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Modal and nonmodal growth of three dimensional perturbations in a shear flow with a free surface

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Shear flows under a free surface arise naturally at the surface of the ocean like at the crest of a spilling breaker, in viscous ship wakes and in wind-drift currents. These flows typically break into turbulent mixing layers and as a result addressing their stability is important. Previous studies of surface shearing currents addressed the instability of the flow with respect to two dimensional perturbations. However, it is well known that three dimensional perturbations in shear flows can obtain larger growth at finite time. In this work we address modal and nonmodal growth of three-dimensional perturbations in a shear flow with a free surface for a wide range of Froude numbers. By approximating the mean flow with a piecewise linear profile, the modal instabilities are shown to arise from the interaction of three-dimensional vorticity and gravity edge waves supported at the interfaces of density and vorticity discontinuity respectively. The mechanism and properties of the instability are explained in terms of the dynamics of the edge-wave interactions. Robust nonmodal transient growth of perturbations within a few advective time units is also found. For low Froude numbers, three-dimensional perturbations with small horizontal scales exhibit the largest growth through a synergy between the Orr and the lift-up mechanisms and produce large streamwise streaks in the interior of the shear flow without affecting the surface. For large Froude numbers, planar perturbations with larger horizontal scales exhibit the largest energy growth by effectively instigating the modal instability and excite surface waves at large amplitude.