The Effects of Initial Conditions on Single- and Two-mode Rayleigh-Taylor Instability

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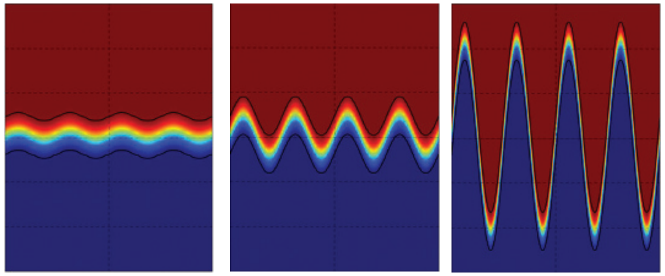
The dependence on initial conditions of single- and two-mode RTI is investigated using DNS. The single-mode RTI results compare well to the linear stability analysis, analytical prediction of Goncharov [1], and experimental results of Waddell et al. [2]. A new stage, chaotic development, was found at very late time of single-mode RTI, after the re-acceleration stage. Details of the shape of the initial perturbation, such as the diffusion thickness and perturbation amplitude, have a strong effect on the growth rate during early and late time development, but a minimal effect during the potential flow regime, such that the Goncharov "terminal velocity" result remains robust. At very late time, single-mode RTI transitions into a chaotic development stage, with strong sensitivity to initial conditions. We also studied the effect of initial conditions on two-mode RTI, and found that growth is strongly affected by the combination of mode numbers and amplitudes, as well as the phase shift between modes. At late times, motions become quite complicated, however some new phenomena, such as "leaning," "ejection," and "mode resonance" can be identified as significantly influencing the growth rate.

Rayleigh-Taylor instability (RTI) is an interfacial instability that occurs when a high-density fluid is accelerated or supported against gravity by a low-density fluid. This instability is of fundamental importance in a multitude of applications, ranging from fluidized beds, oceans and atmosphere, to inertial confinement fusion (ICF) and supernovae. In this work we use direct numerical simulation (DNS) to study the effects of initial conditions on single- and two-mode RTI.

All simulations presented here are 2D and were performed with the CFDNS code. For numerical details refer to [3]. We have carried out extensive resolution studies to ensure that the solution was converged. The 2D perturbations were initialized as sine waves. The simulation results show excellent agreement with linear stability theory (LST), the analytical predictions of Goncharov [1], and the experimental results of Waddell et al.[2].

Fig. 1. Initial density contours of single-mode RTI with different initial conditions. From left to right: Case R02–initial diffusion layer thickness larger than initial perturbation thickness. Case R1–initial diffusion layer thickness about the same as initial perturbation thickness. Case R5–initial diffusion layer thickness much smaller than initial perturbation thickness.



The development of single-mode RTI can be divided into a number of stages. First, for finite Schmidt (Sc) and Reynolds (Re) numbers, if the perturbation amplitude is very small and the interface sharp enough, the initial development can be described by the pure diffusion equation. As the amplitude of the perturbation increases, buoyancy starts to dominate the pure diffusion effects and the mixing layer width grows exponentially following LST. Next, the nonlinear effects become important; however, the flow at the tip at the bubble remains potential. Goncharov [1] showed that, in this case, the bubble tip moves with constant velocity and, since the vorticity remains zero at the tip of the bubble due to symmetry, hypothesized that this is a final or "terminal velocity." Nevertheless, even though the vorticity is zero, vortical motions can have nonlocal contributions. Thus, Ramabprabhu et al. [4] found that the bubble tip velocity does not remain terminal, instead the velocity increases again, due to the induced velocity driven by the first vortex pair generated at the interface. They called this new stage the re-acceleration stage. Our simulations confirmed all these previous findings. Furthermore, we found a new stage after the re-acceleration stage. This development stage is characterized by complex interactions of vortex motions and has strong dependence on the initial conditions. We call this new stage the "chaotic development" stage.

The effects of initial conditions on the different stages of single-mode RTI have been studied by simulations with different wavelengths, and different initial diffusion layer and perturbation thicknesses. For example, Fig. 1 shows the density contours of three initial conditions with the same wavelength: R02, R1, and R5. The three cases have the same diffusion layer thickness, but increasing perturbation thickness.

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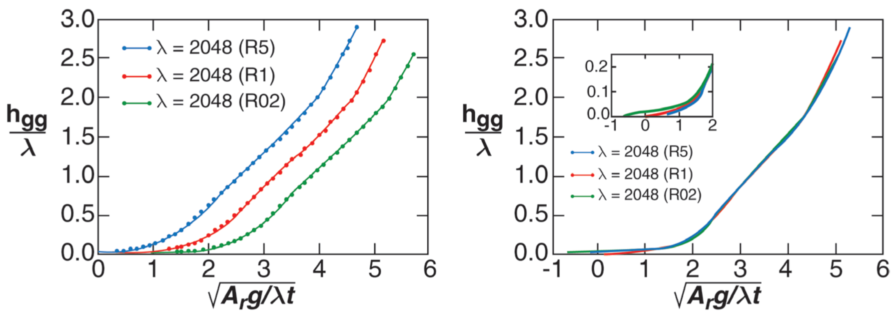

Fig. 2. Left: Evolution of the mixing layer width for the three initial conditions shown in Fig. 1. Right: Time shifted.

The corresponding mixing layer width is shown in Fig. 2. The left panel of Fig. 2 shows that the difference in initial perturbation thickness causes a time shift in the mixing layer development. The right panel of Fig. 2 shows that a proper time shift can collapse the mixing layer width for the three cases, except at very early time and at very late time. At early times, the diffusion growth is sensible to the shape of the interface. The initial conditions have minimal effect during the potential flow regime, such that the Goncharov terminal velocity result remains robust. Interestingly, at very late time, in the chaotic development stage, the development of the mixing layer depends again on the initial conditions. This is because small details of the initial perturbation shape lead to differences in the vortex formation at the interface and can significantly alter the complex vortex interactions.

The mixing layer growth of two-mode RTI is strongly affected by the combination of mode numbers as well as the phase shift between modes. For example, Fig. 3 shows the initial density contours of three different combinations of wave numbers: k2+k10, k3+k9, and k4+k8. The sum of the two modes is the same, and the peaks of the initial perturbation are also the same. The later evolutions of the three cases become very different as shown in Fig. 4. At late times, the motions are quite complicated; however, some new phenomena, such as leaning, ejection and mode resonance, can be identified as significantly influencing the mixing-layer growth. These phenomena are also expected to play a role in the local development of the layer front of multi-mode RTI.

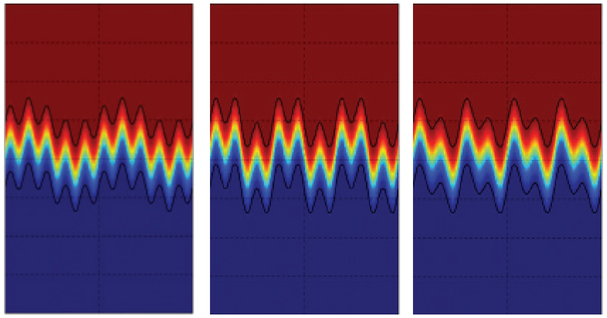

Fig. 3. Initial density contours of two-mode RTI with different mode combinations. From left to right: k2+k10 (wave number 2 and wave number 10); k3+k9; k4+k8.

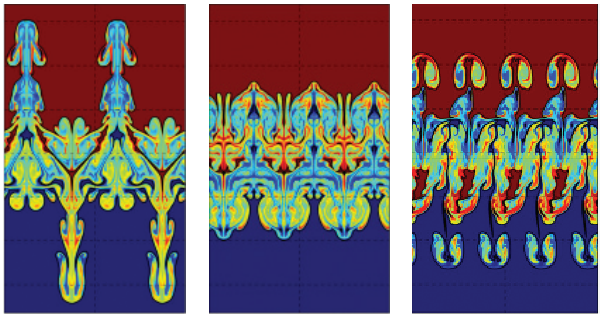

Fig. 4. Evolution of density contour corresponding to the cases shown in Fig. 3.

[1] Goncharov, V.N., *Phys Rev Lett* **88,** 134502 (2002).
[2] Waddell, J.T., et al., *Phys Fluid* **13,** 1263 (2001).
[3] Livescu, D., et al., “CFDNS 1.0,” LA-CC-09-100 (2009).
[4] Ramaprabhu, P., et al., *Phys Rev E* **74,** 066308 (2006).

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