CHAPTER 17

Turbulence Structures in the Surf Zone.

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Abstract

Turbulence due to breaking waves is an important factor in the ocean as it has a direct effect on coastal erosion, sediment transport and marine life. The laboratory study of this phenomenon is important to produce controlled simulations of processes that occur at sea, and has mainly consisted of temporal point measurements. In this paper the results obtained from using PIV to study the turbulence in the laboratory are presented. PIV is a spatial technique and yields unique information on the turbulence structure in such a flow. Of particular interest in this paper are the evolution of the wavenumber spectra and the form of the turbulence from 2-d to 3-d. Separation of the turbulence from the mean motion is important and the method used here is justified. The main results and conclusions are compared with other research, with similarities and differences emphasised and discussed.

1. Introduction

Little is known about the nature of the turbulence produced by a breaking wave event. It is a very difficult flow to model numerically and equally hard to measure experimentally. The traditional approach to experimental investigation has been to use point measuring techniques such as Laser Doppler Annenometry (LDA) [5, 4]. This does not enable the spatial structures of the flow and the way in which the associated vorticity and energy is dissipated, to be measured. Particle Image Velocimetry (PIV) is a well documented velocity measuring technique, yielding full field instantaneous flow information [12]. The implementation of a high resolution digital camera and an image shifting device allows the problem of measuring multi-directional velocities to be solved, imparting a constant velocity throughout the flow that can be subtracted after analysis.

Previous research on laboratory generated single breaking waves is fairly scarce, however a comprehensive study using LDA was done by Rapp and Melville [5] along with other interesting work from Battjes and Sakai [2]. The results obtained by these researchers will be referenced and comparisons made, with results obtained here. There are two main objectives to be addressed in this paper, firstly the validation of PIV as a technique for studying this type of complex flows, and secondly the exploitation of the advantages inherent in using PIV, to characterise the turbulent flow spatially and temporally.

2. Experimental facility

The experiments described in this paper were carried out in the Edinburgh University wave flume. The flume is 9m long 0.4m wide and 1m deep, with the water depth being 0.75m. The wavemaker is a hinged paddle that has a force feedback mechanism, designed to limit reflections. Breaking waves are formed by the superposition of differing frequencies formed by the paddle which are focussed to create a breaking event. The walls of the flume are glass to allow easy optical access. At the far end of the flume there is an absorbing wedge of foam which disperses the remaining wave energy and limits reflections.

Wavegauges can be used to measure the surface elevations during experimentation and in these experiments four were used, two positioned before breaking and two after. These yield important information on the spectral contents of the wave used in the investigation and also the enable the repeatability of the wavemaker to be verified.

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3. PIV

An in depth explanation of PIV is not going to be undertaken in this paper as it has been covered many times before [3]. However there are recent improvements made to the technique that have increased its versatility, which will be outlined here.

Image shifting overcomes the problems that PIV has with measuring multi-directional flows or flows that have a large dynamic range of velocities (for a detailed description see Morrison[6]). The PIV image is obtained through the reflection in a rotating mirror which imparts a constant shift to all the velocities in the flow. It has the effect (when optimised) to shift all the velocities into the range measurable with PIV. The velocity imparted can be removed after the analysis stage, leaving the original flow velocities. There is an added complication, due to the fact that there are differing optical path lengths to the various parts of the mirror, (and hence to the flow region) meaning that the shift velocity is not exactly uniform over the whole flow. However averaging many velocity maps recorded in still water gives the full-field shifting velocity map, which can be subtracted from all measurements.

The use of a high resolution CCD camera for image acquisition has many advantages over the previously used photographic film method. Obviously the primary advantage is the saving in time on the analysis which is done digitally on a PC. Using very large CCD array sizes, however, does create very large image files which fill memory up very quickly. The memory on the frame grabber used in this research was extended to 32mb so that a maximum of seven sequential pictures could be taken, limited only by the frame rate of the camera.

Image analysis is done digitally using an auto-correlation routine which yields the magnitude and direction of the velocity within small areas of the image.

4. Experiments

Both deep water and beach waves were investigated. Four different types of deep water breaker were used, ranging from severe plunging to gently spilling. For the beach experiments a 1:20 beach was built into the flume. Due to the nature of the wavemaker paddle a solitary wave breaking on the beach due to shoaling was not feasible. Therefore the beach waves used broke due to a combination of focusing and shoaling. This was not a huge problem, because the main objective was to see how the shallow water affected the turbulence structures present.

Images of the flow were captured beginning from approximately 3 seconds after the initial breaking event. This was the earliest that the flow could realistically be studied, due to the large amount of aeration that is caused by the breaking. The triggering of the camera was controlled by an external pulse from the wavemaking software which triggered the image-shifter, which in turn triggered the camera at the precise moment the mirror has rotated to an angle of 45° to the line of the flume. The choice of shift velocity was dictated by a number criteria. Firstly the limitation that the same shift had to be used for all images acquired in one sequence, meant that it had to be of a sufficient velocity to shift the earliest flow field into the analysable range of velocities. It is however generally advantageous to use as small a shift as possible, so the loss of resolution is kept to a minimum.

For each different wave used in this experiment a number of different positions of the camera were used in order to cover the full extent of the turbulence and vorticity produced by breaking, which was generally spread over quite a large area. This tends to be split into distinct separate patches of turbulence, which become more merged together as the wave goes from plunging to spilling.

5. Results

Figures 1-6 show vorticity information, on the same scale, derived from a sequence of PIV velocity fields obtained after breaking. These show the evolution of a dominant vortex patch which appears to consist of two counter rotating vortices. The vorticity is shown to be concentrated and fairly focussed soon after breaking. The patch becomes visibly weaker, deepens slightly and occupies a slightly larger area. A notable feature

is that the structures do not seem to translate significantly across the flow. The area shown in these plots are about 60cm wide and 50cm deep.

The vorticity maps give a visual representation of the post-breaking flow, showing a number of significant features. However, in order to make comparisons with the results of other experimenters it was necessary to compute more detailed properties of the turbulence.

The wavenumber spectra for the turbulent velocities obtained at two different times 4s and 17s after breaking are shown in figure 7. The information is shown on a log/log plot with a k^{-3} and a $k^{-5/3}$ line shown for comparison. This can be related to theories on 2-d and 3-d turbulence originally conjectured by Kraichnen [8] and further reviewed by Kraichnen and Montgomery [7] and Lesieur [10]. The proposed slope of the wavenumber spectrum for two-dimensional turbulence is k^{-3} . This seems to suggest that after breaking the flow is dominated by two-dimensional turbulence which decays to three-dimensional turbulence as the structures become smaller and less coherent. This is supports the work of Lemmin and George *et al* [9, 11], who also note this spectral change.

The flow measured using PIV cannot be said to be a solely turbulent flow, as it contains a mixture of mean and turbulent components. A simple method of local averaging was used in order to separate out these two components. Each velocity point was averaged using the nearby velocities, with this average then subtracted from the central velocity value. All turbulent information was obtained using this method.

Figure 8 shows the decay of turbulent energy with time for a deep water post breaking field averaged over four repeats. This is shown for two separate positions after breaking, position 2 being closer to the breaking point. The reciprocal of the mean square turbulence level at position 2 appears to decay approximately in proportion to time. This is analogous to the way in which grid generated turbulence decays with the distance behind the grid. Position 1 does not show such a decay relationship, probably because it is close to breaking where the structures are moving forward more than at subsequent positions, hence leading to a significant flow of turbulent energy out of the region.

Figures 9 and 10 show some examples of turbulent energy depth profiles, averaged across each line of velocities at each depth for a deep water breaker and a beach wave. The essential features of the two cases are that in deep water there is a strong decay of the turbulence level with depth, whereas the turbulence in the beach case is spread out more evenly, with only a slight decay with depth. The two instances in figure 9 correspond to the vorticity plots shown in figures 1 and 2. The spike in turbulence between 20 and 30cm depth clearly falls from the first instant to the second.

6. Conclusions

PIV has been effectively applied to the complex turbulent flow generated by breaking waves, producing a visual representation of the structures and the way in which they decay and dissipate. The characterisation of the turbulence in order to make direct comparisons with the work of others has been attempted and early results suggest a good agreement. Further analysis to examine the mixing process in more depth is planned for both the deep and beach waves.

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Figure 1: Vorticity at T=3.125s.



Figure 3: Vorticity at T=4.625s.



Figure 5: Vorticity at T=6.125s.

Figure 2: Vorticity at T=3.875s.



Figure 4: Vorticity at T=5.375s.



Figure 6: Vorticity at T=7.625s.









Energy depth profiles-deep water