ACTA MECHANICA SINICA (English Series), Vol.16, No.1, Feb. 2000 ISSN 0567-7718
The Chinese Society of Theoretical and Applied Mechanics
Chinese Journal of Mechanics Press, Beijing, China
Allerton Press, INC., New York, U.S.A.

BURST EVENT DETECTION IN WALL TURBULENCE BY WVITA METHOD*

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ABSTRACT: Wavelet Variable Interval Time Average (WVITA) is introduced as a method incorporating burst event detection in wall turbulence. Wavelet transform is performed to unfold the longitudinal fluctuating velocity time series measured in the near wall region of a turbulent boundary layer using hot-film anemometer. This unfolding is both in time and in space simultaneously. The splitted kinetic of the longitudinal fluctuating velocity time series among different scales is obtained by integrating the square of wavelet coefficient modulus over temporal space. The time scale that related to burst events in wall turbulence passing through the fixed probe is ascertained by maximum criterion of the kinetic energy evolution across scales. Wavelet transformed localized variance of the fluctuating velocity time series at the maximum kinetic scale is put forward instead of localized short time average variance in Variable Interval Time Average (VITA) scheme. The burst event detection result shows that WVITA scheme can avoid erroneous judgement and solve the grouping problem more effectively which is caused by VITA scheme itself and can not be avoided by adjusting the threshold level or changing the short time average interval.

KEY WORDS: wavelet analysis, maximum kinetic energy criteria, VITA, wall turbulence, burst event

1 INTRODUCTION

Varying Interval Time Average (VITA) as a method identifying burst event in wall turbulence has been fairly widely used in quantitative study of burst event in wall turbulence. This method was first employed by Blackwelder and Kaplan[1] and later modified by Johansson and Alfredsson[2]. The detection function of this method is defined by

$$D(t) = \begin{cases} 1 & \hat{V}_{\mathrm{ar}}(u(t)) \geq K u'^2 \text{ and } \dfrac{\mathrm{d}u}{\mathrm{d}t} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where K is the threshold level and is usually in the range of $1.2 \sim 2.0$, u' is the root mean square of the longitudinal fluctuating velocity component, and $\hat{V}_{\mathrm{ar}}(u(t))$ is the local and

Received 3 April 1999, revised 25 September 1999
* The project supported by the National Natural Science Foundation of China (19732005) and the National Climbing Project of China

short time average variance of longitudinal fluctuating velocity component and is defined as

$$\hat{V}_{\mathrm{ar}}(u(t)) = \frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} [u(t)]^2 \mathrm{d}t - \left[\frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} u(t)\mathrm{d}t\right]^2 \tag{2}$$

At present, there are two kinds of problems to be solved for detecting burst events in wall turbulence by VITA method:

(1) Erroneous judgement of several ejects in one burst

The typical characteristic of burst event can be detected by VITA method is ejecting section in one burst. Because of the influence of the small-scale fluctuations superimposing on the large-scale eject motions, one eject usually may be distinguished as several ejects. This is the so-called erroneous judgement problem of identifying several ejects as one burst. For example, there is only one eject took place at point A shown in Fig.1. But four ejects can be detected mistakenly at point A if VITA method is used to detect eject event. It is impossible that four ejects have taken place in such a short interval according to our experience. This error is entirely caused by the influence of the small-scale fluctuations superimposing on the large-scale eject motions which conceals the real large-scale eject motion and results in ejects erroneous judgement.

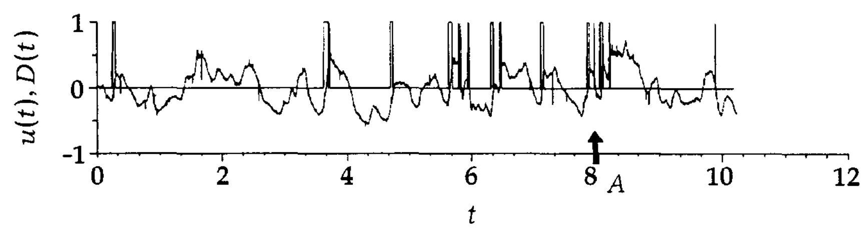

Fig.1 Erroneous judgement problem of several ejects in one burst

Several methods have been put forward to solve this problem by Lu and Willmarth[3], Bogard and Tiederman[4], Luchik and Tiederman[5], Shi[6]. But all these methods are based on their individual experiences and subjectively group ejects between which the time interval is less than a threshold value as one burst. For different experimental conditions, these methods different, so they are not universal.

(2) Grouping problem of several ejects in one burst

Compared with information obtained from flow visualization, eject detection results by VITA method show that there may be more than one ejects take place in the course of a burst. This phenomenon is especially typical in the heated turbulent boundary layer and can lead to mistaken judgement of several ejects in one burst as different bursts. This is the so-called grouping problem of several ejects in one burst. For example, two bursts can be detected mistakenly by VITA method at point B_1 and point B_2 shown in Fig.2. But in fact, these two bursts are two ejects between which the time interval is large in one burst and should not be distinguished as two bursts. This problem is a limitation resulting from VITA method itself and can not be avoided by adjusting the threshold level or the short time average interval.

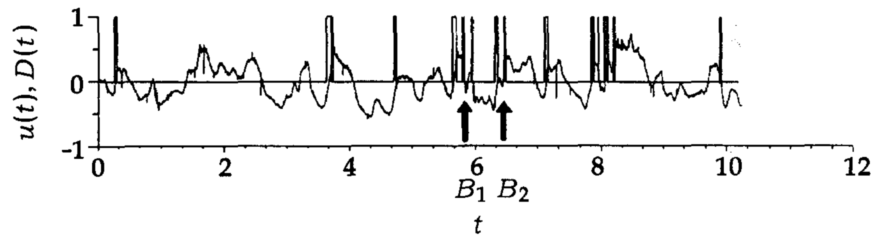

Fig.2 Grouping problem of several ejects in one burst

2 BURST EVENT DETECTION IN WALL TURBULENCE BY WVITA METHOD

The basic idea of Wavelet Varying Interval Time Average Method (WVITA) is to introduce the wavelet transformed localized variance $W(u(b))$ of the longitudinal fluctuating velocity component to replace the localized short time average variance $\hat{V}_{\rm ar}(u(t))$ in VITA method, in which $W(u(b))$ is defined as

$$W[u(b)] = \frac{1}{a}\int_{-\infty}^{+\infty} u^2(t)\bar{\psi}\Big(\frac{t-b}{a}\Big)\mathrm{d}t - \Big[\frac{1}{a}\int_{-\infty}^{+\infty} u(t)\bar{\psi}\Big(\frac{t-b}{a}\Big)\mathrm{d}t\Big]^2 \tag{3}$$

where $\psi(t)$ is the mother wavelet function and $\bar{\psi}(t)$ denotes the complex conjugate of $\psi(t)$.

The scale parameter a is ascertained by the maximum criterion of the kinetic energy evolution across scales[7] while the kinetic energy evolution across scales is obtained by integrating the square wavelet coefficient modulus over the localization of wavelet analysis.

The detection function of WVITA method is defined as

$$D(b) = \begin{cases} 1 & W(u(b)) \geq 0 \\ 0 & W(u(b)) < 0 \end{cases} \tag{4}$$

As pointed out by Blackwelder and Kaplan[1], Johansson and Alfredsson[2], in order to obtain a local average trace of burst event, the short averaging time T of VITA method must be of the order of the time scale of burst event. So a band-pass filter including the frequency $1/T$ or a low-pass filter with $1/T$ representing the cut-off frequency is needed to characterize the burst event and get rid of the influence of small-scale fluctuations. Wavelet transform is such a suitable band-pass filter if the scale parameter a is selected properly so that a is of the order of the burst event time scale. Contributions of different scales' fluctuations to turbulent kinetic energy at definite local position b can be represented through wavelet coefficients at definite scale a and definite localization b. Evolution of contributions of different scales' fluctuations to turbulent kinetic energy across scale parameter a can be obtained by integrating the square of the modulus of wavelet coefficients over the range of localization parameter b. It has been verified that there exists a scale that corresponds to the peak of the turbulent kinetic energy contributions of different scales. At this scale, fluctuating motions make significant contributions to turbulent kinetic energy production. This is in agreement with the knowledge that burst event makes remarkable contributions to turbulence production during bursting occurrence. Maximum kinetic energy criterion can be set up to determine the time scale corresponds to burst event from wavelet coefficient integration.

3 DETECTION RESULTS

Experiments were conducted for a full-developed turbulent flow in a free-surface water channel. Velocity measurements in the water channel were taken by TSI anemometer system and a model 1218-20W single-sensor hot-film boundary probe. The hot-film probe was located at $y^+ = 16$ above the lower wall of the channel. Figure 3 shows the longitudinal fluctuating velocity signal obtained from the hot-film probe located in the near wall region of a turbulent boundary layer.

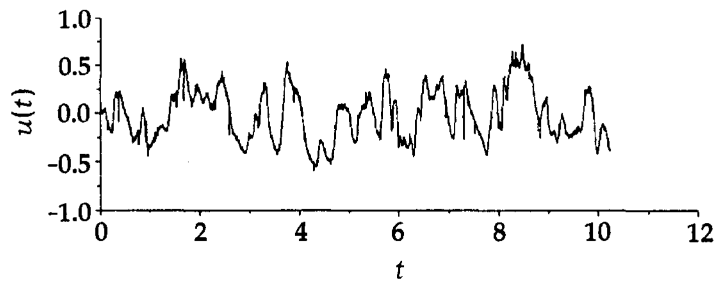

Fig.3 Longitudinal fluctuating velocity in the near wall region of a turbulent boundary layer

Wavelet coefficients magnitude contour is shown on a-b plane in Fig.4 for wavelet transform of the longitudinal fluctuating velocity component shown in Fig.3. Contributions to turbulent kinetic energy of different scales' fluctuations at different local position b are represented on the a-b plane. Figure 4 reveal that wavelet transform is a very powerful tool to represent turbulence into different scale motions. Figure 5 shows the turbulent kinetic energy evolution across different scales a by integrating the square of the modulus of wavelet coefficients over the range of localization parameter b. It can be found in Fig.5 that there exists a scale that corresponds to the peak of the turbulent kinetic energy contributions.

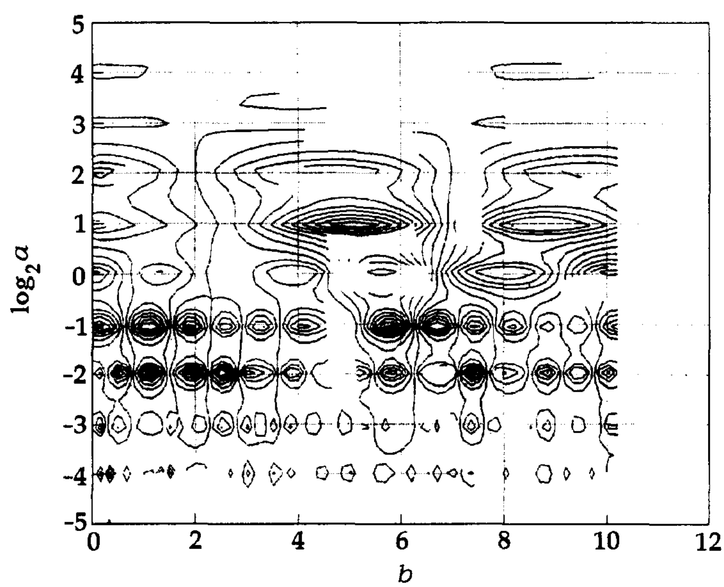

Fig.4 Magnitude contour of wavelet coefficients of fluctuating velocity shown in Fig.3

Figure 6 shows the trace of wavelet transformed variance $W(u(b))$ of longitudinal fluctuating velocity signal shown in Fig.3 where the analyzed scale a is determined by the maximum kinetic energy criterion. The detection results are shown in Fig.7. The wavelet transformed variance function has a rather coherent appearance. The band-pass filter character is well illustrated and the influence of small-scale fluctuating is excluded. The detection function is highly correlated with the whole large-scale organized motions, which include not only the accelerations but also the decelerations. The most striking features are the entirety and similarity of their phase relationship instead of parts of the bursting course.

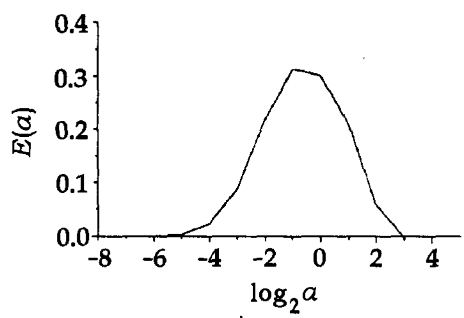

Fig.5 Contribution evolution of each scale kinetic energy to turbulence across scales

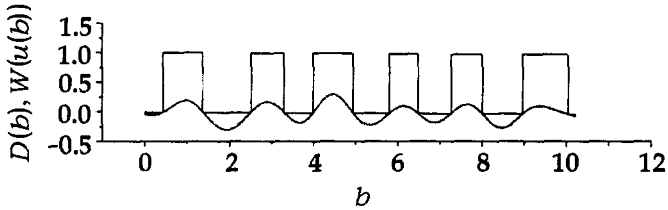

Fig.6 Wavelet transformed short time average variance $W(u(b))$ versus location b

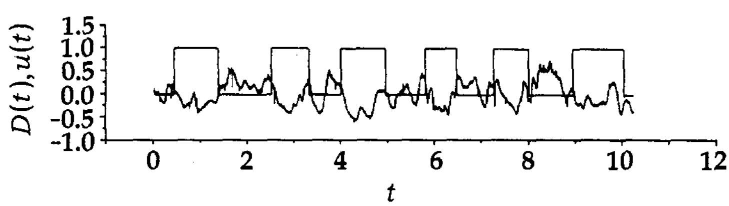

Fig.7 Detection results by WVITA method

4 CONCLUSION

WVITA method is a band-pass filter that can get rid of the influence of small-scale fluctuating motions. So it can avoid erroneous judgement and solve the grouping problem caused by small-scale fluctuating motions and resulting from VITA method itself. The establishment of the maximum kinetic criterion eliminates the arbitrariness in the choice of the threshold level and the short average time in the routine VITA method. The entirety and similarity of the phase information shown in the detection results demonstrate an identifiable sequence of states associated with burst event.

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