Reference pressure for wind load measurements in a turbulent boundary layer.

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SUMMARY

Within a turbulent boundary layer the static pressure is not spatially constant but exhibits extreme negative pressure fluctuations that contribute to a significant negative mean value in static pressure. The mean static pressure relates to turbulence intensity and varies with height which makes wind load pressure coefficients dependent on the location of reference pressure.

1 INTRODUCTION

Surface pressure measurements were made on the Silsoe 6 m cube some time ago (Richards, et al, 2001) but at that time we were not aware of the influence of static pressure variations associated with eddies in turbulent flow. Measurements of static pressure in the lower part of the atmospheric boundary layer were made on two occasions with full experimental details and analysis given in Hoxey et al, 2021. These eddies, which are a characteristic of turbulent flow, are vortical in structure with a low-pressure core; they exist in sizes from a few millimetres to possibly the boundary-layer thickness.

There are two distinct ways in which static pressure is evident in wind-load measurements. The mean static pressure is spatially depressed and varies with height, following the pattern of turbulence intensity within the boundary layer. This means the reference pressure used as the backing pressure applied to the differential pressure transducers is location dependent and of significance in the evaluation of pressure coefficients. Secondly, the static pressure has a distinct spectral pattern compared to the spectrum of dynamic pressure.

There is limited work with which to make comparisons; the only other full-scale work known of is by Albertson et al 1998 who also found similar spectral properties. Brief reference has been made to wind-tunnel studies on boundary layers at much lower Reynolds Number (Tsuji, et al 2007), but no published work has been found where fluctuating static pressure has been measured in industrial boundary-layer flows, where models are present. The findings have application to all pressure measurements in turbulent flows and specifically to the highly turbulent flows in industrial wind tunnels.

2 MEASUREMENTS IN THE ABL

2.1 Introduction

Measurements were made on the experimental site at Silsoe on a 6 m cube which was mounted on a turntable and could be rotated through 360º (Richards et al 2001, Richards & Hoxey 2012). The approach flow for the measurements reported here were from WSW over open farm land and cut grass extending over 500 m with a typical roughness length z_o of 10 mm. The pressures from surface tapings, together with the simultaneous recording of the 3 components of wind speed using a Gill Instruments symmetrical-head ultrasonic anemometer mounted at a height of 6 m, 18 m upstream of the cube, were recorded. The reference pressure was from a static probe (Moran & Hoxey 1979) mounted near the sonic anemometer at a height of 6 m. The measurements used in this paper are from Run 68 for a WSW wind near normal to the face of the cube, and made at 5 samples per second for a 1-hr period (18,000 data points). With the cube rotated by 90 degrees, the same tapping points were monitored in Run 39 with a similar WSW wind direction, recorded at 4.167 samples per second for 36 minutes (9,000 data points).

On the same site, but on different occasions, measurements of static pressure were made. The data set used here is Run 888 with a similar WSW wind direction, recorded at 10 samples per second for 20 minutes (12,000 data

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points). Static pressure was measured at ground level and at 1, 3 and 6 m heights referenced to a time and spatially-averaged ground-level pressure.

2.2 Characteristics of the ABL wind

Many measurements of the boundary layer at the Silsoe experimental site have been made, for example Richards et al, 2000. For the example runs used here, for a WSW wind, the upstream conditions were similar to when measurements were made of static pressure (Run 888).. An example of the velocity (U_z) at height z and the velocity component turbulence intensities (I_u, I_v and I_w) obtained from the ultrasonic anemometer on the 6 m mast are shown in Table 1. The mean frictional velocity, u_τ was derived from the mean Reynolds stress $-\overline{u'w'} = u_\tau^2$.

Table 1 Mean value statistics derived from the ultrasonic anemometer at 6 m height

	z (m)	*Mean U_z* (m s^{-1})	I_u	I_v	I_w	u_τ (m s^{-1})	$\frac{u_\tau}{U_z}$	*Spectral Index*
Run 888	6	8.61	0.188	0.169	0.082	0.577	0.067	-1.66
Run 68	6	11.70	0.229	0.165	0.097	0.787	0.067	-1.66
Run 39	6	9.45	0.203	0.173	0.078	0.651	0.069	-1.68

In the pressure measurements that follow, wind velocity (U_z) is converted to wind dynamic pressure (q_z) where $q_z = ½\rho U_z^2$ (ρ is air density, a value of 1.226 kg m^{-3} has been used). The spectra of q are shown in Fig. 1; the PSD (Power Spectral Density) is of $S_q(n)/\sigma_q$ for each run (σ_q is the standard deviation of q); dividing by σ_q makes the PSD dimension seconds (s). These spectra follow the expected decay close to $n^{-5/3}$ over the frequency range shown in the inertial subrange, with values of the least-squares fit of the spectral index given in Table 1.

A 10-min record of the measured dynamic pressure and of the static pressure at a height of 6 m are shown in Fig. 2. The static pressure was measured relative to a ground-level pressure tapping but 'true zero' (Hoxey et al 2021) for static pressure at z = 6 m has been applied in place of the backing pressure from the ground tapping. It should be noted that extreme negative peaks in static pressure are often missed as the sampling rate is insufficient with only some evident in Fig. 2. For boundary-layer wind-tunnel flows, an equivalent 'true zero' can be obtained from a sensor placed above the turbulent boundary layer in low-turbulence flow, as used by Tsuji, et al 2007.

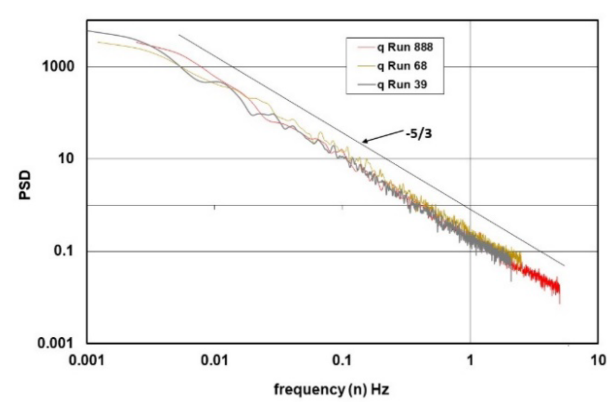

Figure 1 Spectra ($S_q(n)/\sigma_q$) of the wind dynamic pressure at 6 m for the three runs.

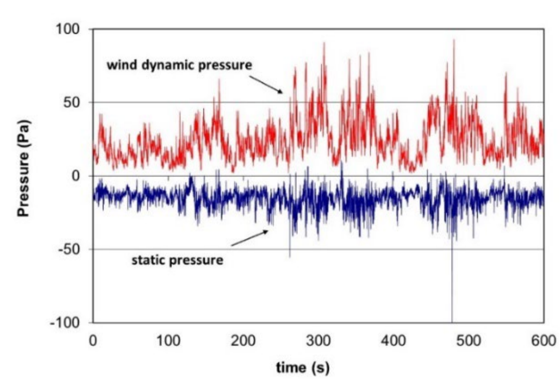

Figure 2 Example of the wind dynamic and static pressure in the ABL at a height of 6 m.

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2.3 Measured values of wind dynamic pressure and of static pressure

The measured mean and RMS values of dynamic pressure (q_z), and of static pressure (p_z) for Run 888 are summarised in Table 2. For Run 888, the mast measurements, p_z are the measured mean static pressure at height z relative to the 'true zero' static pressure (p_t). The derivation of the 'true' static pressure p_t is based on an argument that static pressure excursions are negative. All mean static pressure values are expressed as pressure coefficients (Cp) in terms of the mean wind dynamic pressure at 6 m ($q_{\text{mean 6m}}$). The dynamic pressure turbulence intensity (I_q) is defined as q_{RMS} / $q_{\text{mean 6m}}$.

Table 2 Mean and turbulence intensity of wind dynamic pressure and for Run 888 the mean and RMS of static pressures on the 6 m mast

	z (m)	q_{mean} (Pa)	I_q $q_{RMS}/q_{mean\ 6m}$	p_z-p_t/$q_{mean\ 6m}$	$p_{RMS}/q_{mean\ 6m}$
Run 888	*0*			-0.142	0.029
	1			-0.225	0.055
	3			-0.262	0.062
	6	48.7	0.369	-0.286	0.069
Run 68	*6*	91.3	0.443		
Run 39	*6*	58.5	0.412		

Figure 3 illustrates the sensitivity of static pressure to turbulence which has an impact on the selection of reference pressure when making measurements in boundary-layer flows. This figure includes static pressure measurements on a 10 m mast at 1, 3, 6 and 10 m heights (Hoxey et al, 2021), and show the distribution of static pressure with height. This is consistent with that found by Tsuji et al 2007 for a thin boundary layer on a wind-tunnel floor but as the Reynolds Number and turbulence levels were much lower than at full scale, the magnitude of the pressure coefficients were much reduced.

3.2 Mean surface pressure measurements on the 6 m cube

An example of the measured mean pressure coefficients for the 6 m cube is shown in Fig.4. The example is for a wind near normal to the face of the cube. The coefficients are in relation to the mean dynamic pressure at cube height (6 m) and referenced to a pressure from a static probe (transducer backing pressure) also at cube height, both measured 18 m upstream of the cube.

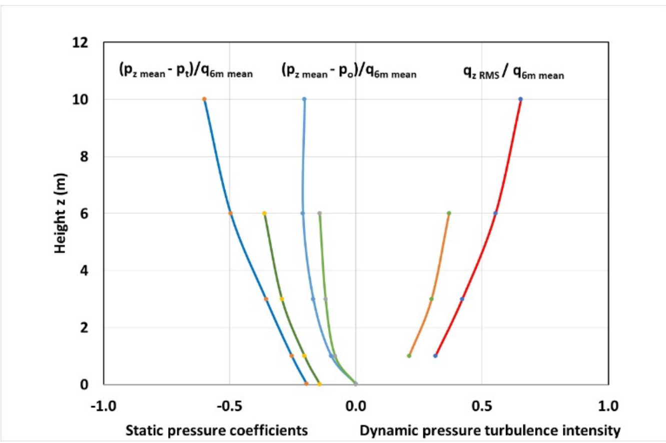

Figure 3 Static pressure coefficients based on $q_{\text{mean 6m}}$: 10 m mast values in blue, 6 m mast values from Run 888 in green. Dynamic pressure turbulence intensity (I_q) for 10 m mast in red and for 6 m mast in orange.

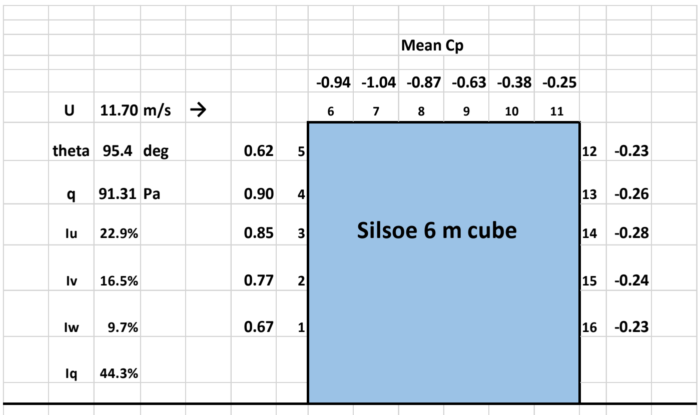

Figure 4 Mean pressure coefficients, and mean wind statistics for Run 68: a one-hour record at 5 samples/s (18000 data points): integers denote tap number. Reference dynamic and static pressure is at cube height sensed at 18 m upstream.

Three example tapping points are presented in Table 3 to illustrate the significance of the location of the

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reference pressure on the evaluation of pressure coefficients. This finding has direct application to all pressure measurement studies in turbulent flows where wind loads are derived relative to a reference pressure from some point in the flow.

Table 3 Mean pressure coefficient for the three example tapping points

	mean Cp relative to static pressure at 6 m	***relative to ground static pressure p_o (-0.144)***	***relative to free stream p_t (-0.286)***
windward wall tap 4	0.903	0.759	0.617
roof tap 9	-0.633	-0.777	-0.919
side wall tap 4*	-0.698	-0.842	-0.984

4 SPECTRAL PROPERTIES OF STATIC PRESSURE

The spectral properties of static pressure fluctuations have been described by Hoxey et al, (2021) and not included in this paper. Surface pressure spectra for the 6 m cube have been examined to show where on the cube surfaces there is evidence of fluctuating static pressure contributing to wind load.

5 CONCLUDING REMARKS

The analysis described above has been developed from measurements of turbulence including static pressure in the ABL. These measurements have shown that turbulent flows consisting of eddies have significant low-pressure centres with a negative mean static pressure which relate to dynamic pressure turbulence intensity. In turbulent boundary layers, the location of reference pressure affects pressure coefficients in wind load experiments.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author (roger@hoxey.com) upon reasonable request.

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