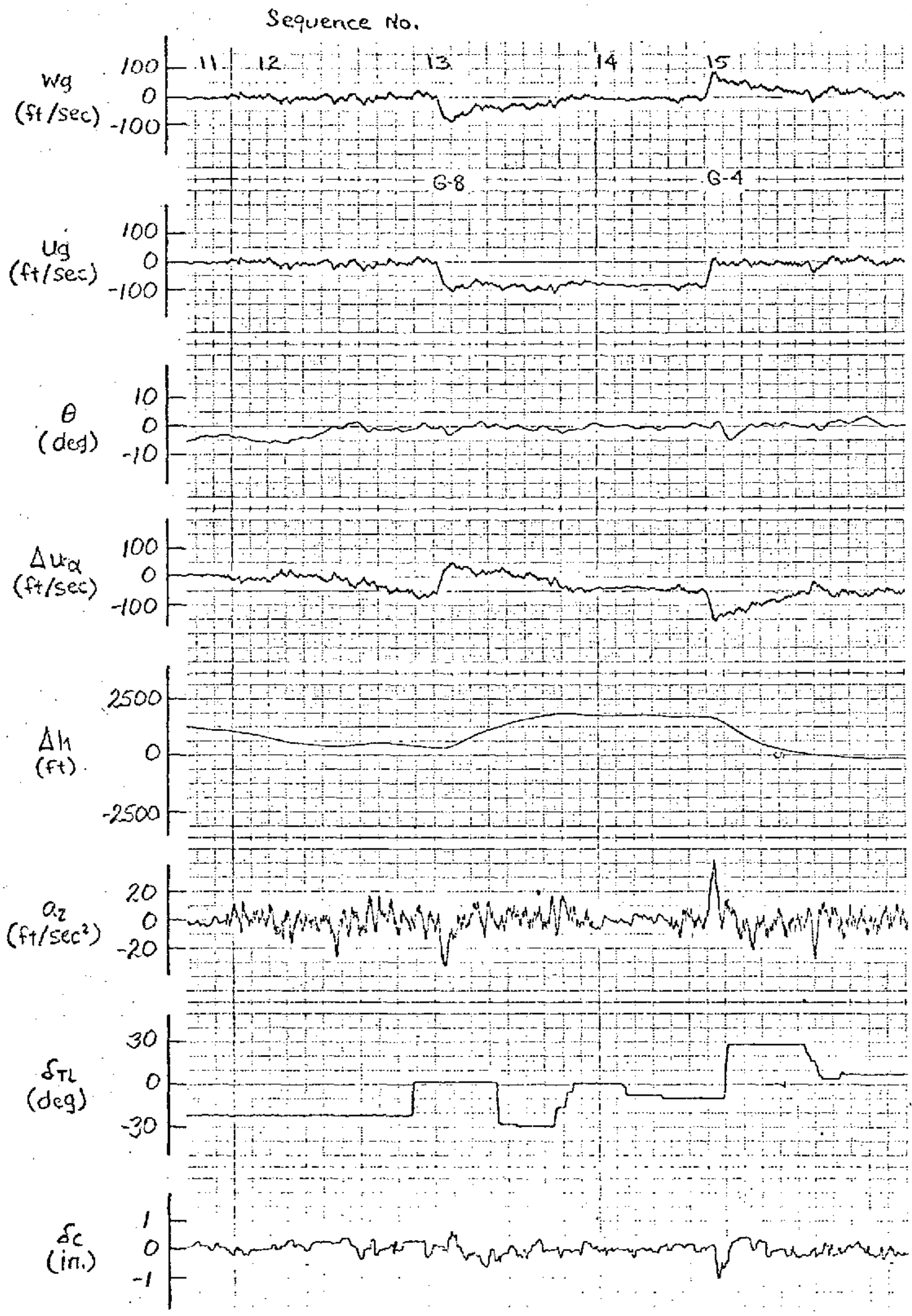
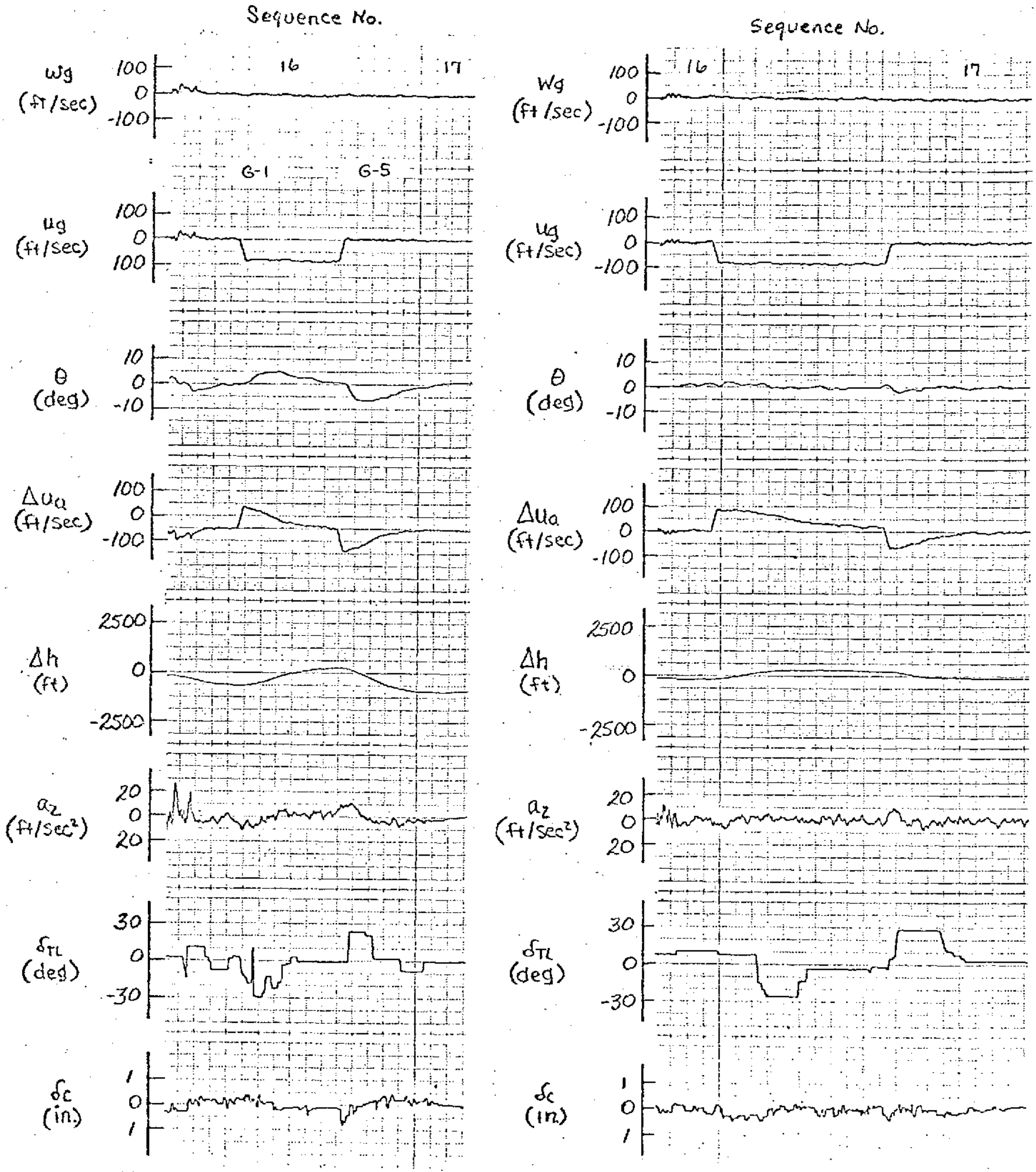


Figure 31. Concluded. (b) No Flight Director



a) With Turbulence Director On

b) No Flight Director

Figure 32. Simulation Time Histories for Gusts 1 and 5; 280 kt at 26,000 ft (144 m/sec at 7925 m)

indicates tighter attitude control than with the director. This last result might be different in a moving-base simulator where the g level would certainly influence the control inputs. However, it is apparent from the decreased control activity (column and throttle) when using the directors that the pilots workload is decreased significantly.

In all cases the random vertical accelerations are approximately $\pm 1/2$ g (5 m/sec^2) about trim. Although the acceleration appears somewhat less with the director. The discrete gust-induced accelerations added 1/2 g (5 m/sec^2) spikes to this level (except Nos. 1 and 5). As indicated previously, the discrete gusts used here are of much greater magnitude and severity than normally encountered. However, the fact that such disturbances can be encountered (and the realism of this simulation) is demonstrated by the comparison of normal acceleration traces previously shown in Fig. 29.

The time histories of Fig. 33 are presented to indicate the smoothness of director (bottom trace) display in the severe turbulence simulated. Although some random turbulence activity is apparent, it was not objectionable to the pilot and the 4 sec gust filter in the airspeed feedback appears adequate. The overall energy management afforded by the combined director systems is also reflected in Fig. 33. The throttle setting required to establish the desired flight path is accomplished in a decisive and precise manner, the associated attitude change is equally decisive and precise, and there is no airspeed perturbation associated with the maneuver.

C. PILOT ASSESSMENT

Pilot opinion of the turbulence director system was favorable as expected. Workload was reduced noticeably. The severe random turbulence did not produce command bar motion in the control column director and hence it was easy to track. There was no noticeable coupling from thrust into the column director and vice versa. Thus the scanning workload between the two directors was minimal. There also was no confusion between the director commands and the vehicle responses during the large discrete disturbance inputs.

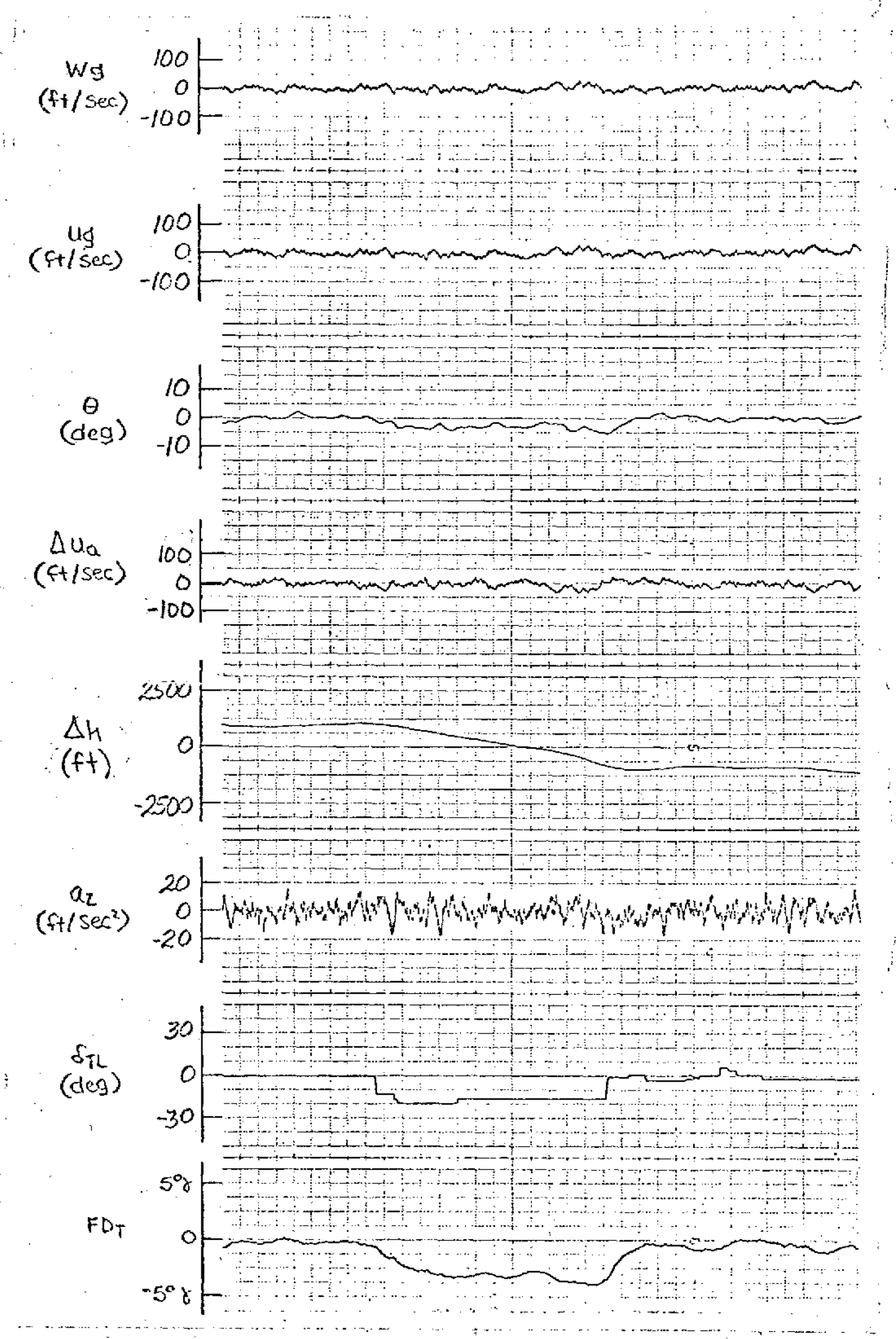


Figure 33. Time History of Constant Airspeed, −2-1/2 deg Descent and Level Off Using Throttle Director

Airspeed recovery was considered to be more than adequate. Even for the largest airspeed disturbance, if the control column command bar was followed closely it was immediately apparent that the airspeed was moving in the right direction to correct the situation. It was felt that any increase in the airspeed-to-attitude gain ratio would merely compromise normal acceleration and altitude excursions without appreciably improving airspeed control.

The feature most appreciated was the thrust director. The ability to set the throttle to the trim value for any desired change in flight path was considered a desirable feature for flight management in general (i.e., for all phases of flight).

There were two significant recommendations for system improvement prior to the formal simulation evaluation. One involved turn-on transients. When the director was turned-on at an airspeed other than that set for the column director reference, a step attitude change was commanded. Any attempt to follow this initial command resulted in excessive change in altitude. A simple fade-in circuit is needed for the airspeed error feedback to reduce this transient.

The second recommendation was that the airspeed error feedback gain should be a function of the sign of airspeed error and/or aircraft rate of descent. That is, low airspeed should have greater weighting than high airspeed. But, if slow and descending rapidly, the attitude command should not be allowed to require negative pitch attitude in order to minimize altitude excursion — especially if at low altitude. The reverse also applies if a headwind is encountered and accompanied by a high rate-of-climb. It also appeared that an increase in airspeed feedback gain for the thrust director would help reduce the commanded attitude response to airspeed error and hence help reduce altitude excursions.

SECTION V

SUMMARY AND RECOMMENDATIONS

The preceding sections have presented the analysis and synthesis of a control column and throttle director system for use in severe turbulence. The column system minimizes airspeed excursions without overdriving attitude and insures loose attitude control regardless of how tightly the pilot attempts to close the loop. The throttle system augments the airspeed regulation and provides an indication of the trim thrust required for any desired flight path angle. In both director systems the effective controlled element (flight director and vehicle) dynamics were tailored to meet a set of pilot-centered requirements unique to manual control tasks. This insured good pilot opinion (and minimum workload) as well as good closed-loop performance in spite of the severe turbulence environment.

A preliminary fixed-base piloted simulation verified the analysis and provided a shake-down for the complete moving-base simulation to be accomplished next. This preliminary simulation utilized a flight scenario concept that was quite successful at combining piloting tasks, random turbulence, and discrete gusts to create a high but realistic pilot workload conducive to pilot error and potential upset. The turbulence director system significantly reduced the pilot workload and minimized unsafe aircraft excursions. The director system is therefore considered to have met the design objectives.

However, based on the preliminary simulation, the following improvements and refinements should be considered and possibly included in the final simulation.

1. Increase the airspeed feedback gain in the throttle director, e.g., $K_u = 0.018$ in/(ft/sec), so that more use will be made of thrust to combat airspeed error and hence reduce the attitude excursions.

2. Make the airspeed feedback gain in the elevator director nonlinear, so that high airspeeds are not weighted as heavily as low airspeeds.

3. Include attitude logic in the elevator director as a function of airspeed error and altitude rate to reduce altitude excursions.

4. Use a fade-in circuit for the airspeed feedback to avoid altitude excursions when the system is turned on with an airspeed error.

REFERENCES

1. Sturgeon, J. R., Turbulence Experience Recorded by CAADRP, International Conference on Atmospheric Turbulence of the Royal Aeronautical Society, London, 18-21 May 1971.

2. Bulletin 71-10, Flight Safety Foundation, Inc., Oct. 1971.

3. Aircraft Accident Report, File No. 1-0001, National Transportation Safety Board, 5 Nov. 1970.

4. Johnston, D. E., Fundamental Control Problems of Turbulence Penetration, Systems Technology, Inc., Tech. Rept. 1003-1, Dec. 1971.

5. Factual Report of Investigation, Civil Aeronautics Board, Bureau of Safety. [United Airlines Flight 746, Boeing 720 N7213U, O'Neill, Nebraska, July 12, 1963].

6. Factual Report of Investigation, National Transportation Safety Board, Bureau of Aviation Safety. [United Airlines Flight 241, Boeing 727 N7027U, Detroit, Mich., Nov. 6, 1968].

7. Pilots Handbook for Critical and Exploratory Flight Testing, Joint SETP and AIAA Publication, 1972.

8. Soderlind, P. A., Luncheon Address, FAA Symposium on Turbulence, Washington, D. C., 22-24 Mar. 1971.

9. Flight Recorder Data Graph, National Transportation Safety Board, RPT No. 71-41.

10. Unpublished notes from NTSB preliminary investigation (no date or number).

11. Total Profile Automatic Throttle Control for Transport Aircraft, AFFDL-TR-70-164, Dec. 1970.

12. Burns, Anne, On the Nature of Large Clear Air Gusts Near Storm Tops, RAE TR 72036, Apr. 1972.

13. Soderlind, Paul A., Jet Transport Operation in Turbulence, AIAA Paper No. 64-353, Jul. 1964.

14. McLaughlin, Milton D., Simulation Study of Three Instrument Displays to Assist in Airplane Thrust Management, NASA TN D-5982, Oct. 1970.

APPENDIX A

AIRCRAFT F OPEN-LOOP CHARACTERISTICS

This appendix presents the vehicle stability derivatives (in body-fixed stability axes) and transfer functions for Aircraft F at the following two flight conditions:

1. 280 kt at 26,000 ft [M = 0.68, q = 247 psf]

   $\gamma_o = -1$ deg

   $W = 590{,}000$ lb

2. 250 kt at 10,000 ft [M = 0.45, q = 207 psf]

   $\gamma_o = +5.2$ (for $\theta = +10$ deg)

   $W = 600{,}000$ lb

It also presents time responses of the open-loop vehicle motions to Gusts 1, 2, 3, and 4. Gusts 5, 6, 7, and 8 would be identically the opposite.

The transfer functions are presented in the following shorthand notation:

For example,

$$N^{u}_{\delta_{TH}} = A_u(s + 1/T_{u_1})[s^2 + 2(\zeta_u)(\omega_u)s + (\omega_u)^2]$$

is written as:

A_u

$(1/T_{u_1})$

$((\zeta_u; \omega_u, \text{Re}, \text{Im}))$

The d.c. gain is shown in angle brackets < >

AIRCRAFT F

h = 26,000 ft
IAS = 280 Kt

GEOMETRY:

VT	ALPHA	GAMMA	LX A	LX P
693.1	.0	-.9400	84.0	.0
A	RHO	MACH	XIO	ZJ
1011.9	.001029	.6850	5.200	10.0
S	C	WEIGHT	IY	ALTITUDE
5500.0	27.3	590000.	32650000.	26000.0

NON-DIMENSIONAL DERIVATIVES

CL	CLA	CLAD	CLM	
.4340	4.660	-6.400	.2500	
CMA	CMAD	CMQ	CMM	
-1.200	-4.600	-21.0	-.09500	
CD	CDA	CDM	TM	TDTH
.02320	.2180	.0	-10300.0	830.0
CDDE	CLDE	CMDE		
.0	.3450	-1.360		

lbs. Thrust / deg Lever

DIMENSIONAL DERIVATIVES

XU	XU STAR	XW	TU
-.004964	-.005517	.02311	-.0005551
ZU	ZU STAR	ZWD	ZW
-.1112	-.1111	.01349	-.5010
MU	MU STAR	MWD	MW
-.0001262	-.0001293	-.0001487	-.001969
MAD	MA	MQ	
-.1031	-1.365	-.4705	
XDE	ZDE	MDE	
.0	-25.6	-1.547 → Per Radian Elevator	
XDTH	ZDTH	MDTH	
.04508	-.004102	.0002542 → Per Degree Throttle Lever	

DENOMINATOR:

.98651E 0
((.42553E 0, .12743E 1, .54225E 0, .11532E 1))
((.35079E- 1, .55683E- 1, .19533E- 2, .55649E- 1))
< .49669E- 2>

```
DE  NUMERATORS:

U   - DE
    -.59155E  0
    (-.41471E  2) ( .95083E  0)   ≐ 24.5
    < .23310E  2>                   (.951)
W   - DE                            <23.3>
    -.25582E  2
    ( .42381E  2)
    (( .43457E- 1, .70785E- 1, .30761E- 2, .70718E- 1))
    <-.54324E  1>
THE - DE
    -.15222E  1
    ( .47053E  0) ( .11020E- 1)
    <-.78932E- 2>
HD  - DE
     .25579E  2
    ( .50372E  1) (-.38932E  1) ( .83942E- 3)
    <-.42108E  0>
AZ  - DE
    -.25582E  2
    ( .50388E  1) (-.38952E  1)
    (( .14725E  0, .28817E- 2, .42434E- 3, .28503E- 2))
    < .41696E- 2>
AZP - DE
     .10220E  3
    (( .70966E- 1, .22178E  1, .15739E  0, .22122E  1))
    (( .14699E  0, .28799E- 2, .42331E- 3, .28487E- 2))
    < .41696E- 2>
```

```
DTH NUMERATORS:

U   - DTH
     .44467E- 1
    (-.60576E- 1)
    (( .45111E  0, .12650E  1, .57066E  0, .11290E  1))
    <-.43106E- 2>
W   - DTH
    -.41022E- 2
    (-.41225E  2)
    ((-.21111E  0, .73928E- 1,-.15607E- 1, .72262E- 1))
    < .92427E- 3>
THE - DTH
     .25139E- 3
    ( .45060E  0) ( .73764E- 1)
    < .83559E- 5>
HD  - DTH
    -.33721E- 2
    ( .51793E- 1)
    (( .11279E  0, .53170E  1, .59969E  0, .52831E  1))
    < .49376E- 2>
AZ  - DTH
    -.41022E- 2
    ( .50218E- 1) ( .91028E- 3)
    (( .12055E  0, .48517E  1, .58487E  0, .48163E  1))
    <-.44140E- 5>
AZP - DTH
    -.25297E- 1
    ( .50112E- 1) ( .91040E- 3)
    (( .14973E  0, .19592E  1, .29335E  0, .19371E  1))
    <-.44140E- 5>
```

```
UG  NUMERATORS:

U   - UG
     .54423E- 2
    ( .92562E  0)
    (( .31678E  0, .99297E  0, .31455E  0, .94183E  0))
    < .49669E- 2>
W   - UG
     .11113E  0
    ( .12765E  1) ( .48148E- 3) (-.30096E-10)
    <-.20556E-14>
THE - UG
     .11103E- 3
    (-.13874E  1) ( .00000E  0)
    <-.15404E- 3>
HD  - UG
    -.11120E  0
    ( .76219E- 3)
    (( .29805E  0, .98055E  0, .29225E  0, .93598E  0))
    <-.81483E- 4>
AZ  - UG
     .11113E  0
    ( .76240E- 3) (-.85272E-13)
    (( .29781E  0, .98003E  0, .29187E  0, .93556E  0))
    <-.69389E-17>
AZP - UG
     .10181E  0
    ( .76247E- 3) (-.85272E-13)
    (( .37323E  0, .10239E  1, .38213E  0, .94983E  0))
    <-.69389E-17>
```

```
WG  NUMERATORS:

U   - WG
    -.23108E- 1
    ( .10942E-11)
    (( .71411E- 1, .15067E  1, .10759E  0, .15028E  1))
    <-.57399E-13>
W   - WG
    -.13483E- 1
    (-.16593E  2) ( .71615E  1)
    (( .61156E- 1, .55668E- 1, .34044E- 2, .55564E- 1))
    < .49669E- 2>
THE - WG
    -.52100E- 3
    (-.31274E  1) ( .62791E- 2) ( .00000E  0)
    < .10231E- 4>
HD  - WG
     .13486E- 1
    (-.37121E  2) ( .95522E  0)
    ((-.17551E- 1, .10191E  0,-.17886E- 2, .10189E  0))
    <-.49662E- 2>
AZ  - WG
    -.13483E- 1
    (-.37149E  2) ( .95520E  0) (-.55942E-14)
    ((-.17483E- 1, .10181E  0,-.17800E- 2, .10180E  0))
    <-.27756E-16>
AZP - WG
     .30250E- 1
    ( .10965E  2) ( .15527E  1) (-.55942E-14)
    ((-.32023E- 2, .10212E  0,-.32701E- 3, .10211E  0))
    <-.27756E-16>
```

Aircraft F
h = 10,000 ft
IAS = 250 kt
$\theta = 10^\circ$
$\alpha_{TRIM} = 4.8$

(For Body Fixed Stability Axes $\omega_0 = \alpha = 0$)

250K @10K

GEOMETRY:

VT	ALPHA	GAMMA	LX A	LX P
485.0	.0	5.200	.0	95.0
A	RHO	MACH	XIO	ZJ
1077.4	.001756	.4502	7.300	10.0
S	C	WEIGHT	IY	ALTITUDE
5500.0	27.3	600000.	32800000.	10000.0

NON-DIMENSIONAL DERIVATIVES

CL	CLA	CLAD	CLM	
.5270	5.160	-6.600	.0	
CMA	CMAD	CMQ	CMM	
-1.000	-3.300	-20.0	-.07800	
CD	CDA	CDM	TM	TDTH
.03200	.3420	-.007500	-13300.0	1465.0
CDDE	CLDE	CMDE		
.0	.3210	-1.260		

DIMENSIONAL DERIVATIVES

XU	XU STAR	XW	TU
-.007612	-.008268	.02323	-.0006620
ZU	ZU STAR	ZWD	ZW
-.1323	-.1323	.02332	-.6519
MU	MU STAR	MWD	MW
-.0001835	-.0001872	-.0001810	-.001949
MAD	MA	MQ	
-.08779	-.9452	-.5320	
XDE	ZDE	MDE	
.0	-19.5	-1.191	
XDTH	ZDTH	MDTH	
.07792	-.009982	.0004466	

DENOMINATOR:

```
   .97668E  0
 ((-.36065E- 2, .57404E- 1,-.20703E- 3, .57404E- 1))
 (( .56207E  0, .11547E  1, .64903E  0, .95506E  0))
 < .42914E- 2>
```

```
CONDITION:     250K @10K

DE  NUMERATORS:

U    - DE
    -.45406E  0
    (-.52808E  2) ( .99073E  0)
    < .23756E  2>
W    - DE
    -.19548E  2
    ( .30087E  2)
    (( .11388E- 1, .91321E- 1, .10400E- 2, .91316E- 1))
    <-.49048E  1>
THE - DE
    -.11596E  1
    ( .63171E  0) ( .13211E- 1)
    <-.96780E- 2>
HD   - DE
     .19467E  2
    ( .49971E  1) (-.36754E  1) (-.66093E- 2)
    < .23631E  1>
AZ   - DE
    -.19548E  2
    ( .49910E  1) (-.36671E  1) (-.12843E- 1) ( .61470E- 2)
    <-.28244E- 1>
HDP - DE
    -.90698E  2
    (-.65836E- 2)
    (( .12759E  0, .19893E  1, .25382E  0, .19731E  1))
    < .23631E  1>
```

```
CONDITION:     250K @10K

DTH NUMERATORS:

U    - DTH
     .76104E- 1
    (-.10202E  0)
    (( .59881E  0, .11593E  1, .69418E  0, .92845E  0))
    <-.10434E- 1>
W    - DTH
    -.99820E- 2
    (-.20069E  2)
    ((-.30122E  0, .99568E- 1,-.29991E- 1, .94944E- 1))
    < .19860E- 2>
THE - DTH
     .43804E- 3
    ( .63695E  0) ( .52174E- 1)
    < .14557E- 4>
HD   - DTH
     .16838E- 1
    ( .24794E- 1)
    (( .18868E  0, .31366E  1, .59181E  0, .30803E  1))
    < .41075E- 2>
AZ   - DTH
    -.99820E- 2
    ( .34568E- 1) (-.78306E- 2)
    (( .14219E  0, .39651E  1, .56381E  0, .39249E  1))
    < .42482E- 4>
HDP - DTH
     .58452E- 1
    ( .24689E- 1)
    (( .24126E  0, .16871E  1, .40701E  0, .16372E  1))
    < .41075E- 2>
```

```
CONDITION:     250K @10K

UG  NUMERATORS:

U    - UG
     .80756E- 2
    ( .10522E  1)
    (( .43450E  0, .71065E  0, .30878E  0, .64006E  0))
    < .42914E- 2>
W    - UG
     .13225E  0
    ( .12220E  1) (-.33809E- 2) (-.28953E-11)
    < .15821E-14>
THE - UG
     .15893E- 3
    (-.85375E  0) ( .00000E  0)
    <-.13569E- 3>
HD   - UG
    -.13098E  0
    (-.60162E- 2)
    (( .45269E  0, .70256E  0, .31804E  0, .62645E  0))
    < .38894E- 3>
AZ   - UG
     .13225E  0
    (-.59786E- 2) ( .28037E-12)
    (( .45347E  0, .70767E  0, .32091E  0, .63073E  0))
    <-.11102E-15>
HDP - UG
    -.11589E  0
    (-.60091E- 2)
    (( .55488E  0, .74737E  0, .41470E  0, .62175E  0))
    < .38894E- 3>
```

```
CONDITION:     250K @10K

WG  NUMERATORS:

U    - WG
    -.23228E- 1
    (-.41161E-11)
    ((-.63333E- 1, .13038E  1,-.82576E- 1, .13012E  1))
    < .16254E-12>
W    - WG
    -.23323E- 1
    (-.12738E  2) ( .43718E  1)
    (( .29281E- 1, .57481E- 1, .16831E- 2, .57457E- 1))
    < .42914E- 2>
THE - WG
    -.89040E- 3
    (-.13864E  1) ( .90569E- 2) ( .00000E  0)
    < .11180E- 4>
HD   - WG
     .23227E- 1
    (-.28046E  2) ( .10777E  1)
    ((-.58251E- 2, .78022E- 1,-.45449E- 3, .78020E- 1))
    <-.42737E- 2>
AZ   - WG
    -.23323E- 1
    (-.27956E  2) ( .10778E  1) (-.10270E-12)
    ((-.62013E- 2, .78441E- 1,-.48547E- 3, .78439E- 1))
    <-.44409E-15>
HDP - WG
    -.61361E- 1
    ( .65752E  1) ( .17347E  1)
    (( .55986E- 3, .78144E- 1, .43750E- 4, .78144E- 1))
    <-.42737E- 2>
```

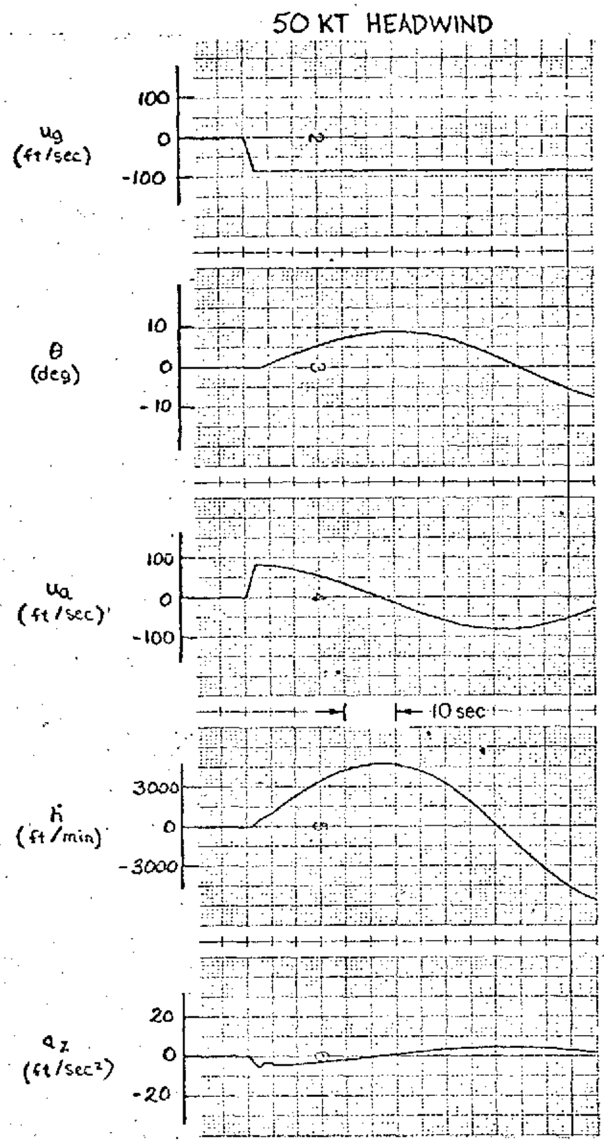


Figure A-1. Open-Loop Gust Responses; Gust 1; 250 kt (129 m/sec) at 10,000 ft (3048 m); $\gamma_o = 5$ deg

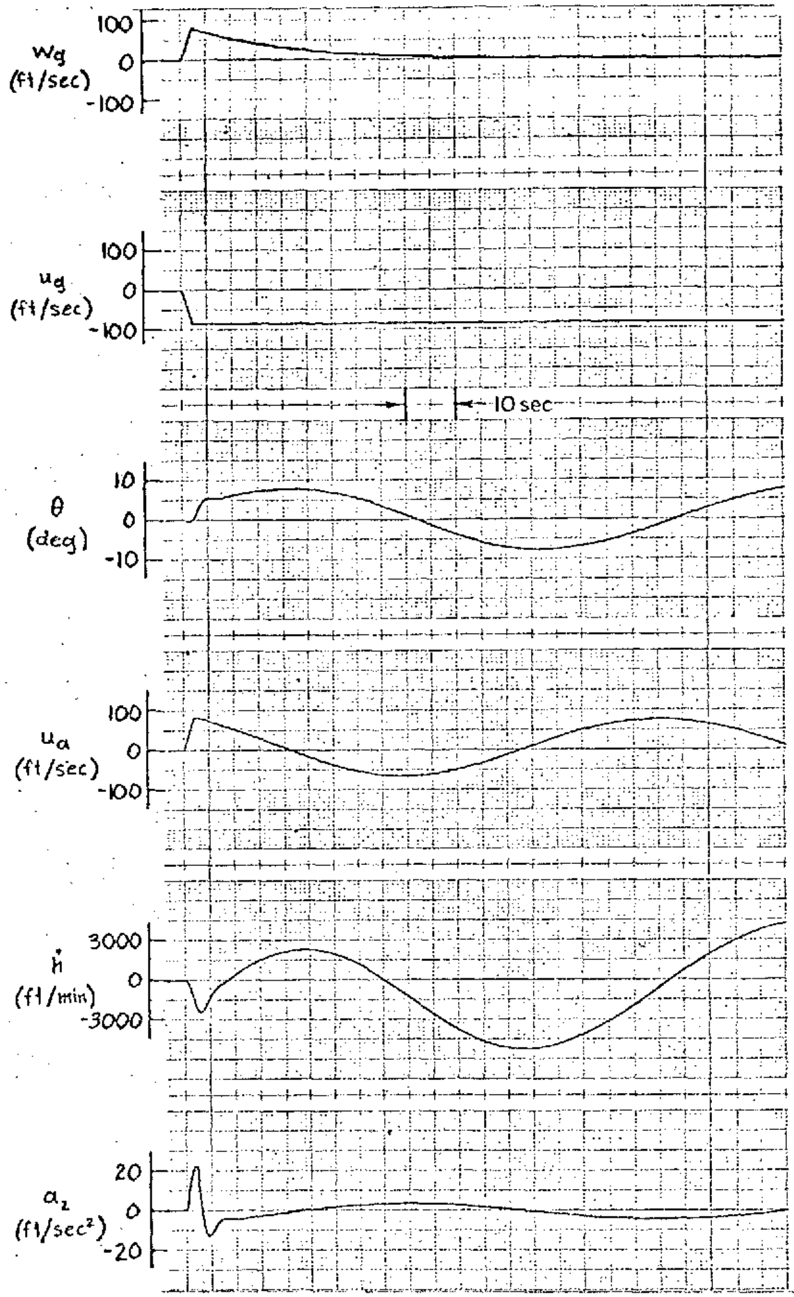


Figure A-2. Open-Loop Gust Responses; Gust 2; 250 kt at 10,000 ft; $\gamma_o = 5$ deg

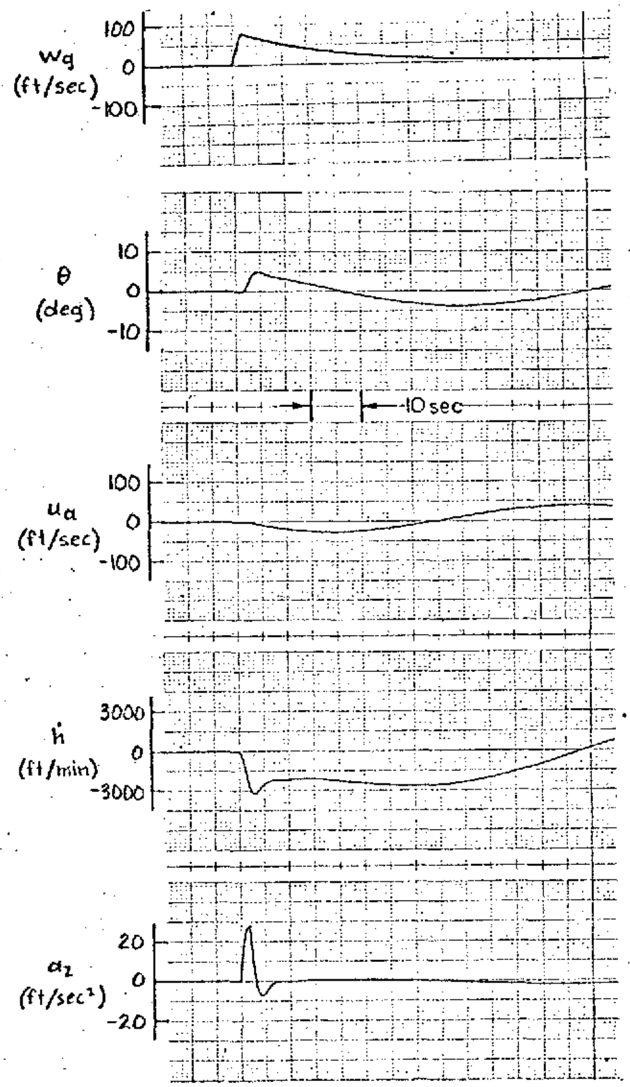


Figure A-3. Open-Loop Gust Response; Gust 3; 250 kt at 10,000 ft; $\gamma_o = 5$ deg

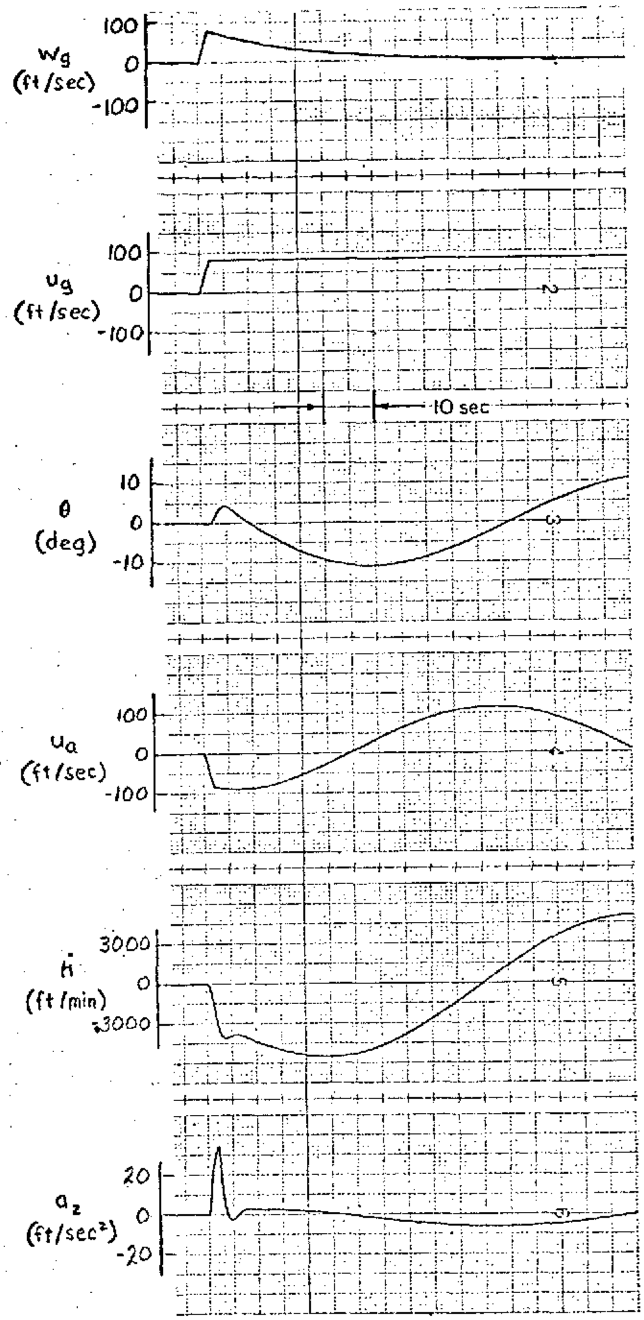


Figure A-4. Open-Loop Gust Response; Gust 4; 250 kt at 10,000 ft; $\gamma_o = 5$ deg

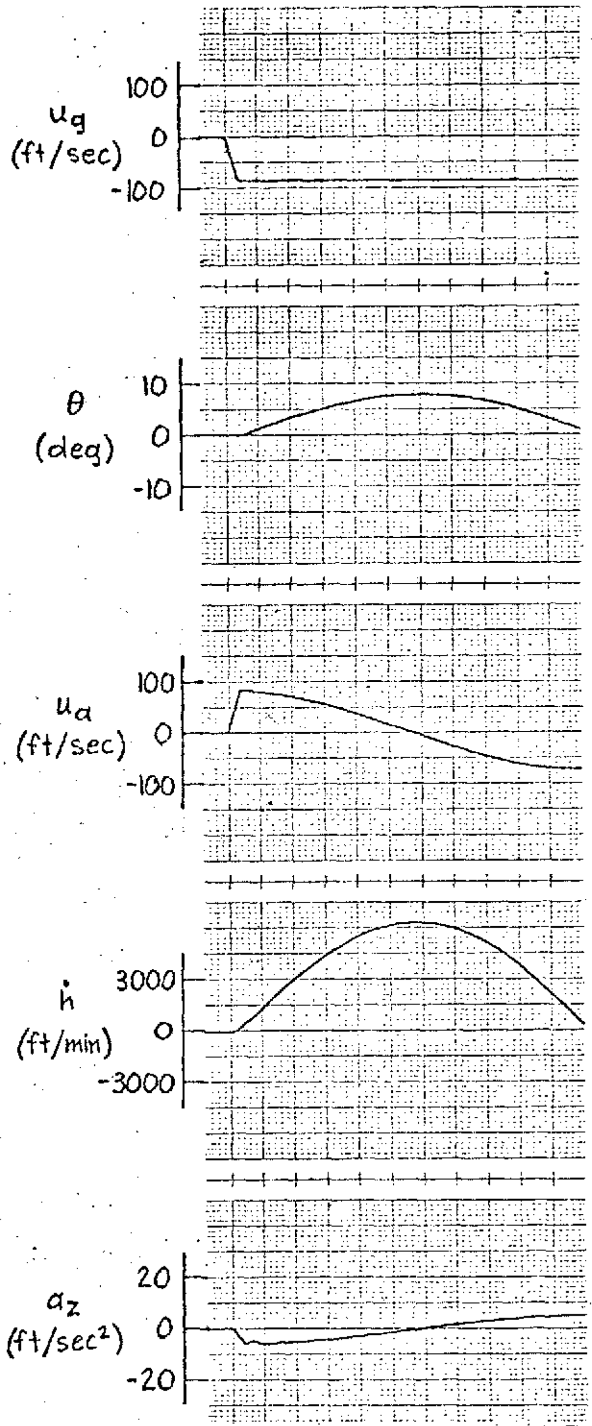


Figure A-5. Open-Loop Gust Response; Gust 1; 280 kt at 26,000 ft; γ_o = 5 deg

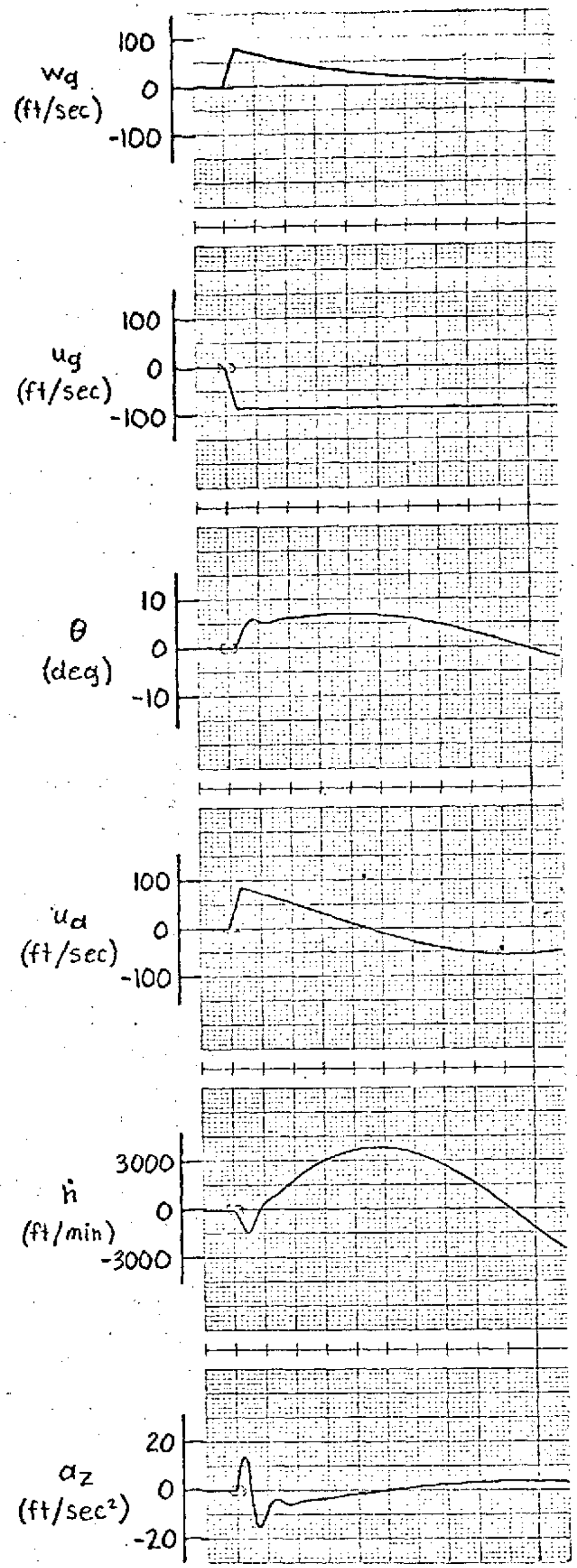


Figure A-6. Open-Loop Gust Response; Gust 2; 280 kt at 26,000 ft; γ_o = 5 deg

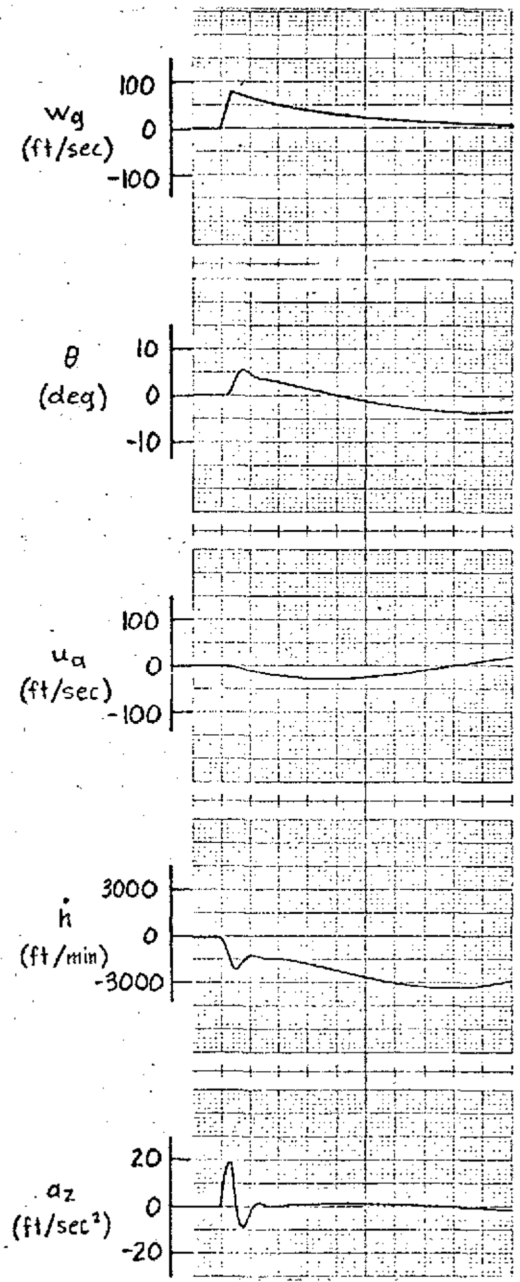


Figure A-7. Open-Loop Gust Response; Gust 3; 280 kt at 26,000 ft; γ_o = 5 deg

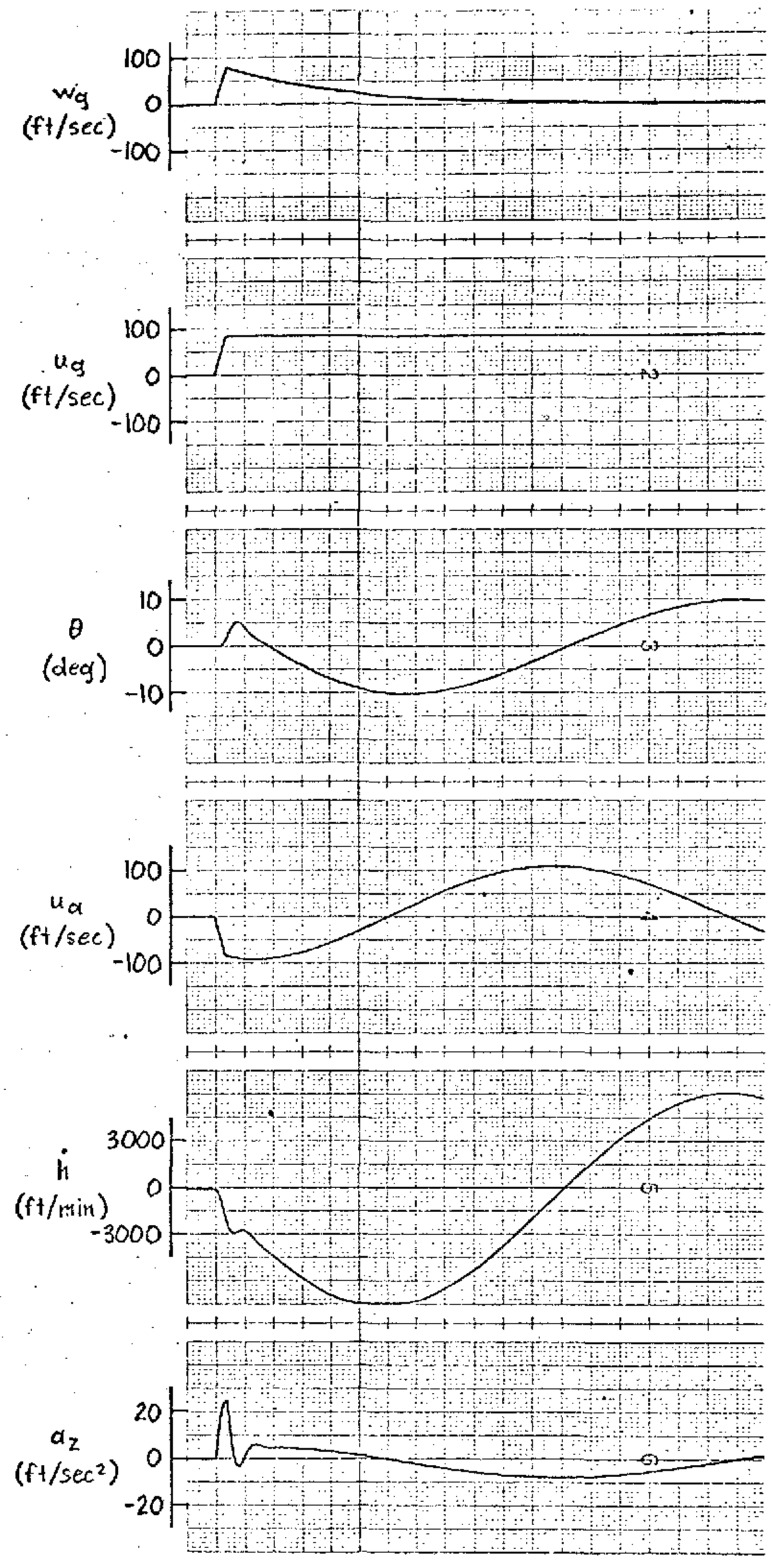


Figure A-8. Open-Loop Gust Response; Gust 4; 280 kt at 26,000 ft; γ_o = 5 deg