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EXPERIMENT INVESTIGATION OF TURBULENCE GENERATED BY SOLITARY WAVE OVER SMOOTH BEDS

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ABSTRACT

Two cases of solitary motion experiment have been conducted over smooth beds by using solitary wave generation system facilitated by two types of rotating disk, the detail explanation about these rotating disks can be found in the former publication (Tanaka *et al.* 2011). In the present study, a deep analysis has been done to verify the sufficiency of tranquil period between two peaks of “solitary-wave-like” motion in turbulent flow regime and also to validate the reliability or sensitivity of ensemble averaging to 50 wave numbers produces by continuous measurement. The analysis results show that the minimum number of “periodical” or continuous wave measurement to attain reliable ensemble average is 45 wave numbers for case of turbulent solitary motion with Reynolds number (R_e) = 7.34 x 10^5.

Keywords: solitary wave, turbulent flow regime, tranquil period, ensemble averaging.

INTRODUCTION

Sea bottom boundary layer characteristics understanding is primacy in near-shore sediment transport modeling. A tsunamis or seismic sea wave has behaviour resembling to solitary waves. Beside that, as an oscillatory wave moves into shoaling water, its amplitude becomes progressively higher, the crests become shorter and the trough becomes longer and flatter and it is similar to solitary wave. And general known that most of flow which occurs in practical condition is turbulent and also some important processes occur in wave boundary layer. Turbulent mixing of mass and momentum, frictional dissipation takes place in wave boundary layer. Because of those some crucial reasons, investigation of turbulent boundary layer characteristics (numerically and experimentally) will be very necessary to hold up in its application for practical purposes such as sediment transport.

Wave flume with free surface was commonly used on previous studies (Liu *et al.* 2006, 2007). Indeed, wave flume experiment facilities have difficulty to attain high Shield’s number. Another problem is hard to reproduce near-bed characteristics at practical scale. Due to these inconveniences, a proper generation set up to shore up an experiment on sediment transport induced by solitary wave is highly required. Then, to figure out some difficulties found in the previous sediment transport experiment and also in the purpose of reproducing near-bed hydrodynamic and sediment transport phenomena at a realistic scale, closed conduit (Tanaka *et al.* 2011) and oscillating water tunnel are used. U-shape oscillating water tunnel have been applied by (Sumer *et al.* 2010), but it has difficulties in generating to boundary layer flow exactly corresponds to solitary wave motion and also performing periodical or continuous measurement. As we know that one wave cycle is not sufficient to make an adequate amount of sediment movement and consequently, it will be less of accuracy.

In the present study, a closed conduit solitary wave generation system which enable to do measurement under single and periodical oscillatory motion is tested for turbulent solitary wave case. Sensitivity analysis is done to check the convergence of solitary motion under turbulent flow regime in order to know the minimum number of generated wave to achieve reliable ensemble average.

THEORETICAL AND EXPERIMENTAL

Solitary Wave

The exact solution of free stream velocity under solitary wave motion given by following equation:

$$U = U_c \operatorname{sech}^2(\alpha t) \quad (1)$$

$$\alpha = a_s c = \sqrt{\frac{3H}{4h^3}}\sqrt{g(h+H)} \quad (2)$$

U_c = maximum velocity under wave crest,
t = time,
c = wave celerity,
h = water depth,
H = wave height,
g = gravitational acceleration.

Solitary Wave Generation System

The detail explanation of a new laboratory generation system such as: general sketch, generation system mechanism was given in the previous publication (Tanaka *et al.* 2011). In the present study, there are 2 cases used to ensure the capability and reliability of generation system in conducting turbulent-solitary motion. Case 1: flow velocity under periodical measurement generated by disk 1 and Case 2: flow velocity under single and

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"periodical" measurement obtained by Disk 2. The experiment conditions are summarized in Table-1 and a Reynolds number (R_e) was calculated by the following equation (Suntoyo and Tanaka, 2011).

$$R_e = \frac{U_c^2}{\upsilon\alpha} \quad (3)$$

υ = kinematic viscosity,
α = α value was determined by fitting the exact solution of solitary wave to the measured free stream velocity.

Table-1. Experimental conditions.

Case	Type of disk	Type of experiment	U_c (cm/s)	α (1/s)	R_e
1	Disk 1	Flow velocity	27.0	0.50	1.46 x 10^5
2	Disk 2	Flow velocity	81.3	0.81	7.34 x 10^5

RESULT AND DISSCUSSION

Rotating Disk 1

Measured free stream velocity and vertical velocity distribution during accelerating and also decelerating phases generated by disk 1 are displayed in Figure-1. As shown in Figure-1(a) measured free stream velocity has a good agreement with an exact solution (equation 1) although a slight discrepancy can be observed in early of periodical motion and in the end of decelerating phases. Because of this minor difference, a numerical laminar solution will be used instead of analytical solution (Keulegan, 1948).

From Figure-1(b) and 1(c) can be seen clearly an agreement between numerical laminar solution and experimental data especially in some elevation points closed to bottom at z below than 0.122cm and in the outside boundary layer at 3cm < z < 5.001cm. Besides that agreement with numerical laminar solution is also achieved during flow reversal. At z = 0.122cm to 2.001cm experimental velocity deviate from numerical laminar computation, it is caused by a negative value of velocity in the early of oscillatory motion as a residual of previous oscillatory motion velocity. A negative value of velocity during early stage of oscillatory motion is an indication that a tranquil period between two peaks of oscillatory motion is not sufficient. A tranquil period is too short to release instantaneous velocity from the previous oscillatory motion in a relatively small of quantity when the next oscillatory motion coming.

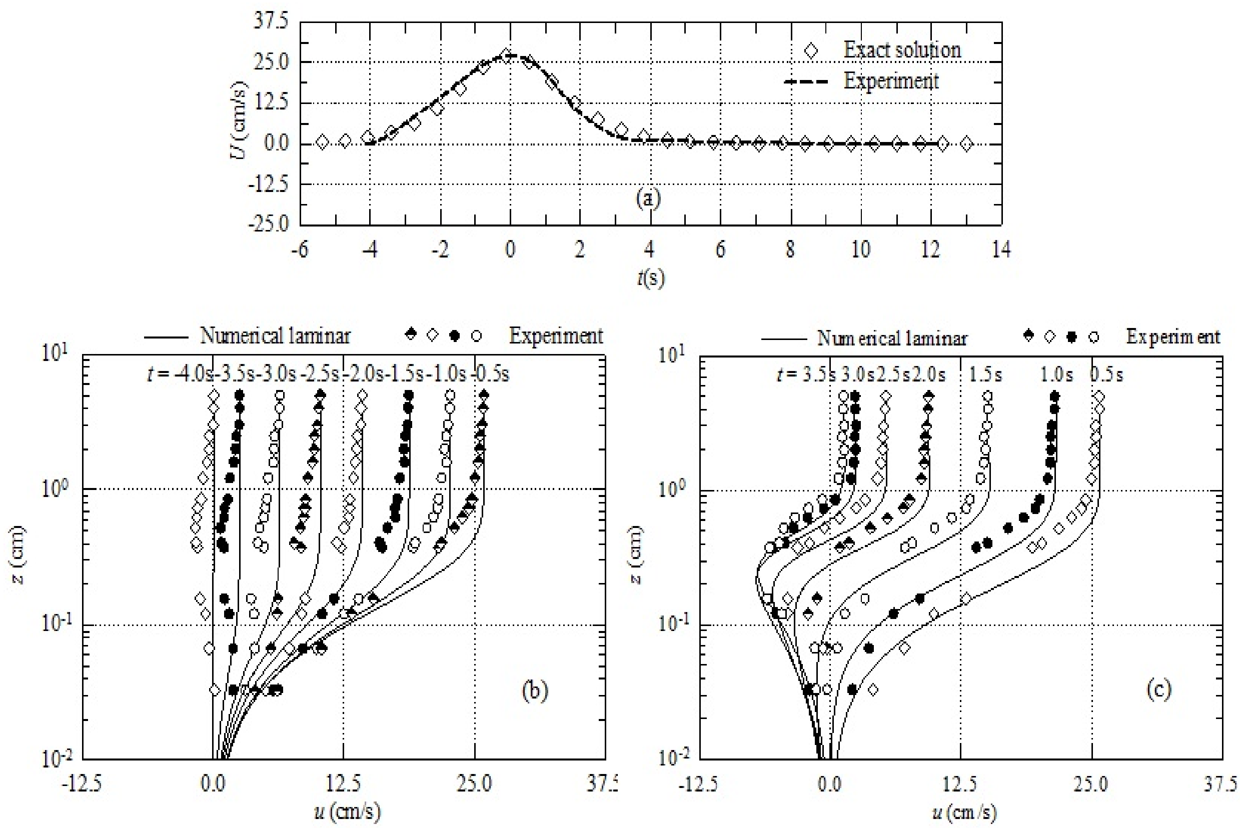

Figure-1. Flow velocity experiment result using disk 1; (a) measured free stream velocity; (b) vertical velocity distribution during accelerating phases and (c) vertical velocity distribution during decelerating phase.

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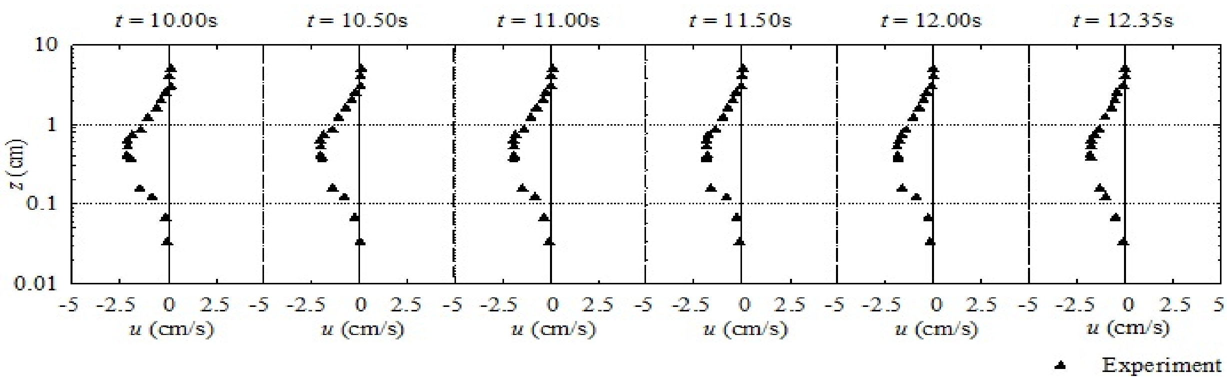

Figure-2. Vertical velocity distribution obtained by using disk 1 in the end of periodical motion.

From this Figure-2, it can be noticed obviously velocity distribution in the end of oscillatory motion at several time variations at t = 10.00s, 10.50s, 11.00s, 11.50s, 12.00s and 12.35s, at t = 10.00s a velocity (u) at z = 0.6cm is -2.5cm/s then it is gradually smaller become -1.5 cm/s at t = 12.35s. The existence of negative value of vertical velocity distribution as shown in this figure is apparently indicating the continuation of velocity distribution as the rest of previous periodical motion and then, it gives direct influence to the next oscillatory motion as depicted in Figure-1(b). As an important conclusion, the generation system facilitated by rotating disk 1 cannot satisfy the inherent requirement of solitary wave as a single wave generation. Hence, the improvement more appropriate solitary wave generation system is necessary.

Rotating Disk 2

Laboratory experiments under single and periodical or continuous oscillatory motion measurements have been carried out by using rotating disk 2. The reason of doing single oscillatory motion measurement is to evaluate the sufficiency of a tranquil period between two peaks of periodical oscillatory motion. Figure-3 displays a time series of the instantaneous velocity at z = 0.029cm; z = 0.052cm and z = 0.070cm as three closest measurement points from the bottom of a closed conduit generation system.

At z = 0.029cm mostly turbulence fluctuation appears during decelerating phase and it is categorized as turbulent flow with conditionally turbulent type (Hino *et al.* 1976). Next, both cases in conditionally turbulent type will be used as a basic analysis of turbulent flow in solitary wave boundary layer.

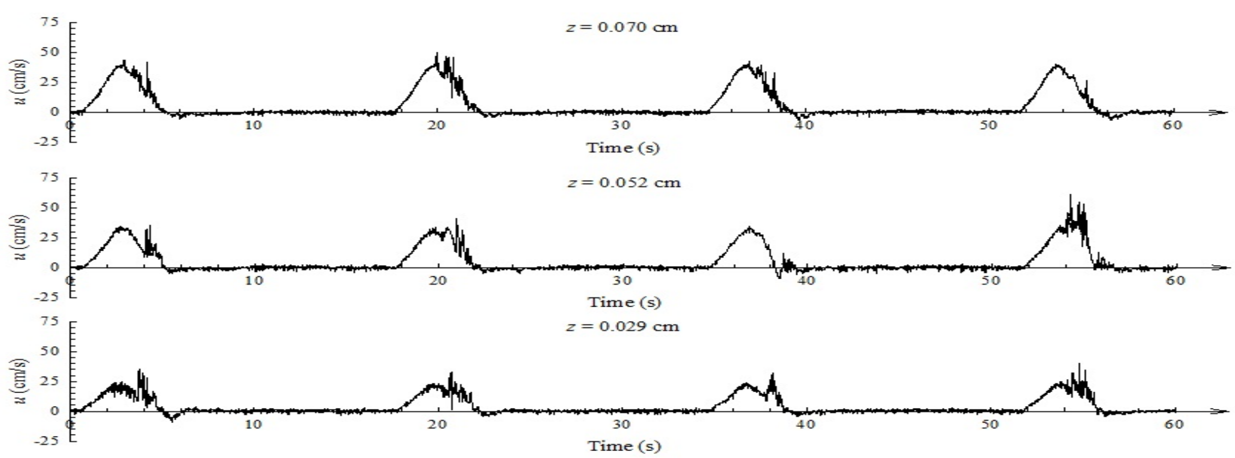

Figure-3. Instantaneous horizontal velocity (Case 2, $R_e = 7.34 \times 10^5$) in 3 different measured elevations.

The measured free stream velocity and vertical velocity distribution under single and periodical measurement obtained by using disk 2 shown in Figure-4. From this figures, it can be concluded that good agreement can be achieved in case of free stream velocity, although there is an insignificant different as compared with an exact solution (equation 1) especially in the early stage of solitary motion. Furthermore, it should be emphasized here that the negative velocity at the trailing of fluid motion inherent in a U-shape oscillating tunnel as reported by (Sumer *et al.* 2010) can be definitely avoided.

Figures-4(b) and (c) show vertical velocity distribution in both measurement methods. As shown in Figure-3, at z = 0.029cm turbulence spike appears

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suddenly during decelerating phase, the same observable fact also occurred at z = 0.052cm; 0.070cm; 0.085cm and 0.101cm, this circumstance makes abruptly fluctuation in vertical velocity distribution as displayed in Figures-4(b) and 4(c). This fact advises clearly why it is need a certain wave number (50) to achieve convergence of turbulent statistics such as turbulence intensity and mean velocity (Sleath, 1987; Jensen *et al.* 1989).

Figure-5 shows vertical velocity distribution at the end of oscillatory motion at t = 13.15s; 13.25s; 13.35s; 13.45s; 13.55s and 13.65s. Velocity value in the end of oscillatory motion is almost closed to zero, this fact is different with the result of experiment by using disk 1 that a negative value of velocity distribution can be observed in the end of oscillatory which it will give direct influence to the next oscillatory motion (Figures-1 and 2). Figure-4 confirms that tranquil period between two peaks of "solitary-wave-like" motions is sufficient and or it can satisfy an inherent requirement of solitary wave as single wave generation. Thus, from a view point of an efficient laboratory experiments, the present solitary wave generation system with an ability to perform periodical or continuous velocity measurement is useful for various kinds of experiment relevant to solitary wave boundary layer, which requires an ensemble averaged quantities and also sediment transport experiment. As general speaking that one wave cycle is not sufficient to make an adequate amount of sediment motion and as a result, it will be less of accuracy.

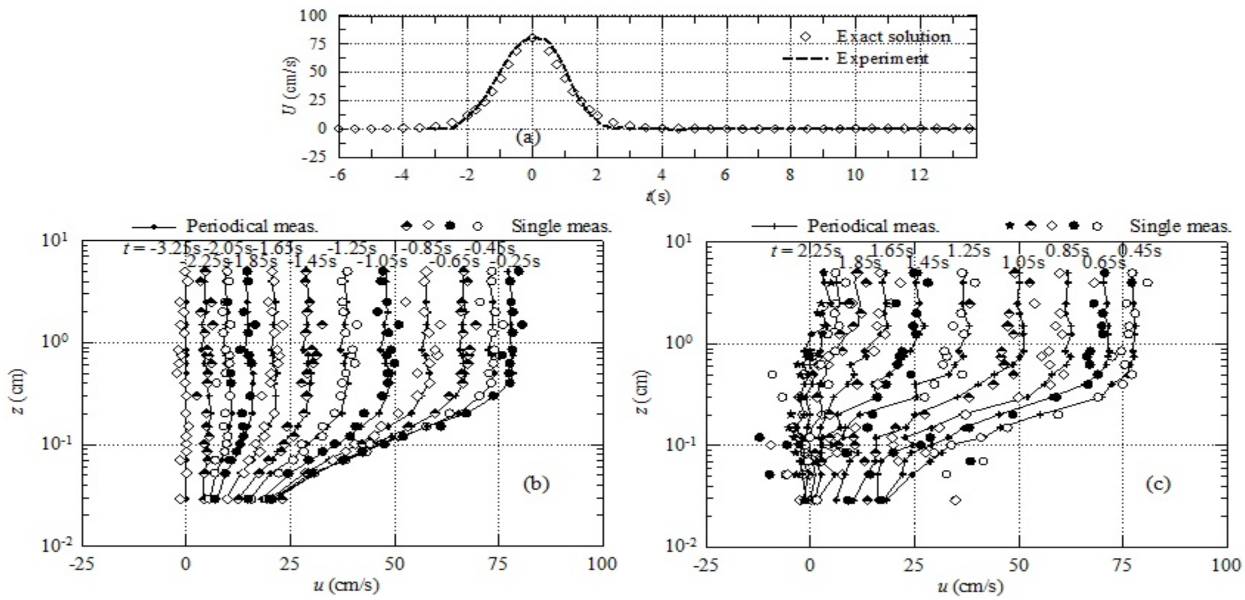

Figure-4. Flow velocity experiment result using disk 2; (a) measured free stream velocity; (b) vertical velocity distribution during accelerating phases and (c) vertical velocity distribution during decelerating phase.

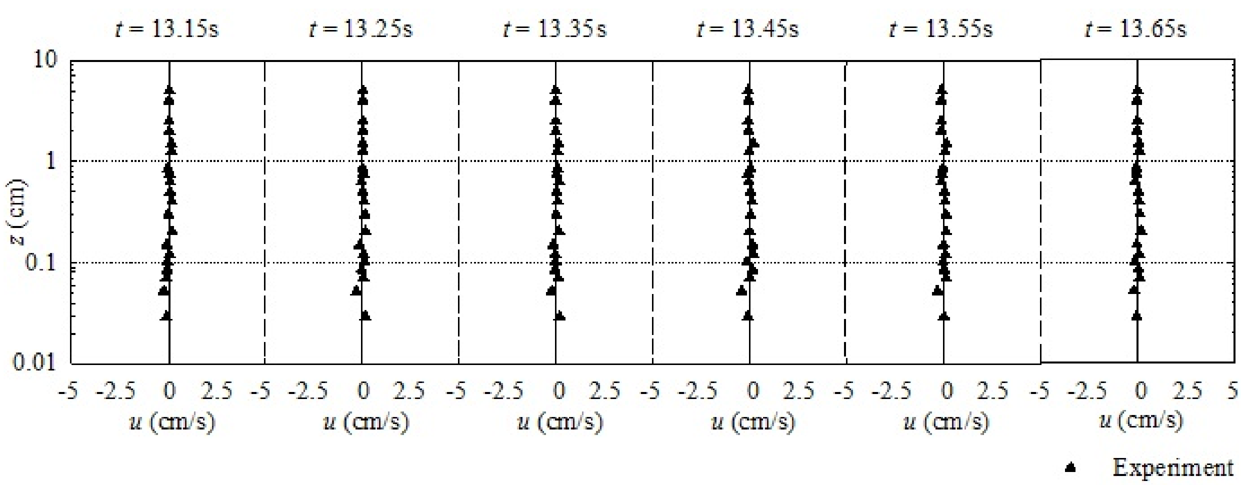

Figure-5. Vertical velocity distribution obtained by using disk 1 in the end of periodical motion.

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The instantaneous horizontal velocity is measured by means of LDV with the interval of 10 milliseconds. Piston displacement is also recorded with instantaneous velocity during laboratory experiment. This recorded will be used to identify the wave cycle of instantaneous velocity data. At first, the highest peak of piston displacement will have been identified and then, the wave cycle will be determined between the first zeros down-cross point preceding the piston displacement peaks.

Mean and fluctuating velocity will be estimated using ensemble averaging over 50 wave numbers. The reasons of wave number sampling have to be at least 50 wave numbers is to achieve convergence of turbulence statistics such as turbulence intensity and mean velocity (Jensen *et al.* 1989; Sleath, 1987). The statistical properties (turbulence intensity and mean velocity) at particular measurement depth were obtained by phase ensemble averaging using the following equations;

$$u(z,\sigma t)=\frac{1}{n}\sum_{i=1}^{n}u_{ins}\left[z,\sigma\{t+(i-1)T\}\right] \tag{4}$$

$$\sqrt{\overline{u'^2(z,\sigma t)}}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[u_{ins}\left[z,\sigma\{t+(i-1)T\}\right]-u(z,\sigma t)\right]^2} \tag{5}$$

n = the total of wave number or the total number of realization,
u' = flow velocity fluctuation,
u_{ins} = instantaneous velocity.

Figures-6 and 7 demonstrate sensitivity to 50 wave numbers under periodical or continuous wave measurement at z = 0.029cm as the closest measurement position from the bottom of closed conduit. As mentioned before that spike of turbulence suddenly occurred at decelerating phase in the "solitary-wave-like" motion. On Figures-6 and 7 show the mean velocity (u) and standard deviation of stream wise velocity at t = 0.25s and t = 0.70s when spike of turbulence frequently happened.

From Figures-6(a) and 7(a) can be noticed divergence of mean velocity (u) when total wave number (n) less than 30, after that when number of oscillatory motions at 30 to 40 degree of variance is getting smaller and then it is almost constant at total wave number (n) = 40 to 50. The value of standard deviation of stream wise velocity is also getting constant when total of wave number (n) is above of 45 for Case 2 with R_e = 7.34 x 10^5. Figure-6 and 7 clearly describe convergence of velocity measurement over 50 wave numbers.

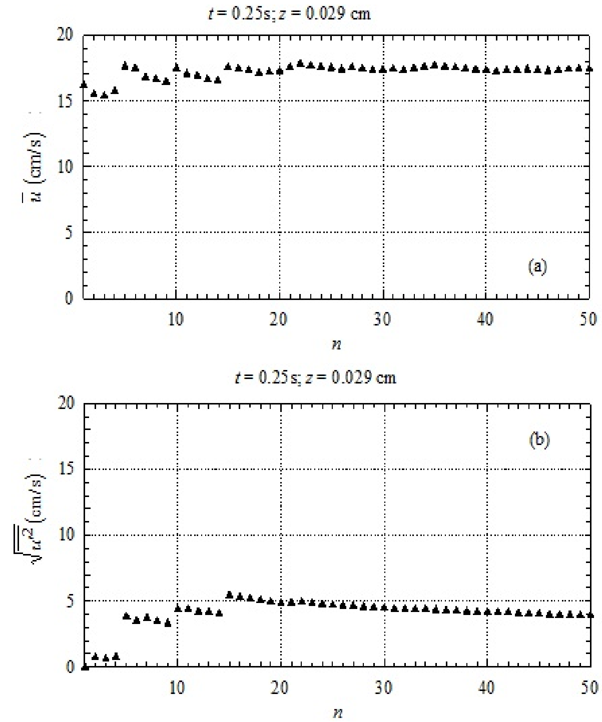

Figure-6. Sensitivity to 50 wave numbers: (a) mean and (b) standard deviation of the streamwise velocity at z = 0.029 cm, t = 0.25s (Case 2; Re = 7.34 x 105).

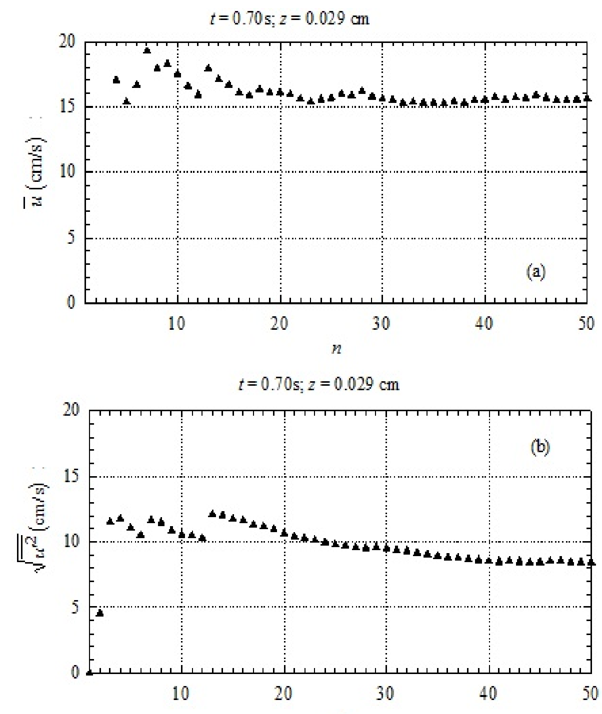

Figure-7. Sensitivity to 50 wave numbers: (a) mean and (b) standard deviation of the streamwise velocity at z = 0.029 cm, t = 0.70s (Case 2; Re = 7.34 x 105).

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CONCLUSIONS

A generation set-up facilitated by two types of rotating disk (disk 1 and disk 2) have conducted flow velocity experiment under single and periodical/continuous measurement. A comprehensive laboratory analysis have been done to verify the sufficiency of tranquil period in between two peaks of "solitary-wave-like" motion and also to validate the reliability of ensemble average or sensitivity to 50 wave numbers. The investigation result shows that tranquil period is insufficiency which is proved by a negative value of velocity in the early of oscillatory motion as a residual of previous oscillatory motion velocity (shown in Figure-2; Case 1; R_e = 1.46 x 10^5). However, Case 2; R_e = 7.34 x 10^5 shows the different result, tranquil period between two peak of oscillatory can be achieved under this experimental case. It confirms that Case 2 by using rotating disk 2 satisfies the inherent requirement of solitary wave as a single wave generation.

This present study also confirms the minimum number of "periodical" or continuous wave measurement to attain reliable ensemble average is above of 45 for Case 2; R_e = 7.34 x 10^5 or turbulent flow regime. In addition, a closed conduit generation system used in this present study can overcome some difficulties of the facilities applied in the previous experimental studies particularly in achieving a reliable ensemble averaging with ease and also in conducting the sediment transport experiment.

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