Turbulence and free surface flow at relevant Froude number

Sandro Longo
Department of Civil Engineering, University of Parma, Viale G.P. Usberti, 181/A, 43100 Parma, Italy, e-mail: sandro.longo@unipr.it

This work concerns the analysis of experimental instantaneous fluid level and three-component fluid velocity measurements in a stationary flow field generated by a Crump weir in a laboratory flume. The tests are characterized by different and increasing Froude numbers (Fr =0.10-0.38), with the free surface of the fluid ranging from flat (low Froude number) to almost aerated (high Froude number). The data are elaborated obtaining the macro-turbulence Reynolds tensor, even using conditional averages based on free surface fluctuation statistics. A free surface boundary layer was detected having a thickness proportional to the root mean square of the free surface height series and with a velocity scale well related to the free surface elevation time gradient. The correlations between free surface elevation and the underlying flow velocities allow the evaluation of the time lag between turbulence and free surface. The results show that free surface motion is delayed with respect to turbulence at low Froude numbers (turbulence acts on the free surface) but is in advance at higher Froude numbers (free surface triggers turbulence). A specific regime occurs with an optimal tuning between free surface and turbulence. In this regime, the length scales are raised and the eddy viscosity assumes larger values.

Keywords: Free surface turbulence, turbulence intensity

1 INTRODUCTION

Many important transfer phenomena take place near the interface between air and water in the rivers, sea and lakes. Gas, chemicals, heat can be transferred in both directions depending also on turbulence level near the interface. Several attempts to quantify the effects of the free surface on turbulence have been successfully completed using numerical methods and experimental techniques, but in our knowledge no attention has been paid to the effects of turbulence on the free surface elevation. In literature no results have been presented with a quantification of the statistics of the free surface.

There are a great variety of free surface patterns and several mechanisms of energy transfer at a free surface such as capillary and gravity waves. In particular, the presence of waves requires the separation of their contribution in the flow field. The problem of separating waves and eddies, essentially a potential and a rotational component of the flow field (even though vorticity is not always turbulent, but turbulence is always vortical), is still unsolved. In the present experiments, we used the filtering method, with a cut-off frequency based on the observation of the energy spectra.

In the present experiments, we use Ultrasound to measure fluid velocity and fluid level in a spilling type breaker generated on a steady current by a Crump weir.

The Ultrasound technique is not new, but its application and recent evolution provide a new system to study velocity measurements in complex flows. The technique is well suited for giving information in a complex flow field, especially if spatial distribution is a main concern (e.g., [1]).

2 PROCEDURE FOR THE EXPERIMENTS

The present analysis refers to experiments in a flume, with free surface turbulence generated by a Crump weir (Figure 1).

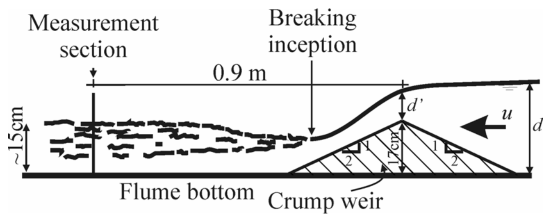

Figure 1: Scheme of the Crump weir set-up.

The flume was 15 m long, 0.30 m wide and 0.47 m high, and was supplied by a pump feeding a small tank at one end. The Crump weir was made with PMMA and was symmetric with an upstream and downstream slope 1:2 and a crest height of 17 cm with respect to the bottom of the flume. The crest was 7.1 m from the tank and the approaching flow had a flat surface with limited turbulence. The measurement section was 0.9 m past the weir, where the mean level was maintained at ~ 150 mm and was controlled by a bottom-hinged flap gate in the exit section of the flume. In all tests, a modular flow condition was obtained, with a head over the weir crest varying from ~ 20 mm (minimum discharge in the tests) to ~ 90 mm (maximum discharge in the tests). The approaching flow has a Froude number in the range 0.02-0.14, while a supercritical flow develops on the downstream face of the weir. Then, it turns to subcritical flow (Fr = 0.10-0.38) after a weak jump located well behind the measuring section.

2.1 Surface elevation and fluid velocity measurements

Free surface elevations were measured using an ultrasonic sensor based on flight-time having a carrier at 10 MHz, with temperature compensation and a sensing range of 50 to 250 mm (distance from the emitter/receiver). The response time was 10 milliseconds and the overall error (including non-linearity and repeatability) was assessed to be equal to 0.3 mm. Fluid velocity measurements below the free surface were taken using an array of three probes of an Acoustic Doppler Velocity Profiler, with a carrier frequency of the probes equal to 8 MHz (the arrangement of the probes is shown in Figure 2). The transducers had an active element diameter of 5 mm in a cylindrical plastic housing 8 mm in diameter. The arrangement of the three probes was chosen in order to guarantee an overlap of the measurement volume in the area of interest, just below the mean free surface, with the aim of mapping out the near surface flow field. In order to increase the S/N ratio, the water was seeded with clay, which proved to be an excellent seeding.

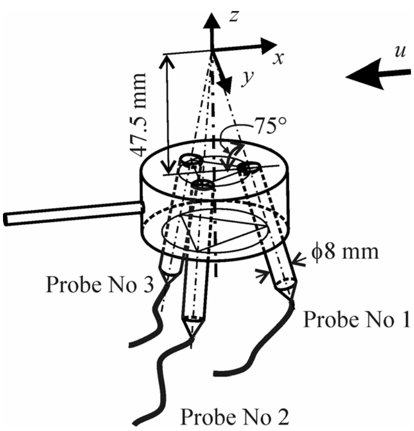

Figure 2: Arrangement of the velocity probes.

The acquisition was multiplexed, with a circular scanning of a single profile for each probe. The time lag between two different probe profiles was equal to 0.03 s on average, whereas the time lag between two subsequent gates was equal to $k \times \delta z/c$, where k is a coefficient roughly equal to two, δz is the distance between two gates and c is the ultrasound celerity in water. The resolution was equal to 1/128 (1 LSB) of the velocity range. For most tests, the resolution was equal to 0.5 cm/s (velocity measured along the probe axis). The presence of the moving interface generates a Doppler shift, which is highly energetic and can persist in the flow field as a stationary signal. The elimination of these stationary components by high-pass filtering implies an increase in the dynamic of the analyzed echoes and a reduction in the sensitivity in the measurement of low velocities. The Doppler frequency shift induced by these movable interfaces cannot be removed if their values have the same values as the flowing particles. In order to balance all these effects, the presence of some artifacts is tolerated, which essentially influence the mean values, but not the statistics of the fluctuations (these artifacts determine a shift of the measured value of the velocity).

2.2 Data acquisition and analysis

Free surface elevation data was acquired at 100 Hz and velocity measurements were stored independently by a second dedicated PC triggered to free surface elevation data by an external cable. The frequency of acquisition of the velocity depends on the ADVP set-up and cannot be forced to a specific value. For a proper timing of free surface elevation (higher data rate) and velocity measurements (lower data rate), free surface data was sub-sampled at the lower rate. Then, velocity data was elaborated in order to obtain the mean values of fluid velocity and of the Reynolds tensor in an Eulerian frame with a coordinate system having its origin at the mean water level.

Free surface elevation was also statistically analysed in the time domain with a zero-crossing analysis in order to extract the root mean square height (H_{rms}) and several zero(-up) crossing statistical estimators.

3 ENERGY SPECTRA

The one dimensional energy spectrum for the vertical component of velocity at various levels and at large-scale normalization is shown in Figure 3.

The velocity scales derive from the turbulent kinetic energy and all variables are time averaged. The large-scale Reynolds number, Re_{Λ}, varies from ~ 4×10^3 well below the mean water level to ~ 2×10^2 in the crest of the free surface fluctuations; Λ is the integral scale. At small wave numbers, the spectrum tends to become flat and is coherent with the energy renewal model of the energy-containing eddies reported in [2]. The exponent of the spectrum in the intermediate wave numbers and at the zero level is slightly higher than the classical Kolgomorov spectrum exponent equal to -5/3. Moving below the zero level, the exponent tends to reduce and to reach the classical value. There are several phenomena to account for when interpreting the measured shape of the spectrum. The assumption of the existence of an inertial subrange relies on the existence of a Reynolds number larger than 4×10^3 [3], which is not the case of the present experiments (the maximum Reynolds number is ~ 1000). That means that the effects of production and dissipation, which usually appear for $k\Lambda < 10$ and $k\Lambda > 1000$, also modify the shape at intermediate wave numbers. Another important phenomenon is intermittency. Turbulence generation is an intermittent phenomenon, but also dissipation seems to be organised in patches, instead of being uniformly present in the flow field.

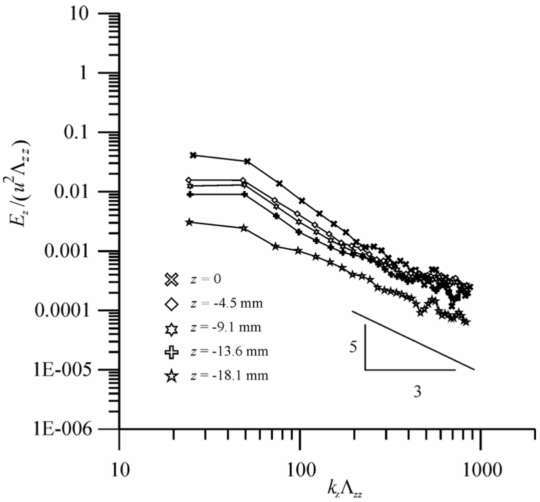

Figure 3: Normalized wave number energy spectra of velocity fluctuations. Energy spectrum vertical velocity fluctuations. Test No 66, H_{rms} = 12.09 mm.

Chorin [4] analysed in detail the possible corrections of the exponent in the Kolgomorov spectrum, and indeed found that the correction proposed should not be addressed directly to intermittence, even though using different arguments also justifies an exponent equal to -2 derived by a cascade construction as a better candidate for a model where fluctuations due to intermittency are ignored. In the present experiments, in the domain below the mean water level, the intermittency is due to the free surface fluctuations and also to the presence/absence of fluid. Its effects should possibly be reduced or disappear far from the free surface. It gives a plausible interpretation of the observed spectra.

At a low wave number, the vertical spectrum E_z shows larger values at z = 0 with respect to the spectra below the free surface (Figure 3). That means that no suppression of the eddies larger than the depth occurs and that eddies are strictly responsible of the free surface fluctuations. Instead, the two other spectra show larger values below the z = 0 level, reaching a maximum at z roughly equal to - H_{rms}.

4 THE EDDY VISCOSITY

Using a phenomenological approach, the eddy viscosity can be expressed as

$$\nu_e = \Lambda_{zz} w' \quad (2)$$

Λ_{zz} is the integral scale in the vertical and w' is the vertical velocity fluctuation. This description seems much more appropriate than the classical expression related to the mean velocity gradient in flow fields characterised by the presence of coherent structures. In fact, according to many researchers, coherent structures generate most of the turbulent shear stress, even in homogeneous turbulence. The main effect of disregarding the presence (or the effects) of these families of eddies, is the poor adherence to the reality of some common assumptions, as eddy viscosity to express the behaviour of the turbulence stresses in terms of the mean velocity gradients.

Figure 4 presents the eddy viscosity profiles for all tests. u_s is the free surface velocity scale based of the time derivative of the instantaneous free surface elevation. The tests with Fr_s > 0.19 show a maximum at $z = H_{rms}$, where the mean shear also has a maximum (not shown) and a fast damping towards the free surface. The damping is mainly associated with the reduction of the velocity scale, because the length scale even increases near the free surface.

The eddy viscosity profiles refer to different Reynolds numbers and do not collapse to a single curve.

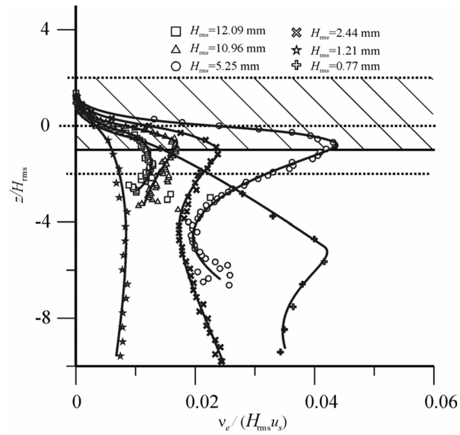

Figure 4: Eddy viscosity profiles.

Rather, the mean value of eddy viscosity generally increases with the Reynolds number up to a maximum, reached at an intermediate level of fluctuation (H_{rms} = 5.25 mm), which also showed the highest values for the macroscale Λ_{zz}; then decreasing once more. This is another consequence of an optimal tuning between free surface oscillations and macrovortices, which also improves the efficiency in momentum transfer between the external region and the boundary layer. As usual, the tests at low levels of fluctuation show an anomalous behaviour due to the fact that other scales are significant in this condition.

5 THE CORRELATION BETWEEN FREE SURFACE AND FLUID VELOCITY

The analysis of the correlation between free surface and vertical velocity fluctuations is shown in Figure 5. The upper box is the coherence map for the vertical velocity component, the lower box is the phase lag map, with positive values of the phase indicating that the free surface elevation has a delay with respect to the velocity fluctuations. The coherence between the two variables a and b ranges between 0 and 1 and is defined as

$$c = \frac{P_{ab}^2}{P_{aa}P_{bb}} \quad (3)$$

where P_{ab} is the power cross-spectral density and P_{aa} and P_{bb} are the power auto spectral densities. Similar maps for the spanwise velocity component show a negligible coherence value and will not be further considered. In the present tests, the coherence generally has a maximum value immediately below the mean water level and at frequencies from 3.3 Hz to slightly less than 2 Hz for decreasing H_{rms}. For all tests, the maximum coherence has a value less than 0.3 and decreases with H_{rms}. The maximum lies at higher frequencies or near the main peak of the free surface elevation power spectrum (not shown). Occasionally, two peaks can be found with the second at twice the main frequency. At high H_{rms} (Test No66), we can observe that the phase lag between the free surface fluctuations and the vertical velocity fluctuations is generally negative in the free surface layer, i.e. the free surface fluctuations are advanced with respect to the vertical velocity fluctuations; it happens that where the coherence is maximum, the phase lag changes from 0° to -90° at the zero level, then increases again (see the dashed and the dotted thick curves in Figure 5). The phase lag is positive below the free surface layer, i.e. the free surface fluctuations have a delay with respect to the vertical velocity fluctuations. In the same test, the phase lag between the free surface fluctuations and the stream wise velocity fluctuations is positive in the domain where the maximum coherence occurs. Note that while two separate curves connecting the maxima can be drawn for the vertical velocity fluctuations (ranging between 1 Hz and 3.5 Hz), a single curve can be drawn for the stream wise velocity fluctuations (not shown). A model of interpretation of the data assumes that the stream wise velocity fluctuations act as forcing term for the free surface fluctuations, with maximum efficiency near the observed peak of 2 Hz; the free surface fluctuations, in turn, force the vertical velocity fluctuations with maximum efficiency in two bands centred at 2 Hz and at nearly twice the peak frequency of 2 Hz. The superharmonic of the response is due to the fact that both crests and toughs excite the eddies and hence, the velocity fluctuations. The mechanism of wave generation by turbulence in the water could be that analysed by Texeira & Belcher [5] with a forcing dominated by turbulent pressure fluctuations. This scenario can also be recognised for the other tests at lower values of H_{rms}.

6 CONCLUSIONS

The presented results show the characteristics of free surface turbulent flows at low, but not negligible, Froude numbers without air inception.

- The eddy viscosity profile depends on Reynolds number, is damped in the free surface boundary layer, has a maximum at the edge of the free surface boundary layer, and assumes larger values in optimal tuning tests.

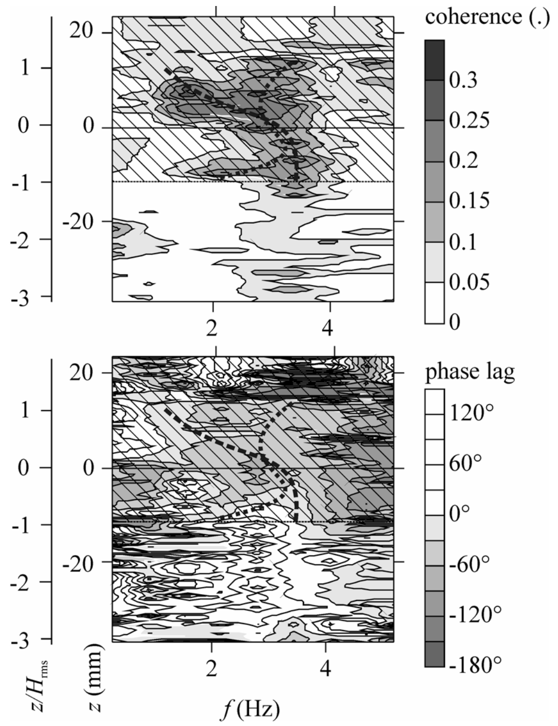

Figure 5: Coherence and phase lag. Test No 66, H_{rms} = 12.09 mm.

- The analysis of correlation between free surface instantaneous elevation and the vertical component of fluctuating velocity reveals that the free surface is generally delayed with respect to fluid velocity, except at high H_{rms}. We can infer that free surface fluctuations are generally triggered by turbulence, but strong fluctuations of free surface can easily invert the roles. The triggering mechanism could be that inferred by Texeira & Belcher [5], with pressure fluctuations related to turbulence and generating the free surface fluctuations.

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