

壁乱流における大規模組織構造と 凍結乱流仮説の数値的研究

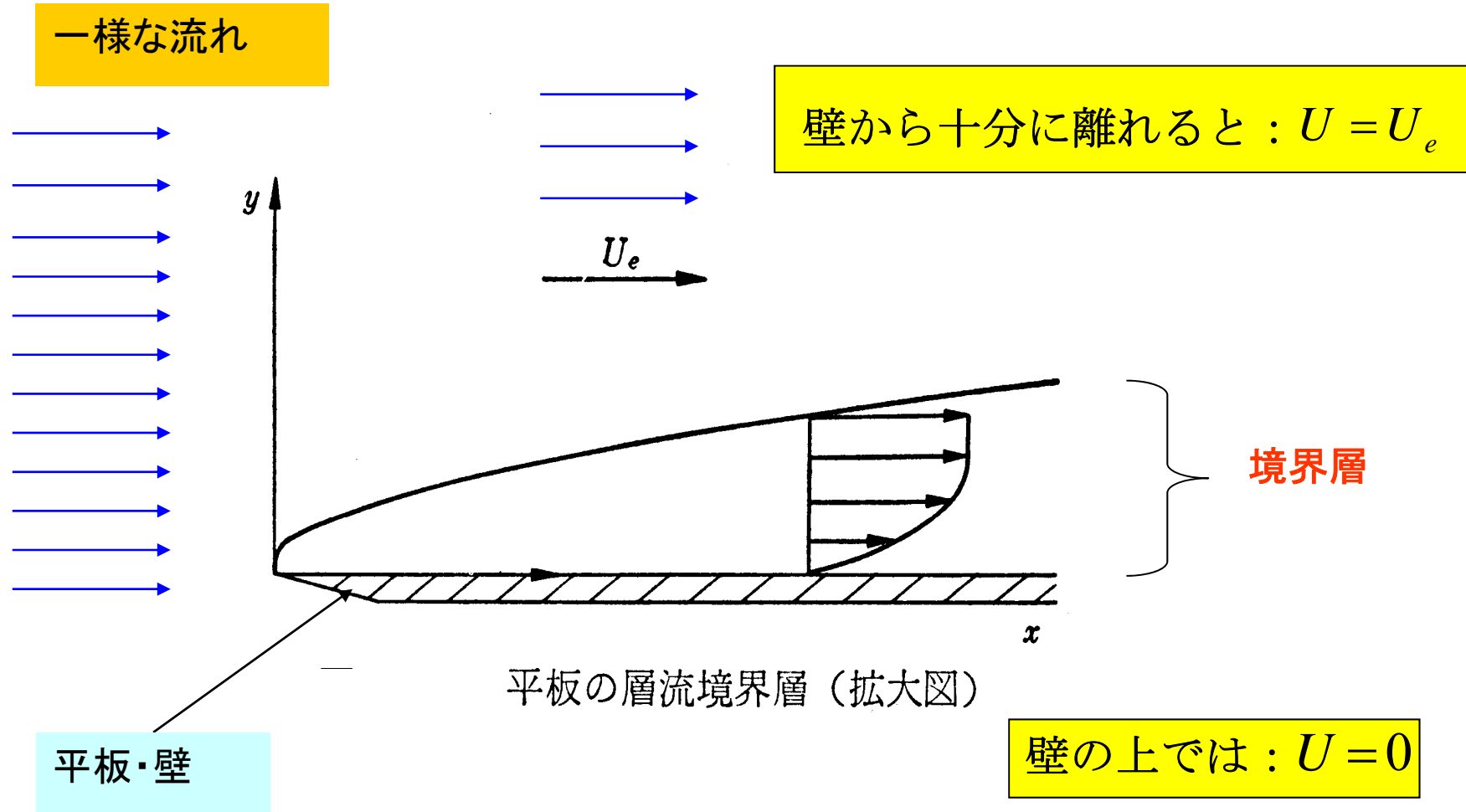
京都大学工学研究科 山本義暢

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名古屋大学情報基盤センター 石井克哉

地球水循環研究センター 坪木和久

壁乱流(境界層、チャネル、円管)

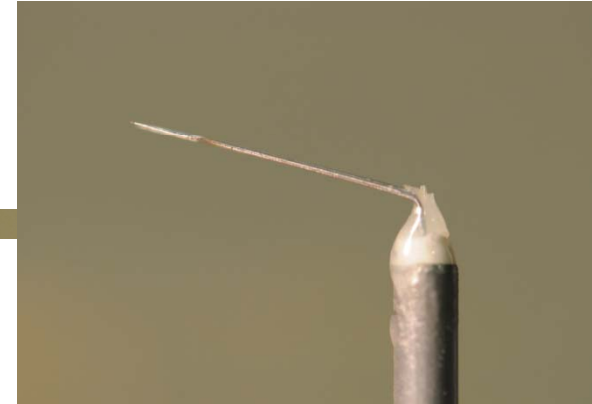


Streamwise turbulence intensity measurements

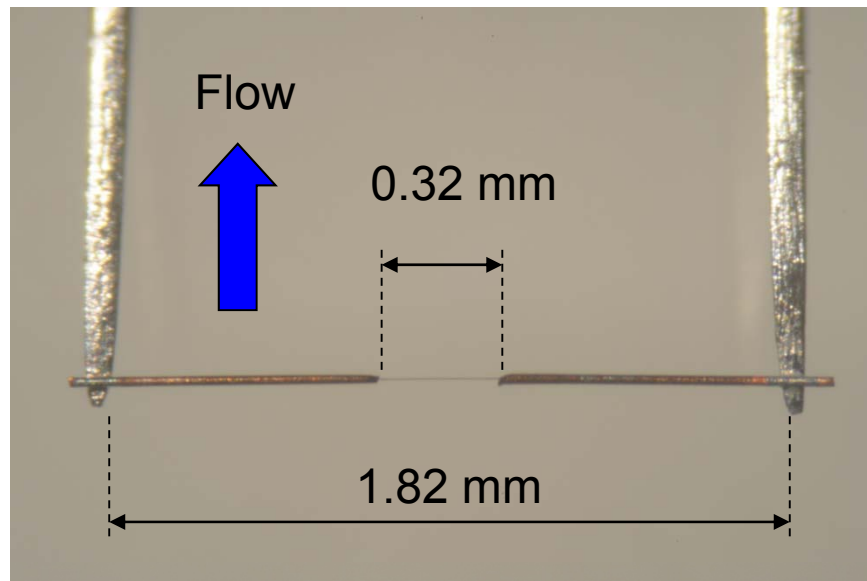
① Probe shape

Hotwire probes

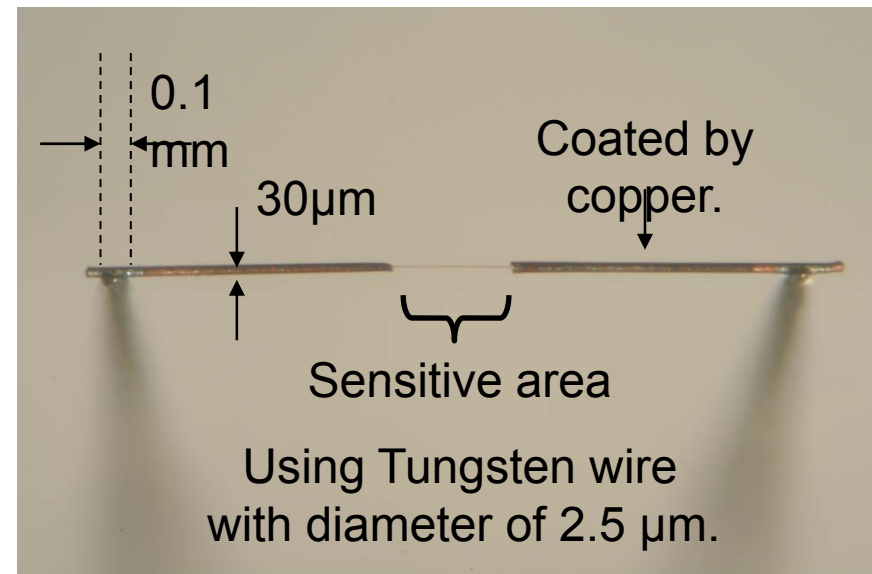
Sensitive area



Top view



Side view



Magnified images of the edge of the probe . The left image is top view (The flow direction is from under to top) and the right image is side view

Taylor's Frozen Flow Approximation

In Taylor (1938), Taylor's approximation of frozen flow states that "if the velocity of the air stream which carries the eddy is very much greater than the turbulent velocity, one may assume that the sequence of changes in U at the fixed point are simply due to the passage of an unchanged pattern of turbulent motion over the point"

$$U(x, t) = U(x - U_c \tau, t + \tau)$$

This can be formed above for not too large value of τ (the time delay), and where U_c is the assumed convection velocity. This approximation is thought to be substantially accurate for boundary layer flow provided that u_{rms}/U_c is small.

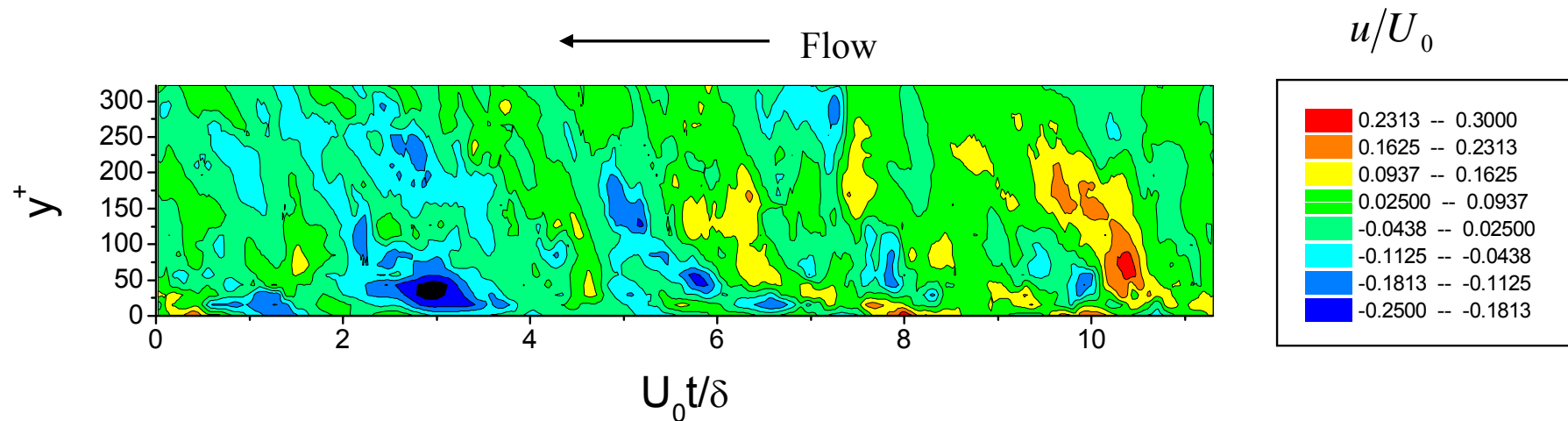
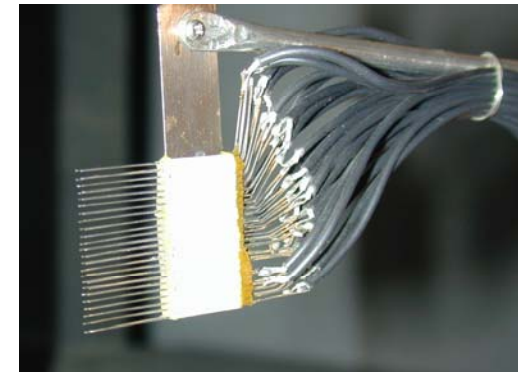
Large scale motion in turbulent boundary layer

There is no clear definition on the structures

cf. hairpin vortex, stream-wise vortex, typical eddy, low speed streaks, ...

Experiments by 24-ch probes measurement.

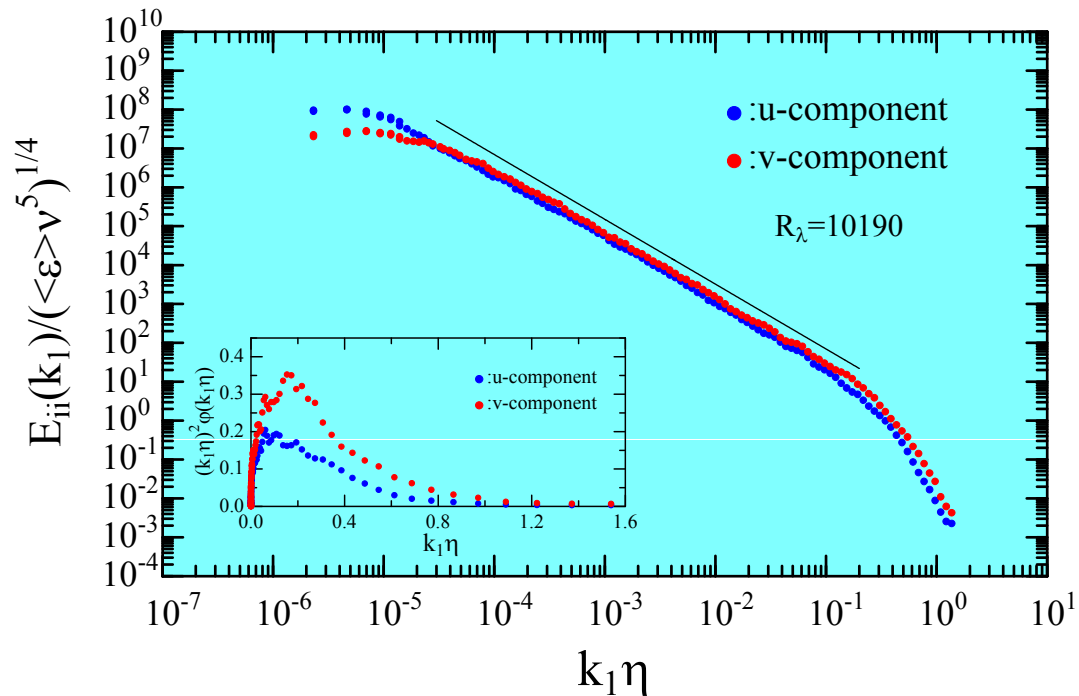
$$U_0 = 13.5[m/s] \quad R_\theta \cong 3300$$



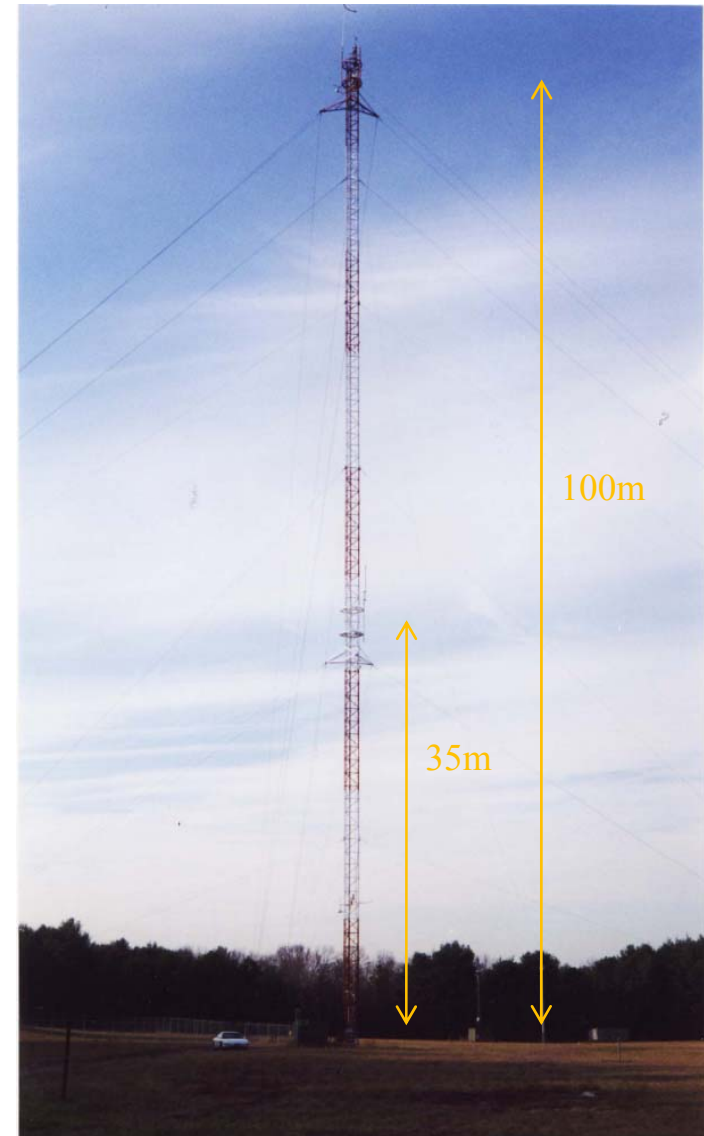
High-Reynolds number experiment 1

On the tower 35m high from the ground.

$$R_\lambda \cong O(10^4)$$



The flow is very close to H.I.T.



Brookhaven National Laboratory

Del Alamo & Jimenez (2009)

The spatial Fourier coefficients of u can be written as

$$\hat{u}(k_x, k_z, y, t) = |\hat{u}(k_x, k_z, y, t)| \exp[i\psi_u(k_x, k_z, y, t)]$$

where ψ_u is the phase of the complex \hat{u} . We define the average phase velocity of each mode as

$$c_u(k_x, k_y, y) = -\frac{\langle \hat{u} \hat{u}^* \partial_t \psi_u \rangle}{k_x \langle \hat{u} \hat{u}^* \rangle} = -\frac{\text{Im} \langle \hat{u}^* \partial_t \hat{u} \rangle}{k_x \langle |\hat{u}|^2 \rangle}$$

which is exact for a monochromic frozen wave proportional to $\exp[ik(x - ct)]$.

Del Alamo & Jimenez (2009)

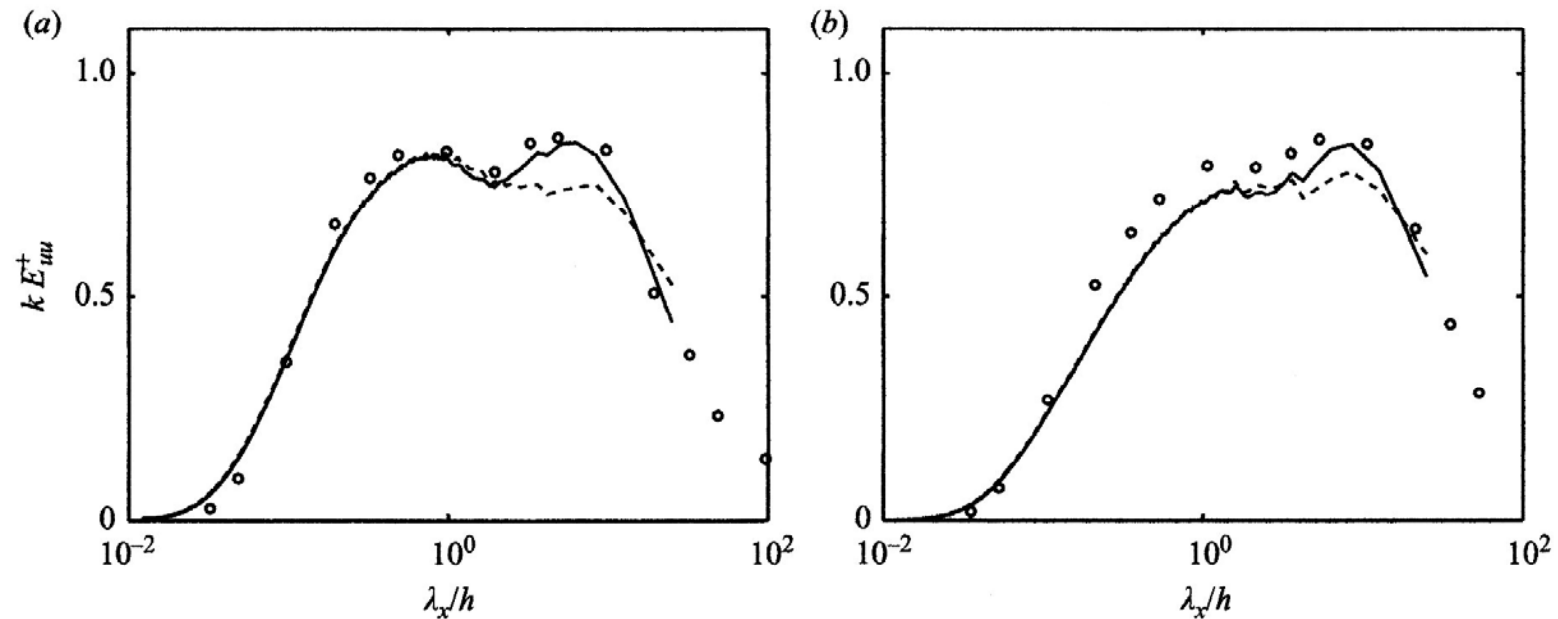
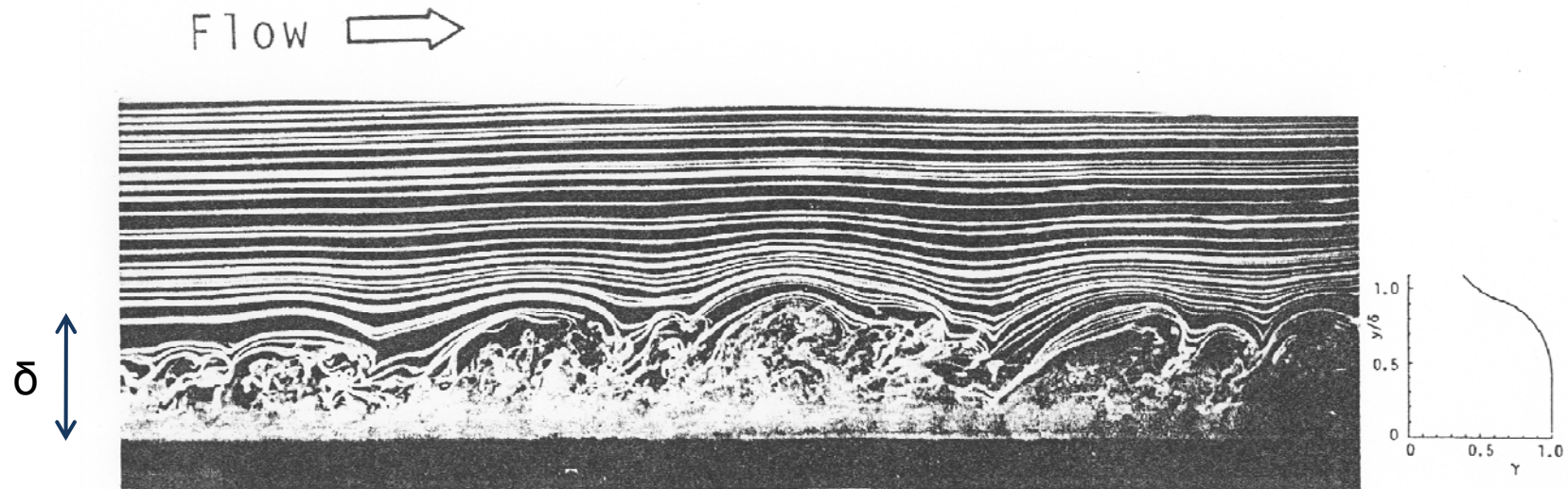


FIGURE 10. One-dimensional pre-multiplied energy spectra, $k_x E_{uu}(k_x)$. \circ , Perry & Abell (1975), $Re_\tau = 2325$. Lines are case (Hoyas & Jiménez 2006): $---$, true wavelengths; $---$, uncorrected Taylor wavelengths. (a) $y^+ = 100$, (b) $y^+ = 200$.

$$E(\omega) = \int E[k_x(\omega, k_z), k_z] dk_x / d\omega | dk_z \quad E_{uu}(k_x) \propto k_x^{-1}$$

model ?

壁乱流の組織構造



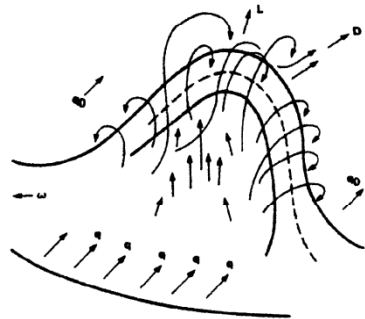
Osaka, H and Mochizuki, S. et.al., JSME, Vol.53(1987), pp27-34

乱流境界層中の可視化写真(スモークワイヤ法)

壁乱流の組織構造

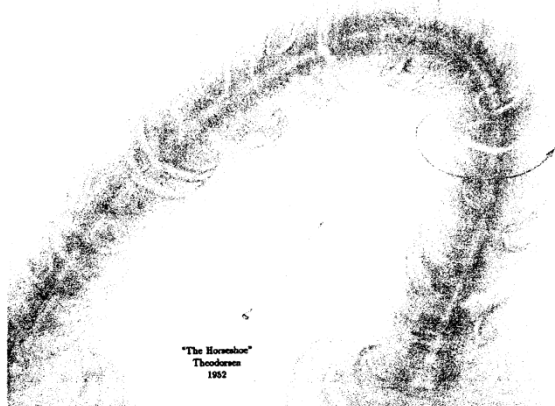
Robinson's summary of structures found in DNS

(a)



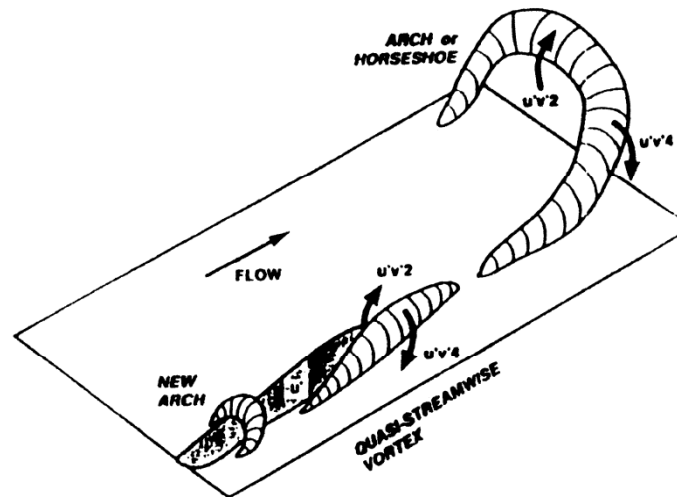
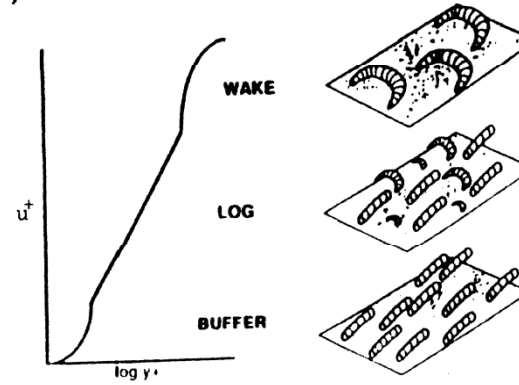
Theodorson's(1952) description of Horseshoe vortex

(b)



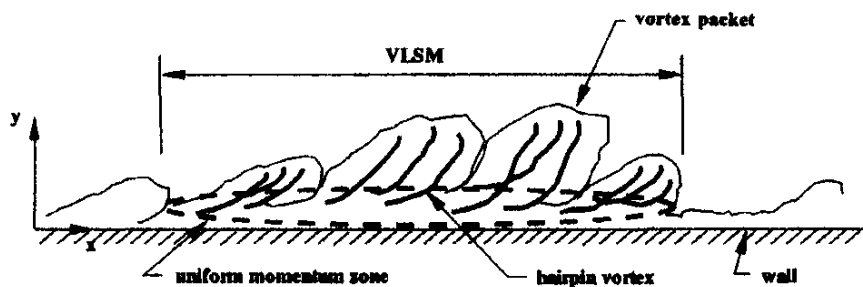
Sketch of "Horseshoe" attributed to Weske

(c)



1980,1990年代

壁乱流の組織構造

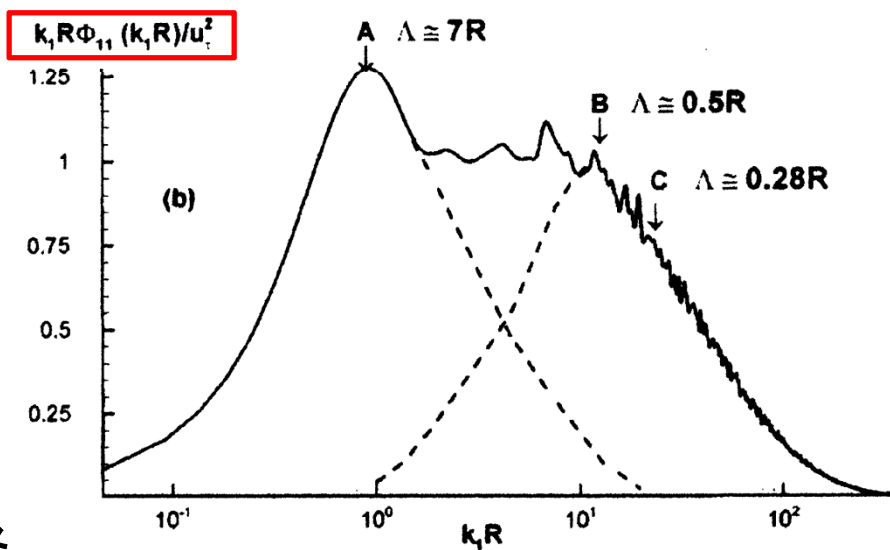
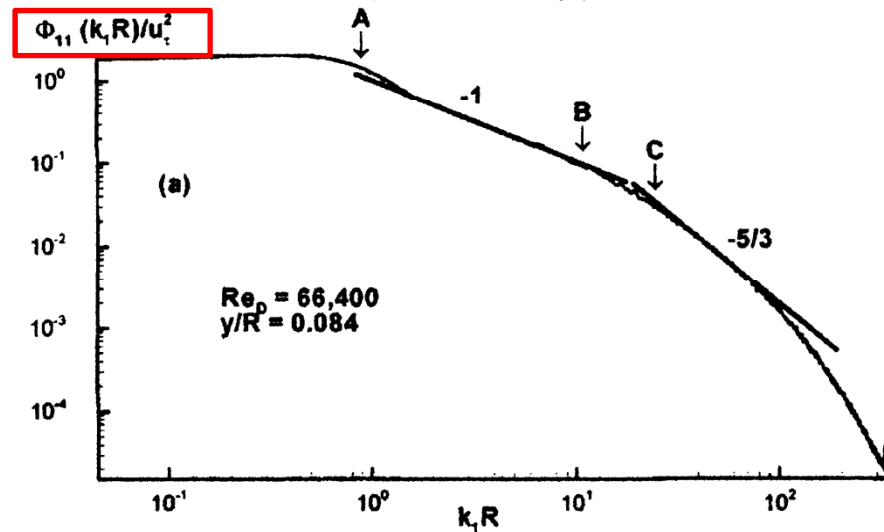


VLSM: Very Large Scale Motion

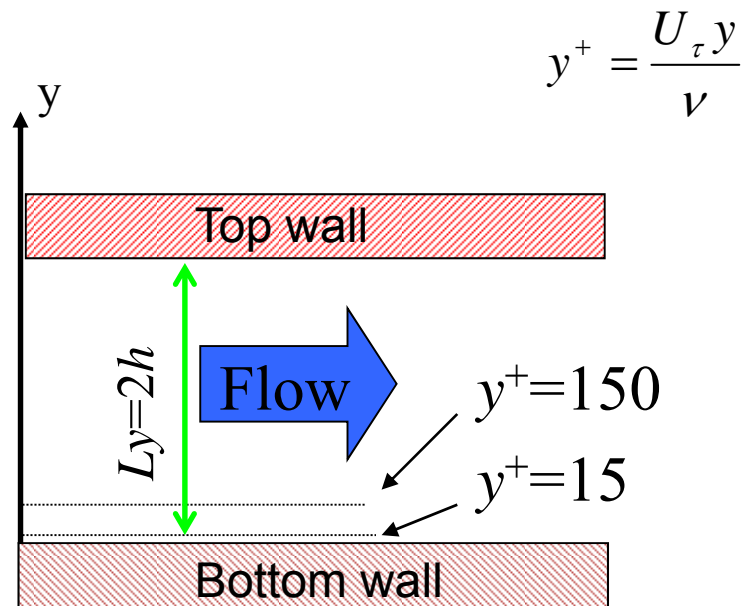
Kim & Adrian (1991), Physics of Fluids, vol.11, pp.417-422

円管実験、R:半径

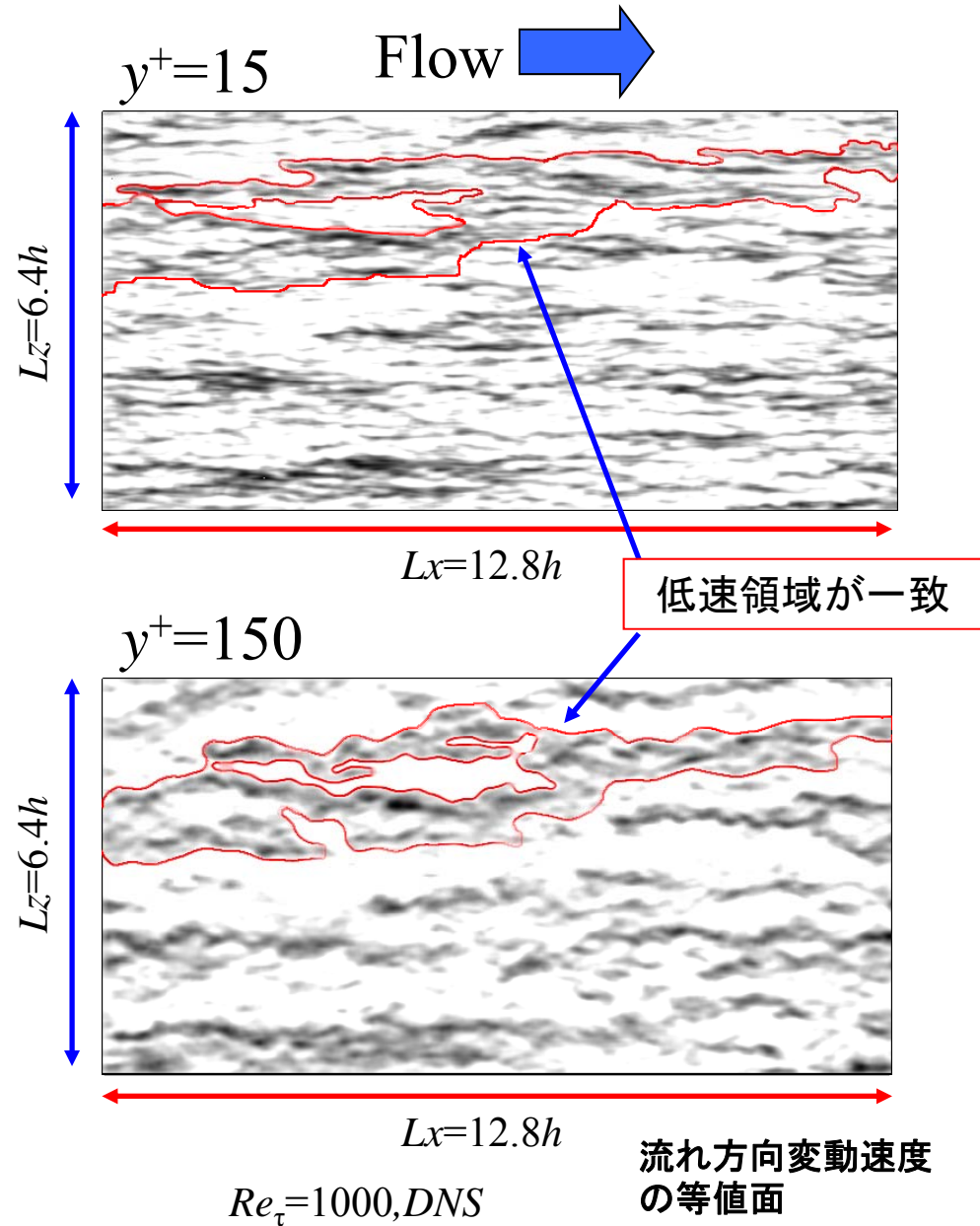
流れ方向速度成分のスペクトル



壁乱流の組織構造: Super structure



- $y^+ = 15$ → 乱流の乱れ成分が多く生産されている場所
 (バッファー層)
- $y^+ = 150$ → SuperStructureが存在する場所
 (対数領域)



Dennis & Nickels (2008)

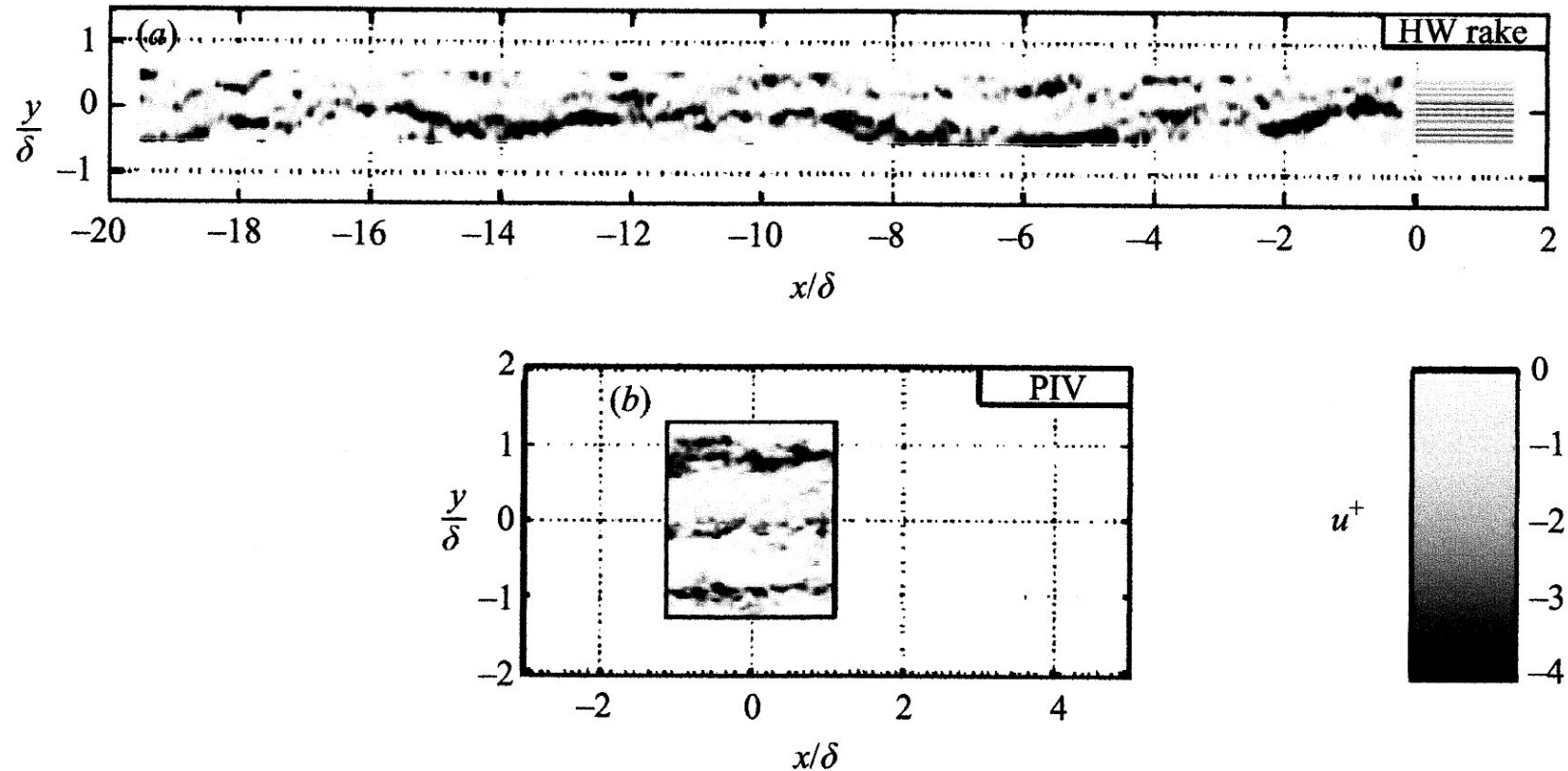
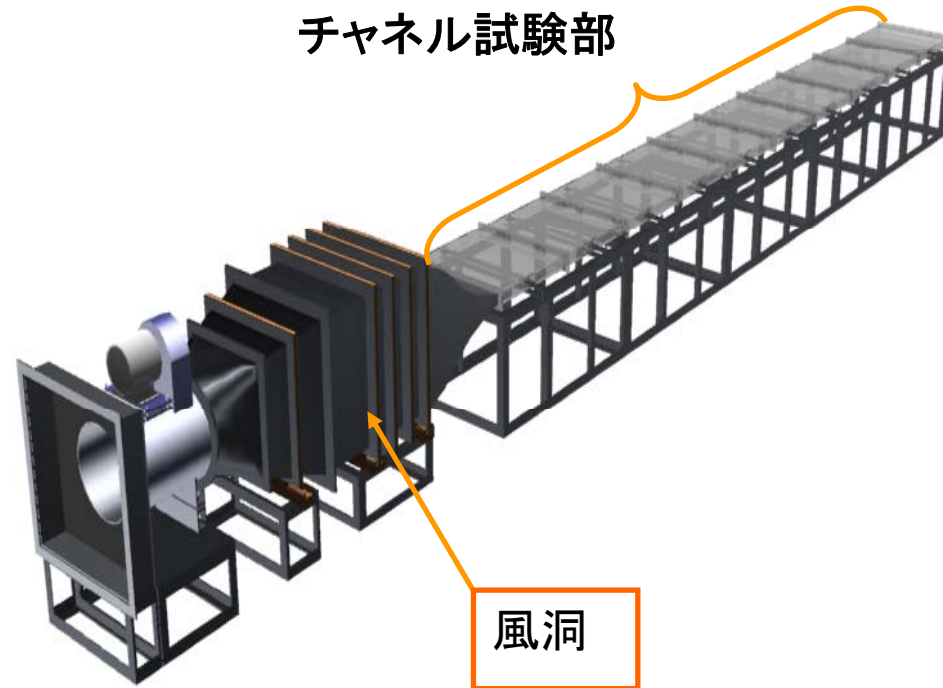


FIGURE 1. (a) Example rake signal at $y/\delta = 0.15$, for $Re_\tau = 14\,380$, and (b) PIV snapshot, from Hutchins & Marusic (2007a). Note their y is our z .

Log-region , large scale motion

チャンネル流路



試験部全長	10.4 m
ダクト断面形状	650mm × 50mm
最大流速	20.0 m/s

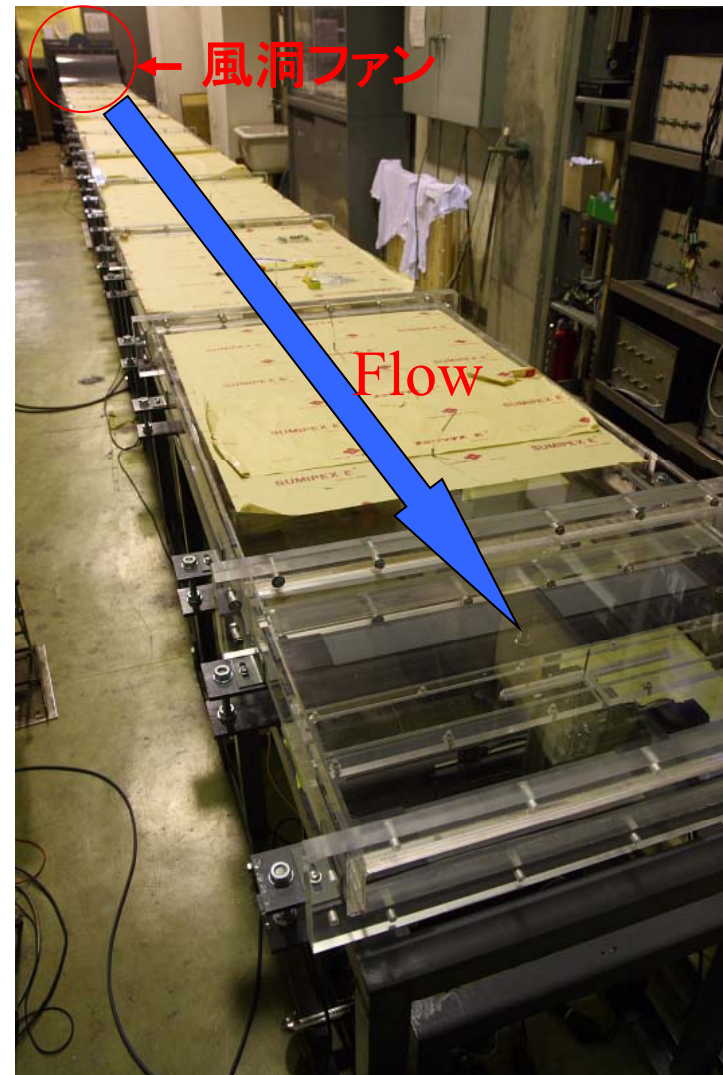
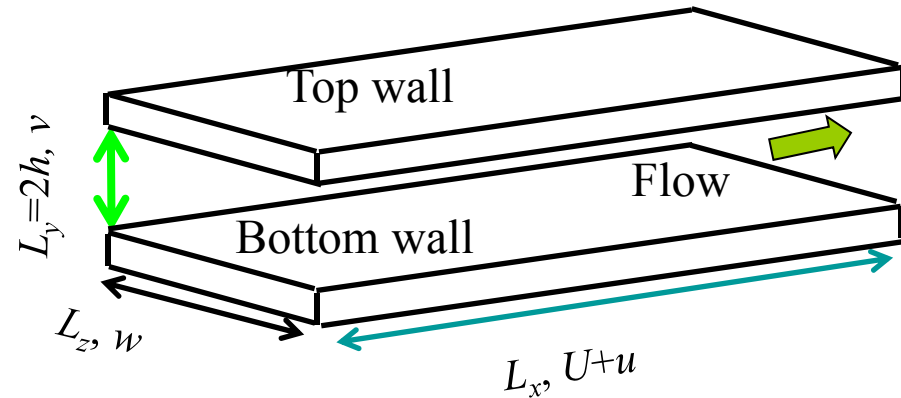


Fig. 測定用風洞全体図

Outline of DNS database

● del Alamo et al. (2004)

- Velocity-Vorticity form
- 3rd-order semi-implicit Runge-Kutta
- x, z: Fourier spectral method,
y: Chebychev-tau method
- or **Compact scheme** ▪ Aliasing error: Padding(3/2-rule)



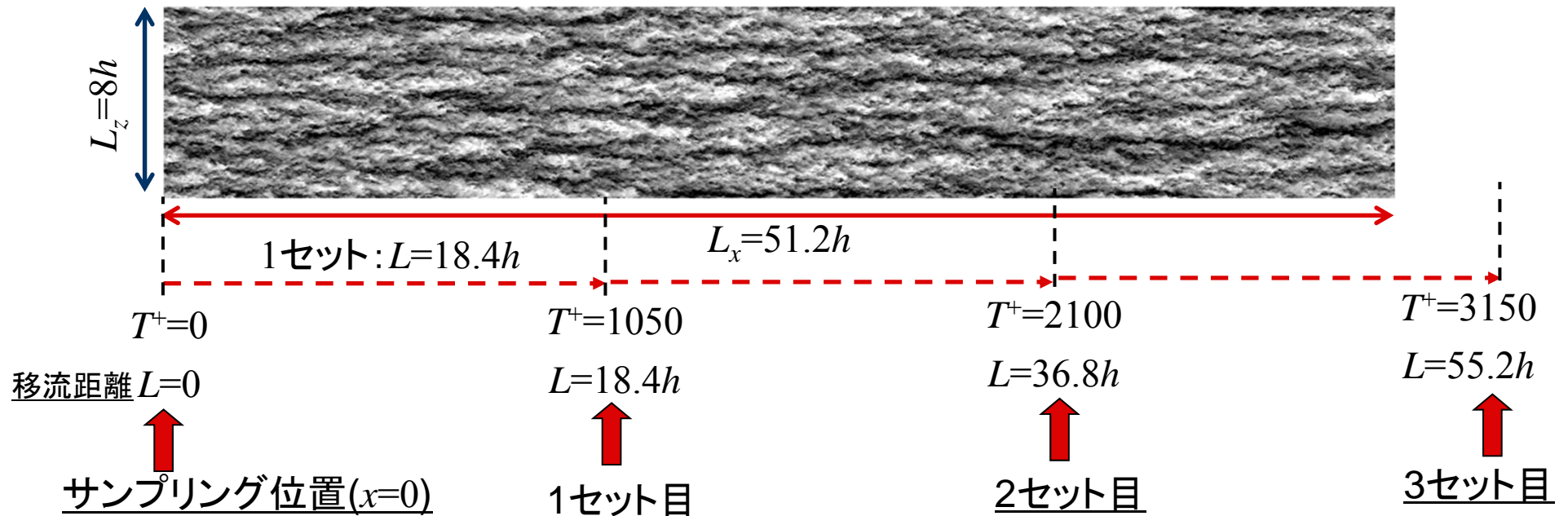
● Present

- Fractional step method
- 3rd-order Runge-Kutta (Convection), Crank-Nicolson (Viscosity), Euler implicit (Pressure)
- x, z: Fourier spectral method, y: 2nd-order FDM
- Aliasing error: Padding(3/2-rule)

	Re_τ	L_x	L_y	L_z	N_x	N_y	N_z	Δx^+	Δy^+	Δz^+
del Alamo et al.	934	$8\pi h$	$2h$	$3\pi h$	3072	385	2304	8.9	?-7.6	4.5
Present	1000	$51.2h$	$2h$	$8.0h$	2916	1032	1024	17.6	0.3- 2.0	7.8

時系列データの概要

$-4.0(\text{black}) < u^+ < 4.0(\text{white}), y^+=150, U^+=17.5$



○1セットあたり


- ・サンプリング間隔: 0.21 (タイムステップ間隔: $\Delta t^+=0.021 \rightarrow 10$ ステップに1回記録)
- ・サンプリング個数: 5000個 ($T^+=1050$)
- ・サンプリング位置: $x=0.0$

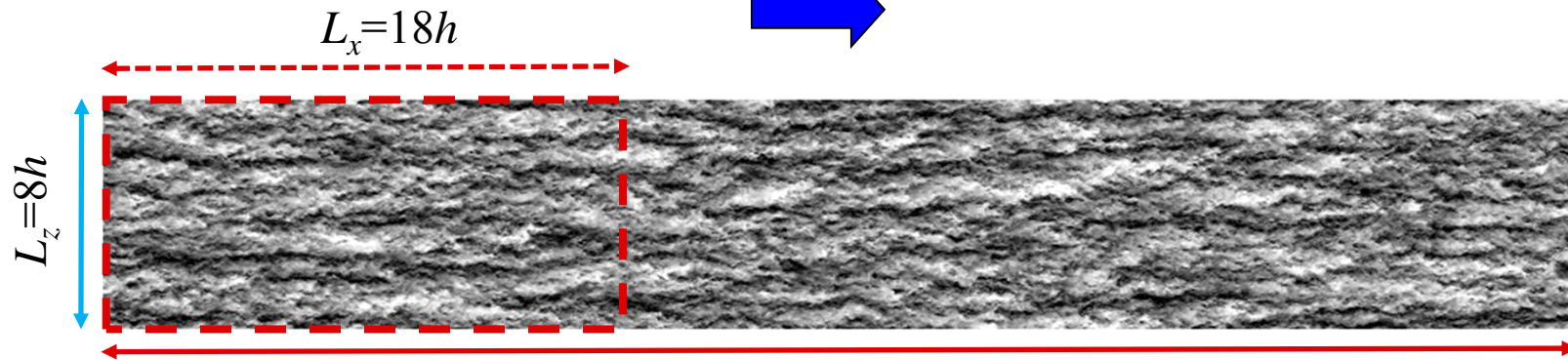
(スパン方向に512点: 1/2間隔で記録, 鉛直方向に516点: チャンネル下半分)

- ・サンプリングデータ: u, v, w, θ

○総データ数: 上記を7セット実行: 1点あたり、35000個(時間) \times 512(スパン方向)のデータで統計処理 \rightarrow 移流距離 = $128.6h$ ($y^+=150$)

Computational domain

Flow


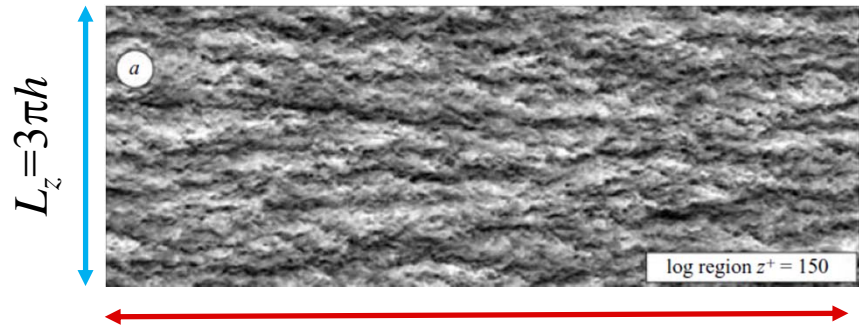


Analysis domain

$L_x = 51.2h$

Present DNS

$-4.0(\text{black}) < u^+ < 4.0(\text{white}), y^+ = 150, U^+ = 17.39$



$L_x = 8\pi h$

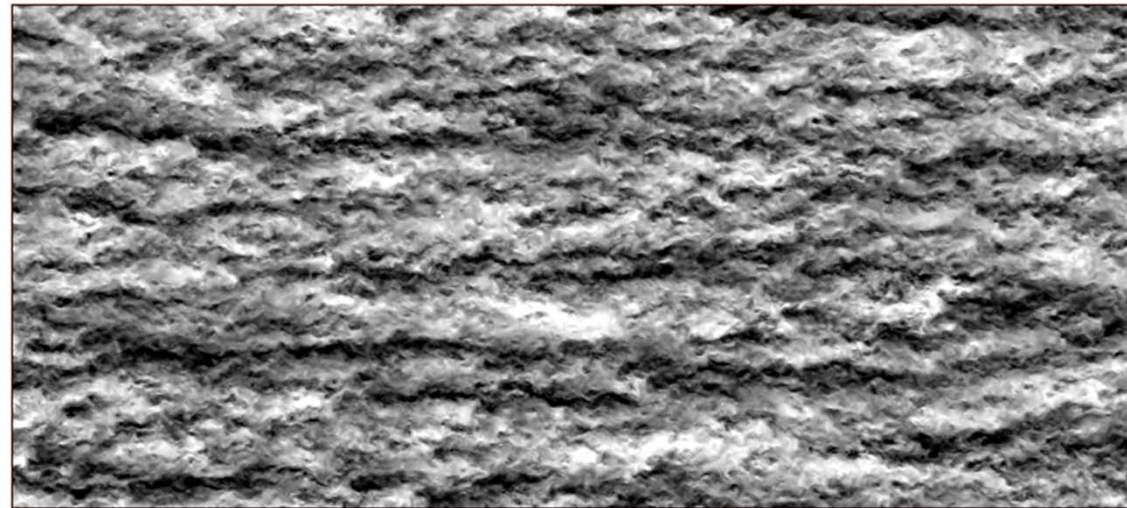
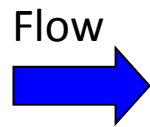
delAlamo & Jimenez

	Re_τ	Domain $L_x \times L_y \times L_z$	Grid number $N_x \times N_y \times N_z$	Resolution $\Delta x^+, \Delta y^+, \Delta z^+$
Present	1000	$51.2h \times 2h \times 8.0h$	$2916 \times 1032 \times 1024$	17.6, 0.5-2.0, 7.8
delAlamo	934	$8\pi h \times 2h \times 3\pi h$	$3072 \times 385 \times 2304$	7.6, ?-?, 3.8

Comparison of the spatial and Taylor fields

No filter

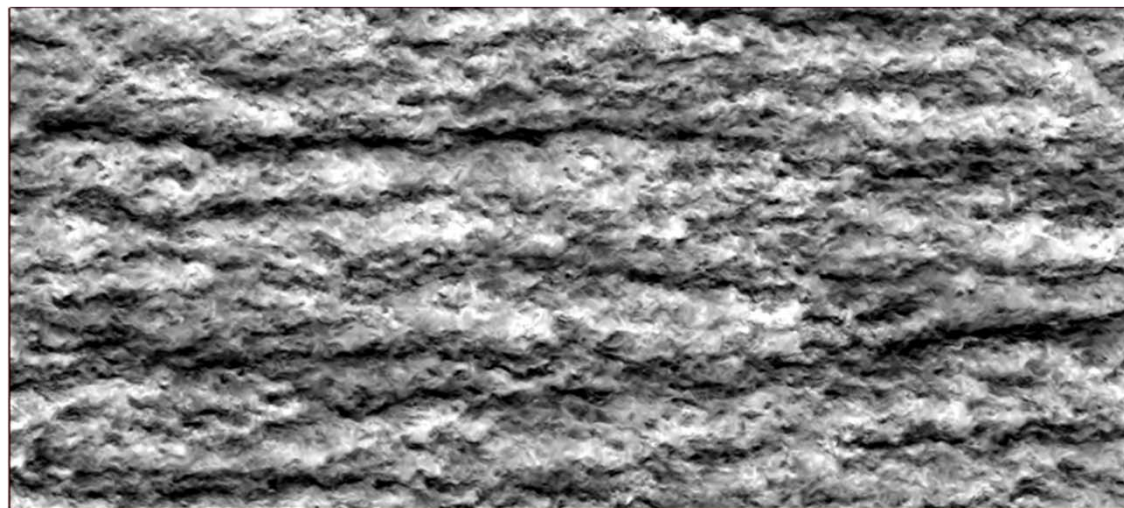
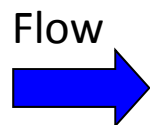
Spatial field



$$L_x = 18h$$

$$y_8^z = 7$$

Taylor field



$$L_x = 18h$$

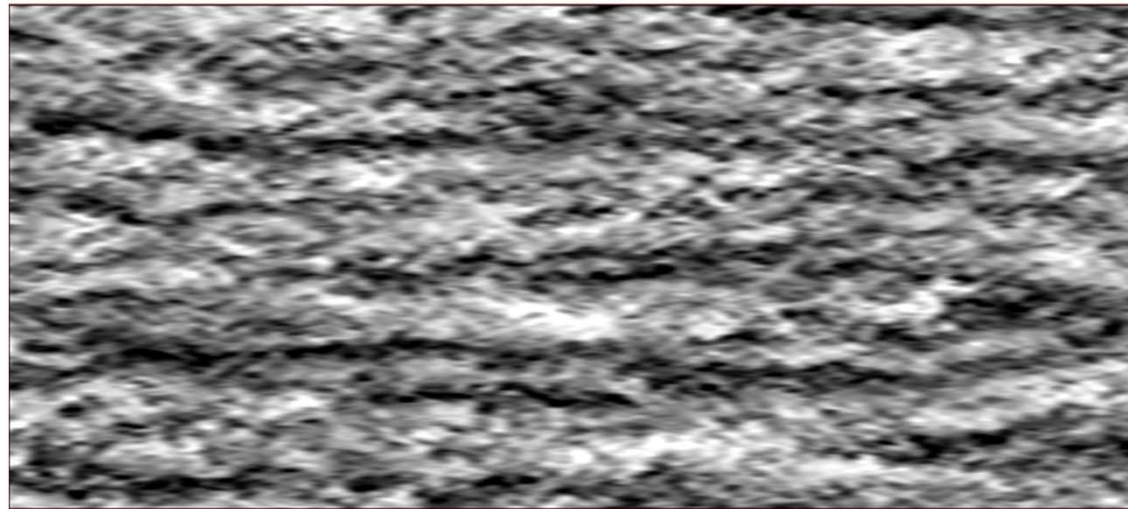
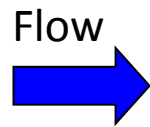
$$y_8^z = 7$$

Contour plots of Streamwise turbulent velocity, $Re_\tau = 1000$, $y^+ = 150 - 4(\text{black}) < u^+ < 4(\text{black})$

Comparison of the spatial and Taylor fields

Filter: $\Delta=0.2h$

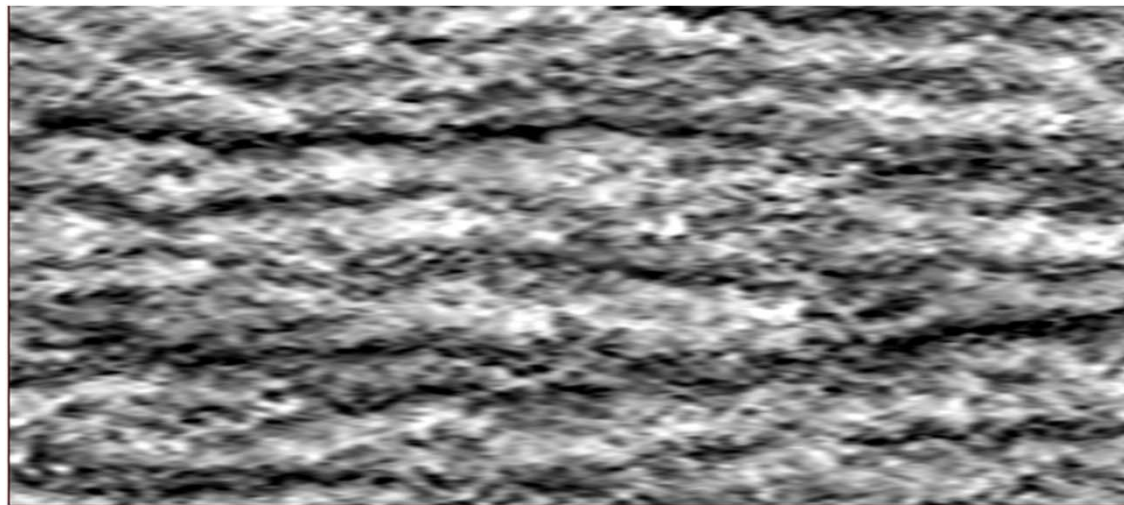
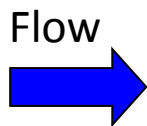
Spatial field



Spectral filter

$$L_x = 18h$$

Taylor field



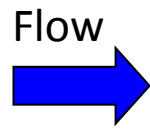
$$L_x = 18h$$

Contour plots of Streamwise turbulent velocity, $Re_\tau=1000$, $y^+=150$, $-4(\text{black}) < u^+ < 4(\text{white})$

Comparison of the spatial and Taylor fields

Filter: $\Delta=2h$

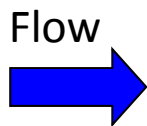
Spatial field



Gaussian filter

$L_x=18h$

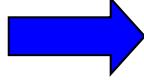
Taylor field



$L_x=18h$

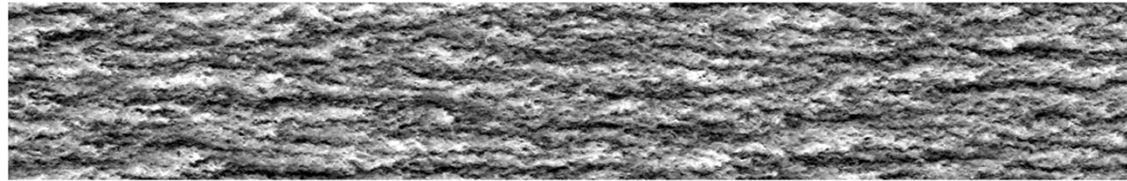
Contour plots of Streamwise turbulent velocity, $Re_\tau=1000$, $y^+=150$, $-2(\text{black}) < u^+ < 0(\text{white})$

可視化(対数領域)

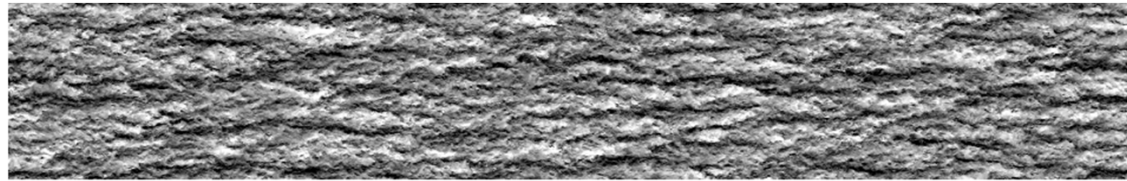
Flow




$T^+=0$

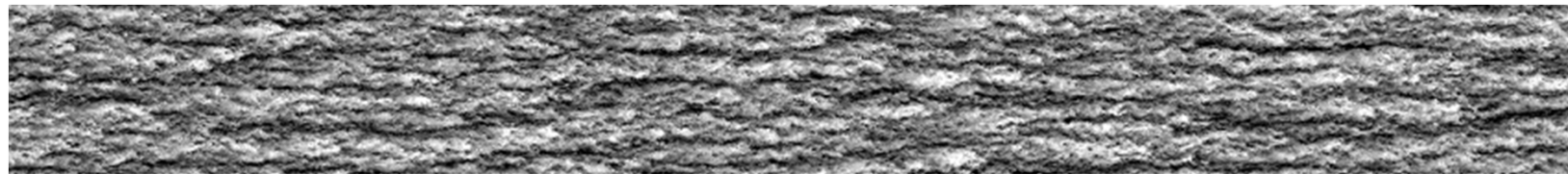


$T^+=2100$



$T^+=4200$

$L_x=51.2h$



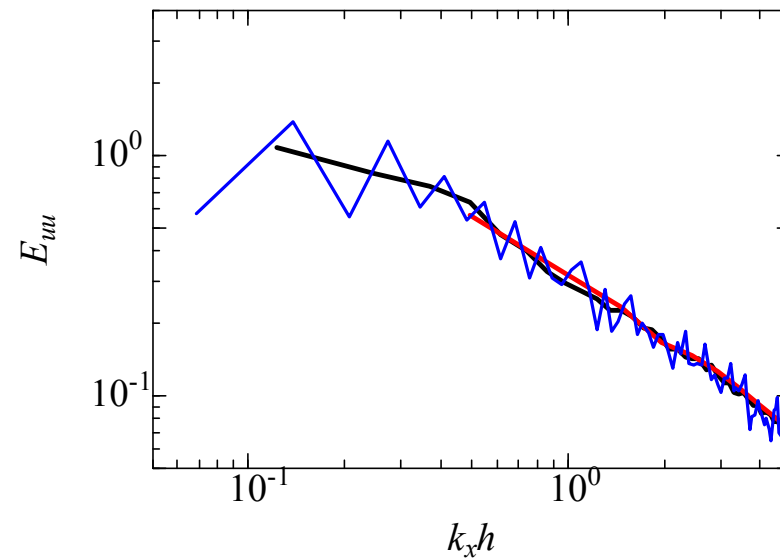
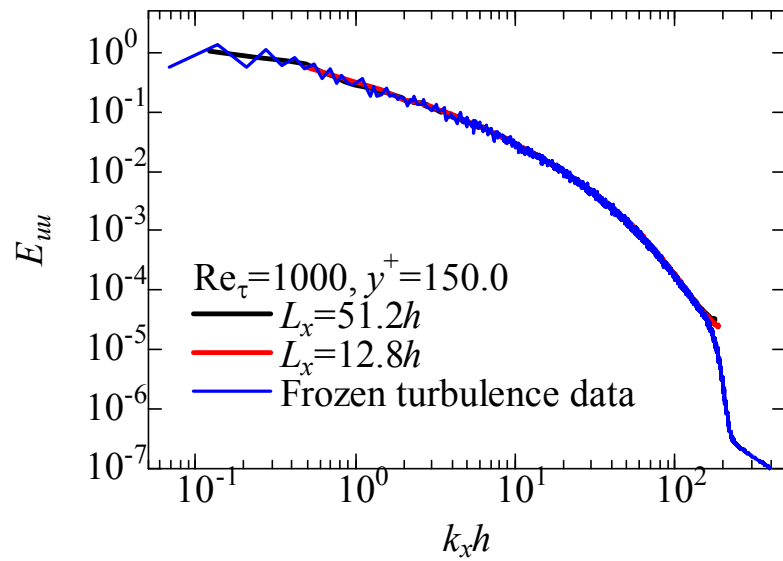
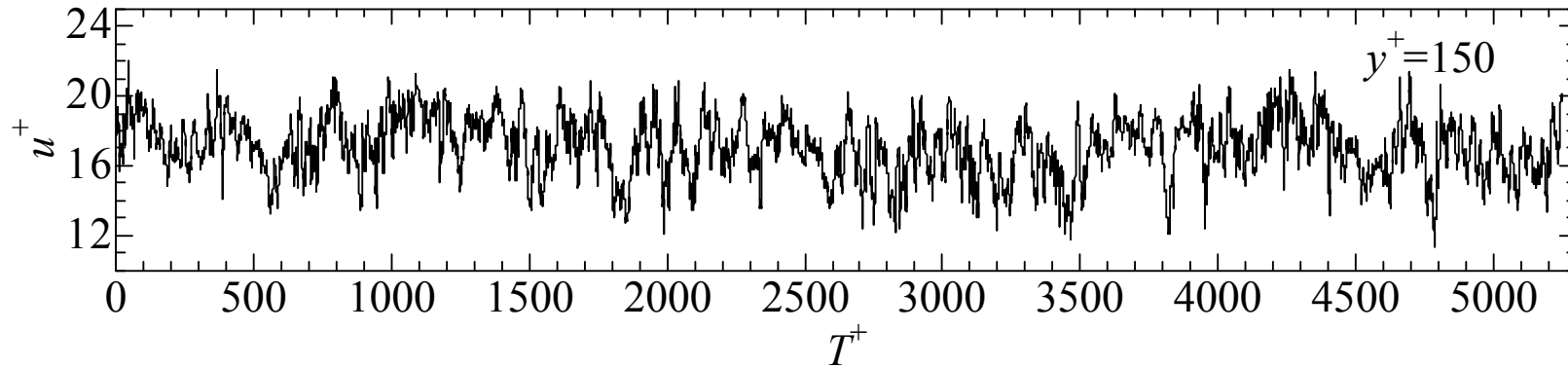
$L_x=73.5h$

$T^+=4200$ における凍結乱流を仮定し、構築した主流方向変動速度分布

$-4.0(\text{black}) < u^+ < 4.0(\text{white}), y^+=150, U^+=17.5$

時系列データとそのスペクトル(対数領域)

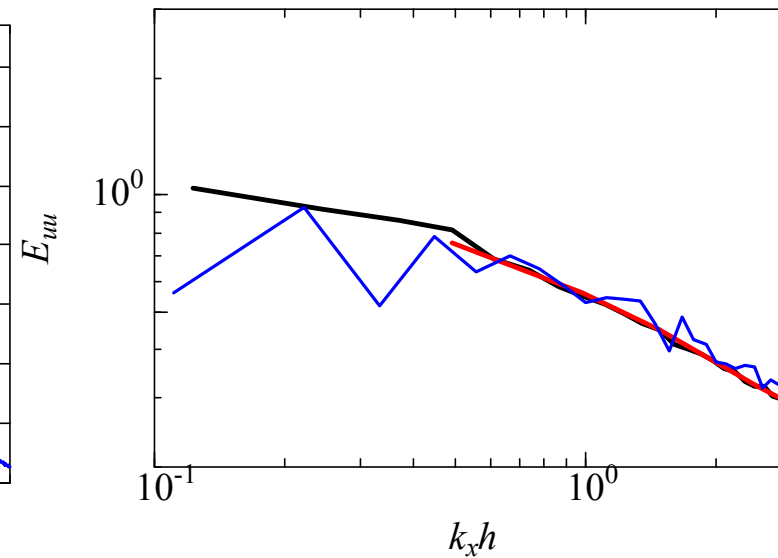
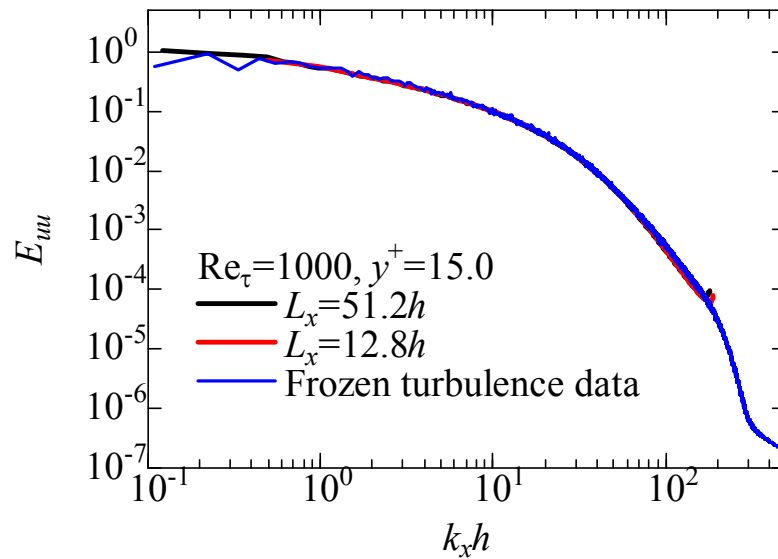
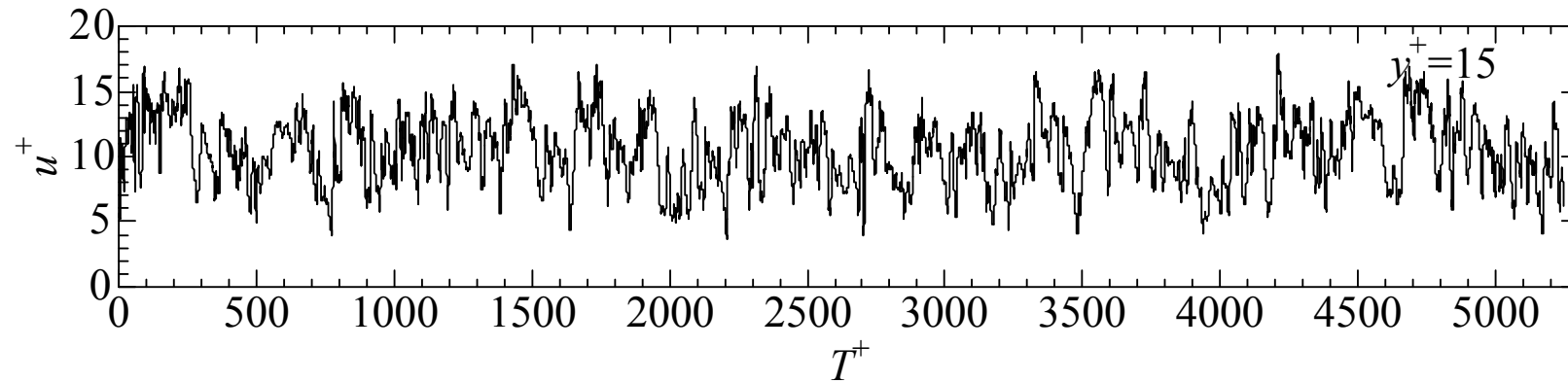
1+2+3+4+5セット目



低波数領域

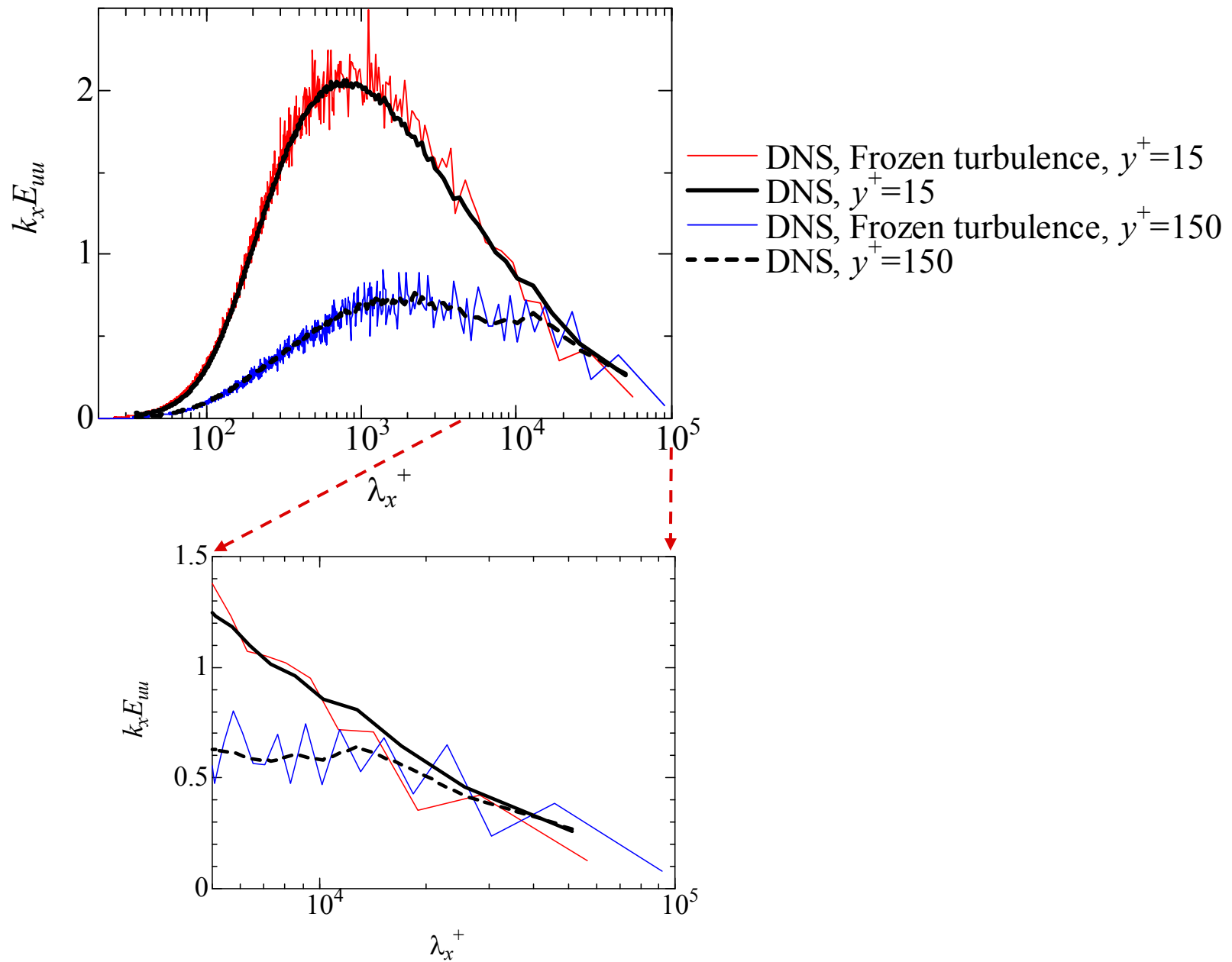
時系列データとそのスペクトル(バッファ層)

1+2+3+4+5セット目



低波数領域

Pre-multiplied spectra



Delalamo and Jimenez (2009)

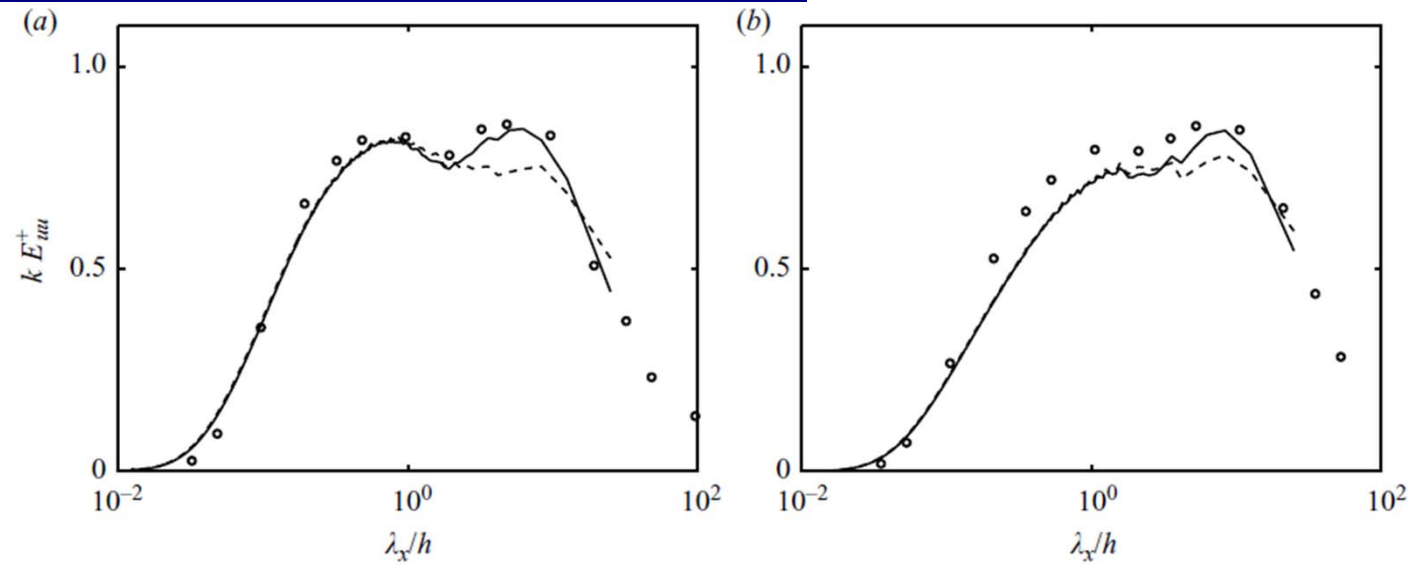
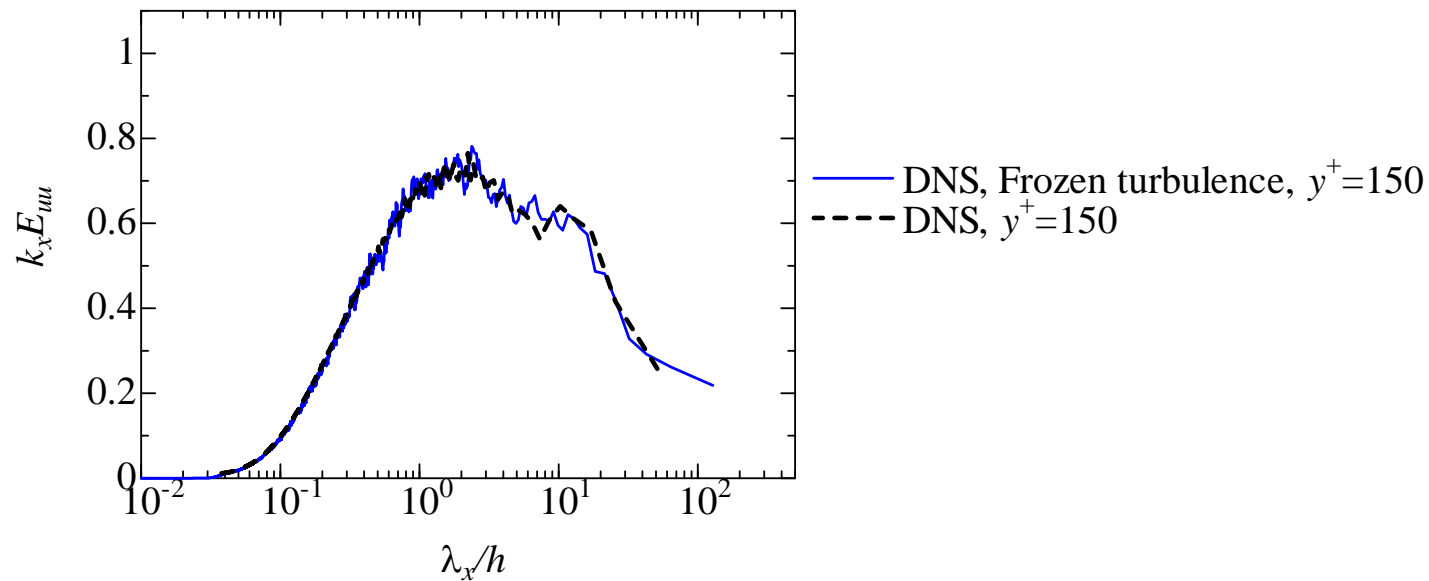
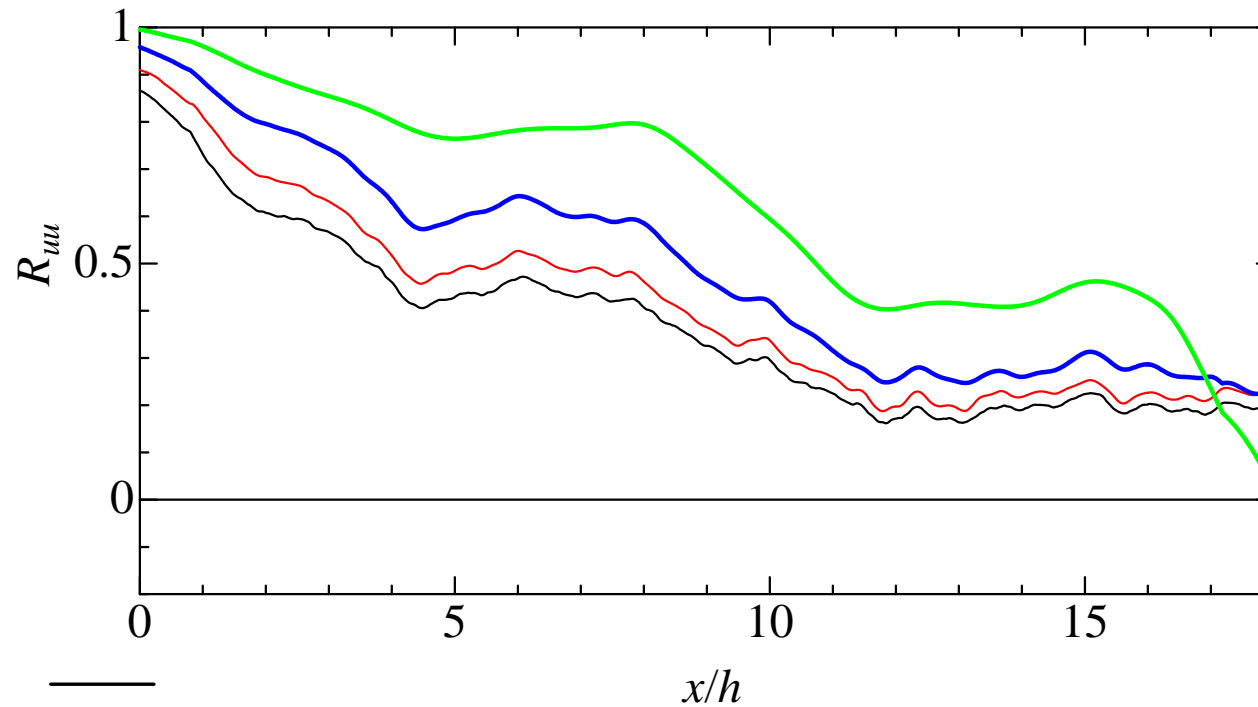


FIGURE 10. One-dimensional pre-multiplied energy spectra, $k_x E_{uu}(k_x)$. \circ , Perry & Abell (1975), $Re_\tau = 2325$. Lines are case (Hoyas & Jiménez 2006): $---$, true wavelengths; $—$, uncorrected Taylor wavelengths. (a) $y^+ = 100$, (b) $y^+ = 200$.



Correlation of the spatial and Taylor fields



$$R_{uu} = \frac{\overline{u_s u_T}}{\sqrt{\overline{u_s^2}} \sqrt{\overline{u_T^2}}}$$

- no filter
- $\Delta=0.2h$ (spectral filter)
- $\Delta=0.5h$ (gaussian filter)
- $\Delta=2.0h$ (gaussian filter)

相関値は主流方向距離に対し、単調減少ではない？

- $x/h < 5$ 実験と同様に単調減少
- $5 < x/h < 9$ 平坦化
- $x/h > 9$ 再び減少

まとめと今後の計画

壁乱流(二次元チャンネル)での大規模計算をおこない、時系列データを長時間にわたり取得する。周波数スペクトルならびに波数スペクトルのPMS(Pre-Multiplied Spectrum)比較から、凍結乱流仮説の妥当性を検証する。

Super Structure (SS)の抽出ならびに、凍結乱流仮説に与える影響を定量的に評価する。境界層厚さ δ の数十倍に及ぶ大規模構造のスパン方向へのゆらぎの大きさ、壁せん断応力への寄与を数値的にみつめる。

瞬時のSSの空間構造を空間に固定された測定点からの時系列データを基に再構成する方法について考察する。特に局所平均速度に代わり、空間スケールへ変換するための代表速度を見出す。

同一体系での実験をおこない、数値計算との比較をおこなう。数値計算における周期境界条件、流れ方向への計算領域の影響、実験計測における測定プローブの空間分解能の影響を両者のデータを比較することから明らかにしたい。得られた成果を広く大気乱流などのデータ解析に役立てたい。