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# Very-large-scale fluctuations in turbulent channel flow at low Reynolds number[☆]

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## ABSTRACT

It is known that there exist very large features in turbulent channel flow at high Reynolds number as well as in pipe flow and turbulent boundary layer. In addition, a low frequency peak was observed in spectra of the streamwise velocity fluctuation in transitional and low-Reynolds-number but turbulent channel flows. In this study, the large-scale fluctuation observed at the low Reynolds number has been experimentally explored with increasing Reynolds number by means of a hot wire anemometry. There are two peaks in the streamwise velocity spectra for transitional flow for $1800 \leq Re \leq 2600$, where $Re$ is the Reynolds number based on the bulk velocity and the channel width. The high-frequency peak corresponds to the turbulent vortices that have the same order of magnitude as the channel width, while the low-frequency peak is due to passages of the turbulent patches whose streamwise scale is greater than ten channel widths. It is surprising that the low frequency peak remains even up to $Re = 3000$ at which the flow is fully turbulent. Furthermore, a spectral plateau around the frequency corresponding to 25 channel widths is confirmed up to $Re = 4000$, indicating that there exist very-large-scale fluctuations in turbulent channel flow even at low Reynolds number.

## 1. Introduction

It has been worthy of note that there exist very large features in turbulent pipe and channel flows at high Reynolds number (Monty et al., 2007; Kim and Adrian, 1999; Guala et al., 2006), as well as in turbulent boundary layer (Hutchins and Marusic, 2007), because it may relate the turbulent properties and coherent structures near the wall. Monty et al. (2007) performed velocity measurements with hot-wire rakes, and they revealed long meandering structures that has the streamwise length up to 25 pipe radii or channel half-heights. Guala et al. (2006) also detected a very large structure in high-Reynolds-number pipe flow whose streamwise length is as long as 16 pipe radii.

Linear and quasi-linear theories (Jovanović and Bamieh, 2005; Cossu et al., 2009; McKeon et al., 2010; Farrell and Ioannou, 2012) predict roll-streak structures of very large streamwise length that might relate to the these very large feature in shear flows. These experimental and theoretical findings strongly suggest that very large features or structures are omnipresent in turbulent wall-bounded shear flows at high Reynolds number.

Monty et al. (2009) made hot-wire measurements in turbulent pipe, channel and boundary layer flows. From the velocity spectra maps with different heights, it was revealed that very large scale motion (VLSM) around 0.3 $\delta$ ($\delta$ is a pipe radii or a channel half height) has the streamwise length larger than 10 $\delta$. They strongly claim that the VLSM in internal flows should not be mixed up with the superstructures in boundary layers.

Recently, Seki and Matsubara (2012) made hot-wire measurements for the transitional channel flow that was realized by decreasing the Reynolds number of turbulent channel flow in a expansion section. They found a spectral peak in the streamwise velocity fluctuation measured in transitional channel flow and observed intermittency with the turbulent patches passing through the channel, and from probability density distributions of the streamwise velocity fluctuation they asserted that the transitional range is for $1400 < Re < 2600$. Reynolds number is defined as $Re = U_b d/\nu$, where $U_b$ is the bulk velocity, $d$ is channel width, $\nu$ is kinematic viscosity. It is surprising that the low frequency peak is confirmed even for the fully turbulent flow at $Re = 2660$, suggesting existence of a large-scale flow pattern. Their investigation raises a question if the two large-scale fluctuations at low and high Reynolds numbers are the same. If they are the essentially same, it is straightforwardly inferred that the VLSM has

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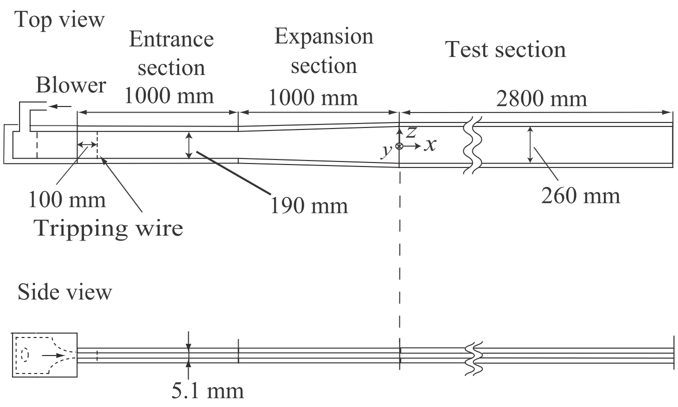

**Fig. 1.** Air channel facility.

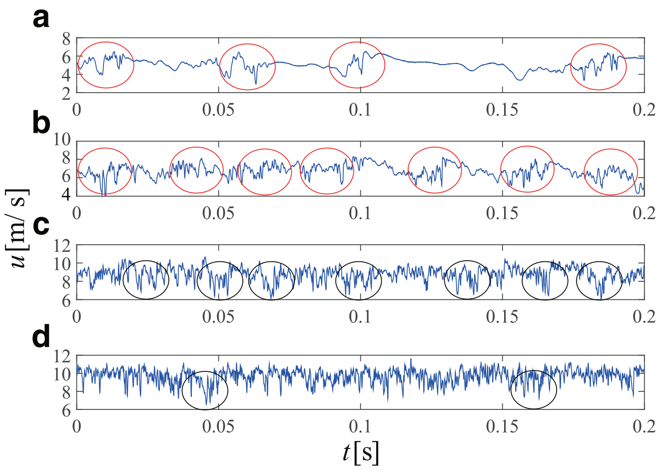

**Fig. 2.** Time traces of the streamwise velocity at the channel center. (a) $Re = 1500$, (b) $Re = 2000$, (c) $Re = 2600$, (d) $Re = 3500$. The red and black circles indicate high-frequency and low velocity periods, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

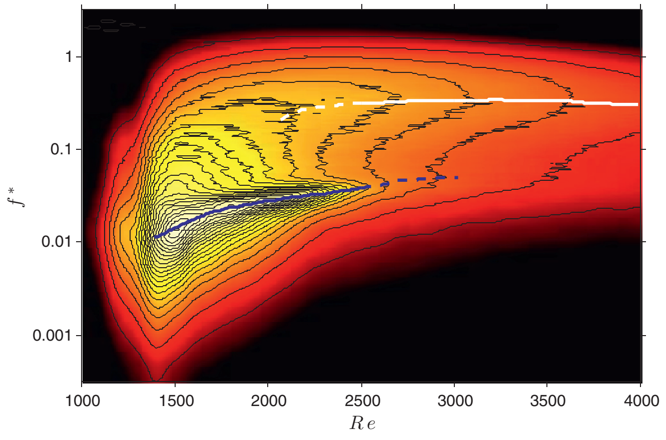

**Fig. 3.** Contour map of streamwise velocity premultiplied spectra density at the channel center. Contours and colours express $f^*\Phi^*$. White and blue lines indicate ridges for the high and low frequency peaks, respectively. The second peaks at each $Re$ are marked as broken lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sustain and/or generation mechanisms common to the turbulent patches in traditional channel flows. As the first step to answer this question, the large-scale fluctuation has been experimentally investigated with gradually increasing Reynolds number from $Re = 1000$, at which the flow is laminar, to $Re = 4000$.

## 2. Experiment setup.

The hot wire measurement was performed in an air channel flow facility shown in Fig. 1. The facility is the same that Seki and Matsubara (2012) used. The air pressurized by a blower gushes from a perforated pipe installed inside a settling chamber whose cross section is 190 mm × 170 mm. A two-dimensional nozzle of a 34:1 contraction ratio is followed by entrance, expansion and test sections whose wall distance, $d$, is 5.1 mm. The entrance section is 1000 mm long and 190 mm wide. Two tripping rods of 0.5 mm diameter are mounted 100 mm downstream from the outlet of the nozzle for triggering transition to turbulence, so that the flow becomes a fully developed turbulent flow at the end of the entrance section. The distance between the channel end walls is gradually widened from 190 mm to 260 mm in the 1000 mm. As a result, $Re$ drops to 73% of the entrance mean velocity in the expansion section. The 2800 mm long test section following the expansion section opens to the atmosphere at its downstream end. In a certain range of $Re$, the $Re$ drop in the expansion section induces transition from upstream turbulent flow to transitional, or intermittent, flow in the test section.

A constant-temperature hot-wire anemometer was used for the streamwise velocity measurement. The single hot-wire sensor is a platinum wire of 2.5 µm diameter and 1 mm length. Velocity calibrations for the sensor were performed with a jet potential core emanating from an axial nozzle connected to the blower for the main channel facility. The relation between the voltage and the velocity was fitted to a calibration curve deduced from King's law modified for low velocity. An analog/digital converter acquired the voltage of the hot wire anemometer with a sampling frequency of 20 kHz and a sampling time of 300 s. A wedge mechanism, which could be inserted in the channel at an arbitrary streamwise position, was used for probe positioning in the wall-normal direction. The symmetry of the velocity profile was utilized for estimation of the channel center. The measurement was made at 300 mm upstream from the channel exit.

## 3. Result and discussion

Time traces of the streamwise velocity measured at the channel center are shown in Fig. 2. At $Re = 1500$, the signal is almost calm but high-frequency fluctuations intermittently appear, as marked by red circles. This intermittent behavior of the flow is also investigated by Seki and Matsubara (2012), thus it is considered that these high-frequency fluctuations indicate the passages of turbulent patches. Appearance of the high-frequency fluctuations becomes more frequent at $Re = 2000$, then finally at $Re = 2600$, the time trace are filled of high-frequency fluctuations, indicating that the flow is fully turbulent. Seki and Matsubara (2012) also confirmed from the probability density distributions that intermittency at $Re = 2600$ is almost 100%. In spite of the turbulent state, the low velocity but high-frequency fluctuating periods (circled in black) still exist. Even at higher Reynolds number, $Re = 3500$, the low velocity periods are still observed though their appearance turns unclear with increase of $Re$.

The rate of their appearance can be estimated in the premultiplied spectral diagram of the streamwise velocity fluctuation as shown in Fig. 3. The measurement was performed at 31 Reynolds numbers with the $Re$ resolution of 100. The non-dimensional frequency $f^*$ and the power spectral density $\Phi^*$ are normalized with the channel width $d$ and the bulk (mean) velocity $U_b$ as $f^* = fd/U_b$ and $\Phi^* = \Phi/U_b^2$. As a consequence of this normalization, the inverse number of $f^*$ corresponds to a length scale in unit of $d$. While