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METHODS TO DETECT COHERENT STRUCTURES - A COMPARISON

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Abstract

The turbulent structures obtained by applying the VITA, the modified u-level, the TERA and the Quadrant methods on a set of data obtained on a rough surface turbulent boundary layer have been compared. It is shown that the TERA method which is applied to the u-velocity signal only, appears to be able to capture all detections obtained by the quadrant method. It is also shown that the modified u-level detections are similar to those of TERA, while the VITA method performs quite differently.

Introduction

Coherent structures have been shown to exist in turbulent flows (e.g. Kline, Reynolds, Schraub and Runstadler, 1967) and are believed to be responsible for most of the turbulent shear stress production (Lu and Willmarth, 1973; Sabot and Commte-Bellot, 1976). A deep understanding of the coherent structures should therefore be a benefit to turbulence modeling work. The best way to evaluate an algorithm for detecting structures is probably to compare its performance with visual information (e.g. Bogart and Tiederman 1986, Luchik and Tiederman 1987). One conclusion from this type of studies has been that detection algorithms based on two velocity components are the most reliable. However, algorithms based on the u-velocity component only appear attractive since single component measurements are easier to perform and may be obtained closer to a wall. In the present study the performance of three algorithms based on u (VITA by Blackwelder and Kaplan, 1976, modified u-level by Luchik and Tiederman, 1987 and TERA by Falco and Gendrich, 1990) are compared to the performance of the Quadrant method by Lu and Willmarth, 1973.

Coherent structure algorithms

The most widely used detection algorithm is probably VITA (Variable Interval Time Averaging). A short time window is used to low-pass filter the fluctuating u-velocity signal and a detection is said to occur when the variance in the window exceeds a predefined threshold K.

$$\mathrm{Var}(u) = \frac{1}{T}\int_{t-T/2}^{t+T/2} \left(\bar{\bar{u}} - u\right)^2 dt > K(u')^2 \qquad (1)$$

Here $\bar{\bar{u}}$ is the window mean and u' the long time standard deviation. The velocity gradient, $\frac{\partial u}{\partial t}$, is used to distinguish between sweeps and ejections. If the velocity gradient is positive at a detection point the event is taken to be an ejection, while a negative gradient is taken to belong to a sweep.

Luchik and Tiederman, 1987, proposed a modification to the detection method on u, originally developed by Lu and Willmarth, 1973. This is known as the modified u-level method. Here the local u-velocity is compared with u' and an event is said to start when u passes a threshold level $u * \mathrm{Sign} \geq L_1 u'$ and ends when u drops below another level $u * \mathrm{Sign} \leq L_2 u'$. Luchik and Tiederman suggested that the threshold levels should be taken as the ratio between the absolute value of the long time average in the second quadrant and u', $L_1 = \frac{|\bar{u}_2|}{u'}$. L_2 is taken as 0.25 L_1 and Sign is used to distinguish between ejections (Sign=-1) and sweeps (Sign=1).

Recently an algorithm called TERA (Turbulent Energy Recognition Algorithm) was proposed by Falco and Gendrich, 1990. This algorithm is based on the idea that a high rate of change of u^2 should be strongly coupled to large values of uv. The argument is based on the transport equation for $\overline{u^2}$.

$$\frac{D}{Dt}\left(\frac{1}{2}\overline{u^2}\right) = \overline{p\frac{\partial u}{\partial x}} - \overline{uv}\frac{\partial U}{\partial y} - \frac{\partial}{\partial y}\left(\frac{1}{2}\overline{u^2 v}\right) - \frac{1}{3}\varepsilon \qquad (2)$$

Since the production of turbulent energy first goes to $\overline{u^2}$, its rate of change should be strongly coupled to the turbulent shear stress. A detection is identified by inspecting the mean rate of change of $\frac{\partial}{\partial t}\left(\frac{1}{2}\overline{u^2}\right) = \overline{\overline{u\frac{\partial u}{\partial t}}}$ over a predefined window. The threshold level is determined from the long time standard deviation of the same quantity, $TR = C * \mathrm{rms}\left(\overline{u\frac{\partial u}{\partial t}}\right)$

The Quadrant method of Lu and Willmarth, 1973, uses the simultaneous u and v signals to enable the decomposition of the flow into the various quadrants. A detection is defined to occur when the shear stress in a certain quadrant exceeds a predefined level $|uv|_n > H_n u'v'$ where n denotes the quadrant. Bogard and Tiederman, 1986, proposed that H_n should be taken as the ratio of the long time averaged shear stress in quadrant n to the product u'v', $H_n = \frac{\overline{|uv_n|}}{u'v'}$

For all algorithms the events detected were grouped according to the method of Luchik and Tiederman, 1987, to prevent multiple detections inside the same structure. The grouping time was $\tau_g^+ = \frac{t_g u_\tau^2}{\nu} = 35$. Unless otherwise specified, the thresholds recommended by the originators have been used. For VITA and TERA these were fixed at K=0.4 and C=0.25 respectively. The averaging time for VITA was set to $\tau_a^+=20$, and the integration time for TERA, τ_i^+, was taken to be the same.

The methods were applied to velocity data obtained in a zero pressure gradient boundary layer over a mesh screen type rough surface with a roughness length of 1.55 mm (Krogstad and Browne, 1991). The Reynolds number based on the momentum thickness was $Re_\theta = 12800$ and the free stream velocity $U_e = 20$ m/s. At the measurement station the boundary layer thickness was $\delta = 75$ mm and the friction velocity $u_\tau = 1.0$ m/s.

Events detected by the four algorithms

Figure 1 a shows a time sequence of the u and v velocity as well as uv and $u\frac{\partial u}{\partial t}$. The ejections detected by the four algorithms for the same time sequence are shown in figure 1 b after grouping.

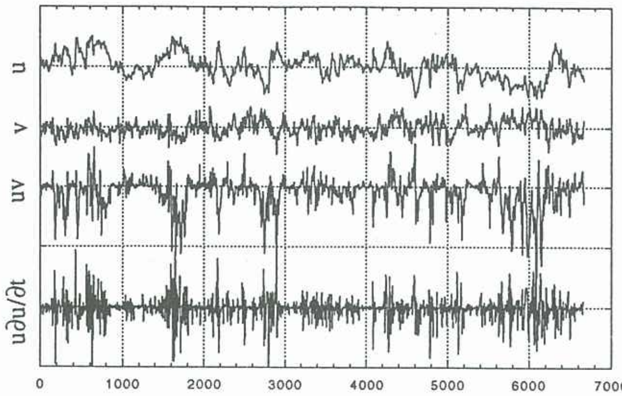

Figure 1 a. Time sequence of u, v, uv and $u\frac{\partial u}{\partial t}$ measured at $y/\delta = 0.135$

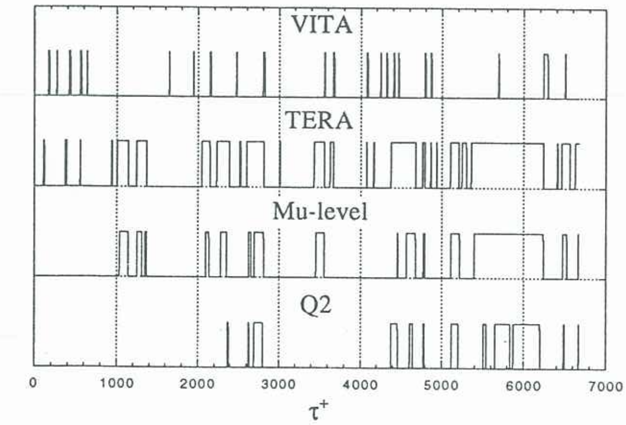

Figure 1 b. Detections for the sequence shown in figure 1a.

Figure 1 b shows that the detections made by VITA are of shorter duration than for the other methods and the detection points do not correspond very well with the other algorithms. It was found that VITA frequently triggers at the end of the detections made by the other methods. This may also be seen in the results presented in Falco and Gendrich, 1990. The modified u-level and TERA seem to trigger mostly on the same events. TERA also have some short duration detections not detected by the modified u-level method.

The distributions of the mean time between ejections and their mean durations through the boundary layer have been shown in figure 2 and 3 respectively. Using the same thresholds and roughly the same averaging and grouping times, Luchik and Tiederman (1987) in a smooth surface channel flow at $y^+ = 15$ found that the Quadrant, the modified u-level and VITA methods all gave about the same mean time between ejections. Figure 2 shows that, except for the modified u-level algorithm, the agreement is verified for $y/\delta < 0.5$. The average time between ejections, at about $T_e u_\tau / \delta = 0.05$ ($T_e^+=250$), is almost constant throughout the whole boundary layer. For smooth walls, values of $T_e^+ \approx 100$ have been found (Luchik and Tiederman, 1987, channel flow, Antonia and Bisset, 1990, boundary layer). The higher value found in the present experiment is believed to be due to the surface roughness.

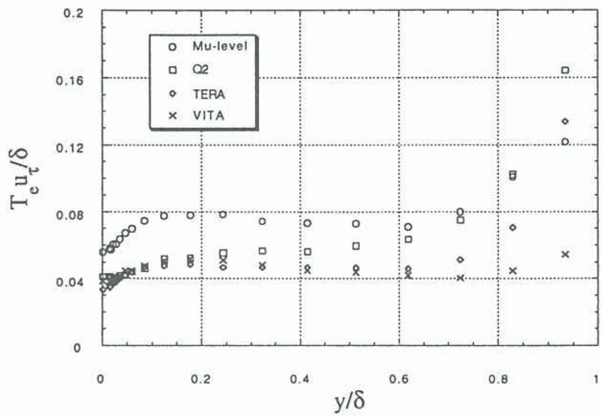

Figure 2. Mean time between ejections

Figure 3 shows, as indicated in figure 1 b, that the events detected by VITA are short compared to the other methods. It may also be seen that the modified u-level and TERA events are longer than those detected by Q2.

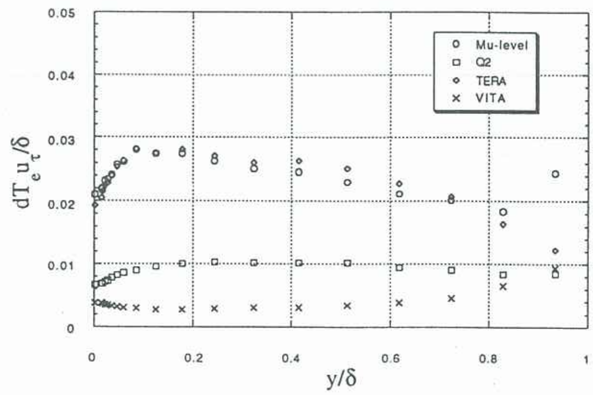

Figure 3. Mean duration of ejections

Conditional averages

Based on the detection points the conditionally averaged signals for both u and v at $y/\delta = 0.135$ are shown in figure 4 and 5 respectively. The plots are centered on the middle of the detection. It is evident that the duration of the <u> signal is longer than <v>, indicating a larger length scale in the streamwise than in the wall perpendicular direction.

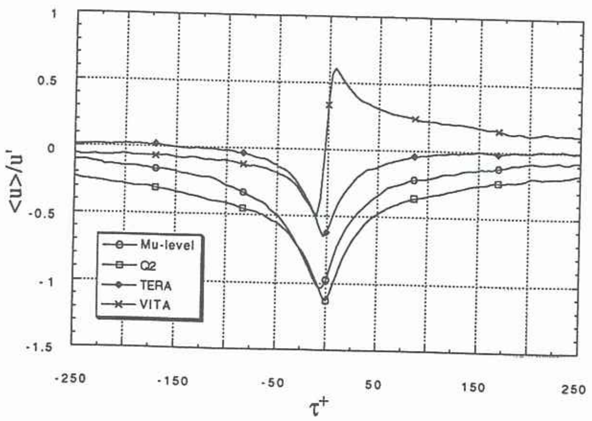

Figure 4. Conditionally averaged ejection signals for u

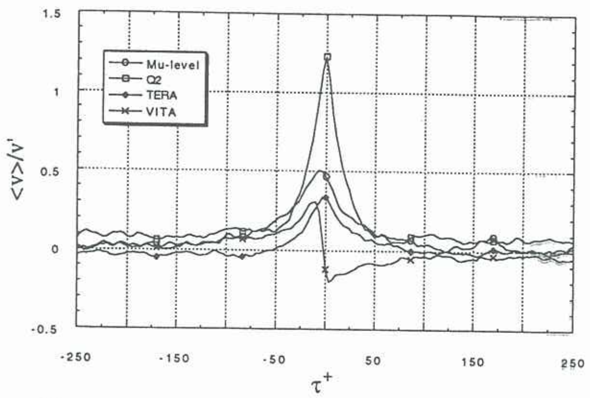

Figure 5. Conditionally averaged ejection signals for v

Both figure 4 and 5 show that the conditional averages based on VITA are quite different from the other averages. Based on the detections shown in figure 1 b this could be expected. Figure 4 shows that the averages from the modified u-level and Quadrant methods are quite similar both with respect to duration and amplitude. Also it may be seen that the TERA and Quadrant results are similar in form, but not in duration and amplitude. The differences are probably due to the additional short detections made by the TERA algorithm. The conclusions which apply to the conditionally averages of u also apply to v, shown in figure 5. Except for the VITA method, the main difference between the Quadrant and the other methods is the amplitude of the signal.

Statistics of the detection points

In order to further explore the detection performace, correlations between the detections made by the different methods were made. The detection files for ejections at $y/\delta = 0.135$ were compared and where two methods both indicated an event, it was checked which method had triggered first. The results, scaled with the number of common detections, are shown in table 2.

Table 2 clearly shows that TERA tends to trigger first compared to any of the other techniques.

In an attempt to decide which of the algorithms that matches the Quadrant method best, a normalized coexistence was computed. This was obtained by counting the number of matching detections between the Quadrant method and the other techniques, and then dividing this number by the number of detections made by the Quadrant method. The result is shown in figure 6.

VITA vs. Quadrant	91.2 % Quadrant first
Quadrant vs. TERA	99.0 % TERA first
MU-level vs. Quadrant	68.8 % Quadrant first
MU-level vs. TERA	99.5 % TERA first
VITA vs. TERA	97.8 % TERA first
VITA vs. MU-level	98.1 % MU-level first

Table 2. Percentage of first detections

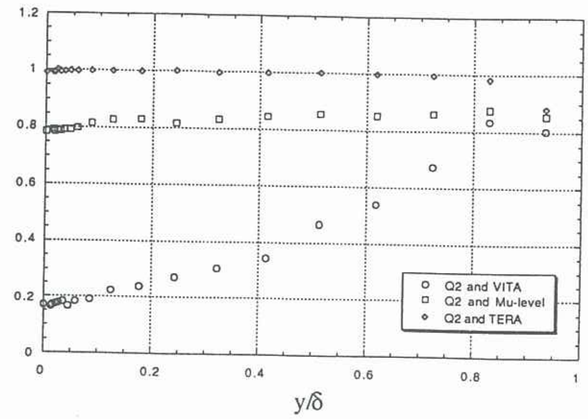

Figure 6. Correlation between the Quadrant method and the other techniques

Figure 6 shows that most of the detections made by the Quadrant method are also picked up by TERA. The figure also shows that the Quadrant method and VITA trigger on different events.

Contributions to $\overline{uv}$

Earlier work for smooth surface boundary layers (e.g. Lu and Willmarth, 1973, Luchik and Tiederman, 1987) has indicated that ejections account for about 75 % of $\overline{uv}$ and sweeps for about 55 % . This leaves about -30 % of $\overline{uv}$ to the inactive motions in quadrant 1 and 3. The contributions to $\overline{uv}$ in a given quadrant defined as

$$\frac{\overline{uv_n}}{\overline{uv}} = \frac{1}{\overline{uv}} \lim_{T\to\infty} \frac{1}{T}\int_0^T uv(t)D_n(t)dt \qquad (8)$$

was computed for the rough wall data. D(t) is the detector function for the algorithm applied which is 1 if an event has been identified and 0 otherwise. Figure 7 shows the contributions obtained from the Quadrant method using H=1.

As can be seen from figure 7 the contribution to $\overline{uv}$ from quadrant 2 (ejections) is about 55 % and nearly constant up to $y/\delta = 0.5$. For $y/\delta > 0.5$ the contribution increases to about 100 % near the boundary layer edge. As found by Raupach (1981) for rough surfaces using cylindrical roughness elements, Quadrant 4 (sweeps) is the main contributor close to the surface, but the contributions decrease further out. The other two quadrants contribute about -10 % each through most of the layer. The differences between the values obtained here and the values obtained by Lu and Willmarth are believed to be due to the reduced damping of v which is expected close to a rough surface since the irregular surface will not be as efficient in damping a sweeping motion as a smooth wall.

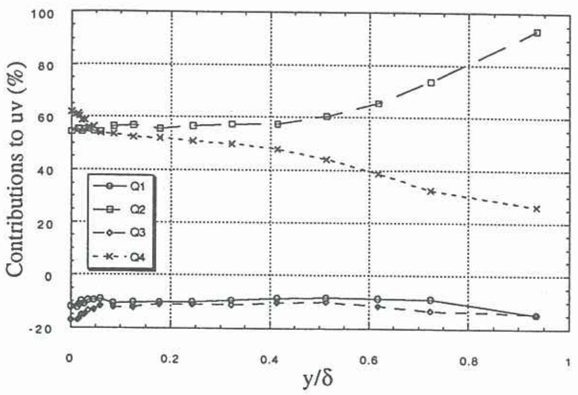

Figure 7. Contribution to the local Reynolds stress from the different quadrants

Contributions to $\overline{uv}$ was also computed using the detections from the other methods. The results are shown in figure 8a and 8b for ejections and sweeps respectively. The agreement between the Quadrant, TERA and modified u-level methods (using L_1=1) is seen to be good. The contributions detected by VITA in the inner part of the layer is much lower than for the other methods.

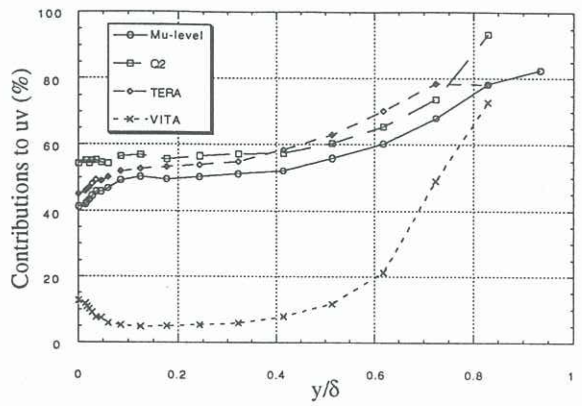

Figure 8a. Contributions to the local Reynolds stress from ejections

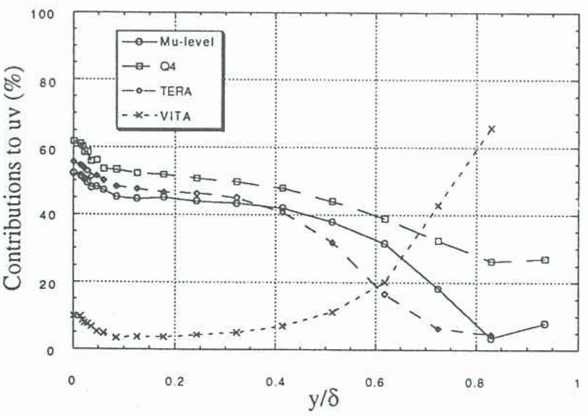

Figure 8b. Contributions to the local Reynolds stress from sweeps

Conclusions

The performance of four algorithms for detecting turbulent structures have been investigated. Except for the modified u-level method, all algorithms gave approximately the same time between events when using the thresholds recommended by the originators. For the methods based on detections on the u signal only, it has been shown that TERA performs best in capturing the detections made by the Quadrant method, although TERA tends to trigger somewhat earlier than the other methods. It was found that the Quadrant, modified u-level and TERA methods all gave similar relative contributions to $\overline{uv}$. In agreement with the findings of Luchik and Tiederman, 1987, the contributions picked up by VITA was generally found to be small.

TERA and the modified u-level single signal methods were found to be reasonable substitutes for the two signal Quadrant method.

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