Abstract

In engineering, oscillatory instabilities and resonances are often considered undesirable flow features and measures are taken to avoid them. This may include avoiding certain parametric regions or implementing control and mitigation strategies. However, the examples considered in this thesis illustrate a different perspective: self-sustained or driven flow oscillations can be harnessed in the design of a wide spectrum of engineering devices ranging from microfluidic circuitry, and bioreactors for cell cultivation, to liquid-based templates for assembling microscale materials. The key to an effective design of these fluidic devices lies in having an adequate predictive understanding of the hydrodynamic processes at stake.

Microfluidic oscillators based on interacting jets, sloshing waves and parametric Faraday waves belong to these flows for which time-oscillations, manifesting spontaneously or as a consequence of external forcing, can be seen as beneficial. Although the emergence of an oscillatory response in these systems can be predicted by linear analysis, the observed flow dynamics and features are typically dependent on the oscillation amplitude through nonlinear mechanisms and may deviate from the anticipated patterns due to the interaction of multiple modes.

This thesis uses the tools of global linear stability analysis and asymptotic techniques to provide a comprehensive theoretical framework that can rationalize some of these oscillatory dynamics. To achieve this, the work draws upon direct numerical simulations as well as existing and new dedicated experiments.

In Part I, we describe a microfluidic oscillator based on two laminar impinging jets. After determining the space of control parameters for which self-sustained oscillations appear, linear stability and sensitivity analysis are used to identify a shear instability located in the jet's interaction region, as the main candidate for the emergence of the oscillatory regime. Further nonlinear features are also described by means of the multiple-scales weakly nonlinear theory.

In Part II, we study the harmonic and super-harmonic resonant sloshing dynamics in orbitally-shaken cylindrical reservoirs. We develop amplitude equations models capable of predicting the wave amplitude saturation and wave patterns associated with various wave regimes, such as planar, irregular, swirling and counter-swirling motions, experimentally under elliptic-like shaking conditions.

In Part III, we consider parametric Faraday waves in two different configurations, which are linked to each other for the importance of the sidewall boundary conditions. First, we describe the weakly nonlinear coupling of sub-harmonic parametric waves and harmonic capillary waves produced by an axisymmetric oscillating meniscus. Successively, we propose a modified gap-averaged Darcy model for Faraday waves in Hele-Shaw cells that translates into a new damping coefficient, whose complex value is a function of the ratio between the Stokes boundary layer thickness and the cell's gap.

To conclude, in Part IV, we develop a mathematical model based on successive linear eigenmode projections to solve the relaxation dynamics of viscous capillary-gravity waves subjected to an experimentally inspired nonlinear contact line model that accounts for nonlinear Coulomb solid-like friction. We show that each projection eventually induces a rapid loss of total energy in the liquid motion and contributes to its nonlinear damping.

Keywords: oscillations, resonance, forcing, stability, amplitude equations, nonlinear dynamics, microfluidics, sloshing