SPATIALLY DETECTED NEAR WALL SHEAR LAYER EVENTS IN SMOOTH AND ROUGH WALL TURBULENT BOUNDARY LAYERS

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ABSTRACT

The characteristics of near wall shear layers in smooth and rough wall turbulent boundary layers have been studied. Events were detected using the VITA technique combined with a recently developed spatial detection technique that could determine the size of these events. In contrast to previous work, the near wall shear layers were found to be associated with large scale events, on the order of half the boundary layer thickness in height.

INTRODUCTION

Studies using conditional sampling techniques have employed detection schemes which utilise certain aspects of the bursting process in identifying the events. The VITA (variable interval time averaging) technique, introduced by Blackwelder and Kaplan (1976), detects strong velocity gradients. The studies of Johansson et al. (1987), Johansson et al. (1991), and Gan and Bogard (1991) have shown that VITA detects shear layer events inclined to the wall. These studies, and previous conditional sampling studies, used single point detection schemes at a particular height. With such detection, the size of the individual events being detected cannot be ascertained.

In this study, a relatively new spatial detection technique, introduced by Bolton and Bogard (1992), was used in conjunction with single point VITA to educe the size of the high and low velocity regions associated with the shear layers. Measurements were made over both smooth and rough walls.

FACILITIES AND PROCEDURES

Measurements were made in a recirculating low speed open water channel facility with a test section that was 5m long, 50cm wide and 30cm high. Flow velocity was nominally 20cm/s, and the boundary layer thicknesses for the smooth and rough wall measurements were nominally the same with δ_s = 67mm and δ_r = 69.5mm. Momentum thickness Reynolds numbers were $Re_{\theta s} = 1600$ and $Re_{\theta r} = 2300$. A single component scanning LDV, scanning at a rate of 28 scans/s, was used to measure instantaneous velocity profiles in the range $0.02 \leq y/\delta \leq 0.5$. This scanning LDV system is the same one used by Kohli and Bogard (1992).

The rough wall comprised k-type cylindrical elements placed in a square array, with the leading edge 1.8m downstream of the test section entrance. In the fully developed rough wall flow, the height of the roughness elements was $k_r^+ = 70$. The equivalent sandgrain roughness Reynolds number was $Re_{ks} = 350$, which was in the fully rough régime and hence independent of viscous effects. This is an important point when considering spatial and temporal scaling of the detected structures since commonly used inner scaling is no longer appropriate.

EVENT DETECTION

VITA detections were performed at $y/\delta = 0.05$ ($y^+ = 30$) and $y/\delta = 0.15$ for the smooth wall, and at $y_r/\delta = 0.15$ for the rough wall, where y_r is measured from the apparent origin of the rough wall boundary layer. For the rough wall, $y_r^+ = 30$ is below the crest of the roughness elements. These detection heights were within the constant stress layer.

The VITA technique was used with the addition of a slope criterion, which separated detections with positive and negative gradients. The thresholds used for the detections were k = 1.0 for positive slope detections, and k = 0.8 for negative slope detections. Different thresholds were used for positive and negative slope to equalise the number of events. For the smooth wall an averaging time of $T_a^+ = 10$ was used. For the rough wall, viscous effects are negligible so that scaling based on inner variables is not appropriate. Thus, the averaging time of $T_a^+ = 10$ is not valid. In order to establish an equivalent averaging time, as detailed in Gan (1994), the ratio of the smooth wall quadrant-detected burst duration to the rough wall burst duration was used as a scaling factor in determining the appropriate averaging time for the rough wall VITA detection. Based on inner variables the rough wall averaging time was $T_a^+ = 42$.

The spatial detection technique used in this study was initially developed by Bolton and Bogard (1992). This technique detects high or low speed regions in the streamwise and wall-normal (x-y) plane. As a first step, detections are made at discrete points in the y-t plane. A low speed detection is made whenever $u < -L_L u'$, where L_L is the user-specified threshold. A high speed detection is made when $u > L_H u'$. Discrete detections are then grouped into spatial events using the following criteria:

1. Discrete detections must be located within $y^+ = 20$ of each other in the same scan.
2. A discrete detection must be located within an adjacent scan of another detection and within $y^+ = \pm 10$.

The time between scans was $t^+ = 3$ for the smooth wall, and $t^+ = 8$ for the rough wall. Events were classified according to the number of discrete detections, as shown in Table 1. As suggested by Kohli and Bogard (1992), thresholds of $L_L = 0.7$ and $L_H = 0.8$ were used for the smooth wall, and $L_L = L_H = 0.8$ for the rough wall.

RESULTS AND DISCUSSION

The general spatial velocity field characteristics associated with VITA-positive slope detections are shown in Figure 1(a) for smooth walls and Figure 1(b) for rough walls. These results are based on an ensemble average of 339 events and 287 events for the smooth and rough walls, respectively. Note y/δ and x/δ coordinates are used, rather than y^+ and x^+ coordinates, to facilitate comparisons between smooth and rough walls. For the smooth wall, the strong, inclined shear layer with high speed (+u) region upstream and low speed (–u) region downstream is similar to the results obtained by Johansson et al. (1987) and Johansson et al. (1991). Similar to the previous results, the –u region is distinctly stronger (larger –u magnitude) than the +u region. The present VITA detection was applied at a height of $y^+ = 30$, resulting in a shear layer slightly higher than obtained by Johansson et al. (1987) and (1991) who detected at $y^+ = 15$. Also the +u region is clearly higher than the –u region, whereas for the previous detections at $y^+ = 15$ the +u and –u regions were at about the same height. The velocity contours associated with VITA-positive slope detections over a rough wall, Figure 1(b), show an inclined shear layer similar to the smooth wall. While the length of the structure is about the same, the height of the structure is distinctly larger. Note that these results were not due to the difference in heights at which events were detected, as verified by comparison with smooth wall detections at $y/\delta = 0.15$.

Velocity contours for VITA-negative slope detections are presented in Figure 2(a) for smooth walls (267 events) and Figure 2(b) for rough walls (323 events). Naturally, the –u region precedes the +u region for these events, but there is no evidence of an inclined shear layer as exists for VITA-positive slope events. Evidently this shear layer occurs for VITA-positive slope events due to the impact of the +u region on the –u region; this would not occur if the +u region was downstream of the –u region as in VITA-negative slope events. For the rough wall the +u and –u regions again have a greater height and the +u region is stronger than that for the smooth wall.

Although the conditionally sampled velocity field characteristics described above appear to give a good sense of the size of the VITA events, these results are misleading since they represent ensemble averaging of all VITA events from very small to very large sizes. For single point detections, events of different sizes cannot be resolved, and including events of all sizes in the ensemble averages must necessarily be done. However, for this study the velocity field that is obtained with the scanning LDV allows us to determine the sizes of the +u and –u regions associated with each VITA event. The regions associated with each VITA detection were examined and each VITA detection was classified in terms of the -u or +u regions associated with it as follows:

1. Low speed event alone
2. High speed event alone
3. Both a high and a low speed event
4. None

A high or low speed spatial structure was considered to be associated with a VITA detection if part of the spatial structure passed through the detection height, and if the time of the spatial structure coincided with or was immediately before or after the VITA detection. The size classes defined in Table 1 do not give a physical size for the spatial structures. Physical sizes for these structures will be discussed following these results, but before presenting these results it is worthwhile noting that the large and extra-large size classes are of the order of the boundary layer thickness.

The following results are based on analyses of data records $TU_\infty/\delta = 1930$ in length for the smooth wall and $TU_\infty/\delta = 2140$ for the rough wall. For the smooth wall there were 866 low speed and 742 high speed spatial events, and for the rough wall there were 921 low speed and 948 high speed spatial events which were identified with some part of the structure passing through the detection height. Table 1 lists the percentage of these structures in each size class. The percentage of VITA detections classified under each of the four categories listed above is given in Table 2 for VITA-positive slope and VITA-negative slope detections for the smooth and rough walls. Looking first at the smooth wall results, 97% of the VITA-positive slope detections and 94% of the VITA-negative slope detections were associated with some high or low speed spatial structure—clearly a strong association of spatial structures with VITA detections. Most striking, however, is that over 80% of the VITA detections were associated with large and extra-large spatial structures. Also, the VITA detections were primarily associated with both high and low speed spatial structures. This last result indicates that the strong shear layers, which are detected by VITA, primarily occur between high and low speed spatial structures which are relatively close to each other.

Results for rough walls listed in Table 2 are similar to the smooth wall results except that there is a definite shift

Table 1 Classification of spatially detected event sizes.

Classification		No. of discrete detections	Pct. of total events (low sp./high sp.)
Smooth wall	Small	3 to 8	31/33
	Medium	9 to 32	28/23
	Large	33 to 256	30/32
	X-large	≥ 257	12/12
Rough wall	Small	3 to 8	23/21
	Medium	9 to 32	22/23
	Large	33 to 256	36/37
	X-large	≥ 257	19/19

Table 2 Percentages of VITA detections with associated spatial events.

Classification		Low	High	Both	None
Smooth wall pos. slope (339 events)	Total	25	12	60	3
	Sm/Med	6	3	6	-
	Large	17	4	31	-
	X-large	2	4	23	-
Smooth wall neg. slope (267 events)	Total	41	8	45	6
	Sm/Med	9	1	2	-
	Large	22	4	20	-
	X-large	9	3	23	-
Rough wall pos. slope (287 events)	Total	16	12	71	2
	Sm/Med	2	2	0	-
	Large	8	4	20	-
	X-large	6	6	51	-
Rough wall neg. slope (323 events)	Total	19	19	53	9
	Sm/Med	2	2	2	-
	Large	8	7	18	-
	X-large	9	10	34	-

to being predominantly associated with extra-large spatial structures, and there is a greater percentage occurring between high and low speed spatial events.

A measure of the physical size of the spatial structures was obtained by averaging the streamwise and wall-normal extents of the spatial structures associated with VITA detections. In the streamwise direction, the extents were obtained by multiplying the duration of the structure by the mean convection velocity of the structure. The convection velocities, obtained from Gan and Bogard (1991) and Gan (1994), were $0.56U_\infty$ ($13u_\tau$) for the smooth wall, and $0.50U_\infty$ ($7.4u_\tau$) for the rough wall.

The extents of spatial events corresponding to positive shear layers are shown in Table 3. As discussed above, the large and extra-large events were the predominant structures associated with VITA detections. These events were 0.25δ to 0.5δ high in the wall-normal direction ($y^+ = 145$ to 290, smooth wall; $y^+ = 270$ to 540, rough wall). In the streamwise direction they were 0.9δ to 2.5δ long ($x^+ = 530$ to 1470) for the smooth wall, and 0.7δ to 1.8δ long ($x^+ = 750$ to 1940) for the rough wall. Note the slight differences in the physical sizes of the spatial structures for smooth and rough walls is not significant because the size classification for the two surfaces were not equivalent owing to differences in the convection velocities of the structures. The aspect ratios of the spatial structures indicate that the smooth wall structures are slightly elongated relative to the rough wall structures.

Velocity contours of VITA-positive slope detections associated with both high and low speed large and extra-large events are shown in Figure 3. When comparing with

Table 3 Physical extents of spatially detected events associated with positive slope shear layers, according to size.

Classification		Streamwise x/δ (x^+)	Wall-normal y/δ (y^+)	Aspect Ratio (y/x)
Smooth wall low sp.	Sm/Med	0.32 (190)	0.09 (50)	0.28
	Large	0.91 (540)	0.28 (160)	0.31
	X-large	2.5 (1470)	0.50 (290)	0.20
Smooth wall high sp.	Sm/Med	0.25 (150)	0.09 (50)	0.36
	Large	0.90 (530)	0.34 (200)	0.38
	X-large	2.1 (1240)	0.50 (290)	0.24
Rough wall low sp.	Sm/Med	0.15 (160)	0.08 (90)	0.53
	Large	0.67 (720)	0.24 (260)	0.36
	X-large	1.8 (1940)	0.48 (520)	0.27
Rough wall high sp.	Sm/Med	0.19 (200)	0.11 (120)	0.58
	Large	0.59 (640)	0.27 (290)	0.46
	X-large	1.8 (1940)	0.51 (550)	0.28

the smooth wall results in Figure 1, it is readily evident that the +u region is much larger than that seen in standard single point VITA detections, but the -u region is about the same. The rough wall results were not altered as much because even the standard detections are dominated by large and extra-large regions. Note that the +u regions for both smooth and rough walls are also stronger than those in Figure 1, while the -u regions are nominally the same.

CONCLUSION

A recently developed spatial detection technique has been used in conjunction with the VITA technique to educe the size of the high and low velocity regions associated with near wall shear layer events over both smooth and rough walls. In contrast to previous conditional sampling analyses which indicated that these structures were confined to the near wall region, we found that the structures are large scale events, ranging in height from $y/\delta = 0.25$ to 0.5, and in length from $x/\delta = 1$ to 2.

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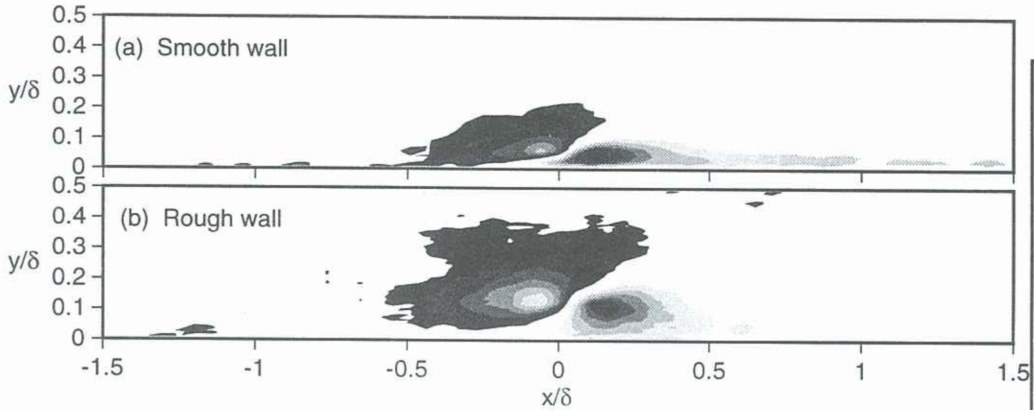
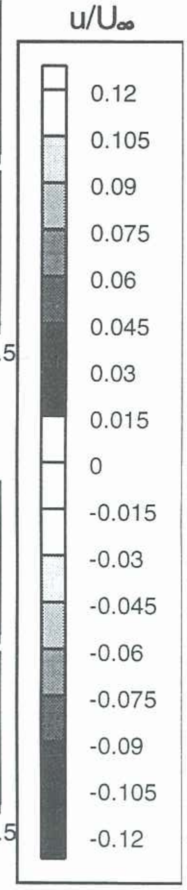


Figure 1 Conditionally sampled u velocity contours of all VITA events with positive slope.



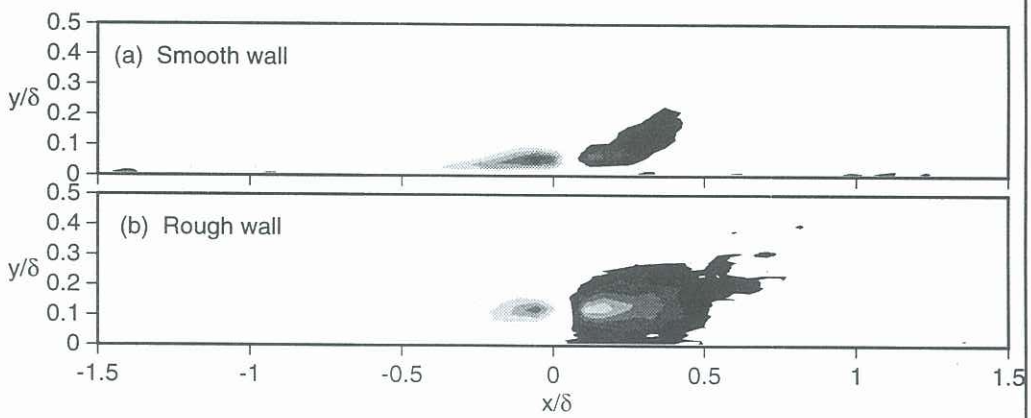


Figure 2 Conditionally sampled u velocity contours of all VITA events with negative slope.

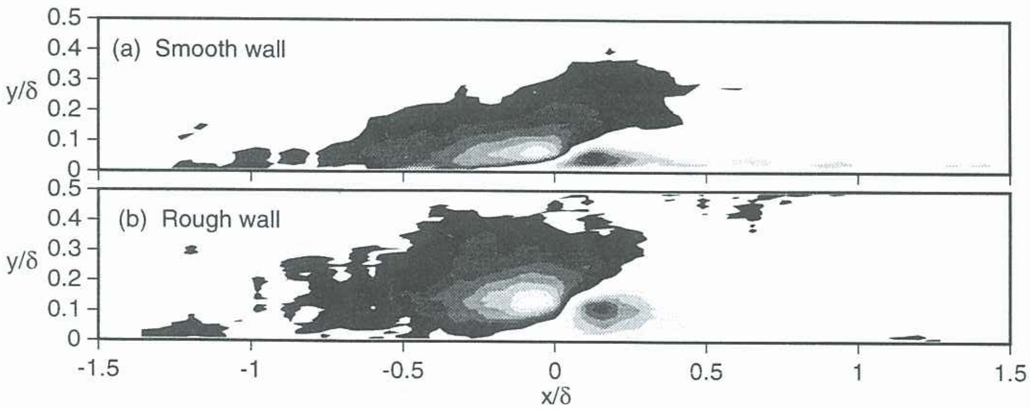


Figure 3 Conditionally sampled u velocity contours of VITA events with positive slope, associated with large and extra-large high and low speed spatially detected events .