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

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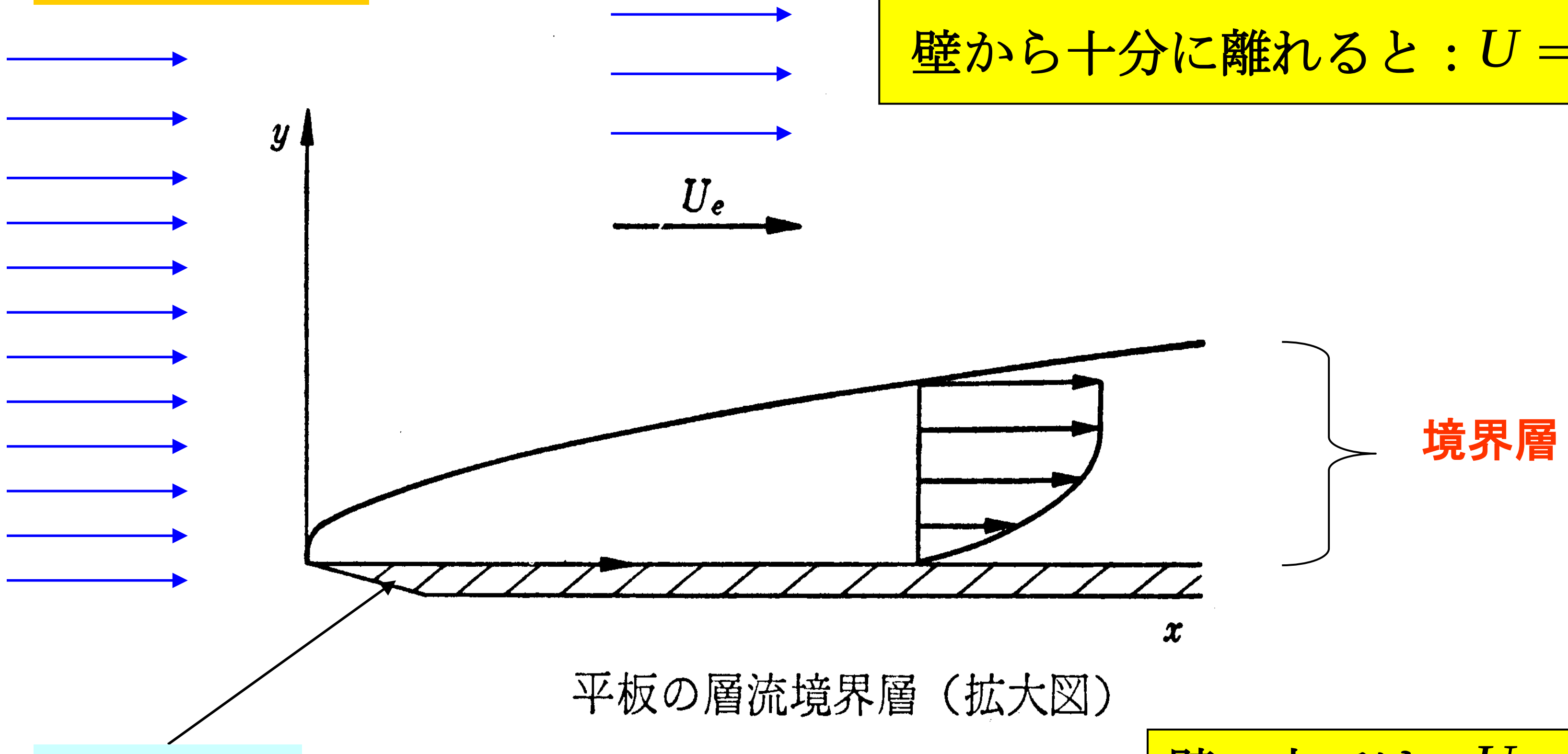
壁乱流（境界層、チャネル、円管）

一様な流れ



平板の層流境界層（拡大図）

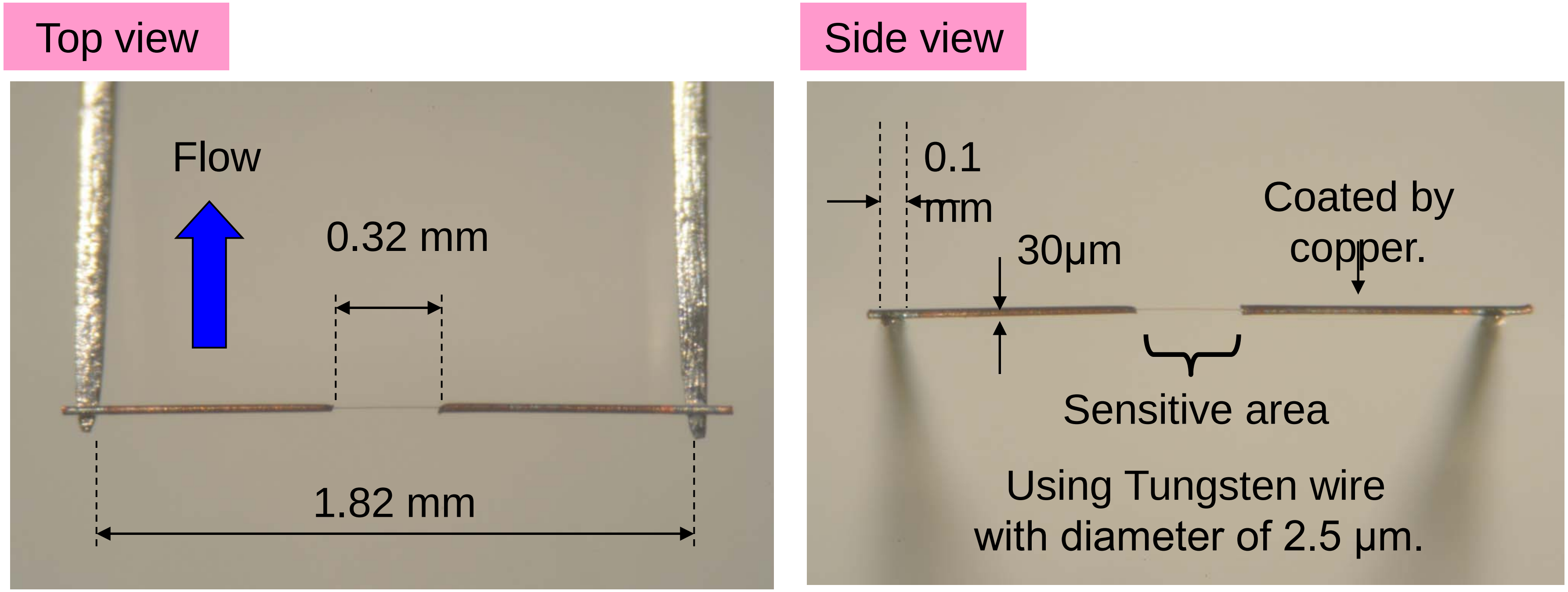
壁から十分に離れると：$U = U_e$

壁の上では：$U = 0$

平板・壁

Streamwise turbulence intensity measurements

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 (The flow direction is from heads to tails.).

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 ”

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

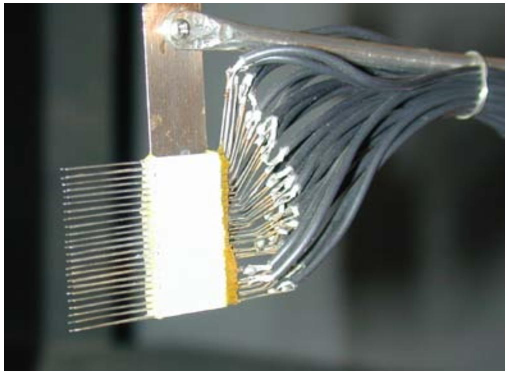
This can be formed above for not too large value of τ (the time delay), and where U_c is the assumed convection velocity. This approximation is thought to be substantially accurate for boundary layer flow provided that u_{rms}/U_c is small.

数値計算によって検証できる

Large scale motion in turbulent boundary layer

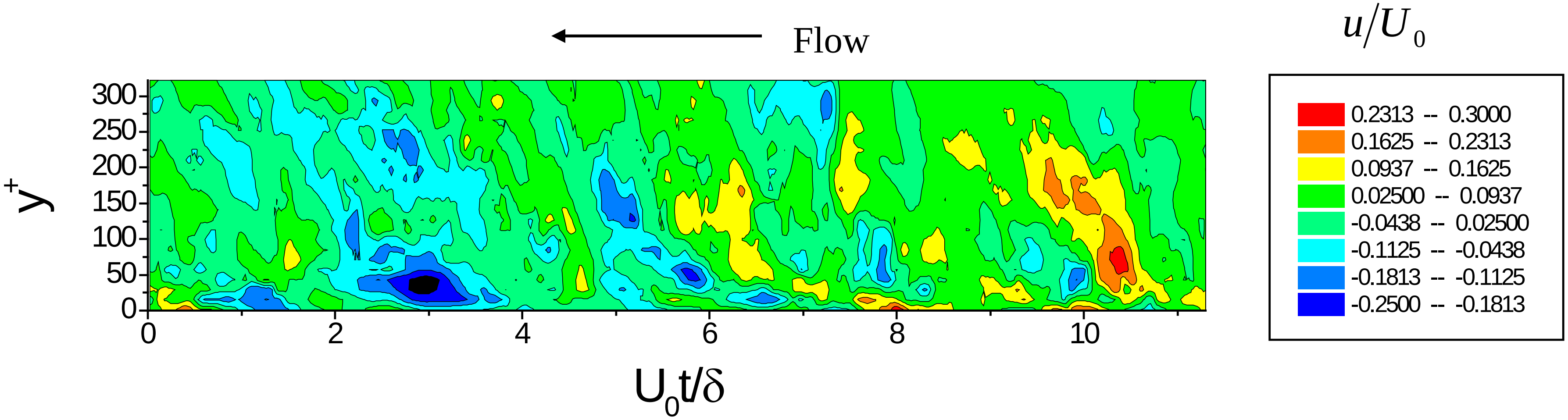
There is no clear definition on the structures

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



Experiments by 24-ch probes measurement.

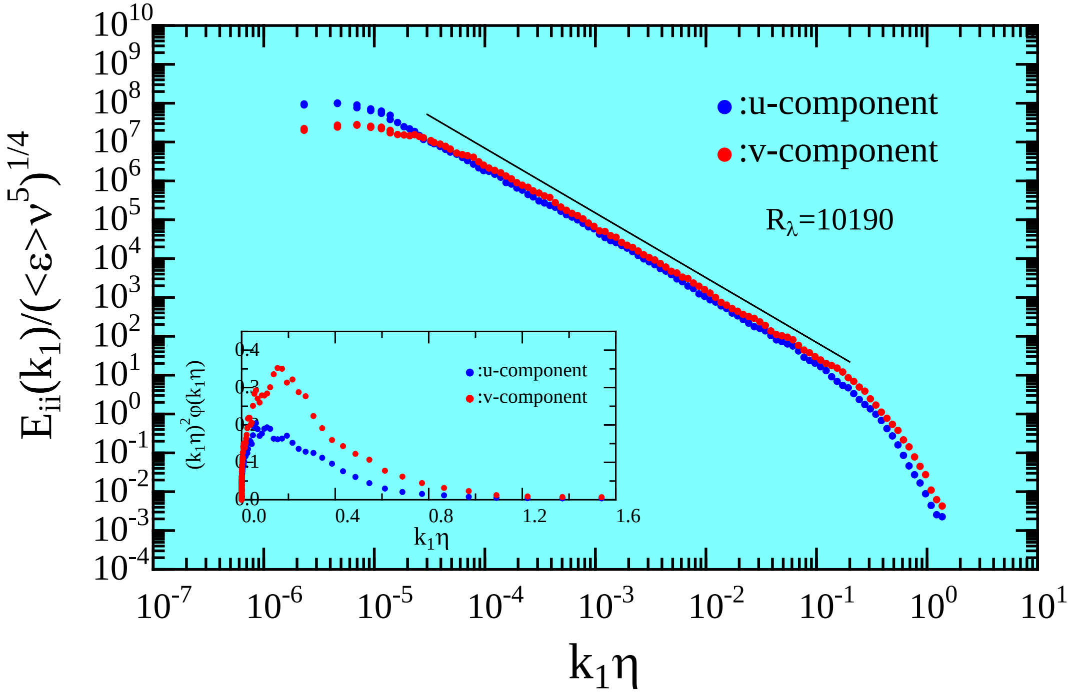
$U_0 = 13.5[m/s] \quad R_\theta \cong 3300$



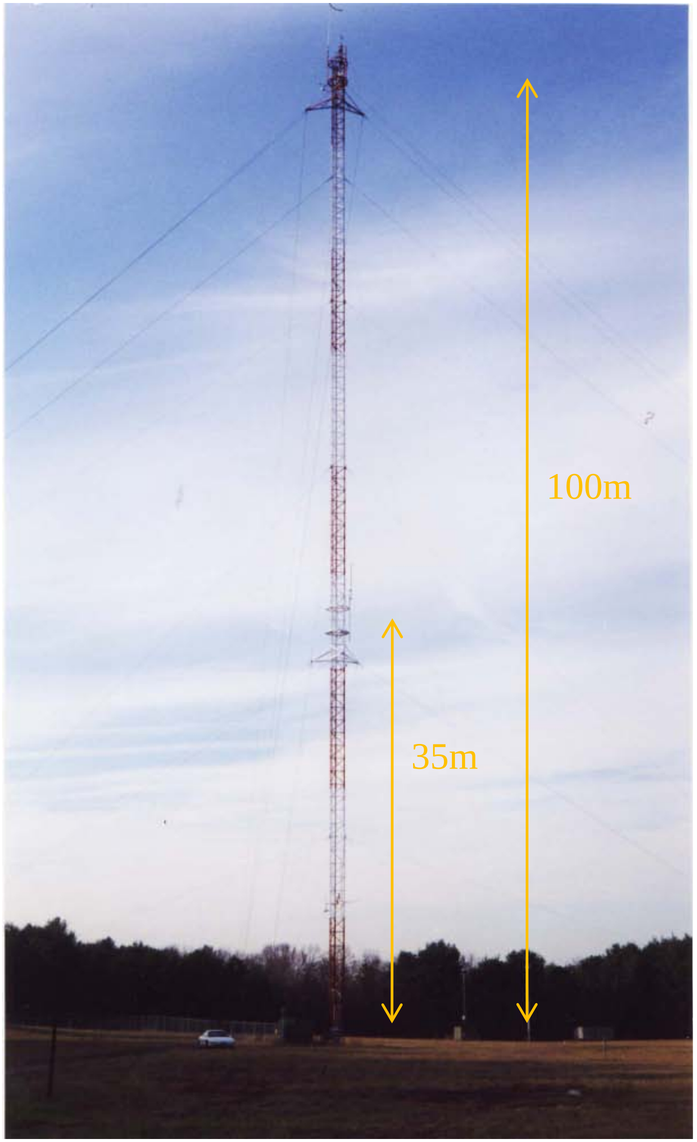
High-Reynolds number experiment 1

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

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

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

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

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

Del Alamo & Jimenez (2009)

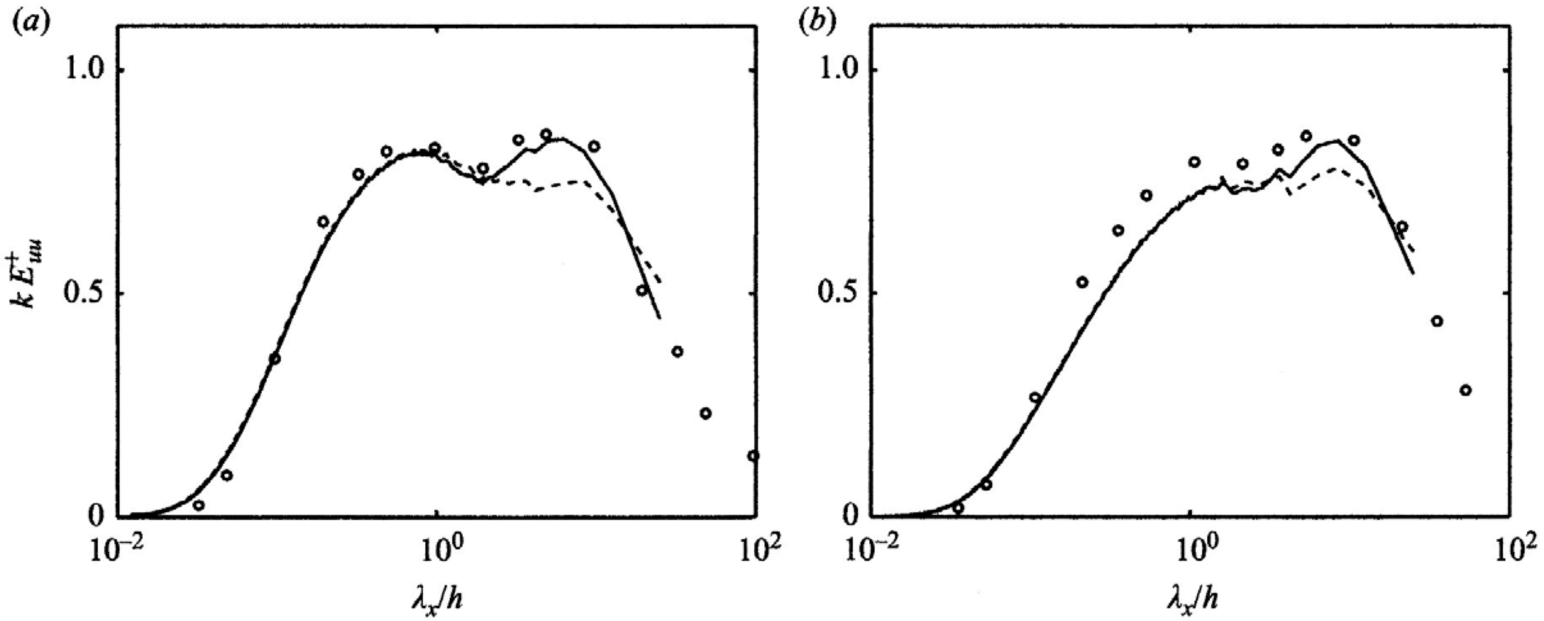
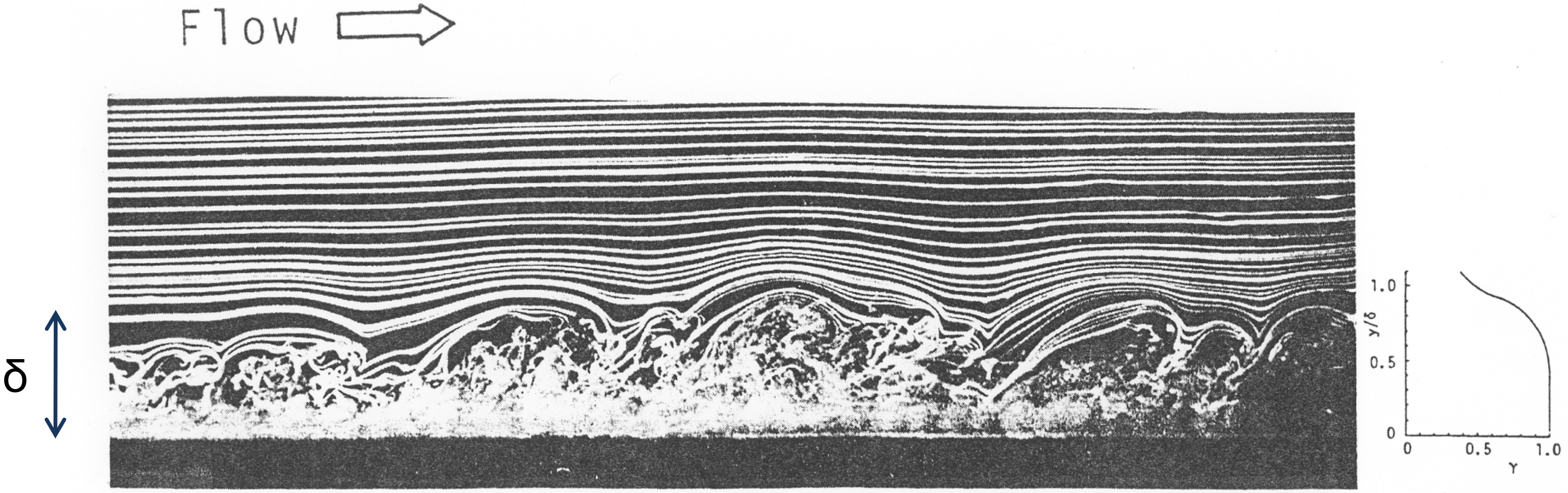


FIGURE 10. One-dimensional pre-multiplied energy spectra, $k_x E_{uu}(k_x)$. ○, Perry & Abell (1975), $Re_\tau = 2325$. Lines are case (Hoyas & Jiménez 2006): ———, true wavelengths; ———, uncorrected Taylor wavelengths. (*a*) $y^+ = 100$, (*b*) $y^+ = 200$.

$$E(\omega) = \int E\left[k_x(\omega, k_z), k_z\right] \underbrace{\left| dk_x / d\omega \right|}_{\text{model ?}} dk_z \qquad E_{uu}(k_x) \propto k_x^{-1}$$

数値計算結果

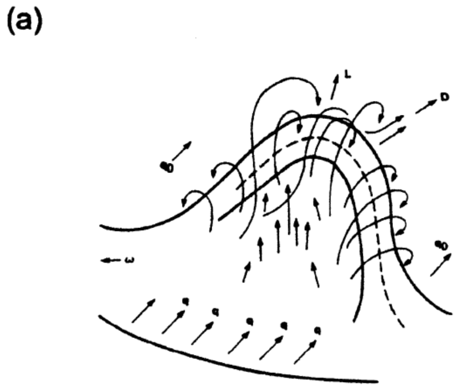
壁乱流の組織構造



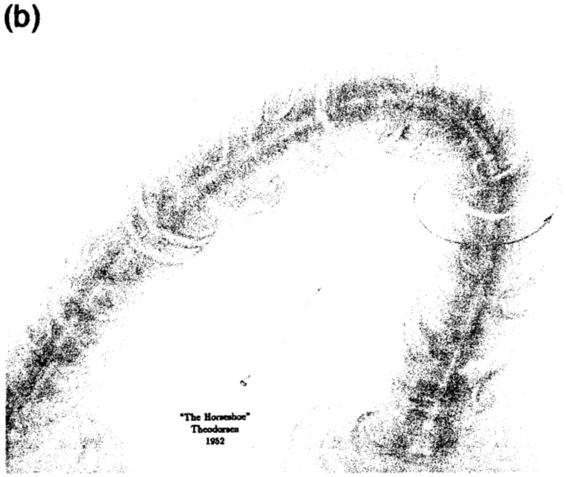
Osaka, H and Mochizuki, S. et.al., JSME, Vol.53(1987), pp27-34

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

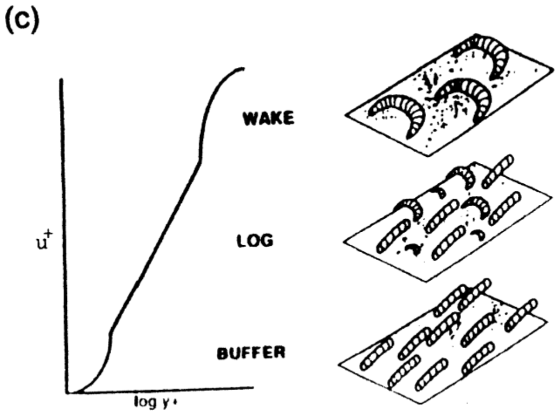


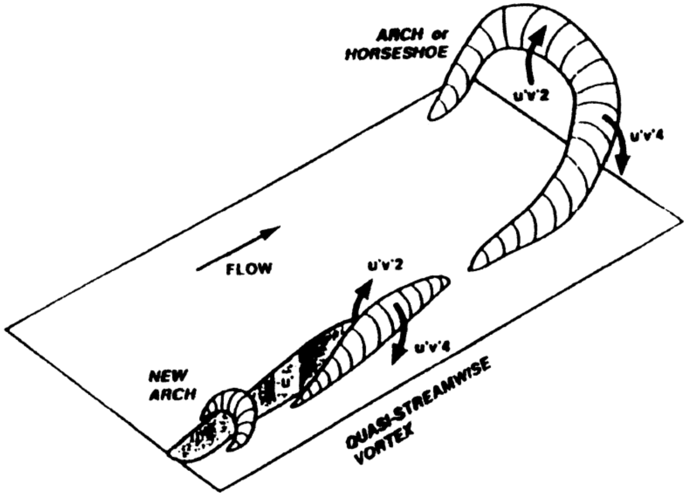
Theodorson’s(1952) description of Horseshoe vortex



Sketch of “Horseshoe” attributed to Weske

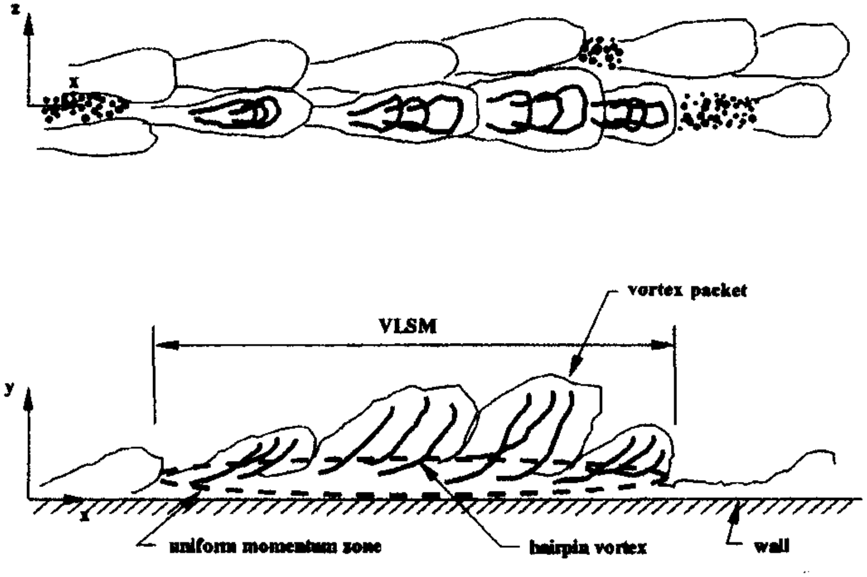
Robinson’s summary of structures found in DNS





1980,1990年代

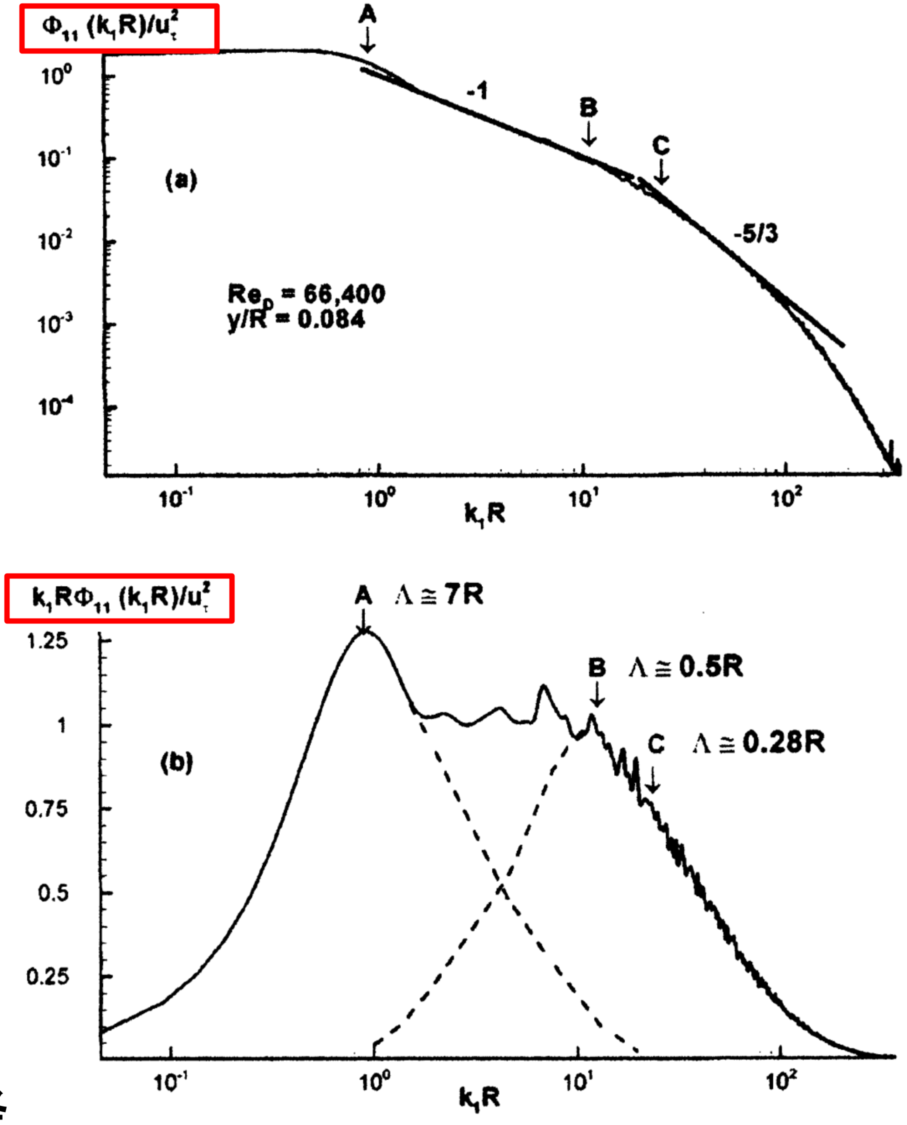
壁乱流の組織構造



VLSM: Very Large Scale Motion

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

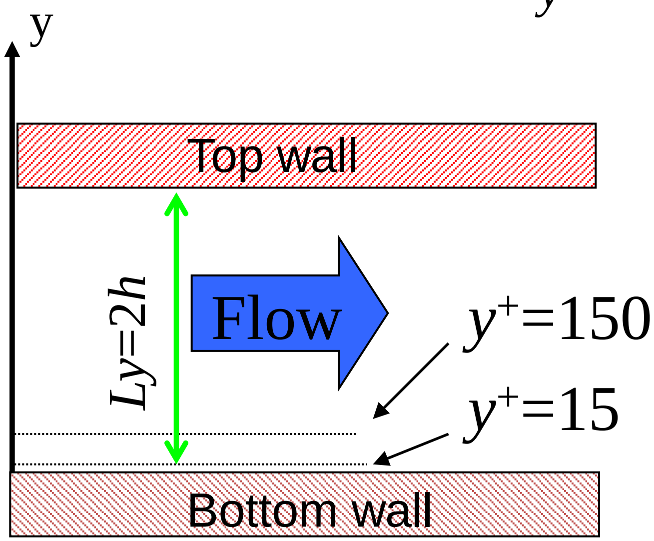
流れ方向速度成分のスペクトル



円管実験、R:半径

壁乱流の組織構造:Super structure

$$y^+=\frac{U_\tau y}{\nu}$$

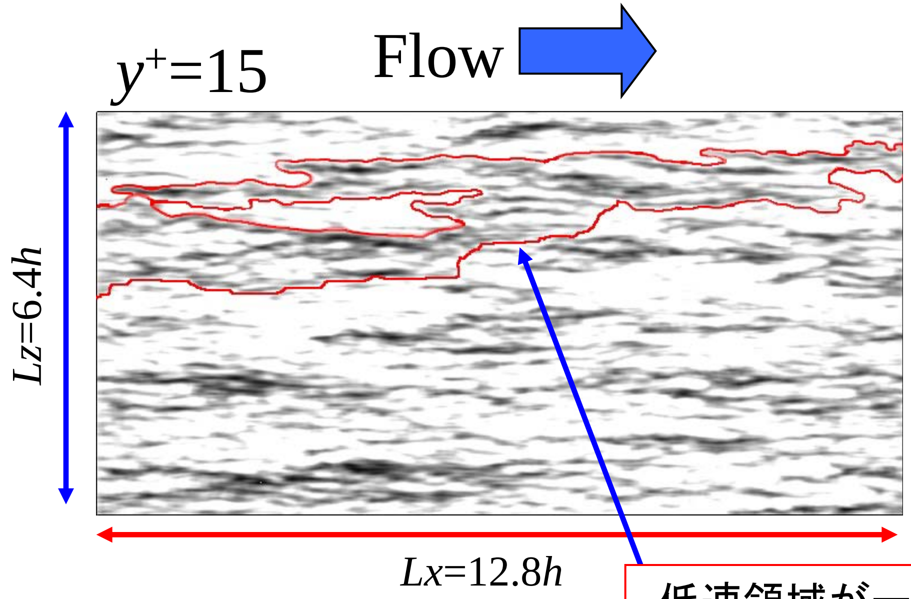


$y^+=15$ → 乱流の乱れ成分が多く生産されている場所

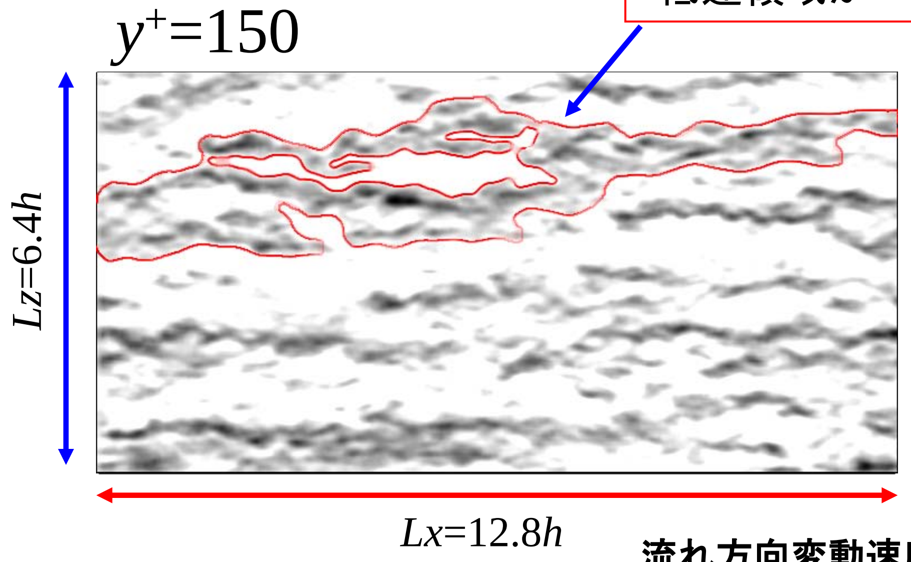
(バッファー層)

$y^+=150$ → SuperStructureが存在する場所

(対数領域)



低速領域が一致



$Re_\tau=1000$,*DNS*

流れ方向変動速度の等値面

Dennis & Nickels (2008)

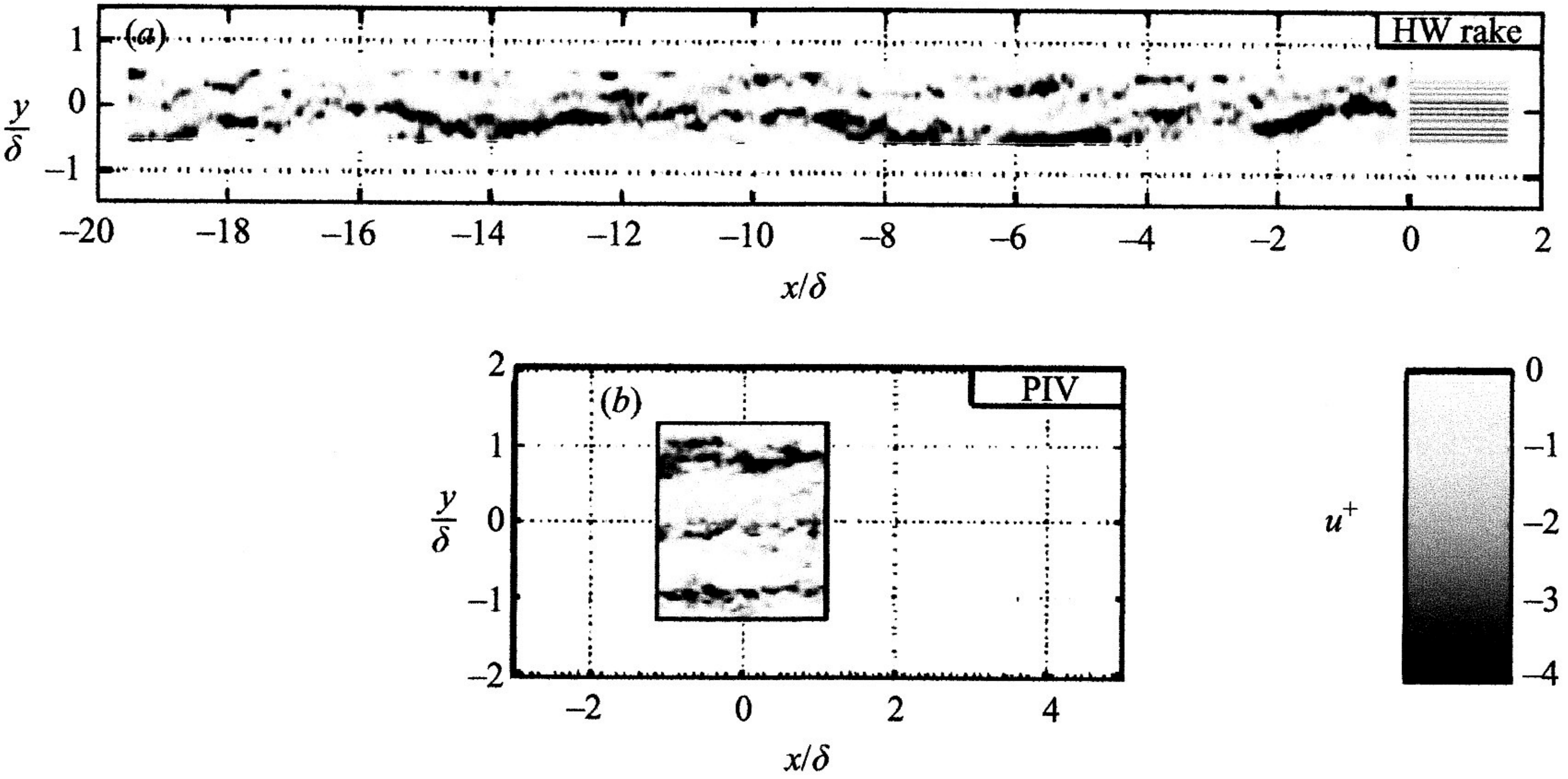
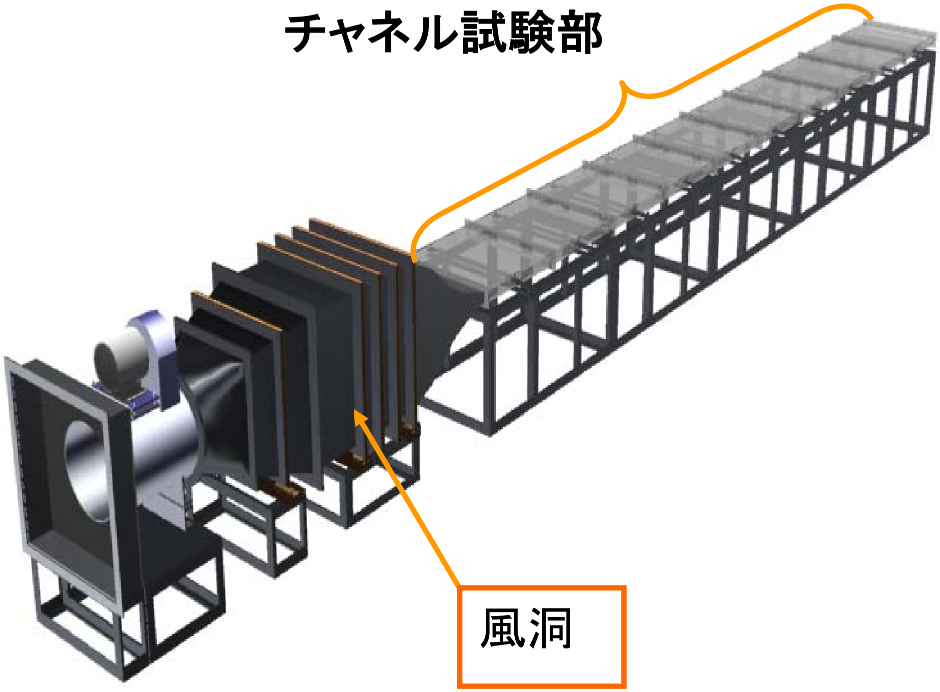


FIGURE 1. (a) Example rake signal at $y/\delta = 0.15$, for $Re_\tau = 14\,380$, and (b) PIV snapshot, from Hutchins & Marusic (2007a). Note their y is our z.

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

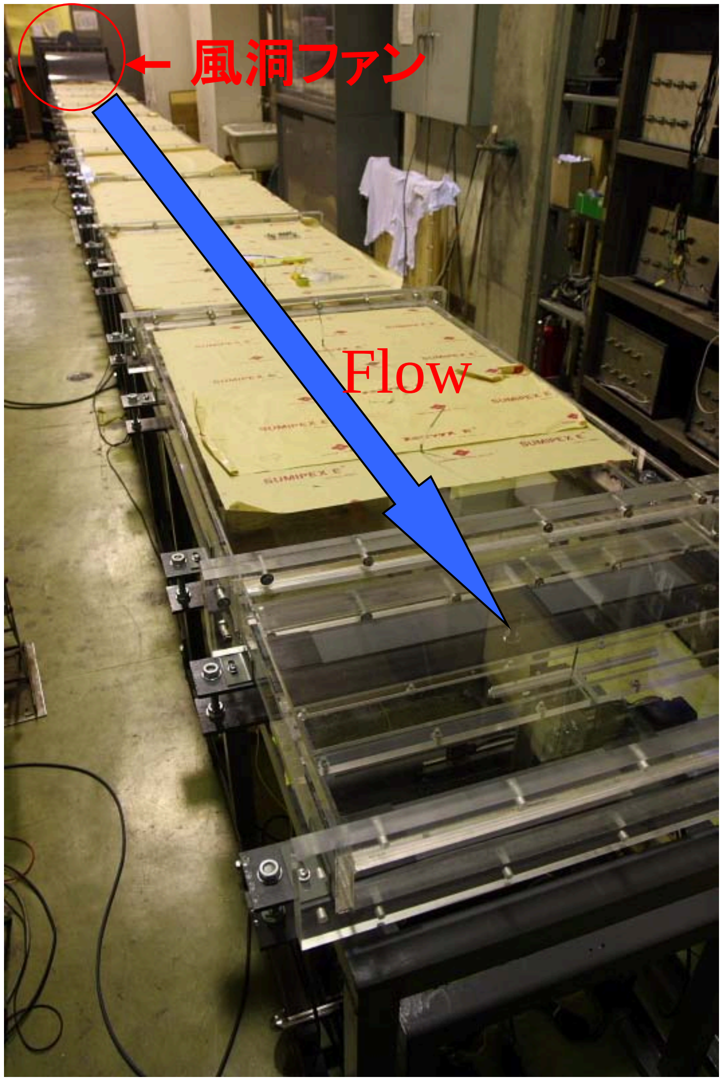


Fig. 測定用風洞全体図

まとめと今後の計画

壁乱流（二次元チャネル）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もる。

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。