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UNDERSTANDING TRANSITION AND TURBULENCE THROUGH DIRECT SIMULATIONS

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Direct simulations consist in solving the full Navier-Stokes equations, without any turbulence model, and describing all the detailed features of the flow. Usually the flows are three-dimensional and time-dependent and contain both coarse and fine structures, which makes the numerical task very challenging in terms of both the algorithm and the computational effort. Most of the work until now has involved spectral methods, which are highly accurate but not very flexible in terms of geometry or complex equations. For that reason, future work will also rely on high-order finite-difference or other methods.

Direct simulations complement experimental work, and both contribute to the theory and the empirical knowledge of turbulence. Once such a simulation has been shown to be accurate the flow field is completely known, in three dimensions and time, including the pressure, the vorticity and any other quantity. On the other hand, most simulations to date solved the incompressible equations in rather simple geometries, and direct simulations will always be limited to moderate Reynolds numbers. Extensive simulations have been conducted in homogeneous turbulence, channel flows, boundary layers, and mixing layers. Much effort is devoted to addressing flows with compressibility and chemical reactions, and to new geometries such as a backward-facing step.

UNDERSTANDING TRANSITION AND TURBULENCE THROUGH DIRECT SIMULATIONS

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- Secondary instability in channel flow.
- Stability and relaminarization of the swept attachment-line flow.
- Improvement of the pressure term in turbulence models.
- Coherent structures in homogeneous and wall-bounded shear flows.
- Lyapunov exponents of a turbulent channel flow.
- Growth of compressible mixing layers.

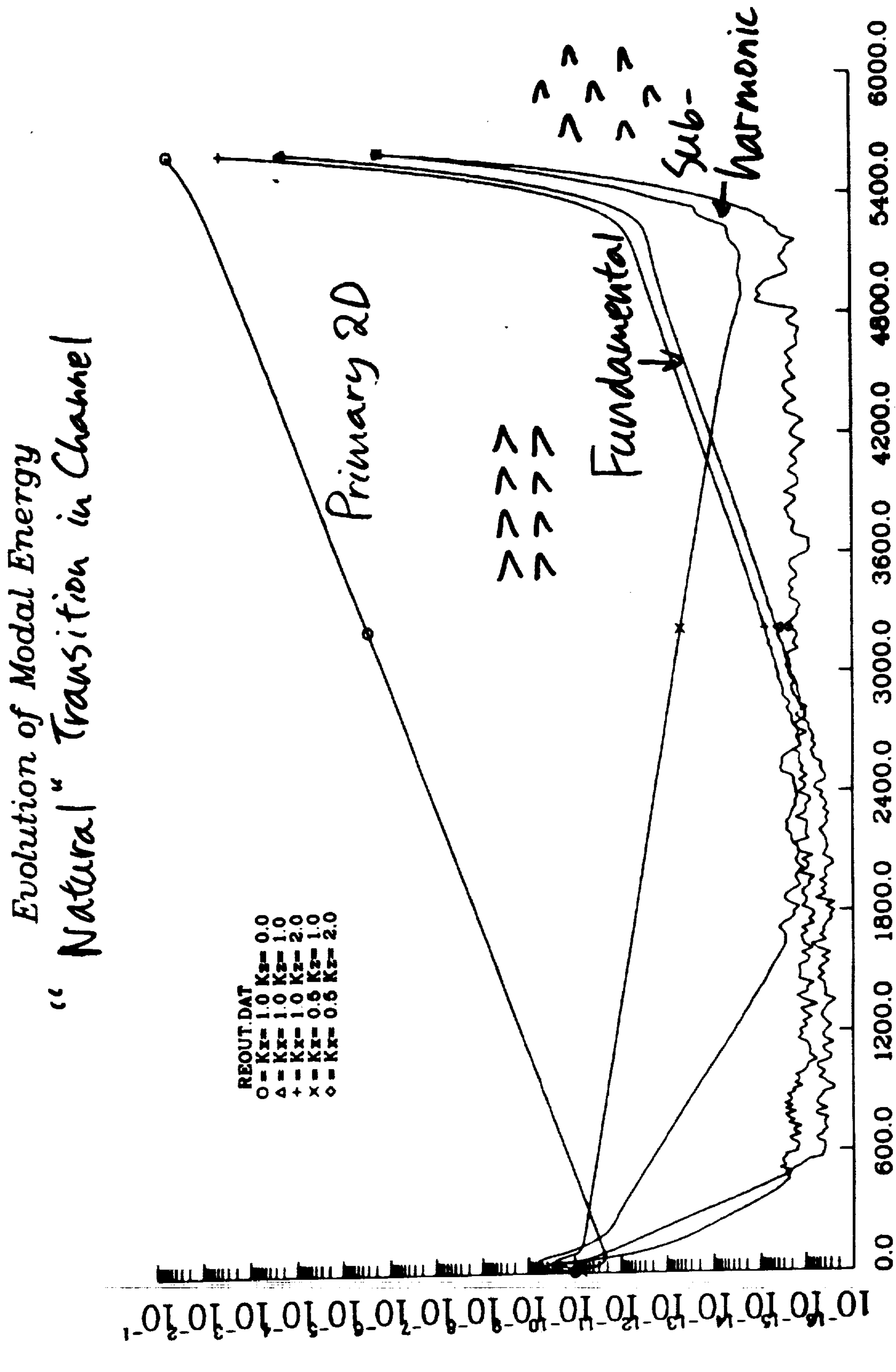
Secondary instability in channel flow

- Direct simulation is applied to "natural" transition; only small ($\approx 10^{-10}$) random disturbances are introduced.

- By the primary instability, a 2D TS wave grows (wavenumbers $k_x = 1$, $k_z = 0$) (x streamwise). The final 3D breakdown may start as a "K" type (fundamental, $k_x = 1$, aligned Λ vortices) or as an "H" type (subharmonic, $k_x = 1/2$, staggered Λ's). Theory and experiments don't fully agree in a channel.

- We find that spanwise nonuniformities ($k_x = 0$, $k_z \neq 0$) accumulate energy much larger than the initial disturbances (by a factor Re) and transfer some to the "K" modes <u>before</u> the Herbert secondary instability.

- This explains the difficulties in observing the "H" type breakdown in experiments.



Evolution of Modal Energy
“Natural” Transition in Channel
REOUT.DAT
O = Kx= 1.0 Kz= 0.0
Δ = Kx= 1.0 Kz= 1.0
+ = Kx= 1.0 Kz= 2.0
× = Kx= 0.5 Kz= 1.0
◇ = Kx= 0.5 Kz= 2.0
Primary 2D
Fundamental
Sub-harmonic
T
0.0
600.0
1200.0
1800.0
2400.0
3000.0
3600.0
4200.0
4800.0
5400.0
6000.0
10^-16
10^-15
10^-14
10^-13
10^-12
10^-11
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1

Stability and relaminarization of the swept attachment-line flow

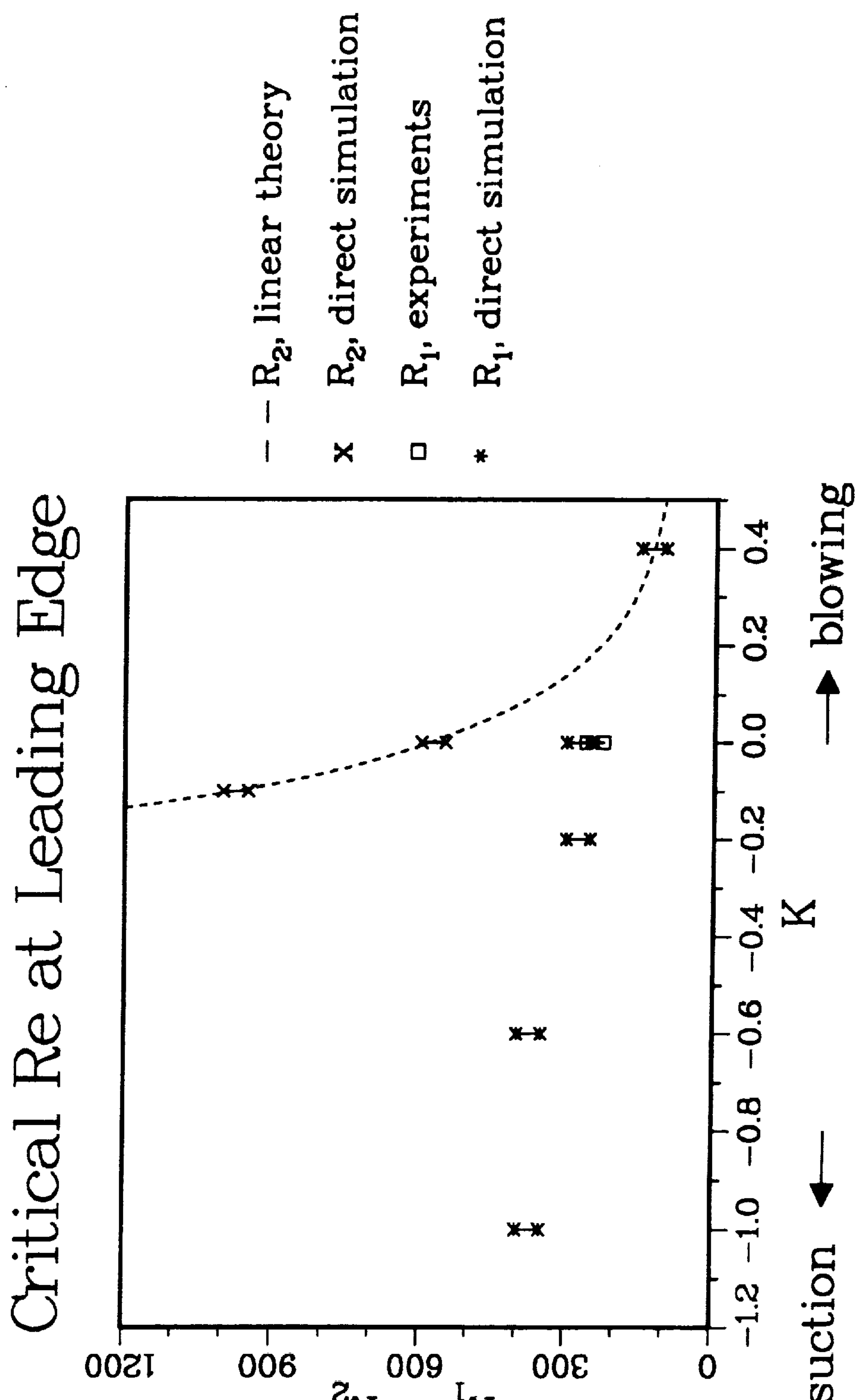
- Turbulence has been found to propagate from the fuselage along the attachment line and render Laminar Flow Control impossible. This is "leading-edge contamination" (Gregory, 1960).

- Direct simulations are conducted in this region. Curvature, compressibility, and spanwise variations are neglected.

- Previous linear-stability results (Görtler & Hämmerlin, 1955, Hall, Malik & Poll, 1984) are confirmed and generalized.

- The unswept flow is found to be linearly and nonlinearly stable.

- The instability and relaminarization boundaries are computed in $(K, \overline{R})$ space, where K is the suction parameter and $\overline{R}$ the Reynolds number based on strain rate and sweep velocity component. Suction has much less effect on relaminarization than on linear stability.


Critical Re at Leading Edge
R₁ R₂
1200
900
600
300
0
−1.2
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
K
suction
blowing
R₂, linear theory
R₂, direct simulation
R₁, experiments
R₁, direct simulation

Pressure terms in a Reynolds-stress turbulence model

- The complete budgets of the Reynolds-stress tensor and the dissipation tensor have been extracted from a direct simulation of turbulent channel flow.

- This allows one to test a turbulence model term by term, instead of as a whole (e.g., using the C_f).

- The published estimates for the terms that are difficult to measure experimentally (pressure, dissipation) were often very inaccurate, especially near a wall.

- As a result, the widespread $k - \epsilon$ and Reynolds-stress models incur large errors near walls.

Pressure-strain term

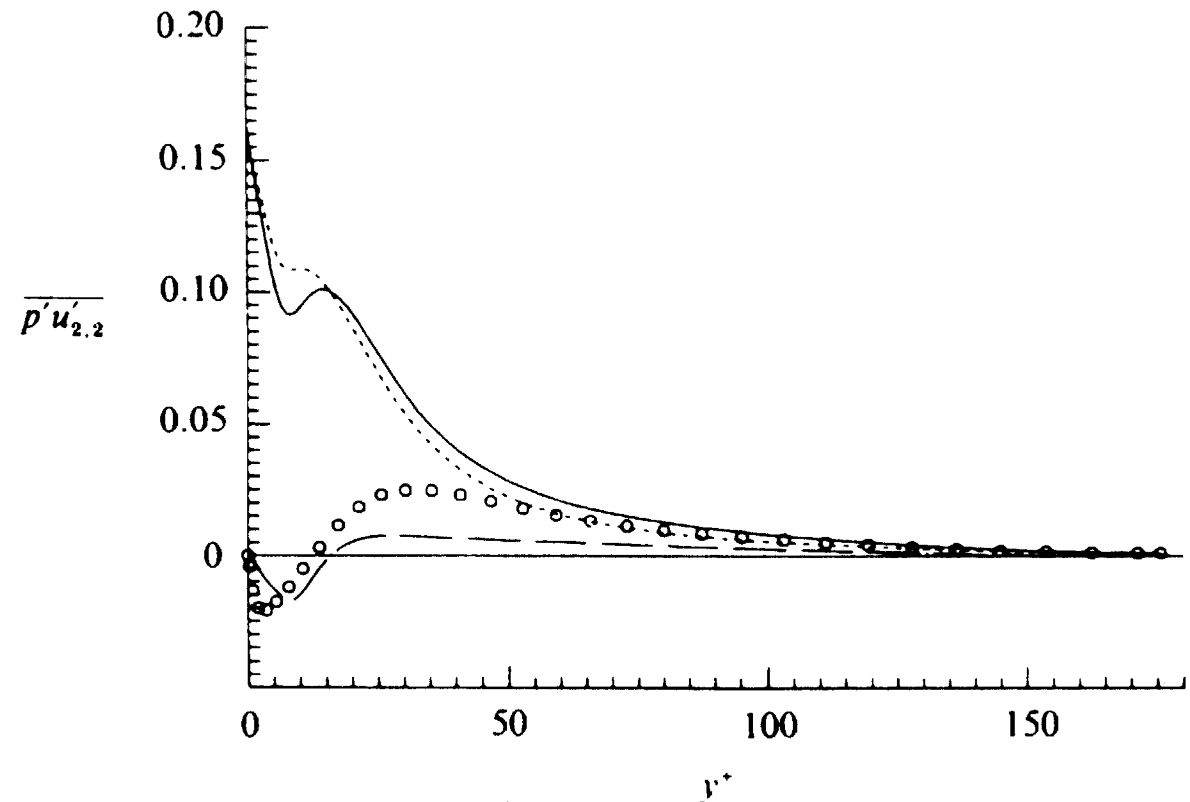


FIGURE 27. Pressure strain term, $\overline{p'u'_{2,2}}$, in the budget equation for $\overline{u'_2 u'_2}$ across the channel. ○, term computed from the channel data; ——, model, (equations (46) + (48) + (49)); – – –, model, equation (46), · · · ·, model, (equations (48) + (49)).

Coherent structures in shear flows

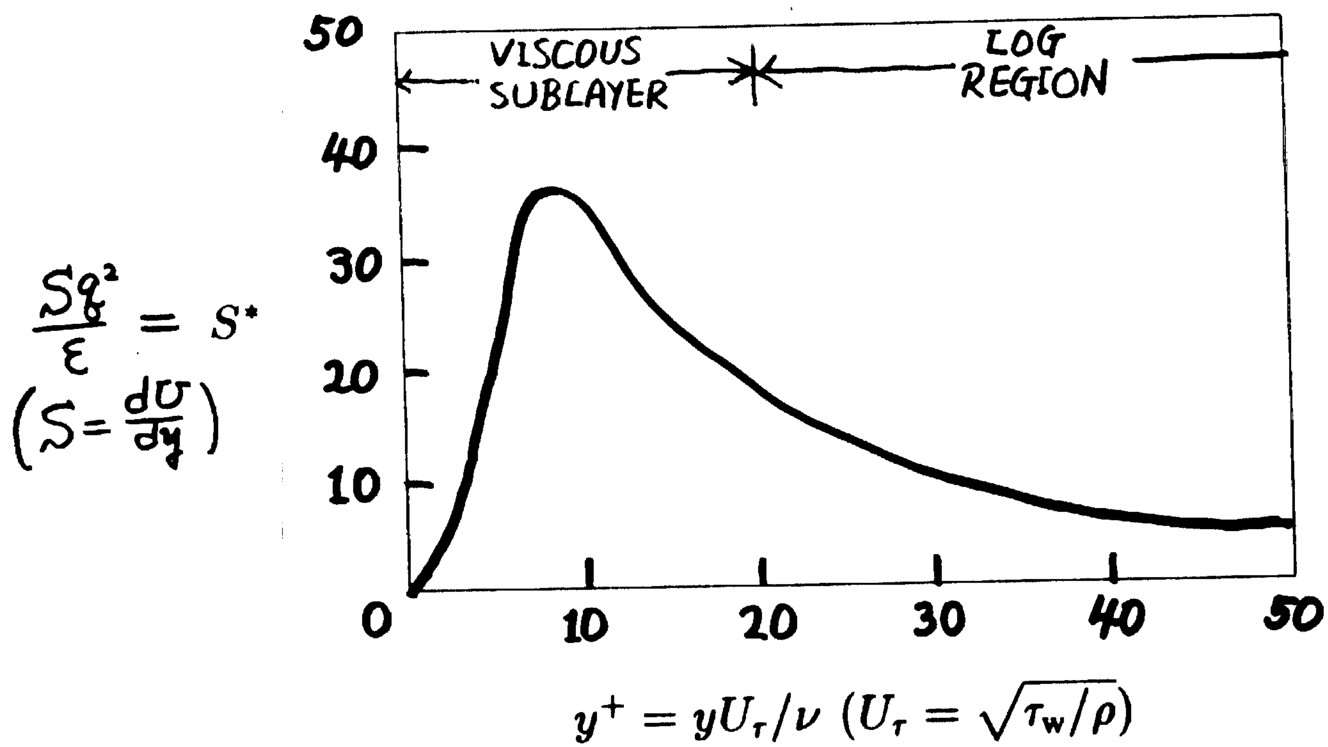
- Streaks have long been observed near the wall in boundary layers ($y^+ < 20$), and horseshoes away from the wall. These observations were confirmed by simulation results.

- Why the difference?

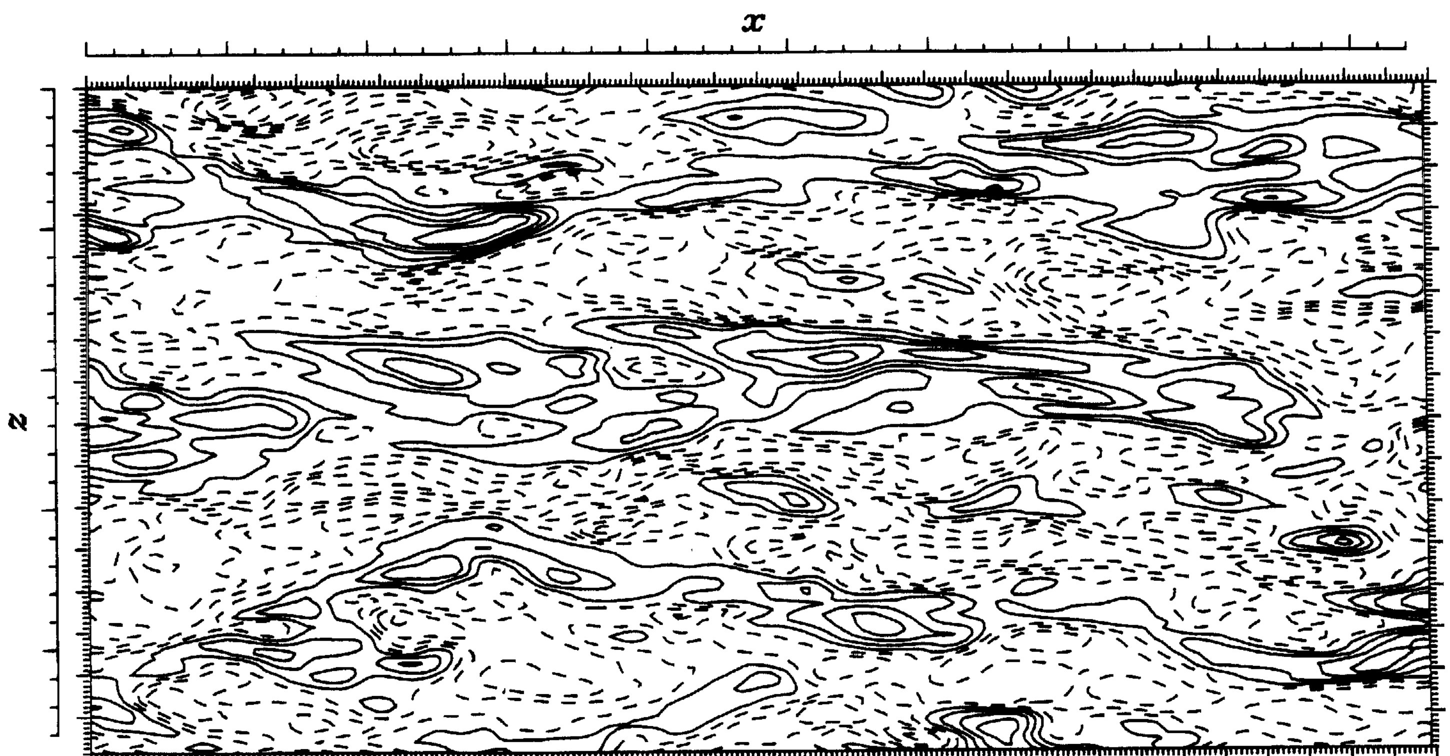
- Near the wall, the nondimensional shear rate $S^* \equiv Sq^2/\epsilon$ takes values much larger than in the homogeneous flows that had been studied (q^2: turbulent energy; ϵ: dissipation rate).

- When S^* is given such values in a homogeneous shear flow, streaks appear, indicating that the presence of a wall is not essential to form them.

Profile of S^* in Boundary Layer



Velocity contours in a homogeneous shear flow



The dimension of strange attractors in turbulent shear flows

- Does a turbulent solution live on a "strange attractor"? (i.e., does its state always return to the same region, but never settle down, with almost identical initial conditions rapidly moving apart?)

- If so, chaos (nonlinear dynamics) theory may provide a new framework to unify known turbulent phenomenology and to understand the <u>dynamics</u> rather than the statistics of turbulence.

- Using numerical simulation of low Reynolds number turbulent channel flow we have confirmed the existence of a strange attractor by measuring its Lyapunov exponent spectrum and calculating its dimension.

- At a Reynolds number R_τ ($\equiv \delta u_\tau/\nu$) of 80 the dimension of the attractor is $\simeq$ 360. This is the <u>first</u> measurement of the intrinsic complexity of a fully developed turbulent flow.

- This result shows that shear flow turbulence cannot be considered to result from the interaction of a "few" degrees of freedom.

Direct simulation of compressible (free shear) flows

- Goal: study compressibility effects on turbulent flows, in particular on their structure, global evolution, and aerodynamic noise.

- Tool: D. N. S. using high-order compact finite differences (close to spectral resolution). Compressible ideal-gas Navier-Stokes equations. No artificial viscosity or filtering.

- Example: Spatially evolving mixing layers. 2D, forced at inflow witth 1% amplitude. $R \equiv \rho_1(U_1 - U_2)\delta_\omega/\mu_1 \approx 200 - 400$.

- Experiments have shown that: a) compressibility reduces the growth rate; b) it scales with the convective Mach number $M_c \equiv (U_1 - U_2)/(a_1 + a_2)$ $(\gamma_1 = \gamma_2)$.

- Simulations have: a) reproduced this effect; b) validated M_c; c) provided a physical explanation.