On Modeling of Atmospheric Surface Layers by the Counter-Jet Technique

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A new technique for tailoring mean profiles, thickness, and turbulent structure by spanwise-discrete upstream oriented wall jets with rapidly controllable velocities U_j and angle θ to the ground is explored in the IIT Environmental Wind Tunnel. The boundary layers can be changed rapidly and reproducibly from outside the tunnel while experiments are in progress. Flexibility of the technique makes it attractive for the hitherto neglected study of sensitivity of measured effects (e.g., wind loads, pollutant dispersion) to changes in atmospheric layer. Separate and combined effects of U_j, θ, and wall roughness on longitudinal mean profiles and velocity fluctuations are illustrated.

Nomenclature

d_i = inner diameter of counter-jet manifold
d_j = diameter of jet-exit holes of counter-jet manifold
d_0 = outer diameter of counter-jet manifold
k = height of elements of surface roughness
n = number of jets emerging from counter-jet manifold
$\dot{q}$ = volumetric flow rate of air through counter-jet manifold
s = distance between centers of jet-exit holes of counter-jet manifold
t = time
U = instantaneous velocity in streamwise direction = $\bar{U}+u$
$\bar{U}$ = time-averaged value of U
U_j = jet velocity of counter-jet based on average flow rate or measured one hole diameter downstream of jet-exit hole
U_∞ = time-averaged value of freestream velocity of test section
u = fluctuating component of velocity in streamwise direction
u' = rms value of u
w = fluctuating component of velocity in direction perpendicular to surface of boundary layer
x = downstream distance measured from counter-jet manifold
y = transverse distance measured from side-wall of test section
z = elevation above ground or floor of test section
δ = boundary-layer thickness defined by $\bar{U}(\delta) = 0.99U_\infty$; i.e., equal to elevation at which U first reaches value of 99% of U_∞
θ = angle of attack of counter-jets; angle between counter-jets' flow direction and surface of boundary layer; positive when jets are aimed toward floor of test section

I. Introduction

THE object of the present research was to develop a satisfactory simulation of atmospheric surface layers for use in design of buildings and plazas subjected to high winds. The point of departure from the traditional approach was the recognition that the atmospheric surface shear layers are highly variable in space and time[1] so that simulation through families of velocity and turbulence profiles should be more realistic than through the customary single, idealized logarithmic or power-law profile. Since there are no reliable techniques for predicting the velocity and turbulence profiles at a specific site of a proposed building or plaza, the idea is to bracket the probable conditions through a family of profiles. For design criteria we then suggest the use of the extreme values of the design variables inferred from measurements on models which are immersed in such a family of shear layers. Whenever the sensitivity of the design variables to changes in the profiles turns out to be significant, the present approach will be safer.

In his 1974 critical review[1] of the knowledge of the atmospheric boundary layers below 500 ft (150 m), Panofsky states that in the neutrally buoyant or unstable atmosphere the turning of the wind with height due to the Coriolis acceleration can be neglected. This "tower layer," described by Panofsky, is the target of our simulation for neutral conditions which are appropriate to high winds. Panofsky shows that, even for neutral winds, there is large variability and many uncertainties due to discrepancies between different data as well as theory. In particular, he proposes a significant revision of the spectra of the fluctuations in the horizontal velocity—the gust spectra of importance in design. In neutral atmospheric tower layers all of the shear stress is roughness-conditioned, and $\overline{uw}$ diffuses freely upward through the shear layer. This appears to be an important mechanism for setting the turbulent scales in this "natural" layer, perhaps a guide for its proper wind-tunnel simulation.

A. What is a Thick Natural Shear Layer in Wind Tunnels?

Everybody agrees[2] that for meaningful simulation the tunnel boundary layer should be thick, and that if possible the scale of its energetic eddies should somehow emulate the "natural" scaling in the atmosphere. The boundary-layer structure should then be controlled primarily by the roughness at the wall, at least in the proximity of the model. Experimenters with "long-tunnels," who achieve[3, 4] the large thickness by providing long 100-ft runs for the build-up of the boundary layer, object to the thickening and tailoring of the velocity profiles by passive grids or grids with jets[5] or by tall obstacles[6-8] in the boundary layer as introducing extraneous scales. They point to the perversely persisting remnants of streamwise vortices riding near the top of Counihan's layer,[7] downstream of his protruding spires-generators, and to strong imprinting of scales by the distance between these generators as evidence of "unnaturalness." The persistence inside shear layers of distinct mean and unsteady wakes due to spanwise rods away from the ground was pointed out a long time ago by Clauser.[9] It lay behind the disappointment of Rose[10] with

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shear-layer simulation by spanwise parallel bars: "...the results indicated that the realized turbulent fields lacked *homogeneity of the scales* and that the true nature of this field was partially obscured by extraneous effects" (our emphasis). The diffidence of the "long-tunnel" enthusiasts is not without ground.

Short tunnels with air injection perpendicular to the wall, such as that of Schon and Mery,[11] avoid the contamination from upstream wakes but lose much of the desirable roughness control. Because of the orientation of the blowing, they rely more on the displacement than on the momentum effect. Hence, they are less likely to be efficient.

On the other hand, there has been a dearth of published data from long tunnels refuting Joubert's statement[12] that the very length of the long tunnels makes the sidewall effects more critical so that Bradshaw's criterion for two-dimensionality of turbulent boundary layers seems to be violated. The answer that along the tunnel centerline the sidewall effects are negligible is not satisfactory per se, because the symmetry does not prevent the spanwise divergence of streamlines. The long sidewall runs, albeit without roughness, may develop non-negligible secondary flows over the long region of interaction with the main boundary layer. Again, what is needed is a sensitivity exploration of key measurements to intentional changes in the spanwise streamtube divergence.

In light of the advantages and disadvantages of the short and long tunnels, one would wish to combine a relatively short run with a thickening technique. This would preserve the control of the boundary-layer structure by the wall roughness and avoid protrusions of solid drag generators and of their wakes into the body of the boundary layer. The technique thus should operate at the wall and should incorporate flexibility to accommodate easy changes of boundary-layer characteristics for the aforementioned sensitivity testing.

B. Generation of Momentum Defect and Boundary Layers Within Boundary Layers

The main difference between "short tunnels" and "long tunnels" emerges clearly from the analysis of Cockrell and Lee[13]: instead of a long fetch with roughness, a drag-producing device is introduced upstream of a $\overline{uw}$-diffusing rough boundary layer. At IIT we prefer to call the device a *momentum-defect producing device* because it becomes obvious then that we should be able to generate large defects by variants of upstream-oriented wall jets. At the same time we minimize the objectionable imprint of solid-obstacle protrusions on the turbulent structure of the layer. In other words, we can have an "almost" freely diffusing $\overline{uw}$ distribution. The qualification "almost" refers to the fact that in a long tunnel the diffusion is quasi-equilibrium throughout the long fetch, whereas here the roughness controlled shear stress diffuses into a retarded "relaxing" boundary layer in the sense of Ref. 14. The atmospheric boundary layer usually differs from its "long-tunnel" cousin because it does not have an origin as such. It is a succession of boundary layers diffusing within older boundary layers as the roughness and topography of the ground change. It is well known[15] that the distance required for quasi-equilibrium conditions to develop to a given height is generally shorter when the secondary boundary layer grows within an older retarded one than when it grows in a uniform stream as in "long tunnels." This represents the essential gain in tunnel length if the diffusion is to be "free." A glance at Fig. 7 (to be discussed in Sec. IIIB) discloses that in our counter-jet generated boundary layer, the shear stress spreads indeed very rapidly from the rough wall. The 2.3-ft thick boundary layer appears to reach a near-equilibrium in a relatively short distance of 13 ft or approximately 100 roughness heights downstream of the device producing the Dirac-function type momentum defect.

Shinn[16] claims that quasi-equilibrium in the atmospheric layer after a change in roughness, i.e., due to a forest, is established after a fetch of approximately 25 times the roughness (tree) height (here without the benefit of the above large Dirac-type local retardation). This is a short distance compared to Counihan's wind-tunnel results[17] of 1000 roughness heights (parallelepipeds with square base). The literature on these types of layers within layers is extensive. Some recent references are: Sadeh et al.,[18] Tani and Makita,[19] Antonia and Luxton,[20] Bradshaw and Wong,[14] the review by Tani,[21] and the review by Panofsky,[1] and references therein. It seems that the change in some properties such as the shear stress $\overline{uw}$ is not monotonic[14,19] (the stress overshoots along a plume-like segment). This behavior may have caused incorrect extrapolations and may explain some of the discrepant assessments.

II. Experimental Approach

A. Wind Tunnel

The wind tunnel used in this study was the "IIT Environmental Wind Tunnel" which operated in the closed return mode permitting the utilization of 2 test sections. Located downstream of the turning vanes in one leg of the tunnel are a honeycomb section and a series of 8 screens followed by a 4 ft long settling chamber and a slow 4:1 contraction leading to the small test section with dimensions $2\times3\times10$ ft. This "high-speed" test section (100 fps maximum freestream velocity) was used in the first set of experiments reported here in part "A" of the results.

The second part of the results was obtained in the larger test section located near the downstream end of the return leg of the tunnel. Air flows from the fan through turning vanes into a transition section (circular to square) and enters the diffuser which is followed by the "low-speed" test section with dimensions $4\times6\times22$ ft, where freestream velocities up to 25 fps can be achieved. A perforated plate and a honeycomb section with a screen just downstream of it are used upstream of the diffuser to reduce the large-scale eddies and to suppress any swirling or secondary flows. At the midsection and the exit of the diffuser, perforated plates provide the necessary back pressure to prevent the diffuser from stalling. An additional perforated plate, 1.5 ft downstream of the diffuser, yields the final uniformization of the flow. It also reduces the level of turbulence intensity to approximately 1% or less throughout the test section for the range of flows used here.

Both test sections are equipped with a traversing mechanism driven by variable speed electric motors. For the "high-speed" section, the traversing mechanism is mounted on top of the test section permitting the probing of the flow along the entire 10 ft length. The probes can be traversed either in the vertical or the streamwise direction. A "minimum-blockage" mechanism capable of traversing in 3 directions is mounted inside the larger "low-speed" test section.

B. Instrumentation and Data Acquistion

A tungsten hot-wire was operated in the constant temperature mode using a DISA 55D01 anemometer with a system frequency response of 30 kHz at a mean velocity of 15 fps as measured by the square wave technique. The anemometer output was processed through a DISA 55D10 linearizer so that the signal was directly proportional to the instantaneous streamwise velocity $U(t)$. The linearized output was then low-pass filtered at 20 kHz by a DISA 55D25 auxiliary unit to reduce the level of high frequency electronic noise. A DISA 55D35 true rms meter was used with integration times from 3 to 10 sec to measure u'. To measure $\bar{U}$ the signal was processed through a low-pass network. The output of the network, proportional to $\bar{U}$, and the output of the rms meter, proportional to u', were recorded on the 2 channels of an H.P. 7100 BM strip chart recorder synchronized to the motor-driven traversing mechanism. The strip-chart records were reduced and then reproduced into the figures presented here.

C. Mechanics of Counter-Jet Controls and Flexibility of the Technique

Figure 1 shows the details of the counter-jet generating device as employed in either of the "Environmental Wind Tunnel" test sections. The schematic diagram is drawn to scale, and the various overall dimensions can be simply obtained by considering the dimensions of the test section used ($2\times3\times10$ ft for the "high-speed" test section or $4\times6\times22$ ft for the "low-speed" test section).

The scheme permits making changes in the mean-velocity and turbulence profiles by varying the jet velocity U_j and/or orientation θ in matters of minutes from outside of the tunnel, while the experiment is in progress. The technique, therefore, represents a simple vehicle for testing the sensitivity of critical characteristics of complex flows around building models and over plazas to change, and hence to uncertainties, in the approaching boundary layer. There are serious uncertainties in urban wind velocity profiles which are hidden by the prescribed handbook power law profiles. This has been pointed out by designers,[22] meteorologists,[23,24] and wind-tunnel experts.[25]

A criticism of short-tunnel techniques was voiced by Prof. Cermak[3]: "However, these methods give no control of the turbulence structure." He was presumably alluding to the need for tailoring of the drag-producing devices and careful matching of the subsequent roughness present in most "short tunnels." We invite the reader to judge for himself whether the counter-jet technique is not more convenient than the time consuming change-over processes in "long tunnels" which in fact are seldom utilized.

The detailed dimensions of the generating device used in the "high-speed" test section are: o.d. of counter-jets manifold tube, $d_0=1.375$ in.; i.d. of counter-jets manifold tube, $d_i=1.25$ in.; diameter of jet orifice holes, $d_j=0.188$ in.; separation distance between neighboring jet center lines, $s=1.25$ in.; and the number of jets along the 2 ft manifold, $n=19$. The dimensions of the manifold used in the larger test section are: $d_0=2.375$ in.; $d_i=2.125$ in.; $d_j=0.25$ in.; $s=1.25$ in.; and the number of jets along the 4 ft manifold, $n=38$. The artificial scales which could be introduced by the counter-jets are d_0, d_j, and s. For positive θ orientations, these relatively small lengths influence only the separation interface upstream and downstream of the manifold. Their effects, therefore, have to diffuse across the much larger boundary layer just like the effects of the wall roughness. With the long roughness fetch following the reattachment downstream of the manifold we would expect that any imprint of these relatively small scales would be obliterated by the roughness effects by the time the testing station is reached. At any rate we have had no indications of any such scales in our investigations thus far.

When measurements were performed in the "high-speed" test section for boundary layers with a rough wall (see results of Sec. IIIA), a thin plate, to which the roughness elements were attached, was fastened to the tunnel wall as shown in Fig. 1. Wooden cubes varying in size from 0.5 to 0.75 in. were used as the surface roughness elements. The cubes were arranged randomly, and the resulting surface density of these roughness elements along the test section is approximately 5%.

As in most of the classical studies[9] of turbulent boundary layers over rough walls, two-dimensional roughness (dubbed Roughness II) was used for the measurements reported in Sec. IIIB. One of the motives behind using two-dimensional type surface roughness was the ease by which one can reproduce the conditions in any wind tunnel at any time. The type of the two-dimensional surface roughness used here was obtained by placing "Unistrut" beams, 1.625 in. high, across the entire width of the tunnel at equal spacings of 8 in. The selection of these dimensions was based on the results of Liu et al.[26]

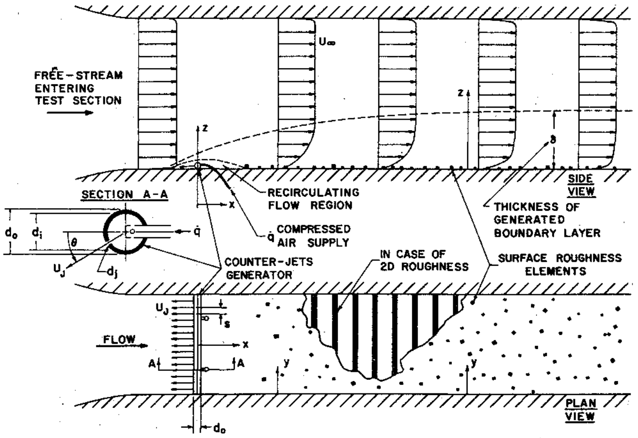

Fig. 1 Schematic representation of counter-jet technique.

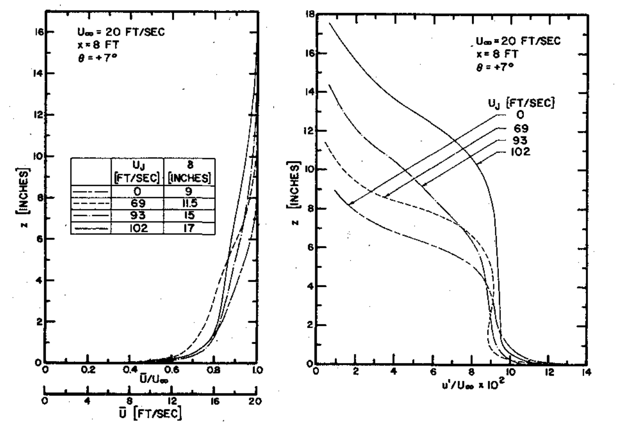

Fig. 2 Effect of variation of counter-jet velocity for a smooth-wall boundary layer.

III. Results and Discussion

A. Sample Characteristics of Turbulent Boundary Layers Generated by Counter-Jets and Roughness

When the counter-jet velocity U_j is zero, as for one of the curves in Fig. 2, the cylindrical manifold, which normally delivers the jets, represents a passive drag-producing device. Thus the velocity profile develops from an inflected profile, rather than from a standard turbulent layer. The increase in the boundary-layer thickness δ at the fixed downstream distance of 8 ft due to the increase of the velocity of the counter-jets up to 102 fps is then readily followed in Fig. 2. Without roughness these profiles are "purely relaxing" so that the attractive u' distribution for $U_j=102$ fps in Fig. 2 does correspond to a slow change in x and may or may not be acceptable. Clearly, the effects in Fig. 2 are highly nonlinear in U_j, the higher counter-jet velocities being especially effective. Based on the results reproduced in Fig. 2 and similar ones obtained in the larger test section (Figs. 40 and 41 of Ref. 29), we believe that the counter-jets aimed at given angles toward the wall become effective when U_j exceeds some threshold value. Below this value the effect of U_j diminishes. Here this threshold is larger than 70 fps but smaller than 90 fps. It is conjectured that this threshold is associated with the full establishment of the separation interface between the jets and the oncoming stream.

Comparison of curves a and b in Fig. 3 gives us an appreciation for the smooth-wall relaxation process in the distance of 4 ft. The considerable decay of the intensity of turbulence and the intensity distribution shapes can be understood better when we recognize that the boundary layer reattaches past $x=1$ ft and has therefore an inflected profile with the concomitant higher production of turbulence near its shifting inflection point (e.g., see Tani et al.[27]). The curves c and d in Fig. 3 exhibit the effect of roughness in the form of the diffusion of higher shear stress on top of the relaxation process of curves a and b. The boundary-layer thickness (a poorly defined quantity) changes little, but clearly there is more activity in the outer regions. This is especially evident from turbulence intensity profiles represented by curves b and c for which the δ's are nominally equal. The full-scale curve of Harris for "natural atmospheric boundary layer" (reproduced from Counihan[7]) is also shown. Unfortunately we have not yet measured the integral scales which may be yet more difficult to match than the disturbance profiles. However, Corke et al.[31] present typical spectra obtained in counter-jet generated boundary layers.

The θ effect in curves c and d of Fig. 3 is exhibited fully for $-20° < \theta < 20°$ in Fig. 4 in absence of roughness. The negative jet angles-of-attack θ correspond to the jets blowing partly upward and generating increasing "pressure obstruction" farther away from the wall. Here the discreteness of the jets as against a spanwise continuous jet sheet helps to stabilize the separated flows and to establish a more "natural" spanwise turbulence structure. We have not yet studied the sensitivity of this turbulent structure to variation of the interjet distance s. Again, we must weigh the attractiveness of, say, the $\theta = -10°$ turbulence intensity distribution for the smooth wall in Fig. 4 against the relatively rapid relaxation of the associated profiles in x.

In Fig. 5 we compare (at our standard 8 ft distance) the effects of increasing both U_j and U_∞ while keeping their ratio constant at 4.6, in the presence of roughness. We interpret the deeper penetration of the momentum defect and turbulence intensity achieved by curves a at the *fixed* distance x as probably due to more rapid diffusion of the roughness influence at the lower stream velocity of 20 fps. If this concept should be verified, it could be combined with the effect of U_j from Fig. 2 for maximization of absolute penetration, a desirable feature for model scaling.

In Fig. 5 our profiles of turbulence intensity are compared to Harris' full-scale profiles (as reported by Counihan[7]) as well as to "naturally" grown profiles of Corrsin and Kistler,[28] who used corrugated cardboard for their rough wall. We feel that profiles similar to the one labeled a show considerable promise, especially when we pursue their development to larger x values in the low-speed test section.

B. Some Experiences in the Larger Test Section

In a wind tunnel without a bleed or flexible wall opposite the test boundary layer, a comfortable operating range seems to be $h/3 < \delta < h/2$, where h is the height of the test section. It achieves acceptable model scaling without inducing excessive streamwise pressure gradients due to boundary-layer displacement. Since our experience (Sec. IIIA) in the "high-speed" test section, with $h = 3$ ft, was satisfactory we asked of the counter-jet system in the low-speed section, with $h = 6$ ft, that it be capable of doubling the boundary-layer thickness. One could extend the analysis à la Cockrell and Lee[13] to our counter-jets (with various undocumentable auxiliary assumptions) in order to arrive at some design guidance for our system. Instead, we employed an asymptotic argument as follows: for $U_j/U_\infty \geq 5$ and $|\theta| < 20°$ a design estimate for the boundary-layer momentum thickness is obtainable when the momentum defect is assumed to be solely due to the counter-jet momentum. The requirement of doubling the boundary-layer thickness then translates into the requirement of doubling the momentum of the jets per unit span. Secondary design considerations then led[29] to the specifications of the counter-jet manifold given in Sec. IIC.

In view of the unknown aspects of the counter-jet interaction, it is always desirable to supply ample compressed air so that higher U_j values can be reached. Sufficient unobstructed distance upstream of the manifold must be provided for the counter-jet interaction with the oncoming boundary layer lest the effectiveness be spoiled. This distance is denoted by x^+ in Figs. 6 and 7; a value of 4 ft was established empirically[29] as adequate for our range of U_j and U_∞ values. The reader will note that the jet spacing s was not doubled in proportion to the design boundary-layer thickness. It is

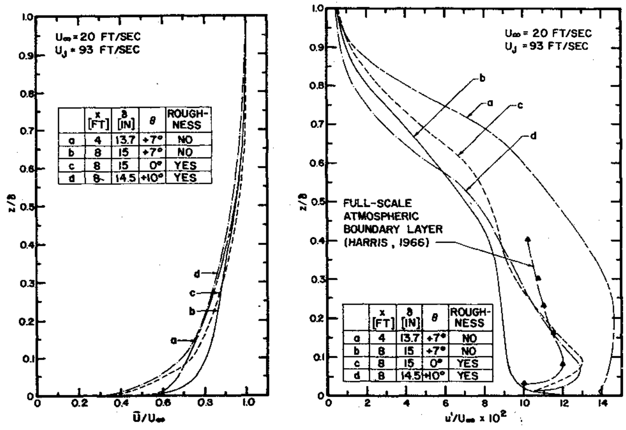

Fig. 3 Mean velocity and turbulence intensity profiles for smooth and rough wall boundary layers, U_∞ & U_j = constant.

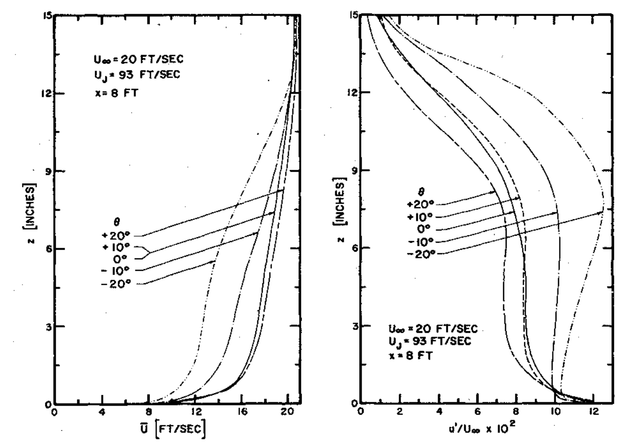

Fig. 4 Effect of variation of angle of attack of counter-jets for a smooth-wall boundary layer.

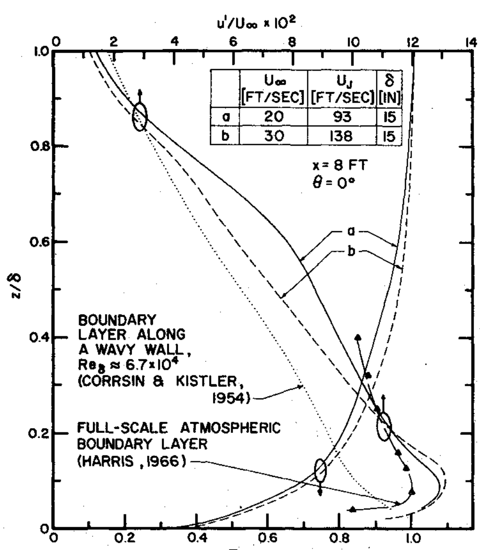

Fig. 5 Mean velocity and turbulence intensity profiles for a rough-wall boundary layer at different freestream velocities.

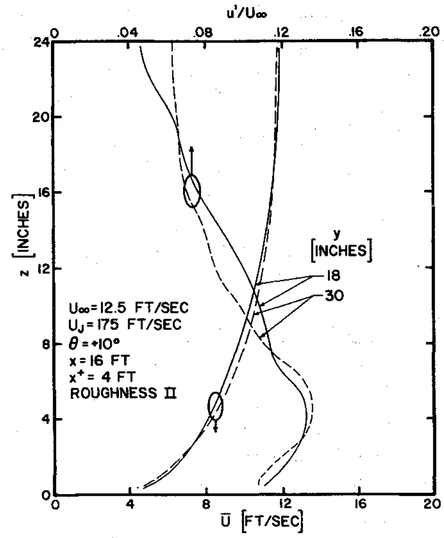

Fig. 6 Transverse uniformity obtained in larger test section with a rough wall.

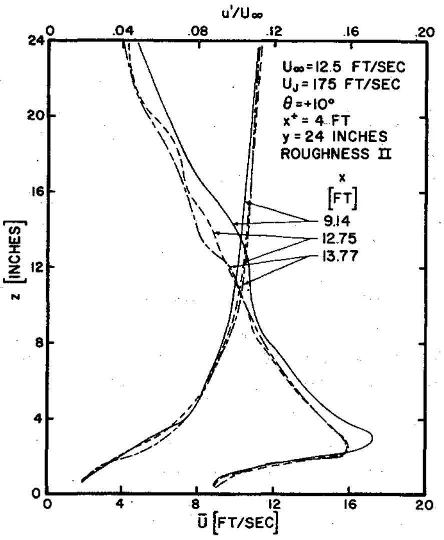

Fig. 7 Downstream development of mean velocity and turbulence intensity profiles obtained in larger test section.

believed that this scale is the most likely one to remain imprinted on the resulting turbulent motions so that it seems desirable to make it small. It should be small enough for neighboring counter-jets to start mixing before reaching the separation line at the wall.

Having reviewed the major considerations in the scaling of the counter-jet system, we proceed to two important results in the large test section. Additional ones are presented in Ref. 29. Using a slower freestream velocity, $U_\infty = 12.5$ fps, the slowly relaxing profiles of Fig. 6 were recorded at a streamwise distance twice that in the small test section, 1.8 ft downstream of the last "Unistrut" roughness element. While the curves of Fig. 6 do not extend to sufficiently large elevations for the reader to estimate the boundary-layer thickness for himself, additional measurements,[29] not reproduced here, indicate a δ of approximately 28 in. This value is close to the expected one, but almost twice the expected value of U_j was required to develop this thick boundary layer. The two curves of Fig. 6, obtained at two spanwise positions 6 in. on each side of the center plane of the test-section, indicate satisfactory transverse uniformity of the generated boundary layer. Complete traverses in the y direction measured at different heights provide[29,30] additional evidence for the uniformity.

Figure 7 presents three surveys of mean and fluctuating velocities at the center plane of the test section from $x = 9.14$ to $x = 13.77$ ft. These profiles were measured with the hot-wire probe at a streamwise position midway between the roughness elements. The similarity between the profiles suggests that this roughness-controlled layer is not "relaxing" as the smooth-wall layer did (curves *a* and *b* of Fig. 3), but that it approaches quasi-equilibrium. Sample profiles of $\overline{uw}$ for counter-jet generated boundary layers are presented by Corke, Nagib, and Tan-atichat.[31]

Such near-equilibria indeed have to be maintained by the stress spreading from the wall. Once the roughness stops, the boundary layers lose their similarity and start relaxing again. This is evident from comparing Figs. 6 and 7 or by examining Figs. 66 and 67 of Ref. 29; see also Panofsky's discussion.[1] This presents some problems with simulation of the approach fetch in scaled-down tests of buildings and plazas. Determination of the smallest roughness which could keep the boundary layers in quasi-equilibrium would be helpful. However, the changes in the profiles in Fig. 7 in the 1—ft increment (0.43 δ) from $x = 12.75$ ft are so small that the effect of x-gradients on tests of models should be negligible. These and other experiences[29] in the large test section then complement the experiences in the "high-speed" test section discussed earlier and provide a gratifying sense of confidence in the counter-jet technique.

IV. Conclusions

Modern measurements[1] in the first 500 ft or so of the atmosphere reveal significant differences with theory and with previously accepted empirical results even for smooth, flat topography. Engineers and architects concerned with simulation and design within realistic atmospheric environment must face the issue of the pervasive variability of the atmosphere. This includes the presence of nonequilibrium layers[1] growing within the surface layer in response to changes in topography and roughness. This paper proposes a practical methodology which would allow for the environmental variability in simulation of the atmospheric surface and tower layers for applications to high wind loads, high heat transfer on buildings, plaza design, etc. The methodology incorporates *sensitivity testing* of design variables *to changes* in the mean and fluctuating structure of the simulated turbulent layer.

The key to the approach is the new counter-jet technique for generating and tailoring mean profiles, thickness, and turbulent structure of the layers. Because it imparts a large horizontal momentum defect to the wall layer over a distance of a few feet, the scheme is adaptable to relatively short wind tunnels. By utilizing retardation through air friction *near the wall*, it avoids introducing objectionable extraneous scales through protrusions of solid drag generators or wake from passive and active grids into the body of the the boundary layer. It is shown that the shear stress generated by surface roughness downstream of the device diffuses *rapidly* into the retarded layer and can establish a roughness-controlled quasi-equilibrium. This is an important condition for meaningful simulation.

The final design of the device itself is simple, permitting rapid changes in the two controlling parameters, the counter-jet velocity U_j, and its near-grazing orientation θ with respect to the wall, even while the tunnel is operating. Thus a given model can be readily tested in a family of reproducible turbulent layers with structural profiles near the previously accepted "official" ones, in accordance with the sensitivity philosophy.

Specific design implementation of the counter-jet manifold in two test sections of different sizes is described as a guide for those who might wish to install the device in their existing tunnels. The operational characteristics of the technique, especially the dependence of the generated layers on U_j, θ, and the downstream surface roughness, are illustrated through examples to provide some "feel" of the boundary-layer mechanisms for the prospective user. The reader is referred to companion papers[30,31] for a demonstration of the sensitivity approach and further detailed characterization of the counter-jet generated boundary layers.

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