CHAOTIC SELF-SUSTAINING TURBULENT-LAMINAR INTERFACE IN TWO-DIMENSIONAL CHANNEL FLOW

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Abstract Another type of self-sustainable coherent structures is found in a two-dimensional channel flow. It is embedded in a turbulent-laminar interface, so it utilizes the inhomogeneity to keep alive. Its spatio-temporally chaotic behavior and sustaining mechanism are investigated using the filtered simulation. This is an example of inhomogeneity induced coherent structures, which will be necessary to understand the spatio-temporal intermittency in three-dimensional turbulent systems.

INTRODUCTION

Turbulent-laminar interfaces appear in various geometrical flows, such as boundary layers, channel flows, and even in isotropic flows. Their dynamics have great importance in the study of turbulence, however, their highly chaotic and fragile nature prevents us from identifying and analysing them in three-dimensional flows. We consider a two-dimensional channel flow, which has a chaotic but less active interface structure than three-dimensional one. It should be noted that we here use the term "turbulence" for the spatio-temporally modulated finite amplitude TS-wave state, although it is much less active than three-dimensional turbulence. This turbulent state creates an interface between the laminar state, and the interface invades the laminar state with a constant speed c_I. This invading process is spatio-temporally chaotic, and this localized chaotic behavior is the subject of this study. We will show below that this chaotic interface is self-sustainable, and their spatial structure is definitely different from the classical sweep-ejection cycle. In this sense, we should not call this buffer structure "interface", but we use this term for consistency. The vortex structure of the interface looks alike that of turbulent spots in three-dimensional channel flows, and thus the mechanism dominating the chaotic interface may also be useful for understanding the dynamics of three-dimensional interfaces.

METHOD : DAMPING FILTER IN MOVING FRAME

We consider the incompressible Navier-Stokes equation in a moving frame where the interface does not move:

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\,\boldsymbol{u} = -\nabla p + \frac{1}{Re}\nabla^2\boldsymbol{u} - A_f H(x)\,(\boldsymbol{u} - \boldsymbol{U}_L)\,, \tag{1}$$

$$\boldsymbol{u}(x, \pm 1) = -c_I \hat{\boldsymbol{x}}, \tag{2}$$

$$H(x;\sigma^2,\Omega) = \int dx' \mathcal{N}_{0,\sigma^2}(x-x')\chi_\Omega(x'). \tag{3}$$

We normalize the half width of channel 1, and impose a periodic boundary condition in x-direction $\boldsymbol{u}(x+L, y) = \boldsymbol{u}(x, y)$, $L = 20\pi$. The Raynolds number Re is set to 8000. The last term is the damping filter term [1], and we choose the filtered region $\Omega = [0, 1.4] \times [-1, 1]$, where the turbulent state is artificially damped into the laminar state $\boldsymbol{U}_L = (1 - y^2 - c_I)\hat{\boldsymbol{x}}$. Since the turbulent state invades the laminar state, the interface cannot be maintained without this spatially selective damping term. Using this setting, we can simulate the chaotic interface permanently. A snapshot is displayed in fig. 1 using the turbulent vorticity $\zeta = (\nabla \times (\boldsymbol{u} - \boldsymbol{U}_L))_z$

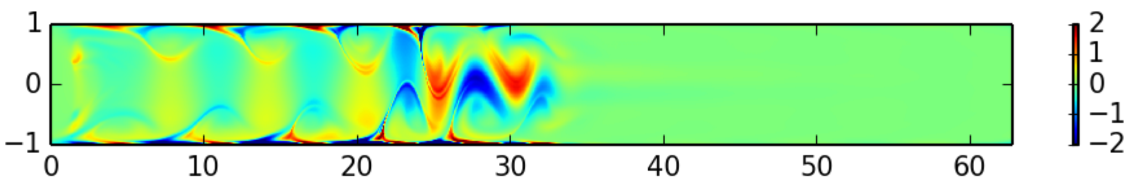

Figure 1. A snapshot of the simulation. The chaotic interface is placed around $20 < x < 32$. More detail definition has done by the statistiacal analysis (fig. 2).

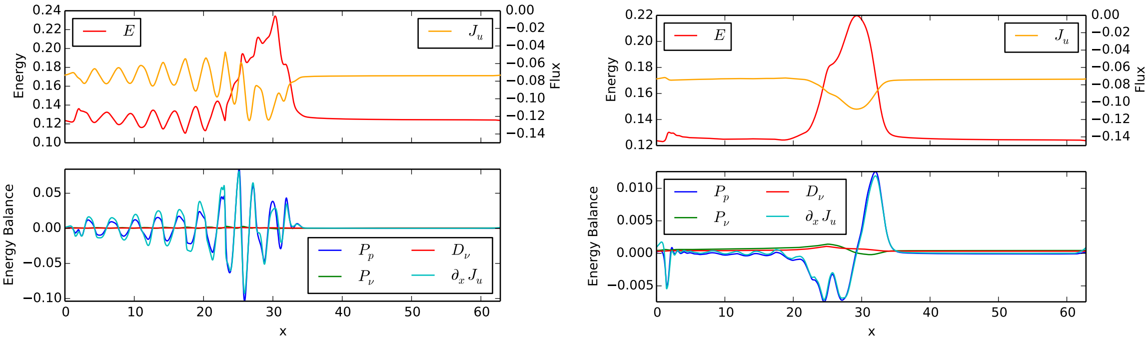

Figure 2. A snapshot (left) and time-averaged (right) values of the local energy balance equation. J_ν is omitted because it is very small.

RESULTS : LOCAL ENERGY BALANCE

To focus on the inhomogeneity in x-direction, we consider the y-averaged energy balance equation:

$$\frac{\partial E}{\partial t} + \partial_x (J_u + J_\nu) = P_p + P_\nu - D_\nu + F. \tag{4}$$

Since the walls move, there is an energy injection due to the viscocity $P_\nu(x,t) = -c_I \left(\partial_y u_x|_{y=1} - \partial_y u_x|_{y=-1}\right)/Re$ in addition to the bulk viscous dissipation D_ν. The flux due to the viscosity J_ν is neglected because it is very small. $F(x,t) = -A_f H(x) \int_{-1}^{1} dy \boldsymbol{u} \cdot (\boldsymbol{u} - \boldsymbol{U}_0)$ is an energy damping by the filter term. A snapshot and time-averaged values of these terms are displayed in fig. 2. The pressure power $P_p(x,t) = -\int_{-1}^{1} dy \, (\boldsymbol{u} \cdot \nabla)\, p$ and the gradient of the energy flux $\partial_x J_u$ are dominant in this equation. The time-averaged profiles help us to define the following three regions:

- tail region ($x \lesssim 20$)
- peak region ($20 \lesssim x \lesssim 28$)
- head region ($28 \lesssim x \lesssim 35$)

The head region generates energy, and most of it is consumed in the peak region. A small amount of residual energy leaks into the tail region. In this sense, the peak and head regions construct a self-sustaining coherent structure, we call “chaotic interface”. We can see a definitely different structure on this region in fig. 1. On the head region, there is a jet without vorticity ejections at the walls. The peak region, on the other hand, has a role to construct the jet from the vorticity ejection, whose seed is generated by the jet on the head region. This ejection-jet cycle is the self-sustaining mechanism of the chaotic interface, and definitely different from the classical sweep-ejection cycle.

DISCUSSION: LOCAL SELF-SUSTAINABILITY

The above descriptions of the ejection-jet cycle indicate that the existence of the downstream turbulent state is not necessary for this cycle. We try to confirm this conjecture using the damping filter. We now set $\Omega = [0, 22] \times [-1, 1]$ to damp the whole tail region, and use an snapshot of the previous simulation as an initial value. Then the chaotic interface keeps alive, and its spatial structure and invading speed c_I are hardly changed. Although we have to treat the effect of the damping filter more carefully, this result supports the conjecture about the local self-sustainability of the chaotic interface.
We will report a more precise comparison on the presentation.

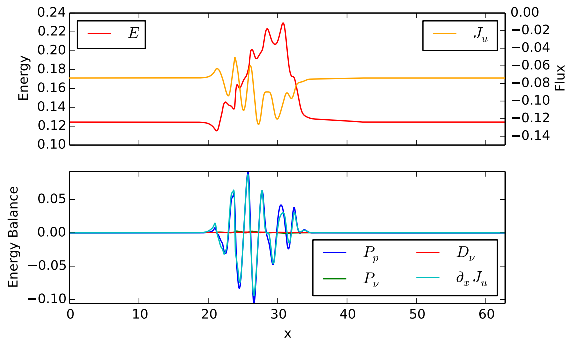

Figure 3. A snapshot of the filtered simulation. It corresponds to the left of fig. 2. These have almost same spatial structure and invading speed c_I.

References

[1] Toshiki Teramura and Sadayoshi Toh. Damping filter method for obtaining spatially localized solutions. *Physical Review E*, 89(5):052910, May 2014.