ICAS-80-22.3 PROCEDURES TO IMPROVE FLIGHT SAFETY IN WIND SHEAR CONDITIONS *)

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Abstract

Wind shear on take-off and landing may crucially restrict flight safety. After a short description of the meteorological weather phenomena most closely associated with wind shear, reasons are given for the existing hazards to aircraft operations with the use of conventional cockpit instruments. Different methods to compensate for wind shear effects are evaluated (open loop wind shear elimination/total energy display/management of specific energy rate) including today's state of the art as well as an outlook on future instrumentation corresponding to the problem and a comment on ground-based wind shear warning systems.

List of symbols and abbrevations

F	thrust
g	constant of gravitation
G	aircraft weight
H	true altitude
$\dot{H}$	vertical speed
H_E	energy height
$\dot{H}_E$	rate of energy height (=SEP)
m	aircraft mass
u_{Wg}	horizontal wind component
u_{WH}	horizontal wind gradient ($= \partial u_{Wg}/\partial H$)
$\underline{V}$	airspeed vector
$\underline{V}_K$	flight path velocity vector
$\underline{V}_S$	stall speed
$\underline{V}_W$	wind velocity vector
w_{Wg}	vertical wind component
α	angle of attack
β	angle of sideslip
γ	flight-path inclination angle
γ_E	potential flight-path
χ	flight path azimuth
act	actual
req	required
SEP	specific excess power ($=\dot{H}_E$)

I. Introduction

"The probable cause of the accident was that the pilot did not recognize the need to correct a high rate of descent induced by a low level wind shear" - in no less than 25 world wide cases of disastrous aircraft accidents the results of the accident analysis in recent years read like this or very similar. (1) Presumably, a lot more aircraft accidents in the terminal control area (TMA) often referred to pilot error have to be contributed to the influences of shear winds. The term WIND SHEAR characterizes the change in wind speed and/or wind direction along a defined track, here along the flight track of an aircraft. The question arises why the influences of wind changes lead to such a threat to air traffic safety on take-off and landing. (2) How is the pilot able to recognize an existing wind shear when using the cockpit instrumentation, respectively what has to be done to make a wind shear perceptible? And, last but not least, what can be done to fly safely, even in a wind shear environment? These questions and others will be discussed in the following paper. At the beginning, a short description is given of the scenario which has been found to form typical wind shear conditions.

II. Meteorological Scenario

Wind shear can exist under a broad variety of weather conditions. (3) It is not only related to stormy weather, as one might presume, but can also be there on a misty morning in early summer as well as in the bright sunshine of a period of fair weather. The following weather phenomena are in great probability pregnant with wind shear (See Fig. 1):

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a) Thunderstorm activity

It has been well known for a long time that extreme up- and downdraughts may exist in thunderstorms. The strong downbursts in the storm cell generally coincide with intense precipitation, also hail showers. Near the ground the vertical air current changes to a horizontal outflow with increasing distance to the cell. The outer boundary of the horizontal wind shear can extend to a range of up to 20 km and is most often associated with severe turbulences.

b) High-base cumulus or altocumulus

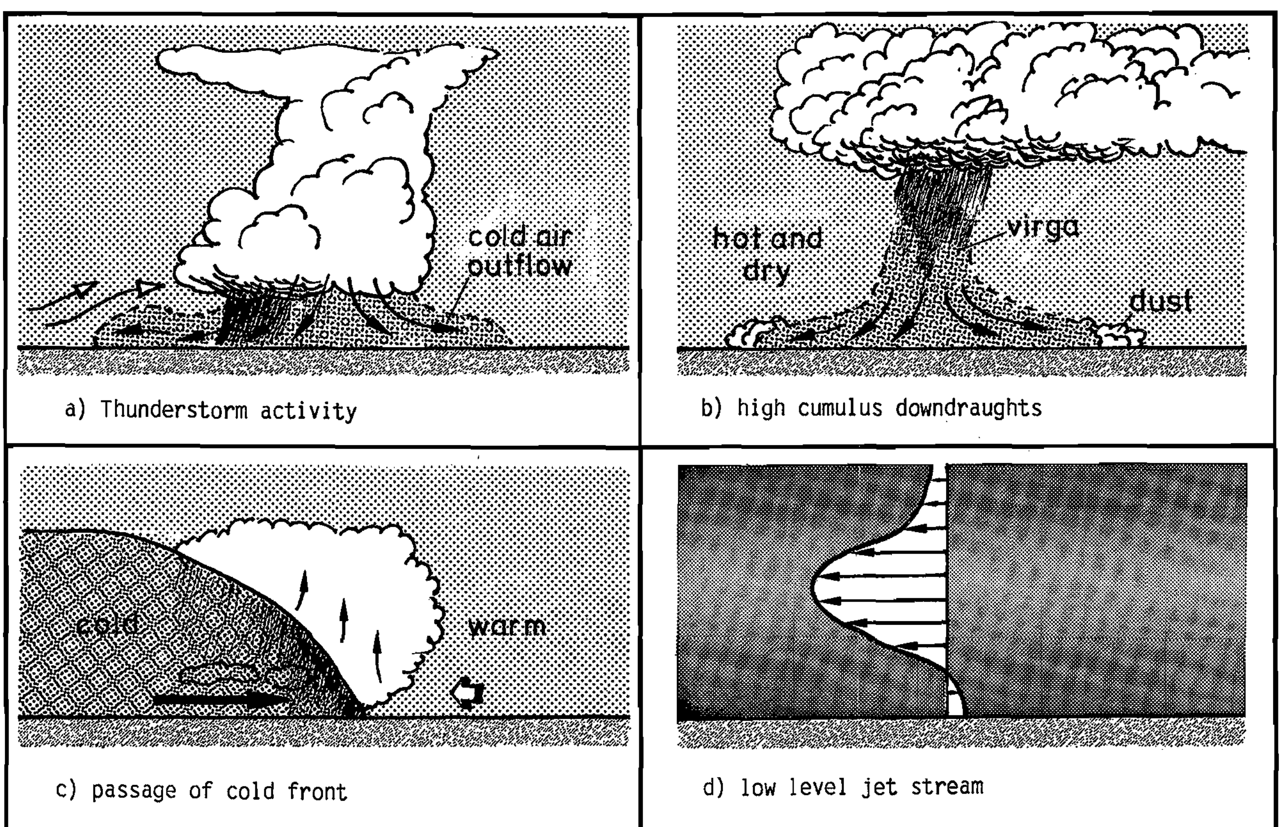
Precipitation falling from high cumulus or altocumulus clouds into hot and dry air in the atmospheric boundary layer may evaporate before reaching the ground (virga). The evaporation of the water drops retracts heat from the surrounding air, thus producing a cold downstream which is turned to a horizontal direction when reaching the ground. The radial outflow is accompanied by strong wind shear. The weather phenomenon is characterized by the evaporating precipitation and a great difference between the air temperature and the dewpoint.

c) Frontal activity

At the passage of fast moving cold or warm fronts considerable wind shear may develop frequently due to changes of wind direction before and behind the frontal line. Wind shear alert can be derived from the frontal speed and the significant temperature jump.

d) Low level jet stream

Even in Central European regions, horizontal jet streams at low altitudes are observed. They move with maximum speeds of up to 40 m/s as stable and narrow flows through otherwise undisturbed (non-turbulent) air masses. At present there are very few ideas about the origins and mechanisms of these wind flows. They are comparable to the well-known jet streams in the troposphere.



a) Thunderstorm activity

b) high cumulus downdraughts

c) passage of cold front

d) low level jet stream

FIG. 1: Meteorological Scenario significant for wind shear conditions.

Similary stable atmospheric conditions are present in horizontally layered air masses that do not mix due to temperature inversions showing wind speeds that are different in magnitude and direction. Most often these temperature inversions are observed in connection with the above mentioned low level jets.

Less influential on landings, but much more significant on take-offs due to limitations imposed by operational requirements may be wind shear which is caused in the atmospheric boundary layer by the influences of surface roughness and obstacles in the vicinity of airports. Terrain may as well have a direct effect on the airflow which may form a permanent wind shear trap to air traffic in certain weather conditions (orographical influence).

III. Effects of wind shear on the aircraft's flight path

The causes and environments of the wind shear phenomenon may be manifold - but without the quick intervention of the pilot or autopilot/autothrottle any wind shear will produce an immediate and potentially dangerous deviation from the trimmed aircraft state of flight. A simplified example of a landing approach with fixed controls (thrust setting/elevator/flaps) shall demonstrate the reaction of the aircraft.

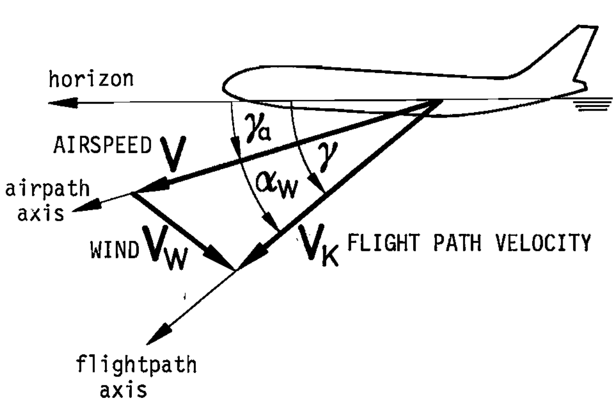


FIG. 2: Velocities and angles in the aircraft's symmetry plane.

Figure 2 shows the geometrical relationship between the different velocity vectors in the aircraft's symmetry plane. The sum of the velocity $\underline{V}$ of the aircraft with respect to the surrounding air (true airspeed) and the velocity $\underline{V}_W$ of the air mass relative to the ground (wind speed) yields the aircraft's flight path velocity $\underline{V}_K$:

$$\underline{V}_K = \underline{V} + \underline{V}_W. \tag{1}$$

Nowadays the majority of landing approaches is performed at a constant airspeed of around 1.3 times the stall speed of the aircraft and at a constant flight path angle given e. g. by a glideslope transmitter when using an Instrument Landing System (ILS). The pilot will take into account constant headwind components or up to a certain limit even tailwind components by accommodating the engine thrust setting adequately.

When the wind changes, the flight path velocity or, much the same, the ground speed has to be adjusted in order to keep the airspeed constant. If this measure does not take place, flight path deviations will occur as demonstrated in Fig. 3 where the corresponding wind shears linearly with height from a constant value to zero within a certain shear layer.

In the case of a headwind shear only a relatively harmless airspeed excursion appears which brings the aircraft above the glide path. But it does not mean a real hazard to flight safety. A go-around will always be feasible in these circumstances.

On the contrary, a tailwind shear produces large deviations from the initial state of flight as the aircraft starts to sink through the shear layer with an increasing flight path angle. Thus the aircraft is self-inducing a more and more intensifying wind shear. When the wind shear takes place at too low an altitude there is not enough time resp. space for the aircraft to regain stationary flight conditions. The result will be a typical "short landing" with the aircraft crashing in the immediate vicinity before the runway threshold.

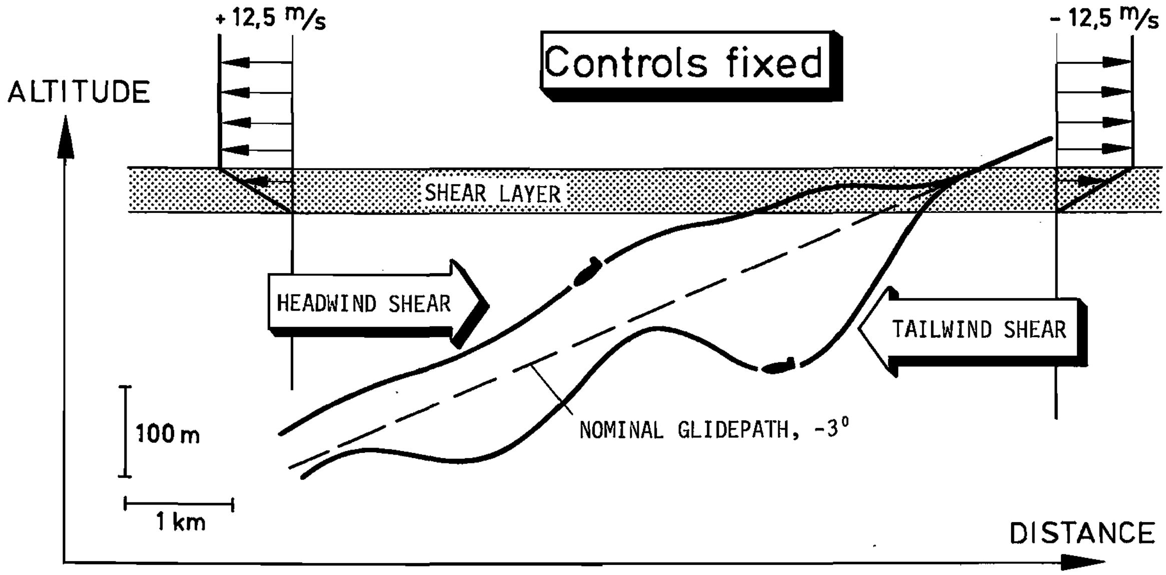


FIG. 3: Landing approaches in headwind resp. tailwind shear, controls fixed.

The accelerating and decelerating forces generated by the dynamic wind changes have a direct effect on the stability of the phugoid mode. Headwind shear increases the frequency of the flight path oscillation, whereas a slight tailwind shear already leads to aperiodically undamped phugoid characteristics.[4] The pilot will be confronted with an unusual change in the dynamic characteristics of the aircraft. Frequently the effect is combined with inexplicable, even contradictory displays on the cockpit instrumentation. The pilot may for instance realize an excursion of the aircraft below the glideslop and a loss in airspeed at the same time both resulting from a tailwind shear, It is impossible to correct the two errors by actuating only the elevator: the attempt to keep the flight path by pulling the stick will bring the aircraft near to stall speed, whereas pushing the stick in order to keep the airspeed will result in even greater and more hazardous glide slope deviations, especially in ground proximity. The latter will also produce an increasing wind shear effect due to the steeper flight path inclination angle.

It should be noted here that several airlines recommend their pilots to keep the flight path in all circumstances when facing a wind shear, even at the cost of flying close to stall speed for some time. In review of the fact that almost all wind shear accidents ended with the aircraft crashing to the ground at reference airspeed (1.3 V_S), this is a first and very suitable procedure to prevent the worst until better methods will have been developed. However, detailed pilot training in flight simulators is necessary in order to train the unnatural behaviour of abandoning the "safe" reference airspeed.

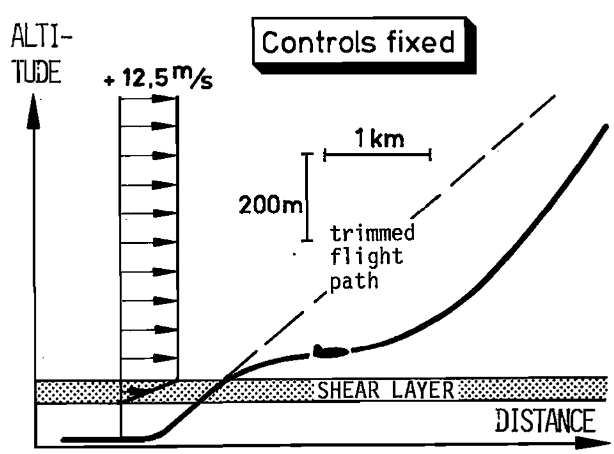


FIG. 4: Take-off flight path in tailwind shear, controls fixed.

Like on landing approaches, a tailwind shear may be dangerous on take-offs, too. As for the engines already set to maximum power during this flight phase, the compensation for the developing drastical deviations in airspeed is attainable only by shifting potential to kinetic energy. This procedure is obviously the more limited the lower the wind shear happens. The hazard is increased by two more facts: first, the influence of the positive flight path angle leads to an additional destabilization of the phugoid mode, and secondly, the take-off climb is performed at essentially steeper flight path angles as on landings, thus intensifying the effective wind shear as already mentioned above. In this situation the pilot has to react utmost correctly and immediately in order to maintain the safety of flight.

In Fig. 4 the take off climb phase through a shear layer (tailwind shear of the same magnitude as in Fig. 3) is illustrated, taking again fixed controls into account.

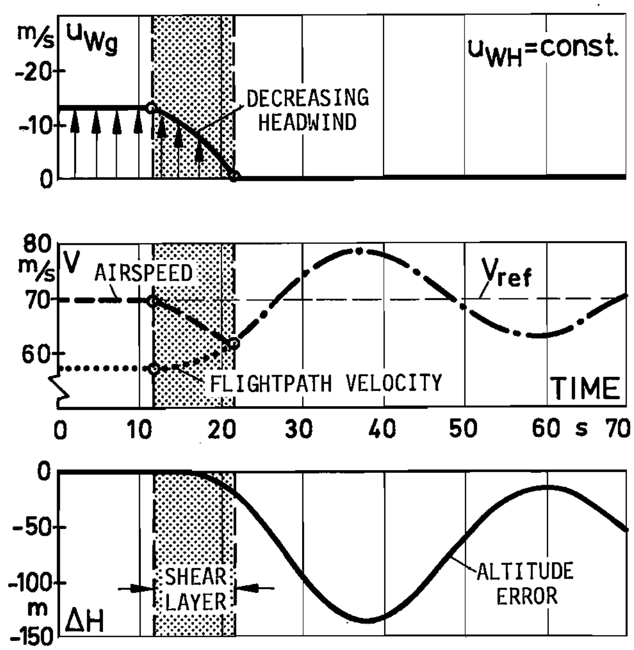


FIG. 5: Effects of tailwind shear on velocities and altitude error.

The flight physical relationship will be discussed with the aid of detailed time histories of different states of flight variables, using once again the example of the landing approach. The knowledge of the stick-fixed process gives the aeronautical engineer implicit means to solve the wind shear problems.

IV. Dynamic aircraft response in wind shear environment

Basic position for the following considerations shall be the same linear tailwind shear as in figure 3. An aircraft, trimmed for a stationary landing approach in steady upper wind conditions, is exposed to the changing wind speed in the shear layer assuming no pilot control activities. The different velocities diverge from their initial values with respect to time as represented in Fig.5. Whereas the velocity of the aircraft's inertia or flight path velocity remains relatively constant, the airspeed shows an immediate response to the diminishing headwind (same as increasing tailwind component). Thus the dynamic pressure and consequently the aerodynamic forces are disturbed.

This yields unbalanced forces on the aircraft which produce an acceleration towards the resulting component by strictly following NEWTON's law. The aircraft will begin to deviate from the original flight path which is reflected in the increasing altitude error ΔH. As the aircraft is going to lose altitude more and more rapidly, the effect of the height dependent wind shear is permanently magnified.

The further events depend on one hand on the stability characteristics of the aircraft and on the other hand on the distinctive parameters of the wind shear that is to say the shear gradients and the magnitude of the shear layer. A statically stable aircraft always tends to keep the airspeed and the angle of attack constant whenever disturbances of the trimmed flight conditions take effect.

From Fig. 5 may be drawn that the airspeed does not decrease to the same extent as the headwind due to the slowly self-adjusting flight path velocity. In more intense or persistent shears the airspeed may even increase again within the shear layer, yet always combined with extreme flight path angles of - 20° to - 30° or steeper.

In a stationary landing approach and constant wind conditions the total energy of the aircraft

$$E_{tot} = \frac{1}{2} m V_K^2 + m g H \qquad (2)$$

or, when related to the aircraft's weight, the energy height

$$H_E = V_K^2/2g + H \qquad (3)$$

decreases steadily as a result of the reducing portion of the potential energy. Observing the rate of the energy height or, more common, the specific excess power (SEP)

$$\dot{H}_E = \frac{1}{mg} \cdot \frac{\partial}{\partial t}(E_{tot})$$

$$= \frac{V_K \dot{V}_K}{g} + \dot{H} \; (= \text{SEP}) \qquad (4)$$

the following facts may be stated in wind shear conditions (Fig. 6):

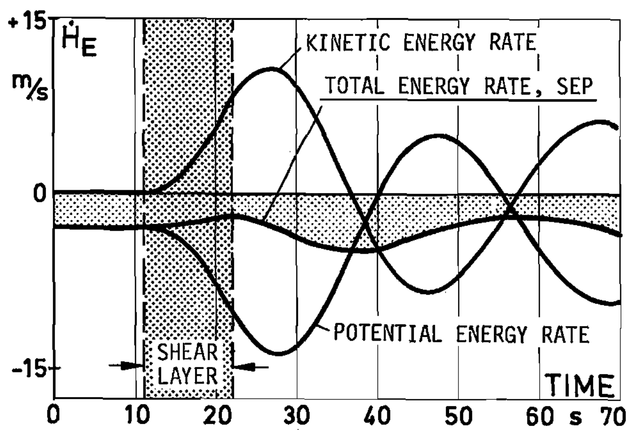


FIG. 6: Total energy rate (SEP) in linear tailwind shear, controls fixed.

The phugoid mode is largely stimulated by the rapid wind change and leads to an oscillatory exchange between the portion of the kinetic and the potential energy rate. Large excursions of airspeed and altitude arise even after the aircraft has left the shear layer (compare Fig. 5). These deviations are not acceptable in any circumstances.

The specific excess power, however, remains nearly constant within the shear layer. Consequently, the wind supplies only very little energy to the aircraft. A wind shear warning system based exclusively on a display of the potential energy or the potential glide path

$$\gamma_E = \dot{H}_E / V_K \qquad (5)$$

can thus deliver no useful evidence of the wind shear hazard as the discussed physical relationship proved.

V. Required measures to compensate for wind shear effects

If in changing winds the airspeed shall be kept constant at any time ($\dot{V} = 0$) (response to turbulence will be discussed later), the flight path velocity has to be changed proportionally to the wind with respect to time:

$$\dot{V}_K \overset{!}{=} \dot{V}_W. \qquad (6)$$

So the aircraft must be accelerated or decelerated with the wind. To avoid at the same time an undesired change in the flight path inclination, the required thrust can be determined [5] as

$$\Delta F \approx G\,(\dot{u}_{Wg}/g + u_{Wg} \cdot \sin\gamma/V + w_{Wg} \cdot \cos\gamma/V). \qquad (7)$$

Note that there are no aircraft specific parameters in this equation except the aircraft weight, and remember that the flight path angle is prescribed by navigational aids and the reference airspeed has almost the same range on most of the heavy aircraft. When the predescribed linear tailwind shear is considered again, we get the curves for the required specific total energy rate ($\dot{H}_E$) shown in Fig. 7. Depicted are the individual portions of the kinetic and potential energy rate as well as the sum of both portions which is a direct measure for the required thrust:

$$F_{req} \sim \dot{H}_{E,req} \tag{8}$$

The required change of the total energy is obtained by adjusting the thrust setting. The specific distribution of the energy portions that is necessary according to Fig. 7 has to be adjusted through the pitch attitude by means of the elevator.

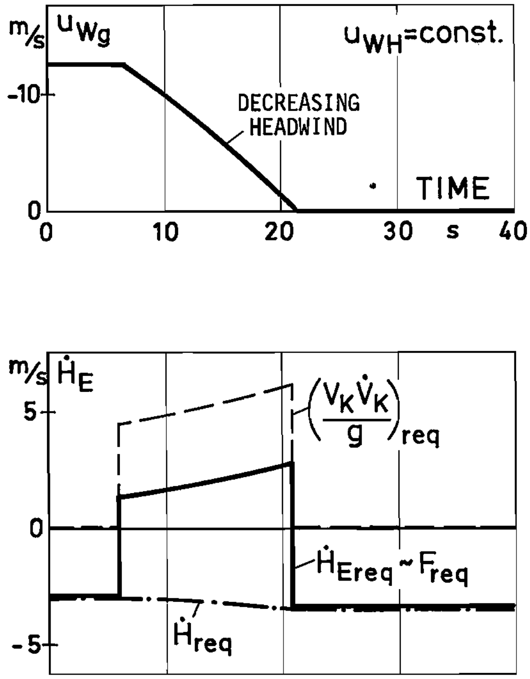


FIG. 7: Required energy rates in linear tailwind shear with constant airspeed and flight path.

Eq. (7) is the key equation for the solution of the wind shear problems. Supposed is would be possible

a) to measure the wind components and their time derivatives at any moment and

b) to adjust the thrust setting without any delay

the reference airspeed and flight path could always be flown as long as the engine performance limits were not violated.

Nevertheless these requirements can be satisfied only in simulation programs. In real aircraft systems we have to deal with the following problems:

a) Using Eq. (1) the components of the wind speed can only be determined if beside the "air data" (true airspeed V, angle of attack α and angle of sideslip β) the inertial values

   flight path velocity V_K
   flight path inclination angle γ
   flight path azimuth χ

   are available. They can be achieved by means of Inertial Navigation Systems (INS), but also by radio navigational aids as e. g. Microwave Landing System (MLS)(6, 7), VOR/DME, DECCA, Doppler-Radar, or the future Global Positioning Satellite System (GPS), to name a few, all of which are predominantly in use only on board modern wide-body aircraft.

b) The wind signal is composed of the low frequency wind shear portion in question here and the higher frequency gusts which are statistically

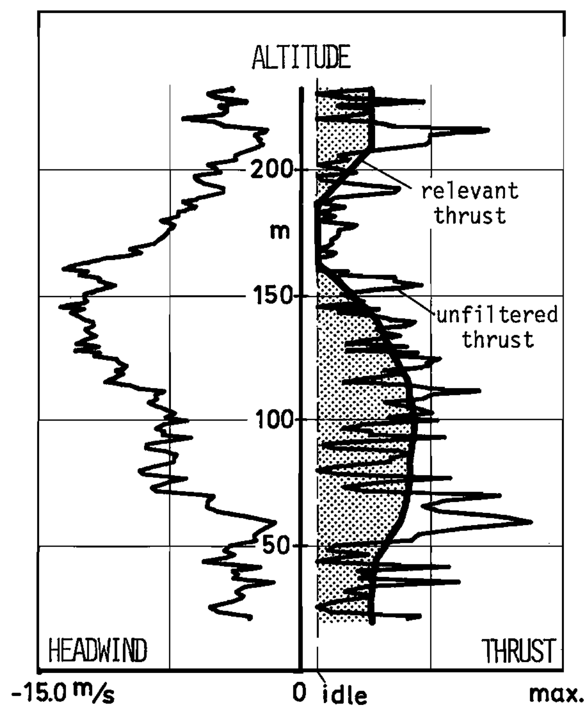


FIG. 8: Wind profile and thrust for a stationary landing approach.

distributed and form no significant disturbance in relation to keeping the flight path or the average reference airspeed (See Fig. 8). The turbulence, however, produces considerable values of the wind variation with time, $\dot{V}_W$. If these signals were fed to the throttle without any filtering process a strong and undesired throttle activity would arise. (8, 9) So the wind shear and the gust signals have to be separated according to their effectiveness on the motions of the aircraft. The problems involved herein are discussed in a succeeding paper. (10)

c) When the effects of wind shear are automatically compensated for using a flight control system, the following characteristics of the control devices have to be considered:

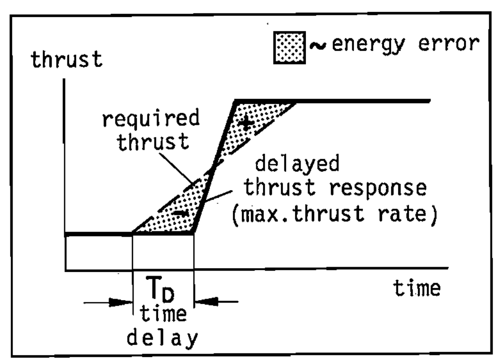
- time delays given by signal filters and jet engine spool-up times;
- limitations in the thrust response;
- integrating behaviour frequently found in thrust setting servos.

d) In addition, in the manual approach mode and on take-off the pilot is an element of the control circuit that has to be considered. The pilot will only intervene if he is informed most adequately about the existing external situation and the related hazards to flight safety. The displayed informations shall enable him to perform manually a take-off or a landing approach in wind shear conditions as well as to evaluate the control activity of an automatically controlled flight. Remember the tragic crash of a DC-10 in Boston in 1973. (11) This accident apparently happened when the pilot had to disengage the autopilot below the decision height of around 200 ft. He was transferring to the manual approach mode at the moment when the wind shear was at its maximum without having a proper guidance in the cockpit instrumentation at his disposal. A crash was forcibly inevitable although avoidable as for the aircraft's performance. Today's cockpit instrumentation displays part of the wind shear effects by the following signals:

- vertical speed
- indicated airspeed
- glide slope deviation
- pitch attitude
- fast-slow-indication.

Just a combination of all these signals in the right way can among others contribute to get over the situation without damage. This is not only a problem of pilot training. More problems arise from the pilot time delay which is attributed to diverse reasons:

- different scanning of the instruments causing time delays between the onset of the wind shear and the recognition of the situation;
- physically conditioned reaction times between instrument reading and the required corrective actions of the pilot;
- time delaying qualities of the instruments.



Definition of allowable time deleay, T_D

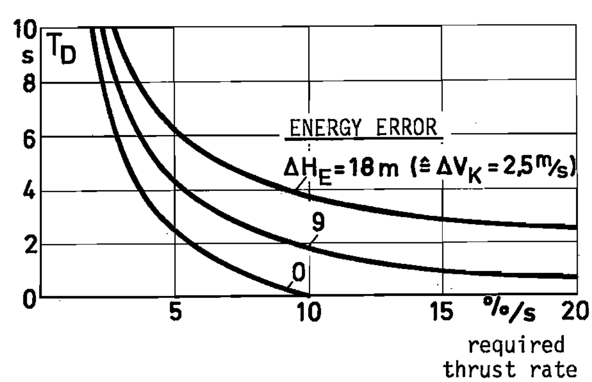


FIG. 9: Relationship between allowable time delay, required thrust rate, and energy error.

The magnitude of the time delays from items c) and d) which can be allowed for is illustrated schematically in Fig. 9. [12] Taking a required thrust rate $\dot{F}_{req}$ as a basis, the allowable time delay T_D is outlined. This time span is defined in such a way that no permanent energy error remains when the pilot adjusts the thrust setting to the required level at maximum thrust rate after a time delay of T_D. The specific time delay of a basic linear jet engine model has been taken into account in the plot. The allowable delay times resp. dead times increase as figured when certain displacements of the thrust response and therefore of the total energy level are admitted. Given for instance a required thrust rate of 5 %/sec tolerates a summarized time delay of 2 to 3 seconds with no permanent energy error. If the pilot and the system delay times add up to about 6 seconds, a stationary error of the energy height of 18 m or a speed error of 2.5 m/sec at a bug speed of 70 m/sec (140 kts) will result.

The wind shear situations known so far required thrust rates which would have allowed for average time delays of 6 to 9 seconds. It should not be ignored, however, that extreme wind shifts may lead to required corrections of the pilot within 2 to 3 seconds in order to avoid dramatic energy excursions.

VI. Wind shear-proof control systems

The safest method to cope with wind shear hazards would be to generally avoid flying in suspicious wind shear environment. This solution appears trivial - yet it is condemned to fail continuously in day to day airline service. This is due to the high density of air traffic which makes take-offs and landings indispensable even in adverse weather conditions, and to the manifold meteorological environment in which wind shear may exist (frequently unknown).

Having in mind the continuously developing automation of take-off and landing procedures, to us the second-best method appears to be the design of wind shear-proof flight control systems.

Today's flight control systems based on the classical concept of separating autopilot and autothrottle can already reduce the hazards of wind shear to a considerable amount. In Fig. 10, curves A, the throttle activities of such an automatic control system of a European wide-body aircraft is given in the above mentioned linear tailwind shear.

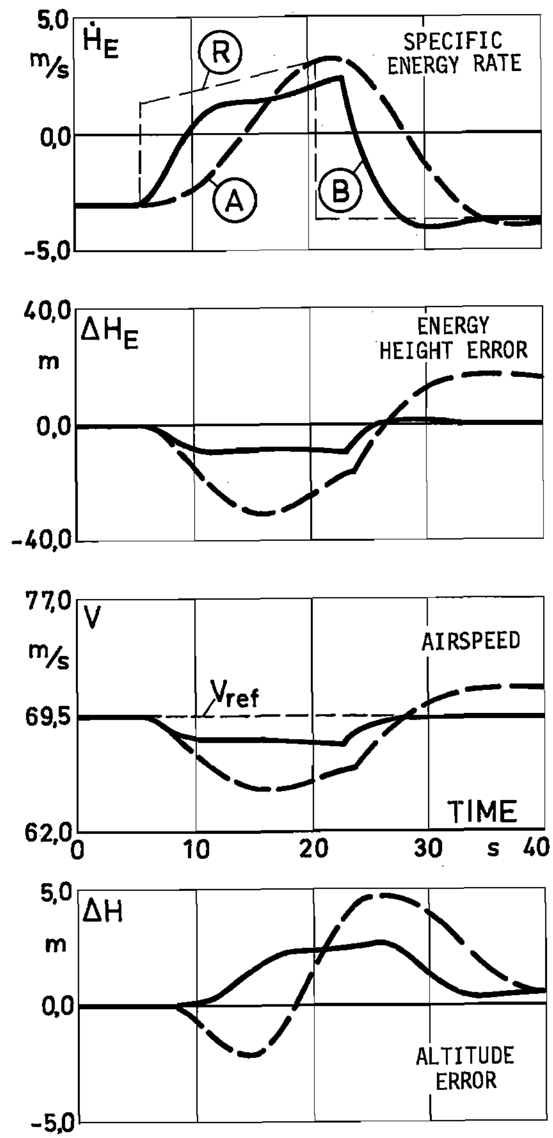


FIG. 10: Effects of flight controls activity in linear tailwind shear.

R: Required specific energy rate
A: Conventional automatic flight controls
B: Specific energy rate mangagement

A comparison with the required values (curve R) reveals that this modern flight guidance and control system executes principally correct compensations.

The excursions in the airspeed and flight path signals originate from the special flight control structure. A high throttle activity as a response to higher frequency gusts is avoided here by means of a complementary filtering technique. This brings the disadvantage of a delayed counteraction against the low frequency wind shear disturbances only after relatively great offsets of airspeed and flight path have established.

The employment of stronger cross-coupled flight control systems, no longer separated into autopilot and autothrottle and operating on the base of an energy management,(8) leads to a further, considerable reduction of the total energy excursions while using conventional sensoring.

By means of an additional direct open-loop compensation the offsets in airspeed and flight path caused by wind shear can be eliminated almost entirely.(13) This method is based on the on-board measurement of the wind vector components and their time derivatives and a corresponding thrust command signal resulting from eq. (7). In this way an ideal thrust signal in wind shear is generated (See Fig. 10, curves R) without changing the original stability of the controlled aircraft. Two weighty disadvantages have to be noted, however: first, apart from the air data V, α and β, the inertial quantities V_K, γ, and x must be available on board the aircraft in order to determine the wind components. Secondly, the above mentioned complementary filtering of the wind signal can no longer be maintained because it would counteract the open-loop activation of the thrust due to its structural composition. This method cannot be employed successfully until the problem of separating the wind shear and gust signals has been solved completely.

A management of the aircraft's energy and energy rate leads despite its simple structure to very small deviations of the airspeed and height. The concept for such a flight control system can be derived from the following idea: Eq. (4) delivers the required amount of the specific excess power, whereras the time integral of this equation (the energy height error ΔH_E) is a measure for the total energy state of the aircraft system. Defining as control error of the specific excess power a quantity

$$\Delta\dot{H}_E = \dot{H}_{E,req} - \dot{H}_{E,act} \tag{9}$$

where in good approximation can be set

$$\dot{H}_{E,req} \approx (V_{ref} + u_{Wg}) \left(\frac{\dot{u}_{Wg}}{g} + \gamma_{ref}\right) \tag{10}$$

yields after linearization and simplification and by use of Eq. (3)

$$\Delta\dot{H}_E \approx -\left(\frac{V\dot{V}}{g} + V \cdot \Delta\gamma + \gamma \cdot \Delta V\right) \tag{11}$$

with $\Delta\gamma = \gamma_{ref} - \gamma_{act}$, $\Delta V = V_{ref} - V_{act}$.

To determine Eq. (11) no expensive measuring of wind components is necessary. It is sufficient to combine existing sensor signals in the right way and to generate a thrust command signal according to Eq. (8). Extending the management of the specific total energy rate in Eq. (11) to its integral (energy height error) part

$$\Delta H_E = \int \Delta\dot{H}_E \, \partial t \tag{12}$$

completes a proportional-integral control as represented in Fig. 11. Curve B in Fig. 10 shows the answer of the specific energy rate and the corresponding state of flight variables when the principle of the total energy rate management is applied. The difference between the introduced approximate method and the ideal control of $\Delta\dot{H}_E$ (Eq. 9) is negligibly small. The unimportant deviations of the airspeed and height are substantially referred to the influences of engine time delays. Nevertheless, filtering of the V- und $\dot{V}$-signals is still necessary in order to prevent the thrust from following each gust.

VII.
Comparison of different wind shear warning displays

Wind shear can be described by characterictic values of the shear gradients, the thickness of the shear layer or the overall shape of the wind changes. On board the aircraft can be determined only the momentary wind gradients. But note that in contrary to the opinion among experts,[14] the gradients alone are no exclusive measure for the hazard. No forecast of the expected total event of the wind shear can be given based only on the knowledge of the momentary wind shear gradients. And there is yet no evidence that an aircraft is more endangered by a high wind gradient, lasting only a short time, than by a small but persistent gradient which is possibly not recognized by the pilot. A better means for evaluating the threat of a wind shear to the aircraft appears to be an energy height error. As far as we could investigate, energy height errors of a magnitude of 15 to 20 meters (resp. kinetic energy errors of around 2.5 m/s) may be tolerated at higher altitudes during take-off and landing. However, the allowable errors have obviously to be narrowed with decreasing height of the aircraft above the ground. To avoid uncomfortable and unnecessary miswarnings, the pilot should not be warned until these limits are violated.

It appears difficult to supply the pilot with another information in view of the great burden of control tasks he has in a landing approach. The question arises whether to install additional instruments or to modify already existing displays. This is more or less a question of philosophy that is certainly going to answer itself when new or modified instruments fulfil the one and only requirement: They must display the proper quantity that will only warn the pilot when it is necessary and that will give him appropriate guidance when he needs it.

Intensive research has been done in the last five years evolving a number of displays, some of which shall be discussed here in the light of the foregoing. Just recently, the instruments reached commercial hardware stage, so no relevant airline experience is known to us at this time.

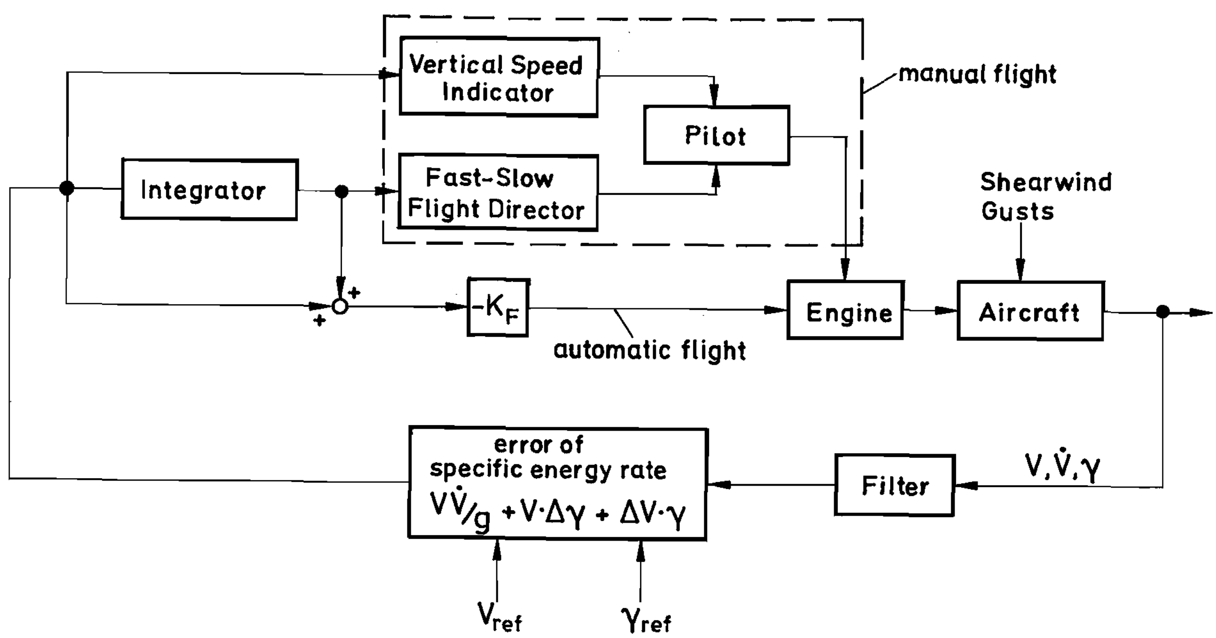


FIG. 11: Windshear-proof control system realizing management of aircraft's specific energy rate.

In the USA a wind shear warning display is distributed (See Fig. 12) which determines the wind shear influence on the base of an indirect measurement of the disturbances (i. e. from the aircraft's response) displaying the required acceleration of the aircraft. This is a small separate instrument to be installed above the existing airspeed indicator.

FIG. 12: Wind shear warning instrument.

As the pilot basically refers to the signals of the flight director and the indicated airspeed while on instrument landing, this kind of installation arrangement is quite favourable. The additional instrument has the job to make a wind shear warning and a decision threshold for a required go-around available. These duties do not include a guidance display for a safe termination of the landing approach due to the fact that no comparison of the required and the actual acceleration can be performed. A correct compensation of the wind changes according to Eq. (6) will not alter the displayed information. On the other hand a great number of the above cited aircraft accidents would certainly have been avoided, if the pilots had performed a balked landing relying on a wind shear warning of this instrument.

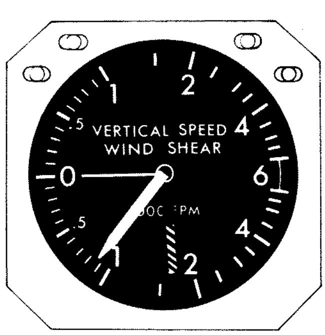


FIG. 13: Vertical speed indicator modified for wind shear guidance.

Along other lines go the efforts of a British manufacturer. Here the already existing Vertical Speed Indicator (VSI) is supplemented with the display of a required energy rate (See Fig. 13) moving an additional pointer besides the conventional vertical speed pointer. No extra space on the cockpit panel is needed. However, an instrument is used which is not so frequently scanned by the pilot. The pilot will have to change his scanning behaviour and look at the VSI more often in order to compensate for the wind shear effects by means of this display. The required energy rate is defined here by approximation (compare Eq. 4) as

$$\dot{H}_{E,S} = \frac{V\dot{V}}{g} + \dot{H} \qquad (13)$$

resembling Eq. (11). The displayed value informs the pilot of the vertical speed $\dot{H}$ that is going to develop in the very next future through the influences of external disturbances. When the pilot uses the information as a guidance, trying to bring both pointers to coincidence by means of the thrust, he will supply the required energy to the aircraft. At any rate he has to adjust the throttle continuously. If persistent differences between the two signals are experienced due to pilot reaction time or engine time delays, permanent energy errors occur. These offsets cannot be compensated by use of the displayed energy rate. We believe that this indicator is a first step into the right direction, but other steps must follow.

Our proposal of improving the display of wind shear guidance is based on the idea of using the signals for the automatical management of the total energy rate as display quantities, too (See Fig. 11). Certain parts of the energy rate resp. the energy error are already displayed on existing instruments:

- Well-known to soaring pilots is the total energy variometer which displays the vertical speed or (switchable) the total energy rate taking into account the kinetic energy portion (according to the approximation eq. 13);

- the fast-slow indication of the flight director is driven by the airspeed error ΔV which only corresponds to the kinetic energy error ΔV_K when no wind change is present.

These displays should be completed as follows:

a) The VSI should be supplemented with a second pointer similar to the British instrument but displaying the total energy rate error in accordance with Eq. (11) (proportional part);

b) the fast-slow indicator of the flight director should be driven by the full total energy error in accordance with Eq. (12) (integral part).

This concept carries a number of advantages:

- No extra panel space is needed because of the use of already existing instruments;
- the flight director is one of the most important instruments in flight. It can be supposed that the pilot uses the fast-slow indication more often when he is aware of finding the energy error there. Arranged directly in front of the pilot, this display can also be used as a wind shear warning display, as the energy error is somewhat a measure for the wind shear hazard;
- when the pilot is conscious of the danger he will scan the VSI-display more frequently and hence show quicker response in adjusting the thrust;
- the pilot has a proper guidance on the improved VSI, but deviations between the two pointers (resulting e.g. from delay times or dead times) may be allowed for because the pilot is informed about the existing energy error as well (fast-slow-indication).

The improved instruments may help the pilot in his day-to-day routines as well as in a wind shear situation.

VIII. Summary and outlook

Wind shears are one of the main hazards to aviation in take-off and landing phases. Due to the manifold meteorological origins they cannot be avoided intrinsically. Different procedures to solve the wind shear problems have been introduced:

- design of wind shear-proof flight controls (open-loop-compensation/total energy rate management) for the automatical flight;
- improvement of wind shear warning and guidance display (modification of existing displays/new proposal of a display of the errors of the total energy and total energy rate) for manual flight.

All these methods have in common the problem of separating gusts and wind shear signals which has to be solved indispensably to guarantee a low thrust activity. Suitable results become apparent here with the use of digital filtering.

A final comment on the wind shear warnings related to ground-based remote wind measurements is to remember the complex signals of the required thrust the pilot has to follow continuously in order to keep the airspeed and flight path constant, allowing for time delays of no more than 3 to 10 seconds. On the other side imagine the information series

wind measurement → evaluating meteorologist or computer → air traffic controler → pilot.

In our opinion the ground-based wind shear warning can be no more then a qualitative warning to the pilot that a wind shear may exist. The pilot cannot be sure that the (maybe micrometeorological) event measured some time ago is still existing. On the other hand he gets no proper guidance of how to adjust the thrust level by the knowledge of e. g. two wind speeds at two altitudes. The conclusion can only be that actions should be taken just where the hazards are threatening - on the aircraft.

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