FACTORS INFLUENCING TOLERANCE TO WIND SHEARS IN LANDING APPROACH

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SUMMARY

Flight simulator studies were conducted to examine the piloting problems resulting from encounters with unusual atmospheric disturbances late in landing approach. Simulated encounters with disturbances, including examples derived from accident data, provided the opportunity to study aircraft and pilot performance. It was observed that substantial delays in pilot response to shear-induced departures from glide slope often seriously amplified the consequences of the encounter. In preliminary assessments, an integrated flight instrument display featuring flight path as the primary controlled element appeared to provide the means to minimize such delays.

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INTRODUCTION

This paper reports findings from piloted simulator tests conducted to obtain a better understanding of the piloting problems induced by encounters, in landing approach, with localized atmospheric disturbances such as wind shears or downdrafts. This work was motivated by the increased concern that followed recent major accidents in which such disturbances were convincingly identified as the cause. The formulation and conduct of these tests were influenced by the background gained during NASA consultation with the National Transportation Safety Board (NTSB) during their investigations of these accidents.

To illustrate the real hazards of wind shear, this paper begins with a review of two accidents from which descriptions of the atmospheric disturbances were derived. The simulator tests, which include encounters with similar wind environments, are described. Data and observations from these tests are discussed. A flight instrument display principle that appears to have potential for improving tolerance to disturbances in landing approach is then described.

Examples of Wind-Shear Accidents

In December 1973, a DC-10 descended below glidepath on an approach to Logan Airport (Boston), striking the approach light standards short of the runway. The aircraft was destroyed, but fortunately there were no fatalities. The aircraft had performed a normal coupled ILS approach, with autothrottle, to an altitude of 60 m. At this point, while the pilot was completing his transfer from instrument to visual reference, he disengaged the autopilot, but left the autothrottle engaged. Data from the flight recorder indicate a subsequent 10-knot loss in airspeed, accompanied by an increasing sink rate. Corrective action was first too little, then too late. This aircraft was equipped with a very comprehensive digital flight data recorder (DFDR) that provided the data defining the winds shown in figure 1. The shear from a strong tailwind component at 150-m altitude to a light headwind at 50 m caused the aircraft to overshoot the desired approach speed, even though the autothrottle had reduced thrust to near flight idle. When the shear terminated, the aircraft decelerated toward its target speed, and an undetected sink rate developed. This wind-shear-induced accident is notable for its unusual circumstances, not for the severity of the disturbance. At no time was the performance capability of the airplane challenged — in fact, it struck the obstructions at a speed slightly above its reference approach speed.

In June 1975, at John F. Kennedy Airport (New York), during local thunderstorm activity, several aircraft encountered severe shears late on final approach. The last of these, a 727, hit approach light standards well short of the runway, with catastrophic results. This aircraft was equipped with the more common four-parameter foil recorder, providing insufficient data to define winds with confidence. Six minutes before the accident, an L-1011 aircraft, encountering a severe disturbance, had successfully executed a go-around. This aircraft was equipped with a DFDR. The maneuvers of these two aircraft are described in figure 2. Examining the flight paths and speed variations, the observer is led to conclude that the disturbances experienced by the two aircraft must have been very similar. Flight-path departure rates and speed losses are nearly identical; however, the L-1011 had the good fortune to suffer its encounter at a higher altitude than did the 727. Note that, in each case, downward departure from the ILS path preceded the sharp speed decay by about 6 sec. The pitch and thrust data, as well as angle-of-attack data, from the L-1011 enabled the derivation of the winds that aircraft encountered (fig. 3). These data are plotted to the same time reference as the previous figure. The initial disturbance, a substantial downdraft of nearly 10 knots (1000 ft/min), was followed by a 30-knot change in the along-track wind component. This disturbance has been hypothesized to result from a localized cold air downflow from a thunderstorm cell which, impinging on the surface, produced a high-velocity horizontal flow radially outward. The meteorological situation at New York at the time of the accident is analyzed in detail in reference 1. The wind profile (fig. 3) played a prominent role in the simulator program discussed here.

Atmospheric disturbances of the type documented at New York have since been identified in accidents at Denver (727 take-off) and Philadelphia (DC-9 go-around). Unfortunately, these airplanes were not DFDR equipped, and thus winds cannot be determined with certainty. Further details of the Boston, New York, and Denver accidents can be found in references 2 through 4.

SIMULATOR TESTS

Objectives

The examples of shear encounters just discussed contrast the case of subtly induced sinking in the Boston accident with the awesome disturbances experienced by the airplanes at New York. Fortunately, the severe cases are rare, and warning is offered by the thunderstorms that breed them. It appears that many other approach accidents and "near misses" have been induced by the more modest type of disturbance. Thus it was intended that the simulator tests explore encounters with a wide variety of shears. Answers to the following questions were sought:

1. In the present operational environment, what type and magnitude of disturbance represent an obvious hazard in landing approach?

2. What are the pilot factors that might escalate the effects of a modest disturbance to produce an accident?

3. What "onboard" means or techniques to reduce shear hazards appear worthy of development?

Simulation

Facility — The tests were conducted in the Ames Flight Simulator for Advanced Aircraft (fig. 4). This facility includes a transport-aircraft-type cockpit, large-amplitude cockpit motion, and a Redifon TV-model board visual simulation system. During these tests, the pilot station incorporated a pneumatic "G-seat," on loan from the Air Force, which was intended to produce the cues of sustained or lower frequency vertical accelerations.

Simulated aircraft — Airplane characteristics used in the simulator tests were typical of a short-range, twin-jet transport of the 737, DC-9 category. The engines were assumed to be aft-fuselage-mounted, with thrust contributing essentially no pitching moment to the aircraft. A landing weight of 43,100 kg (95,000 lb) was used for all tests. Take-off static thrust per engine was 62,274 N (14,000 lb) with 10-percent overboost available. The approach reference speed, V_{ref}, or "bug" speed, was established as 125 knots, approximately 1.25 times the speed for maximum lift in 1-g flight.

Cockpit controls and displays were conventional for transport category aircraft. The attitude indicator/horizontal situation display (ADI-HSI) were of the Sperry HZ-6 configuration. The ADI included an "expanded" pitch scale, a "fast-slow" indicator needle that was activated only for special tests, and a glide-slope deviation needle. The flight director needles were driven by signals computed in the basic simulation computer. The pitch command signal did not employ the HZ-6 system logic; it was computed using the logic of another commonly used flight director system. Pitch attitude commands were derived from a summation of pitch attitude and beam error. This system incorporated a major attenuation of the beam-error input at middle-marker passage.

An ILS-coupled autopilot mode was available in the simulation. Glide-slope guidance computation for the autopilot included beam-error rates derived from vertical acceleration and was representative in its capabilities of the newer "autoland" autopilot systems.

A "head-up" display system was used late in the tests to evaluate modified flight data display concepts. The symbology (discussed later) was optically combined (with a mirror beamsplitter) with the scene presented by the Redifon visual simulation system. The combined images were viewed through collimating lenses.

Visibility simulation.- Reduced visibility due to cloud or fog was simulated electronically. Visibility conditions as low as 30-m ceiling and 300-m visual range (RVR) were simulated to the satisfaction of the pilots who participated in the tests. In this program, no cases of interrupted visibility were simulated; the RVR never decreased as altitude decreased.

Wind and turbulence simulation.- A large number of wind profiles (velocity varying with altitude below 250 m) were established for the program. Three "logarithmic" profiles characteristic of widely disparate atmospheric lapse rates, constituted the basic program. On these shear profiles were superimposed perturbations that defined discrete shears varying in altitude of initiation, total amplitude, and gradient (knots per unit altitude). Examples of the along-track shear profiles used in the tests are shown in figure 5. Crosstrack wind profiles were defined as a percentage of the along-track amplitudes. A "40-percent" crosswind component from either the left or right was commonly used. In addition to these generalized altitude-dependent wind profiles, a facsimile of the atmospheric variations recorded in the L-1011 (discussed earlier) was programmed as a function of distance along the approach path, initiating at a point corresponding to that of the 727 encounter. Discrete geographically defined vertical drafts were also programmed. Simulated random turbulence, appropriate to the wind conditions, was superimposed on the shear profiles.

TESTS

Six pilots who currently fly transport category aircraft participated in the tests. After appropriate familiarization with the simulated aircraft, they each flew approaches in 20 to 30 different combinations of atmospheric disturbance and visibility. All but a few approaches were manually controlled, with flight director guidance available. Exposure to the New York thunderstorm profile was included well along in each pilots experience in the simulation while he was evaluating disturbances of lesser magnitude. A strong effort was made to create the levels of warning, readiness, and surprise that characterized the real encounters.

All approaches were initiated at an altitude of about 300 m. Normal control tower information regarding winds and visibility were transmitted to the pilot. In most cases of large disturbance, tower reports of previous encounters were included. Use of conventional cockpit procedures, including standard call outs, was encouraged. All pertinent pilot inputs and aircraft responses were recorded, and the pilots' observations were recorded on voice tape after each approach. At the end of the simulator exercise, and during a brief opportunity several months later, panel display modifications and several electronic head-up display formats were evaluated subjectively in the presence of disturbances.

RESULTS AND DISCUSSION

Aircraft Performance Potential

Since the response to a shear encounter involves both pilot and aircraft performance, it is appropriate to preface a discussion of the results with a review of aircraft performance capabilities assumed in these tests.

Figure 6 represents an attempt to put in perspective the level of disturbances experienced in the simulator relative to airplane performance capabilities for both the generalized shear cases and for the New York profile. Any point on this graph represents the duration of a "head-wind to tail-wind" or "negative" shear of given rate of change (in knots/sec). A useful approximation is the equivalence, in terms of energy loss, of a 6-knot downdraft to 1-knot/sec shear. The top line defines the theoretical shear (or equivalent combination of shear and downdraft) that can be tolerated without leaving the glidepath or falling below stall-warning speed — *if* take-off thrust is instantaneously available at the onset of the disturbance and appropriate pitch corrections are made. The lower curve represents the case of continued approach thrust. The crosshatched area is an envelope of all the generalized disturbances experienced in the simulator tests. Also indicated is the disturbance level of the New York profile. It can be seen that the generalized shear cases do not challenge the aircraft's performance potential. On the other hand, the New York profile leaves a comparatively small margin of performance.

Observations from Simulated Encounters

The simulator exercises provided a wealth of observations — and generated some new questions — regarding the significance in shear encounter of factors such as training, individual piloting techniques, flight director logic, and concurrent transfer from instrument to visual references. However, most of these points deserve more analysis and perhaps more experimentation before they are reported. This paper is limited to a discussion of pilot response delays in wind-shear encounters and means to reduce those delays.

New York shear profile — As indicated earlier, each of the six pilots in the simulator program suffered one well-conditioned encounter with a model of the New York downdraft-wind-shear phenomenon. In two of the six simulated encounters, the aircraft descended to altitudes where they would have encountered obstructions, in almost exact duplication of the 727 accident. A third resulted in a near miss, and the remaining three recovered with sizeable terrain clearance. Figure 7 compares the smallest and the largest altitude divergences seen in these encounters. While one of the simulated aircraft in effect "crashes," the other executes a successful go-around with a minimum altitude of 40 m, only 20 m below ILS glide-slope altitude. The single most important difference in pilot response is seen in the record of thrust. The successful pilot perceived the sink rate induced by the downdraft and had added substantial thrust by the time the shear was encountered. The pilot also pitched the aircraft to regain near normal sink rate. When the speed was seen to decay even farther, even with the initial addition of power, take-off thrust was immediately applied. Speed did not fall below 124 knots. The other pilot made no significant response to the downdraft. In response to the rapid decrease in airspeed due to the shear, power was tentatively added. By the time this response was recognized as inadequate, the aircraft was below 30 m, in a high sink-rate condition, and 10 knots below approach reference speed — recovery was highly improbable.

Further evidence of the value of quick response is seen in figure 8, which illustrates the performance of an autopilot-autothrottle system in an encounter with the same profile. Flight path was held tightly, but with significant speed loss. The automatic systems perceived and acted with a very modest delay. As indicated in figure 7, the pilot cannot be counted on to act as effectively.

Generalized shear program — The performances recorded in the other disturbances can be reviewed for further evidence of the perception problem. As might be expected, since these disturbances did not seriously challenge airplane performance and the pilots were considered well warned, no simulated accidents occurred. There was a small number of aborted approaches and several hard landings. Subjective observations by the pilots were highly variable for the lesser disturbances — sometimes the disturbance was hardly noticed; at other times, the same disturbance caused a very significant workload. The shears that the pilots considered hazardous were of the highest amplitudes and gradients, for example, 15-20 knots in 30 m of altitude, and initiating below 100-m altitude. Figure 9 shows characteristic values of speed and altitude losses for several levels of shear intensity. The shaded points represent the larger disturbances. Generally, these levels of speed and flight-path deviation do not seem large or dangerous; however, if they are considered to occur very low in the approach, at times in low visibility, the hazard is more apparent. The observation can be made that the energy losses represented in these excursions represent roughly 75 percent of the energy loss in the disturbance input. This would indicate delay in effective countering of this loss by the pilot.

Figure 10 illustrates example response times for thrust and pitch inputs. From the data represented by the circled points, a wide variation of responses is seen. This might be expected due to differences in rates of onset of the disturbance, as well as variations in flight condition at the point of onset.

Initial thrust responses are seen within 3 to 4 sec, indicating tight monitoring of airspeed. However, pitch attitude increases required to arrest the increased sink rate occur 6 to 10 sec after shear initiation, indicating that flight-path angle or rate-of-descent divergences are slow to be recognized.

The response lags shown for the simulated New York shear encounters are ev[illegible]re pronounced. The quickest responses were exhibited by the pilot that s[illegible]aneously added thrust and pitched up within 5 sec of the disturbance onset. The delays in thrust addition are presumed due to the fact that the initial disturbance was a downdraft that did not create an immediate speed decay. The delays in pitch response are more surprising in view of the immediate increase in sink rate induced by the downdraft.

Means for Improving Flight-Path Control

These observations of performance in shears led to the conclusion that conventional displays do not provide the pilot with the means for uninterrupted awareness of his flight path, and that visual cues outside the aircraft can also be tenuous. As indicated earlier, the tests were concluded with evaluations of display concepts aimed at improving the pilot's capability to control speed and flight path in strong disturbances. By far the most encouraging results were obtained using the electronic head-up display equipment available to the simulator to create integrated displays of various configurations. The format described in figure 11, which has been the subject of very brief experience in the simulator, appears to essentially eliminate the path and speed perception delays demonstrated with conventional displays. In addition to the fixed airplane symbol and moving horizon, the display includes the following elements: a runway symbol, in approximate perspective, with a touchdown reference point; a glide slope angular error indication, referenced to a negative three-degree pitch scale index; a flight-path symbol, referenced to the horizon; and a speed error indication referenced to the airplane symbol.

The effectiveness of the display in reducing time delays in the perception of flight-path changes results from the fact that the flight-path indicator can be substituted for the airplane symbol as the primary controlled element. To correct the flight situation illustrated, the glide-slope line is simply tracked with the flight-path symbol, resulting in a convergence as indicated in figure 12. In the experiments, the flight-path information was assumed to be inertially derived, and a small component of lagged pitch rate was added to compensate for the normal time lag between attitude and flight-path response. The speed error symbology was well received and could usually be sensed in peripheral vision while concentrating on the flight-path symbol.

Several points regarding this display concept must be discussed. The concept of flight path as the primary element is not original here; it is utilized in a well publicized commercial HUD system. The format shown is not a developed display. While it demonstrates effectiveness in tracking the glide slope, it is inadequate for lateral guidance without additional information. There is no reason that the concept cannot be used in a panel-mounted display.

CONCLUSIONS

Analysis of simulator data and accident records indicates that the consequences of wind-shear encounters are seriously aggravated by delays in perception of speed and flight-path divergences when conventional cockpit displays or visual references are used. The significance of these delays is apparent when piloted performance is compared with the performance of a modern autothrottle system in the same disturbance. Cockpit display concepts, integrating flight-path and speed information, hold promise of eliminating delays in pilot perception and are worthy of concerted development efforts.

REFERENCES

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2. Aircraft Accident Report — Iberian Airlines DC-10 at Logan Airport, Boston, Mass., Dec. 17, 1973. NTSB-AAR-74-14, Nov. 8, 1974.

3. Aircraft Accident Report — Eastern Airlines Boeing-727 at John F. Kennedy Airport, Jamaica, New York, June 24, 1975. NTSB-AAR-76-8, Mar. 12, 1976.

4. Aircraft Accident Report — Continental Airlines Boeing-727 at Stapleton Airport, Denver, Col., Aug. 7, 1975. NTSB-AAR-76-14, May 5, 1976.

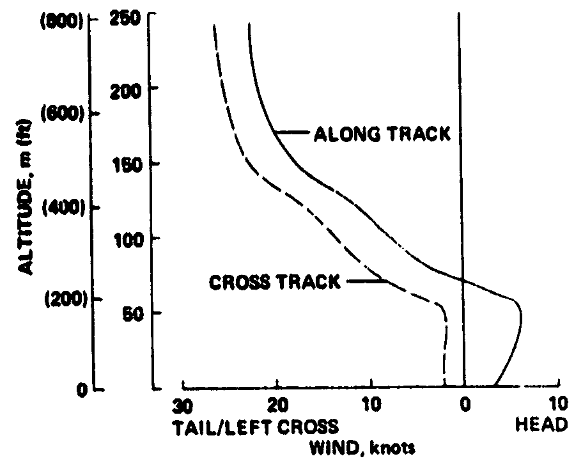

Figure 1.- Winds derived from digital flight data recorder, DC-10, Boston.

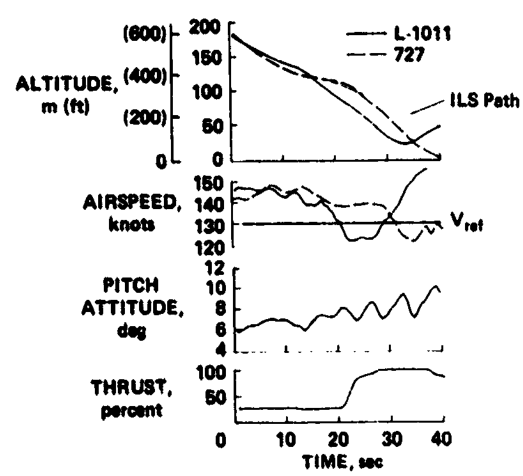

Figure 2.- Encounters with thunderstorm-related wind shears, New York.

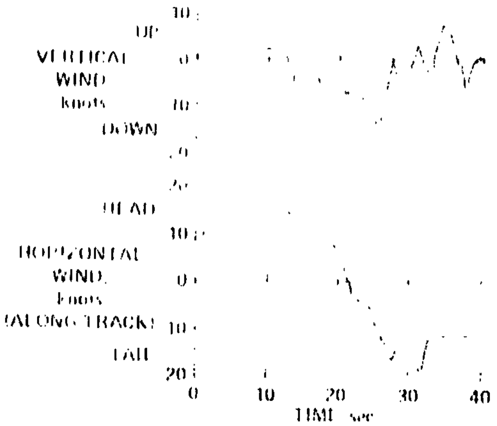

Figure 3.- Downdraft and wind shear encountered by L-1011 aircraft, New York.

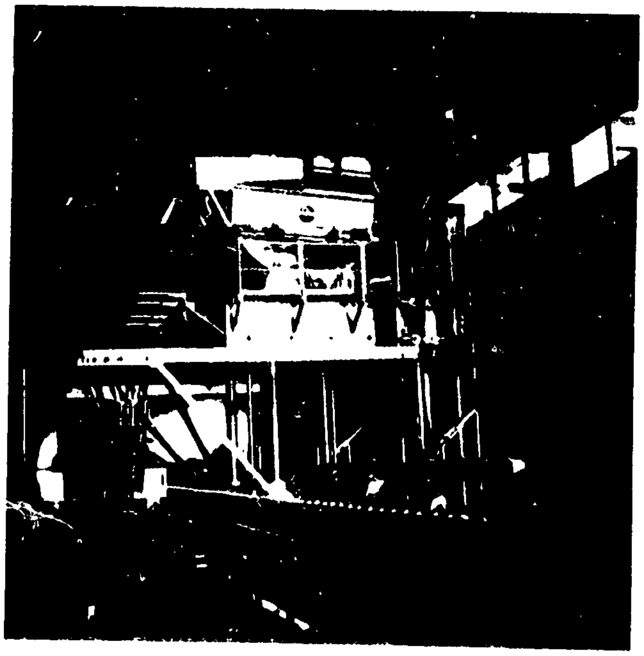

Figure 4.- Flight simulator for advanced aircraft.

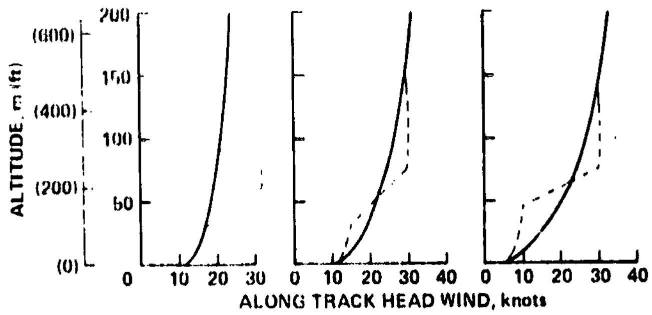

Figure 5.- Examples of simulated shears.

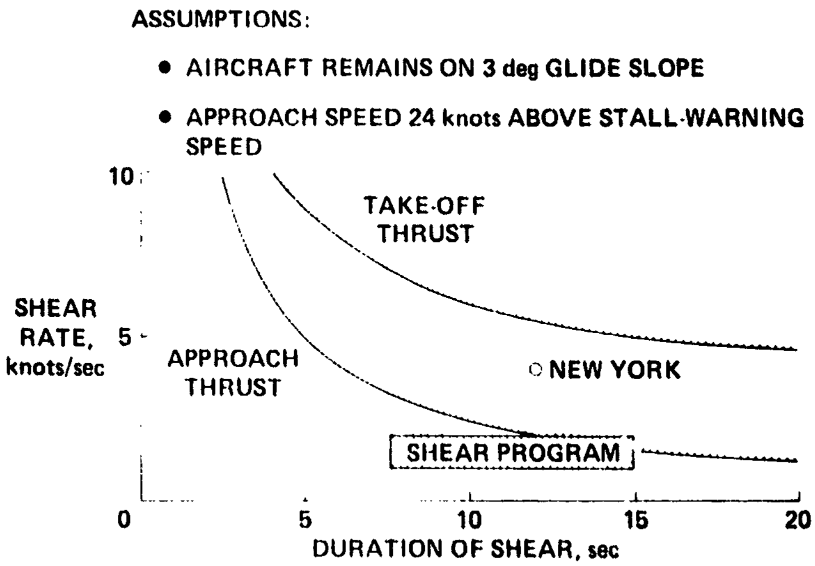

Figure 6.- Performance available to counter wind shear on approach.

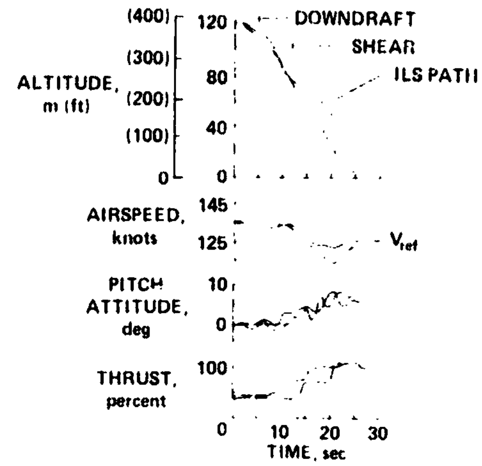

Figure 7.- Effects of response delays, New York profile.

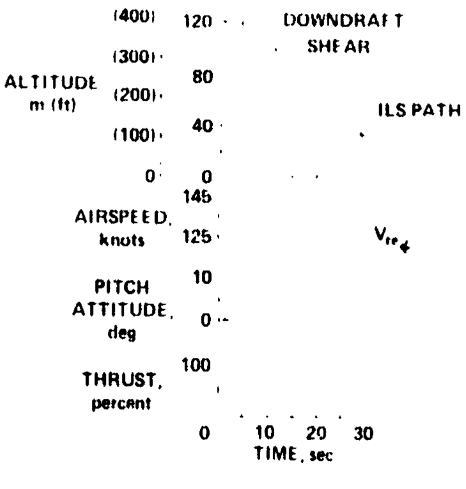

Figure 8.- Automatic systems performance in New York profile.

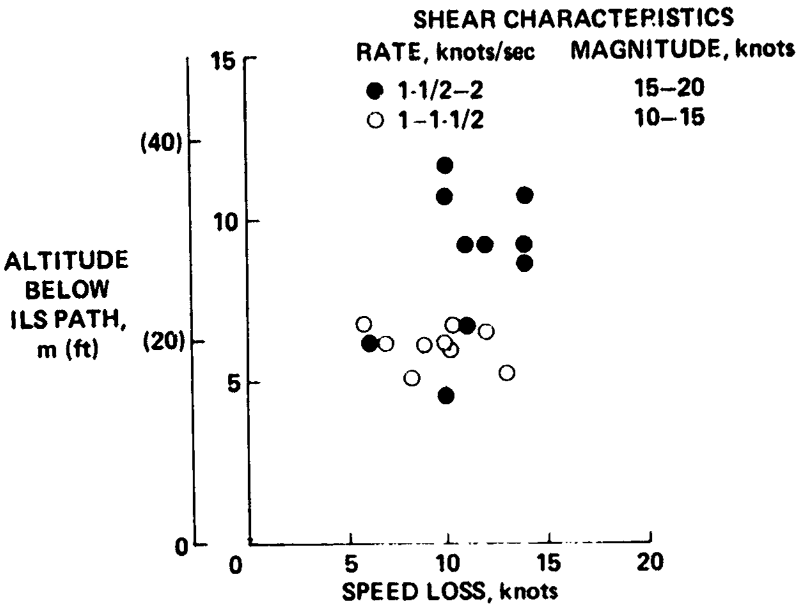

Figure 9.- Altitude and speed perturbations in simulated shear encounters.

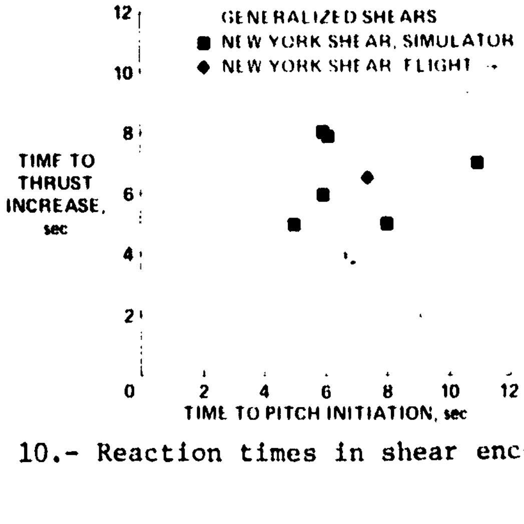

Figure 10.- Reaction times in shear encounters.

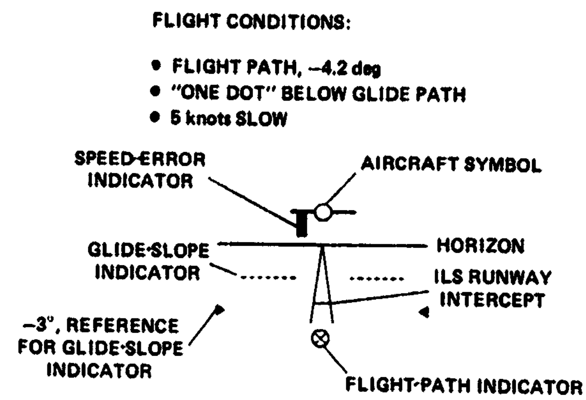

Figure 11.- Integrated flight-path display.

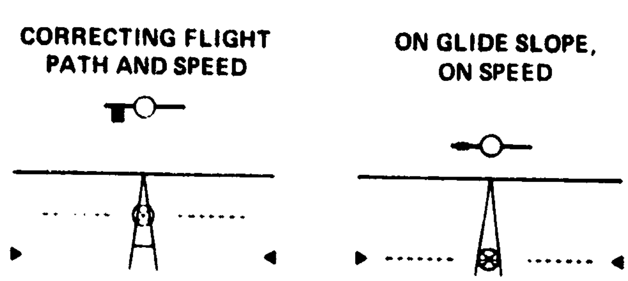

Figure 12.- Integrated flight-path display. Correction to glide slope.