Extended Summary-------Yu-lu Liu Jian-bo Jiang Xiang Qiu

Orthonormal Wavelet Analysis of CGT in Fully Developed Asymmetric Turbulent Channel Flow

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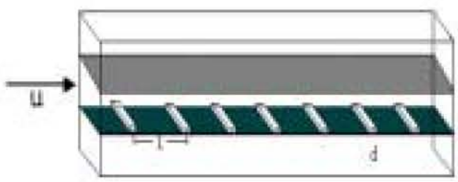
1. **Introduction** One of fundamental characteristics of turbulence is its stronger transport than laminar flows. In most of turbulent models, gradient transport assumption is adopted, which assumes that momentum, scalar flux and energy flux are transported towards the direction where mean velocity or scalar decreases. In fact, underlying of gradient transport is Fourier law. However it is well known in laboratory and engineering that counter gradient transport (abbr. CGT) phenomena exist (Jiang et al 2000). For example, there exists a region in the central region of fully developed asymmetric channel where $< uv >$ and $\partial U / \partial y$ have the same sign, that means momentum is counter gradient transported. Traditional cascade theory （Kolmogorov 1941） can't explain these phenomena. Mechanisms and reasons of CGT phenomena still remain open. Results obtained till now only show that coherent structures may be one of many reasons.

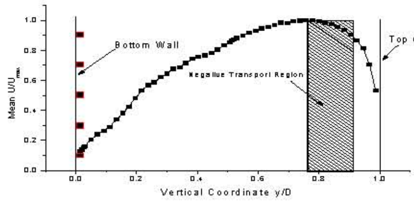
In this paper, four families of orthogonal wavelets are applied to investigate CGT phenomena in the fully developed asymmetric flow. Comparing to continuous wavelets, orthogonal wavelets are mutual orthogonal to each other and remain the original information. So orthogonal wavelets are more reliable to use when investigating the statistics of turbulent flows (Yamada & Ohkitani 1990, Meneveau 1991, Mouri et al 1999).

2. **Analytical method** Due to the uncertainty principle, the spatial localization and temporal localization are affected each other. So in this paper, following the work of Mouri et al (1999), four families of orthogonal wavelets are used: Haar wavelet, Db20 wavelet, Meyer wavelet, Harmonic wavelet. It has been stated in Mouri et al (1999) that most spatial localization is obtained for Haar wavelet, while most scale (frequency) localization is obtained for Harmonic wavelet. The localization of other two wavelets lie between Haar and Harmonic wavelets.

3. **Experiment** The experimental scheme is shown in fig.1 (Lu et al 2001). The asymmetry is introduced by roughening the bottom wall while top wall remains smooth. By roughening the wall, small ribs with length d=0.003m and width 0.22m are glued on the bottom wall. The measuring instrument is TSI9100－9 laser Doppler velocimetry made by TSI company. Data collection and analysis are completed by the accompany software FIND (Flow Information Display).



(Fig.1)

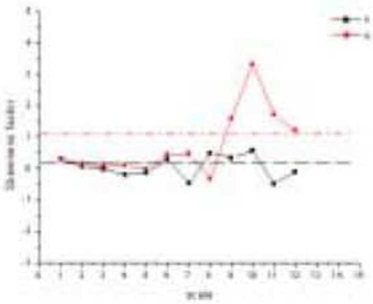


(Fig.2)

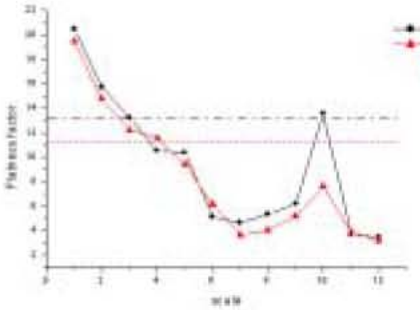
CGT region in fully developed section is sketched in fig. 2

4. **Main Results (**Statistical Characteristics, turbulent structure**)**

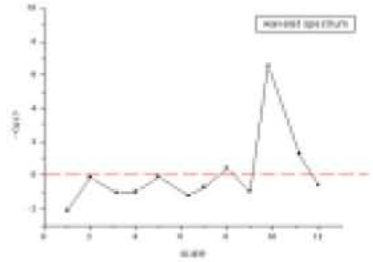
Fig 3a shows the skewness factor on each scale of streamwise and longitudinal velocity using four families wavelets (same results) in CGT region. It is evident that the skewness factors are functions of scales and aren't zero on each. It should be emphasized that skewness factor on scale 10 deviates zero more. Fig3b gives the flatness factors on each scale. For flatness factors, we could see that flatness factors decrease before scale 6, but begin to increase from scale 7 and reach the maximum at scale 10. From scale 11, they decrease again. There sre some difference between present results and those of Meneveau(1991), Lili (2001), Mouri et al(1999). Our observations show that intermittency between scale 6 and 10 is increased. The results of PDFs (not listed here) for each scale also indicate that intermittency increases with the scale. Furthermore when scale is increasing, PDF is approaching Gaussian distribution. But scale 9,10 and 11 needs more attention: scales 9,11 approaches distribution Gaussian distribution more than scale 10. Combining the results for skewness and flatness factors, it could be seen that in CGT region, the intermittency of small scales are generally stronger than larger scales, but CGT causes intermediate scale(s) more intermittent than larger and smaller scales.



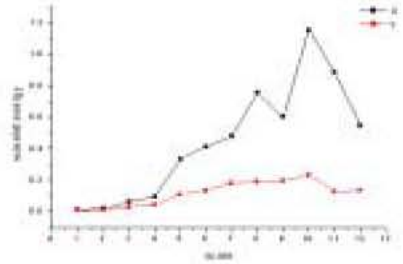
(Fig.3a)



(Fig.3b)



(Fig.4)



(Fig.5)

Fig4 gives the wavelet cross spectrum for Reynolds shear stress at the point in CGT region. It is evident that different scales make different contributions to Reynolds shear stress. The maximum contribution comes from scale at 10 and is positive, which means momentum transport is local CGT. Other scales give negative contributions to Reynolds stress, which means that momentum transport is gradient transport. Reminding that Reynolds stress is positive here, so it is evident that structures with scale 10 lead to CGT phenomena. For other points, although local CGT and gradient transport coexist, but total momentum transport is gradient transport. For example, for Ansym3 where $\partial U/\partial y < 0$, $-uv > 0$. Scales 8 and 11 give negative contributions to Reynolds stress while other scales give positive contributions. But total contributions are positive, which means total transport is gradient transport.

There still exist many opinions about principal scale of coherent structures, including maximal energy method (Jiang Nan et al 1998), energy method (Liandrat et al 1990), energy method (Farge 1992) and de-noising method (Szilagyi et al 1999). In this section, we will extend the maximal energy method for CWT to DWT.

By using the method given above, the ration is constant on all scales for white noise. Fig 5 gives the principal scale of coherent structures. Here only the results for Db20 are given. It could be observed that the principal scales are scale 10 in CGT, 5 in asym2, 5 in asym3 and 7 in asym1. It should be noted that scale 10 for CGT region is just the scale that determines the global CGT phenomena.

5. Conclusion

It is well known that random, multiple scale and structures are most essential characteristics of turbulence. Thus wavelet analysis is a suitable tool to investigate turbulence. In this paper orthogonal wavelets are applied to study the counter gradient transport phenomena in fully developed asymmetric channel flow. We study on each scale the flatness, skewness factors, probability density functions, scale-scale and velocity-velocity correlations, the principal scale of coherent structures. Finally we investigate the relationship between CGT phenomena, principal scale of coherent structures and Non-Gaussian characteristics of turbulence.

The results show that in CGT region, skewness and flatness factors deviate strongly the corresponding values of Gaussian distribution on certain scale(s). PDFs on each scale confirm this observation. Scale-scale correlation and velocity-velocity correlation give further support that CGT phenomena will cause certain scale more intermittent. Cross wavelet spectra indicate that local CGT phenomena could be present at different scales.

Investigation of principal scale of turbulent coherent structures shows that, when that scale contributes most to Reynolds stress and causes local CGT phenomena at the same time , the total momentum is global counter gradient transported.