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ACQUISITION OF CONTROL INFORMATION IN A WIND SHEAR

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Introduction

When an aircraft encounters a change of air mass it may experience a change in horizontal wind sufficient to cause appreciable change in airspeed and, therefore, in lift. It may also suffer a change in vertical wind and, therefore, in vertical speed. The adverse combination of these effects may result in a significant excursion below the correct vertical profile and this may be especially serious if it happens during the latter part of an approach. Appropriate action should then be taken very quickly to avoid a situation from which the aircraft can scarcely recover, implying that suitable information needs to be readily accessible to the pilot. The purpose of this paper is to explore circumstances in which it is difficult to meet this requirement in conventionally equipped aircraft, because of time factors affecting the flow of information.

Temporal Aspects of Acquisition of Control Information

The manner of acquiring information affecting control of an aircraft as it encounters wind shear may vary according to the flight mode and may influence the delay in gaining that information. If an instrument approach is in progress, so that the onset of shear is learned from the instruments, the delay may be small compared with the time remaining until touchdown because of the pilot's habitual division of attention between the panel instruments. The longest dwell (or reading) time for an instrument is about two seconds, which is the value for the attitude-director indicator (reference 1). Allow- 'or an instrument lag of about one second, the delay in noticing the of shear would be about three seconds, assuming the first signs of shear to be shown by other instruments, such as the altimeter, the vertical speed indicator, or the airspeed indicator. A delay of this magnitude would perhaps be sufficiently small in relation to the time until touchdown, unless the shear occurred at very low altitude. For example, some thirty seconds of flight would remain after meeting shear at 400 feet during a 3° approach at 135 knots (though this time could be reduced by path steepening due to the shear).

In the case of a purely visual approach, information relating to control in the vertical plane would be gained from the information mechanisms which support visual flight. If the relevant mechanism were the apparent expansion of the ground scene in relation to the end point of the flight path (reference 2), the time taken to determine that point would depend on the time for which the expansion had been apparent. Supposing the flight path to be directed towards a point lying between two ground objects, such as runway approach lights, which are distance S apart and subtend an angle $S\gamma^2/H$ at the pilot's eye, to the first order, where γ is the inclination of the flight path and H is the height of eye, as in Figure 1. Then for an approach at constant γ the objects appear to expand with angular velocity $S\gamma^2 V_z/H^2$, where V_z is the vertical speed. So expansion of the ground scene is less apparent for points close to the projected flight path than for points more remotely situated, and the limit of perceptible movement, at a particular time, occurs at that value of S for which the rate of expansion exceeds the threshold for detecting angular velocity. Conversely, for ground points at a given separation, the expansion becomes apparent when H is reduced sufficiently, assuming the vertical speed to remain constant. Taking the velocity threshold to be 10 minutes of arc per second of time for objects moving in a field having no reference framework (reference 3), the value of S is given with sufficient accuracy by

$$S = H^2/350\,\gamma^2 V_z$$

in which S and H are in feet, V_z is in feet per second, and γ is in radians.

Variation of S with height is shown in Figure 2 for two cases of interest. In one case, the approach is for a conventional path angle of 3° and a vertical speed of 12.5 feet per second. In the other, the path is assumed to have been steepened by wind shear to give a path angle of 5° and the vertical speed is taken to be 25 feet per second. If the conventional approach is directed to a point 1000 feet beyond threshold, the 3° curve shows that an apparent expansion with respect to the aim point will first become perceptible at a height of just over 110 feet, indicating that the flight path will terminate beyond threshold. On the other hand, if the 5° path finishes at a point short of threshold by, say, 2000 feet, expansion of threshold with respect to this point is first perceptible at a height of just over 360 feet, when the path may be seen to be dangerous.

Combining these results, if shear of the kind assumed is encountered at 400 feet during a 3° approach, the (safe) end point of the flight path will not have been detected visually at this time, and the steepened (unsafe) path will not become discernible until about 1.6 seconds later, when the height of 360 feet is reached at the increased vertical speed. Since the remaining flight time will be about 14.5 seconds, it should be possible to save the situation if visibility is adequate and if the new end point is perceived as rapidly as is theoretically possible. But this is only so if the relevant ground points are continuously identifiable, otherwise the end point may be misjudged through observing the apparent expansion of another part of the external scene.

Another temporal effect to be considered is the time needed for the transition between instrument and visual flight modes. This process requires muscular action to alter the line of regard and to refocus the eyes. It also requires a change in the method of interpreting visual patterns because information is already abstracted and quantified in the instrument flight mode but it has to be abstracted from a perspective scene and, as far as possible, quantified in the visual flight mode. The transition thus takes time and since the components of the process would appear susceptible, on general grounds, to effects of age, training, stress, and physical condition, the total transition time may be expected to vary between quite wide limits. For present purposes, the transition time will be taken as not less than 3 seconds, which is the time for one complete cycle between instrument and visual fields when only muscular actions are involved (reference 4), and possibly as great as 8 seconds. On this basis, the transition may act to constrain the flow of information when there is only limited time available, as in the latter stages of an approach. A simple illustration of this effect is shown in Figure 3, where acquisitions from the field of flight instrument information and from the external visual field are shown cumulatively, and where each acquisition is for simplicity assumed to be discrete and to occupy an equal interval of time. The horizontal bar represents the transition, during which no information is acquired from either field.

Information Flow During Approach to Kennedy Airport in Low-Altitude Wind Shear

By considering these temporal aspects of the acquisition of control information, it is possible to construct a model for the approach by Eastern Airlines Flight 66 to Kennedy International Airport on June 24, 1965, when the shear effect was similar to that which has been assumed and the pilots were, or were about to be, in visual flight during the period following the encounter. Thus, Table 1 shows mean sea-level height, vertical speed, and indicated airspeed as extracted from Appendix F of the National Transportation Safety Board's report on the ensuing accident (reference 5). It is seen that vertical speed increases significantly at a height of 425 feet and this is followed by a decrease in indicated airspeed beginning at 350 feet. So the aircraft started to encounter adverse shear at about 400 feet and this resulted in a vertical speed of 21 feet per second, increasing later to 30 feet per second, or about 25 feet per second overall. The flight path angle, as shown by the height trace of the appendix, was approximately 5°.

Table 1 also lists pilots' comments which can be used to infer sources of control information. Thus, the pilot made a visual acquisition of the approach lights at a height of 450 feet, when he said "I have approach lights." From then on, he probably continued to search the forward view until observing the runway lights at 200 feet ("Runway in sight"). This can be inferred with some confidence because it would be his primary concern to see the runway as soon as possible, because a complete transition cycle would occupy a large part of the interval up to the time of the second acquisition (13.6 seconds), and because there seems to have been no recognition of the effect of shear on the flight instruments. In this interval, it would have been possible to observe the change in path direction, from the apparent expansion of the approach lights, at a height of 360 feet, according to the model which has been proposed and assuming adequate visibility. But no change seems to have been observed, in spite of having advance warning of the possibility of shear (a report by another flight, Eastern 902, was acknowledged). It has therefore to be assumed that, if the model is correct, visibility was insufficient to support the visual mechanism on which it is based. This assumption is consistent with reports of poor visibility by ground observers and the recorded sound of heavy rain.

The copilot made an instrument approach, with an eventual transition to visual flight at a time which cannot be determined precisely. In response to the pilot's instructions to "stay on the gauges" at 525 feet and at 440 feet, the copilot was evidently in the instrument flight mode until at least 425 feet ("I'm with it"). From this point on, his source of information is uncertain until the pilot acquired the runway at 200 feet and, almost immediately (0.9 second), the copilot indicated his own acquisition of the runway by saying "I got it" (it could scarcely mean he was continuing an instrument approach at that height). The inference can thus be drawn that the copilot had already completed his transition by that time, and this is consistent with the prohibition on instrument flight below 200 feet at Kennedy Airport. If this were so, the copilot could have started his transition at, say, 300 feet which, at the prevailing rate of descent, would allow barely 5 seconds for the change of flight mode. It seems reasonable to suppose that the transition was actually started earlier at, say, 350 feet. In that event, the copilot would have been observing flight instruments for only 3 or 4 seconds from the time of the first instrument indication of windshear, at 425 feet, when vertical speed increased. And it is quite

TABLE I INFORMATION ANALYSIS FOR ACCIDENT AT KENNEDY AIRPORT ON JUNE 24, 1975

Time h.m.s.	Height* MSL ft	Vertical Speed* ft/min	Indicated Airspeed* Kts	Pilot's Source of Information	Copilot's Source of Information	Pilot's Comment	Copilot's Comment
1604:40.5	525	725	147		Instruments	Stay on the gauges	
1604:41.5	500	725	145		↓		Oh yes, I'm right with it
1604:52.6	450	0	139	External World	↓	I have approach lights	
1604:53.2	450	0	139	↓	↓		Okay
1604:54.7	440	725	140	↓	↓	Stay on gauges	
1604:55.8	425	1250	140	↓	Instruments		I'm with it
1605:00.0	350	1250	138	↓	↓		
1605:02.5	265	1250	123	↓	↓		
1605:06.2	200	1250	125	External World		Runway in sight	
1605:07.1	160	1250	128	↓	External World		I got it
1605:09.3	120	1800	129	↓	↓	Got it?	
1605:10.2	90	1800	128	↓	↓		Takeoff thrust
1605:11.4	50	1800	127	↓	↓	- - - -	- - - -

* Approximate values from Appendix F of NTSB Report

possible that the vertical speed indicator was not included in the copilot's scan during this short interval, because of the small dwell fraction and link value associated with this instrument (Reference 1), in which case the wind shear would not be noticed. On establishing contact with the external visual world, the copilot would be in the same situation as the pilot, in that the steepened flight path would have been discernible below 360 feet, according to the model and given adequate visibility. Since the copilot was also unable to make this visual observation, at that time, the apparent expansion of the ground scene was either not used or not usable, through impaired visibility.

From the height of 200 feet onwards, both pilots were probably in visual flight, without recourse to instruments, because it would hardly have been possible to make a complete transition in the remaining 5.2 seconds of flight. Yet the direction of the flight path remained unknown, even though the threshold of perception had been exceeded by a factor of 2 at 180 feet. The moment of first recognizing the true state of affairs cannot be identified with certainty. It could perhaps have been as early as 120 feet, when the pilot said "Got It?" or it could have been as late as 90 feet, when "Takeoff thrust" was commanded. In any event, the direction of the flight path was perceived at a time when the apparent expansion of any visible ground objects would seem to have reached gross proportions, and in a situation where flight instrument information was inaccessible through the constraint imposed by transition time.

Discussion

It has been taken as axiomatic that an excursion below the correct approach path due to low-altitude wind shear must be corrected as rapidly as possible, with the implication that the requisite information needs to be immediately accessible. This appears to be possible for the instrument flight mode when shear is encountered at about 400 feet and conventional instruments are used but it can be seen that instrument lag begins to be significant in this context, contributing a sizable fraction of the delay expected in recognizing the situation. It may therefore be desirable to use flight instruments having a rapid response in such cases, and this suggests consideration of an electronic flight instrument system, with which negligible delays can be achieved.

In the visual flight mode, an indefinite delay is possible when flying a 3° path, until the end point becomes discernible quite late in the approach. The situation could be improved by superimposing a ground-stabilized reference on the visual scene, with the effect of reducing the threshold of perceptible angular velocity (reference 3) and thus increasing the discernibility of apparent expansion of the ground scene. When the approach path is steepened by wind shear, the end point should be discerned in time, without any such aid, if visibility is adequate and perception continuous. In the approach to Kennedy Airport by Eastern Flight 66, however, both pilots seem to have been in a position to make such a determination, and since the end point was only seen to be dangerous at a time when the phenomenon of apparent ground expansion had reached gross proportions, this mechanism of visual information could evidently not be used in the prevailing circumstances of visibility. In such cases, a superimposed display might help stabilize the flow of otherwise interrupted information by filling in gaps caused, for example, by intermittent cloud, as well as by improving the detection of angular velocity.

The transitional phase between instrument and visual flight modes is highly significant to the flow of information when wind shear is met at low altitude because it may occupy a time large in relation to the remaining time of flight, especially when the path is steepened by the shear. In the Kennedy approach, the transition may have prevented the copilot observing important instrument indications shortly after meeting adverse wind shear. This kind of situation could, of course, be avoided by using a flight instrument system which effectively eliminates the transition, and allows observations in the flight instrument and external visual fields to be made in rapid succession, as indicated in Figure 4. It would then be possible to continue to acquire significant instrument information while observing the forward view, or while starting to do so.

The temporal constraint imposed by the transition appears also to have prevented both pilots acquiring vital instrument information during the final, visual, phase of the approach. Had vertical speed and airspeed information been immediately accessible at that time, steepening of the flight path could have been detected earlier, but this was not possible with the conventional display equipment used in the aircraft. Again, this type of situation could be avoided by eliminating the transition with a suitable display system.

By stressing the importance of temporal factors, the analysis thus leads to the simple conclusion that safety could be improved in a low-altitude wind shear situation by changes in the method of presenting information. The display system could be given the rapid response of an electronic medium to improve reaction time for the man-machine system. Presentation could be made in the head-up mode to provide a stabilized visual reference and thus improve detection of angular velocity. And the same type of presentation could be used to eliminate the transition, as is well known, and thus allow immediate access to critical information. In short, much could be done to improve the capacity for arousal to timely action.

The analysis also goes beyond the accident report (Reference 5) which concluded that the delay in recognizing the large descent rate was probably due to reliance on visual rather than flight instrument cues, while acknowledging that the copilot needed to make a transition to visual flight in order to complete the approach. The dilemma implicit in this finding may perhaps be resolved by the present proposal to change quite radically the flight instrument system.

The question of what should be shown in a head-up display is beyond the scope of the present paper. It should be noted, however, that not all information is equally useful or reliable in a wind shear. For example, a velocity vector symbol driven by a signal computed from an angle of attack sensor can be dangerously misleading in the presence of a strong vertical wind. On the other hand, an entirely suitable and reliable guidance signal can be derived from inertial sources, according to the method of J. R. Lowe.

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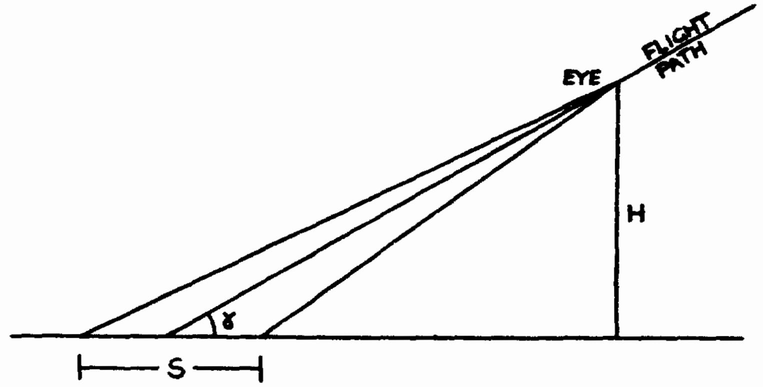

FIGURE 1 APPARENT EXPANSION OF GROUND OBJECTS

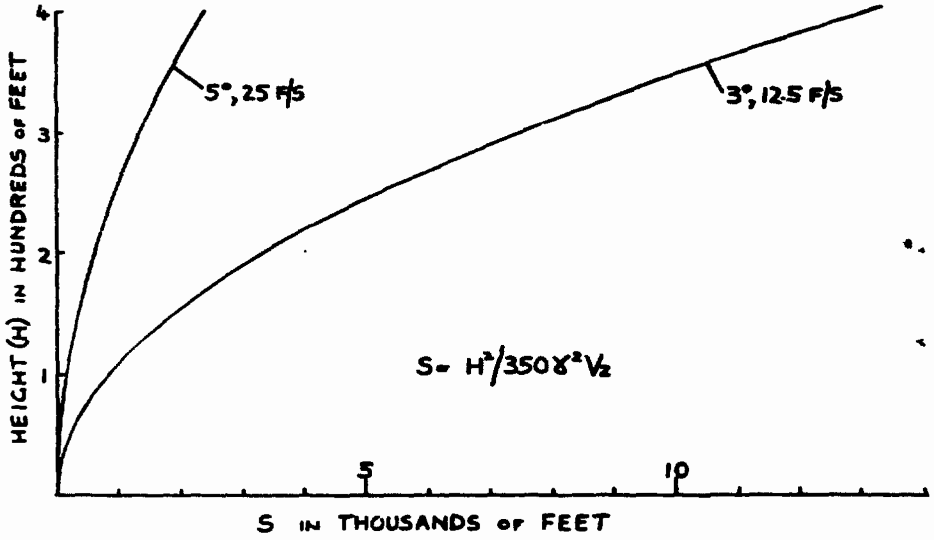

FIGURE 2 DISCERNIBLE SEPARATION OF EXPANDING OBJECTS

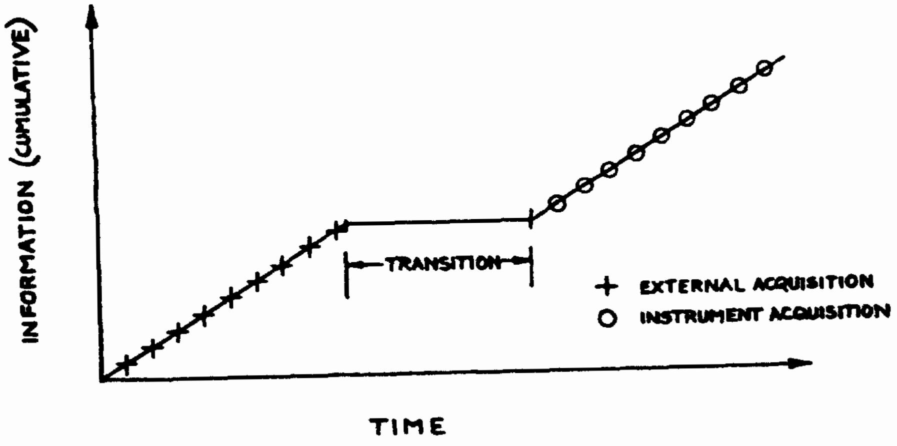

FIGURE 3 EFFECT OF TRANSITION ON INFORMATION ACQUIRED FROM SEPARATED FIELDS

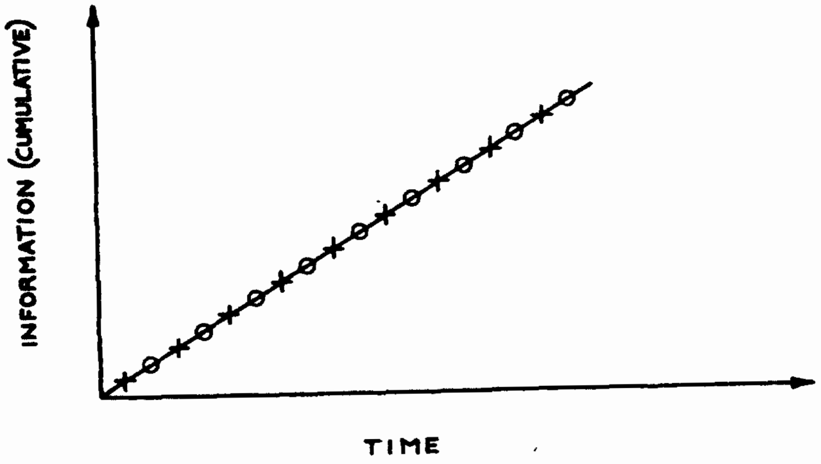

FIGURE 4 INFORMATION ACQUIRED WITH TRANSITION ELIMINATED