Numerical Simulation of Nonlinear Wave Interactions with Linearly Sheared Currents

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ABSTRACT
A numerical investigation of nonlinear wave interactions with approximately linearly sheared currents is presented. The numerical model is based on the Navier-Stokes Solver, and the Volume of Fluid method is applied to capture the water wave surface. The numerical model is validated with the experimental measurements in the case of a uniform current and a linearly sheared current. The effects of wave nonlinearity and current shear on the water surface profiles are examined. It was found that in the presence of the current shear, the wave crests are sharper and troughs flatter for the following current; while for the opposing current, the troughs tend to be deeper. The effect is more pronounced when the wave steepness increases.

KEY WORDS: Wave-current interaction; CFD; linearly sheared currents; nonlinear waves; current shear.

INTRODUCTION
Waves and currents coexist in most marine environments. The interactions between these flows have been studied for decades, both theoretically and experimentally. The review articles by Peregrine and Jonsson (1983), Jonsson (1990) and Thomas and Klopman (1997) document well the previous studies on this topic.

Waves traveling over currents experience a modulation in their kinematics. In the simplest case involving a current which is uniform with depth, the Doppler shift (Fenton, 1985) is a common concept to explain such modulations in wave dispersion and the associated water particle kinematics. When the current profile is not uniform and has some weak or strong shear across the water depth, the resulting wave motions become more complex. Several studies (Thomas 1981, 1990; Swan, 1990; Swan, Cummins and James, 2001) have established the importance of the current shear, or vorticity, in affecting the wave kinematics and water surface elevations.

In the past few decades, some weakly nonlinear analytical solutions (Tsao, 1959; Kishida and Sobey, 1988) have been obtained for a linearly sheared current, and it’s shown that the current shear produces changes in the water surface elevation. Nonlinear inviscid numerical models, e.g. Dalrymple (1974) and Thomas (1990), have also been proposed for weakly and strongly sheared current. The approach by Dalrymple (1974) divides the water column into a number of discrete layers, approximating the current in each layer by a linear shear, and uses a Fourier series expansion of the stream function to represent the resulting wave form.

Most of the early experimental studies (Brevik, 1980; Kemp and Simons 1982, 1983; Umeyama 2005, 2009) have considered waves on a uniform current. In perhaps the most detailed investigation of current shear effect, Swan, Cummins and James (2001) studied two-dimensional surface water waves propagating on depth-varying currents. In the case of a following sheared current, it was observed that the water-particle velocities arising beneath a wave crest were substantially larger than those predicted by an irrotational wave-only solution.

Recently, Li, Troch and Rouck (2007) presented a Volume of Fluid (VOF) based flow solver using a finite-volume scheme and the sub-grid scale (SGS) turbulence model for the interactions between breaking waves and the current over a cut-cell grid. In the case of waves following the current, an external generator combining the inflow motions of the waves and the current is applied at the inflow boundary. In the case of waves in an opposing current, an internal generator is used to describe the opposing current by adding source functions in the mass and the momentum equations. The RANS-VOF method solves the Reynolds-Averaged Navier-Stokes (RANS) equations, on a fixed mesh and uses the VOF method to capture the free surface. Zhang et al. (2014a, 2014b) applied a RANS-VOF solver to study the solitary wave propagation in the presence of a steady current.

Most studies using RANS models, e.g. Li, Troch and Rouck (2007), Peng, Ma and Gu (2014), Zhang et al. (2014a, 2014b), have focused on waves interacting with a uniform current. Markus et al. (2013a, 2013b) used RANS-VOF to study the loading of waves and depth-varying currents on structures.