A pilot study to test a method to enhance the turbulence of a water flow in a laboratory flume

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1. Introduction

In this report we present some results of a laboratory pilot study which has been conducted to test a method to artificially enhance the turbulence of a water flow in a laboratory flume. The purpose of this test is to provide data which will be used to verify whether the method is suitable for the study of the dissipative effects of turbulence on surface waves.

In order to study the dissipative effects of turbulence on the surface waves, it is essential to enhance the turbulent intensity of the flow. On the other hand, it is desirable to enhance the shear rates of mean flow, and to generate turbulence of relatively large length scales. A strong interaction between the turbulent motion and the surface waves might be expected in cases where the turbulent length scale is of the same order as the wave length of the surface waves.

In this study, we investigate the feasibility of a method to intensify the turbulence of the flow and to establish larger structures ("turbulence") in the flow of length scale of order of the surface waves wave length. For this purpose, we disturb the flow in the flume of smooth walls by constructing a number of rectangular plates at the bottom of the flume. As first estimates, we use plates of height of about 20 percent of the water depth and width of about 20 percent of the flume width. The plates were fastened at the bottom on two rails by using T-shaped chords. It is possible to adjust the orientation of a particular plate by rotating it around the horizontal part of the T-chord and by rotating the T-chord itself on the rail around its vertical leg. Further, it is possible to adjust the distance between two subsequent plates on the rail. However, once the plates have been fastened on the rails, it is not possible to change their orientation and position during a particular test.

In this series of experiments, we measured the flow velocity at a number of measurement points in a cross section of the flume. From the velocity measurement, a number of flow parameters are determined: mean velocity, standard deviation (r.m.s.-value of the velocity fluctuation), lateral shear stress and mean rate of shear. From the same measurement, we determine also the auto-correlation function of the flow velocity at each measurement point. In the analysis, these parameters and the plot of the auto-correlation function determined from the measurement in the presence of the plates are compared with those determined from a reference measurement, that is the measurement in the absence of the plates. The results are discussed and some conclusions are drawn. A number of recommendations are given for further studies.

2. Experimental conditions and procedures

This study has been conducted at the Laboratory of Fluid Mechanics of the Faculty of Civil Engineering, Delft University of Technology, The Netherlands. The flume is 14.0 m long, 0.5 m wide and 0.7 m deep. A pump system of the laboratory allows to generate a flow circulation through the flume. The flow rate can be controlled with a valve. In all the tests, both the water depth and the flow rate were kept constant. The water depth was 0.40 m and the flow rate was 0.053 m$^3$/s. Figure 1 shows a sketch of the longitudinal section of the flume.

For this series of experiments, six plates of 10 cm by 10 cm were used. The distance between two subsequent plates on the rail was 0.90 m and the lateral distance between the two rails was 0.30 m. The position of these plates in the flume is shown in Figure 2. Two configurations were tested: a configuration where all the plates were vertical oriented with the plane normal to the flow direction, and a configuration where all the plates that were vertical oriented with the plane normal to the flow direction $1/4\pi$ rotated from the vertical around a lateral axis (the horizontal part of the T-chord) and with the upper edge tilted downstream.

An electromagnetic velocity meter was used to measure the flow velocity. The probe measures two components of the velocity: a longitudinal component $u$ in the flow direction, and a lateral component $v$ perpendicular to the flow direction. The positive direction of $u$ and $v$ is illustrated in Figure 2. The probe was aligned so that the
mean lateral velocity $V$ was about zero. The data were collected at 16 measurement points in a cross section which lied at about 0.30 m downstream of the last plate. The position of the measurement points in this section is shown in Figure 3. The duration of the data collection at a measurement point was two minutes. The sampling rate was 10 s$^{-1}$. The data were stored on a disk for further analysis.

3. Data analysis and results

In the analysis, we represent the flow velocity as a sum of mean velocity and turbulent velocity fluctuation. We denote the mean velocity by using an uppercase letter and the turbulent velocity fluctuation by a prime after the lowercase letter, so that the longitudinal velocity component is represented as $u = U + u' \text{ and } \text{the lateral component as } v = V + v'$. First, we determine the mean velocity in order to study the influence of the plates on the mean flow, and the standard deviation to study the influence on the turbulent intensity of the flow. Further, we calculate the lateral shear stress and the mean rate of shear. The lateral shear stress is, apart from $\rho$, expressed as $\tau_{xy} = U'V + U'V'$, where the indices $x$ and $y$ refer to axes in the longitudinal and lateral direction respectively. $U'V$ is the mean flow contribution and $U'V'$ (the time average value of $U'V$) the turbulent contribution to the lateral shear stress. The mean rate of shear is the component of the tensor $\partial U / \partial x_j$, $i, j = 1, 2, 3$ for the case where $i \neq j$. (Note that in the representation above we have used the following notations: $u_i = u$, $u_2 = v$, $u_3 = w$, $x_1 = x$, $x_2 = y$ and $x_3 = z$.) Because in this series of experiments only two components of the velocity ($u$ and $v$) were measured in one cross section, the only components of the mean rate of shear that can be estimated are $\partial U / \partial y$, $\partial U / \partial z$ and $\partial V / \partial z$. At last we plot the auto-correlation function of the flow velocity to study the effect of the plates on the time scales of the turbulence. Three cases were analyzed: without plates, with vertical plates and with tilted plates.

Because of a mistake in the data storing procedure, the data collected at measurement point 1 were unfortunately lost.

Figure 4 shows the mean longitudinal velocity component at measurement points 2 - 16. At points 2, 3, 4, 6, 7 and 8, we see that the vertical plates give an increase of mean velocity of about 20 percent. At these points, except point 8, the tilted plates also give an increase of mean velocity, but the increase is smaller. At points 5, 9 and 13, both the vertical and the tilted plates decrease the mean velocity. At points 14, 15 and 16, the vertical plates give a decrease while the tilted plates give an increase of mean velocity.

In the locations from point 5 to point 6, from point 9 to point 10 and from point 13 to point 14, both the vertical and the tilted plates give a significant increase of the magnitude of the lateral gradient of mean longitudinal velocity component.

The mean lateral velocity component is shown in Figure 5. In general, both the vertical and the tilted plates give a slightly increase of mean velocity of this component. The value of $V$ for the case without plates at points 2 and 3 are rather large. This may be due to a misalignment. Further, this value at point 5 is rather strange, and very likely this value is not correct. Comparing Figure 5 with Figure 4, we observe further that the change of magnitude of the lateral gradient of $V$ is smaller than that of $U$.

Figure 6 shows the standard deviation of the longitudinal velocity component at measurement points 2 - 16. In general, the presence of the plates in the flume increases the standard deviation of the longitudinal velocity component. In case of vertical plates, the standard deviation at points 3, 4 and 5 increases about 25 percent, and from point 9 through to point 16, the increase is very significant, by a factor two to four. In case of tilted plates, the increase at points 3 and 4 is slightly larger than that for the case of vertical plates. However, the increase at points 9 through to 16 is very much smaller than that caused by the vertical plates.
The standard deviation of the lateral velocity component is shown in Figure 7. In general, the presence of the plates in the flume influences the standard deviation of the lateral velocity component in the same trend as the longitudinal component. The increase of standard deviation of \( v \) at points 9 through to 16 is very much larger than that caused by the tilted plates. The increase caused by the vertical plates at these points is again very significant, by a factor two to three. Also here we remark that the value of the standard deviation of \( v \) at points 2, 3, 4 and 5 are very likely not correct.

Figures 6 and 7 show that the presence of the plates in the flume increases the standard deviation of the particle velocity and thus the turbulent intensity of the flow. The increase caused by the vertical plates is very much larger in the locations near the bottom and slightly smaller in the locations near the free surface than that caused by the tilted plates.

Figure 8 shows the mean flow contribution, Figure 9 the turbulent contribution (the Reynolds stress) and Figure 10 the total shear stress. We remark here again that the shear stresses at point 5 for the case without plates and at points 2, 3 and 4 for all the three cases are very likely not correct. Before we proceed to discuss shear stresses and shear rates, we will give here two possible origins of this mistake (after a discussion with R. Booij):

1. A misalignment of the probe with regard to the mean longitudinal flow direction
2. The electromagnetic velocity meter is very sensitive to disturbances from the environment, for example if the probe is installed nearby heavy metal or if it is installed in a relatively strong magnetic field.

Because of this presumed mistake, in the following we will not consider the measurement at points 2, 3, 4 and 5 in the discussion. First, consider the case without plates: the mean flow contribution at points 6 - 16 is nearly constant for points at the same elevations (Figure 8) and the turbulent contribution is practically zero everywhere in the cross section (Figure 9). The presence of the plates in the flume increases the mean flow contribution (Figure 8) and the increase caused by the vertical plates is in general smaller than that by the tilted plates. The Reynolds stress (Figure 9) at points 7 and 8 is nearly the same for the cases with vertical and tilted plates and at points 9 - 16 the increase of magnitude of Reynolds stress caused by the vertical plates is larger than that caused by the tilted plates. Looking at Figures 8, 9 and 10, we conclude that the magnitude of the turbulent contribution to the total shear stress at points 9 - 16 is, in case with tilted plates, of order of 2.0 percent, and in case with vertical plates, of order of 5.0 percent.

The mean rates of shear \( \partial U/\partial y, \partial U/\partial z \) and \( \partial V/\partial z \) are estimated as \( \Delta U/\Delta y, \Delta U/\Delta z \) and \( \Delta V/\Delta z \) respectively. Table 1 presents \( \Delta U/\Delta y \), Table 2 \( \Delta U/\Delta z \) and Table 3 \( \Delta V/\Delta z \). Tables 1, 2 and 3 show that, in general, the presence of the plates in the flume increases the value of these components. The increase of \( \Delta U/\Delta y \) caused by the vertical plates (Table 1) is smaller in the locations at higher elevations (locations: 6-7, 7-8) and larger in the lower elevation (locations 13-14, 14-15 and 15-16) than that by the tilted plates. The increase of \( \Delta U/\Delta z \) caused by the vertical plates (Table 2) is in general larger than that by the tilted plates. The increase of \( \Delta V/\Delta z \) caused by the vertical plates (Table 3) is smaller in the locations at higher elevations (locations 6-10, 7-11 and 8-12) and larger in the lower elevations (10-14, 11-15 and 12-16) than that by the tilted plates.
WP - - - - -0.21 -0.25 -0.36 -0.18 -0.19 -0.25 -0.22 -0.09

VP - - - - -0.21 -0.05 -0.86 -0.40 0.18 -0.75 -0.45 0.31

TP - - - - -0.39 -0.39 -0.66 -0.49 0.39 -0.61 -0.19 0.13

Table 1. Mean rate of shear $\Delta U/\Delta y$ [s$^{-1}$] in the locations between points 1-2, 2-3, 3-4, 5-6, 6-7, 7-8, 9-10, 10-11, 11-12, 13-14, 14-15 and 15-16: WP: without plates, VP: with vertical plates and TP: with tilted plates.

WP - - - - -0.13 -0.08 0.01 - -0.04 -0.04 - -0.04 0.09

VP - - 0.26 - 0.63 0.40 - 0.39 0.39 - 0.68 0.50

TP - - -0.50 - 0.29 -0.44 - 0.16 0.16 - -0.05 -0.39

Table 2. Mean rate of shear $\Delta U/\Delta z$ [s$^{-1}$] in the locations between points 1-5, 5-9, 9-13, 2-6, 6-10, 10-14, 3-7, 7-11, 11-15, 4-8, 8-12 and 12-16: WP: without plates, VP: with vertical plates and TP: with tilted plates.

WP - - 0.04 - 0.01 -0.06 - 0.03 -0.04 - -0.04 0.00 -0.03

VP - - -0.13 - -0.13 -0.21 - -0.04 -0.19 - -0.11 -0.15

TP - - -0.06 - -0.34 -0.20 - 0.10 -0.04 - -0.39 0.09

Table 3. Mean rate of shear $\Delta V/\Delta z$ [s$^{-1}$] in the locations between points 1-5, 5-9, 9-13, 2-6, 6-10, 10-14, 3-7, 7-11, 11-15, 4-8, 8-12 and 12-16: WP: without plates, VP: with vertical plates and TP: with tilted plates.

The auto-correlation functions of the longitudinal velocity component at measurement points 2 - 16 are plotted in Figures 11 - 25 and those for the lateral component in Figures 26 - 40. Looking at these figures carefully, we conclude that the presence of the plates in the flume does not introduce turbulence of larger time scales.
4. Conclusions

1. The presence of the plates in the flume changes the mean longitudinal flow velocity; a decrease near the bottom and an increase at higher elevations.

2. The increase of turbulent intensity caused by the vertical plates is very much larger in the locations near the bottom, slightly smaller in the locations near the free surface and, over the whole cross section, very much larger than that caused by the tilted plates.

3. The increase of magnitude of the Reynolds stress caused by the vertical plates is larger than that caused by the tilted plates.

4. The increase of mean rates of shear caused by the vertical plates is smaller in the locations at higher elevations and larger in the locations near the bottom than that caused by the tilted plates.

5. The plates do not introduce turbulence of larger time scales.

5. Recommendations

1. It will be very useful to test plates of other dimensions, especially those of larger dimensions.

2. To get a better insight into the change of mean velocity and the transport of turbulent kinetic energy, it is desirable to do measurements in other cross sections along the flume.

3. Perform tests of plates in other configurations. (Larger structures to be established in the mean flow.)

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Figure 1. Longitudinal section of the flume (lengths expressed in meters)

Figure 2. Plan view showing the position of the plates in the flume (lengths expressed in meters)

Figure 3. Position of the measurement points in cross section A - A (lengths expressed in meters)
Figure 4. Mean longitudinal velocity at measurement points 2-16; $U_{wp}$: without plates, $U_{vp}$: with vertical plates and $U_{tp}$: with tilted plates.

Figure 5. Mean lateral velocity at measurement points 2-16; $V_{wp}$: without plates, $V_{vp}$: with vertical plates and $V_{tp}$: with tilted plates.
Figure 6. Standard deviation of the longitudinal velocity component at measurement points 2-16; $Su_{wp}$: without plates, $Su_{vp}$: with vertical plates and $Su_{tp}$: with tilted plates.

Figure 7. Standard deviation of the lateral velocity component at measurement points 2-16; $Sv_{wp}$: without plates, $Sv_{vp}$: with vertical plates and $Sv_{tp}$: with tilted plates.
Figure 8. Mean flow contribution ($UV$) to the lateral shear stress at measurement points 2-16: $tss;wp$: without plates, $tss;vp$: with vertical plates and $tss;tp$: with tilted plates.

Figure 9. Turbulent contribution (the Reynolds stress $u'v'$) to the lateral shear stress at measurement points 2-16: $tss;wp$: without plates, $tss;vp$: with vertical plates and $tss;tp$: with tilted plates.

Figure 10. Total lateral shear stress ($UV + u'v'$) at measurement points 2-16: $totss;wp$: without plates, $totss;vp$: with vertical plates and $totss;tp$: with tilted plates.
Figure 11. Auto-correlation function of the longitudinal velocity at point 2: autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.

Figure 12. Auto-correlation function of the longitudinal component of the particle velocity at point 3; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.

Figure 13. Auto-correlation function of the longitudinal component of the particle velocity at point 4; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.
Figure 14. Auto-correlation function of the longitudinal component of the particle velocity at point 5; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.

Figure 15. Auto-correlation function of the longitudinal component of the particle velocity at point 6; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.

Figure 16. Auto-correlation function of the longitudinal component of the particle velocity at point 7; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.
Figure 17. Auto-correlation function of the longitudinal component of the particle velocity at point 8; autou\(_{wp}\): without plates, autou\(_{vp}\): with vertical plates and autou\(_{tp}\): with tilted plates.

Figure 18. Auto-correlation function of the longitudinal component of the particle velocity at point 9; autou\(_{wp}\): without plates, autou\(_{vp}\): with vertical plates and autou\(_{tp}\): with tilted plates.

Figure 19. Auto-correlation function of the longitudinal component of the particle velocity at point 10; autou\(_{wp}\): without plates, autou\(_{vp}\): with vertical plates and autou\(_{tp}\): with tilted plates.
Figure 20. Auto-correlation function of the longitudinal component of the particle velocity at point 11; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.

Figure 21. Auto-correlation function of the longitudinal component of the particle velocity at point 12; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.

Figure 22. Auto-correlation function of the longitudinal component of the particle velocity at point 13; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.
Figure 23. Auto-correlation function of the longitudinal component of the particle velocity at point 14; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.

Figure 24. Auto-correlation function of the longitudinal component of the particle velocity at point 15; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.

Figure 25. Auto-correlation function of the longitudinal component of the particle velocity at point 16; autou;wp: without plates, autou;vp: with vertical plates and autou;tp: with tilted plates.
Figure 26. Auto-correlation function of the lateral component of the particle velocity at point 2; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 27. Auto-correlation function of the lateral component of the particle velocity at point 3; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 28. Auto-correlation function of the lateral component of the particle velocity at point 4; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.
Figure 29. Auto-correlation function of the lateral component of the particle velocity at point 5; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 30. Auto-correlation function of the lateral component of the particle velocity at point 6; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 31. Auto-correlation function of the lateral component of the particle velocity at point 7; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.
Figure 32. Auto-correlation function of the lateral component of the particle velocity at point 8; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 33. Auto-correlation function of the lateral component of the particle velocity at point 9; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 34. Auto-correlation function of the lateral component of the particle velocity at point 10; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.
Figure 35. Auto-correlation function of the lateral component of the particle velocity at point 11; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 36. Auto-correlation function of the lateral component of the particle velocity at point 12; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 37. Auto-correlation function of the lateral component of the particle velocity at point 13; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.
Figure 38. Auto-correlation function of the lateral component of the particle velocity at point 14; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 39. Auto-correlation function of the lateral component of the particle velocity at point 15; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.

Figure 40. Auto-correlation function of the lateral component of the particle velocity at point 16; autov;wp: without plates, autov;vp: with vertical plates and autov;tp: with tilted plates.