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Dynamics of large turbulent structures in a steady breaker

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ABSTRACT

The flow near the leading edge of a steady breaker has been studied experimentally using Bubble Image Velocimetry (BIV) with the aim of characterizing the dynamics of the large eddies responsible for air entrainment. It is well reported in the literature, and confirmed by our measurements of the instantaneous velocity field, that this flow shares some important features with the turbulent shear-layer formed between two parallel semi-infinite streams with different velocities. Namely, the formation of a periodic array of coherent vortices, the constant convective velocity of those vortices, the linear relation between their size and their downstream position and the self-similar structure of both mean velocity profiles and Reynolds shear stresses. Nonetheless, important differences exists between the dynamics of the large eddies in a steady breaker and those in a free shear-layer. Particularly, the convective velocity of these large structures is slower in a steady breaker and, consistent with this, their growth rates are larger. A physical interpretation of these differences is provided together with a discussion of their implications. To support our measurements and conclusions, we present a careful analysis of the accuracy of the BIV technique in turbulent flows with large bubbles.

1. Introduction

Turbulent spilling breakers or bores occur in a wide variety of flows relevant to both engineering and environmental applications, such as hydraulic jumps, flow in dam spillways, breaking waves in the ocean or the formation of bubbly wakes in ships. They are, however, far from being fully understood. The key difficulty is that the flow field close to the leading edge, or toe, is not easy to characterize using conventional measurement techniques in fluid mechanics nor is it easy to study using well established analytical or numerical tools. This is particularly true in strong breakers, that is in breakers where a properly defined Froude number is high enough. This paper presents an experimental investigation conducted with the purpose of clarifying several aspects of these complex flows. In particular, a steady breaker configuration has been implemented in our laboratory facility. In such configuration, the breaker remains stationary with respect to the laboratory frame of reference, which facilitates the application of diagnostic techniques and statistical tools. It should be kept in mind that the steadiness of the flow must be understood in a statistical sense, due to its turbulent nature.

A significant amount of knowledge about the flow structure of steady breakers has been gathered in the past. It is commonly accepted that near the leading edge of the breaker, where the high-speed stream impinges into a region of slower and deeper fluid, an unsteady two-dimensional shear-layer forms between the upper (nearly stagnant) and lower (fast) streams. This phenomenon was first described by Peregrine and Svendsen [23], who also pointed out that even in flows where the bottom of the channel is close enough to affect the overall flow field, the initial development of this mixing-layer may be considered to be free from wall effects. This idea was further developed by Hoyt and Sellin [8], who investigated various similarities between the steady breaking in a hydraulic jump and a free mixing-layer between two semi-infinite streams. In their experimental investigation, they used high-speed photographic techniques to show the existence of large coherent structures that grow linearly beneath the free surface. Unfortunately, since they did not measure velocity fields, very little quantitative information could be drawn from their results.

Velocity fields in steady breakers have been obtained experimentally by several authors [26,25,2,4,3,9,17,16]. However, in highly aerated regions, difficulties to obtain precise measurements arise. In an attempt to avoid the difficulties of measuring in two-phase flows, Rouse et al. [26] substituted one of the flat walls of a wind tunnel by a smooth wall reproducing the shape of the free surface of a hydraulic jump. This allowed the researchers to characterize the turbulent velocity field with a hot-wire anemometer.

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However, gravity effects, which are known to be key in any breaker, are neglected in this experiment.

Accurate experimental characterization of the instantaneous velocity field in the shear-layer found in a steady breaker was obtained by Lin and Rockwell [10] from PIV measurements. This technique allowed them to clearly identify large coherent structures developing between the lower, high-speed stream and the upper, slow-moving body of fluid. Svendsen et al. [28] used laser Doppler anemometry to characterize the mean velocity field and the Reynolds stresses in a steady breaker. They obtained mean velocity and shear stress profiles that clearly showed the existence of a shear-layer. More recently Liu et al. [11] used Doppler ultrasound velocimetry to characterize the turbulent stresses in low Froude number hydraulic jumps, where the void fraction is small enough for this technique to operate properly. These authors found the maximum Reynolds stress at the center line of the mixing-layer, where the turbulent intensities were greater than 20%. Interestingly, they also suggested that these shear stresses exhibit a self-similar profile. Misra et al. [17] also investigated the structure of the shear-layer in a weak hydraulic jump and measured a number of parameters of the shear-layer that further support the analogy of this flow with homogeneous free shear-layers.

The location of the mean free surface and its fluctuations in this type of flows, as well as the role that the turbulent structures have on it, has been studied under different conditions [18,22,20]. Experimental observations reveal that in strong turbulent breakers (such as those found in large hydraulic jumps) the collapse of the free surface is the leading mechanism of air entrainment. Misra et al. [17] tried to quantify the air entrainment along the whole length of a weak hydraulic jump, with a Froude number of 1.19, using the fluctuations of the free surface. They observed that, in the region occupied by the hydraulic jump, the free surface exhibits large fluctuations that may be associated with the entrapment of air cavities. However, this result does not explain the precise physical mechanisms that lead to the collapse of the free surface and the resulting air entrainment.

Despite of all the available knowledge on turbulent breakers, there are several key aspects that are poorly understood. One of the most important in terms of both fundamental scientific understanding and technological application, is the mechanism by which air bubbles are entrained underneath the free surface. A significant fraction of the total air amount entrained by the breaker is known to occur at the leading edge [3,21], where the flow separation occurs, which is consistent with the flow structure proposed by Longuet-Higgins and Turner [13] and Cointe and Tulin [4] among others. This mechanism is particularly important in weak breakers. However, as the breaker becomes stronger, the air entrainment occurs all along the length of the breaker rather than being localized at the toe, although part of the entrainment still occurs at that location. The large coherent structures that develop in the shear-layer are energetic enough to produce overturning at the free surface, thus entrapping air cavities that are then broken up into smaller bubbles by the ambient turbulence [12,19,20].

As the large coherent structures occurring in the shear-layer are ultimately responsible for the collapse of the free surface and the subsequent entrapment of air cavities, it seems logical that any accurate model of air entrainment should be based on the knowledge of the dynamics of these large vortices. This is precisely the aim of this paper, to experimentally characterize a number of features describing the behavior of these structures, relating them to global parameters of the overall flow. Moreover, by studying the structure of the mean velocity field we describe some similarities and differences between the turbulent structures found in this flow and in free plane turbulent mixing-layers. A deep water, weak Froude number (1.4–2.3) hydraulic jump set-up was chosen as a convenient way to generate a steady breaker in the laboratory. Since our work focuses on the dynamics of the flow near the leading edge, where the bottom effects are negligible [23], most conclusions of this investigation are of general nature, in that they can be applied to natural flows that share the same characteristics, such as spilling breakers or turbulent bores. This study could also be of interest to quantify certain aspects of man-made flows such as that found at a ship stern.

The paper is organized as follows: Section 2 describes the experimental set-up and the postprocessing techniques used to analyze the flow. The experimental results are presented in Section 3. Interpretation and discussion of the results is done in Section 4. Finally, Section 5 summarizes the main conclusions from this study.

2. Experimental set-up

The experiments were carried out in a recirculating water channel with a capacity of roughly five cubic meters. The test section was 2 m long and had a square cross section of 0.6 m $\times$ 0.6 m. The plenum was connected to the test section by a series of grids and honeycombs, followed by a contraction, to assure that fluctuations originating at the pump are damped out before the flow reached the test section. The underlying turbulent intensity of the free stream measured from previous experiments [1] was very low, less than 0.5%.

A plexiglass plate was cut to dimensions 0.6 m $\times$ 0.0127 m $\times$ 1 m and placed vertically across the test section of the water channel. An auxiliary horizontal plate was fixed to the upstream-looking side of the vertical plate at a shallow depth under the free surface (about 5 cm), as is sketched in Fig. 1. In this way, the surface oscillations and spurious bubbles entrained upstream of the region of interest were avoided. Once positioned inside the test section, the vertical flat plate extended through the entire width of the test section, from a distance of about 0.2 m (depending on the experimental session) from the bottom of the channel to well above the free surface. The end of the vertical plate that induced the hydraulic jump was machined to a sharp edge so that the free stream detaches cleanly from the gate without any possible boundary layer growth that would perturb the experiment and hinder its reproducibility. A sketch of the facility and the flow, are shown in Fig. 1.

The gate aperture together with the flow rate were used to vary the upstream flow velocity and water depth at the toe of the jump. For each experimental session, the free stream velocity was measured using a pitot tube. The tube was mounted on a rail system that allowed its displacement in the three directions with a positioning accuracy of 0.5 mm. It must be pointed out that the velocity of the free stream was measured at different locations downstream of the gate under the region of interest to check that it remained constant, thus allowing us to discard any possible effect of the bottom in the dynamics of the large coherent structures. More specifically, we checked that the thickness of the boundary layer at the bottom of the test section was always smaller than 1 cm under the toe.

2.1. Computation of the velocity fields and associated turbulent magnitudes

Light scattered by the air bubbles entrained by the flow was captured by a Kodak ES 1.0 (1 Mpixel) digital camera at 180° collection angle (first mode reflection). Illumination was provided by a strobe light positioned nearly coaxial with the optical axis of the camera. The camera was focused in a vertical plane aligned with the mean direction of the flow and located about 10 cm from the channel walls. Since the duration of the strobe light is extre-