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Dynamic structures of a submerged jet interacting with a free surface

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ABSTRACT

The spatial structures of a submerged jet interacting with a free surface were examined experimentally. The time-resolved PIV technique was used for the quantitative measurements. Two Reynolds numbers (1920, 3480) were examined for a configuration, in which the depth of the jet beneath the free surface was fixed to $H = 2D$. The dynamics of the flow structures were examined further using the space–time proper orthogonal decomposition (POD) analysis technique. Some common characteristics were found in both jet flows, which are believed to be the general features of the free-surface jet flows. On the other hand, the dynamic characteristics of the large-scale turbulent motions differed significantly with respect to the Reynolds number. In the low Reynolds number case, three dominant dynamic structures were found: flapping motion of the jet, very large scale vortical structure interacting with the free surface at the right side, and the transverse stretching of large scale structure due to the presence of free surface. The reconstructed fluctuating velocity fields and the swirling strength contours demonstrated that the very large scale structures began to move downward at about 10*D* downstream the initial interaction. In the high Reynolds number case, the first two dominant spatial modes showed the momentum exchange process between the jet flow and the free surface. The third mode displayed a vortex just below the free surface at the left side and the fourth mode showed the elongated vortex structures. The scale of vortical structures was much smaller in the high Reynolds number case than that in the low Reynolds case, and the downward motion of large scale structures was not found in the high Reynolds number case.

1. Introduction

The interaction between turbulent flow and a free surface has attracted considerable attention in recent years. Much of this interest has come as a result of the recent advances in remote sensing technology. In particular, the synthetic aperture radar method can detect the free surface disturbances created by a ships' turbulent wake [17,18]. This research topic also has many other applications, such as discharging wastewater into a shallow body of water, where an understanding of the turbulent structure is essential for optimizing the discharge characteristics. On the other hand, due to the great complexity and variety of the phenomena observed, there is a lack of understanding of the nature of the interaction of turbulent shear flow, such as a ship's wake, with a free surface. The interaction of a jet flow with a free surface is a simple and typical flow configuration, which contains many of the vortical interactions in the problem of turbulent shear flow interacting with a free surface. Thus far, an experimental study on a submerged jet interacting with a free surface is needed to obtain a comprehensive understanding of this problem.

Evans [6] reported the earliest results of an investigation of the interactions of a jet flow with a free surface. He revealed the calming effect on surface waves caused by the surface currents produced by the jet. Although Evans did not examine the turbulent flow structures in detail, he showed that when the waves and surface currents move in the same direction, the wave amplitude is decreased but the wavelength is increased. Rajaratnam and Humphries [15] examined the scaling behavior of the mean flow field of turbulent, non-buoyant surface jets, and Rajaratnam and

Abbreviations: D, Nozzle diameter; H, depth to jet axis; L, length of pipe; M, ensemble size of POD dataset; $R_{1/e}$, jet width up to 1/e of the centerline velocity on the cross-section; u, streamwise velocity; U'_{rms}, root-mean-square streamwise velocity fluctuation; U_0, exit velocity; U_c, local centerline velocity; V, vertical velocity; X, streamwise coordinate; Y, vertical coordinate; Z, transverse coordinate; λ_{ci}, swirling strength; FOV, field-of-view; LDV, laser doppler velocimetry; LIF, laser induced fluorescence; PIV, particle image velocimetry; POD, proper orthogonal decomposition.

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Subramanyan [16] investigated the behavior of planar buoyant surface jets. Swean et al. [24] reported the measurements of the mean velocities and turbulent fluctuations in a two-dimensional turbulent jet at a free surface. They found that the growth rates of the length and velocity scales resemble more closely those observed in wall jets than those in free jets. Bernal and Kwon [4], who examined the vortex-ring problem, provided the first convincing evidence that a vortex tube will disconnect in the vicinity of the surface and reconnect to the surface. Subsequent important studies by Gharib and Weigand [7] on the interaction of a vortex ring with a free surface revealed the stages involved in the early disconnection and subsequent connection process.

Anthony and Willmarth [2] examined the mean velocity field and Reynolds stress tensor of a turbulent jet issuing from a circular nozzle beneath and parallel to the free surface using a three-component LDV. They reported that the turbulent fluctuations normal to the free surface were diminished, whereas those parallel to the surface were enhanced. They also reported the existence of a flow outward, away from the jet axis in a thin layer near the surface. Based on the flow visualization results, they showed that this outward flow or 'surface current' consisted mainly of vortical structures ejected from the jet. Within the surface current, turbulent mixing was reduced greatly. Madnia and Bernal [14] examined the same flow over a wide range of Reynolds and Froude numbers using flow visualization and single-component hot-film measurements. Using the shadowgraph method, they reported that significant surface disturbances occurred, where the large-scale structures in the jet first interact with the free surface. These surface disturbances form approximately planar waves with a symmetrical pattern. They also noted

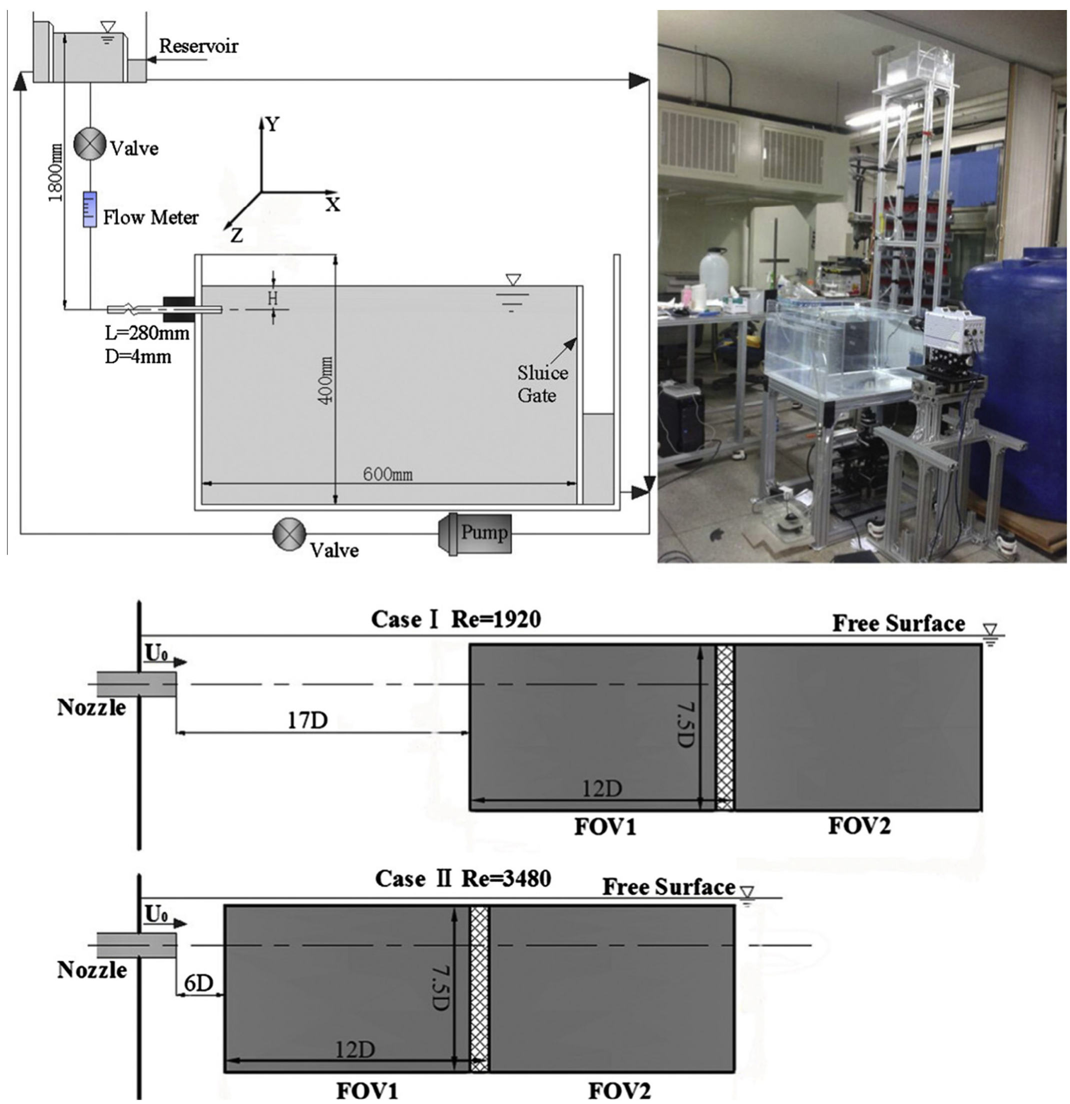

Fig. 1. Schematic diagram and photo of the experimental setup. Coordinate system and detail dimensions of measurement sections of the time-resolved PIV are indicated.

Table 1
Experimental conditions.

Exit diameter D (mm), U_0 (m/s)	Exit velocity	$Re = U_0d/\upsilon$	$Fr = U_0/(gD)^{1/2}$ H/D	Depth to jet axis
4	0.48	1920	2.42	
4	0.87	3480	4.42	