SIMULATION OF AN ADIABATIC URBAN BOUNDARY LAYER IN A WIND TUNNEL*

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Abstract—The adiabatic boundary layer appropriate to flow over an idealised urban terrain has been simulated using a modified version of the system previously used to produce a rural boundary layer simulation.

Where possible, measurements in the simulated flow were compared with full-scale measurements and reasonable agreement was obtained. However, because of a general lack of measurements in urban areas, several assumptions had to be made concerning the characteristics of some of the flow properties.

It is concluded that the characteristics of the simulated boundary layer are consistent with the interpretation of the available full-scale measurements.

NOMENCLATURE

F	coriolis parameter
f	non-dimensional frequency—$nh/\bar{u}$
f_m	non-dimensional frequency at which peak $nS(n)$ or $nS_{uv}(n)$ occur
H	generator height
h	vertical distance from tunnel floor
h_1, h_2	barrier height to base and top of castellations respectively
h_r	height of roughness element
L_x	length scale of turbulence in the axial direction
n	frequency
$p(x)$	probability density
$R_{ii}(r_1, r_2, r_3)$	correlation coefficient
R_o	Rossby number $\bar{U}_{MAX}/F y_o$
r	separation distance
$S(n)$	power spectral density at frequency n
$S_{uv}(n)$	power co-spectral density at frequency n
$\bar{U}_{MAX}$	free-stream velocity
U_τ	friction velocity
u	longitudinal velocity
v	vertical velocity
w	lateral velocity
y_o	roughness length
$1/\alpha$	power index of velocity profile power law
δ	boundary layer thickness ($= H$)
μ	mean value (reference to probability density)
σ	S.D. (reference to probability density)
Bar	denotes an average w.r.t. time
Prime	denotes a fluctuating contribution.

1. INTRODUCTION

THE WIND loading on a building or a group of buildings depends on the turbulence and shear in the approaching flow; these properties are determined by the terrain roughness for the case of adiabatic equilibirum. Therefore, in a wind tunnel in which

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wind loadings are to be investigated, it is essential that the boundary layers appropriate to flow over both moderately rough and very rough surfaces should be reproducible. The problem of simulating moderately rough surface flow (i.e. rural terrain) has previously been considered and an adequate simulation has been obtained (COUNIHAN, 1969b, 1970).

When simulating the very rough surface (i.e. urban terrain, which is taken as the extreme rough case), the first problem to resolve was modelling of the buildings (i.e. the large roughness elements) to obtain the appropriate roughness parameter. It was noted that this roughness length was a function of the density distribution of the buildings and the fetch. Therefore, its variation as a function of these two quantities was determined initially (COUNIHAN, 1971). Hence, knowing the degree of roughness or the roughness length to be simulated, the appropriate distribution of roughness elements could be selected to represent equilibrium flow over that particular terrain; the equilibrium state being defined as one in which the boundary layer characteristics do not change appreciably along the flow direction. Typically such flow would not occur in an urban area due to insufficient fetch being available. However, as a basis from which to work, the equilibrium state is considered here.

There is also difficulty in defining the urban boundary layer since the full-scale measurements available for such sites are sparse. In many cases, the sites considered have varied widely and measurements have been affected to some degree by local buildings. This being so, local effects have been measured rather than those appropriate to a particular mean urban condition. Usually it is impossible to assess such effects since detailed knowledge of the site geometry is not available.

Urban wind measurements and their analysis are also affected by the magnitude of the local roughness length and the zero-plane displacement (COUNIHAN, 1971). Allowances for these quantities have, until recently, tended to be neglected in the literature; exceptions to this are included in e.g. PAESCHKE (1937) and PASQUILL (1950).

It is possible that more consistent results would be obtained if, as stated by CHANDLER (1968), "a standard non-standard site" could be defined, or if more care were to be taken in the selection of sites for full-scale measurements.

The rural terrain simulation was achieved by the use of a barrier, vorticity generators and surface roughness. The intention of that system was to produce the complete spectrum of turbulence as it exists in the atmospheric boundary layer. However, in considering the problem of simulating such a flow it seemed much more practical to approach it by saying, "how can a certain mean velocity profile and turbulence intensity distribution be produced", (while still keeping the large scale turbulence required in mind), rather than say "what can be used to produce turbulent eddies of some particular shape, size etc." Hence the approach was based on modelling the velocity profile and turbulence intensity required and assuming that this system would produce the complete spectrum, which it did (COUNIHAN, 1969b). The ground roughness was matched to the barrier and provided for the continuing production of turbulence at ground level.

On the basis of the above simulation it was anticipated that, having decided on the urban terrain characteristics to be simulated, the geometry and spacing of the generators would not need to be changed. The only alterations envisaged to the system were a change of the barrier height and the use of large roughness elements.

This paper presents the main points which were considered in choosing a typical urban terrain, how it was represented in a wind tunnel and some of the measurements made in this simulated urban boundary layer.

2. EXPERIMENTAL DETAILS

All of the tests were carried out in the C.E.R.L. Boundary Layer wind tunnel at a scale of 1:4000 and the instrumentation was as previously described in COUNIHAN (1969b, 1970). This wind tunnel is used only for boundary layer simulation work; wind loading and other tests are carried out at scales of 1:250–1:500 in the Low Speed Wind Tunnel. The measurements were made over the full boundary layer height at Stations A and B which are 3 and $4\frac{1}{2}$ boundary layer heights, respectively, downstream of the generators (COUNIHAN, 1969b). Some additional measurements were made at a downstream distance of 6 boundary layer heights. The majority of the measurements were made at spanwise positions in-line with the generator centre-line and in-line with the generator mid-span. At Station B, additional measurements were made at various spanwise positions relative to a particular roughness element in order to assess the local effects of the large roughness elements.

The roughness elements used were the same as those used in COUNIHAN (1971). These were "LEGO" bricks measuring 9·5 mm (0·375 in.) high, (i.e. $h_r/H = \frac{1}{16}$) and 15·9 mm (0·625 in.) square which were fitted to "LEGO" baseboard on the wind tunnel floor. The spacing of the bricks used to represent the urban terrain was two brick widths between brick centres in a spanwise direction and three brick widths in a streamwise direction. The ratio between the brick plan area and the total area was approximately 0·15.

The geometry of the barrier castellations was similar to that used in the rural terrain simulation. The height of the barrier determined for the urban simulation was

$$h_1/H = 0{\cdot}208;\ h_2/H = 0{\cdot}250$$

where h_1 and h_2 are measured to the base and to the top of the castellations respectively.

3. DEFINING THE URBAN BOUNDARY LAYER

3.1 *The velocity profile*

It was assumed that the variation of velocity with height in an urban area could be represented by a power law, as in the case of the rural terrain. Initially it was thought that a power law having an exponent of 0·40 should be considered; this was suggested by DAVENPORT (1963) as being appropriate to heavily built-up urban areas. However, this was later reconsidered for the following reasons:

Firstly, a survey of the available literature showed that urban power law exponents varying from 0·21 to 0·40 had been measured at various urban sites as follows:

Site	$1/\alpha$	*Ref.*
Liverpool	0·21	JONES *et al.* (1971)
London	0·23	SHELLARD (1963)
Kokubunji	0·25	SHIOTANI (1962)
Suburbs	0·28	DAVENPORT (1960b)
Japanese towns	0·33	KAMEI (1955)
City centre	0·40	DAVENPORT (1963)

The prevailing vertical temperature gradients appropriate to the above data have not always been quoted in the literature; however the measurements were mostly obtained during high winds, implying near-adiabatic conditions.

Secondly, from the measurements previously made in rough boundary layers where the roughness height was a significant part of the total boundary layer height (COUNIHAN, 1971), it was shown that a wide range of indices could be fitted to the measured profiles. This depended on where the measurements were made relative to a particular roughness element and the height range over which the profile was fitted. For example, if measurements were not made to a height great enough to be free of local effects of the roughness, variations in the local mean velocity of ± 15 per cent could be measured over small spanwise distances. Some of the measurements of KAMEI (1955) quoted above may be subject to errors of this type.

Additionally, in the measurement of velocity profiles in rough-wall boundary layers, (COUNIHAN, 1971), high values of the power law index were found only in non-equilibrium flows. Similar conditions probably applied to the cases where such exponents had been obtained from full-scale measurements.

The final point considered was that an exponent of about 0·28 had been measured previously (COUNIHAN, 1969b) in a rough-wall equilibrium boundary layer, in which the ratio of the roughness height to the boundary layer height was similar to that for the intended urban boundary layer simulation.

Taking all the above points into consideration, an exponent of 0·28 was chosen for the urban site near the equilibrium state. Local modifications caused by large obstructions can be obtained by representing these in the model and producing local areas having a greater shear flow and indices up to 0·40.

Furthermore, the 0·28 index has been chosen by the Commonwealth Aeronautical Advisory Research Committee (C.A.A.R.C.) (WARDLAW and MOSS, 1970) as being typical of sites having obstructions of the order of 25 m high and is to be used as the shear flow requirement for some basic industrial aerodynamic investigations.

3.2 *The turbulence intensities*

The available data on urban turbulence measurements are not very extensive and are insufficiently detailed to present graphically as in the case of rural data. This is probably due to the fact that the main effort has been directed towards trying to define a representative velocity profile as a first step in the understanding of the urban environment. Estimates of the longitudinal turbulence by DAVENPORT (1960) and HARRIS (1970) suggest that the turbulence intensities, based on the gradient velocity, for urban sites, are not significantly greater than those associated with rural sites. Based on local velocities however, they should be 20–30 per cent in the lower regions of the boundary layer.

The full-scale measurements of the longitudinal turbulence by SHIOTANI and YAMAMOTO (1948), lie in the above range, as do measurements made at the Brookhaven site (SINGER, 1960), which has a velocity profile power law index of 0·28. More recent measurements by HELLIWELL (1971) in the London area have indicated values ranging from 10 to 30 per cent based on local velocities. There is naturally a greater amount of scatter in the urban measurements than in the case of the rural measurements due to the fact that the measured intensities, like the mean velocities, are more dependent on the measuring position relative to the local buildings.

Flat plate data applicable to the lower 10–15 per cent of the boundary layer indicate the ratios of the lateral and vertical turbulence intensities to the longitudinal turbulence intensity should be of the order of 0·75 and 0·54 respectively.

3.3 *The power spectral densities*

The available measurements and discussions of urban power spectra (e.g. DAVENPORT, 1963, 1967 and PANOFSKY, 1969) all suggest that the forms of the urban and rural spectra should be similar. Therefore it is to be expected that the high frequency end of the spectrum when plotted in the $nS(n)$ form will follow Kolmogoroffs $-2/3$ law (KOLMOGOROFF, 1941). The longitudinal spectra should also be invariant with height except possibly at heights which are low in comparison to the local building height. Here, a shift of the peak $nS_u(n)$ value to a higher frequency would be expected. Additionally, a secondary peak $nS_u(n)$ value may be detected at a frequency associated with the building eddy shedding frequency at heights comparable to local building heights.

With these exceptions, the form should be that proposed by HARRIS (1968):

$$nS_u(n) \propto \frac{x}{(2+x^2)^{5/6}}$$

where,

$x = nL/\bar{U}_{10}$, $L = 1800$ m and $\bar{U}_{10} =$ Reference velocity at a height of 10 m.

The form of the vertical spectrum is assumed to be that proposed by BUSCH and PANOFSKY (1968):

$$n\,S_v(n) \propto \frac{1\cdot 075\, f/fm}{1 + 1\cdot 5\,(f/fm)^{5/3}}$$

the lateral spectrum, as in the rural simulation, is assumed to lie between the longitudinal and vertical spectra.

3.4 *Reynolds stresses*

Full-scale measurements of the Reynolds stresses are relatively few for rural terrain and are even more sparse in the case of urban terrain. However, the ratio of the rural to urban stresses can be derived on a semi-theoretical basis from data which predicts the variation of the Reynolds stresses with the Rossby Number ($R_o = \bar{U}_{MAX}/F y_o$). The Rossby Number mostly reflects variations in the roughness lengths of the surfaces considered. Therefore the choice of a reasonable mean value of the roughness length for an urban area is desirable if a good estimate of the stresses is to be obtained.

When a moderately rough surface is being considered, local variations in the roughness length are not significant. However, with a very rough surface, i.e. urban terrain, the roughness length is very dependent on the position at which it is measured. Additionally, it is a function of the distribution of roughness, i.e. whether the area is lightly or heavily built-up. Therefore, it is necessary to adopt some mean value for the roughness length which specifies a typical urban site, and it was decided that this should be between 2~3 m full-scale. This is consistent with SLADE (1969). On this basis the ratio of the urban to rural shear stresses near ground level was estimated as approximately 1·50 (from SMITH, 1971), for the same free-stream velocity in an atmosphere in adiabatic equilibrium.

From the analysis of some full-scale measurements by DELAND and PANOFSKY (1957) it is possible to obtain an estimate of the ratio of the stresses based on local velocities. For heights comparable to the height of the roughness, this ratio is about 10.

If the turbulence scales and intensity are correctly modelled it can be assumed that the dissipation term is scaled correctly (TAYLOR, 1935). The corresponding rate of production of turbulent energy, which is proportional to the product of the shear stress and the velocity gradient, should also be simulated correctly and should equal the dissipation. If the scales and intensities of turbulence and the velocity profile, associated with the above terms, are correctly simulated and are constant in a streamwise direction, then the resulting shear stresses should be correctly scaled.

3.5 *The co-spectrum of the Reynolds stresses*

The available co-spectral data for rural situations have been correlated and analysed by PANOFSKY and MARES (1968) who derived a semi-empirical expression to describe the co-spectrum. A similar relation may be assumed for urban co-spectra.

Clearly the positioning of the co-spectrum on the frequency scale is dependent on the relative positions or frequency bands of the longitudinal and vertical velocity spectra. In this context, the work of Panofsky and Mares indicates that the majority of the stress contribution lies in the range,

$$0{\cdot}01 \leqslant f \leqslant 1{\cdot}0.$$

Since the spectra of the vertical velocity are height dependent, it can be assumed that the co-spectral measurements will also be a function of height above the constant stress layer. However, most of the available measurements have been made at heights of less than 50 m (160 ft) where variations of the co-spectra due to height would probably not be significant. The slope of the co-spectra at the high frequency end is taken as $-\frac{5}{3}$ when plotted in the $n\ S_{uv}\ (n)$ form; this has been adequately verified by the recent measurements of MIYAKE, STEWART and BURLING (1970) and of SITAMARAN (1970).

3.6 *The probability density distribution*

A review of the relevant meteorological papers by GIBLETT (1932); SHIOTANI (1950); CRAMER (1952) and SUTTON (1953) suggests that the measured full-scale velocity distributions are Gaussian within the range of $\pm 3\sigma$, but outside this range the measurements show variations from the Gaussian form which do not appear to be insignificant. At present, a reliable comparison between model and full-scale data can only be made within the $\pm 3\sigma$ range due to lack of full-scale measurements.

Although the above data are relevant to rural sites, it is assumed that the comments and conclusions apply equally well in the case of urban terrain.

3.7 *The scales of turbulence*

It has already been established that the scales of turbulence simulated in the rural terrain boundary layer were the correct size, relative to the boundary layer height, for compatability between it and a naturally grown boundary layer (COUNIHAN, 1970). It now remains to be decided what modifications, if any, could be expected to be imposed on the length scales in flow over an urban area.

At heights which are relatively free of the effects of the building wakes, it seems reasonable to assume that there will be no significant change of the scales of turbulence

except perhaps that of the vertical scale. A change of this scale seems possible because of the greater roughness elements, in the form of buildings, producing a greater degree of energy transfer in the vertical direction. At heights which are the same order of magnitude as the buildings, it is assumed that the scale lengths in the streamwise direction would be reduced due to obstruction and breaking up of the flow by the buildings.

3.8 *The typical urban terrain boundary layer*

From the above discussion it can be seen that despite the lack of full-scale data in many areas, some conclusions can be made regarding the flow to be simulated.

Since the majority of the available full-scale data are mean velocity profile measurements, then this quantity will be used initially as a guide towards defining the urban boundary layer.

It is assumed that the velocity profile can be represented by a power law and on the basis of the available data and the arguments put forward, an index of 0·28 is assumed to be the most representative choice—as is the associated value of the mean roughness length (i.e. 2·50 m).

However it has been emphasised previously (e.g. COUNIHAN, 1969a) that the simulation of the large scale turbulence, rather than that of any specific velocity profile, is also an essential requirement in this simulation work.

4. DISCUSSION AND RESULTS

4.1 *The effect of increasing the barrier height*

The suggested range of theoretical power law velocity profiles covering variations in terrain between rural and urban is shown in FIG. 1.

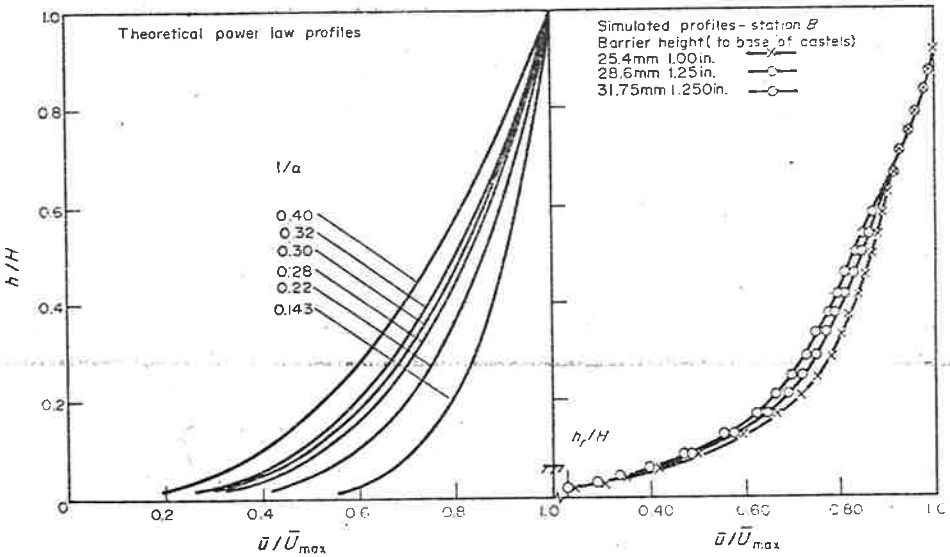

FIG. 1 Boundary layer simulation—urban terrain

The work on the rural simulation has shown the effect on the momentum loss due to increase of the barrier height; a similar effect for the urban simulation is also shown in FIG. 1. In this case it is probable that the momentum loss due to the roughness is considerably greater than in the case of the rural roughness. Therefore, the roughness should define the lower section of the velocity profiles independently of the height of the barrier.

As a rough guide, an increase of 0·021 h/H in the barrier height will result in a velocity defect of about 0·03 $\bar{u}/\bar{U}_{MAX}$. Some of this loss must be attributed to the roughness elements and some allowance made when interpolation of the data is required in the range $0{\cdot}143 \leqslant 1/\alpha \leqslant 0{\cdot}28$. It can be seen from FIG. 1 that a barrier height of $h_1/H = 0{\cdot}208$ is adequate for producing a velocity profile having an index of 0·28.

4.2 *Mean velocity and turbulence intensity measurements*

The measurements of the mean velocity and Reynolds stress at Station *B* are shown in FIG. 2 and the corresponding turbulence intensities in FIG. 3. It can be seen that the simulated velocity profile approximates fairly closely to a 0·28 power index profile over the majority of the boundary layer height. At a height of the order of the roughness height, the ratio of the urban and rural stresses based on the gradient velocity is approximately 1·40 compared to the estimate of 1·50. Similarly, the ratio based on the local velocity is 7 compared to 10 from the full scale measurements. This degree of agreement is considered to be acceptable when the inherent inaccuracies involved in full-scale Reynolds stress and mean velocity measurements are considered.

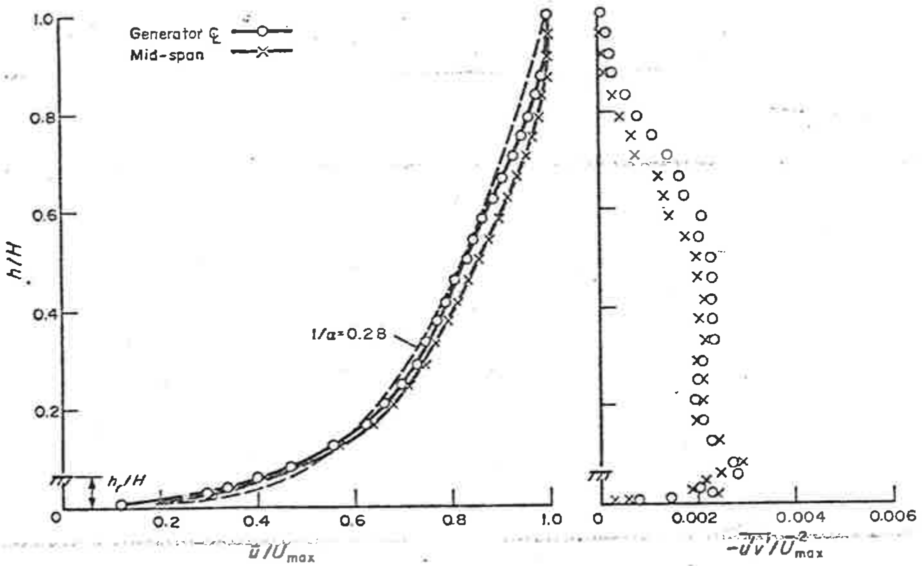

FIG. 2. Boundary layer simulation—urban terrain, Station *B*.

The measurements of the turbulence intensities are shown in FIG. 3. The ratios of the lateral to longitudinal and vertical to longitudinal turbulence are 0·75 and 0·59 respectively, in the lower section of the boundary layer, compared to 0·75 and 0·54

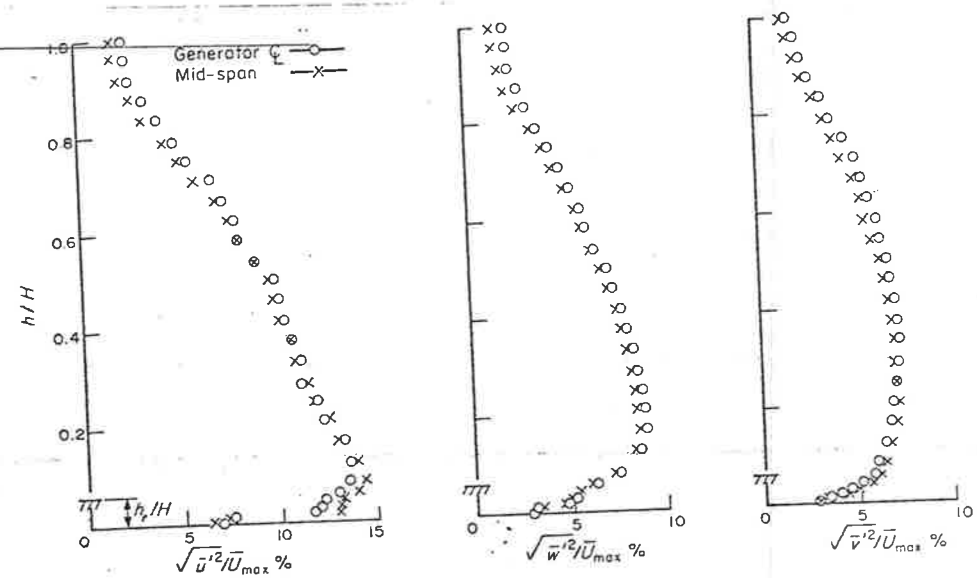

FIG. 3. Boundary layer simulation—urban terrain, Station *B*.

for flat-plate data. The results also indicate a good degree of spanwise uniformity of the flow. The magnitude of the longitudinal turbulence intensity, based on the free-stream velocity, is greater than that of the rural terrain, but is not very different. The comparison of the results, based on local velocities, with those of HELLIWELL (1971) is as follows:

h/H	Simulated turbulence (%)	HELLIWELL (1971) (%)
Just above roughness height	27	15~30
0·33	14	12

The local effects due to the large roughness elements are shown in more detail in FIG. 4. Spanwise variations in the measured quantities are fairly large up to heights of about 1·5 h_r, which shows the difficulty in defining mean values of measurements made in urban sites. The amount of spanwise scatter, and its extent in the vertical direction, was similar in the case of the longitudinal turbulence but was insignificant in the case of the lateral and vertical turbulence intensities.

4.3 *Correlation measurements and turbulence scales*

Some of the correlation measurements have been compared with the rural terrain results and are presented in FIGS. 5–7. At heights comparable to the building (or roughness) height, and at lower heights, the urban scales of turbulence in the vertical and lateral directions are not significantly different from those of the rural terrain. At heights greater than the building height the lateral scales are again similar in size to the rural scales of turbulence; the vertical scales however are consistently larger (FIG. 5). This is attributed to the greater vertical transfer of energy associated with the large roughness elements which represent the urban buildings.

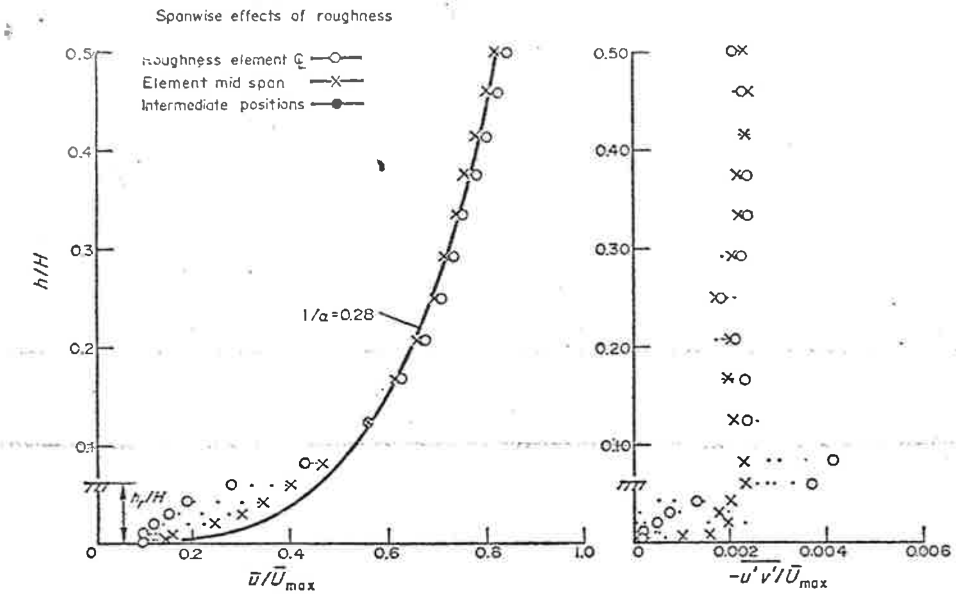

FIG. 4. Boundary layer simulation—urban terrain, Station *B*.

It was assumed in Section 3.7 that the scales of turbulence in the streamwise direction would be reduced in the urban terrain in the range of heights influenced by the building wakes. This is shown to be the case in FIG. 7 which shows the variation of the along-wind length scale with height in the simulated boundary layer. It can be seen that the length scale increases with increase of height up to about y/δ (i.e. h/H) of about 0·40. Above this height the intermittency in the flow (COUNIHAN, 1970) will tend to reduce these scales of turbulence.

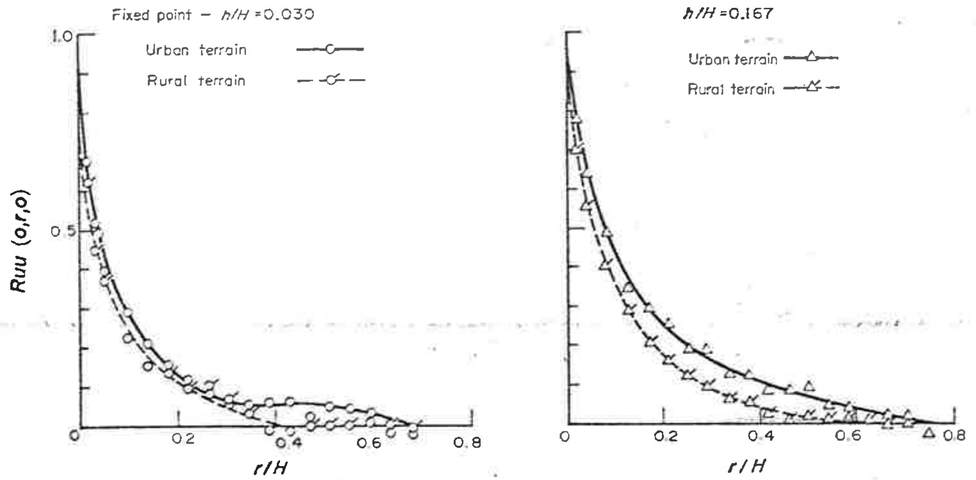

FIG. 5. Comparison of correlation coefficient distribution in simulated boundary layers. Spanwise position: generator centre-line.

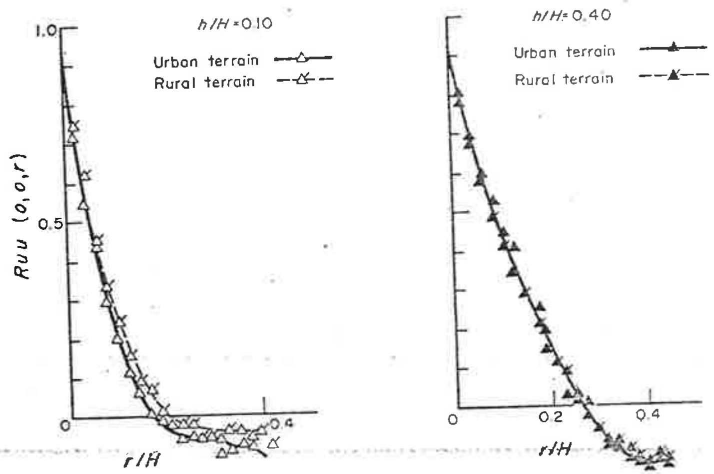

FIG. 6. Comparison of correlation coefficient distributions in simulated boundary layers. Fixed point: 0 mm (0 in.).

Very good agreement was obtained between the simulated boundary layer results and the measurements of ANTONIA and LUXTON (1971) in rough and smooth boundary layer flow: their ratio of roughness height to boundary layer height was similar to that of the urban simulation and their smooth surface was smoother than the rural simulation surface which consisted of "LEGO" baseboards. Therefore the rural

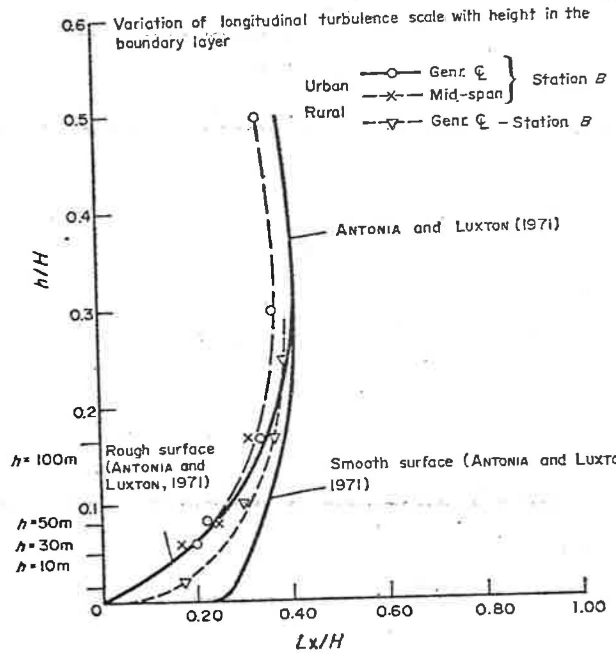

FIG. 7. Boundary layer simulation—urban terrain.

simulation length scales should, and in fact do, lie between the rough and smooth results of Antonia and Luxton.

From the above results the turbulent length scales were considered to be adequately simulated in the urban boundary layer.

4.4 *The power spectral densities*

Typical spectra of the longitudinal, lateral and vertical fluctuating velocities are compared with the rural spectra in FIG. 8. The longitudinal spectra are seen to be similar in form; the urban spectrum has been normalized with respect to the rural terrain longitudinal spectrum to illustrate this. A small secondary peak is evident in the urban longitudinal spectrum which is consistent with the comments of Section 3.3. The size of this peak is clearly dependent on the position at which the measurement is made relative to the roughness elements.

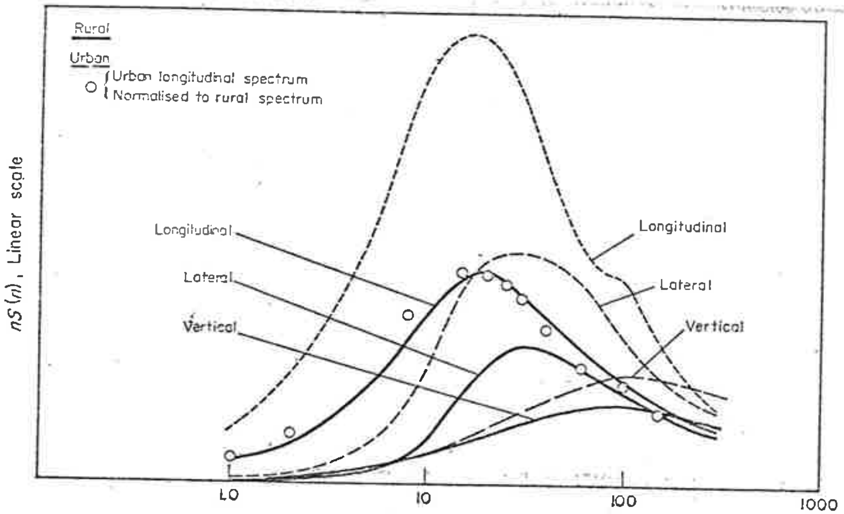

FIG. 8. Urban boundary layer simulation. Power spectral densities of fluctuating velocities at $h/H = 0{\cdot}167$.

The longitudinal spectra, measured over a height range of $0{\cdot}06 \leqslant h/H \leqslant 0{\cdot}50$, have been normalized by the mean squares of the respective fluctuating velocities and have collapsed generally to a single curve (FIG. 9). Spectral measurements made below $h/H = 0{\cdot}06$ would not be expected to follow this invariance however, for the reasons stated in Section 3.3.

The variation of the spectra of the vertical fluctuating velocity with height, in the range $0{\cdot}06 \leqslant h/H \leqslant 0{\cdot}50$, is shown in FIG. 10. In this case, the peak $n\,S_v(n)$ values occur at progressively lower frequencies with increase of height in the boundary layer. In order to determine whether this behaviour is consistent with observations from full-scale data the following table has been derived from FIG. 10:

h/H:	0·06	0·083	0·167	0·30	0·50
$(h/H)n_p$:	9·00	11·6	18·4	21·00	27·00

where n_p is the frequency at which the peak $n\,S_v(n)$ occurs.

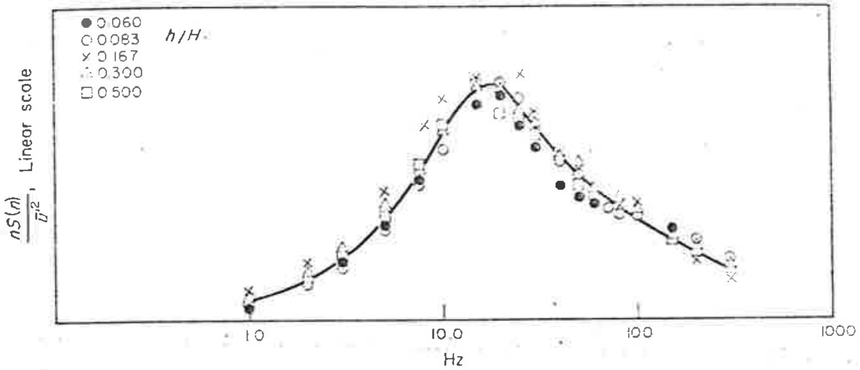

FIG. 9. Urban boundary layer simulation. Normalised power spectral densities of longitudinal velocity on generator centre-line.

It can be seen that $(h/H)n_p$ increases with increase of height in the boundary layer, the rate of increase being greater at heights below about $h/H \simeq 0{\cdot}15$. PANOFSKY's (1969) analysis of many full-scale measurements made over mainly rural terrain, suggests that below h/H of about 0·10 the above product is essentially constant, which implies that the scale of turbulence increases linearly with increase of height. Above this height he found the product $(h/H)n_p$ to increase, which implies that the turbulence scale increases less rapidly with height. Above h/H of 0·15 the simulated flow measurements are consistent with these full scale observations. Near ground level (i.e. $h/H <$ 0·15) the vertical scales of turbulence in the urban simulation increase less rapidly with increase of distance from the ground due to the greater ground roughness,

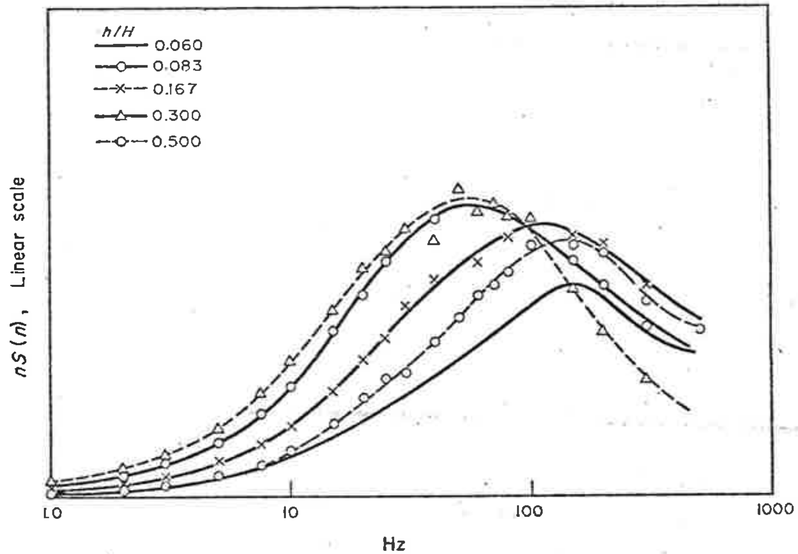

FIG. 10. Urban boundary layer simulation. Power spectral densities of vertical velocity on generator centre-line.

consequently a constant $(h/H)n_p$ is not observed. This is consistent with the observations made in Section 4.3 concerning the comparison of the vertical scales of turbulence in urban and rural boundary layers.

4.5 *The co-spectra of the Reynolds stresses*

The measured co-spectra of the Reynolds stresses are shown in FIG. 11 and compared with the rural terrain co-spectra and the semi-empirical form suggested by PANOFSKY and MARES (1968). As can be seen, the major part of the energy contribution lies between $0{\cdot}01 \leqslant f \leqslant 1{\cdot}0$.

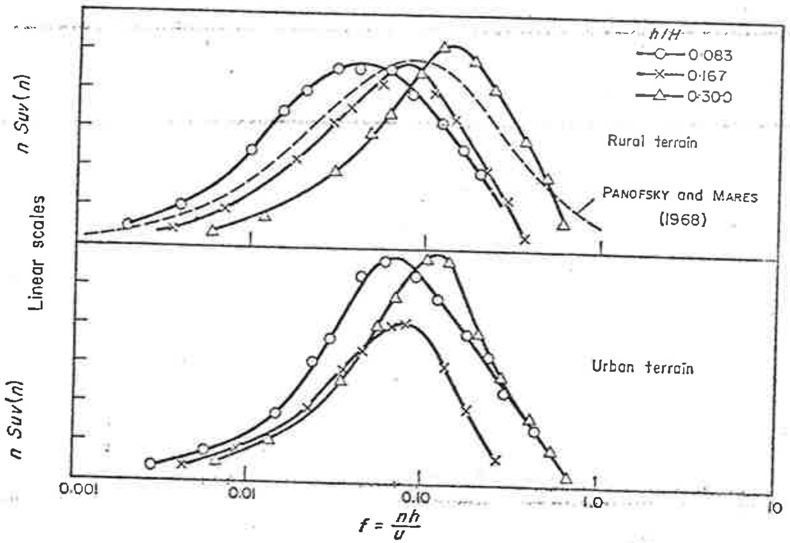

FIG. 11. Boundary layer simulation: co-spectra of the longitudinal and vertical fluctuating velocities.

The forms of the semi-empirical curve and the rural terrain measurements at $h/H = 0{\cdot}083$ are very similar. This is to be expected since the curve of Panofsky and Mares was derived from data mainly obtained near ground level.

The co-spectral measurements in the urban terrain at various heights generally agree with these made in the simulated rural terrain, apart from one inconsistency which has not been explained. However, since the forms of the longitudinal and vertical spectra and their variation with height, in the height range considered, were considered acceptable, it follows that this variation of the co-spectra with height is also acceptable.

4.6 *The probability density distributions*

Typical measurements of the probability density distributions of the longitudinal fluctuating velocity in the simulated urban and rural boundary layers are shown in FIG. 12. The measurements cover a range of ± 2–$3\ \sigma$. Within the limits of accuracy to which full-scale measurements are termed Gaussian, these distributions can also be considered as Gaussian. However, they do show variations from the Gaussian distribution at high values of the standard deviation which could be significant in

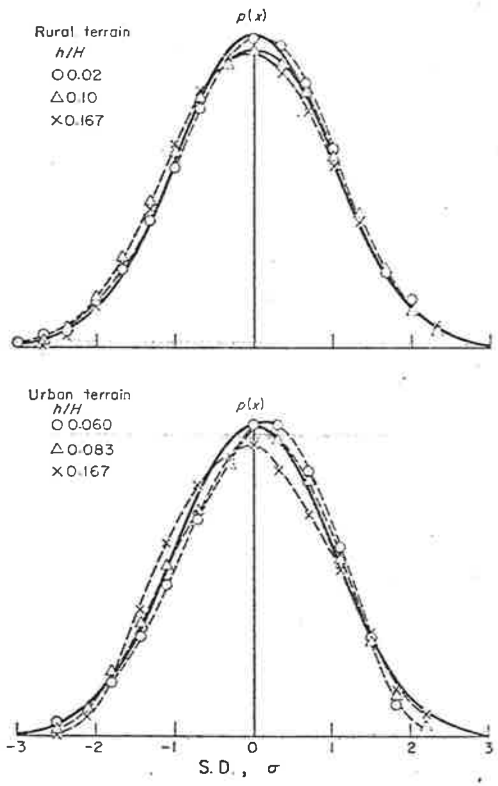

FIG. 12. Probability density distribution of the longitudinal fluctuating velocity in simulated rural and urban boundary layers.

relation to wind loading problems, if the full-scale data, when it is available, also shows this feature. Similar distributions were obtained for the lateral and vertical fluctuating velocities.

4.7 *The variation of the power index with the roughness parameter*

Having achieved a satisfactory simulation of urban and rural types of terrain, it is desirable that intermediate types of flow could also be simulated. Suburban conditions can be interpolated from available meteorological data and from the boundary layer simulation work. Hence three main types of terrain can be defined as follows:

Terrain	Rural	Suburban	Urban
$1/a$	0·143	0·21–0·22	0·28
y_o(m–full scale)	0·10	1·00	2–3
h_1/H	0·146	0·175	0·208

(h_1 = barrier height to base of castellations)

The full-scale mean boundary layer depth has been assumed in all cases to be of the order of 600 m (2000 ft).

Hence if the roughness parameter of a particular site can be defined, then the adiabatic atmospheric boundary layer flow can be modelled in a wind tunnel within the range of terrain types tabulated above.

5. CONCLUSIONS

(a) The definition of the urban boundary layer, in Section 3, is considered to be the best available consistent with the small amount of full-scale information.

(b) The simulation is considered to be an adequate representation of a boundary layer so defined.

(c) An attempt has been made to define the scaling factors for the main terrain types for the purpose of simulating such flows.

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