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SIMULATION STUDY TO EVALUATE A CONSTANT-GROUNDSPEED APPROACH METHOD IN MODERATE AND SEVERE WIND SHEARS

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16 Abstract

A simulation study was conducted to investigate the use of a constant-groundspeed procedure for flying final approaches in moderate and severe wind shear environments. Performance was compared to results of simulated constant-airspeed approaches in identical wind profiles. The simulation model was a medium twin-jet transport equipped with an autothrottle for maintaining constant groundspeed or constant airspeed. For both moderate and severe wind shears, the constant-groundspeed approach method was shown to provide a way to more safely negotiate the shears while also providing predictable and acceptable touchdown performance. Results showed airspeeds on final approach to be considerably higher using the constant-groundspeed method, which supplied the additional stall margin needed when tail-wind shears were encountered. Throttle movements were noticeably reduced in all wind profiles when constant-groundspeed approaches were flown. Touchdown conditions were practically identical for both approach methods in moderate wind shear.

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SUMMARY

A simulation study was conducted to investigate the use of a constant-groundspeed procedure for flying final approaches in moderate and severe wind shear environments. Performance was compared to results of simulated constant-airspeed approaches in identical wind profiles. The simulated airplane was a medium twin-jet transport equipped with an autothrottle system which was capable of maintaining either a constant groundspeed or constant airspeed.

Using the study wind profiles, results showed that airspeeds on final approach were considerably higher using the constant-groundspeed method when either head winds or tail winds existed at the runway. The higher airspeeds provided additional stall margin for protection against tail-wind shears. In a severe tail-wind shear, the simulated airplane stalled on final approach when a constant-airspeed approach was flown. However, when the constant-groundspeed procedure was used for the same shear profile the airplane safely completed the approach and landing. Throttle movements were noticeably reduced in all wind profiles when the constant-groundspeed autothrottle was used. Touchdown conditions were practically identical for both approach methods in moderate wind shear.

Based upon the cases studied, it appears that the constant-groundspeed approach method provides a way to more safely negotiate moderate or severe wind shears than does the constant-airspeed method, while providing predictable and acceptable touchdown performance.

INTRODUCTION

The effects of wind shear on airplane approaches and landings have been the subject of numerous recent studies (ref. 1-3). It is recognized that wind shears usually degrade the approach and landing performance of airplanes and may sometimes cause serious control difficulties. Encounters with wind shear often result in undesirable sink rates, excessive throttle activity and touchdowns which are short of or beyond the intended touchdown point. Furthermore, several recent airplane accident investigations determined that wind shear was a causative factor in the loss of the airplane (refs. 4-6).

Therefore, any developments which may help to make wind shear encounters less hazardous are of particular interest to the aviation community. The purpose of the present study is to investigate an approach groundspeed control procedure to determine whether the procedure may provide more optimum - and safe - landing performance than the airpseed control procedures which are commonly used.

The most common approach procedure (constant airspeed) usually calls for maintaining an indicated or calibrated airspeed which will provide adequate stall margin for the airplane gross weight and configuration. Further airspeed corrections are normally made to account for wind conditions which are reported to exist at the runway. However, wind velocity and direction occurring along the approach path are often significantly different from those existing in the touchdown zone, giving rise to considerable wind shears on the approach. In some cases of severe wind shear the approach airspeed may not provide adequate stall margin even with quick pilot reaction and application of maximum thrust.

An alternative procedure, developed in this study, is based upon the control of groundspeed instead of airspeed during the landing approach. Referred to as the constant-groundspeed approach method, this procedure calls for maintaining airplane groundspeed at some selected value throughout the approach while airspeed is allowed to vary as necessary, subject to safe minimum airspeed constraints. The study examines whether this procedure, which may result in higher final approach airspeeds, can provide additional safety in wind shears without compromising other operational aspects of the approach and landing.

A previous study (ref. 7) indicated that a constant-groundspeed approach method could increase airport landing operations by 12-15 percent when operating in head-wind conditions.

The simulation model represents a small commercial transport airplane equipped with automatic landing equipment which includes an autothrottle for either airspeed or groundspeed control. Lateral control problems are not addressed in the study. Therefore the wind shear models include only longitudinal and vertical components. Turbulence effects are also not included.

SYMBOLS AND ABBREVIATIONS

Values are given in SI and U.S. Customary Units. Calculations were made in U.S. Customary Units.

F_n	net thrust, N
$\dot{h}$	airplane vertical speed (positive climbing), m/s
ILS	instrument landing system
V_a	calibrated airspeed, knots
V_g	groundspeed, knots
$\dot{V}_g$	rate of change of groundspeed, knots/s
V_{gust}	magnitude of wind speed fluctuation, knots
V_{ref}	reference approach airspeed, knots
V_t	true airspeed, knots
V_w	wind speed, knots
x	distance along extended runway centerline (negative on approach path), n.mi.
α	angle-of-attack, deg
Δh_{gp}	distance above or below the ILS glideslope, (positive above), m
δ_e	elevator position (positive trailing-edge down), deg
δ_f	trailing-edge flap deflections, deg
δ_h	horizontal stabilizer position (positive trailing-edge down), deg
δ_{th}	throttle position (always positive), deg
Θ	airplane pitch angle, deg

Subscripts:

c	desired or commanded value
o	trim value
TH	existing at the runway threshold
TD	existing at touchdown

SIMULATION MODELS

Airplane

Figure 1 shows a sketch of the transport airplane which was modeled for the simulation study. The airplane is equipped with triple-slotted trailing-edge flaps, leading-edge slats, and Krueger leading-edge flaps. Elevators provide longitudinal control, with trim provided by a movable horizontal stabilizer. The two turbofan engines are equipped with deflector doors for reverse thrust operation on the ground to reduce stopping distance. Table I lists several characteristics of the airplane in the study configuration.

The simulation model used nonlinear equations of motion and nonlinear aerodynamic characteristics including ground effect. Only the longitudinal degrees-of-freedom were simulated. A nonlinear model of engine thrust characteristics was included in the simulation and is shown in figure 2. Engine thrust response was modeled as a first-order lag with a 2.0-second time constant.

Wind Models

Definitions. - From the point of view of an airplane flying through an air mass, wind shear is a change in wind speed and/or direction which occurs along the flight path of the airplane. A head-wind shear is defined as an increasing head-wind component (or decreasing tail wind), while a tail-wind shear is an increasing tail-wind component (or decreasing head wind). Vertical wind shear (referred to as updrafts and downdrafts in the report) is a change in the vertical wind component. Head winds and updrafts are signed positive ($+V_w$), while tail winds and downdrafts are negative ($-V_w$).

Wind-shear profiles. - The three wind-shear profiles which were chosen for this study are shown in figure 3. These particular profiles were used because they contain the moderate-to-severe levels of wind shear which were of interest in this study and they represent both head-wind and tail-wind landing conditions. Profiles 1 and 2 are representative of moderate wind-shear levels. Profile 3 is considered a severe wind shear and is modeled after the wind profile which is suspected to have been in existence at the accident described in reference 5. The wind components shown in the figure are those which would be encountered along a 3.0-degree ILS approach path to the runway.

TEST PROCEDURES

Approach Path

The approach profile used for the simulated landings is shown in figure 4. The simulated 3.0-degree ILS glideslope intersected the runway at a distance of 304.8 m beyond the threshold. Distance from the runway threshold to the ILS gate (starting point for the approach) was 4.0 n.mi.

A simulated automatic landing system, described in appendix A, performed glideslope tracking, flare and touchdown. Simulations began with the airplane established on the glideslope 4.0 n.mi. from the runway threshold. All controls, including throttles, were initially trimmed for a -3 degree flight path angle. Approaches and landings were made for each of the three wind shear profiles, using both constant-airspeed and constant-groundspeed methods.

Determination of Approach Speeds

The speed selection criteria for final approach depends upon whether a constant airspeed or constant groundspeed is to be maintained. The criteria for each approach method is developed below.

Constant-airspeed approach method. - The proper airspeed on final approach for the study airplane depends upon gross weight, trailing-edge flap position, and wind conditions. The operating manual recommends that either 30- or 40-degree trailing-edge flap deflections be used for landing. The 30-degree configuration was selected for this study because it resulted in more desirable (slightly higher) pitch angles (Θ) on the approach and landings conducted with the study wind conditions. (Effects of trailing-edge flap position will be discussed further in the results section).

The desired final approach airspeed was computed by the formula:

$$V_{a_c} = V_{ref} + 0.5\, V_w + V_{gust} \qquad (1)$$

which includes airspeed corrections for steady and gusting head-wind components. For the airplane weight and 30-degree flap configuration used in this study, the basic final approach airspeed (V_{ref}) was 125 kts. The V_{gust} factor and wind correction factor ($0.5V_w$) were based upon wind velocities existing at the runway. The $0.5V_w$ factor is only applied when landing headwinds exist. No correction is made for landing tail winds.

Table II summarizes the approach airspeeds used for each profile. Airspeed was controlled throughout the approach and landing by an automatic throttle system which is described in appendix B.

Constant-groundspeed approach method. - This method is based upon the selection of an approach groundspeed, V_{g_c}, which is maintained throughout the approach until the landing flare is initiated. Airspeed is allowed to vary as necessary (subject to the restrictions described below) in order to hold groundspeed at the selected value.

Several operational constraints may be imposed upon this approach method. The primary constraints considered in this study are:

A. Airplane groundspeed at touchdown should permit acceptable stopping distances with normal braking.

B. The resulting airspeed on final approach must provide compliance with stall margin requirements.

Compliance with the first constraint is more conveniently expressed in terms of a groundspeed just prior to flare, since groundspeed bleed-off during the flare may be somewhat variable depending upon the flare technique used. Therefore, a clearly acceptable groundspeed just prior to flare is $V_g = V_{ref}$, since that is the condition which normally results from a constant-airspeed approach in no winds, flown according to flight manual specifications. This same groundspeed (i.e., $V_g = V_{ref}$) is also acceptable for landing in head winds because, although the resulting flare airspeed is higher, stopping distance is a function of groundspeed and remains practically the same as for the no-wind case.

Therefore, the desired final approach groundspeed, V_{g_c}, may be conveniently expressed in terms of a desired groundspeed at the flare. As a result, the first rule for groundspeed selection is:

1. When no-wind or head-wind conditions exist in the touchdown zone,

$$V_{g_c} = V_{ref}. \tag{2}$$

The desired groundspeed just prior to flare is therefore the same for all wind conditions other than a tail wind. This differs from constant-airspeed approaches, where head winds result in lower groundspeeds at flare and touchdown.

The presence of tail winds at touchdown demands higher groundspeeds due to the necessity of maintaining airspeed at or above V_{ref}. Therefore, to comply with constraint B, the following groundspeed selection rule must be used:

2. When tail winds exist in the touchdown zone,

$$V_{g_c} = V_{ref} + \text{tail wind component}. \tag{3}$$

As a result of this rule, the condition $V_a = V_{ref}$ should exist at the beginning of the flare, which is the objective of the second constraint.

Theoretical groundspeeds at the runway threshold are plotted in figure 5 for the study airplane and a range of touchdown wind values. The groundspeeds which are shown resulted from the application of equation (1) for the constant-airspeed approach method and equations (2) and (3) for the constant-groundspeed method. It can be seen that in no-wind and tail-wind conditions, threshold groundspeeds ($V_{g_{TH}}$) are identical for both methods, and in head winds they are slightly higher with the groundspeed method. It should be noted that the curves shown are planned (desired) values and do not represent simulation results.

Corresponding airspeeds at the threshold are shown in figure 6. Note that the airspeed constraint (V_{ref}) is not violated at the threshold using either approach method.

Airspeed-priority considerations. - Tail winds existing on the approach path prior to the runway threshold may make it impossible to comply with recommended minimum airspeeds while attempting to maintain V_{g_c}. In this case, airspeed should not be allowed to fall below V_{ref} during any part of the approach, even though the resulting groundspeed may be greater than V_{g_c}. The groundspeed-hold autothrottle used in this study included an airspeed-monitor feature to prevent airspeed from being reduced below V_{ref} (or any other selected minimum airspeed).

Table III lists desired approach groundspeeds for each of the study wind profiles, calculated by equations (2) and (3). The groundspeed-hold autothrottle described in appendix C was used to maintain V_{g_c}.

RESULTS AND DISCUSSION

Profiles 1 and 2

Results of approaches in the moderate wind shear profiles are discussed below in terms of selected flight parameters which were recorded. Airplane response is first analyzed on the approach path up to and including the runway threshold. Following that discussion, an analysis of touchdown conditions is presented.

Air Density and Compressibility Effects. - Normally, the effects of air density and compressibility produce differences between calibrated airspeed (V_a) and true airspeed (V_t) at all flight conditions other than standard sea level, and the magnitude of those differences becomes greater as both speed and altitude are increased. However, both effects are negligible in this study due to the low approach airspeeds and simulated standard sea level conditions. Therefore, for a no-wind landing $V_g = V_t \simeq V_a$ at touchdown. At runway altitudes higher than sea level, more pronounced differences will exist between V_a and V_g and these differences should be considered, particularly with regard to their effect on stopping distance.

Airspeed. - Calibrated airspeeds (V_a) for the constant-airspeed and constant-groundspeed approaches are shown in figure 7. Results are presented for both wind profiles 1 and 2, and considerable airspeed differences are seen to exist on each profile for the two approach methods. Note that on profile 1, large head-winds components (20-30 knots) exist along the approach path. For the constant-groundspeed approach, this resulted in airspeeds above 145 knots throughout most of the approach, with 156 knots required at one point to maintain the desired groundspeed (125 knots). Conversely, V_a was fairly steady at 128 knots throughout the constant-airspeed approach.

Airspeeds in excess of 145 knots also occurred on profile 2 using the groundspeed approach method, although the approach head-wind components was only 10 knots. This occurred as a result of a landing tail-wind component of 13 knots, which suggested a V_{g_c} of 138 knots according to equation (3). The higher threshold groundspeed requirement in this case resulted in higher airspeeds on the approach. Again, V_a was approximately 20 knots lower using the constant-airspeed method.

To summarize, the higher airspeeds noted on the constant-groundspeed approaches were due in one case to the large head-wind components on final approach, and in the other case (a landing tail-wind situation) the higher airspeeds were due also to an increased groundspeeds requirements at the threshold.

Airspeed margin relative to V_{ref} (125 knots) is shown in figure 7 for both approach methos. Prior to encountering tail-wind shears, airspeed remained at or above V_{ref} for both approach methods. However, when tail-wind shears were encountered on the constant-airspeed approaches, airspeed fell below V_{ref} in both wind profiles. The maximum speed error (-5 knots) occurred on profile 2 at 0.8 n.mi. prior to the threshold. Conversely, for the constant-groundspeed approaches V_a remained well above V_{ref} even during the tail-wind shears.

The desired threshold airspeed, $V_{a_{TH}}$, for each approach was derived from figure 6. For profile 1 (a landing-heading-wind condition) desired $V_{a_{TH}}$ was 128 and 131 knots, respectively, for the constant-airspeed and constant-groundspeed approach methods. For profile 2 (a landing-tail-wind condition) both approach methods called for $V_{a_{TH}}$ = 125. It is shown in figure 7 that threshold airspeeds were very close to the planned values for both approach methods. Maximum $V_{a_{TH}}$ errors of ±3 knots were recorded for both profiles using either approach method. On profile 2, threshold airspeed was identical (128 knots) for both approach methods.

Groundspeeds. - Groundspeed (V_g) variation during the approaches is presented in figure 8. Wind shears contributed to considerable groundspeed variation with the constant-airspeed approach method, since V_g was not a controlled variable. However, for the constant-groundspeed method, the selected approach groundspeed (see table III) was maintained very precisely throughout both profiles.

Threshold groundspeed ($V_{g_{TH}}$) is a direct indicator of the amount of energy which the airplane must dissipate during the flare, touchdown and landing roll. It is therefore closely related to touchdown groundspeed and stopping distance. Using the constant-groundspeed approach method, threshold groundspeed was exactly equal to the desired value (125 knots) on profile 1. On profile 2, the $V_{g_{TH}}$ error was only +1.0 knot ($V_{g_{TH}}$ = 139 knots). Corresponding values of $V_{g_{TH}}$ for the constant-airspeed method were 115 and 138 knots for profiles 1 and 2. All of the threshold groundspeeds were compatible with normal braking procedures and stopping criteria for the study airplane.

Engine thrust. - Variations in throttle position (δ_{th}) are presented in figure 9. For the constant-airspeed approaches considerable throttle activity resulted as the autothrottle system attempted to maintain V_{a_c} in the wind shears. Even though a shear detector circuit was included in the airspeed-hold autothrottle, airspeed dropped 5 knots below V_{ref} on profile 2. As a result of this low-airspeed condition, thrust was increased rapidly and the airplane developed an airspeed excess (V_{ref} + 6 knots) just prior to the threshold.

Less throttle activity resulted when the groundspeed-hold autothrottle was used on the same approach profiles. As can be seen in figure 9, throttle position variations were small in comparison to the airspeed-hold case, and the rate of throttle movement was much less. The reduced throttle activity was a direct result of the fact that the controlled variable, V_g, responds much more slowly to wind speed changes than does airspeed.

Pitch angle. - Airplane pitch angle, Θ, is presented in figure 10 for each approach. The higher airspeeds required for the constant-groundspeed approaches resulted in pitch angles which were generally 2.5-3.5 deg less (more nose-down) than the constant-airspeed approaches. The differences in Θ became less, however, toward the latter part of the approaches. At the runway threshold, differences in Θ for the two approach methods were within 1.0 deg, and in each case permitted a normal flare and landing.

Vertical speed. - Variations in vertical speed ($\dot{h}$), or sink rate, are presented in figure 11. Larger variations were noted with the constant-airspeed method, particularly as shears were encountered on the last mile of the approaches. During those shear encounters, $\dot{h}$ increased by 0.65 m/sec (26%) on profile 1 and 1.0 m/sec (33%) on profile 2. In contrast, vertical speed variations with the constant-groundspeed method were fairly small, approximately ±0.1 m/sec on profile 1 and ±0.2 m/sec on profile 2.

Glideslope tracking. - Vertical distance above or below the ILS glideslope (Δh_{gp}) is shown in figure 12 for each approach. Although the pattern of glideslope errors was different for the two approach methods, the errors in either case did not preclude a normal landing.

Touchdown conditions. - Table IV lists the longitudinal flight parameters which were used to compare touchdown performance. Remarkable similarities existed in the two approach methods, landing in either the head wind or tail wind. There was a negligible airspeed difference (2 knots) and groundspeed difference (2 knots) between the two approach methods at touchdown for either wind condition. Distance from runway threshold varied no more than 58 m (192 ft) between methods. Pitch angles were within 0.5 deg in both cases and sink rates at touchdown ($\dot{h}$) were nearly identical. Engine thrust was near idle for each touchdown.

Each touchdown condition was considered normal for the study airplane with the existing suface winds. Both approach methods therefore produced acceptable, and nearly identical, landing performance for the study wind conditions.

Profile 3

Wind profile 3 (fig. 3) was flown using the constant-airspeed and constant-groundspe' ' approach methods. In a wind shear of this severity it is likely that a pilot would, in actuality, initiate a go-around at some point in the approach. However, the automatic (coupled) approaches were continued in this study in order to measure the capabilities of each approach method to complete the landing task if a go-around were not selected.

Approach speeds for each method are listed in tables II and III. For the constant-airspeed approach, 10 knots was added to V_{ref} to account for gusts ($V_{a_c} = 135$). Although gusts were not included in the simulation, it was assumed that turbulence would likely exist on such a wind profile and the extra 10 knots was considered a more realistic approach speed. For the constant-groundspeed approach method, $V_{g_c} = 135$ knots was selected, using equation (3), in order to compensate for the landing tail-wind condition.

The flight parameters resulting from both approaches are shown in figure 13. For the constant-airspeed approach, airspeed control (fig. 13(a)) was difficult due to the occurrence of a rapid head-wind shear followed immediately by a severe tail-wind shear. As the head wind was encountered, airspeed increased 5 to 10 knots above V_{a_c} causing the throttle (fig. 13(c)) to be reduced to the minimum position (10 deg). A severe tail-wind shear quickly followed, causing a rapid drop in airspeed and application of full throttle. As the airplane dropped below glideslope, both the elevator (fig. 13(e)) and horizontal stabilitor (fig. 13(f)) were rapidly applied in an attempt to correct the altitude loss. However, at approximately 0.9 n.mi. from the threshold, the airplane exceeded the stall angle-of-attack (fig 13(g)) followed immediately by a high sink rate (fig. 13(h)) and ground impact short of the runway.

In contrast, when the constant-groundspeed approach was used, the airplane was able to negotiate the same severe wind shear and complete the landing. The success of this approach was due primarily to the fact that airspeed was allowed to build up during the head-wind shear. Subsequently, with an airspeed of 165 knots at the onset of the tail-wind shear, the airplane was able to maintain flying airspeed through the entire shear. Note that as the airspeed dropped below V_{ref} the airspeed-hold autothrottle was engaged. The landing was completed with touchdown occurring 620 m down the runway. Touchdown airspeed was 123 knots and pitch angle was 3.7 degrees (fig. 13(i)).

CONCLUDING REMARKS

This study has dealt primarily with an analysis of the relative performance of two speed-control methods which were used on simulated final approaches in the presence of wind shears. The performance comparison was based upon the capability of each approach method to maintain airspeed above a recommended minimum value during all phases of the approach and to subsequently complete a normal flare and landing.

In light of the performance objectives, the primary operational constraints on the constant-groundspeed approach method were identified as (1) maintaining an airspeed that provides adequate stall margin, and (2) avoiding high groundspeeds at the runway threshold in order to permit acceptable stopping distances. It was shown that a suitable method to satisfy these constraints involved the selection of a final approach groundspeed which was based upon wind conditions existing at the runway.

In moderate wind shears, results showed that the constant-groundspeed approaches were characterized by higher final approach airspeeds than the constant-airspeed approaches. These results were observed whether a head-wind or tail-wind condition existed at the runway. The higher airspeeds provided greater stall margins and prevented the occurrence of low-airspeed situations when tail-wind shears were encountered. When the same shears occurred on constant-airspeed approaches, airspeed dropped 5 knots below the value recommended for final approach.

Although differences in flight conditions were noted during the approach phase, touchdown conditions (airspeed, groundspeed, sink rate, pitch angle, runway location and throttle setting) were practically identical when the two approach methods were compared. This was true for both head-wind and tail-wind conditions. Touchdown groundspeeds, which affect stopping distance, were acceptable by both approach methods.

When a severe wind-shear profile was encountered on the approaches, significant performance differences were noted for the two approach methods. The constant-airspeed approach method resulted in a rapid loss of airspeed during the tail-wind shear and the airplane was not able to maintain flying airspeed even though full throttle was applied. However, when the constant-groundspeed approach method was used the airplane safely completed the landing and the approach airspeed never fell more than 10 knots below recommended final approach airspeed.

It should be noted that the capability of the constant-groundspeed approach method to maintain high final approach airspeeds, and to subsequently attain normal threshold airspeeds, is due to proper selection of the approach groundspeed. Specifically, the approach groundspeed is chosen to give acceptable airspeed and groundspeed at the threshold. An arbitrary increase in airspeed on final approach could also provide greater stall margin protection, but would not provide desirable groundspeeds at the threshold unless a systematic airspeed reduction procedure were also devised.

Pitch angles during the approaches were lower for the constant-groundspeed method as a result of the higher airspeeds encountered. However, for the particular wind profiles studied, pitch angles at the threshold were nearly identical for both approach methods, permitting a normal flare and landing.

Additional studies should be conducted to determine whether high-velocity head winds will impose restrictions on use of the constant-groundspeed approach method, due to airspeed or pitch angle limitations. For instance, airspeed restrictions on trailing-edge flaps may limit attainable groundspeeds on the approach. Also, pitch angle limitations may be affected by pilot acceptance or touchdown requirements. Some latitude may be afforded in these areas by selection of a lower flap deflection angle.

Throttle movements were noticeably reduced with the constant-groundspeed approach method, although the groundspeed-hold autothrottle was a simpler system than the airspeed-hold autothrottle. This was an expected result since groundspeed, which typically varies much more slowly than airspeed, does not require very rapid throttle response for control.

Variations in vertical speed (sink rate) during wind shear encounters were considerably reduced when the constant-groundspeed method was used.

Based on the cases examined in this study, it appears that the constant-groundspeed approach method provides a way to more safely negotiate moderate or severe wind shears than does the constant-airspeed method, and results in predictable and acceptable touchdown performance for either head-wind or tail-wind conditions.

APPENDIX A

PITCH AUTOLAND CONTROL LAW DESCRIPTION

Symbols and Abbreviations

ALCT	elevator command used to intercept and track the ILS glideslope beam (trailing-edge down, positive), deg
FLARE	logic switch used to initiate elevator commands for flare
GSE	deviation from glideslope beam (above beam, positive), deg
GSEGP	deviation from glideslope beam, adjusted to provide signal de-sensitizing as altitude is reduced (above beam, positive), deg
GSTRK	logic switch used to initiate glideslope tracking mode
h_{RAD}	height above ground, measured by radar altimeter (always positive), m
$\dot{h}$	airplane vertical speed (climbing, positive), m/s
$\ddot{h}$	airplane vertical acceleration (upward, positive), m/s^2
HDER	flare height detection signal
ILS	instrument landing system
INS	inertial navigation system
V_g	airplane groundspeed, knots
δ_{e_c}	elevator command (trailing-edge down, positive), deg
$\dot{\theta}$	pitch rate (nose up, positive), deg/s

Discussion

The ILS autoland system longitudinal control laws are shown in figure 14. On a typical approach, the airplane approaches the glideslope in level flight from an altitude of approximately 500 - 1000 m. The control laws are engaged when the ILS glideslope receiver indicates a signal deviation (GSE) of ±0.108 deg or smaller. At that time, the autoland system commands a nose-down pitch change to intercept the glideslope beam.

Ten seconds after the control laws are engaged, the glideslope track (GSTRK) mode is activated which provides inertial flight-path augmentation to the ILS beam-error signal. Augmentation is provided by $\dot{h}$ and INS-derived V_g signals, which produce elevator commands to correct any deviations from a ground-referenced -3 deg flight-path angle. The use of ILS beam-error and INS augmentation signals together results in accurate glideslope tracking in adverse wind conditions and in the presence of ILS beam disturbances. Vertical acceleration ($\ddot{h}$) and pitch-rate ($\dot{\Theta}$) feedback provide additional stability augmentation throughout the approach.

As the aircraft descends below an altitude of 50 m, flare detection computations are initiated. The flare detector uses a combination of radar altitude (h_{RAD}) and $\dot{h}$ signals to detect the proper flare height. Flare is initiated at the moment the HDER signal becomes negative. As an example, assume the aircraft is tracking the glideslope with a -3.5 m/sec rate of descent. In this case the HDER signal will be positive for all altitudes above 17.3 m, and as the airplane descends through 17.3 m, the HDER signal becomes negative and flare is initiated. If the rate of descent were higher, flare would start at a higher altitude. Correspondingly, flare would occur at a lower altitude for slower descent rates. A ramp elevator signal is used to start the nose up for the flare maneuver.

It should be noted that the HDER signal, in addition to initiating flare, also commands a sink rate which is programmed as a function of altitude. The purpose of the 4.57 m bias altitude signal is to achieve a predetermined sink rate at touchdown. For example, at zero altitude, a vertical speed of -0.73 m/sec is required to null the HDER signal. Thus, -0.73 m/sec is the desired vertical speed at touchdown.

APPENDIX B

AIRSPEED-HOLD AUTOTHROTTLE SYSTEM

The airspeed-hold autothrottle system used in this study was designed to hold a calibrated airspeed, V_{a_c}, which is selected by the pilot. The control law is shown in figure 15 and described in detail in references 8 and 9. During autothrottle operations, the difference between V_{a_c} and the actual airspeed, V_a, forms an error signal which is used as an acceleration comand. The acceleration command is summed with a longitudinal acceleration feedback signal from the inertial navigation system to form an integrator input signal. The integrator output is an incremental throttle command which drives the throttles from the position existing at the time of autothrottle engagement (δ_{th_o}). The final throttle command is formed by summing δ_{th_o} with the integrater output and a longitudinal acceleration signal.

A shear-detector circuit is included in the design to enhance autothrottle operation in wind shears. The circuit is essentially a complementary filter which utilizes true airspeed, V_t, and inertial longitudinal acceleration to generate a signal which compensates for wind shears. The filter design causes steady-state winds to be washed out and turbulence to be filtered, so that only wind shears significantly affect the shear detector output.

During flare, the shear detector outputs are not used and the throttle is reduced at a constant rate which results in approximately idle thrust at touchdown.

APPENDIX C

GROUNDSPEED-HOLD AUTOTHROTTLE SYSTEM

The groundspeed-hold autothrottle control law is shown in figure 16. The speed error signal is the difference between measured groundspeed, V_g, and pilot-selected groundspeed, V_{g_c}. This groundspeed error signal is then used as an acceleration command which is combined with $\dot{V}_g$ to form the throttle command.

During flare, the groundspeed-hold mode is interrupted as the throttles are reduced to idle for landing.

As a safety feature, a minimum airspeed detector is included in the autothrottle design. The purpose of the detector is to assure that V_a is not reduced below some selected minimum value. In this study, V_{ref} was selected as the minimum airspeed. If such a detector were not included in the design, it would be possible for the autothrottle to reduce V_a to a dangerously low value in an attempt to hold V_g constant. Such a situation might exist in strong tail-wind or head-wind shearing-to-tail-wind conditions.

Therefore, with the groundspeed-hold system used in this study, both V_{g_c} and V_{ref} are selected, In the event airspeed falls below V_{ref}, autothrottle operation reverts automatically to an airspeed-hold mode (appendix B).

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2. Sherman, Windsor L.: A Theoretical Analysis of Airplane Longitudinal Stability and Control as Affected by Wind Shear. NASA TN D-8476, 1977.

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4. National Transportation Safety Board: Aircraft Accident Report, Allegheny Air Lines, Inc., Douglas DC-9, N994VJ, Philadelphia, Pennsylvania, June 23, 1976. NTSB-AAR-78-2.

5. National Transportation Safety Board: Aircraft Accident Report, Eastern Air Lines, Inc., Boeing 727-225, John F. Kennedy International Airport, Jamaica, New York, June 25, 1975. NTSB-AAR-76-8, March 1976,

6. National Transportation Safety Board: Aircraft Accident Report, Iberia Lineas Areas De Espana (Iberian Airlines), McDonnell Douglas DC-10-30, EC CBN, Logan International Airport, Boston, Massachusetts, December 17, 1973. NTSB-AAR-74-14, November 1974.

7. Hastings, Earl C. Jr., A Preliminary Study of the Benefits of Flying by Groundspeed During Final Approaches, NASA TM 78777, August 1978.

8. Lambregts, A. A.: Turbulence Compensated Throttle Control System. U.S. Patent No. 3892374, 1975.

9. Lambregts, A. A.: Wind Shear Detection System. U.S. Patent No. 3955071, 1976.

TABLE I. - CHARACTERISTICS OF AIRPLANE USED IN THE STUDY

Weight, N (lb)	364,754	(82,000)
Moments of inertia:		
I_{XX}, kg-m^2 (slug-ft^2)	508,432	(375,000)
I_{YY}, kg-m^2 (slug-ft^2)	1,079,150	(795,938)
I_{ZZ}, kg-m^2 (slug-ft^2)	1,659,521	(1,224,000)
I_{XZ}, kg-m^2 (slug-ft^2)	70,502	(52,000)
Center of gravity, percent of mean aerodynamic chord	20	
Dimensions:		
Length, m (ft)	28.65	(94.0)
Height to top of vertical fin, m (ft)	11.28	(37.0)
Wing:		
Area, m^2 (ft^2)	91.04	(980)
Span, m (ft)	28.35	(93.0)
Mean aerodynamic chord, m (ft)	3.41	(11.2)
Incidence angle, deg	1.0	
Aspect ratio	9.07	
Dihedral, deg	6	
Sweep, deg	25	
Trailing-edge flaps:		
Maximum deflection, deg	40	
Deflection used for approaches in study, deg	30	
Maximum airspeed limits, knots		
25 deg	190	
30 deg	185	
40 deg	170	
Landing gear position	Down	
Propulsion system (two turbofan engines):		
Maximum uninstalled thrust per engine (sea level static), N (lb)	62,275	(14,000)

TABLE II. - ELEMENTS OF EQUATION 1 USED TO COMPUTE FINAL-APPROACH AIRSPEEDS FOR CONSTANT-AIRSPEED APPROACHES

Wind Profile	V_{ref} knots	$0.5\ V_w$ knots	V_{gust} knots	V_{a_c} knots
1	125	3	0	128
2	125	0	0	125
3	125	0	10	135

TABLE III. - ELEMENTS OF EQUATIONS 2 AND 3 USED TO COMPUTE FINAL-APPROACH GROUNDSPEEDS FOR CONSTANT-GROUNDSPEED APPROACHES

Wind Profile	V_{ref} knots	Touchdown zone winds, knots		V_{g_c} knots
		head wind	tail wind	
1	125	6	0	125
2	125	0	13	138
3	125	0	10	135

TABLE IV. - TOUCHDOWN CONDITIONS FOR STUDY AIRPLANE FLYING CONSTANT-AIRSPEED AND CONSTANT-GROUNDSPEED APPROACHES IN MODERATE WIND-SHEAR PROFILES

	Profile 1		Profile 2	
	Constant-airspeed method	Constant-groundspeed method	Constant-airspeed method	Constant-groundspeed method
V_a	122	124	116	118
V_g	115	117	129	131
x	472 (1548)	487 (1597)	601 (1972)	543 (1780)
Θ	4.0	3.5	5.5	5.0
$\dot{h}$	-0.69 (-2.3)	-0.65 (-2.1)	-0.71 (-2.3)	-0.68 (-2.2)
F_n	12364 (2780)	8896 (2000)	8907 (2002)	8896 (2000)

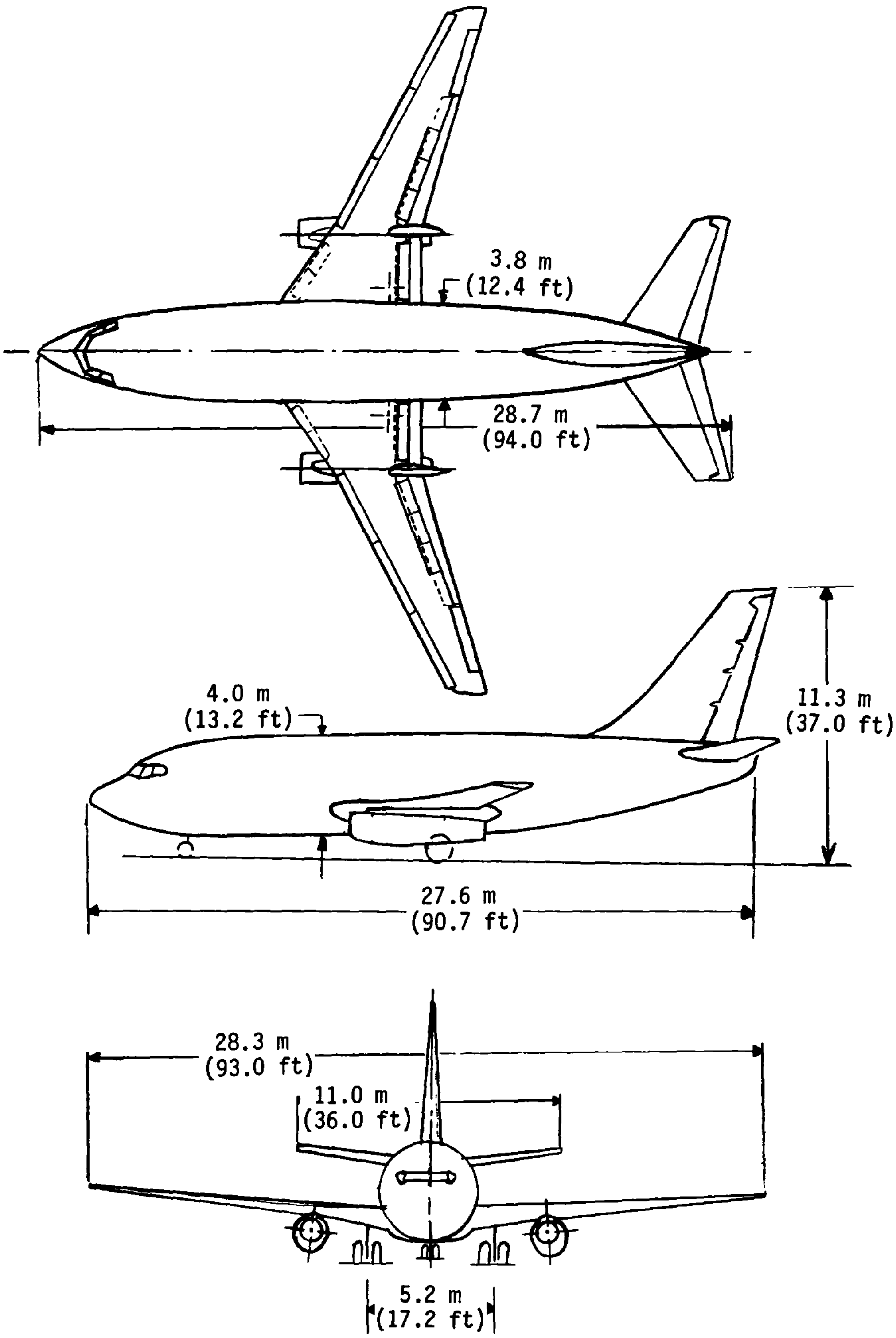


Figure 1.-Drawing of the airplane modeled in the simulation study.

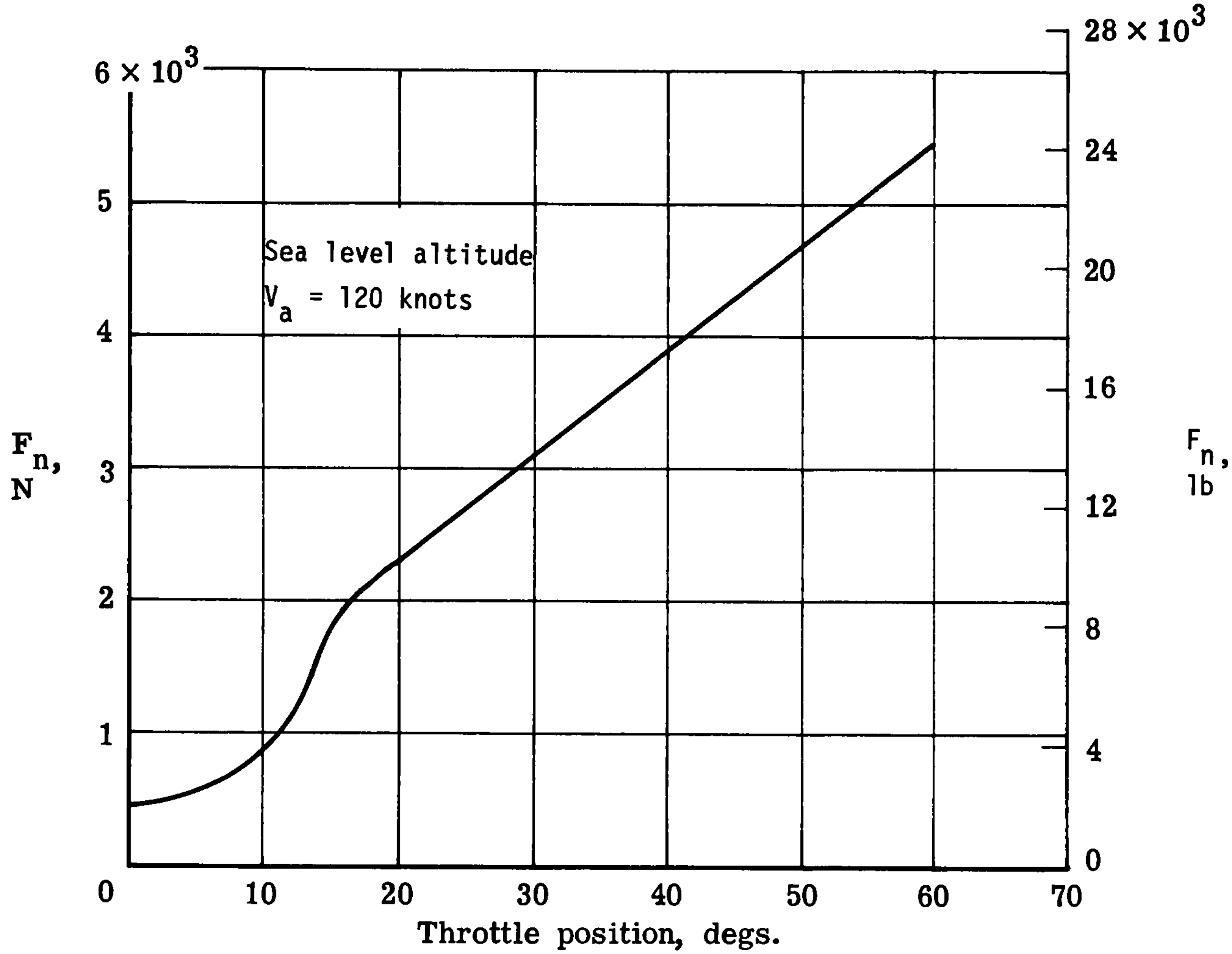
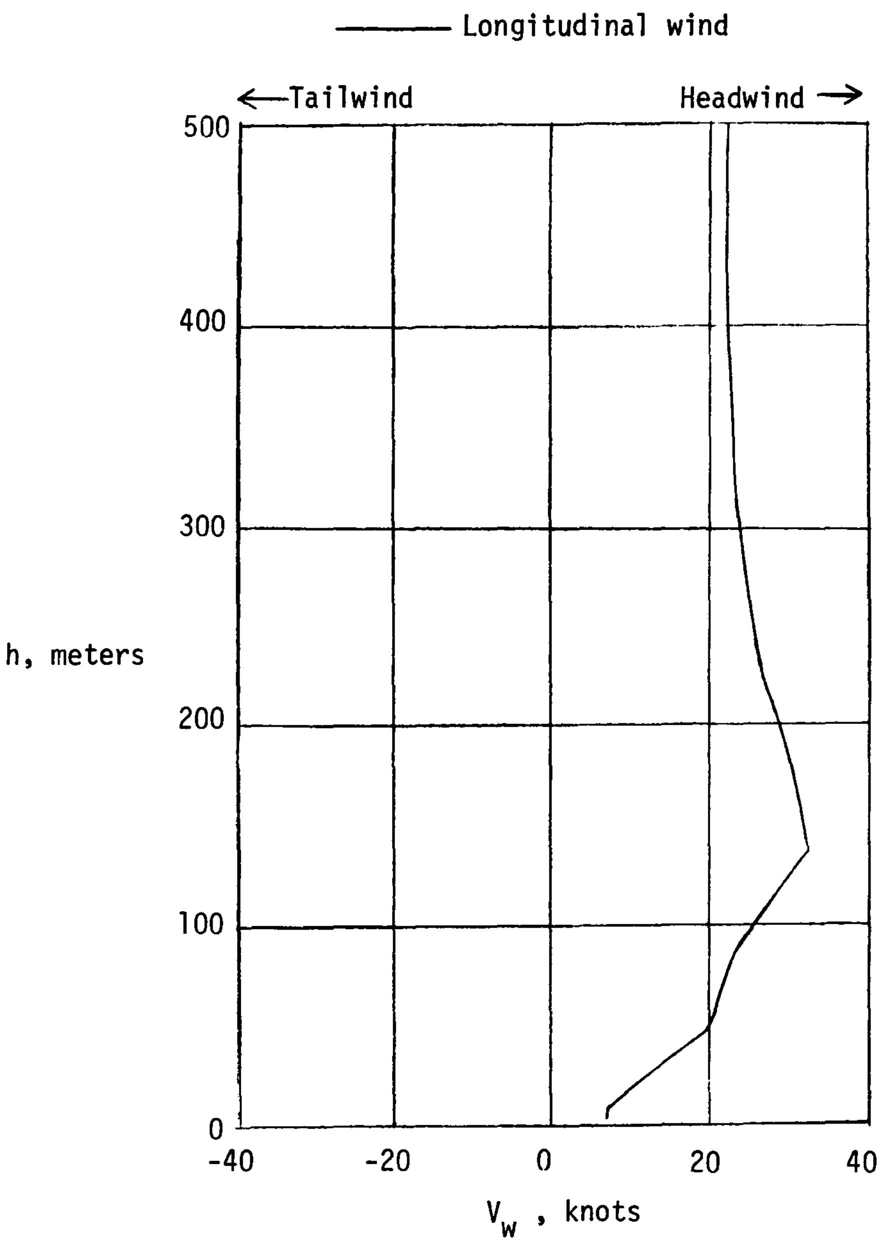
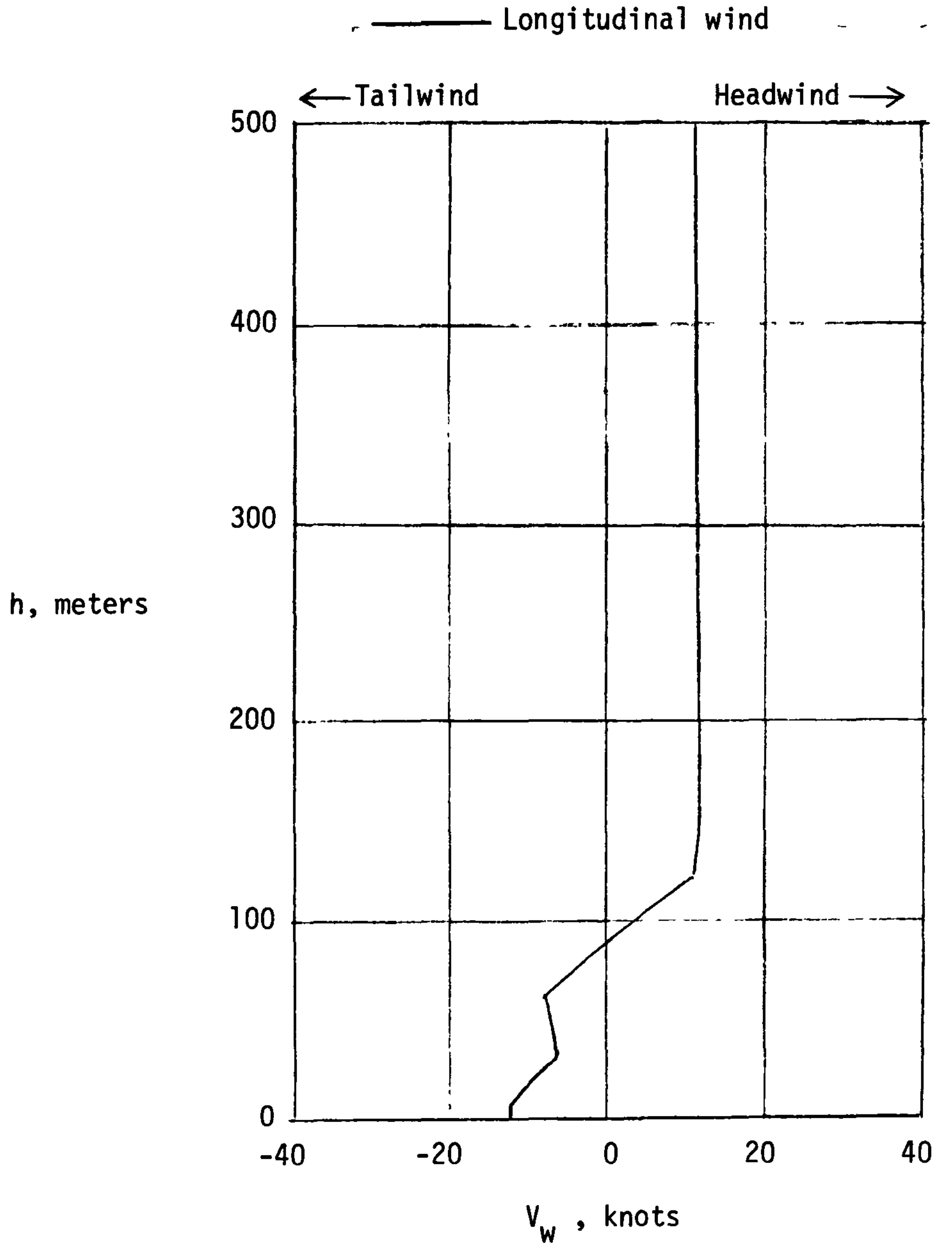


Figure 2.-Total thrust characteristics of the study airplane (both engines).



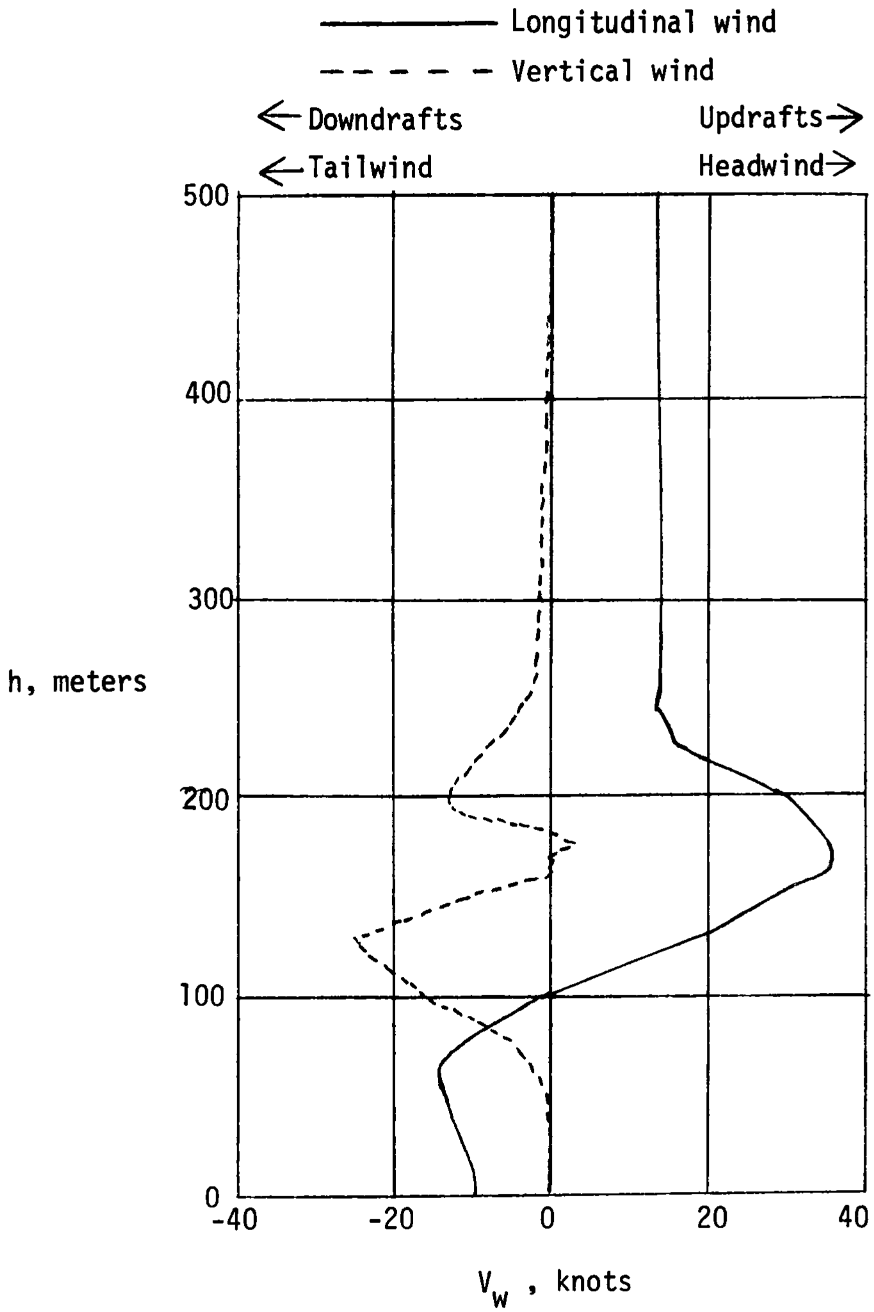
(a) Profile 1

Figure 3.-Wind shear profiles used in the study.



(b) Profile 2

Figure 3.-Continued.



(c) Profile 3

Figure 3.-Concluded.

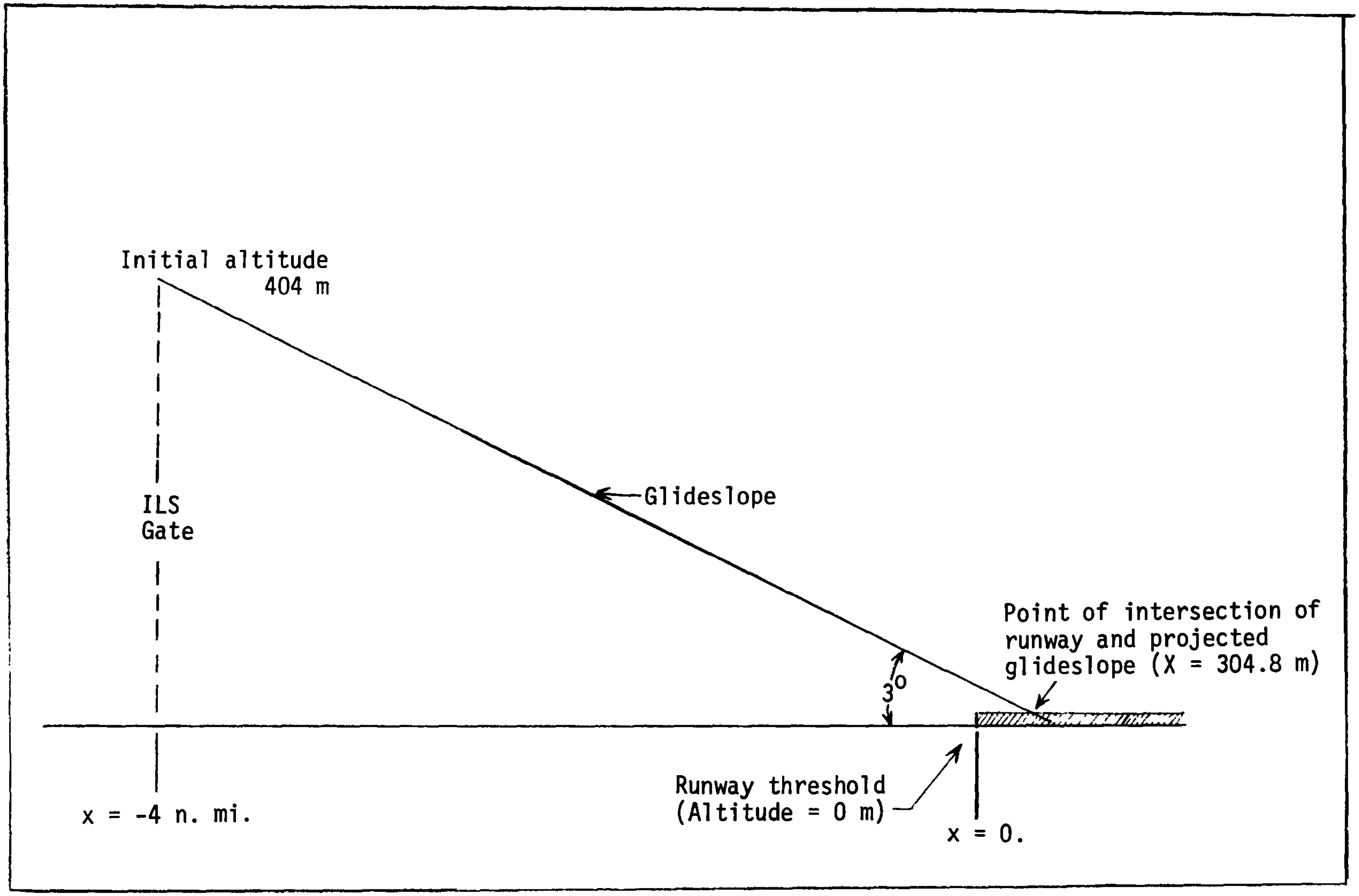


Figure 4.-Approach profile used in the study.

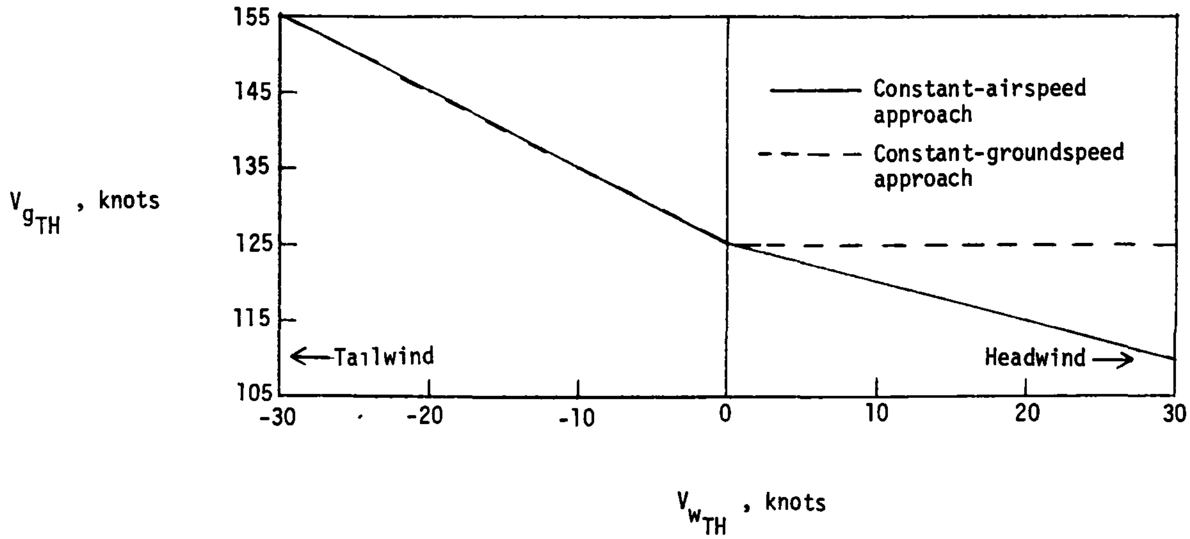


Figure 5.-Desired threshold groundspeeds for airplane with V_{ref} = 125 knots.

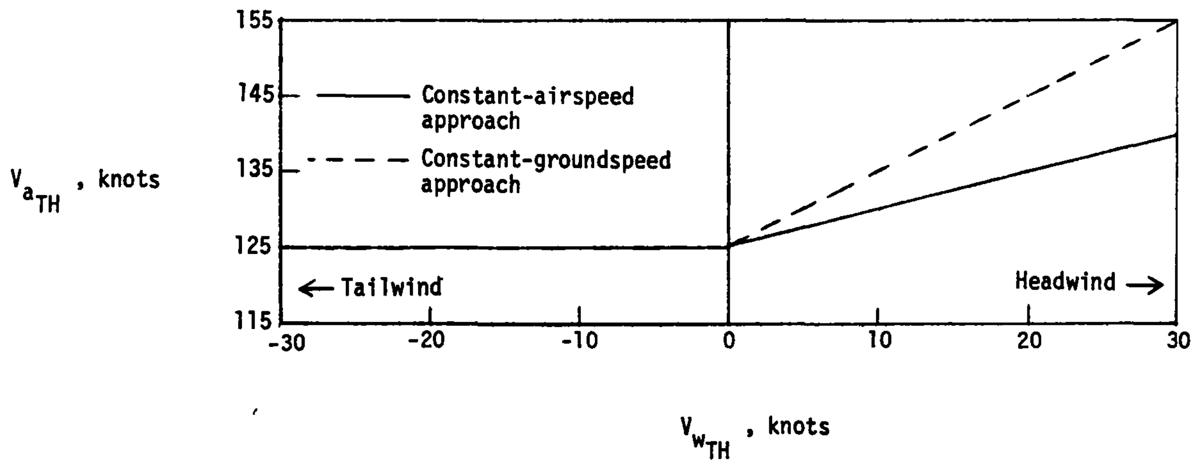
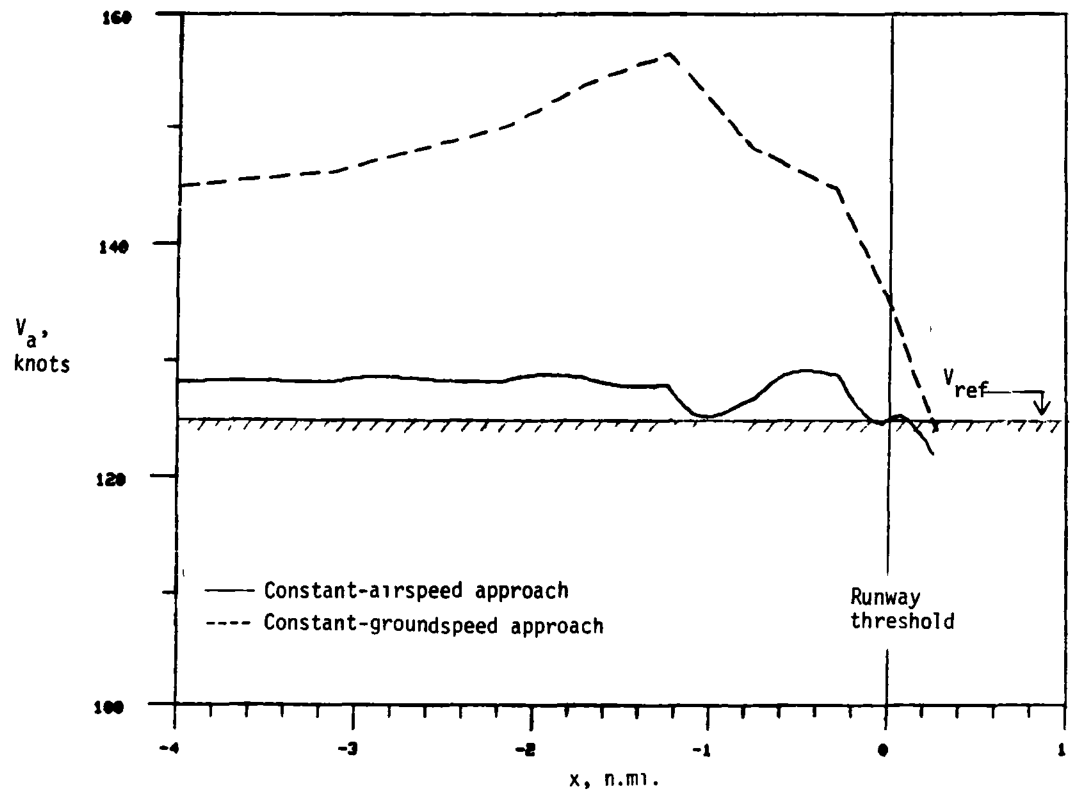
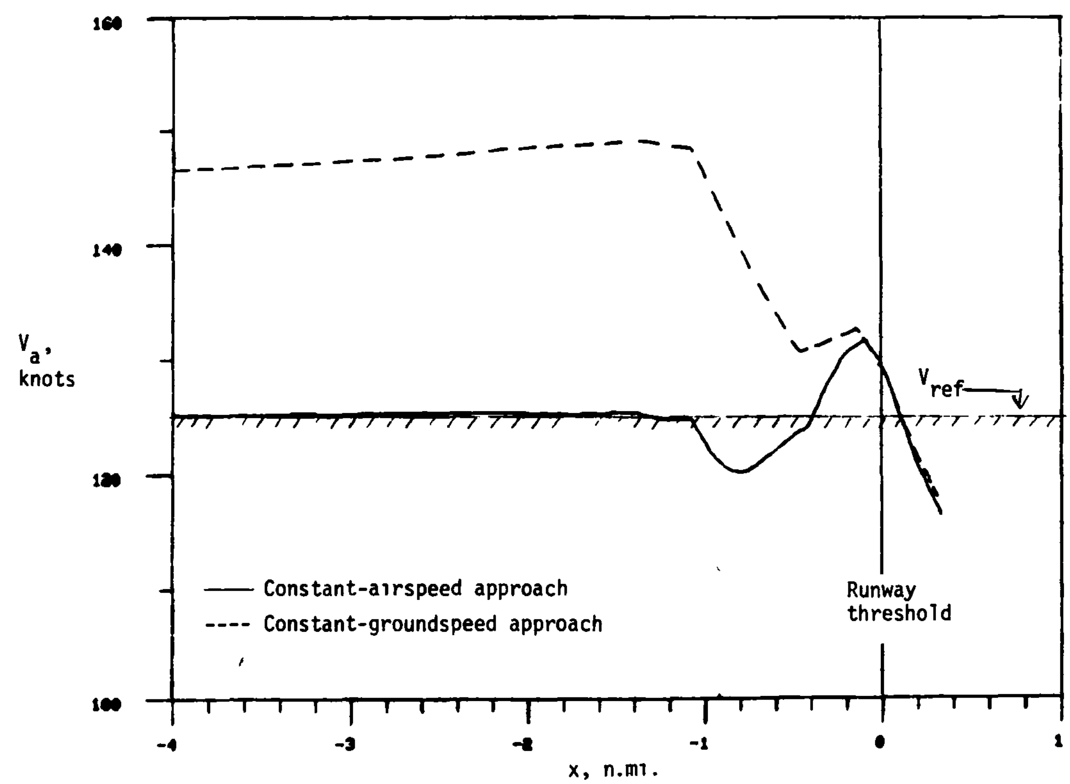


Figure 6.-Desired threshold airspeeds for airplane with V_{ref} = 125 knots,

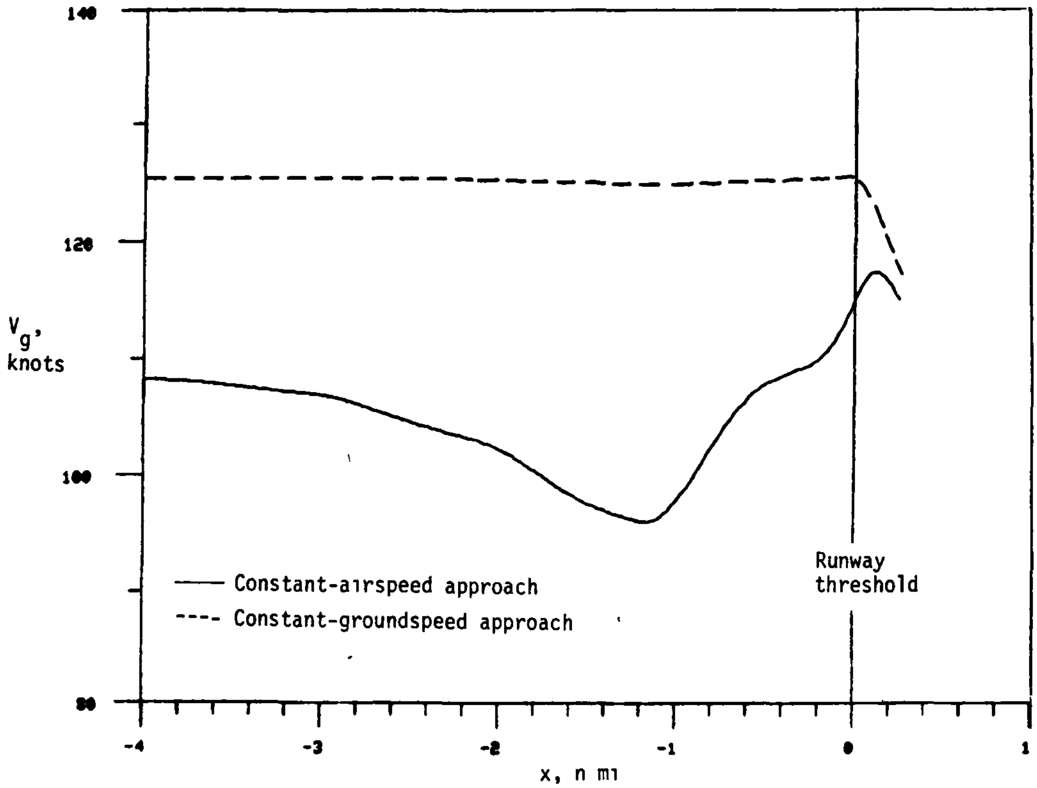


(a) Profile 1

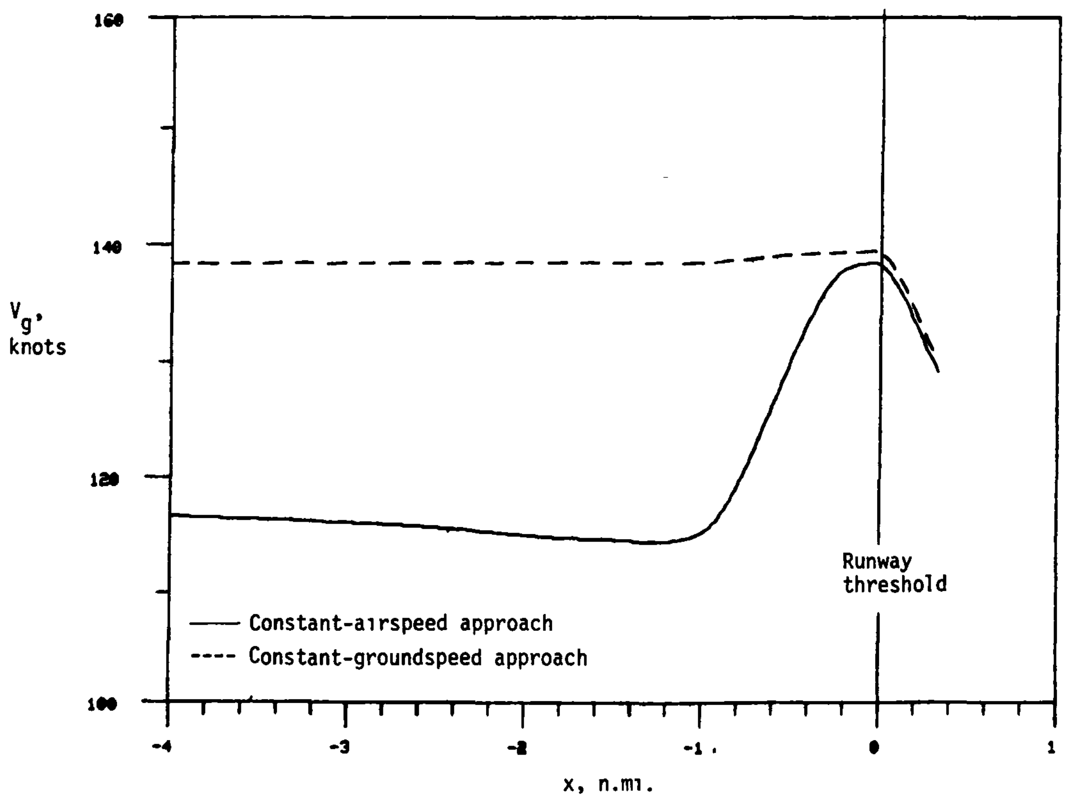


(b) Profile 2

Figure 7. - Airspeeds recorded on approaches in moderate wind-shear profiles.

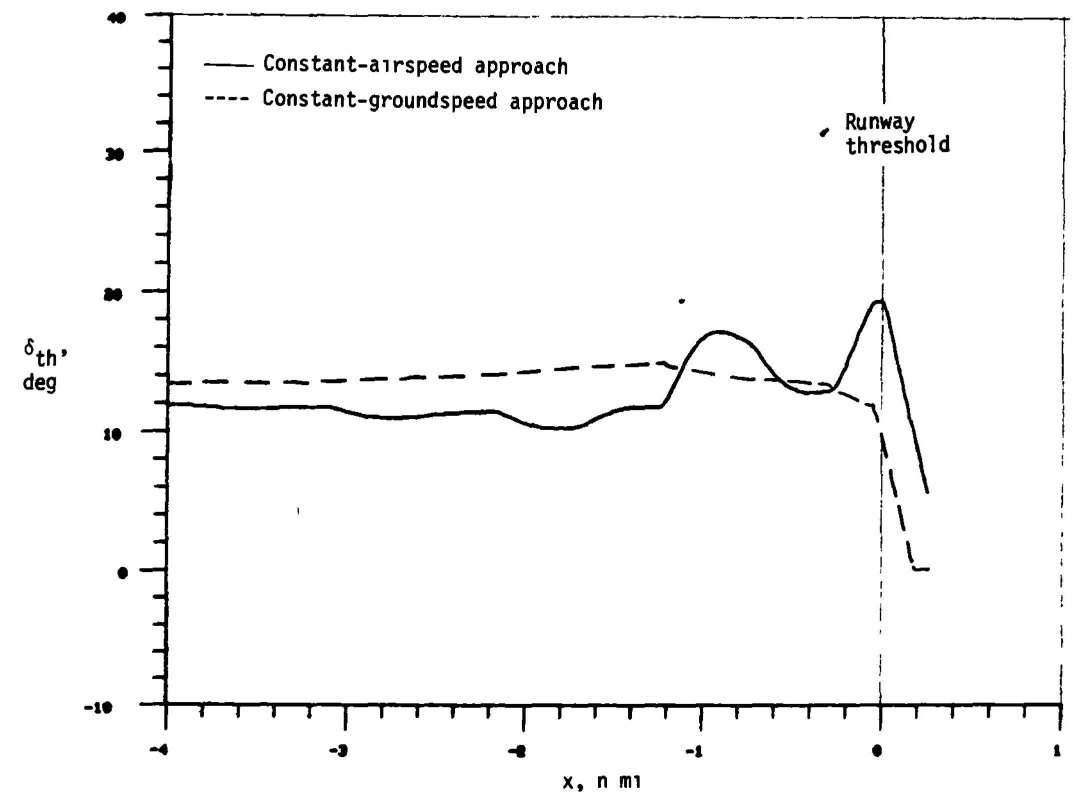


(a) Profile 1

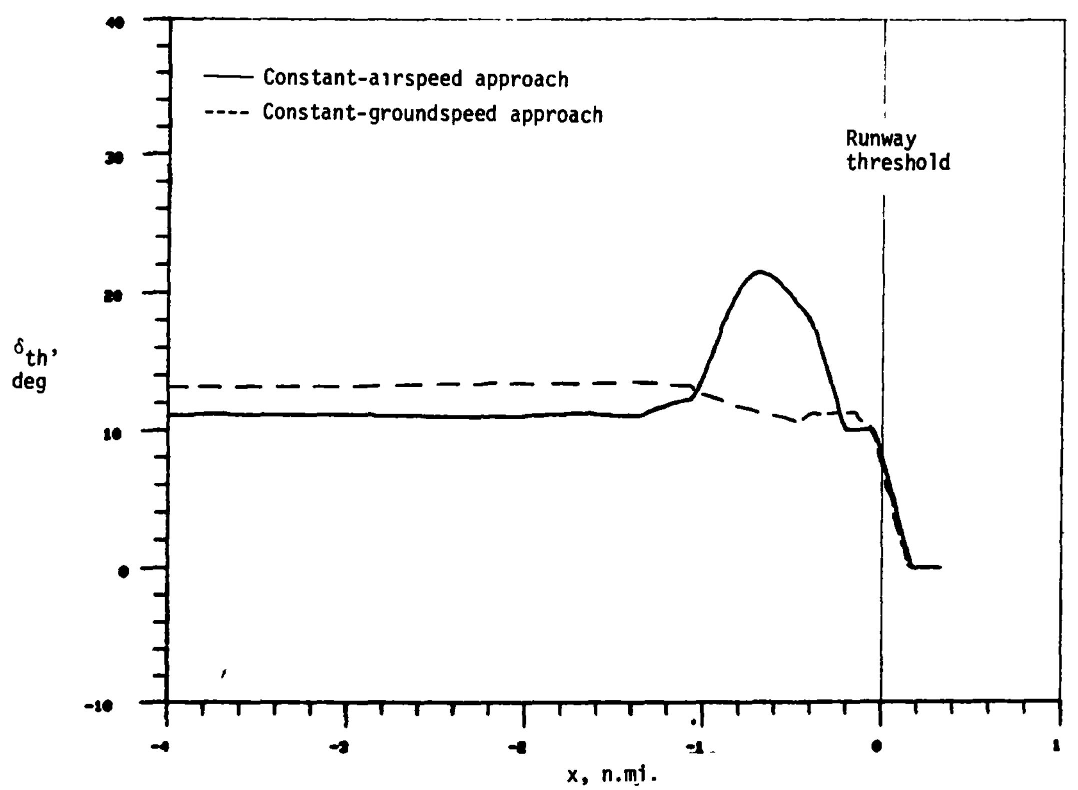


(b) Profile 2

Figure 8. - Groundspeeds recorded on approaches in moderate wind-shear profiles.

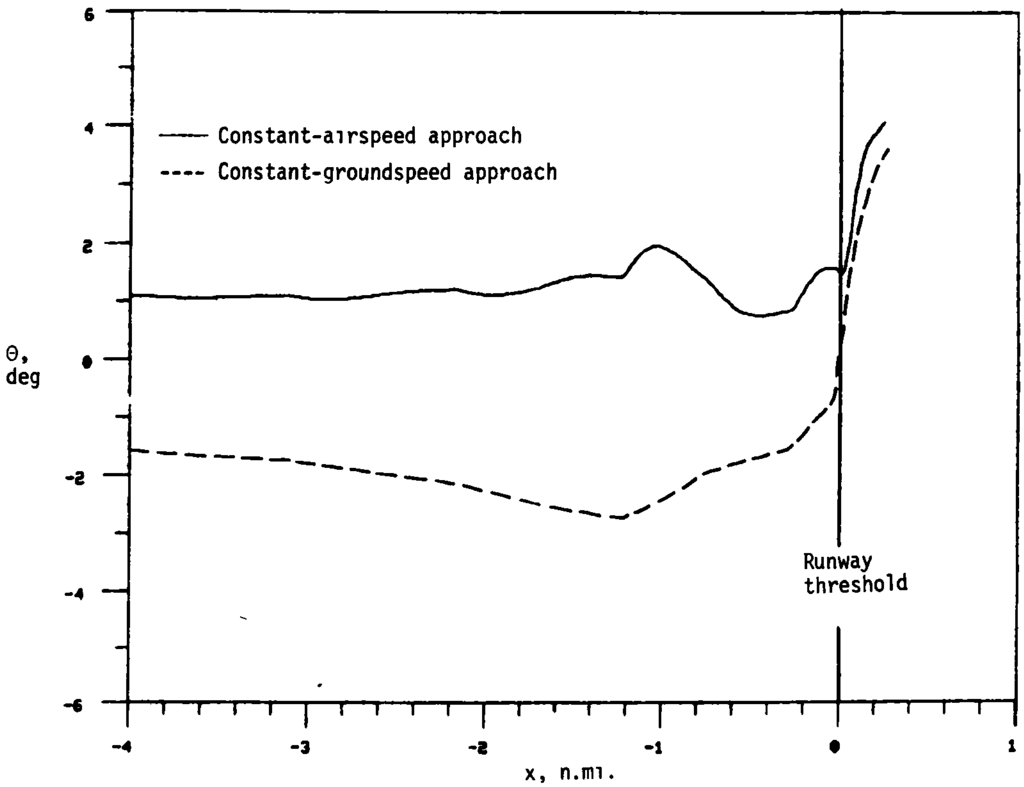


(a) Profile 1

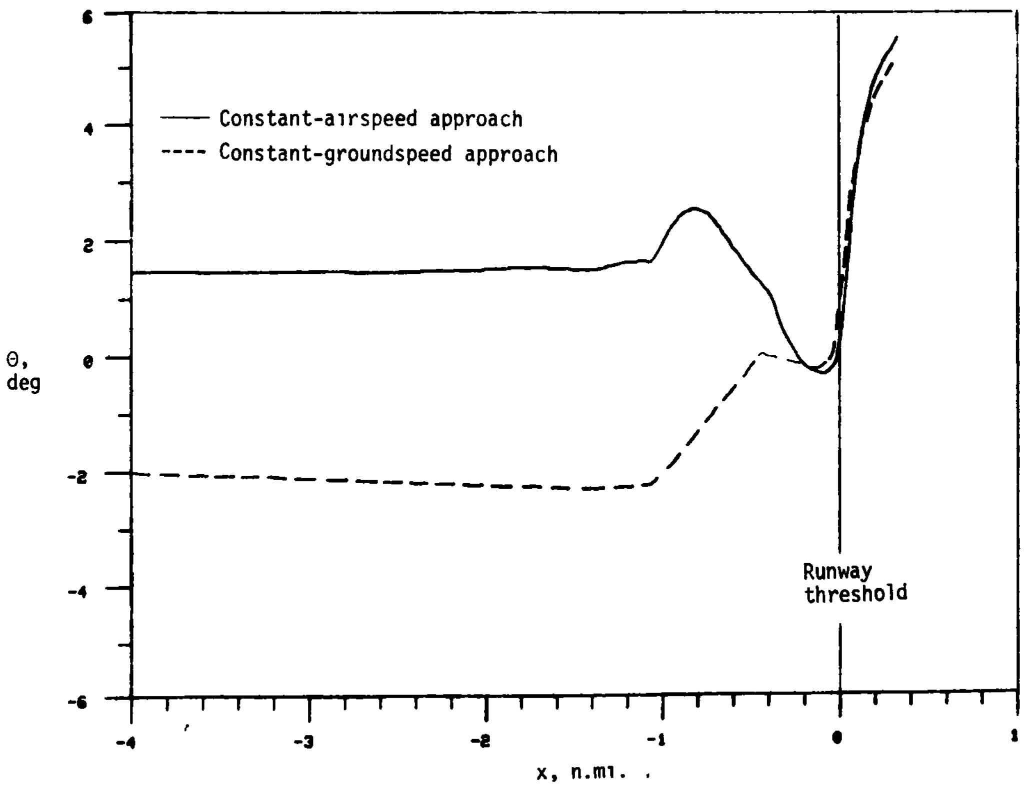


(b) Profile 2

Figure 9. - Throttle positions recorded on approaches in moderate wind-shear profiles.

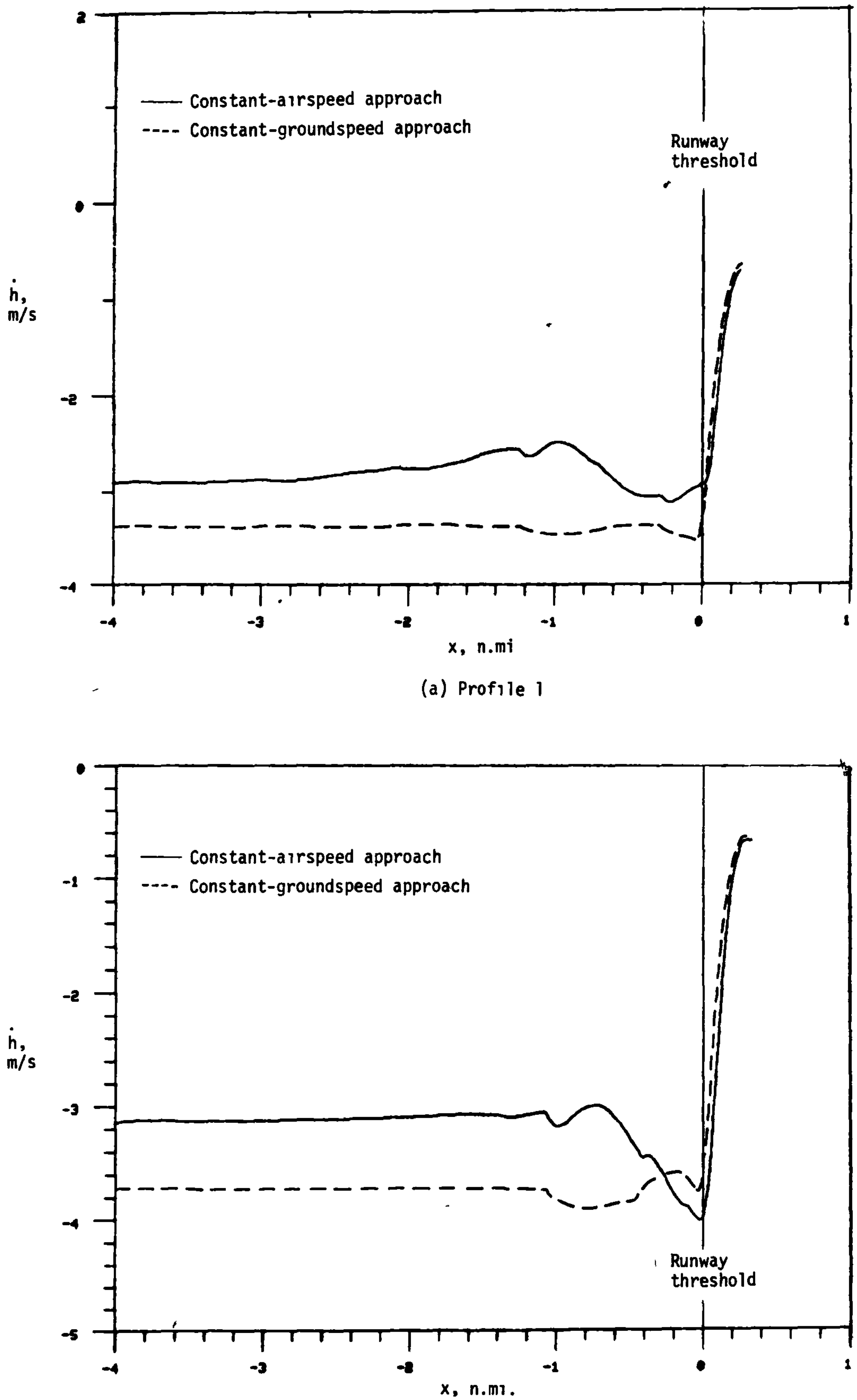


(a) Profile 1



(b) Profile 2

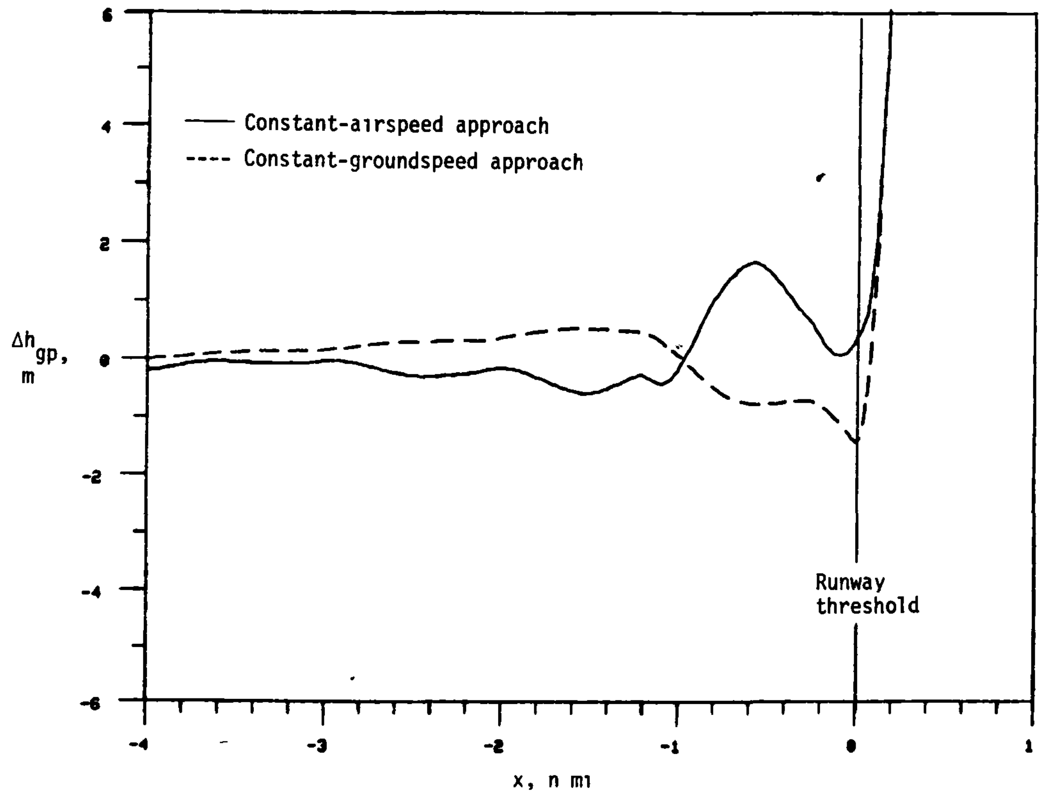
Figure 10. - Pitch angles recorded on approaches in moderate wind-shear profiles.



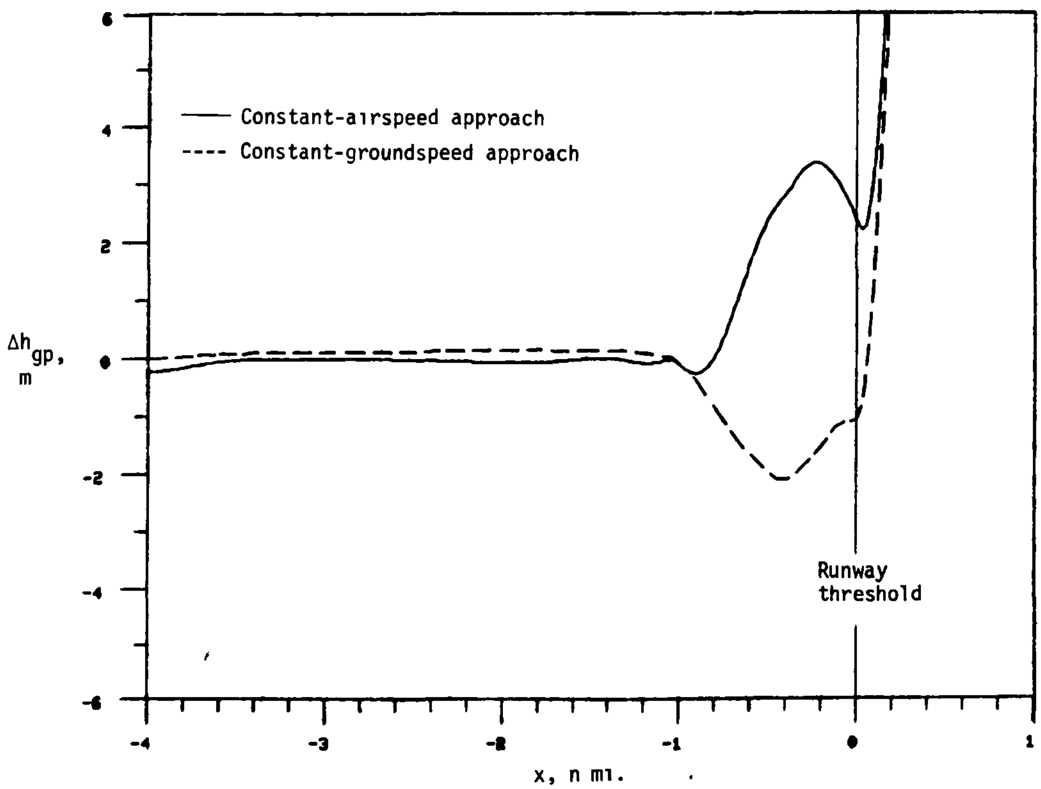
(a) Profile 1

(b) Profile 2

Figure 11. - Vertical speeds recorded on approaches in moderate wind-shear profiles.

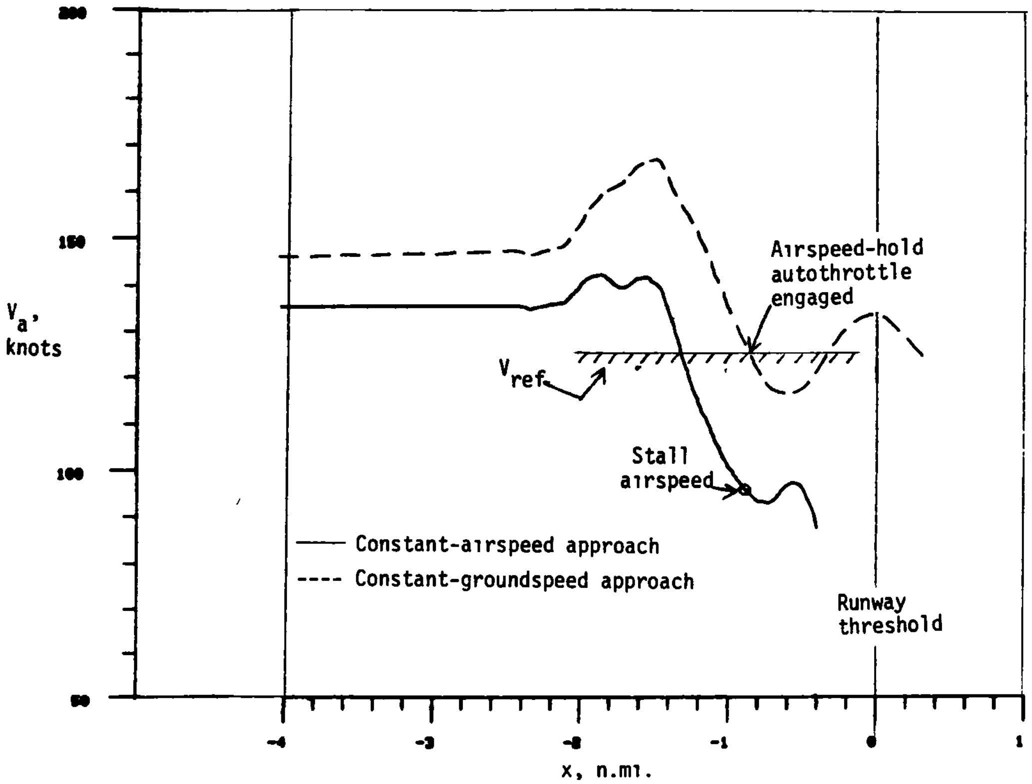


(a) Profile 1

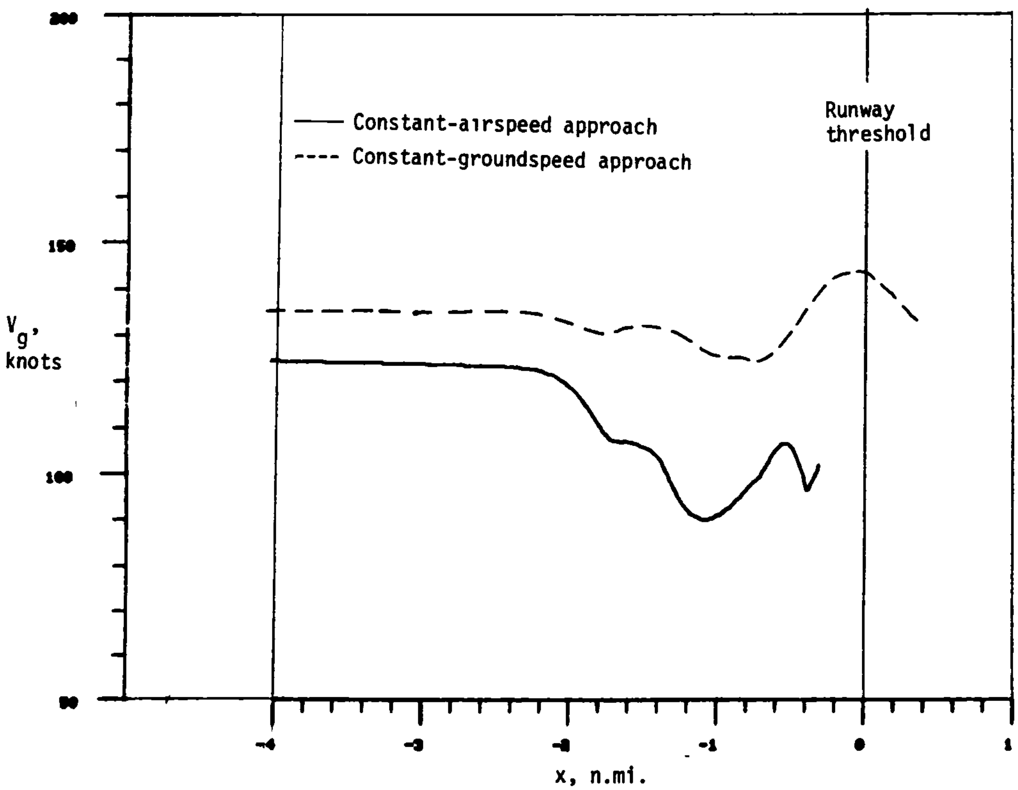


(b) Profile 2

Figure 12. - Glideslope deviations recorded on approaches in moderate wind-shear profiles.

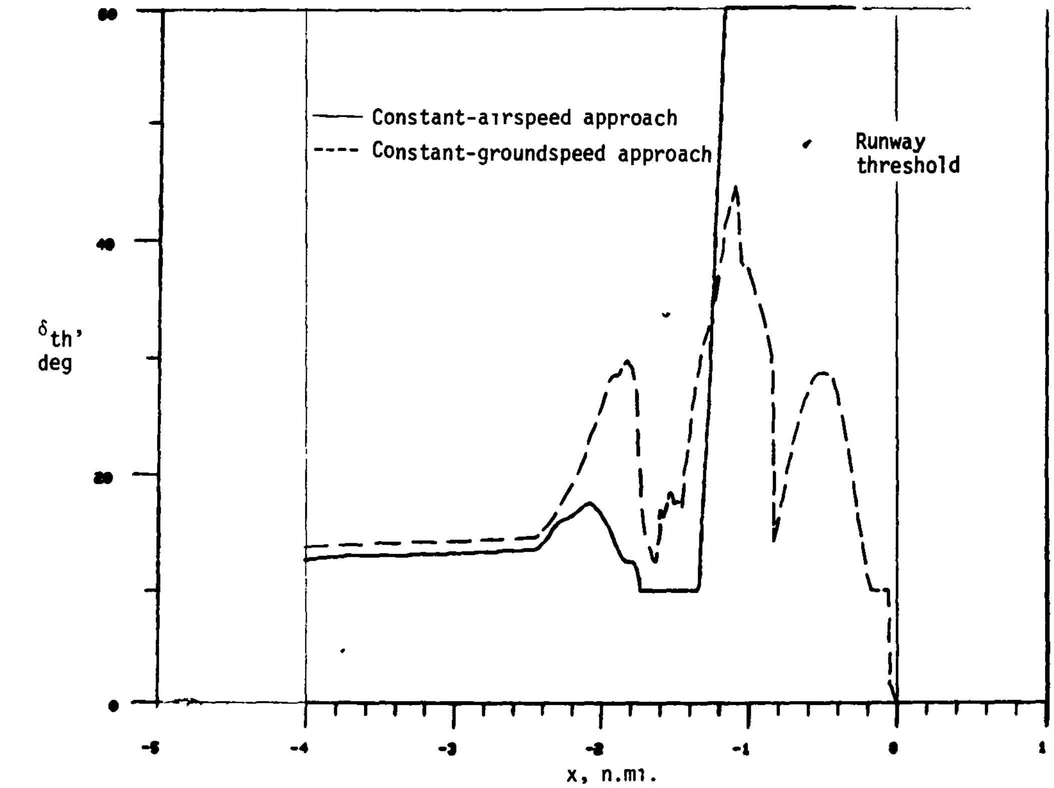


(a) Airspeed

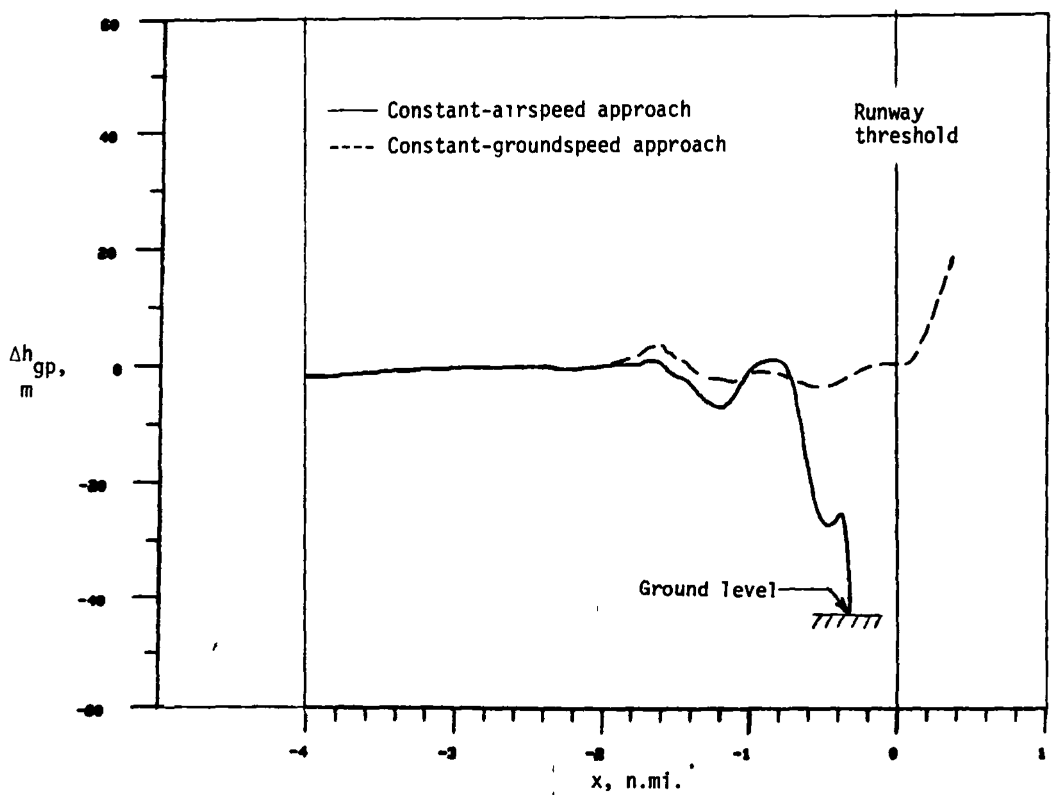


(b) Groundspeed

Figure 13. - Data recorded on approaches in a severe wind-shear profile.

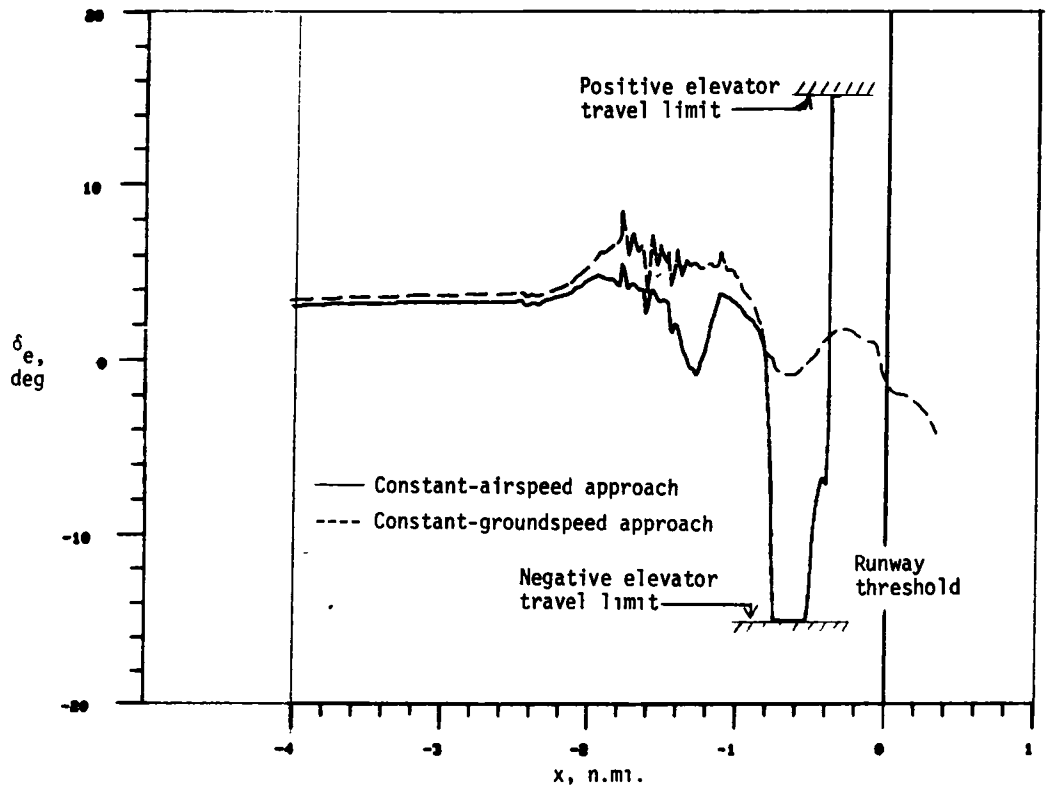


(c) Throttle position

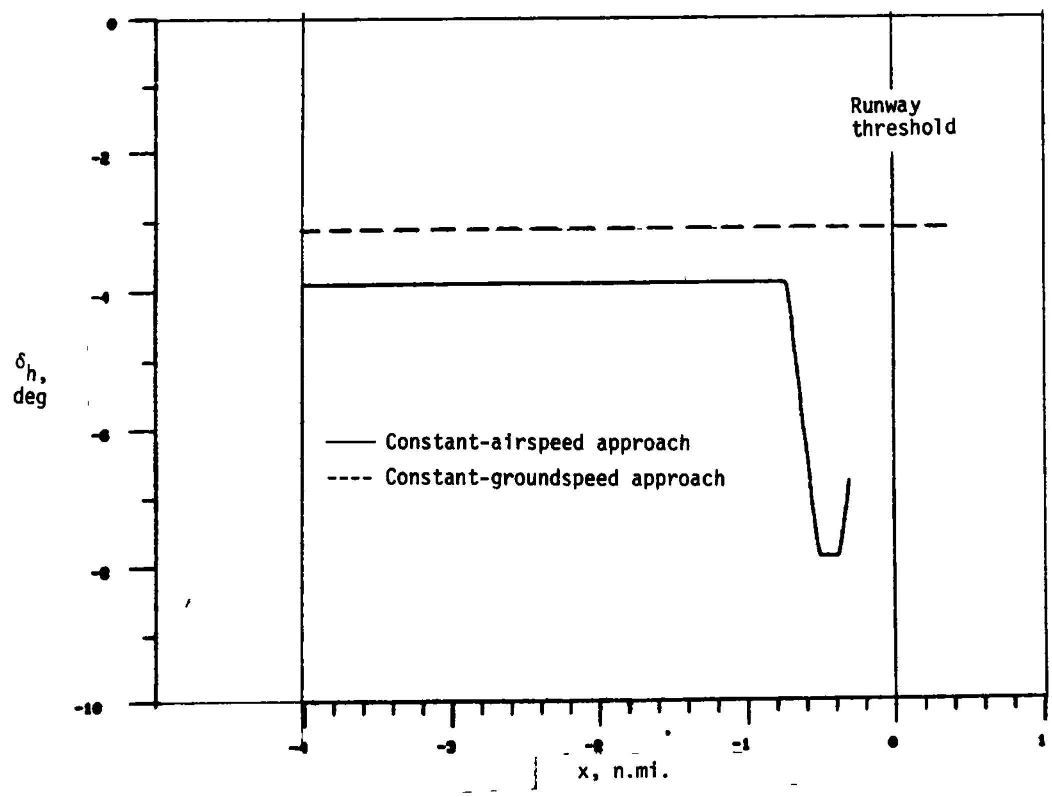


(d) Glideslope deviation

Figure 13. - Continued.

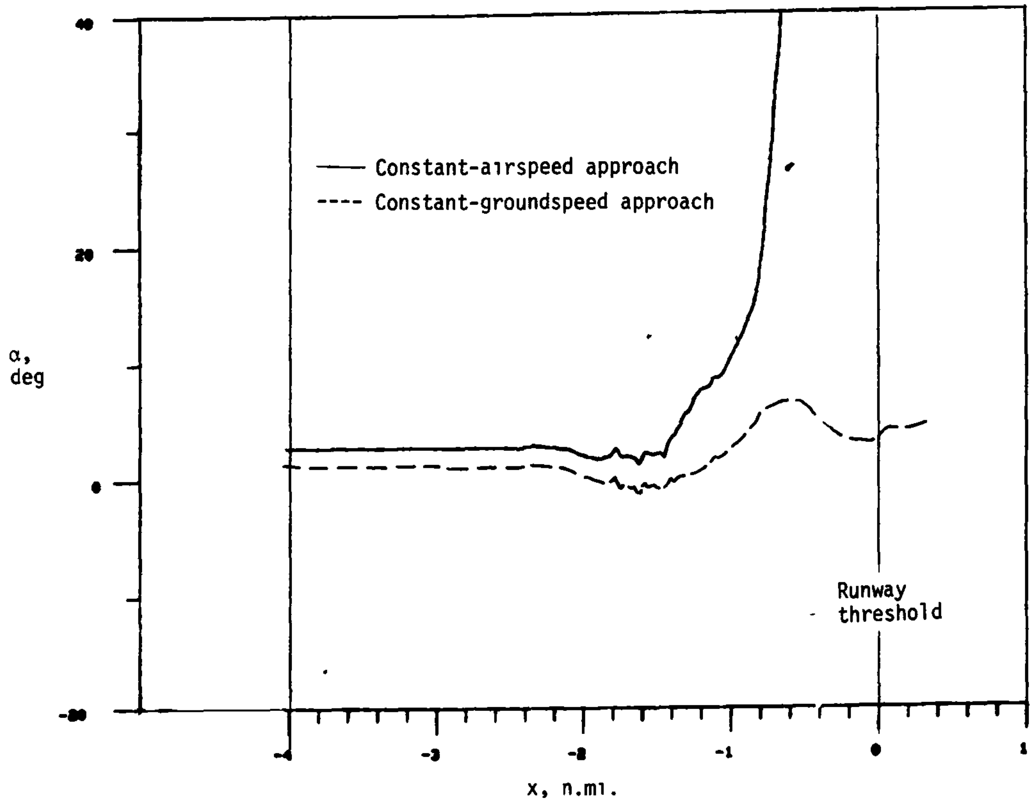


(e) Elevator position

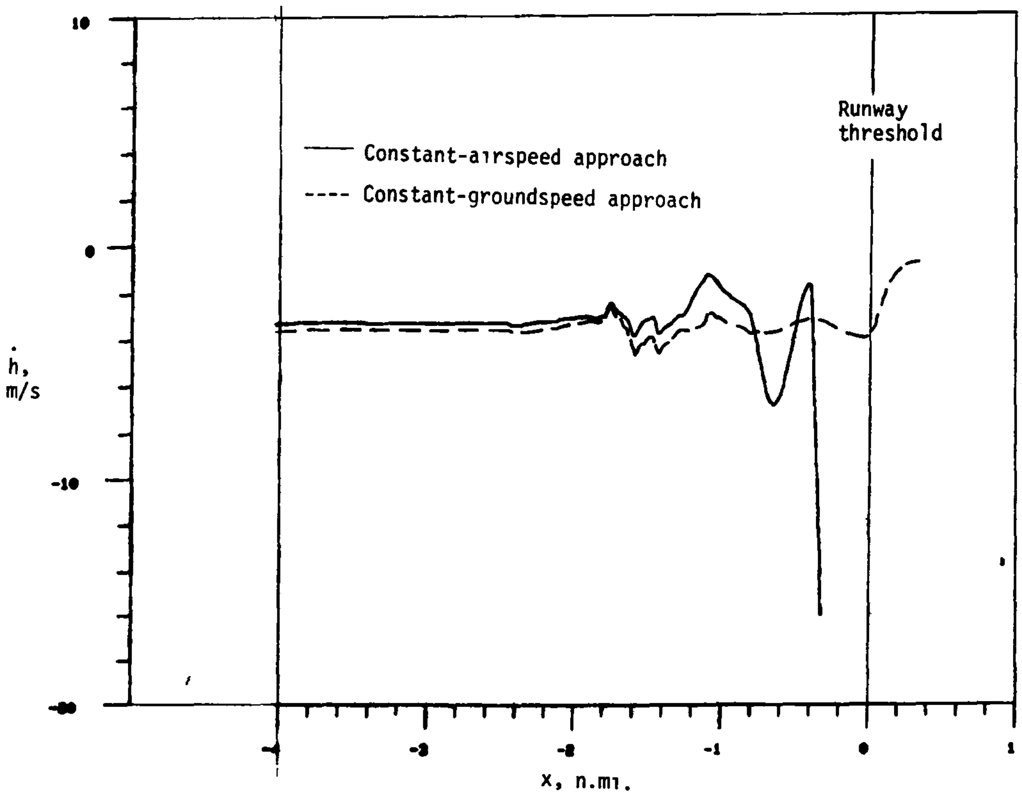


(f) Horizontal stabilizer position

Figure 13. - Continued.

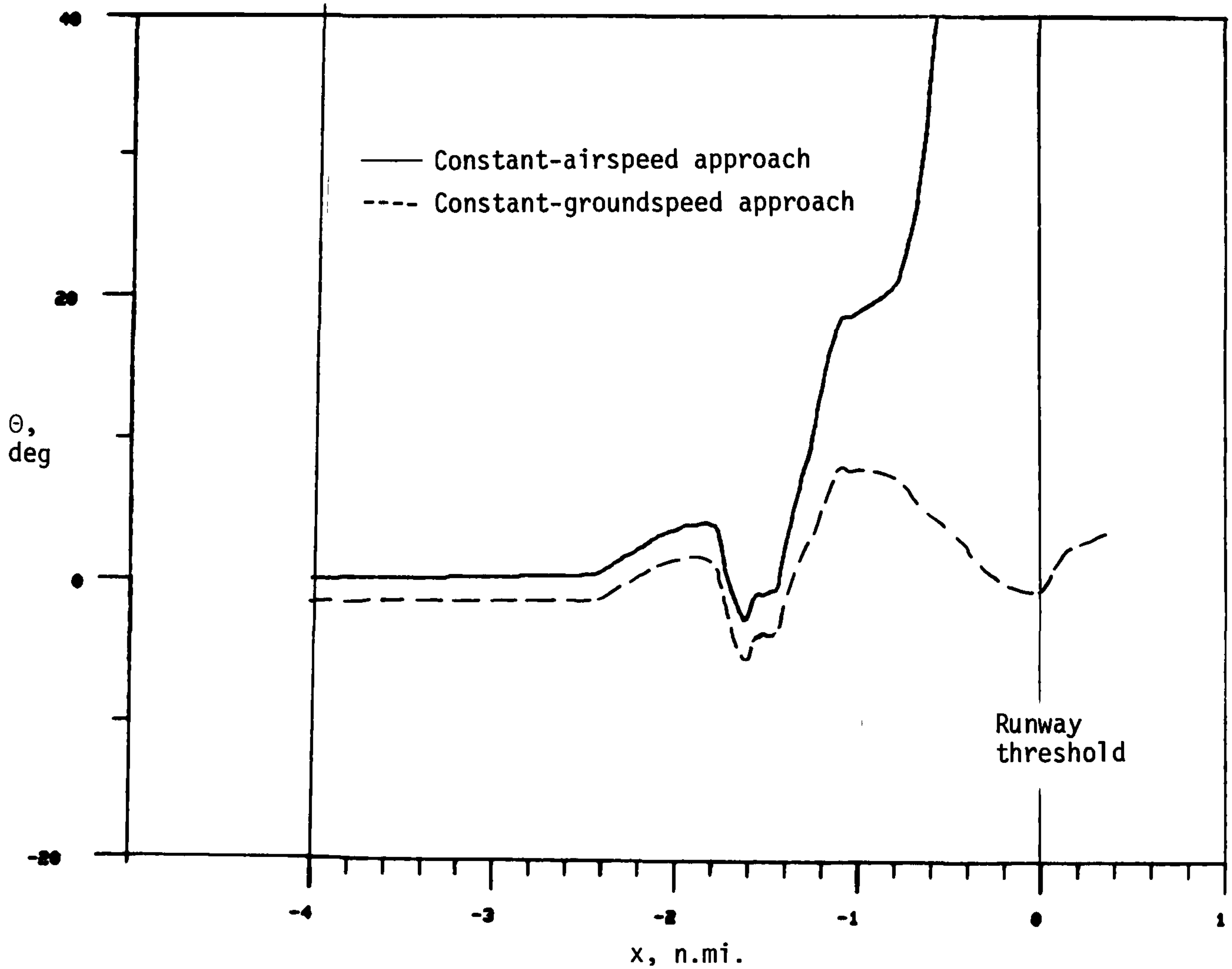


(g) Angle-of-attack



(h) Vertical speed

Figure 13. - Continued.



(i) Pitch angle

Figure 13. - Concluded.

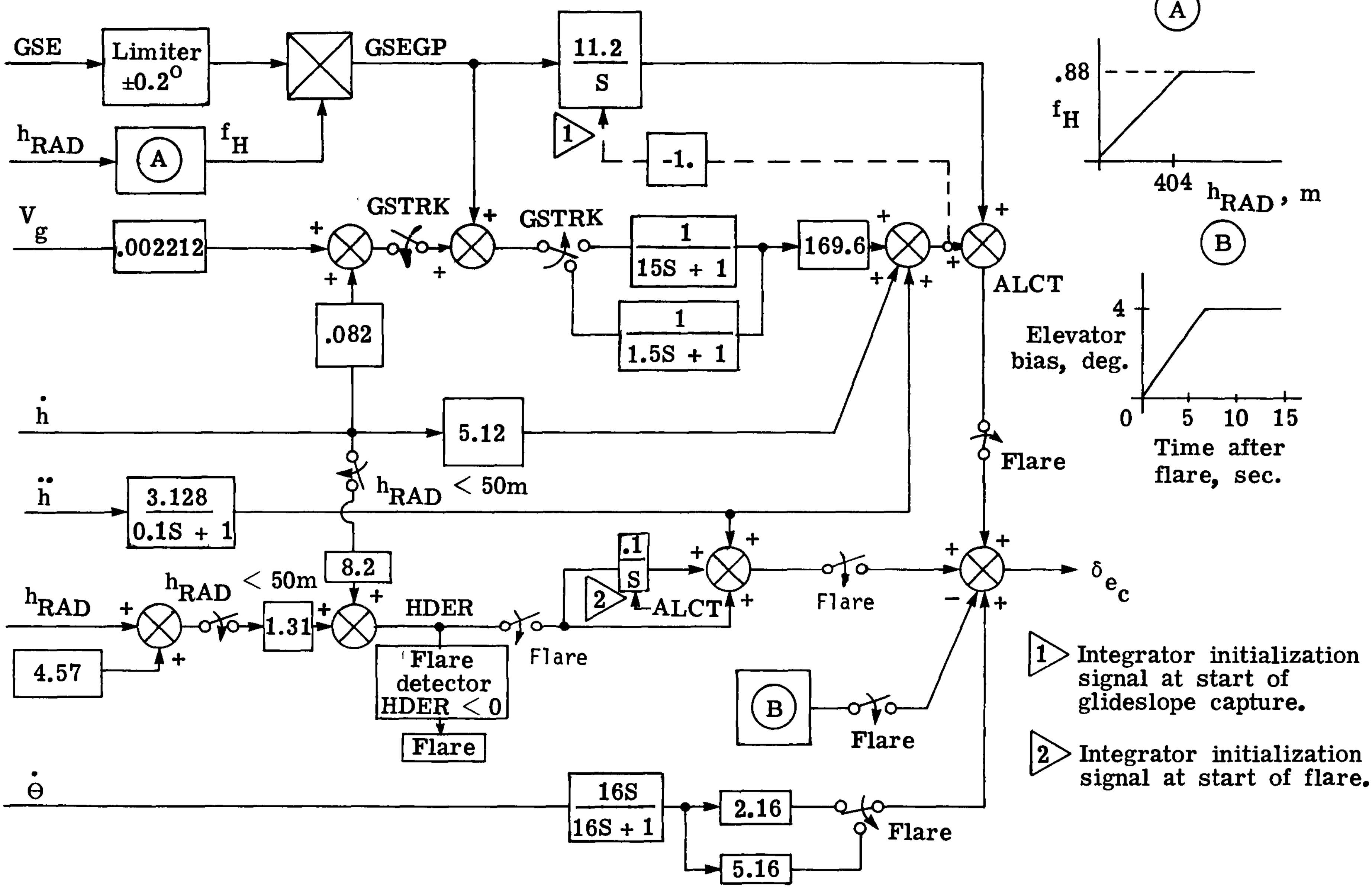


Figure 14.- Glideslope tracking and flare control laws.

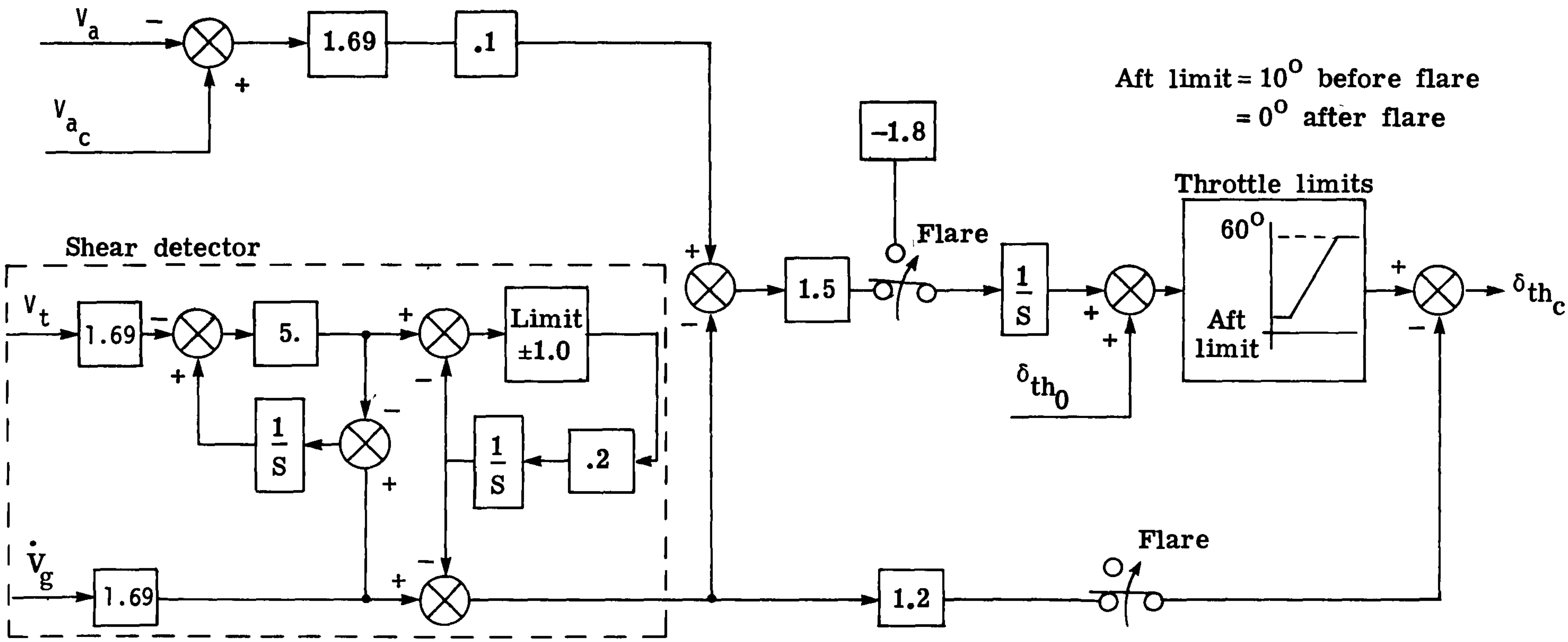


Figure 15.-Airspeed-hold autothrottle control law.

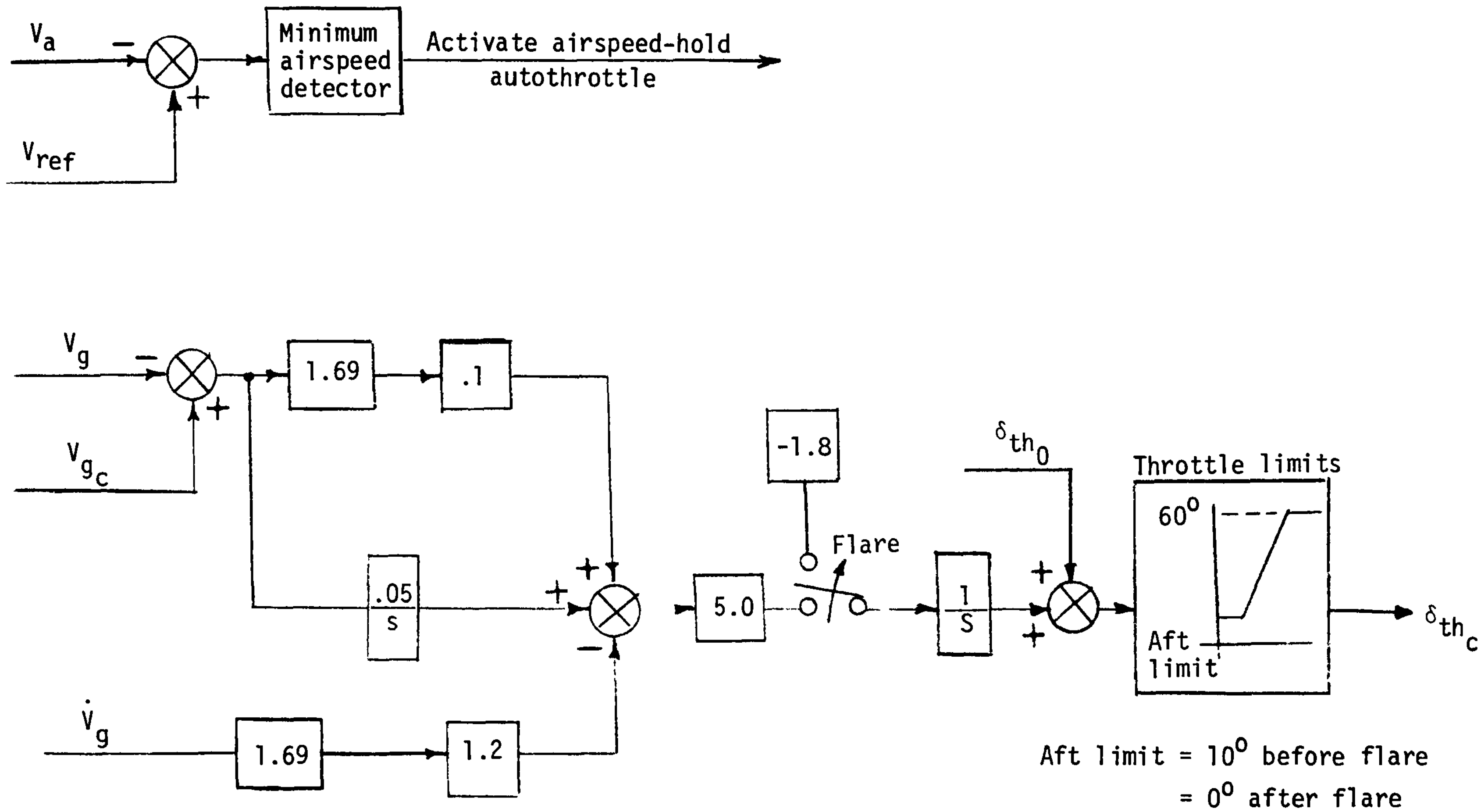


Figure 16.-Groundspeed-hold autothrottle control law.

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