# Turbulence at the free surface

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## *Introduction*

Strong turbulence occurs at the free surface, after waves have broken, at the front of moving bodies with bluff bows, and in numerous other situations. A semi-quantitative descriptive review with discussion of the factors that may determine the nature of the surface disturbances is given by Brocchini & Peregrine (2001a), referred to as BP1. The paper makes evident a lack of both detailed experimental measurements and a framework in which to interpret them. Brocchini & Peregrine (2001b), BP2, follow this up with an account of averaged equations and discussion of the properties of the foot of a breaker. In this context many different averaged terms appear, and again it is hard to estimate their relative importance because of the paucity of measurements.

Here we report on initial work in a project on the title topic, abbreviated to TAFS, at the Universities of Bristol and Southampton, which is to develop the ideas of BP1 and BP2. A full range of problems is being considered from the fundamental processes whereby vorticity enters the liquid at the surface in high Reynolds number flows to the behaviour of the whole turbulent region in breakers etc. Theoretical, numerical and experimental methods are being used. Some of our avenues of approach are discussed below.

## *Standard flows*

In other studies of turbulence there are “standard" flows for which experimental measurements have been influential in the development of concepts and semi-empirical models, such as boundary layers, mixing layers and fully turbulent flow near a wall. Such flows have yet to be defined for free-surface turbulence, though there is one obvious candidate: the hydraulic jump. This has the advantage that its overall properties can be easily modelled, although we know its internal flow can depend strongly on the structure of the incoming flow.

Figure 1. Flow near the crest of a weir.
(Murzyn DSCN1432)

Peregrine & Svendsen (1978) extended this concept by including the hydraulic jump in a 'spectrum of quasi-steady breaking flows'. Amongst other flows, this includes flow down a weir: an example is shown in figure 1. As may be seen this flow is not a traditional hydraulic jump because of the slope of the bed. It is much closer to being a 'scar' on the free surface, which is a common sight around the edge of upwelling eddies. The foot of the flow is the obvious place for generation of turbulence and initial air entrainment. However, the photograph also shows other sharp downward lines of minor scars which can have the same effect. Measurements have commenced on flows of this type, where slight differences in the incoming water's speed can make significant changes in the free surface. A slower flow gives no air entrainment. As can be seen the flow in figure 1 is marginal for air entrainment, which increases rapidly with water speed. The measurements are being related to BP1's diagrams of turbulent velocity against length scales to assess the hypothesis that these two parameters can usefully categorise TAFS. We have yet to investigate how to quantify a "standard scar" but at least this flow is easy to set up and replicate.

Another example is flow in front of a bluff body. A laboratory example is seen in figure 2. Here the subsidiary scars on the surface are easily seen. Preliminary experiments with this type of flow, and with "two-dimensional floating bodies" indicated a surprising sensitivity to the approaching flow velocity. This may be related to the depth of submergence of the obstacle. Again there is a wide range of parameters to be investigated. Workshop members may wish to discuss priorities.

Figure 2.Flow in front of a circular cylinder.

*Fundamentals 1: vorticity*

Dabiri & Gharib (1997) and Sheridan et al. (1997), for example, give PIV diagrams with vorticity arising from the free surface, but unfortunately with no surface measurements. However, it seems reasonable to consider this as development of the vortex shedding from a curved surface discussed by Longuet-Higgins (1998) and earlier. Jeong and Moffatt's (1992) solution of Stokes flow shows that cusps, or near-cusps, can form. Any asymmetry at a cusp will lead to vorticity streaming into the fluid. This is the essence of a scar at its smallest scale. Eggers (2002) goes further and indicates how the presence of air modifies such a flow and can lead to air entrainment. [Note J.Eggers will be joining the group in Bristol in July 2003.] Although most of our study to date has ignored the dynamic effect of air, Eggers's result suggests that we need to consider it, since it could make a significant alteration to the zero surface stress result in some cases due to increased air pressure.

In general turbulence studies, direct numerical simulation (DNS) is making a useful contribution to understanding turbulent flows. There are some examples of free-surface DNS that appear to model breakers and turbulent flows, but they mostly aim to model the largest scale of motions without full resolution of capillary and viscous effects. We are therefore trying to look at the 'smallest breaker' that generates turbulence as a more suitable starting point for DNS. For shallow water breaking, experiments with water of only several millimetres depth, this means that Reynolds numbers are generally not more than 1000 and thus within the scope of DNS. Using a suspension of tiny aluminium flakes for flow visualisation gives results such as shown in figure 3.

Figure 3. Flow visualisation of a “smallest breaker” in shallow water, the wave moves to the right, the water depth is approximately 7mm.

It seems that a shear layer separates from the trough of the steepest part of the wave, and is almost two-dimensional at first. The shear layer, being unstable, develops turbulent eddies that reach the surface well back from the crest. Some unsteadiness is needed to create this. In figure 3 the vorticity is shed from the steepest of the capillary wave troughs. A slightly stronger wave gives less capillary waves and has a body of water travelling with the wave held back by a meniscus. A simple analytical version of the free surface, with a cusp for commencing the shear layer, is shown in figure 4, and a flow that may be a near realisation of this model is shown in figure 5. We intend to use these as starting points for DNS, then work to higher and stronger breakers.

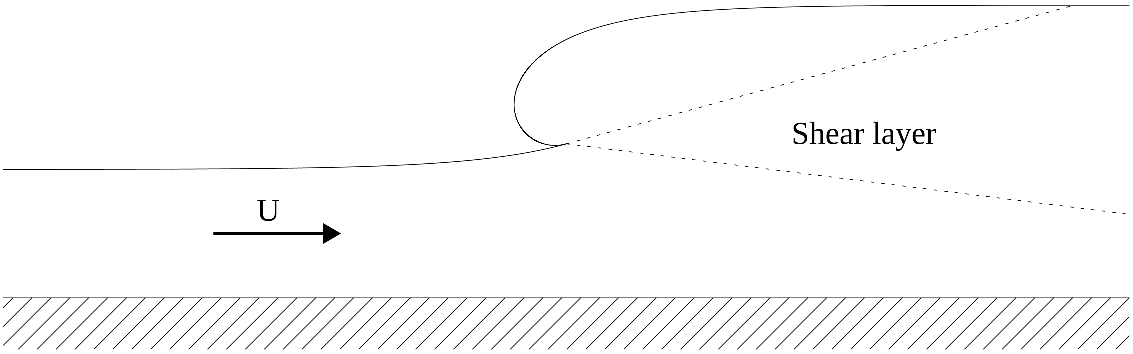

Figure 4. A static meniscus touching an evanescent wave calculated for the appropriate water depth and speed, modelling a breaker creating a shear layer.

Figure 5. Another small 'breaker', moving to the right.

These tiny waves may seem to be of purely academic interest. However, the effects of surface tension are sufficient to avoid any air entrainment for breakers of heights as big as 5 cm. Such ‘microbreakers’ are ubiquitous on the surface of oceans, seas and lakes and an essential component in transfer of heat and mass between ocean and atmosphere.

### *Fundamentals 2: bubbles and drops*

As already mentioned air entrainment can occur by air being dragged into the water at a scar or cusp-like flow, but there are other mechanisms which are more important for larger scales. Just as a plunging breaker traps air, any folding over of the surface can do so. Similarly, projections from the surface can break off into drops. Such events occur on short time scales such that viscosity is much less important and useful insight is expected from inviscid studies. At the simplest, an irrotational flow solver is being used with the turbulent eddies modelled by submerged singularities in forced motion. Although this can not give realistic motions, it should permit greater understanding of the competing effects of gravity and surface tension for differing length scales and strength of motions.

### *Large-scale effects*

Our measurement programme to give data relevant to statistical properties is only now commencing. One of the main features to be investigated is the foot of breakers which can reasonably be considered to be the primary source of their turbulence. BP2 argues that the mean surface flow and mean height of the surface layer at the foot are suitable parameters for modelling that turbulent source. In some ways the model of figure 4 shows relevant features. It represents a static region of water held up by a mensicus, and the detailed analysis gives the strength of the shear layer arising from the incoming flow. hence the initial growth of the shear layer can be simply modelled. In the high Reynolds number examples, say like figure 2 and larger, we need to consider a similar shear layer, but one can only entrain a limited amount of water on its upper side. In addition the flow may depend on the scale and strength of turbulence affecting the air content of the surface layer.

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Brocchini, M & Peregrine D.H. (2001) The dynamics of strong turbulence at free surfaces. Part 1. Description. *J.Fluid Mech.* **449**, 225-254.

Brocchini, M & Peregrine D.H. (2001) The dynamics of strong turbulence at free surfaces. Part 2. The boundary conditions. *J.Fluid Mech.* **449**, 255-290.

Dabiri, D. & Gharib,M. 1997 Experimental investigation of the vorticity generation within a spilling water wave, *J.Fluid Mech.* **330**, 113 - 139.

Eggers, J. 2001 Air entrainment through free surface cusps. *Phys. Rev. Lett.* **86,** 4290-93

Jeong, J.-T. & Moffatt, H.K. (1992) Free-surface cusps associated with flow at low Reynolds number, *J.Fluid Mech.* **356**, 1 - 22.

Longuet-Higgins, M.S. 1998 Vorticity and curvature at a free surface, , 149 - 153.

Peregrine, D.H. & Svendsen, L.A. (1978) Spilling breakers, bores and hydraulic jumps, *Proc. 16th Int. Conf. Coastal Engng.* **1,** 540-550.

Sheridan, J., Lin. J.-C. & Rockwell, D. 1997 Flow past a cylinder close to a free surface, *J.Fluid Mech.* **330**, 1 - 30.

**Comment by** : M. Tulin
The model you indicate in Figure 4 looks identical to the model introduced by Cointe & Tulin to describe the breaker above a hydrofoil (JFM 1990). However this model cannot describe the front of a bore. Instead cyclical breaking and large scale vertical motions have been observed in numerical studies.

**Author's reply**:
The diagram in Fig.4 is a sketch of possible initial conditions for studying the time evolution of the flow. It is clear that the flow will be unstable.

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