Sources of Low-Level Wind Shear around Airports

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Introduction

THE subject of this paper concerns the sources of low-level wind shear at and about airports. Wind shear is widely recognized as being a significant aircraft operating hazard during takeoff and landing.[1,2] In fact, the Commission on Aeronautical Meteorology (CAeM) recognized this hazard and recommended at the Eighth Air Navigation Conference held in Montreal, Canada that there be an operational requirement for low-level wind shear and turbulence information to be provided to aircraft at the commencement of the final approach and prior to takeoff.[3] The CAeM further states that this information should indicate variations in wind direction and speed along the last 1000 m of the glide path or along the first 1000 m of the climb path.

As an airplane ascends or descends through the atmospheric boundary layer (approximately the first kilometer of the atmosphere), changes in wind speed will be experienced along the flight path that will result in an increase or decrease in aerodynamic lift depending on whether or not the shear corresponds to an increase or decrease of wind speed along the flight path.[4,5] The wind change or shear produces a near-instantaneous change in the lift to which the aircraft and pilot respond in a finite time. Accordingly, when wind shear is encountered in the boundary layer, the airplane will respond by accelerating away from the flight path. The net effect of the wind shear with pilot response could result in long or short landings. Other, more subtle examples of the effect of wind shear can be cited. For example, Etkin[6] points out that wind

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shear can induce pitch, roll, and yaw moments during takeoff or landing. This point is discussed in greater detail subsequently.

From an aircraft operations point of view, it is extremely important to keep in mind that wind shear does exist over and about runways. A broad synoptic scale view of air flow may often imply benign low-level wind-shear conditions for aircraft operations, when in actual fact local conditions may result in severe wind shears. If local wind shear conditions were to result in an aircraft accident in a seemingly safe wind shear condition on the synoptic scale, then wind shear might be overlooked as the source of the accident. Thus, potential sources of local wind shear at airports should be recognized.

Many of the sources of low-level wind shear are common to the majority of airports, while others are unique to a particular airport. The uniqueness of the shear conditions can result from the distribution of buildings and natural obstructions at and around the airport, the distribution of terrain roughness, land/water interfaces, etc.

In this paper we discuss many of these sources of wind shear from an aircraft hazard point of view. Our discussion is primarily concerned with the mean flow or steady-state wind shear conditions, i.e., the time averaged (2-min averaged, for example) wind field. However, we occasionally refer to shear resulting from atmospheric turbulence.

Wind Shear Over Homogeneous Terrain

We now review wind shear conditions over flat terrain with near-homogeneous surface properties (roughness, specific heat, etc.). The discussion is primarily based on models of the horizontally homogeneous boundary layer derived from meteorological tower data, aircraft data, and theory. The models are reasonably accurate for flat terrain; however, care should be exercised when applying the models to a given situation, because certain local conditions could exist at the site of the application that would preclude their validity (sea breezes, obstacles, etc.). Nevertheless, many airports are characterized by sufficiently flat, horizontally homogeneous terrain to justify application of these models. Reviews of low-level wind shear over flat terrain from an aeronautical design and operations point of view have been given by Luers[7] and Fichtl.[5,8] In addition, Luers and Reeves[9] calculated the effects of low-level wind shear on aircraft landing for a variety of aircraft configurations with, however, no pilot feedback.

Overview of Flat-Terrain Shear Flow

From a descriptive point of view, the atmospheric boundary layer (approximately the first kilometer of the atmosphere) in other than near-calm conditions can be divided into a constant mean wind-direction layer and wind-turning layer. The constant mean wind-direction layer occurs in approximately the first 150 m.[10] The exact height of the constant mean wind-direction layer depends on surface roughness, solar heating of the ground, latitude, etc. The turning layer occurs above the 150-m level and is characterized by a marked turning of the steady-state wind vector as altitude increases, so that in the northern hemisphere, looking toward the earth, the wind vector normally turns clockwise as height increases. In certain extraordinary cases associated with sufficiently large synoptic scale horizontal temperature gradients (usually with cold fronts), the direction of rotation can be counterclockwise. This turning is a result of the interation of horizontal pressure-gradient forces, Coriolis forces, and vertical gradients of vertical transport of horizontal momentum by atmospheric turbulence.[11,12] Typically in mid latitudes the turning angle between the surface wind vector (at the 10-m level, for example) and the wind at the 1-km level is approximately 20-50. Departures of up to ±180° from this nominal turning angle can occur. The turning of the wind vector as described here is believed to be the source of wind shear which resulted in aircraft landing difficulties and aircraft accidents as reported recently by Kraus.[2]

Constant Wind-Direction Layer

Let us first examine the constant mean wind-direction layer in more detail. The wind shear in this layer as experienced by an aircraft during takeoff or landing is due to vertical variations in wind speed. Wind shear results from the steady-state wind speed being zero at the ground.

Figure 1 is a schematic plot of wind profiles for various stability categories. The strongest wind shears occur near the ground. The three characteristic wind profiles that occur are the neutral, unstable, and stable profiles. The neutral case corresponds to relatively high wind speed at the 10-m level (wind speed ≥ 10 m/sec), such that mechanical production of turbulent kinetic energy is in excess of buoyant production. The neutral wind profile is characterized by a logarithmic distribution of wind speed with height z and has been verified numerous times for many sites[13,14]; i.e., $u=u_* \ln(z/z_0)/k$, where $u_*=(\tau/\rho)^{1/2}$ is the friction velocity, z_0 is the empirically determined surface roughness, k is Von Karman's constant and τ is surface shear stress.

The unstable wind profile is associated with strong solar heating of the ground and is thus associated with buoyant production of turbulent kinetic energy in excess of mechanical production. The air adjacent to the ground is heated by conduction and results in convective mixing of the boundary layer. This mixing, in turn, results in a uniform vertical distribution of steady-state wind speed over the bulk of the constant wind-direction layer, except in the layer immediately adjacent to the ground, as can be seen in Fig. 1. In this particular case, the unstable wind profile is benign from an accident point of view. However, the turbulence levels associated with this profile can be rather strong, resulting in a bumpy ride typical of hot-afternoon flying conditions.

The stable wind profile is asociated with nighttime conditions when thermal energy is transferred to the ground from the air by conduction and, in turn, radiated to space or to clouds. This boundary layer can lead to rather hazardous steady-state wind-shear conditions from an aircraft point of view because in this boundary layer the associated negative buoyant forces tend to reduce the turbulence intensity levels. The reduction of the turbulence levels results in decoupling of

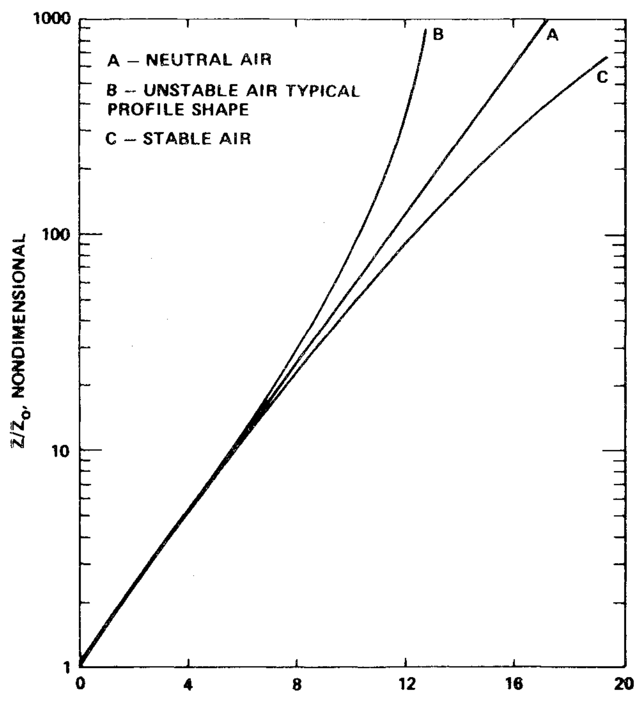

Fig. 1 Wind profiles for various stability conditions over horizontally homogeneous terrain. u_* denotes the surface friction velocity and z_0 denotes surface roughness.

layers,* which, in turn, results in the layers "slipping relative to each other, thus resulting in larger mean flow wind-shear conditions than would occur in the unstable and neutral boundary layers with all other things being equal (see Fig. 1). Furthermore, if the negative buoyancy forces are sufficiently strong, turbulence could cease altogether in certain layers, resulting in rather complicated and perhaps dangerous wind profiles.

Wind-Turning Layer

Let us now turn our attention toward the turning layer. In view of the multitude of possible combinations of mean flow pressure gradient, surface heating, and surface roughness that are available, a virtually infinite variety of wind profile shapes are possible for the flow in the turning layer. As noted earlier, this layer is characterized by significant turning of the wind vector.

A number of theories are available that are able to predict the behavior of the profile for a number of restrictive cases. For example, in the neutral barotropic boundary layer, which is the simplest model of the atmospheric boundary layer, Blackadar and Tennekes[15] provide a theory that can be used to calculate total turning of the neutral layer wind vector. This theory predicts typical turning angles on the order of 20-30°. At this time, the unstable boundary layer is in a state of controversy because two competing theories are available. One theory consists of a straightforward extension of the Blackadar and Tennekes model,[15] and experimental data that tend to confirm this theory have been provided by Clarke.[16] Another theory due to Deardorff[17] rejects the fundamental hypotheses upon which the extension of Blackadar and Tennekes model for the unstable case are based. We will not dwell on this point except to say that both theories appear to be consistent insofar as both theories predict smaller total turning angles than those found in the neutral boundary layer, all other things being equal. The smaller turning angles are on the order of 10-25°.

The stable turning layer is the least understood boundary layer because of the tendency for decoupling of the layers due to diminished turbulence intensity levels. An attempt has been made by Csanady[18] to model this layer; however, his theory as well as others are merely speculative due to the sparsity of data and the large scatter that exists in the presently available data. In general, the net turning angles in the stable boundary layer tend to be larger (25-50°) than those found in the neutral and unstable boundary layers. This is an additional reason for considering the nighttime stable boundary layer potentially the more hazardous boundary layer to aviation. Nightime stable decoupling is responsible for the generation of the "low-level jet stream." These nocturnal jets can produce significantly large values of low-level wind shear. For example, vertical shear of the horizontal wind in excess of 8 m/sec per 30 m in the 100- to 150-m layer, and greater than 12 m/sec per 30 m in the 10- to 25-m layer have been observed at the Cedar Hill, Texas, meteorological tower site (tower height is approximately 500 m). Total shears from approximately the 470-m level to the surface have exceeded 30 m/sec.[19]

The wind shear in the turning layer can be accentuated by the presence of strong horizontal temperature gradients. In this case, the atmospheric boundary layer is a baroclinic one, so that in addition to the wind shears which result from the frictional retardation of the flow by the ground, a background wind shear can also exit in the form of a geostrophic wind shear or rather a thermal wind. The thermal wind is directed normal to the horizontal mean flow temperature gradient and blows horizontally such that when one stands with his back to the thermal wind, the warm air is on the right. If the wind vector at the top of the boundary layer and the thermal wind vector are parallel, then additional contributions to wind shear in the atmospheric boundary layer can occur in the form of "speed shears" with very little enhancement of wind vector turning along the vertical. If, on the other hand, the wind vector at the top of the boundary layer and thermal wind vector are not parallel, then additional contributions to wind shear in the atmospheric boundary layer can occur in the form of both "speed and direction shears," thus resulting in possible significant enhancement of wind vector turning along the vertical due to thermal wind effects. Depending on the magnitude and orientation of the thermal wind relative to the wind at the top of the boundary layer, the angle between the surface wind (10 m, for example) and the top of the boundary layer can greatly exceed the corresponding barotropic turning angles by a factor as great as ±4, so that counterclockwise turning of the wind vector, looking toward the earth, can occur. Cold and warm fronts are characterized by relatively strong horizontal temperature gradients, and it is well known to pilots that significant "speed and direction shears" occur in association with fronts. This is a direct result of the baroclinicity of the atmospheric boundary layer as discussed above. A recent artical by Sowa[20] gives an excellent account of low-level wind shear and fronts relative to aircraft operations.

*Note that in the unstable case with high turbulence intensity levels, the mean flow momentum is relatively uniform because of the strong turbulent coupling between the layers.

Nonhomogeneous Shear Flows

In the previous sections, we discussed shear flows over homogenous terrain. However, the airport environment does not always satisfy the necessary conditions of reasonably homogeneous terrain. In this section we shall indicate some of the characteristics of nonhomogeneous flowfields. The intent here is not to give an exhaustive treatment of the subject, but rather to point out some effects that surface roughness discontinuities can produce. A recent paper by Logan[21] gives a review of the subject and also a new approach to the problem of computing flowfields associated with surface roughness discontinuities. In addition, the reader is referred to Refs. 22-29 for details on the subject.

Because of the explosive economic growth that occurs around airports, most of the major airports and many of the minor ones are surrounded by highly urbanized terrain. The resulting situation is one in which the flow over the surrounding terrain is characterized by roughness lengths (z_0) on the order of 1-2 m, and the flow over the airport is characterized by relatively smooth terrain with roughness lengths on the order of 0.01 to 0.1 m. Accordingly, as the air blows from the urban area to the airport, the flowfield must undergo modification such that the flow over the airport is consistent with the associated surface roughness conditions. The consequence of this modification is the formation of an internal boundary layer as indicated in Fig. 2. The upper boundary of this internal boundary layer grows as $x^{0.8}$, where x is the distance from the surface roughness discontinuity. The flow

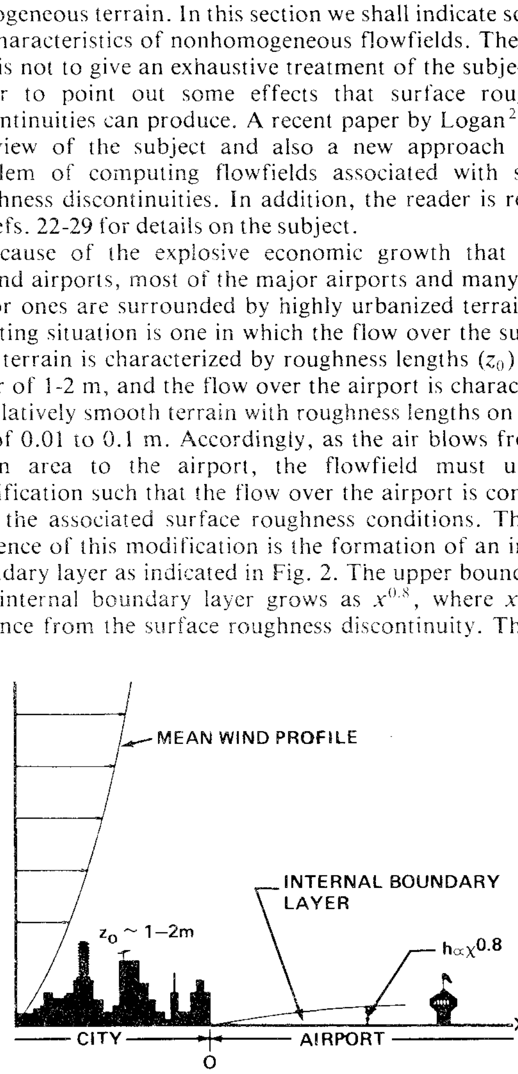

Fig. 2 Schematic diagram of the internal boundary layer over an airport resulting from air moving from rough to smooth terrain.

in the internal boundary layer is characterized by the relatively small roughness lengths associated with airport environment, whereas the flow above the internal boundary layer is characterized by the surface roughness length associated with the surrounding urban area. Since the roughness over the airport is generally less than over the city, the air near the ground accelerates as it blows from the city to the airport. Thus, an airplane on takeoff first encounters the internal boundary layer and then encounters a sudden, or nearly so, increase in vertical wind shear; the reverse of this condition occurs for the landing case. In addition to vertical wind shear, the aircraft also encounters horizontal variation (horizontal wind shear) in the steady-state wind below the interface due to the acceleration of the air downstream of the surface roughness discontinuity. Although internal boundary layers have been verified experimentally, determination as to whether these effects are important to aircraft flight requires further study. Nevertheless, these effects and ones of a similar nature should be kept in mind during aircraft accident investigations.

The reverse of the above situation can occur if the airport is rougher than the surrounding terrain. An example of this situation is that of a body of water in place of the urban area indicated in Fig. 2. In this case vertical wind shear increases below the interface.

The magnitude of the enhancement of the wind as it blows from the city to the airport can be as high as 50-100% depending on the distance of the point of concern from the surface roughness discontinuity. This could have important implications on the representativeness of runway wind speed measurements.Depending on the location of the runway anemometer from the surface roughness discontinuity, the runway wind speed could be under- or overestimated. Thus, care in site selection for meteorological instruments at airports should be exercised.

Thunderstorms

The violence of the thunderstorm and the threat it poses to aviation is well-known. In addition to high turbulence intensity levels, the thunderstorm is a source of low-level wind shear. Figure 3 is a schematic of the flow associated with the cold-air outlfow in advance of the thunderstorm. Verification of these flow patterns is well-documented in Refs. 30-33. The flow near the ground in the cold-air region behind the windshift line is characterized by a horizontally nonhomogeneous, high-speed boundary layer following the thunderstorm. The nonhomogeneous character is not the result of horizontal variation in surface properties, as discussed earlier, but rather is the result of the fact that ahead of the windshift line of the warm area the flow is different from that in cold air.

At the leading edge of the thunderstorm, the wind speed increases rapidly with distance. Following the initial cold-air surge, a secondary surge tends to occur due to the presence of a secondary vortex in the coldest air (see Fig. 3). Studies by Sinclair et al.[34] show that sufficiently near the ground (altitude $< \approx 100$ m) after the initial surge cold air, a logarithmic wind profile tends to be established, so that the comments in the previous sections relative to the logarithmic wind profile are applicable after the initial surge.

Theoretical studies have been conducted by Mitchel[32] that show a number of additional features of thunderstorm cold-air outflow. First, his numercial studies show that the strong initial wind surge wall, called the gust front, is characterized by extreme horizontal shear of the wind speed on the order of 10 (m/sec)/km. Given the typical gust front propagation speed of 20 m/sec used in his studies, this wind shear produced a rapid increase of wind speed from nearly zero to 20 m/sec in 3 to 4 min at a fixed point as the front passed. After the gust front has passed, his computer simulation shows that surface friction causes a rapid decrease of surface-wind speeds because the horizontal pressure field behind the front is flat. Since the surface winds behind the front were significantly retarded, a core of maximum winds was consistently observed in the various computer simulations between the downdraft at the thunderstorm core and the front at approximately 700 m above the surface. Thus, between the surface and the level of this maximum wind core, strong vertical shears of the horizontal wind approximately equal to 20 (m/sec)/km were consistently observed, suggesting that large shears can occur along the flight path of an airplane as a result of a combination of both horizontal and vertical shear of the horizontal wind. Experimental studies by Goff[33] show that significant departures from the "ideal" storm surge can take place, so that care should be exercised when applying ideal models to aviation problems.

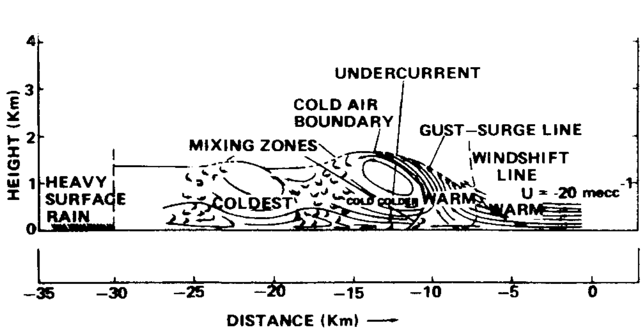

Fig. 3 Schmatic diagram of the structure of the cold-air outflow from thunderstorm.[30,31]

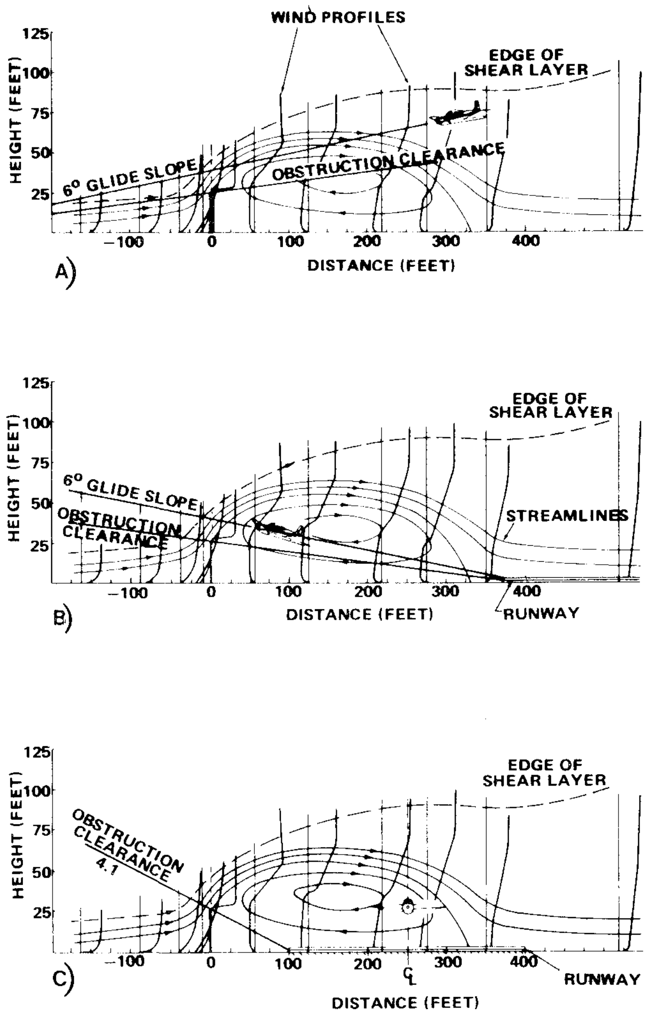

Fig. 4 a) Flow over a fence and the landing path of a STOL vehicle through the associated flow disturbance. b) Flow over a fence and the takeoff flight path of a STOL vehicle through the associated flow disturbance. c) Flow over a fence for the crosswind case.

Potential Area of Flighter Disturbances Due to Ground-Wind Surface Obstructions

This section of the paper reviews the areas where potential flight hazards may be encountered due to wind shear created by obstructions to ground winds. The discussion is based primarily on aerodynamics data obtained in wind tunnels for flow around bluff-body models. The mean upstream wind profiles over uniform homogeneous terrain described earlier can be well-simulated with proper tunnel design, and thus good modeling of mean wind flow over bluff bodies can be expected. In fact, the few reported full-scale tests conducted in the natural atmosphere indicate that the mean flowfields extrapolated from wind-tunnel models are reasonably correct.[3] These wind-tunnel data, on the other hand, may not accurately account for the large eddies and gusts inherent to the atmospheric boundary layer.

Frost[35] reviewed the literature pertaining to turbulent flowfields over bluff bodies typical of individual buildings. Other surverys relevent to wind field around man-made surface structures are given in Refs. 36-39.

Two-Dimensional Flowfields

Most data for bluff-body flow are for two-dimensional geometries, such as infinitely long fences and rearward- and forward-facing steps. Consider first a fence that might be used to simulate a long, narrow structure. Figure 4 shows velocity profiles and streamlines for fence flow measured by Good and Joubert.[40] Superimposed on the flowfield, assuming direct scaling, are the FAA recommended obstruction clearance surfaces for a STOL port and a typical STOL 6° glide slope. the recirculating region extends approximately 16 fence heights, h, downstream and 2 fence heights vertically. Figure 4a illustrates that an aircraft approaching into the wind passes through the top of the recirculating zone, experiencing initially a downdraft and then a strong updraft directly over the obstruction.

In addition to the change in vertical direction of the wind, the aircraft is exposed to a strong shear gradient throughout the region approximately 12 fence heights downstream to 1 fence height upstream. Etkin[6] showed that a linear wind profile causes an overshoot of the landing site with fixed controls and constant relative velocity approach. Leurs and Reeves,[9] on the other hand, showed that a logarithmic wind profile produces an undershoot for the same constant velocity approach. This effect has been confirmed by the present authors.[41] Obviously, the undershoot is more hazardous since it tends to draw the aircraft toward the fence; however, the updraft due to the vertical flow over the fence tends to counteract this undershoot. Caution is required in drawing conclusions from these data because they represent wind-tunnel measurements with a well-defined freestream velocity, whereas the atmospheric flow must return to a logarithmic profile well above the disturbance.

Figure 4b illustrates takeoff over a fence. A potentially serious situation is encountered very near the obstruction at $x/h = 2$, encounters a reversal of flow and experiences a high head wind produced by the acceleration of the wind. Mathematical models of the atmospheric fluid mechanics are needed to assess the quantitative influence of the flowfield on the flight path.

In this recirculating zone behind the fence, it is established that a shear layer emanates from the edge of the fence and spreads out downstream. The velocity field in the shear layer has an error function distribution.[42] No analytical expressions describing the recirculating flow beneath the shear layer are presently available; however, these models, should be available in the near future.

Figure 4c shows crosswind landing or takeoff conditions. The FAA recommended that a 4:1 transitional surface is indicated. One observes that at given heights, strong rolling moments are possible on the aircraft due to the wind vector having opposite direction along the wing. Until a mathematical model is developed, however, an estimate of the magnitude of this moment is not possible.

The wind field data used in the above discussion are based on wind-tunnel studies over two-dimensional fences. Excluding the fact that these are not exact representatives of the atmosphere, which is of a higher turbulent eddy scale and very gusty, the fence geometry is also not typical of the types of ob-

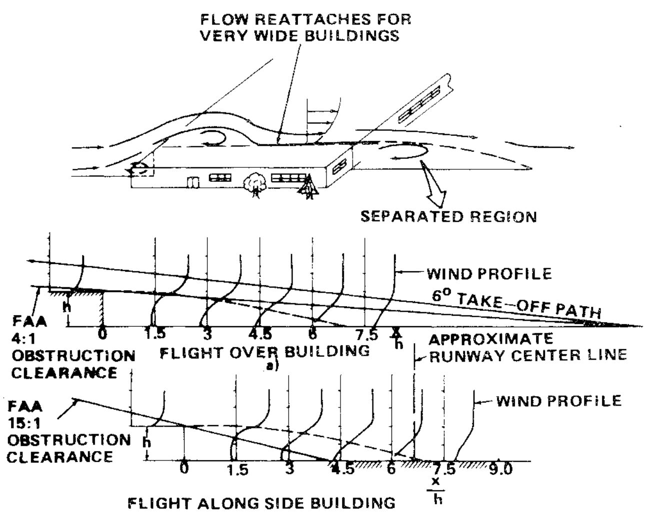

Fig. 5 Flow over a relatively wide, low building and the relationship between the wind profiles and the runway orientation relative to the flow for (a) the headwind case, and (b) the crosswind case.

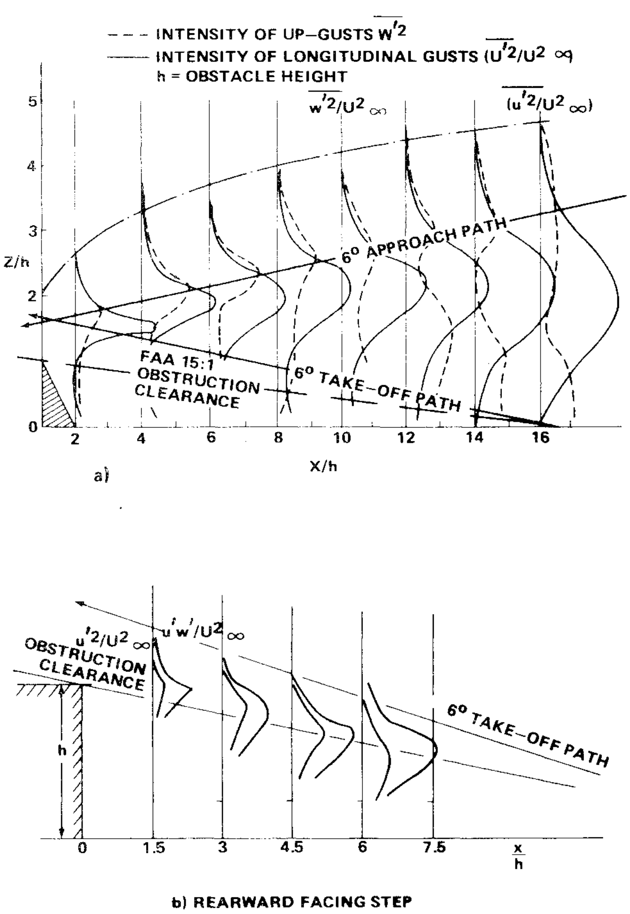

Fig. 6 a) Turbulence intensity as a function of position downstream of a fence and the takeoff and landing flight paths of a STOL vehicle through the turbulence intensity pattern. b) Turbulence intensity as a function of position downstream of a rearward-facing step and the takeoff flight path of an aeronautical system.

struction geometries encountered around airports. The data for this geometry were used, however, since they are the most complete in the literature and are indicative of flow disturbance around long, narrow buildings.

Considerable wind-tunnel data are also available for flow over a rearward-facing step, which tends to simulate a long, very wide building where flow that separates at the leading edge reattaches on the roof. Figure 5 shows data from Tani et al.[43] with the 6° takeoff path and obstruction clearance planes indicated; again, direct scaling is assumed. Rearward-facing step geometries have recirculating regions typically half of those for fences, and thus, as is apparent from Fig. 5a, the recommended 15:1 FAA obstruction clearance surface appears appropriate for buildings characterized by rearward-facing steps. Notice that during takeoff the plane experiences no sudden changes in flow direction as with the fence and only a somewhat stronger shear flow than that which would occur over uniform terrain with the building absent. Landing over long, very wide buildings would require passing through the separated flow region near the front of the building similar to that of the fence. Hence, during landing the effects are expected to be the same as in Fig. 4a.

Figure 5b illustrates the flowfield for landing parallel to the building. The center line of the runway is positioned according to the 4:1 transitional surface requirement and to the assumption of a 25-ft building with a 3000-ft wide runway safety area. Figure 5b indicates that crosswind landings take place in a region where the separated flow reattaches to the ground. This is called the reattachment zone. Although the physics of the reattaching flow are not yet well-understood,[44] some semiempirical predictive analyses are available from which an estimate of its effects on aircraft flight dynamics can be made.

In addition to the strongly varying mean flowfields encountered during takeoff and landing over bluff bodies, regions of very intense turbulence are also present. Wind-tunnel measurements of turbulence behind a model fence[42] and behind a rearward facing step[43] are shown in Fig. 6. It is apparent that associated with the particularly hazardous mean flowfield near the roof is also a region of intense turbulence. As pointed out earlier, the takeoff flight path over a rearward-facing step passes over the mean flow recirculating zone; however, Fig. 6 suggests that the turbulent free shear layer extends further downstream than the mean flow disturbance and the aircraft must pass through it during takeoff. The extent to which the turbulence persists downstream is not well-established, since measurements of the rate of decay of the turbulence behind bluff bodies with distance downstream are scarce.

Hunt[36] gives mathematical evidence that turbulence intensity induced by individual block buildings decay more slowly than the velocity deficit in the wake, $\bar{u}$, where velocity deficit decays as $\bar{u} \propto h/x$ for long, low buildings and as $\bar{u} \propto (h/x)^{3/2}$ for cube-like buildings. Hence, it is anticipated that the turbulence shown in Fig. 6 will persist into the flight path. Halitsky[45] reports that the aerodynamically generated turbulence intensity as determined by excess over that of the atmospheric background flow appears to vary inversely with background flow turbulence.

For the shear immediately behind the separation point, Plate[46] and Mueller et al.[47] report that the turbulence shear

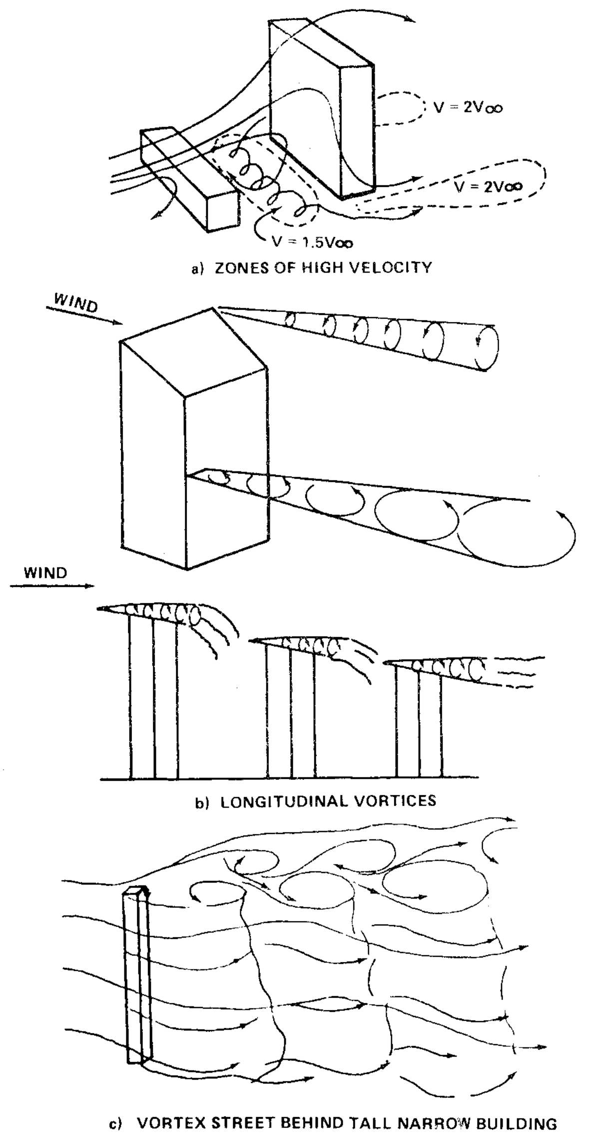

Fig. 7 Flow patterns associated with three-dimensional bluff body.

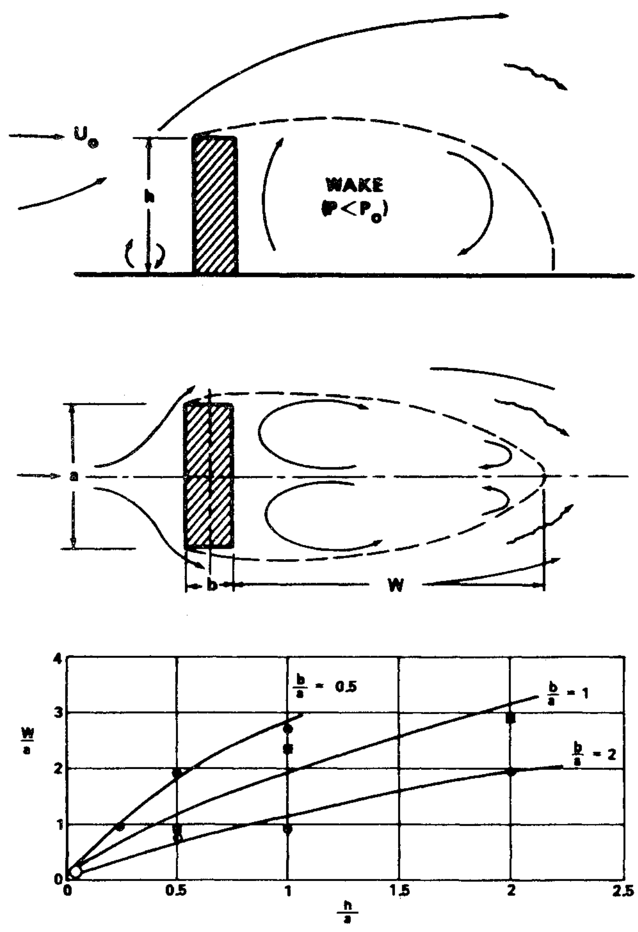

Fig. 8 Wake geometries behind a three-dimensional bluff body.[48]

stress distribution $u'w'/(u'w')_{max}$ is Gaussian in z/x. The introduction of this turbulence distribution into predictive models of aircraft motion in a turbulent atmosphere is now under investigation.

Three-Dimensional Flowfields

The two-dimensional flowfields previously described give insight into potential problems of flight through winds disturbed by surface obstructions and are expected to be descriptive of very long buildings typical of the hangars and manufacturing complexes near airports. In general, however, most surface obstructions will be three-dimensional, for which the wake regions are smaller but for which a number of other flow disturbances occur. These consist of regions of high-velocity flow sweeping down and around the sides of buildings (Fig. 7a), longitudinal vortex shedding from slanted roofs (Fig. 7b), and vortex shedding (von Karman vortex streets) from the sides of tall, narrow structures (Fig. 7c).

The extent of the recirculating wake behind three-dimensional block bodies in wind tunnels is correlated by Leutheusser and Baines[48] and shown in Fig. 8. For fixed dimensions a and b, the wake increases almost linearly with height h. No Reynolds number dependence is given.

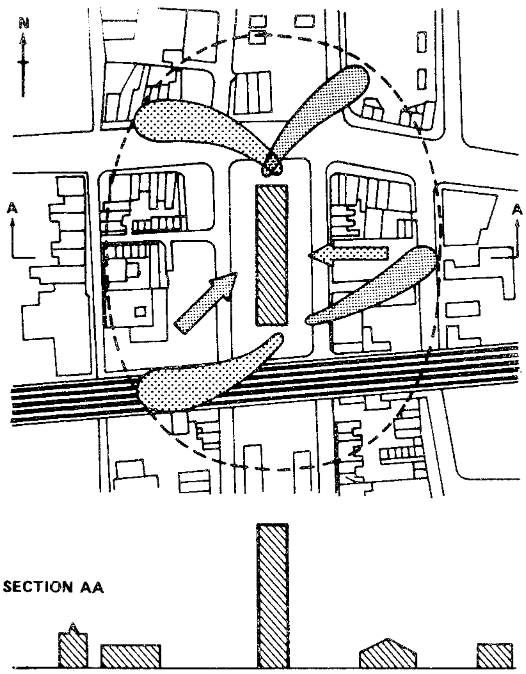

Fig. 9 Regions of high-velocity wind due to the presence of high-rise building.[51]

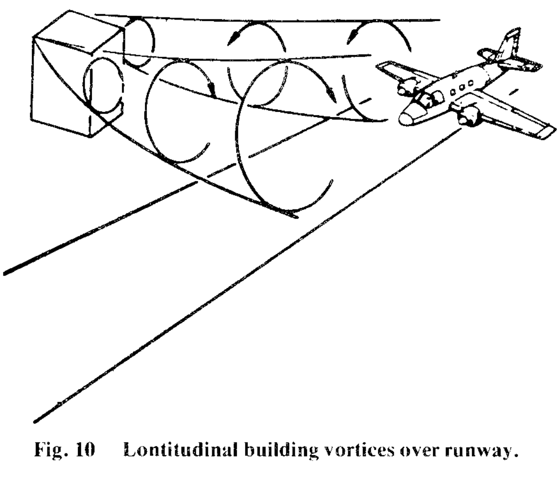

Fig. 10 Lontitudinal building vortices over runway.

Measurements of velocities on a slab building model preceded by a low building are reported in Ref. 49. The wake extends beyond 2.5 building heights downstream, at which point no further data are given. Figure 8 shows that the length of the recirculating zone behind a three-dimensional bluff body is considerably less than behind an infinitely wide rearward-facing step and hence not likely to extend into the obstruction-clear zone specifications of FAA nor into the flight path during take-off. The upward-directed flow over the roof of a three-dimensional building appears to extend to one-half a building height, and an aircraft landing directly over the building would experience an updraft as with the fence flow. It should be emphasized that for a VTOL aircraft the recirculating zone, even for three-dimensional bodies, is a very severe problem (see preliminary work of Krynytzky[50]).

If the aircraft's approach or takeoff is into the wind and toward either side of the building, the previously mentioned vortices and downwash zones are encountered. It appears from the limited existing data that aircraft passing to the side of a tall building would experience a downwash. The extent and location of the downwash for given wind directions is illustrated in Fig. 9 as reported in Ref. 51. Regions of increased speed extend downwind for a distance roughly equal to the height of the tall building.

Computed flowfields around a building-like block structure are reportd in Ref. 52. Although these three-dimensional computer solutions indicate the nature of the flow, the extent of the flow disturbance from the building cannot be completely resolved since it is a function of the imposed mathematical boundary conditions. Thus, more knowledge about three-dimensional flows is required before conclusions may be drawn regarding satisfactory obstruction clearance planes for V/STOL aircraft. A recent report, FAA-RD-75-94, "Meteorological Information for Vertical and Short Take-off and Landing (V/STOL) Operations in Built-Up Areas – Results of Meteorological Survey," covers winds and turbulence and provides some experimental insight in this regard.

Figure 10 illustrates longitudinal vortices originating on the leading edge of three-dimensional bodies. Ostrowski et al.[53] have measured pressure disturbances and smoke patterns produced by these vortices behind model buildings in wind tunnels. Their results show that more intense circulation occurs with increased angle of attack and sweep of a sloping roof. Hence, the architecture of buildings near airports may be significant in the creation of flight disturbances. Ostrowski et al.[53] report that pressure disturbances due to vortex shedding are measurable at least 2.5-3 building widths downstream. They also found that the longitudinal vortices extend further downstream with decreasing building height.[53] This observation coupled with the more intense disturbance due to

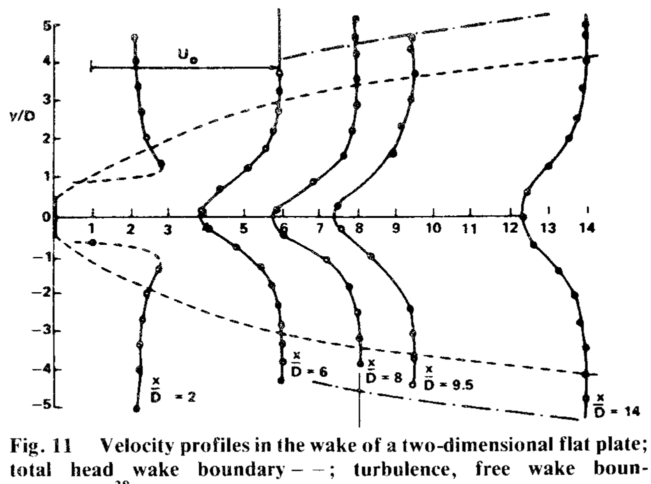

Fig. 11 Velocity profiles in the wake of a two-dimensional flat plate; total head wake boundary – –; turbulence, free wake boundary – · – .[38]

a sloping roof may explain the poor performance of the Trident automatic landing system reported by McManus.[54] He notes that the presence of a long hangar with a double apex roof at approximately 45° to the wind apparently created a disturbance which resulted in a landing impact close to the structural limits of the aircraft.

Model studies of tall buildings indicate that von Karman vortex streets occur in the wake as illustrated n Fig. 7. Again, there is no measurement in the atmosphere of these vortices behind buildings. Attention is drawn to the fact, however, that they have been recorded in the upper part of the atmospheric boundary layer in the lee of several isolated islands.[55] Wind-tunnel data, although not extensive enough to provide a working mathematical model, do indicate that the vortices may persist a considerable distance downstream. For example, Maull and Young[56] report that vorticity was easily measured 6 building widths downstream of a given bluff-body model. Figure 11 shows that the mean velocity is influenced at least 14 building widths downstream. Insufficient data are available to answer the question as to whether these vortex street disturbances extend into the obstruction-clear space designated by the FAA[57]; however, the aforementioned data do suggest a potential problem that requires further research. An understanding of this problem may be available if knowledge gained from the extensive literature on aircraft trailing vortices is applied to building geometries. Once the vortices can be mathematically modeled, their influence on an aircraft can be analyzed (for example, see Refs. 58 and 59).

Many other buildings and structural arrangements as well as natural terrain may create wind disturbances that will be appreciable under the less stringent obstruction clearance and flight path specification for V/STOL aircraft which heretofore have not affected CTOL aircraft. Bearman[38] reports double vortex patterns measured behind two cylindrical columns. Disturbances created by a trough such as a street between rows of buildings have been computed.[60] High wind velocities may occur on the tops of Quonset huts or hills, as illustrated by the calculations of flow over an elliptical obstruction in Ref. 61. Numerous other laboratory fluid-flow studies suggest regions where disturbed ground winds may generate dangerous flight conditions around V/STOL ports. Also of note is that in most of these laboratory studies the stratification or instability of the atmospheric boundary layer is not taken into account, and these aspects of flow around buildings require considerably more research.

Aircraft Response Calculations

The motion of an aircraft may be determined theoretically once mathematical models of the discussed flowfields are available. Caution is necessary, however, in applying the standard text equations of aircraft motion (see, for example, Ref. 62) since in most cases these equations incorporate simplifications and aerodynamic coefficients that are based on the assumption of uniform winds. Strong wind gradients can, for example, generate nonuniform wing and/or tail loading and additional roll, yaw, or pitch moments due to differences in angle of attack at the wing and at the center of gravity. In turn, the linearized form of the equations of motion which permit only small departures from an equilibrium state[59] cannot be applied when the wind field varies significantly with the spatial coordinate, and hence no well-defined equilibrium state exists.

One anticipates rolling moments due to wind gradients that would require rapid control response to avoid hard ro asymmetric landings. Analyses of landing in wind over homogeneous terrain have been made for linear wind profiles employing a linearized theory[6,63] and for more general wind profiles using a theory that assumes the longitudinal and lateral motion of the aircraft may be uncoupled.[9] The latter is valid for wings-level flight directly into the wind; however, the effect of a yawing or rolling angle is not taken into account.

Flight in winds near ground level over homogeneous terrain, and particularly around buildings, thus requires analysis employing equations of motion that include time-and spatially dependent wind components and aerodynamics forces modified in accordance with the presence of the wind gradient.

Concluding Comments

The intent of this paper is to point out to the aircraft operations, and particularly to the aircraft safety investigation communities, some of the potential sources of low-level wind shear at and around airports. The paper is by no means exhaustive; much work remains to better define low-level wind shear for both aircraft design and operational applications. Perhaps through a better definition of these environments, aircraft may be designed and operated such that they can negotiate and avoid harsh shear environments. At the present time, operational equipment (other than rawinsonde, etc.) is not available to provide wind-shear data on a routine basis at airports. A possible solution to providing wind-shear data for operations is remote-sensing equipment. Such equipment does exist; however, it needs to be developed such that it can be used in an operational context will be a positive step toward the elimination of wind shear as a source of aircraft accients. In view of the goal of the aviation community to develop "all-weather" automatic landing systems, the need for wind-shear design environment definition for design studies is critical. If these wind-shear environments are not properly specified, then automatic landing systems may be designed that are characterized by unacceptably high risks of encountering low-level shear environments that exceed the design and certification wind-shear levels, thus providing a potential future source of aircraft accidents. It is evident from the survey that mathematical models of wind shear, particularly over and around buildings, require considerably more development to provide guidance material for the design of airports and aircraft and for establishing requirements, criteria, and procedures for reporting wind shear to pilots.

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