TURBULENT STRUCTURES IN OPEN-CHANNEL FLOWS WITH STRONG UNSTEADINESS

Iehisa Nezu
Department of Civil and Global Environment Engineering, Kyoto University
Kyoto, 606-8501, Japan
nezu@nezu.gee.kyoto-u.ac.jp

Kouki Onitsuka
Department of Civil and Global Environment Engineering, Kyoto University
Kyoto, 606-8501, Japan
onitsuka@nezu.gee.kyoto-u.ac.jp

ABSTRACT

Turbulence measurements in unsteady open-channel flows over a smooth wall including wide unsteadiness ranges were conducted with two sets of LDAs. It is concluded that the von Karman constant κ is regarded to be a universal constant, i.e., $\kappa = 0.41$, if the unsteadiness parameter α is smaller than 0.002. The spanwise velocity fluctuations in unsteady open-channel flows were successfully measured for the first time in this study. It was found that the distributions of spanwise turbulent intensity can be described well by Nezu's(1977) empirical formula except for strong unsteadiness flow.

INTRODUCTION

Turbulence measurements in unsteady open-channel flows have been conducted by several researchers. Hayashi *et al.*(1988) suggested that the turbulence in the outer layer became stronger in the rising stage than in the falling stage by making use of a hot-film anemometer. Tu & Graf(1992) and Song & Graf (1996) have measured unsteady open channel flows over gravel beds by making use of a micro-propeller flow-meter and an acoustic Doppler velocity profiler and examined the unsteadiness effect on turbulent structures by the use of Clauser's equilibrium pressure gradient parameter. Nezu & Nakagawa(1991, 1993 and 1995) have measured unsteady smooth and rough open-channel flows with a two component three-beam laser Doppler anemometer(LDA), and indicated that a peak discharge and a peak wall shear stress appear before a time of peak depth in proportion to the unsteadiness. Further, they indicated that mean velocity distributions up to the free surface are described by the log-law in the case of low Reynolds numbers and those are described by the log-wake law in the case of high Reynolds numbers. However, these researchers evaluated the local friction velocity U_* from a standard log-law under the assumption that the von Karman constant κ was not affected by the unsteadiness, i.e., $\kappa = 0.41$ (Nezu & Rodi, 1986).

Until recently, turbulence measurements in the viscous sublayer of open-channel flows have been almost impossible by making use of Pitot tubes, propeller flow-meters, hot-film anemometers and acoustic Doppler velocimetry(ADV). This is because a thickness of the viscous sublayer is much smaller than the sensor scales of these instruments. Nezu *et al.*(1997) have first measured successfully the viscous sublayer in unsteady open-channel flows in the case that the flow depth increased or decreased monotonically, and suggested that the von Karman constant changes very slightly against the time of flood. Nezu *et al.*(1998) and Onitsuka & Nezu(1999) also pointed out that the von Karman constant changes in strong unsteady open-channel flows with a hydrograph of sine curves. However, the unsteadiness was not so changed widely in their experiments.

In this study, turbulence measurements of unsteady open-channel flows including the strong unsteadiness were carried out by making use of two sets of two-components laser Doppler anemometers(LDA). The effects of unsteadiness on the von Karman constant in the log-law were investigated intensively. Furthermore, the spanwise turbulent-fluctuation component was first measured by the U-W LDA probe.

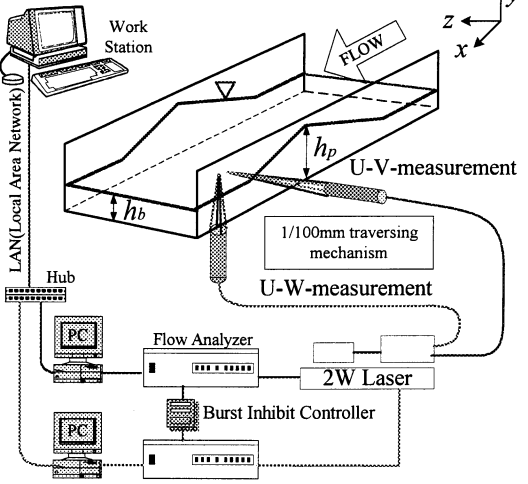


Fig.1 Experimental Setup

Case Name	α $\times 10^{-3}$	T_d (s)	h_b (cm)	h_p (cm)	U_{mb} (cm/s)	U_{mp} (cm/s)	R_{*b}	R_{*p}	Re_b $\times 10^3$	Re_p $\times 10^4$
N30	6.31	30	6.0	7.9	5.2	14.3	150	480	2.5	8.9
N60	3.39	60		8.3		16.8	159	579		10.9
N120	1.75	120		8.4		17.5	153	609		11.7
N240	0.90	240		8.5		17.9	158	610		12.0

Table 1 Hydraulic Conditions, in which $R_* \equiv U_* h/\nu$ and $Re \equiv U_m h/\nu$.

EXPERIMENTAL SETUP AND HYDRAULIC CONDITIONS

The experiments were conducted in a 10m long, 40cm wide and 50cm deep tilting flume as shown in Fig.1. In this water flume, the discharge can be automatically controlled by a personal computer in which the rotation speed of a water-pomp motor involving an inverter transistor is controlled by the feedback from the signals of an electromagnetic flow-meter, as described by Nezu & Nakagawa(1995).

Two sets of two-component LDAs(Dantec) were used for all three components of velocity. One LDA fiber probe was located side of the channel and the other one was located below the channel bottom, as shown in Fig.1. The former can measure the instantaneous streamwise velocity $\tilde{u}(t)$ and the instantaneous vertical velocity $\tilde{v}(t)$. The latter can measure $\tilde{u}(t)$ and the instantaneous spanwise velocity $\tilde{w}(t)$. The LDA probes were placed at 8m downstream from the channel entrance. The ultrasonic water-wave gauges were located each at the velocity measuring section, 10cm downstream and 10cm upstream of the velocity measuring section. The LDA probes were moved by 3-D traversing mechanisms. The accuracy of these traversing mechanisms was 1/100mm. The measurements very near the wall, i.e., up to y =0.1mm, were conducted accurately. All output signals of two LDAs and three water-wave gauges were recorded in a digital form with a sampling frequency more than 100Hz into a HDD of the personal computer. After experiments, all experimental data were transferred to the workstation through the LAN.

Four cases of experiments were conducted as shown in Table 1. In these experiments, an unsteadiness parameter α is changed widely. The unsteadiness parameter α was defined by Nezu & Nakagawa(1991) as follows:

$$\alpha \equiv \frac{V_s}{U_c} \approx \frac{1}{(U_{mb} + U_{mp})/2} \frac{h_p - h_b}{T_d} \qquad (1)$$

in which V_s is the rising velocity of free surface and U_c is the convention velocity. U_m is the mean bulk velocity, h is the flow depth and T_d is the duration time from the base flow to the peak flow. The subscripts b and p denote the base flow and the peak flow, respectively. LDA measurements

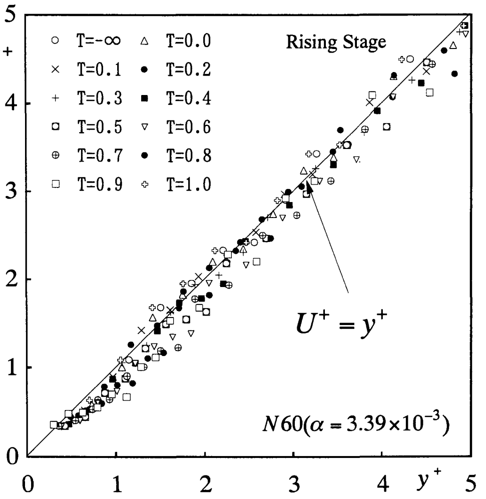


Fig.2 Velocity Distributions in the Viscous Sublayer in the Rising Stage (case N60). $T \equiv t/T_d$.

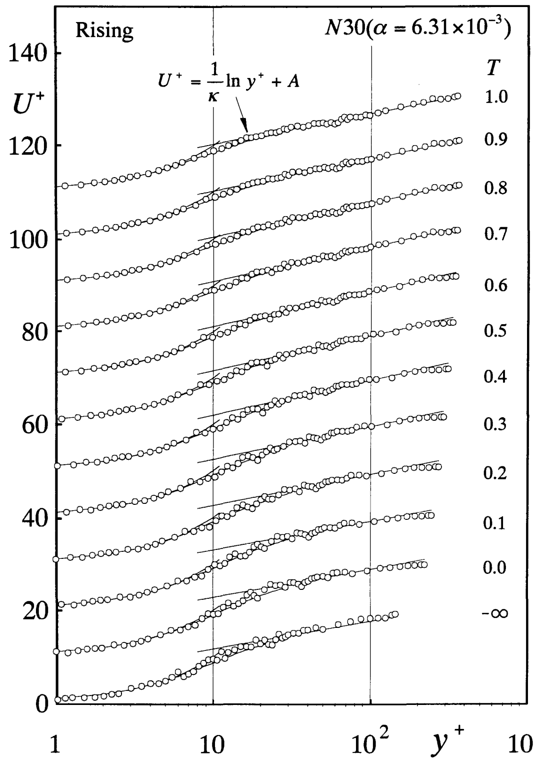


Fig.3 Velocity Profiles in the Rising Stage (case N30)

were conducted repeatedly four times for each experiment. The following experimental results are ensemble-averaged data of these experimental data, see Nezu *et al.*(1997).

EXPERIMENTAL RESULTS

Friction Velocity and von Karman Constant

Almost researchers, e.g., Nezu *et al.*(1995), have evaluated the local friction velocity $U_*(t)$ from the standard log-law by assuming that the von Karman constant κ is adapted by the value of steady open-channel flow (κ =0.41) obtained by Nezu & Rodi(1986):

$$U^+ = \frac{1}{\kappa}\ln y^+ + A \qquad (2)$$

in which $U^+ \equiv U/U_*$ and $y^+ \equiv yU_*/\nu$. However, it has not yet been made clear whether the von Karman constant is affected by the unsteadiness or not. Fig.2 shows the mean velocity distributions in the viscous sublayer($0< y^+ \leq 5$) in the rising stage. T is the time normalized by T_d, i.e., $T \equiv t/T_d$. $T = -\infty$ implies the base flow, i.e., a steady flow before the rising stage. The mean velocity distributions in the viscous sublayer obey a theoretical linear formula, irrespective of T, as follows:

$$U^+ = y^+ \quad (y^+ \leq 5) \qquad (3)$$

The local friction velocity U_* was evaluated from the linear formula(3). It is known that the linear formula(3) is valid in unsteady open-channel flows (see Nezu *et al.*(1997)) and steady boundary layers with adverse pressure gradients (see Nagano *et al.*(1993) and Nezu *et al.*(2000)).

Fig.3 shows an example of velocity profiles in the rising stage. The velocity profiles are described well by the log-law(2) which is shown by straight line. The von Karman constant κ can be calculated from the log-law(2), by using the value of U_* which was evaluated from the linear formula(3).

Fig.4 shows the variation of the von Karman constant κ against the normalized time T, together with LDA data of Nezu *et al.*(1998) and Onitsuka & Nezu(1999). Nezu *et al.* 's (1997) data, which were obtained in monotonically rising and falling flows in flood, were also plotted in Fig.4. It is found that the value of κ decreases until the middle time in the rising stage and increases with the normalized time before the middle time in the falling stage. This tendency coincides with the results of Nezu *et al.*(1997, 1998) and Onitsuka & Nezu(1999). Spalart & Leonald(1987) have calculated turbulent boundary layers with pressure gradients by making use of a direct numerical simulation(DNS) and have pointed out that the von Karman constant κ is not universal constant in the case of non-uniform boundary layers.

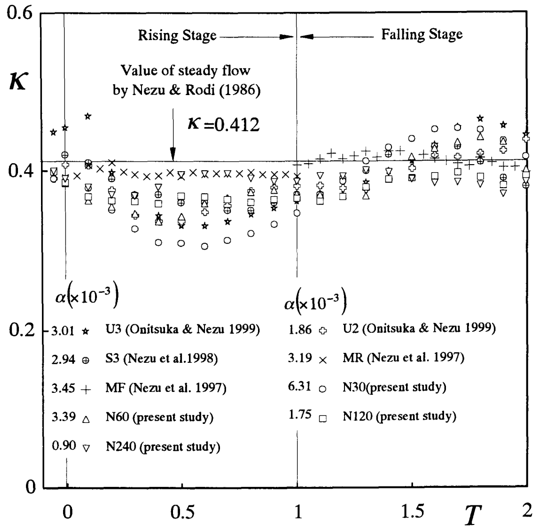


Fig.4 Variation of von Karman Constant

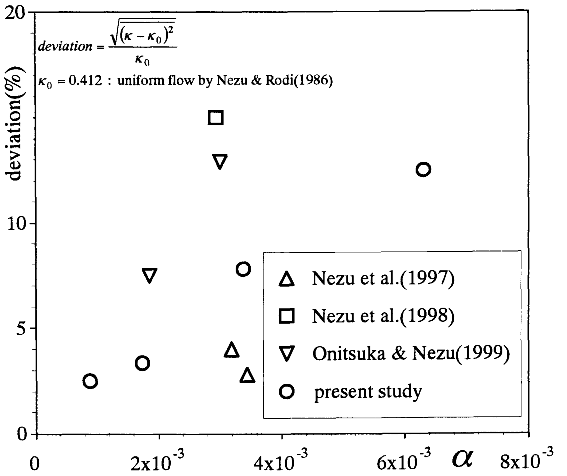


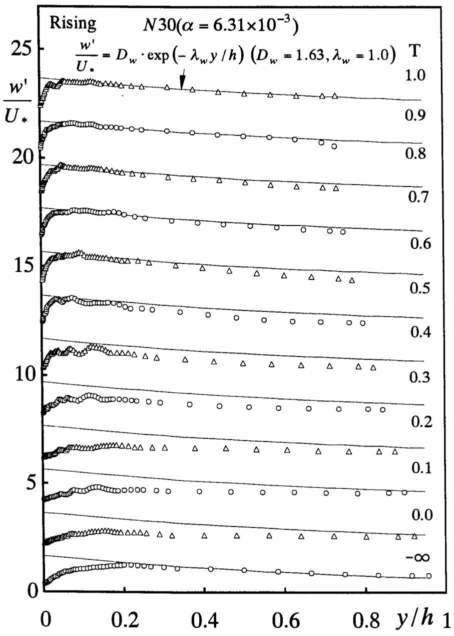
Fig.5 Standard Deviation of von Karman Constant from the Value of κ =0.41

Recently, Onitsuka *et al.*(1999) indicated that the von Karman constant is not universal one in the case of open-channel flows with favorable pressure gradients.

The magnitude of the deviation from the value in uniform flows (κ =0.41) increases with an increase of the unsteadiness parameter α. Fig.5 shows the magnitude of the deviation of the von Karman constant, together with Nezu *et al.*(1997, 1998) and Onitsuka & Nezu's(1999) data. If an allowable margin of error is set 5%, it is concluded that the von Karman constant is regarded as a universal one in the range of α <0.002.

Spanwise Turbulence Intensity

Nezu & Nakagawa(1991), Tu & Graf(1992), Song & Graf(1996), Nezu *et al.*(1997, 1998) and Onitsuka & Nezu(1999) have conducted turbulence measurements in unsteady open-channel flows. All of them measured only the streamwise and vertical velocity



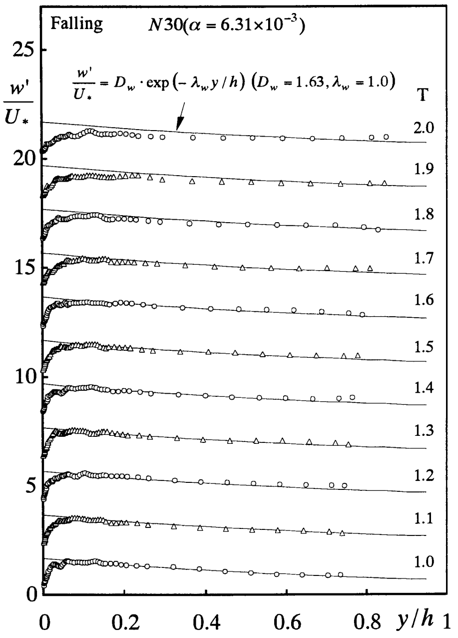
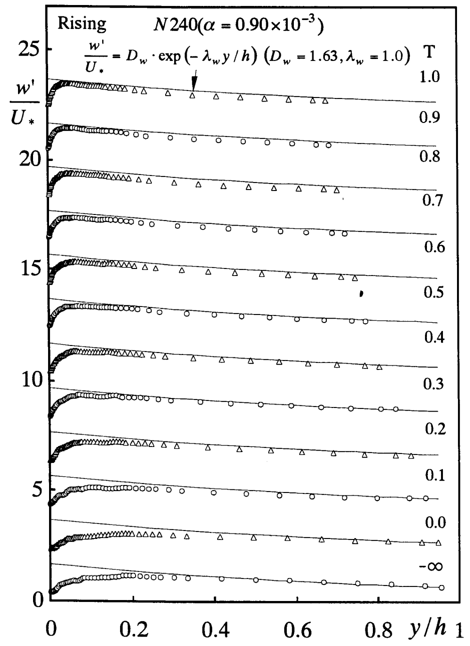


Fig.6(a) Distributions of Spanwise Turbulence Intensity in Rising Stage (case N30)

Fig.6(b) Distributions of Spanwise Turbulence Intensity in Falling Stage (case N30)



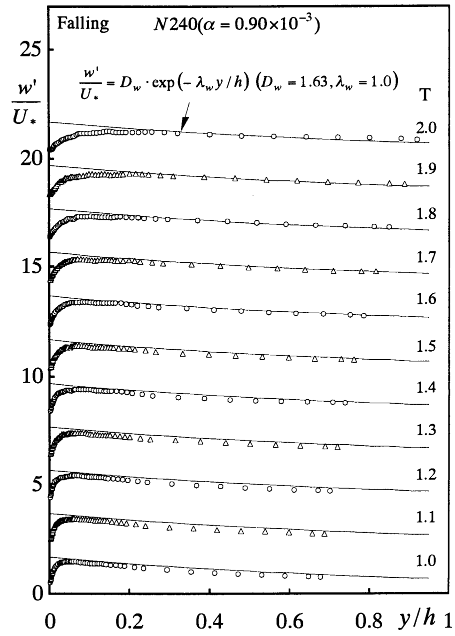


Fig.6(c) Distributions of Spanwise Turbulence Intensity in Rising Stage(case N240)

Fig.6(d) Distributions of Spanwise Turbulence Intensity in Falling Stage(case N240)

components and clarified the features of turbulence intensities u' and v'. In this study, the spanwise velocity component w' was first measured successfully. Fig.6 shows distributions of spanwise turbulence intensity w' normalized by the local friction velocity U_* in case of N30(α =6.31×10^{-3}) and N240(α =0.90×10^{-3}). In the case of N240, the distributions of w'/U_* in the rising and falling stages are well described by Nezu's(1977) empirical formula (see IAHR monograph of Nezu & Nakagawa(1993)) which is shown by curved lines. This tendency agrees with those of u'/U_* and v'/U_* obtained by Nezu *et al.*(1997). In the case of N30, in contrast, these distributions deviate downward from the Nezu's empirical formula at $0.0 \le T \le 0.5$ in the rising stage. The value of w'/U_* reaches gradually Nezu's empirical formula toward the wall. An effect of wall shear may not appear

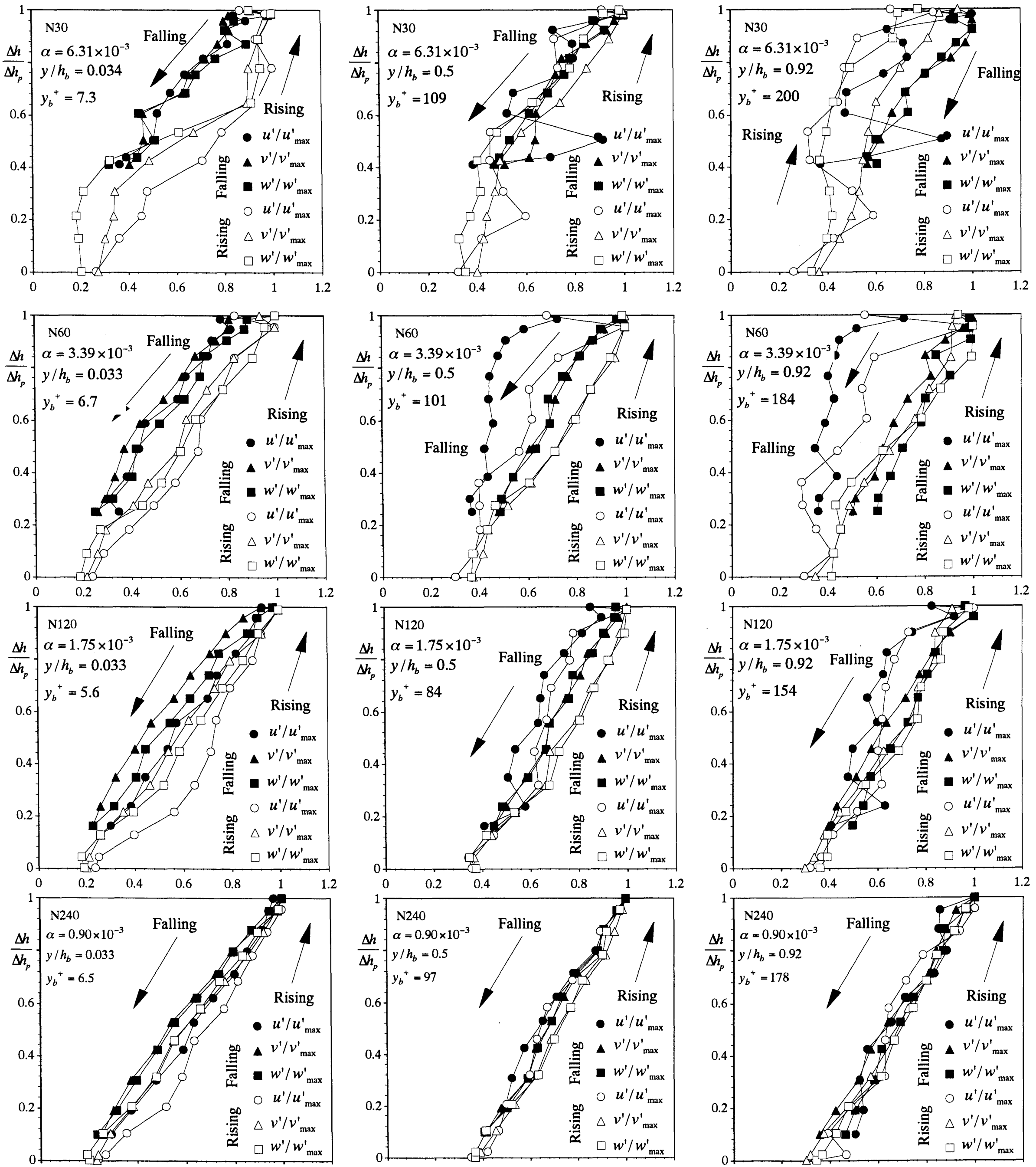


Fig.7 Loop Property of Turbulence Intensities *u'*, *v'* and *w'* against Depth Changes (Cases N30, N60, N120 and N240).

Compare the unsteadiness and the elevation of *y/hb*.

farther from the wall, i.e., say $y/h>0.3$ in the rising stage. On the other hand, the values of w'/U_* in case of N30 are described well by Nezu's formula(1977) in the falling stage. This is because the flow in the falling stage may be fully developed.

Loop Property of Turbulence against Depth

Fig.7 shows the distributions of turbulence intensities u', v' and w' against the depth variation $\Delta h \equiv h - h_b$ at three points, i.e., near the viscous sublayer, at middle depth and near the free surface. The loop property can be seen in the cases of N60, N120 and N240. The loop of turbulence is counter-clockwise. This implies that the strength of the turbulence in the rising stage is larger than that in the falling stage. The area of the loop increases with an increase of unsteadiness parameter α. These characteristics are coincident with those of Nezu *et al.*'s(1997) data. In contrast, the locus of turbulence near the free surface in case of N30 is clockwise. This implies that the turbulence intensity in the rising stage is smaller than that of falling stage. In strong unsteadiness flow such as N30, the rising speed V_s of free surface is comparatively high, and thus the effect of wall shear does not reach near the free surface, as mentioned previously.

CONCLUDED REMARKS

Measurements of unsteady open-channel flows with various unsteadiness were conducted by making use of two-sets of LDAs. It was found that von Karman constant is universal one on the condition that the unsteadiness parameter α is smaller than 0.002. The unsteadiness parameter α in natural river is usually smaller than 0.002. Therefore, von Karman constant can be dealt with a universal constant, i.e., $\kappa=0.41$ in river engineering. The spanwise turbulence intensities in unsteady open-channel flows were measured for the first time. The spanwise turbulence intensity can be described by Nezu's(1977) empirical formula. However, it deviates downward from the Nezu's formula in strong unsteady flow. The loop of turbulence near the free surface is clockwise. This characteristic is different from that for weak unsteady flow.

References

Hayashi, T., Ohashi, M. and Oshima, M., 1988, " Effect of the unsteadiness of flood waves on their turbulence structure", *Proc. 20th Symp. on Turbulence*, pp.154-159(in Japanese).

Nagano, Y., Tagawa, M. and Tsuji, T., 1993, "Effects of adverse pressure-gradients on mean flows and turbulence statistics in a boundary layer", *Turbulent Shear Flows 8* (ed. F. Durst et al.), Springer-Verlag, pp.7-21.

Nezu, I., 1977, "Turbulent intensities in open-channel flows", *Proc. of Japan Soc. Civil Eng.* No.261, pp.67-76(in Japanese).

Nezu, I. and Rodi, W., 1986, "Open-channel flow measurements with a laser Doppler anemometer", *J. of Hydraulic Engrg*, ASCE, Vol.112, pp.335-355.

Nezu, I. and Nakagawa, H., 1991, "Turbulent structures over dunes and its role on suspended sediments in steady and unsteady open-channel flows", *Proc. of Int. Symp. on Transport of Suspended Sediments and its Mathematical Modeling*, IAHR, Firenze, pp.165-190.

Nezu, I. and Nakagawa, H., 1993, "Basic structure of turbulence in unsteady open-channel flows", *Proc. of 9th Symp. on Turbulent Shear Flows*, Kyoto, pp.7.1.1-7.1.6.

Nezu, I. and Nakagawa, H., 1993, "*Turbulence in Open-Channel Flows*", IAHR-Monograph, Belkema, Netherlands.

Nezu, I. and Nakagawa, H., 1995, "Turbulence measurements in unsteady free-surface flow", *Flow Measurement and Instrumentation*, Butterworth-Heinemann, UK, Vol.6, No.1, pp.49-59.

Nezu, I., Nakagawa, H. and Kadota, A., 1995, "General log-law and turbulence characteristics in unsteady depth-varying free-surface flows", *Proc. of 10th Symp. on Turbulent Shear Flows*, Pennsylvania, USA, pp.P1.1-P1.6.

Nezu, I., Kadota, A. and Nakagawa, H., 1997, "Turbulent structure in unsteady depth-varying open-channel Flows", *J. of Hydraulic Engineering*, ASCE, Vol.123, pp.752-763.

Nezu, I., Onitsuka, K. and Yamamoto, Y., 1998, "Inner-layer characteristics in unsteady open channel flows over smooth bed", *Proc. of 11th Congress of APD-IAHR*, Indonesia, pp.517-526.

Nezu, I., Onitsuka, K., and Fujita, M., 2000, "Experimental study on turbulent structure in open-channel flows with adverse pressure gradients", *4th Int. Conference on Hydrodynamics*, Yokohama, Japan, pp.851-856.

Onitsuka, K. and Nezu, I., 1999, "Effects of unsteadiness on von Karman constant in unsteady open-channel flows", *Proc. of 28th Congress of IAHR*, Graz, Austria, pp.1-6, (in CD-ROM).

Onitsuka, K., Nezu, I. and Fujita, M., 1999, "Effect of favorable pressure gradients on turbulent structure in open-channel flows", *Hydraulic Modeling*, (eds. V.P. Singh *et al.*), Water Resources Publications, Colorado, USA, pp.3-16.

Song, T. and Graf, W. H., 1996, "Velocity and turbulence distribution in unsteady open-channel flows", *J. of Hydraulic Eng.*, ASCE, vol.122, pp.141-154.

Spalart, P.R. and Leonald, A., 1987, "Direct numerical simulation of equilibrium turbulent boundary layers", *Turbulent Shear Flows 5*, Springer-Verlag, pp.234-252.

Tu, H. and Graf, W. H., 1992, "Velocity distribution in unsteady open-channel flow over gravel beds", *J. of Hydroscience and Hydraulic Eng.*, JSCE, vol.10, pp.11-25.