2002年上海大学博士学位论文 ㉑

湍流逆梯度输运的理论与实验研究

作　者：蒋剑波
专　业：流体力学
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答辩委员会对论文的评语

湍流是自然界与工程实际中普遍存在的现象。论文针对湍流逆输运现象展开研究，选题具有前沿性。该项研究具有重要的理论意义和工程实用价值。论文作者查阅了大量与湍流研究相关的文献资料，把握了该领域国内外研究的动态和发展趋势，对问题的难点有深入恰切的了解。论文的特点为理论、实验和计算研究并重，分别在槽道流动的逆输运现象的统计特征、湍流结构、模式理论以及数值模拟方法等多方面作了大量的工作。主要成果如下：

(1) 利用正交子波变换，根据实测的数据，分析了槽道流（非对称以及内置翼型工况)中湍流逆梯度输运区域内，不同流动尺度上的湍流运动学特征；并且引入了局部和整体逆梯度输运的概念，得到了整体逆梯度输运出现的特征；

(2) 利用 $k-\varepsilon$ 模式和湍流雷诺应力两种模式，对内置翼型的工况进行了数值计算，表明微分应力模式能够再现湍流逆梯度输运现象，而标准 $k-\varepsilon$ 模式则不适用，并且发现：湍流能量负产生率并不直接与湍流逆梯度输运现象对应；

(3) 对内置翼形的槽道湍流进行了 Mexihat 子波分析，用子波系数刻画了流动中涡的大小和位置，揭示了涡的存在和发展；

(4) 改进了 Zimin 的层次模型，借助 Lewalle（1994）的方法，初步建立了一个新的多尺度的可用于二维剪切湍流的湍流模式，并从理论角度分析得出此模式能够反映逆梯度输运现象；

(5) 发展了 Lewalle(1994,2001)用高斯子波对 N-S 方程的变换，参照王诚（1997）处理层流的办法，导出了适用于有限流域

湍流的积分形式的解方程，对非对称流动和对称槽道流动进行了数值计算，在壁面区外，获得了和已有的计算或实验一致的结果。

论文研究方法正确，工作具有创新性，表明作者在本学科领域已经掌握了坚实的基础理论和系统深入的专业知识，具有比较强的独立从事科研工作的能力。论文行文流畅，条理清晰。答辩过程中，表达清楚，叙述简单明了，能够准确地回答委员们所提出的问题，答辩委员会认为该论文达到了博士学位论文的要求，是一篇比较优秀的博士论文。

答辩委员会表决结果

经答辩委员会表决，全票同意通过蒋剑波同学的博士学位论文答辩，建议授予工学博士学位。

答辩委员会主席：刘应中

2002 年 8 月 3 日

摘　要

湍流是自然界与工程实际问题中普遍存在的现象，同时也是经典物理领域中少数几个尚未解决的难题之一．子波分析是近年来新兴的一门数学工具，本文运用正交子波分析研究了湍流逆梯度输运现象，主要工作如下：

第一部分：利用正交子波研究了非对称槽道流动中湍流逆梯度输运区域的统计特性，着重研究该区域内的湍流结构特性．我们测量了光滑壁面、粗糙壁面以及中心区域内的湍流脉动速度，并且利用正交子波研究了各个尺度的平坦因子、偏斜因子、概率密度函数、尺度–尺度关联、横向速度–流向速度关联，同时测量了逆梯度区域内的傅立叶能谱、子波能谱以及子波交叉谱．之后考察了逆输运区域内的最大相干结构的尺度、整体标度指数、局部标度指数并且计算了速度的分数维．最后我们考察了湍流逆梯度输运与湍流最大相干结构尺度、湍流非高斯特性之间的关系．本文的研究表明：①逆梯度输运区域内偏斜因子在某些特定尺度上远远偏离了零值，而平坦因子在小尺度的时候偏离了高斯分布对应的值 3，当尺度增加的时候，总体趋势是逐渐减小（但是一直大于 3），并且在与偏斜因子情形类似的尺度上出现一个小脉冲．与此一致的是发现小尺度概率密度函数偏离了高斯分布，而在上述的特定尺度上也偏离高斯分布，在大尺度的时候接近高斯分布．对于尺度–尺度的关联和横向速度–流向速度关联的分析得到了一致的结论，即：小尺度的间歇性要高于大尺度的间歇性，同时存在着某个（些）特定尺度，

在这些特定的尺度上存在着结构，该结构与逆梯度输运现象存在着紧密联系. ②子波能谱与傅立叶能谱吻合得较好，但是前者比后者光滑. 对于雷诺应力的子波分析得到了子波应力交叉谱，将之用以研究距离壁面的不同位置的速度，发现局部逆梯度输运现象在不同的尺度上都有所体现：当局部逆梯度输运在所有尺度上占优的时候，则出现整体的逆梯度输运. ③对逆梯度输运区域内相干结构尺度的研究表明，最大相干结构对应的尺度如果对应于局部逆梯度输运发生最明显的尺度的时候，则导致整体逆梯度输运；反之则是正常的顺梯度输运. ④对脉动速度的分形特征的研究表明，在靠近光滑或者粗糙壁面的位置处，标度律偏离各向同性湍流的对应的标度律很大，当偏离光滑壁面但是未进入 CGT 区域内的时候，标度指数略微下降，间歇性反而增强；而进入到 CGT 区域内标度指数又有所回升，间歇性下降；离开 CGT 区域靠近粗糙壁面的区域内标度指数又有所回升，间歇性下降. 对于距离壁面不同距离点的脉动速度的标度指数的研究表明，横向速度的指数均要大于流向脉动速度的指数，这说明横向脉动速度的间歇性要高于流向脉动速度的间歇性. 本文还比较了利用几种不同的方法得到的标度指数，发现利用连续子波研究局部标度指数并不可靠，因此需要慎重考虑在湍流研究中出现的负的标度指数的情形. 对于分维的测量表明，逆梯度输运区域内的低频和高频部分的维数随着尺度的增加都逐渐减少，趋向于 1.

第二部分：从实验角度研究了放置翼型的槽道流中压力梯度对湍流逆梯度输运现象的影响. 得到了与完全发展的非对称槽道流一致的结果，即，在逆输运出现的区域内概率密度函数远远偏离了高斯分布. 然而逆梯度输运的区域在置翼槽流中沿

流向的变化趋势与非对称槽道流不同，呈现出先增大后缩小再增大的趋势，而后者的逆输运区域基本不变. 同时，在流向不同的逆输运区域内，雷诺应力为零的点与流向最大平均速度的相对位置存在着变化. 之后，利用微分应力模式和 k-epsilon 模式数值模拟了该流动，结果表明：微分应力模式可以反映湍流逆梯度输运现象，而 k-epsilon 模式则不能. 同时发现，湍流能量负产生率沿流向的变化与逆梯度输运的情形不同：负产生率区域沿流向逐渐缩小，至翼型中心位置消失. 最后利用连续子波(墨西哥帽)分析了其中的湍流结构，并且研究了压力梯度对湍流结构的影响.

第三部分：建立能够反映湍流的多尺度有结构的本质特征的湍流模式是模式理论发展的正确方向，作为子波分析在湍流模式中应用的初步探索，本文建立了一个湍流多尺度模式. 传统的湍流模式大多数是单点模式，只包含了单个湍流时间或者空间尺度；而反映湍流多（双）尺度特性的湍流模式则以丧失空间信息为代价，也就是说不能考虑湍流中的结构. 本文在前人的基础之上，将 N-S 方程投影到正交子波基上，得到了一个包含空间-尺度信息的湍流级串模型. 该模型与 Zimin（1981）、Nagano（1988）的模型类似. 之后着重考虑了多尺度特性，在各向同性的假定下，将上述得到的模型简化为一个只体现多尺度特性的湍流模型. 然后采用与 Lewalle（1994）相同的方法推广到剪切湍流中，得到了剪切湍流中的多尺度湍流模式. 该模式以标准 $k-\varepsilon$ 模式为基础，采用了涡粘度假设，但是将涡粘度分解为不同尺度的贡献. 该模式具有如下的特点：①可以反映湍流逆梯度输运现象；②将所有尺度收缩则得到标准的 $k-\varepsilon$ 模式；③对于均匀湍流则得到湍流级串模型.

第四部分：数值计算了高斯子波变换 N-S 方程后得到的积分方程. 本文是 Lewalle 工作的继续，Lewalle 利用高斯子波，得到了以弯曲度为基本量的无穷域中 N-S 方程，此时 Lapalace 算子降低为一阶导数，并且 N-S 方程变形为具有局部化双线性相互作用的扩散方程的形式. 本文采用王诚提出的方法，得到了有界区域内的以弯曲度为基本量的 N-S 方程. 之后将 N-S 方程看作一个特殊的扩散方程，将压力与对流项看作是源项，得到一个积分方程. 利用特征线法对该方程求解，得到通解. 之后将所得结果运用于对称槽道湍流和非对称槽道湍流的研究中. 计算方法与直接数值模拟类似，但是为了避免计算量过于庞大，因此并没有直接处理边界条件，而是将计算区域的边界设在对数速度剖面的区域内，同时假定最接近壁面的第一个网格点上的流动速度与壁上剪应力成正比. 实验计算所得的平均量与实验结果基本吻合.

关键词　湍流逆输运现象，子波分析，多尺度湍流模式，相干结构

Abstract

Turbulent flows are ubiquitous in nature and engineering while turbulence remains one of the major unresolved problems of classical physics. Wavelet analysis is a new mathematical research tool developed in recent years. In this paper, orthonormal wavelet analyses are applied to investigate the counter-gradient-transport phenomena in turbulent flows. This paper contains four parts of work:

Part I: Orthonormal wavelet analyses are applied to the study of characteristics of velocities in the counter gradient transport region in the fully developed ansymmetric turbulent channel flow. The emphases are focused on the coherent structures in that region. We have measured the turbulent fluctuating velocities near the rough, smooth walls and in the CGT region. Moreover we applied the orthogonal wavelet to analyze the flatness factors, skewness factors, probability density function, scale-scale correlation and longitudinal-transverse velocity correlation. The Fourier spectrum, wavelet energy spectrum and wavelet cross spectrum in the CGT region are also obtained. We further consider the principal scale of coherent structures, global scaling exponents, local scaling exponents and fractal dimensions in the CGT region. Finally we examine the relation between the CGT phenomena, principal scale of coherent structures and non-Gaussian properties of turbulence. The results show that (1) Intermittency at various scales in the CGT region is different from other region in the channel. In particular, there exhibits the enhancement of intermittency at some given scales in the CGT region due to the CGT phenomena. This could be observed by investigating the PDFs of every scale or flatness factors, skewness factors of every scale, which depart from those of Gaussian distribution. The study shows that, in the CGT region, the skewness factors at some scales depart drasticly from zero value, the flatness factors at the small scales depart from the Gaussian PDF more than those of large scales: when the scales increase, the flatness factors decrease and tend to be larger than 3, but at some intermediate scale, there exists a small pulse. Those observations are further confirmed by examining the correlation between scale-scale and longitudinal-transverse velocities: fluctuations in the small scales are more intermittent than that in large scales and there exist structures at some given scales. (2) Study on the wavelet energy spectrum shows that it is in agreement with but smoother than that of Fourier energy spectrum. The wavelet cross-spectrum analyses of Reynolds stress at several points in the ansymmetric channel shows that there exist local counter gradient transport phenomena at some scales while gradient transport occur at other scales. In the CGT region, the sum of contributions from those scales that exhibit local CGT is more than that of contributions from those scales who exhibit gradient transport. (3) Study on the principal scale of coherent structures in the CGT region shows that the principal scale is identical to the scale that exhibits the largest local CGT

phenomena. Analyses of other points out of CGT region show that the principal scale of coherent structures is different with the scale exhibit the largest local CGT. (4) The multi-fractal analyses of velocities are also conducted. In the smooth wall or rough wall, the scaling law departs strongly from that of isotropic turbulence; in the region which is out of CGT region but close to smooth wall, with the departure from the wall, the scaling exponents is lowered and intermittency increases; however in the CGT region the scaling exponents increase a little. After departing from the CGT region to the center region, the scaling exponents tend to increase. The analyses of fluctuating velocities at several distances from the wall (including the CGT region) also show that scaling exponents of transverse velocity is larger that of longitudinal velocity, which shows that the former is more intermittent than latter. We also investigate the local scaling exponents and find that the method for calculating local scaling exponents by use of CWT is not reliable; hence it should be cautious for the negative local scaling exponents obtained from CGT. Multifractional dimensions of velocities in the CGT region indicate that both low frequency part and high frequency part tend to decrease and become simpler and smoother.

Part II: The effect of pressure gradient on the counter-gradient transport phenomena is experimentally studied through the wing flow, which is formed by placing a wing in the channel on the bottom. The conclusion is similar to that of asymmetric channel flow, i.e., probability density function departs from that of Gaussian distribution. However, the CGT region in the wing flow behaves differently with that in the asymmetric flow: first enlarging, then shrinking and then enlarging again. Furthermore the relative position between zero Reynolds stress and maximum mean velocity is changing along the flow. Later the wing flow is numerically simulated with the RSM and $\kappa-\varepsilon$ models, the results show that RSM can describe the CGT phenomena while $\kappa-\varepsilon$ can't. Moreover, negative turbulent energy production behaves differently with CGT: it gradually shrinks until the poison of wing central part is reached, where it vanishes. Finally, continuous wavelet (Mexican hat) is applied to investigate the turbulent structures and effect of pressure gradient.

Part III: Those embodying the turbulence essential characteristics such as multiple-scale, having structure and irregularity are the most promising turbulent models. As the preliminary work for the application of wavelet to analysis of counter-gradient-transport phenomena, this paper has tried to construct a multiple-scale turbulent model. Traditional turbulent models are single-point models, i.e., only having single turbulent time or space scale. On the other hand, multiple or two-scale turbulent models obtain the multiple scale by the sacrifice of spatial information hence they could not take the turbulent structures into consideration. On the basis of existing work, this paper projects the N-S equations onto orthonormal wavelet bases thus obtains a turbulent cascade model which contains both space and scale information. The model obtained is similar to those of Zimin (1981) and Nakano(1988). Later the focus is put on the multiple-scale characteristics of turbulence by averaging all the points. Hence the premise of isotropy is contained. Later, the model is generalized to turbulent shear flows by use of the methods proposed by Lewalle (1994). Based on the standard $k-\varepsilon$ model, this model has decomposed the viscosity into multiple scale contributions and has the characteristics as bellows: (1) It could represent the turbulent counter-gradient-transport phenomena; (2) when all the scale are contracted, the model reduces to standard $k-\varepsilon$ model, while in homogenous turbulence it reduce to the multiple turbulence model (cascade model).

Part IV: In this paper numerical investigation has been conducted by solving the integral N-S equations transformed by Gaussian wavelet transform. This paper is the continuance of that of Lewalle (2001). Lewalle has made use of Gaussian wavelet to obtain the N-S equations with flexion as fundamental quantity in the infinite domain. In that work, Lapalace operator has been degraded to one-order operator. Moreover the resulted N-S equations take the form of diffusion equations with local bilinear mutual interaction kernel. Using the method adopted by Wangcheng, we have obtained the N-S equations with flexion as fundamental quantity in finite domain. Then the integral N-S equations are regarded as special diffusion equations and the pressure term, convective term are regarded as source terms then integral N-S equations are obtained. The general solution of the integral equations are solved by characteristic method. Then the results are applied to the analysis of channel flows (asymmetric and symmetric flows). The numerical methods are similar to those of Direct Numerical Simulation. To

avoid the enormous calculation, we haven't dealt with the boundary directly. We have set the artificial boundary in the logarithmic layer of mean velocity and supposed that the velocity of first grid point is proportional to wall shear velocity. The mean statistical quantities agree the experimental results well.

Key words turbulent counter-gradient-transport phenomena, wavelet analysis, multiple turbulent model, coherent structures

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