Hydrodynamic Instability: visualization of traveling waves and related linear and nonlinear evolution stages.

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Introduction

The *Kelvin-Helmholtz instability* is one of the shear fluid-instability phenomena mostly widespread in nature. In the atmosphere, for instance, this process plays a major role for generation of clear-air turbulence above the troposphere. In the oceans, it affects large-scale currents. Moreover, it is found in plasmas such as the solar photosphere, in planetary magnetospheres and in the heliosphere at the interface between the heliosheath and the local interstellar medium.

In fact, this instability occurs between parallel streams of different velocities and densities. The original theory (1870s) was developed by Lord Kelvin and H. Helmholtz in the framework of neutral, incompressible, inviscid, parallel fluid layers with a net discontinuity of velocity and density. The analytic solution leads to a dispersion relation for the linear stage of evolution for the wavy perturbations. Currently, the *Kelvin-Helmholtz instability* name is broadly adopted for more realistic contexts, where other factors are relevant, among which the viscosity, continuous and nonhomogeneous density profiles, the surface tension, magnetic fields, etc.

It is possible to produce a stratified shear-flow instability under controlled conditions in a laboratory. The experimental facility consists of a long horizontal channel with high aspect ratio. The fluid-containing part of our channel is 192 cm long and has a rectangular cross-section of 10 x 2 cm. The total size is 200x20x4 cm. The apparatus is made of a wooden frame with closed ends, supporting two plexiglass sides. Silicone glue and metallic bands are used to make it watertight. At one end, an inlet tube provides the fluid supply. At the other end, an outlet tube is used for removal of air inside the channel and for draining the liquid after the experiment. The channel is filled from the bottom with two layers of fluids - the upper water (lighter fluid) and the lower solution of water and salt (the denser fluid) – while it is being kept tilted by 45 degrees. One of the two layers is typically colored with dye to visualize the instability. When completely filled, the channel is slowly returned to a horizontal position. Afterwards, the channel is quickly tilted through a small angle (around 10 degrees). A shear flow is then generated at the center of the tank, due to the acceleration of the lower layer which pushes up the lighter layer. The instability arises after few seconds.

Figure 1. Kelvin-Helmholtz instability in the atmosphere. Credits: Pinterest (image subject to copyright)

Expected observations

The students will observe the spatiotemporal evolution of the instability phenomenon, from the basic equilibrium state the transition to turbulence, and critically compare results with existing theories. The following points summarize the expected results, which can be derived by high-quality movies recorded during the experiments.

- **Basic state.** Estimation of the diffusive time scale of the dye; the speed of the two layers of fluid; the time scale of the accelerated flow (comparison with inviscid and viscous laminar models).
- **Stable traveling waves**. Estimation of the phase speed and decay rate of traveling perturbations (gravity waves) in a horizontal channel.
- **Linear stage of Kelvin-Helmholtz waves**. Estimation of the growth rate of the wave amplitude; the phase speed; the wavelength of the most unstable wave. Critical comparison with the Kelvin' s inviscid theory and more recent literature results.
- **Nonlinear stage of Kelvin-Helmholtz waves.** Observation of wave self-interactions; vortex pairing; vortex merging.
- **Transition to turbulence.** Observation of further instabilities and the transition to turbulence. Estimation of spatial and temporal scales of the turbulent eddies.

The students will conduct different experiments to investigate the effect of density stratification between layers, and the effect of the tilting angle.

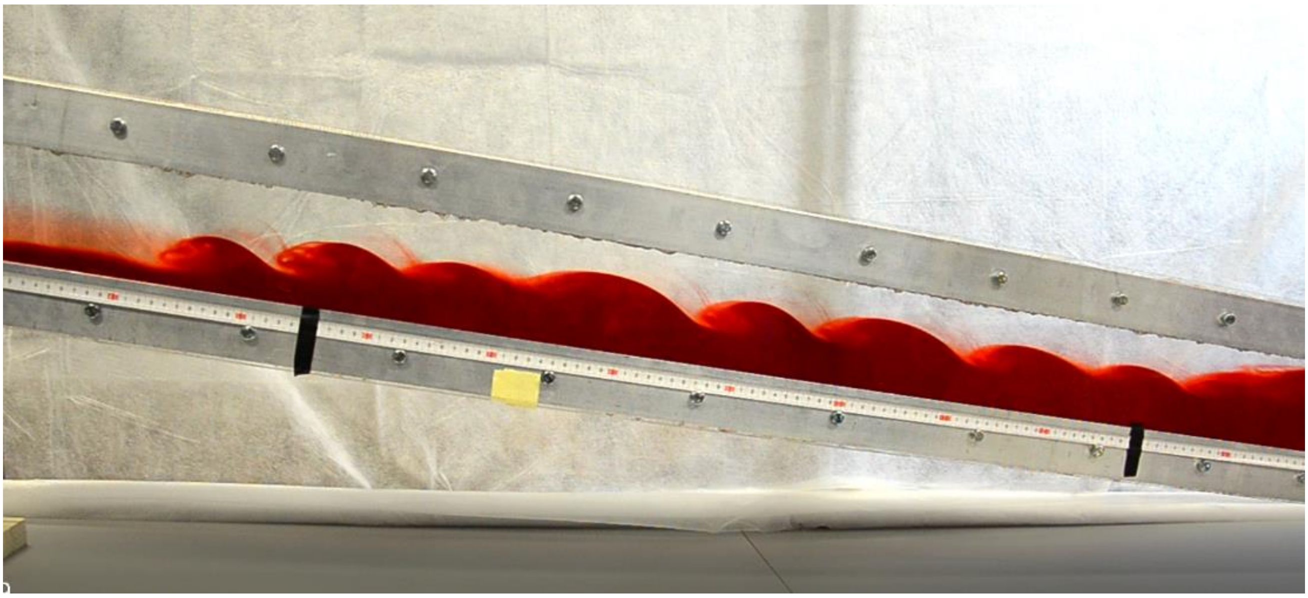

Figure 2. A fluid instability is triggered in our experimental facility, between a layer of brine (10% salt/water solution, red-colored) and a layer of fresh water. A movie of the experiment is available at https://drive.google.com/open?id=1xz5WB57FMXuC3uSHbU4rzLbhLCVaI1yT

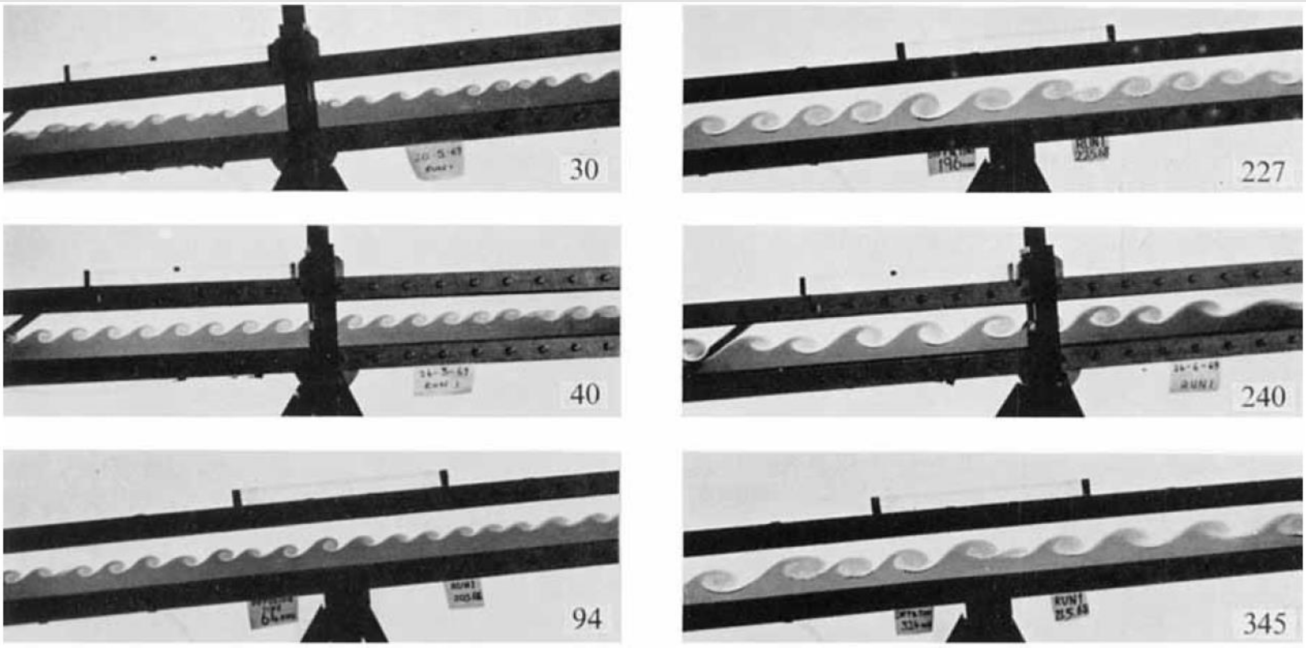

Figure 3. Experiment by S. A. Thorpe, JFM 46, 1971 (Figure 7).

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