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ANALOG STUDY OF THE LONGITUDINAL RESPONSE OF A SWEPT-WING TRANSPORT AIRPLANE TO WIND SHEAR AND SUSTAINED GUSTS DURING LANDING APPROACH

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SUMMARY

Analog-computed time histories and altitude-ground track plots indicate the longitudinal responses of the airplane to varying wind conditions. Controls-fixed runs first demonstrated the differences in responses of an airplane to horizontal gusts and to vertical gusts. Airplane static stability, lift-curve slope, lift-drag ratio, and airplane size were varied while the airplane, with controls fixed, was subjected to wind shear and sustained gusts.

Controlled responses showed the effect of maintaining constant pitch attitude or constant airspeed during flight in a wind shear region, into a downdraft, and into a combined wind shear and downdraft. Realistic combinations of downdraft and shear (of decreasing head wind) were found that could significantly steepen descent with little initial attitude change. In fact, the initial changes in attitude and airspeed might induce the pilot to steepen the flight path further.

INTRODUCTION

Wind shear, a variation in the primary or "steady" horizontal wind component with a change in altitude, has been recognized as a probable contributing factor, if not the direct cause, of numerous aviation landing accidents and incidents. Therefore, information on airplane responses to wind shear and gusts is of considerable interest; it hopefully could prove useful for accident investigations and for warning flight crews of the possible effects of unusual winds.

Wind shear becomes of greatest concern when coupled with environmental factors that hinder the recognition of wind shear effects. Typical of such factors are:

(1) Marginal or limited visibility conditions that would deprive the pilot of some of the indications of an appreciable attitude change,

(2) Turbulence, which causes motions that might obscure both the vertical acceleration changes and the attitude changes associated with a flight path change,

(3) Lag in vertical speed indicators, which would delay the warning from these instruments of flight-path steepening,

(4) Heavy workload during landing approach.

In order to evaluate the effects of wind shear on the flight path of the swept-wing transport class of aircraft and the accompanying cues to the pilot, a brief analog simulation program was conducted at the Ames Research Center, and the results are presented here. The data from these tests refer to a rather limited set of conditions, intended primarily to provide a general indication of the magnitude and direction of such effects.

NOTATION

$\bar{c}$	wing mean aerodynamic chord, ft
C_D	drag coefficient, $\frac{D}{qS}$
C_{D_o}	drag coefficient at zero angle of attack
C_L	lift coefficient, $\frac{L}{qS}$
C_{L_o}	lift coefficient at zero angle of attack
C_m	pitching-moment coefficient, $\frac{M}{qS\bar{c}}$
C_{m_o}	pitching-moment coefficient at zero angle of attack
D	aerodynamic drag, lb
F	force
g	acceleration due to gravity, 32.2 ft/sec^2
h	altitude, ft
I_y	pitching moment of inertia, slug-ft^2
L	aerodynamic lift, lb
m	airplane mass, slugs
M	aerodynamic pitching moment, ft-lb
MSL	mean sea level

n_z normal acceleration (up, positive), g

q dynamic pressure, $\frac{\rho V^2}{2}$, lb/ft^2

$\frac{R}{D}$ rate of descent, ft/min

S wing reference area, ft^2

T total thrust, lb

V equivalent airspeed, ft/sec or knots

V_o initial airspeed (before disturbance), knots

W gross weight, lb

x ground distance, ft

α angle of attack, radians or degrees

γ angle between relative wind and horizontal reference plane (see appendix A), radians

Δ incremental change

θ pitch angle of airplane body axis relative to horizontal reference plane (nose up, positive), radians or degrees

ρ air density, slugs/ft^3

$(\dot{\ })$ time derivative, $\frac{d}{dt}$

$$C_{D_\alpha} = \frac{\partial C_D}{\partial \alpha} \qquad C_{L_{\dot\theta}} = \frac{\partial C_L}{\partial(\dot\theta\bar{c}/2V)} \qquad C_{m_{\dot\alpha}} = \frac{\partial C_m}{\partial(\dot\alpha\bar{c}/2V)}$$

$$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha} \qquad C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha} \qquad C_{m_{\dot\theta}} = \frac{\partial C_m}{\partial(\dot\theta\bar{c}/2V)}$$

$$C_{L_{\dot\alpha}} = \frac{\partial C_L}{\partial(\dot\alpha\bar{c}/2V)}$$

Subscripts

H horizontal

I inertial

max maximum

V vertical

W wind

COMPUTER PROGRAM

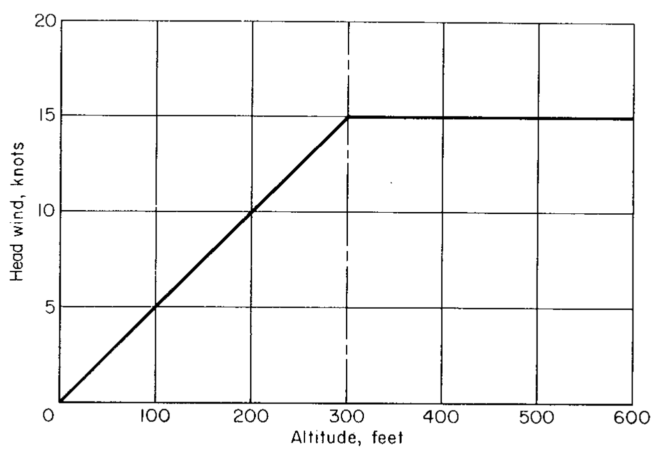
Equations of Motion

The longitudinal equations of motion, given in appendix A, were programmed into a general-purpose analog computer. In these equations, the airplane was represented as a point; thus when the airplane encountered a wind shear or gust, the wind was assumed to act immediately on the airplane's center of gravity. Standard air density for an altitude of 1000 feet, 0.00231 slug/ft^3, was used for all computations.

Airplane Characteristics

Appendix B lists the basic aerodynamic and geometric parameters used to represent the airplane in the present study. These values are for a swept-wing subsonic jet transport in the landing-approach configuration with a landing gross weight of 121,000 lb (77.5 lb/ft^2 wing loading) and a center-of-gravity location midway between fore and aft limits.

Wind Conditions



Sketch (a)

Characteristic wind-shear values for the lowest 100 feet of the atmosphere lie between 3 and 5 knots per 100 feet under moderately strong inversions, with extreme values reaching 10 knots per 100 feet, as shown by observation and analysis in a study by the U. S. Weather Bureau (ref. 1). Reference 2 further substantiates these values for the lowest few hundred feet.

Three basic wind conditions were used in the study: (1) a 15-knot shear (5 knots/100 feet) in the horizontal component, which varied linearly with altitude as shown in sketch (a), (2) a 15-knot step change (sustained gust) in the horizontal wind component, and (3) a 5-knot sustained vertical gust (downdraft). Other wind conditions were derived from these three by changing the sense or combining them as indicated in the text.

PROCEDURE

Tests

All runs were initiated from a trimmed flight condition at an equivalent airspeed of 160 knots and a vertical velocity of -800 feet per minute. Initial altitude was 500 feet; this allowed 15 seconds for monitoring the run to insure a well-trimmed steady flight condition before the onset of the wind disturbance at the 300-foot point.

Two series of runs were conducted; the first determined the responses of the airplane as it entered the disturbance with controls fixed. The recorded transient response indicated how rapidly the airplane would assume the new flight path, and whether the airplane motions would be detectable. The primary variables were the airplane parameters C_{m_α}, C_{L_α}, C_{D_O}, and airplane size.

The second series of runs determined the effects of holding nearly constant pitch attitude or airspeed during entry into the disturbance. These were intended to indicate trajectories that might result from reasonable pilot control inputs if the wind shear were not recognized. For the controlled runs, control system response was instantaneous. The constant-pitch-attitude records represent an idealized case, as a high-gain attitude-error feedback was programmed to generate a corrective pitching moment in this mode, thereby eliminating a lag in pilot's response. For the constant airspeed runs, airspeed was monitored on the brush recorder by the computer operator and a potentiometer (representing the control column) was manipulated in an attempt to maintain nearly constant airspeed.

Measurements

Time histories of the horizontal wind component and the following airplane parameters were recorded on an eight-channel Brush recorder: equivalent airspeed, angle-of-attack, pitch attitude, pitch rate, incremental normal acceleration, vertical velocity, and altitude. An X-Y plotter was used for recording altitude versus horizontal displacement (ground track).

RESULTS AND DISCUSSION

The emphasis of the present study was on defining the conditions necessary to reproduce a significant increase in descent rate with minimal cue to the pilot. Therefore, in the following time histories, situations were sought that would result in deceptively small changes in either pitch attitude or airspeed, on the assumption that these would be the items most likely to be monitored by the pilot.

Controls-fixed responses of the simulated airplane to various wind conditions are first described - as well as the sensitivity of these responses to variations of the airplane parameters C_{m_α}, C_{L_α}, C_{D_o}, and airplane size. Then, the responses of the simulated airplane to a wind shear and downdraft, with pitch control used to maintain constant pitch attitude or constant airspeed, are examined. The manner in which such wind conditions might contribute to an unintentional steepening of flight path is indicated.

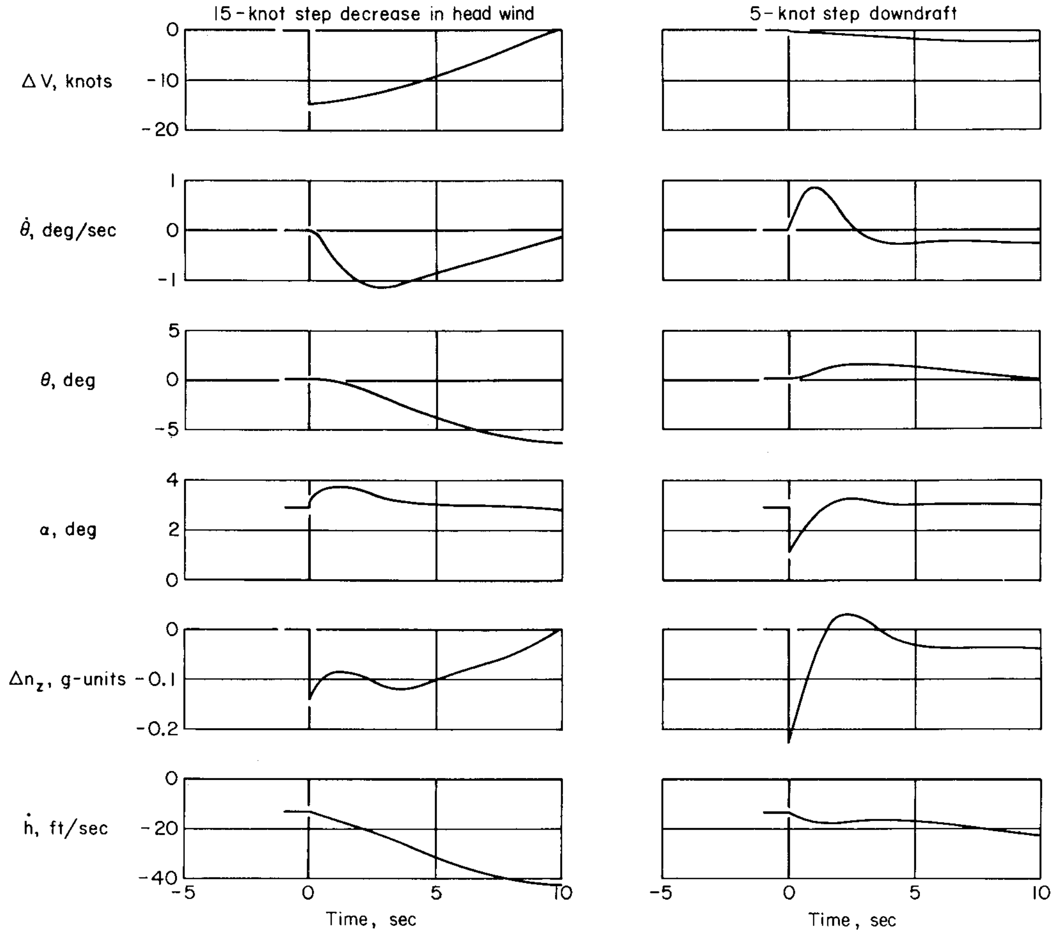


Figure 1.- Dynamic responses of a swept-wing transport airplane to step changes (sustained gusts) in horizontal and vertical wind components; controls fixed, landing approach configuration, V_o = 160 knots.

Controls-Fixed Responses

Responses to sustained vertical and horizontal gusts.- The basic responses of the airplane are indicated by the time histories resulting from step changes (sustained gusts) in horizontal and vertical wind components. These are shown in figure 1 for a 15-knot step change in horizontal wind component and a 5-knot step change in vertical component, both in the direction to steepen flight path.

In the range of flight path angles normally associated with transport aircraft operation, a horizontal gust initially causes a step change in airspeed, whereas a vertical gust causes a step change in angle of attack with little effect on airspeed. The subsequent response to the horizontal gust has a long period as compared with the response to the vertical gust which disturbs primarily the short-period oscillatory mode. Thus, although the order of magnitude of $\Delta n_{z_{max}}$ is the same for the two wind conditions chosen, the negative Δn_z corresponding to the horizontal gust (of decreasing head wind or increasing tail wind) is sustained for a considerable time, slowly returning toward zero as airspeed returns toward the initial value. On the other hand, Δn_z corresponding to the vertical gust is large initially, but returns toward zero rapidly. Substantially greater vertical velocity is generated by the integration of the sustained Δn_z due to the horizontal gust, but the initial effect on vertical velocity is greater for the vertical gust.

Perhaps the most significant observation shown by this comparison is the opposing directions of the initial pitch rate $\dot{\theta}$. This suggests that the downdraft and tail gust in proper combination could steepen descent with little change in attitude, or with a deceptive attitude change - in a direction opposite to the flight path change. This circumstance is discussed in more detail later in this report.

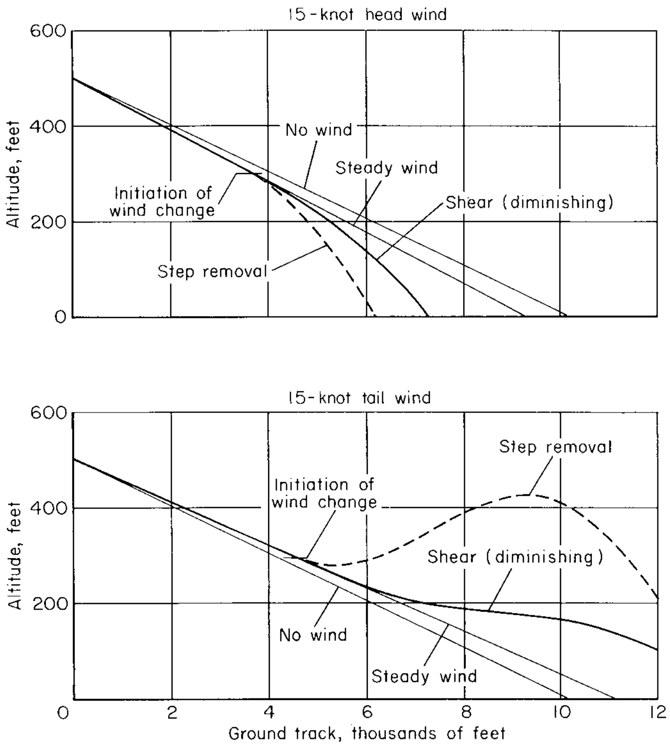


Figure 2.- Effect of various horizontal-wind conditions on flight path; controls fixed, landing approach configuration, V_o = 160 knots, initial rate of descent 800 ft/min.

<u>Horizontal wind effects on flight path</u>.- Altitude versus ground distance is shown in figure 2 for various horizontal wind conditions, that is, no wind, steady wind, step change (sustained gust), and wind shear for the head-wind[1] and tail-wind cases.

Disregarding the airplane response and considering the effect of the movement of the air mass alone, one would expect that decreasing the head-wind or tail-wind component would result in a flight path between that for a steady wind and that for no wind. As seen in the preceding discussion, however, the dynamics of the airplane with controls fixed cause a steepening of the flight path as the head wind decreases, thus overriding the effect of the translation of the encompassing air mass.

Figure 2 shows that the 5-knot-per-100-foot diminishing head-wind shear caused the airplane to contact the ground nearly 2000 feet short of the steady-wind intercept point. A diminishing tail-wind shear caused the airplane to balloon above the desired path,

[1] Throughout the report, the term head wind or tail wind will be used to identify the direction of the horizontal wind component.

with touchdown 3500 feet long. The responses to step wind changes (sustained gusts) are presented to give a reference quantitative indication of the magnitude of such effects.

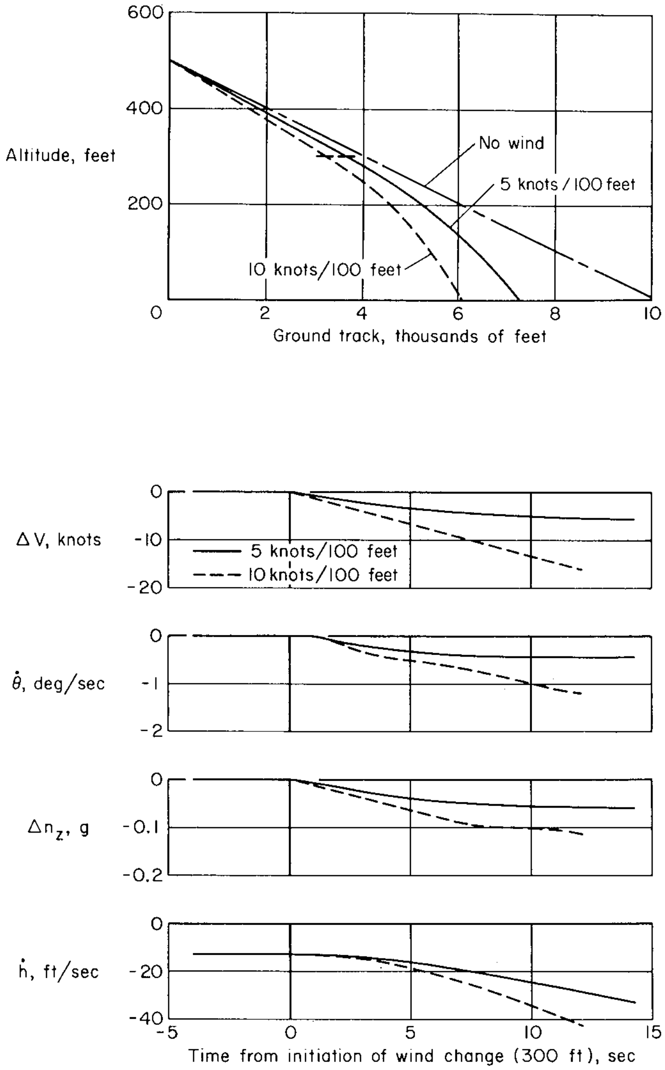


Figure 3.- Effect of variation in strength of wind shear; headwind diminishing to zero velocity linearly with decreasing altitude between 300 feet and ground level, controls fixed, landing approach configuration, V_o = 160 knots.

Effect of strength of wind shear.- In addition to those for the basic 5 knot/100 foot wind shear, analog runs were recorded for a shear strength of twice this magnitude (10 knots/100 feet). Figure 3 presents comparative data for the two conditions.

For the 5 knot/100 foot shear of decreasing head wind, the longitudinal acceleration due to the steepened flight path counters the deceleration created by the wind shear; thus airspeed stopped diverging with a 6-knot net decrease in airspeed. For the 10 knot/100 foot shear, the change in flight path was insufficient to offset the deceleration from the wind shear; a nearly constant deceleration rate existed throughout the 300-foot altitude range.

Effect of static longitudinal stability. Controls-fixed runs with the 5 knot/100 foot wind shear and the 15-knot horizontal wind step were repeated with static longitudinal stability (C_{m_α}) variations representing forward and aft c.g. limits. No first-order differences in response resulted from the stability changes tested, especially for the wind shear. Some remarks of incidental interest can be made, however, regarding these effects.

Consider the time histories, figure 4, of the responses to the 15-knot step reduction in head wind. Horizontal wind disturbances caused a greater change in flight path for the higher stability or forward c.g. condition. This can be explained in the following way. During descending flight, a step reduction in head wind (horizontal component) causes (1) a step decrease in the relative wind (shown in fig. 1) and (2) a slight step increase in angle of attack. Since the rate of change of flight path angle depends upon the incremental normal acceleration Δn_z, the incremental changes in V and α have somewhat countering effects on each other. For example, decreasing V alone would cause a negative Δn_z, whereas increasing α alone would produce a positive Δn_z. The decrease in V is the dominant influence in this case since

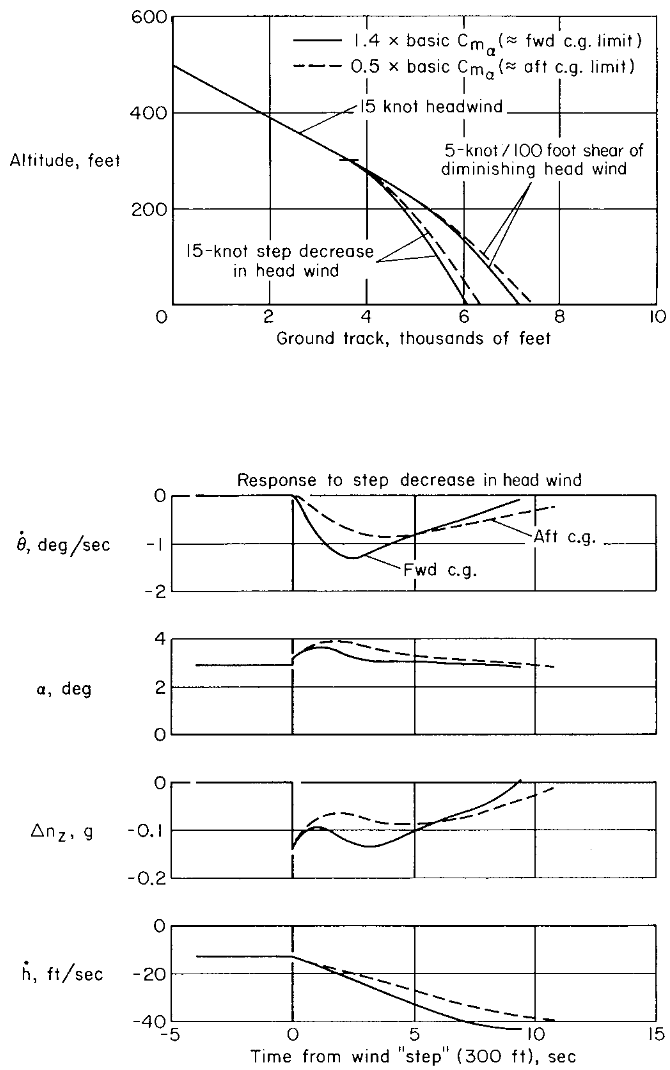


Figure 4.- Effect of varying static longitudinal stability on controls-fixed response to wind "step" and "shear"; landing approach configuration, V_o = 160 knots.

the wind disturbance causes a step negative Δn_z. For the lower stability, the α restoring forces were lower, allowing α to remain larger; this produced a lower net Δn_z for the subsequent time period and hence a lesser change in flight path.

Effects of C_{L_α}, C_{D_o}, size.- To evaluate the sensitivity of the test results to changes in airplane lift-curve slope C_{L_α}, tests were made with 75 and 125 percent of the basic value. The C_{L_o} term was adjusted to allow the same trim α and L/D. For the horizontal wind disturbances, increased C_{L_α} reduced disturbance of the airplane's flight path, although the differences were small. Again this is the result of the countering influence of the $\Delta\alpha$ and ΔV, where the $\Delta\alpha$ contribution is weighted more heavily as lift-curve slope is increased. For quantitative comparison: 5 seconds after the 15-knot step change, $\dot{h}$ was -30 ft/sec for 1.25 × basic C_{L_α} and -33 ft/sec for 0.75 × basic C_{L_α}. Variations in C_{L_α} affected the response to the wind shear even less.

To evaluate the effect of aircraft L/D characteristics on response to the test wind conditions, C_{D_o} was reduced to about 70 percent of the basic value, trim thrust was reestablished, and the wind shear and horizontal gust (step) runs were repeated. There were no observable differences between these runs and those that utilized the basic C_{D_o}.

The characteristics of an operational swept-wing jet transport, larger than the subject airplane (approximately 75-percent greater wing area) were readily available. A few check runs were made with these characteristics in order to evaluate the applicability of these data to swept-wing jet transports in general. The data from these runs nearly duplicated those from the basic airplane characteristics. Therefore, these results appear to be reasonably insensitive to variations of this magnitude from the airplane characteristics listed in appendix B.

Closed-Loop (Controlled) Responses

Two hypothetical pilot control methods were studied in combination with various conditions of wind shear and drafts. The responses under the constraint of constant pitch attitude are discussed first, then runs in which an attempt was made to maintain a constant airspeed are discussed. Control inputs produced pitching moments only; thrust remained constant throughout each run.

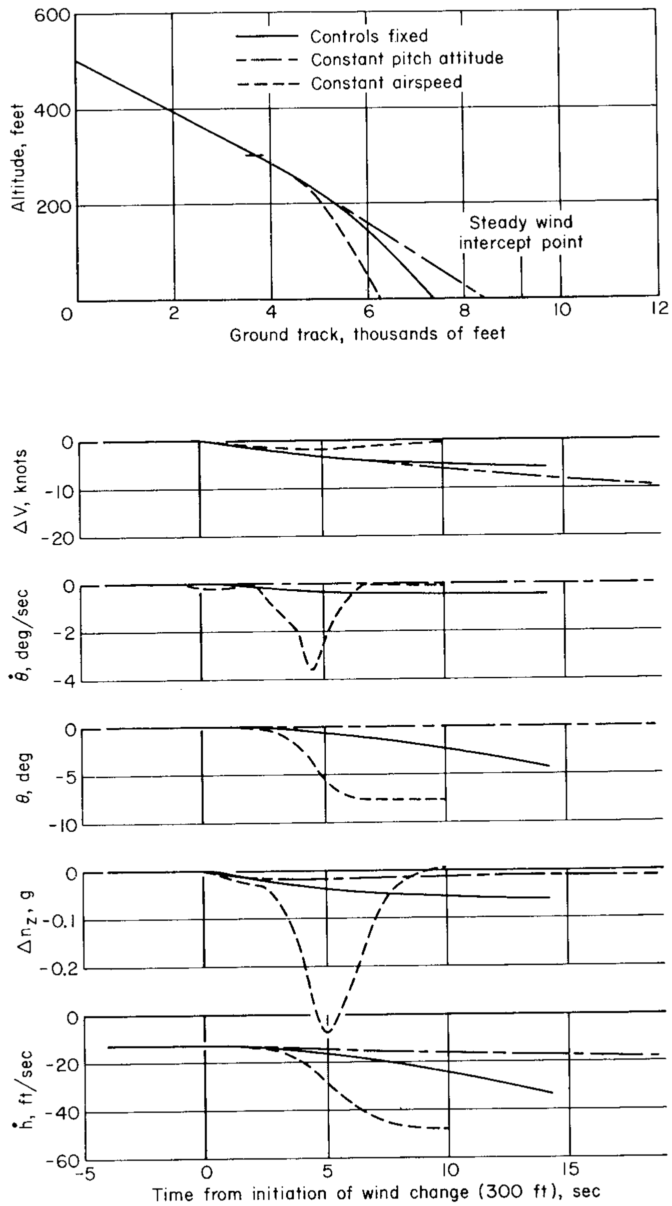


Figure 5.- Effect of various control techniques on airplane response to 5 knot/100 ft diminishing headwind shear; landing approach configuration, V_o = 160 knots.

<u>Effect of maintaining constant pitch attitude in a 5 knot/100 foot wind shear</u>.- Figure 5 clearly shows that flying constant pitch attitude significantly reduces the effect of the wind shear as compared with the controls-fixed results. For the 5 knot/100 foot shear, a sustained negative Δn_z of -0.01 to -0.02 g occurs, gradually steepening the flight path. Rate of airspeed bleed-off was not rapid - about 6 knots in 10 seconds. When pitch attitude was held constant, the 5 knot/100 foot shear of diminishing head wind resulted in ground contact 700-800 feet short of the steady head-wind intercept point.

<u>Effect of attempting to maintain constant airspeed in a wind shear</u>.- Attempts to maintain constant airspeed in a wind shear yielded the following responses. With thrust constant and only pitch control, a large nose-down change in pitch attitude (7^o-8^o) was required to arrest the divergence of airspeed resulting from 5 knot/100 foot shear. For the run shown in figure 5, an incremental normal acceleration of about one-third negative g was reached (Δn_z of -0.4 to -0.5 g at the pilot compartment); about 15-20 percent of available control was used and maximum pitch rate was about 3.5^o/sec. Sink rate reached nearly 50 ft/sec or 3000 ft/min. It is unlikely that this severe pitch maneuver would be initiated just to prevent the relatively mild airspeed loss indicated, especially during flight near the ground.

Effect of 5-knot downdraft combined with the 5 knot/100 foot shear.- Runs with controls fixed and with constant pitch attitude were conducted for the 5 knot/100 foot diminishing head-wind shear in combination with a 5-knot downdraft. Figure 6 presents the results of these runs. The major difference between these runs and those without the downdraft was the Δn_z "spike" which occurred when the downdraft was introduced; it resulted in an immediate steepening of the flight path that was followed by the gradual effect of the wind shear. When pitch attitude was maintained constant, sink rate increased over 50 percent in only a few seconds. The airspeed decreased continuously with time at about 1 knot/sec.

Although no runs at constant speed were actually made with the combination downdraft and shear, the effect of this combination can be approximated if the downdraft response of figure 1 is added to the constant air-speed time history of figure 5. (The validity of this technique can be demonstrated graphically by adding the downdraft response of figure 1 to the 5 knot/100 foot response time history of figure 3; the combination yields a very close approximation to the controls-fixed response of figure 6.) The resultant time history, shown in figure 7, indicates a

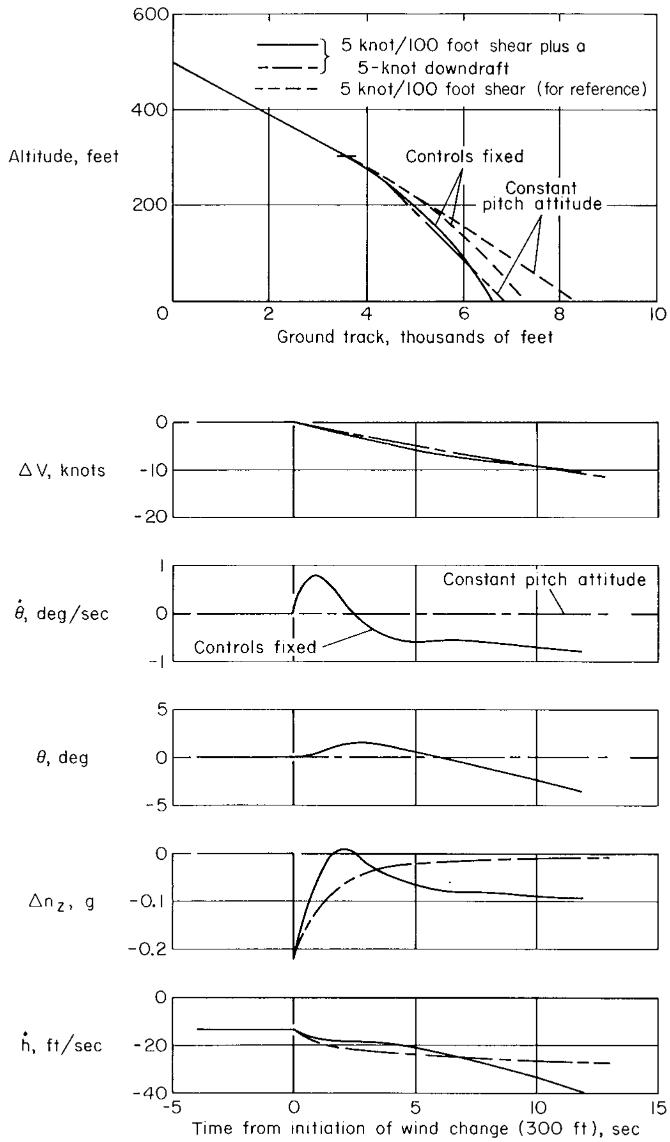


Figure 6.- Effect of 5-knot downdraft in combination with 5 knot/100 ft diminishing headwind shear; landing approach configuration, V_o = 160 knots.

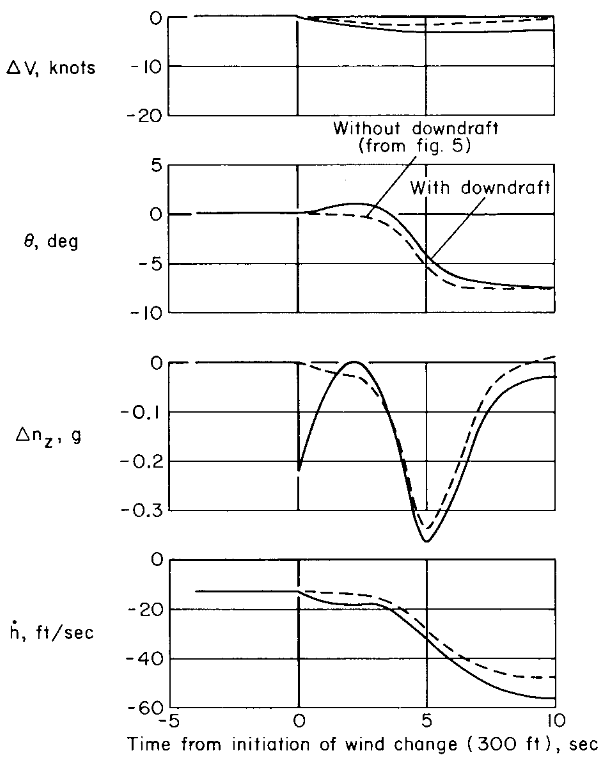


Figure 7.- Graphical addition of response to 5-knot step downdraft and the constant airspeed response to 5 knot/100 ft shear of diminishing headwind.

realistic combination of wind conditions (in this case, a 5 knot/100 foot shear plus a 5-knot downdraft) that could lead to a steepened flight path with minimum cue to the pilot. Although the downdraft has generated an increased sink rate, a deceptive increase in pitch attitude occurs initially along with the decreasing airspeed, encouraging a pitch-down control action by the pilot. To maintain constant airspeed, the required increase in sink rate is quite large (30 to 40 ft/sec).

Even though cues from the pitch attitude and airspeed are deceptive, there are warnings of the steepening flight path in the kinesthetic cues and in the instrument readings of vertical speed and altitude (following a small time lag). The adequacy of these indications may be compromised by the environment inside and outside the cockpit; for example, during an approach in a turbulent atmosphere when visibility is marginal, kinesthetic cues are obscured, and the pilot's attention may be diverted from the instruments in an effort to distinguish the runway.

In view of the assumptions necessary in an analysis of this sort (constancy of wind drafts, linearity of gradients, etc.), studies of additional cases do not appear justified. The study has improved the understanding of the effects of such conditions and can conclude that reasonable combinations of wind conditions can produce insidious situations leading to inadvertant steepening of flight path. Application of this analog technique, using the equations in appendix A, can provide results for specific situations of interest if needed.

CONCLUDING REMARKS

An analog study has been conducted to investigate the longitudinal response to wind shear and sustained gusts of a swept-wing transport airplane during a landing approach. Parameter variations have indicated the results to be generally applicable to the swept-wing transport class of airplanes.

Concerning first the general nature of the responses, differing aircraft responses to vertical and horizontal disturbances were demonstrated. Perhaps most significant was the initial pitch attitude response which was nose-down for a tail gust but nose-up for a downdraft, although flight path angle steepened in both instances.

Realistic combinations of downdraft and shear (of decreasing head wind) were found that could significantly steepen descent with little initial attitude change. In fact, the initial changes in attitude and airspeed might be in a direction that would induce the pilot to steepen the flight path further. Although the speed and altitude instruments indicate the steepening flight path, there is a question as to the attention that might be given them under critical approach conditions (marginal visibility, turbulence, etc.) Also, turbulent atmospheric conditions would tend to obscure the kinesthetic cues of the steepening flight path.

Wind shear of diminishing head wind steepened the flight path and resulted in an undershoot even when pitch attitude was held constant. Quantitatively, with a 5-knot/100 foot shear of diminishing head wind during the final 300 feet altitude and thrust held constant, the resultant undershoots were 700-800 feet for the constant-attitude runs and nearly 2000 feet for the controls-fixed runs.

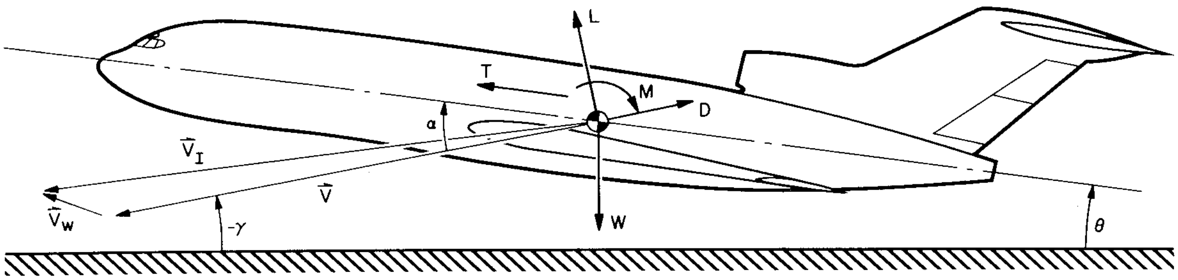
With constant thrust, a severe pitch maneuver (pitch attitude change of the order of 7°) was required to arrest the relatively mild airspeed divergence corresponding to a reasonable level of wind shear (5 knots/100 feet). Thus, the use of pitch control alone to maintain constant airspeed in a wind shear was considered an unlikely pilot technique or response.

This analog technique appears to offer considerable potential in such applications as (1) investigating aircraft accidents, (2) evaluating and establishing piloting techniques in abnormal weather conditions, and (3) defining the most pertinent parameters to be presented to the pilot in display optimization programs.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Dec. 1, 1967
126-16-05-07-00-21

APPENDIX A

EQUATIONS OF MOTION



Sketch (b)

Velocity relationships.- By letting

$\vec{V}_I$ = inertial velocity of aircraft

$\vec{V}$ = velocity of aircraft relative to encompassing region of air

$\vec{V}_W$ = velocity of wind (region of air) relative to earth

we have

$$\vec{V} = \vec{V}_I - \vec{V}_W$$

The equivalent airspeed is given by

$$V = \left[\left(V_{I_H} - V_{W_H}\right)^2 + \left(V_{I_V} - V_{W_V}\right)^2\right]^{1/2}$$

where the subscripts H and V indicate the horizontal and vertical components, respectively.

The sum of the horizontal forces acting on the aircraft is

$$\sum F_H = m\dot{V}_{I_H} = T \cos \theta - L \sin \gamma - D \cos \gamma$$

where

$$L = \frac{\rho S}{2}\left(C_{L_o} + C_{L_\alpha}\alpha\right)V^2 + \frac{\rho S\bar{c}}{4}\left(C_{L_{\dot{\theta}}}\dot{\theta} + C_{L_{\dot{\alpha}}}\dot{\alpha}\right)V$$

and

$$D = \frac{\rho S}{2}\left(C_{D_o} + C_{D_\alpha}\alpha\right)V^2$$

(Drag coefficient C_D was assumed to vary linearly with angle of attack α, a reasonable assumption for the small α variations encountered. The thrust line inclination from the fuselage reference line was assumed to be zero.) The sum of the vertical forces is

$$\sum F_V = m\dot{V}_{I_V} = L \cos \gamma - W - D \sin \gamma + T \sin \theta$$

Incremental normal acceleration.- The incremental normal acceleration (normal to the flight path) can be expressed by the equation

$$\Delta n_z = \frac{\dot{V}_{I_V} \cos \gamma - \dot{V}_{I_H} \sin \gamma}{g}$$

Pitching equation.- Summing the moments acting on the aircraft and dividing by the pitching moment of inertia, we have for the pitch acceleration

$$\ddot{\theta} = \frac{M}{I_y}$$

where

$$M = \frac{\rho S \bar{c}}{2}\left(C_{m_o} + C_{m_\alpha}\alpha\right)V^2 + \frac{\rho S \bar{c}^2}{4}\left(C_{m_{\dot{\theta}}}\dot{\theta} + C_{m_{\dot{\alpha}}}\dot{\alpha}\right)V$$

(The simplifying assumption has been made that the pitching moment due to thrust-line offset is insignificant. For the low thrust levels used in the approach and the small speed variations that occurred, this was considered a reasonable assumption.)

Angle (γ) between $\vec{V}$ and horizon.- For small γ,

$$\gamma \doteq \frac{V_V}{V_H}$$

Angle of attack.- Angle-of-attack rate is given by

$$\dot{\alpha} = \dot{\theta} - \frac{1}{V}\left(\dot{V}_V \cos \gamma - \dot{V}_H \sin \gamma\right)$$

For simplification of programming, let $\dot{V}_{W_V} = \dot{V}_{W_H} = 0$. The above equation then becomes

$$\dot{\alpha} \approx \dot{\theta} - \frac{1}{V}\left(\dot{V}_{I_V} \cos \gamma - \dot{V}_{I_H} \sin \gamma\right)$$

and is used only for the generation of the $\dot{\alpha}$ damping in pitch. Because of the above simplification and to provide the proper step change in α that accompanies a gust, α is calculated from the values for θ and γ rather than by integrating $\dot{\alpha}$. Thus,

$$\alpha = \theta - \gamma$$

Vertical and horizontal displacement.- Altitude h and horizontal displacement x are obtained simply by integrating the inertial velocity components.

$$\dot{h} = V_{I_V}$$

$$\dot{x} = V_{I_H}$$

APPENDIX B

BASIC CHARACTERISTICS FOR AIRPLANE IN THIS STUDY

W	gross weight	121,000 lb
I_y	pitching moment of inertia	2.7×10^6 slug-ft^2
S	wing area	1560 ft^2
$\bar{c}$	mean aerodynamic chord	15.0 ft
δ_f	flap deflection	25°
C_{L_0}	C_L at $\alpha = 0$	0.60
C_{L_α}	$\dfrac{\partial C_L}{\partial \alpha}$	6.1 rad^{-1}
$C_{L_{\dot\alpha}}$	$\dfrac{\partial C_L}{\partial(\dot\alpha \bar{c}/2V)}$	-7.0 rad^{-1}
$C_{L_{\dot\theta}}$	$\dfrac{\partial C_L}{\partial(\dot\theta \bar{c}/2V)}$	9.0 rad^{-1}
C_{D_0}	C_D at $\alpha = 0$	0.0845
C_{D_α}	$\dfrac{\partial C_D}{\partial \alpha}$	0.373 rad^{-1}
C_{m_0}	C_m at $\alpha = 0$	as necessary for initial trim
C_{m_α}	$\dfrac{\partial C_m}{\partial \alpha}$	-1.6 rad^{-1}
$C_{m_{\dot\alpha}}$	$\dfrac{\partial C_m}{\partial(\dot\alpha \bar{c}/2V)}$	-1.2 rad^{-1}
$C_{m_{\dot\theta}}$	$\dfrac{\partial C_m}{\partial(\dot\theta \bar{c}/2V)}$	-20.0 rad^{-1}

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