Low-Altitude Atmospheric Turbulence around an Airport

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A small airplane was used to measure vertical accelerations due to atmospheric turbulence around an airport surrounded by large buildings, trees, and other objects. The vertical and lateral extent and the intensity of turbulence in the wake of buildings and at other locations around the airport were measured. Results are presented which indicate that the vertical accelerations of the airplane are related to gust intensities measured by conventional anemometers, and that reasonable forecasts of atmospheric turbulence which an airplane could expect to encounter near an airport surrounded by buildings, etc. may be made from wind data appropriately measured and analyzed.

Introduction

WITH the rapid increase of air traffic in the United States come many complex problems. As more people fly from point to point, or city to city, the network of ground transportation becomes clogged, and more people suffer long delays in reaching their destinations from the point of landing. The primary problems center around 1) moving large numbers of people from within a large metropolitan area to outlying "jet-ports," and 2) transporting similar numbers of passengers between city-centers located no more than 300–400 miles apart.

The logical solution appears to be in the improvement and subsequent mass employment of STOL, or "short takeoff and landing" aircraft. These aircraft will be encountering even more severe and unpredictable conditions of atmospheric turbulence than coped with before, because of the nature of the terrain surrounding the proposed STOL ports. Around the restricted boundaries of these small airports will be located a variety of buildings and other obstacles normally associated with urban or metropolitan areas. Accordingly, wind flow through these areas will be extremely erratic and difficult to predict, and the familiar problem of turbulence and its effect on aircraft flight will assume even greater significance than before.

The FAA[1] warns that much investigation is needed in both the design of aircraft to improve their ability to operate safely in this environment, and in the prediction and reporting of turbulence conditions. Burnham and O'Hara[2] compared the predicament facing STOL operations within built-up areas to that facing VTOL (vertical takeoff and landing) craft. VTOL vehicles could clear the turbulent region more quickly, but would by their own peculiar mode of operation create even greater turbulence on the ground. Rooftop and elevated STOL ports were discussed as having much merit, since the operating region then might be above the effect of the wind flow around surrounding buildings.

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Burnham[3] earlier had discussed at length the particular problem associated with landing and takeoff of aircraft in such an environment. He noted that gusts can adversely affect operations in many ways, and stated that the fore-and-aft and vertical components of the gusts are normally more critical than the lateral component. Further, even a change of only 10 knots in the fore-and-aft component lasting for 2–3 sec during the last 100 ft of the approach could be critical. He noted also that, for STOL ports surrounded by buildings, the wind information required for takeoff is essentially the same as that required for landing, but that topographic effects may be more significant for takeoff than for landing. In the latter instance for airports surrounded by obstructions the wind normally will have blown over at least 0.5 miles of relatively flat terrain, whereas the takeoff end of the runway will be nearer to significant obstacles to the wind. Burnham recognized also that there appeared to be a lack of a valid relationship between turbulence encountered on takeoff or landing and the wind readings noted on the airfield anemometer.

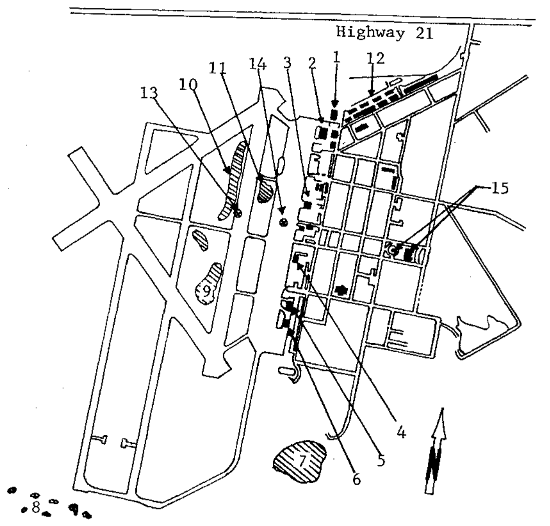
Morrissey[4] discussed the landing sequence of an aircraft (final approach, flare-out, float, and touchdown) as it was affected by wind variations around STOL ports. He noted that wind gusts were most critical to the flare-out and float sequences, since the craft was close to stalling and had limited response to control inputs. In this context a gust as seen by the aircraft is the difference between the average wind during the approach stage and the wind during the float stage.

The problem, then, as defined for this study, is basically: 1) to what extent do the buildings and other obstacles near STOL ports affect the intensity of atmospheric turbulence, and 2) can the atmospheric turbulence produced by airflow over the obstacles be related to average values of meteorological variables so that forecasts of turbulence can be made?

In addition to the work cited previously, many investigations have been made in both the United States and England relating in part, at least, to both aspects of the problem as defined. The turbulence experienced by an aircraft landing or taking off may be generated by both thermal and mechanical sources; however, only mechanically-produced turbulence is considered here. Turbulence due to convection normally can be encountered more safely than that produced or resulting solely from surface roughness. As the wind speed increases, the resultant mixing near the surface produces a condition of near-neutral stability, and consequently mechanical turbulence predominates.

An investigation was made in 1965 of the turbulence created by the "Rock" on landings and takeoffs at Gibraltar.[5] With the runway extending east and west, and with the 1300-ft-high Rock to the south, tremendous turbulence was produced under certain wind conditions. The main result of this investigation was the establishment of critical conditions of wind speed and direction for the creation of intense atmospheric turbulence; when these limits were reached, the airfield would be closed operationally. It was definitely established, for instance, that any time the wind was gusting in excess of 25 knots from a direction of 130° to 230°, turbulence would be encountered on the approach that exceeded structural tolerances of most aircraft.

A single 40-min run of anemometer measurements was analyzed to ascertain the effect of a large aircraft hangar on the structure of atmospheric turbulence.[6] Analysis of measurements of wind at specified levels in the upstream direction, as well as at various points in the wake of the hangar, revealed some interesting features. The mean wind speed in the wake five hangar heights downstream was substantially reduced from the upstream value, but this velocity deficit had decayed at a height equal to that of the building at a distance of 14 hangar heights downstream. On the other hand, a large increase in the intensity of turbulence was measured in the near wake, and this increase decayed more slowly than the velocity deficit and was still apparent 14 hangar heights downstream. These data indicated that the center-line of the wake oscillated by approximately ±10° from its mean position. This oscillation varied so slowly that it would appear as a discrete gust to a conventional aircraft; the effect on a STOL or VTOL aircraft could be large.



No. from sketch	Description	Length x Width	Height
1	Warehouse	140 x 130 ft	25 ft
2	Hangar (slight pitch)	200 x 175 ft	40 ft
3	Hangar (flat top)	135 x 125 ft	35 ft
4	Hangar (flat top)	135 x 125 ft	35 ft
5	Hangar (slight pitch)	150 x 150 ft	30 ft
6	Hangar (slight pitch)	150 x 150 ft	30 ft
7	Grove of trees		15 ft
8	Scattered trees		20 ft
9	Grove of trees		12 ft
10	Grove of trees		12 ft
11	Grove of trees		12 ft
12	Warehouse buildings		15-25 ft
13	Instrument Site No. 2		8,65 ft
14	Instrument Site No. 1		8,65,155 ft
15	Office buildings		15 ft

Fig. 1 Comparative heights of towers, buildings, and other obstructions.

Other pertinent observations were noted by Jones[7] in regard to flow around buildings. He stated that an increase of roof pitch increased the depth and length of the downwind eddy, as did an increase in the height of the building. A wider building is associated with a lesser depth of a leeward eddy, and the flow reattaches normally when the ratio of height to width exceeds unity.

Instrumentation

Airplane

A Beechcraft T-34 airplane with cruise airspeeds of 140–150 mph was used to collect flight data. The equipment on the airplane consisted of three Model 4310 Donner linear accelerometers, capable of measuring acceleration (g) forces on all three primary axes, and a Honeywell Visacorder Oscillograph, Model 2206. The accelerometers were located at or near the center of gravity of the aircraft and, although all three were functional, only vertical accelerations were measured. Over-all accuracy on the order of 0.1% is stated by the manufacturer for the Model 4310, and no reason was found to refute the claim. It was calibrated both before the tests began, and once during the research as a check.

The oscillograph is a portable, direct-writing model that records on light-sensitive paper through a frequency range of 0–13 kHz. It operated from the 28-v aircraft power supply, and was located in the rear passenger section of the aircraft. It could be controlled either remotely by the pilot or by an observer. The accelerometer trace was recorded on the light-sensitive paper at a speed of 0.2 in./sec. Time lines of 1-sec intervals were used for ease of data reduction. No problems were encountered during the research with any of the equipment aboard the aircraft.

Meteorological

All wind data were measured by cup-type anemometers and recorded on strip charts. Each system including its recorder was calibrated prior to use. This was done by mounting each anemometer immediately adjacent to a "standard" anemometer, which in turn was monitored by a "comparator." Each anemometer was found to have an accuracy within 5% at a speed of 12–15 mph. The vanes were aligned to true north and calibration procedures indicated an accuracy of 10° or less in wind direction.

Site Description and Data Collection

Description of Site

The site chosen for the data collection was the former Bryan Air Force Base, now used as the Texas A&M University Research Annex. The base is located on Texas State Highway 21 approximately 6 miles west of Bryan, Texas. All major obstructions lie to the east of the anemometer sites, with the exception of several small groves of trees ranging in height from 12 to 20 ft. The largest buildings are immediately adjacent to the parking ramp on the east, and are mostly the flat or low-pitched hangar type. These obstructions extend primarily in a north-south line for over 4000 ft, and extend to the east in small clusters for about the same distance.

The terrain is fairly flat in all directions from the site with only a slight rolling contour toward the northwest. The Brazos River turns past the southern portion of the west runway, with banks approximately 7–10 ft high. Vegetation in all quadrants consists of grass, occasional crops, and relatively dense groves of trees. Trees to the northeast and northwest are dense and range to about 25 ft in height. Buildings outside the site boundaries are scattered and in most cases fairly low.

Location of Meteorological Sensors

The heights of the instrumentation towers in relation to the surrounding obstructions are shown in Fig. 1. Site 1, located approximately 250 ft west of the main line of buildings, consisted of three meteorological systems mounted on towers 8, 65, and 155 ft high. Site 2, consisting of two towers, 8 and 65 ft high, is located further west. Site 1 was chosen to take advantage of a permanently emplaced 155-ft tower, and also to sample the effect of the buildings on the wind.

Collection of Data

The collection of data commenced on January 25, 1972, with one run being made on each of 6 days, ending March 8, 1972. Total aircraft flight time for the six collection periods was 13.5 hr. The same pilot was used for all data runs, and his prior experience consisted of more than 5000 hr of flying in several types of aircraft including helicopters. The flight plan for each data run usually consisted of at least three passes, each at a different altitude. A "run" consists of all data collected on one day, while a "pass" constitutes one flight path of the aircraft across the airport. The same power settings were used at all altitudes above 150 ft, while a higher but consistent setting was used at lower altitudes. Airspeeds varied slightly, but most were between 115 and 120 mph. In order to eliminate as much as possible the pilot "reaction-inputs" when encountering gusts, the pilot rested his right arm on his leg (in the fashion used by helicopter pilots) while manipulating the control stick.

As an individual collection pass was begun, an "event mark" was recorded on the paper of the airplane visacorder. Observers on the ground at each site were notified simultaneously by radio, and they in turn marked all charts by turning the electrical power off and back on. In this way, there was reasonable correlation between the data as recorded in the aircraft and those recorded on the ground.

Data were collected primarily on days when wind speeds were gusting to at least 15 mph; at least one run was taken with lower wind speeds for purposes of comparison. An attempt was made to collect data near the same time on each day to minimize thermal effects. The temperature lapse rate measured by aircraft was near adiabatic during each run. Turbulent mixing associated with the strong winds resulted in near-neutral or neutral lapse rates. Selected wind and flight data for each run are shown in Table 1.

Theoretical Basis

The simplified equation for eddy kinetic energy can be written in the form[8]

$$\underset{1)}{\frac{D(\overline{KE'})}{Dt}} = \underset{2)}{\frac{\mu_e}{\bar{\rho}}\left(\left|\frac{\partial \bar{\mathbf{V}}}{\partial z}\right|\right)^2} - \underset{3)}{\frac{\mu_h g}{\bar{\theta}\bar{\rho}}\frac{\partial \bar{\theta}}{\partial z}} - \underset{4)}{\epsilon} \tag{1}$$

where KE' is the kinetic energy of the turbulence, ρ is air density, $\mathbf{V}$ is wind velocity, θ is potential temperature, g is gravity, z is height, t is time, μ_e and μ_h are exchange coefficients for momentum and heat, respectively, and an overbar denotes an average. The numbered terms have the following meaning: 1) is the time rate-of-change of the average kinetic energy of turbulence following the mean motion, 2) is the mechanical production or shear term, 3) is the buoyancy production term, and 4) is dissipation of turbulent kinetic energy. This equation shows that wind shear and stability are primary factors which lead to turbulence. During conditions of neutral stability, wind shear is the only important parameter in the production of turbulent kinetic energy. For such conditions, it is found that

$$\overline{KE'} = \bar{V}^2/[\ln(z/z_0)]^2 \tag{2}$$

where $\bar{V}$ is measured at height z, and z_0 is the roughness length.

During neutral stability conditions, the average wind profile is given by the log-law in the form

$$\bar{V} = (u^*/k)\ln(z/z_0) \tag{3}$$

where u^* is the friction velocity ($u^{*2} \equiv \tau/\rho$), τ is stress, and k is von Kármán's constant. The stress, τ, usually is written

$$\tau = \mu_e(\partial\bar{V}/\partial z) \tag{4}$$

where only the vertical component of wind shear is considered.

Also, for neutral conditions, similarity theory suggests that

$$\sigma_w = C_1 u^* \tag{5}$$

and

$$\sigma_u = C_2 u^* \tag{6}$$

where σ_W and σ_U are standard deviations of the vertical and longitudinal wind components, respectively, and C_1 and C_2 are constants with values of 1.25 and 2.50, respec-

Table 1 Selected wind[a] and flight data for each run

Run	8 ft, #1				65 ft, #1				155 ft, #1				8 ft, #2				65 ft, #2				Altitudes
No.	$\bar{u}$	Dir	Var	$\sigma_{\bar{u}}$	$\bar{u}$	Dir[b]	Var	$\sigma_{\bar{u}}$	$\bar{u}$	Dir	Var	$\sigma_{\bar{u}}$	$\bar{u}$	Dir	Var	$\sigma_{\bar{u}}$	$\bar{u}$	Dir	Var	$\sigma_{\bar{u}}$	flown, ft
1	13.0		3.25	1.80	15.1		4.64	2.15	17.6	044	3.72	1.93	13.4	058	2.67	1.63	17.4	030	2.16	1.47	100, 200, 500
2	19.1	335	7.31	2.70	19.2		7.44	2.73	20.2	321	8.16	2.86	13.1	344	5.41	2.33	17.8	332	7.94	2.82	100, 200, 500, 1000
3	13.2	121	4.94	2.22	17.0		4.88	2.21	19.3	112	4.11	2.03									100, 200, 500
4	14.6	340	2.58	1.61					14.9	325	1.79	1.33									100, 200, 500, 1000
5	19.7	169	7.33	2.71	20.3		8.42	2.90	21.6	166	7.48	2.74									10, 150, 500
6	15.2	048	5.86	2.42	18.9		11.98	3.46	22.0	043	3.97	1.99	16.4	066	4.79	2.19	20.1		10.75	3.28	50, 100, 150, 200, 500, 1000

[a] Wind speed measured in mph; $\bar{u}$—average wind speed for entire run; Dir—average wind direction in degrees; Var—variance in wind speed; $\sigma_{\bar{u}}$—standard deviation in 30-second average wind speeds.
[b] Not measured.

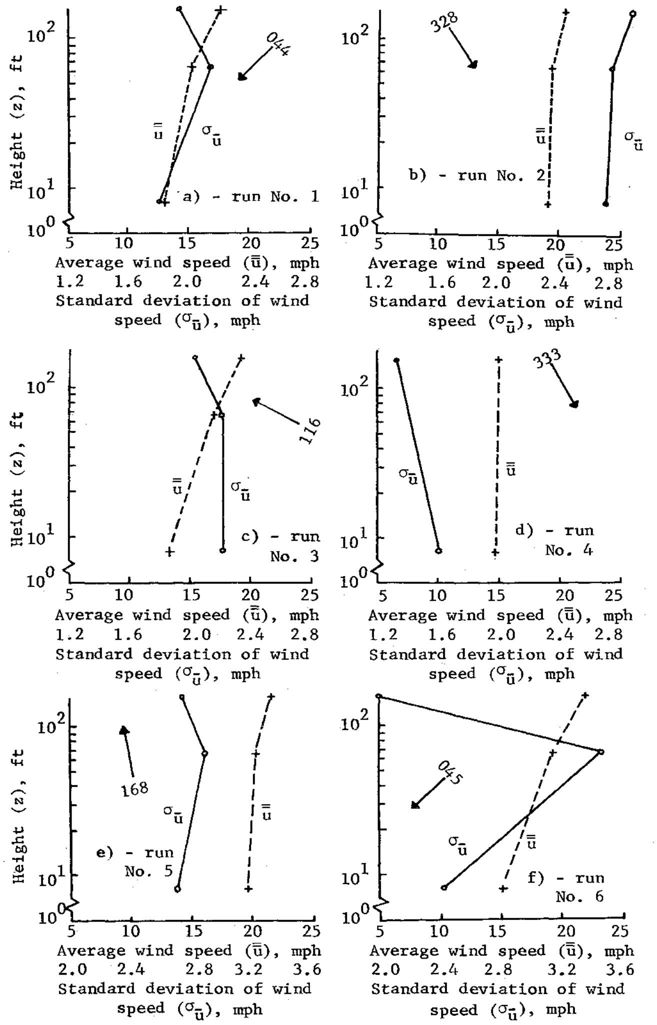


Fig. 2 Profiles of $\bar{u}$ and $\sigma_{\bar{u}}$ vs ln z for each run.

tively. Substitution for μ^* from Eq. (3) gives

$$\sigma_w = 0.5\bar{V}/\ln(z/z_0) \tag{7}$$

and

$$\sigma_u = \bar{V}/\ln(z/z_0) \tag{8}$$

where $k = 0.4$, and $\bar{V}$ is measured at height z.

Results

Turbulence and Wind Profile Data Measured by Anemometers

Wind data for each run were recorded at all three levels at Site 1, and plotted against the height of the respective instruments. Figure 2 shows the results. In this figure, $\bar{u}$ represents the average wind speed for the entire period of observation. Wind speed increased with height in every case, in general agreement with the log-law [Eq. (3)]. Profiles of $\sigma_{\bar{u}}$ (standard deviation in 30-sec average wind speeds) varied from run-to-run as might have been expected with a change in wind and surface roughness conditions.

With winds from the northeast during run 1 (Fig. 2a), a typical increase in wind speed took place from 8 ft to 155 ft, but a nontypical trend was observed for $\sigma_{\bar{u}}$. Turbulent energy normally decreases with height as indicated by Eqs. (7) and (8), but here it increased at midlevel, and decreased only slightly at the upper level. Obstructions 35 to 40 ft high are located within 300 ft to the east of this site, so that the instruments were within the wake of the turbulence created by the buildings. A similar result was observed by Colmer,[6] who theorized that the wake spread upward as it moved downstream, and did so noticeably to a distance of five hangar heights leeward of the obstructions.

During run 2 (Fig. 2b), the wind speed increased with height, though less than during the previous run. A grove of trees 15 ft high is located to the northwest (upstream) at a distance of about 700 ft. This would not be expected to affect the wind speeds as noted, nor would it be expected to produce the observed values of $\sigma_{\bar{u}}$. Nevertheless, the value of $\sigma_{\bar{u}}$ increased at both mid- and upper-levels, indicating an unusually intense wake produced by the obstructions upstream. The intensity of turbulence as represented by $\sigma_{\bar{u}}$ is much greater in this than the previous run. This increase in turbulence intensity is accompanied by an increase in wind shear near the ground. Hence, according to Eq. (1), the production of turbulent energy should be greater than in the previous run.

Run 3 (Fig. 2c) had greater vertical wind shear than either run 1 or run 2. The average wind speed was less than during run 2 and about equal to that of run 1. The wind was blowing across the main line of buildings, but since the wind direction was more southerly than in run 1, it crossed fewer obstructions prior to reaching the anemometers. In this case, $\sigma_{\bar{u}}$ decreased only slightly between 8 and 65 ft, then decreased rapidly between 65 and 155 ft. Apparently, considerable effect of the wake was being observed within the low- and midregions.

Data for run 4 (Fig. 2d) show a decrease in $\sigma_{\bar{u}}$ with height; however, measurements were made at only two levels. The wind was from the northwest as it was during run 2, and the wind profiles are similar. However, the $\sigma_{\bar{u}}$ profiles are completely different. The average wind speed was less than during run 2, but the decrease in $\sigma_{\bar{u}}$ was much greater in proportion; this implies a critical speed for the production of turbulence. Lapse rates calculated for both days were identical, surface temperatures were the same, and in neither case should there have been much thermal effect on the wind flow.

Profiles of $\bar{u}$ and $\sigma_{\bar{u}}$ for run 5 (Fig. 2e) are similar to those for run 1 even though the wind direction was different and the average wind speed slightly higher. A high value of $\sigma_{\bar{u}}$ was computed for the midlevel, which again is assumed to be the result of a turbulent wake downstream from a large hangar located about 400 ft to the southeast.

The final run (Fig. 2f) produced the most startling $\sigma_{\bar{u}}$ profile of all. Wind speed increased sharply with height, as during run 1 when northeast winds also were present. A peak of 3.5 mph of $\sigma_{\bar{u}}$ at midlevel was observed, which decreased to 2.0 mph at the upper level. Turbulence in the wake of the large hangar was apparently strongest at the 65-ft height.

In summary, the profiles indicate a definite relationship between wind speed and direction and the intensity of the turbulence. Two runs with northwest winds produced similar wind profiles, while the $\sigma_{\bar{u}}$ profiles were vastly different. The difference indicates that wind blowing across obstructions has a critical speed, above which the intensity of turbulence increases with height. Northeast winds blowing across the largest obstructions at the Annex produced a definite turbulent wake. This wake was particularly evident at the midlevel tower during two runs. Again, the wind speed appears to be the critical factor. A northeast wind with a speed of 18.9 mph at midlevel resulted in a $\sigma_{\bar{u}}$ of 3.5 mph, whereas a wind speed of 15.1 mph at the same level resulted in a $\sigma_{\bar{u}}$ of 2.2 mph.

Turbulence Measurements by Aircraft for Each Data Run

Turbulence intensities were recorded with the aircraft during all six data runs. The peak-to-peak vertical acceleration sensed by the aircraft for each 5-sec increment of flight time was extracted from the records and plotted on maps of the type shown in Fig. 1. Because of obstructions such as buildings and trees, the amount of turbulence encountered should logically be a function of wind direction. According to Eq. (2), we would expect the kinetic energy of turbulence to increase with wind speed, and from Eq. (6) the intensity of turbulence should increase as u^* increases where u^* depends upon surface roughness. The fact that large hangar-type buildings create turbulent energy in their wake has been shown by Colmer[6] and Burnham and Spavins.[5]

Flight paths were chosen across the Annex at different altitudes (see last column in Table 1) to determine the intensity and extent of turbulence in relation to buildings and other obstacles, and how it changed with height. The flight paths varied for each run depending upon the direction of the wind relative to the buildings and the intensity and extent of the turbulence observed. The measurements showed that turbulence is more intense downstream of the buildings than at other locations and the intensity decreases with height in the wake of the major obstructions, while at other locations no noticeable decrease was observed. In most instances, the intensity of turbulence recorded upwind of the obstructions was relatively low, although in the vicinity of trees the intensity was as great as it was near the buildings.

While the intensity of turbulence was generally observed to decrease with height, the decrease was more pronounced at the lower than at the upper flight levels. Also, the decrease with height was dependent upon the position relative to the obstructions with the greatest decrease taking place near the buildings.

Some interesting features are noted in summarizing this portion of the data collection. First, several strong vertical accelerations were encountered at locations outside any turbulent wake created by the major obstructions. This fact was especially evident in the northeast and northwest quadrants of the Annex area, and indicates that vast expanses of trees may affect wind flow in the same manner as large, isolated obstacles.

The grove of trees at the south of the complex apparently created a wake as turbulent as that created by the buildings, even though they were 20–25 ft high compared to the 30- to 40-ft height of the buildings. The presence of turbulence at the 500- and 1000-ft levels appeared to depend on wind speed and orientation of the wake in relation to the flight path of the aircraft. When winds were lighter, or no appreciable wake was evident, the intensity of the turbulence decreased rapidly, even between 100 and 200 ft. No appreciable difference was noted in the intensity of the turbulence when flying upwind compared to flying downwind at the same altitude and over the same path on the ground. Next, some very high readings were encountered on run 6 at 50 ft, which is the altitude that a STOL aircraft would normally begin a "flare" on landing approach. This further validates the large perturbation in the $\sigma_{\bar{u}}$ profile in Fig. 2f.

An unusual number of high readings was observed in the vicinity of the crossing point of the two diagonal runways directly west of the meteorological sites. No explanation is offered for this observation, since the high readings occurred when the wind direction was NW as well as NE. Finally, the change in the intensity of turbulence at low altitudes measured by the aircraft agreed with that measured by the anemometers. At heights well above anemometer heights, the intensity of turbulence appeared to be a function of upwind obstructions and wind speed.

Figure 3 consists of cross sections of turbulence measurements recorded during runs 3 and 6. The three passes made for run 3 were flown diagonally (relative to runway orientation) across the complex. At an altitude of 100 ft, the intensity of turbulence increased along the flight path as the aircraft flew toward the buildings. At 200 ft the readings were nearly constant along the path, with a few larger values noted near the beginning, and then at 500 ft the distance downwind appeared to have little effect on the accelerations of the aircraft. This gives further indication of how the turbulent wake spreads upward as it extends downwind. For run 6, the aircraft accelerations exhibit evidence of the rate of decrease in turbulence intensity from 100 to 1000 ft. Here again the flight paths crossed the complex downwind from the buildings so that the wake was completely traversed. The high intensities noted at 100 ft had decayed somewhat at 200 ft, but held surprisingly steady through 1000 ft. High values recorded at 100 ft did not appear consistently at the higher levels; this probably is due to a smaller influence of surface roughness at the greater height.

Aircraft Response vs Measured Wind Conditions

Several methods of comparing data gathered from the aircraft to those observed at the anemometers were investigated. Only those aircraft passes that crossed the anemometer sites were compared. In the analysis, $\bar{A}_p$ is the mean of the three 5-sec peak-to-peak accelerometer readings recorded during the 15-sec portion of the pass bracketing the site, $\sigma_{\bar{u}}$ is one-sixth of the maximum peak-to-peak wind speed occurring during the same 15-sec period used for computing $\bar{A}_p$, and $\sigma_{\bar{u}}$ is similar to σ_u except that it is computed from the wind speed averaged over 30-sec periods for the entire run at the appropriate anemometer.

The linear correlation coefficient between $\bar{A}_p$ and σ_u was found to be 0.06 for all passes over the anemometer sites regardless of the flight altitude. This result was expected since wind at heights of 65 and 155 ft only were being compared to aircraft data taken at levels from 10 to 1000 ft. A similar lack of correlation was noted when wind data taken at 155 ft were compared to aircraft data taken at 500 and 1000 ft. However, the correlation coefficient increased to 0.27 when aircraft data recorded at 50, 100, 150, and 200 ft were used. Wind data from 65-ft towers were compared to aircraft data taken at 50 and 100 ft, and 155-ft tower data were compared to aircraft data taken at 150 and 200 ft; however, in a few cases the aircraft flew only over Site 2, which required that the 65-ft tower data be used regardless of the altitude of the aircraft.

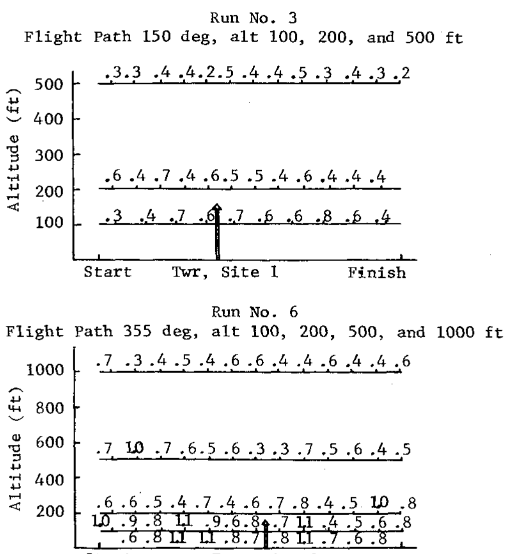


Fig. 3 Cross sections of turbulence readings ($g \times 10^{-1}$).

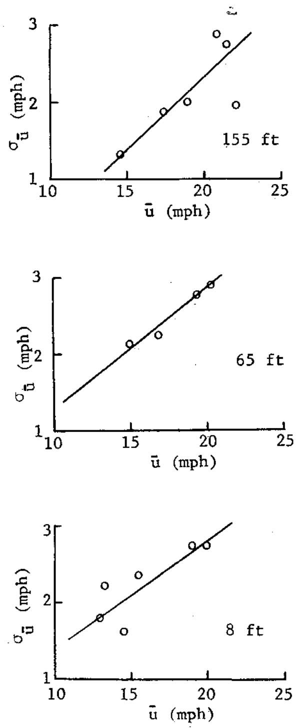


Fig. 4 $\sigma_{\bar{u}}$ vs $\bar{u}$ at site 1 (all 6 runs), computed from 30-sec averages.

The correlation coefficient of 0.27 is significant at about the 10% level.[9] This seemingly poor correlation is not as poor as might first appear, since on many passes the aircraft passed below or above the wind instrument by as much as 135 ft. Thus, the standard deviation of wind speed measured by the anemometers can be used to estimate the intensity of turbulence sensed by the aircraft and vice versa.

Fluctuations in wind speed over intervals of a few seconds and less cannot be predicted, yet these gusts may be sensed as significant turbulence by aircraft. Wind speed averaged over a longer time interval becomes more predictable than that averaged over a few seconds. Even when averaged over a period no longer than 30 sec, it often is possible to predict changes in this average from the cyclic character of the wind speed trace. A forecast of turbulence for the final approach of an aircraft at a STOL port could be made if a relationship was established between 30-sec average wind speed and aircraft response. It was shown previously that the response of the airplane when flying near the wind observation site was correlated with the gusts measured by the anemometer. It follows that if the response of the airplane could be related to wind speed averaged over a few minutes, it would be possible to predict the intensity of turbulence an airplane might expect to encounter.

The next logical step in the attempt to find a practical relationship between predictable wind parameters and turbulence was to compare $\bar{A}_p$ with $\sigma_{\bar{u}}$. The results were encouraging because the correlation coefficient (0.26) was nearly identical to the correlation coefficient computed using σ_u (0.27). This fact appears significant, since the same aircraft passes were considered in each comparison. The correlation coefficients suggest that the standard deviation of the 30-sec mean wind speed measured by the anemometers can be used to estimate the intensity of turbulence sensed by the aircraft.

A final comparison was made to see if, in fact, the $\sigma_{\bar{u}}$ could be predicted from $\bar{u}$ measured over some convenient time period. Figure 4 shows the results for $\sigma_{\bar{u}}$ vs $\bar{u}$ at Site 1. All six runs were plotted for each tower, and the lines drawn by inspection. The sample ($N = 6$) is too small to draw statistical conclusions; however, for all levels the relationship appears extremely good.

Concluding Remarks

Some interesting observations were made during the course of this research. First, height profiles of wind speed and fluctuations (turbulence) about the average wind speed indicate a correlation between wind speed and the intensity of the turbulence. All measured parameters were a function of wind direction because of changes in the roughness of the surface. For example, two runs with the same wind direction but different wind speeds resulted in entirely different turbulence profiles. The difference indicates that wind blowing across obstructions has a critical speed, above which the intensity of turbulence increases with height. Similarly, two other runs from the same direction, but different from that above, had profiles displaying an intense turbulent wake at the midlevel. Again, wind speed appeared to be the critical factor. The profiles appear to verify the results obtained by Colmer.[6] Downstream from large obstructions the wake appears to spread upward for some distance downwind. Within this wake the wind speed is slower and turbulent energy greater than that upstream or outside the wake.

The conclusions reached from the turbulence maps prepared from aircraft measurements indicate that the turbulent wake behind obstructions was not entirely predictable. With a high wind speed the wake was well defined, and extended farther downstream and to a greater height than when the wind speed was low. However, several strong vertical accelerations of the airplane were encountered at locations outside the turbulent wake created by the major obstructions. This occurred primarily in the NW and NE quadrants of the test area, and indicates that vast expanses of trees may affect the flow in the same manner as large obstacles. The over-all effect of the terrain irregularities on the measured parameters agrees with the findings of Brook.[10]

Comparisons of the average peak accelerometer measurements ($\bar{A}_p$) and turbulence measured by anemometers (σ_u) indicated that a reasonably good correlation (r = 0.27) between the two could result only when the $\bar{A}_p$ measurements were taken in close proximity to the anemometers. A good correlation was found between $\bar{A}_p$ and σ_u when the latter was computed from peak-to-peak speeds. A similar correlation coefficient was found between $\bar{A}_p$ and $\sigma_{\bar{u}}$, where $\sigma_{\bar{u}}$ was the standard deviation of mean wind speed averaged for 30-sec periods over an entire run. Also, the average wind speeds measured at each level for each run were plotted against $\sigma_{\bar{u}}$ for the same level and run. A definite lack of scatter was noted, even though the sample was small. It appears that the average wind speed measured over some convenient period of time (e.g., 1–3 min) is a reasonable predictor for $\bar{A}_p$ and $\sigma_{\bar{u}}$ at low altitudes in the vicinity of the airport considered and, presumably, in the vicinity of any airport surrounded by buildings and other obstructions.

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Determining STOL Ride Quality Criteria—Passenger Acceptance

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The ability to mathematically model human reaction to variables involved in transportation systems offers a very desirable tool both for the prediction of passenger acceptance of proposed systems and for establishing acceptance criteria for the system designer. As a first step in the development of a general model for STOL systems, a mathematical formulation is presented which accepts as inputs nine variables felt to be important in flight under STOL-type conditions and presents an index of human response as the output. The variables used are three linear motions, three angular motions, pressure, temperature, and noise level. The model is based on a deterministic approach, and was calibrated using data obtained by recording quantitative subjective responses of special test subjects while simultaneously measuring all variables. Several aircraft types were used under both experimental flight conditions and commercial airline operations. Ride quality criteria developed by using the model to study response to various combinations of the variables over extended ranges of frequency, amplitude, and rates of change will be presented. The results can be used to establish specifications for stability augmentation systems to improve the ride quality of existing STOL aircraft.

Introduction

UNTIL recently the matter of understanding the relationships between the several parameters involved in a transportation system and the passenger's acceptance of that system has received little attention. Although the literature contains many reports of work related to demand modeling or the prediction of modal splits, most approaches are concerned only with the tradeoff of time and cost. Other important factors are lumped together and arbitrarily included in some sort of empirical coefficient.

In an air transportation system of the type being proposed for short-haul STOL operations, the quality of the ride as it affects the comfort of the passenger has been recognized as an important parameter. This is illustrated in Figs. 1 and 2, which present data obtained from two recent surveys of the attitudes, habits, and preferences of travelers.[1,2] One involved the interviewing of frequent travelers from the academic community with the interviews being conducted in their offices; the other analyzed questionnaire data obtained in flight from a group of test subjects whose occupations ranged the gamut from secretary and student to airline pilot and engineer or scientist.

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It is clear from Fig. 1 that comfort rates as one of the most important considerations for both groups. The relative importance of the various factors included in an overall judgment on comfort is shown in Fig. 2. Here it is seen that the motion of the aircraft is perceived as quite important in determining over-all comfort. However, such factors as temperature, noise, and seat comfort cannot be ignored in any study of the effect of ride quality on passenger acceptance.

The ability to study these relationships quantitatively and develop a mathematical model of human reaction to variables involved in transportation systems is a very desirable step. Because of the importance of the comfort variables and the relative ease with which numerical relationships between stimuli and response can be obtained, ride quality was selected as the first acceptance variable for detailed study in a program to develop such models. This paper reports on the initial results from that program. Extension is planned to include all essential inputs due to vehicle properties, system characteristics, passenger characteristics, and passenger preconditioning. This should provide a powerful tool for the prediction of passenger acceptance of proposed systems and for establishing acceptance criteria for both the system and hardware designers. For example, the present results are being used to establish standards of comparison to determine the level of stability augmentation (if needed) to improve the ride quality in a Twin Otter.

Experimental Program

The experimental program consisted of a series of flights by a selected subject group on a regularly sched-