Discussion on frozen turbulence hypothesis in turbulent channel flow by means of large-scale DNS

Yoshinobu Yamamoto[1], and Yoshiyuki Tsuji[2]

[1] Department of Education interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Japan

[2] Graduate School of Engineering, Nagoya University, Japan

1 Introduction

Taylor's frozen turbulence approximation is often used in laboratory experiments to investigate the large-scale turbulent structures [1,2]. Meanwhile, the applicability of Taylor's frozen turbulence approximation to large-scale structures corresponded to more than 10 times of a boundary layer thickness, was not clear. In fact, the direct numerical simulation (DNS) results by delAlamo & Jimenez [3] raised the doubt on recent interpretations of bimodal spectra in relation to large-scale turbulent structures in experimental measurements by using Taylor's frozen turbulence approximation. However, we should be warned that they did not investigate the applicability of Taylor's frozen turbulence approximation by using the time-series data as well as in laboratory experiments.

In this study, large-scale direct numerical simulation of a high-Re turbulent channel flow was carried out to make space–time high accuracy database which resolved both scales of Kolmogorov length and time. The established total database capacity was corresponded to 144 TB. By using this huge-database, we directly investigated that the effect of frozen turbulent hypothesis on streamwise wave-number spectrum profiles as well as in the previous laboratory experiment [4].

2 Direct numerical simulation

The Navier–Stokes equations for incompressible fluid and the continuity equation were solved by the fractional-step method, and the third-order low-storage Runge–Kutta scheme and the Crank–Nicolson scheme were used for the convection and viscous terms, respectively. A Fourier-spectral method for the horizontal directions and the second-order finite-difference method in the wall-normal direction were adopted for spatial discretization. Aliasing errors for the horizontal directions were removed using the three-halves rule. Grid arrangements for the streamwise and spanwise velocities were located at the pressure point, and the grid point of the wall-normal velocity was shifted a half-grid distance away from the pressure point.

Streamwise mean pressure gradient was imposed as the driving force and non-slip at the walls and periodic conditions for stream and spanwise directions were adapted for boundary conditions.

The numerical condition in this study was listed in table 1. The present computation was conducted by using a Fujitsu FX1 server at Nagoya University, a NEC SX-9 server at Tohoku University, and the Earth Simulator at JAMSTEC. The computation speed was 15.2 TFLOPS, when using 128 nodes (1024 CPUs) of the Earth Simulator.

The total computational times for the statistical averaging were about 2688 in the normalized time units based on the friction velocity and kinematic viscosity. Consequently, four-dimensional (1280(time) x 2916(x) x 1032(y) x 1024(z)) DNS database of velocities, pressure, temperature have been established, and total database capacity was corresponded to 144 TB.

Table 1 Numerical condition

Re_τ	Pr	N_x, N_y, N_z	Δx^+, Δy^+, Δz^+
1000	5	2916, 1032, 1024	17.6, 0.5-2.0, 7.8

$Re_\tau=u_\tau h/\nu$: Turbulent Reynolds number, Pr$=\nu/\alpha$: Prandtl number, N_x,N_y,N_z ; grid number for stream, vertical, and spanwise direction, $\Delta^+=u_\tau\Delta/\nu$

3 Results and discussion

Figure 1 shows the instantaneous streamwise velocity distributions compared of the DNS filed with the Taylor field constructed by Taylor's frozen turbulence approximation. In the short fetch region ($L_x < 10h$), the Taylor field was well accorded with the DNS field, but apparent differences between them were observed in the long fetch region ($L_x > 30\ h$).

Figure 2 shows the contour lines of one-dimensional pre-multiplied spectra with wall-normal position compared of the true DNS spectra with the Taylor spectra. In near wall region ($\log(y^+) < 1$; $y^+ < 10$), the convection velocities were underestimated in case of Taylor's frozen turbulence approximation, and in the log-layer region ($\log(y^+) > 2$; $y^+ > 100$), The appearance of a long-wavelength peak due to Taylor's approximation is obvious as well as the DNS results by delAlamo & Jimenez [3].

Figure 3 shows the Effect of the sampling time-length on one-dimensional pre-multiplied energy spectra used Taylor's frozen turbulence approximation. The appearance of a long-wavelength peak in the experimental result [4] plotted by blue line, which used the long time-length ($T^+= 20840$) data, was not observed despite using Taylor's approximation. On the other hands, the overestimation of a long-wavelength peak was observed in both the DNS (plotted by red line) and the experiment result (plotted by dot blue line) using short time-length ($T^+=2600$) data with Taylor's approximation. Consequently, overestimation of a long-wavelength peak might be depended on the sampling time-length. In the final paper, we will show the detail results.

References

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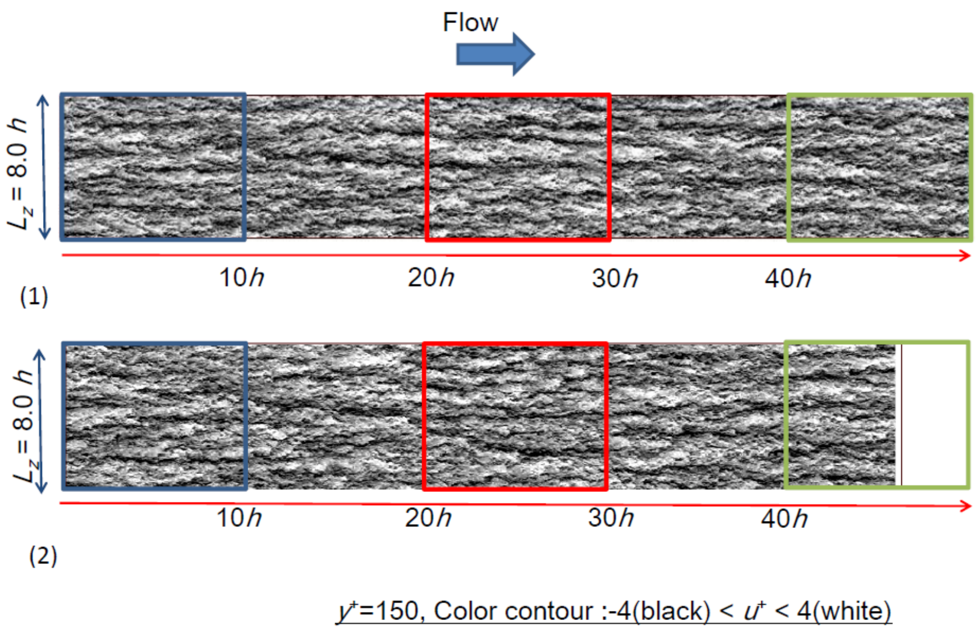

Fig.1 Instantaneous streamwise turbulent velocity distribution at log region (y^+=150),
(1) true DNS field, (2) Taylor field.

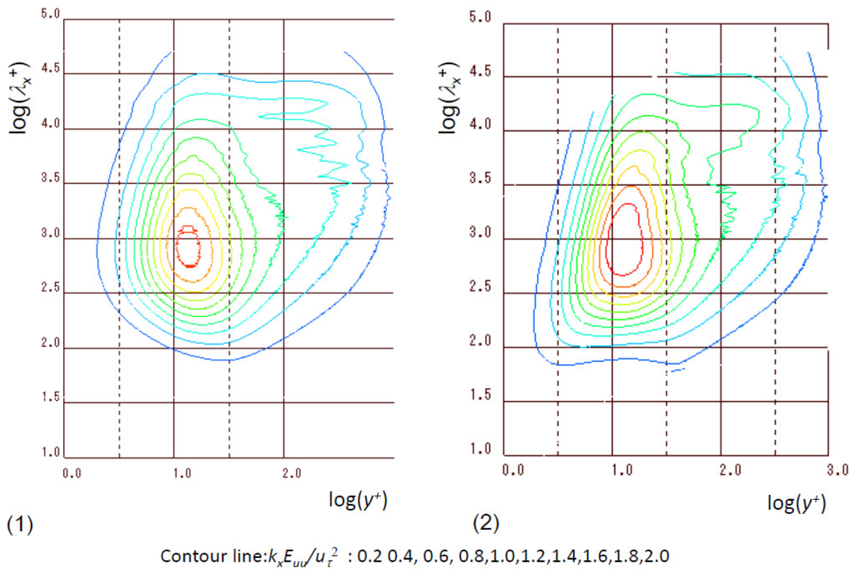

Fig.2 Contour lines of one-dimensional pre-multiplied spectra withwall-normal position, (1) true DNS spectra, (2)Taylor spectra.

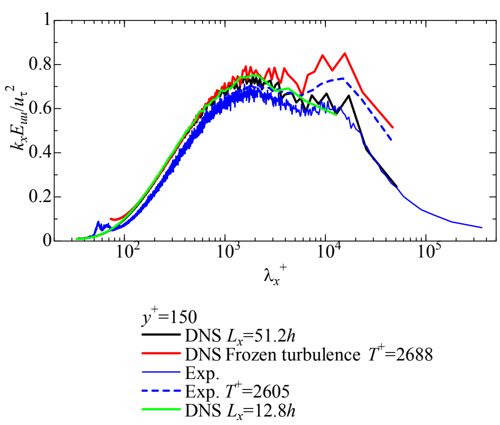

Fig.3 Effect of the sampling time- length on one-dimensional pre-multiplied energy spectra by using Taylor's frozen turbulence approximation.