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WIND SUSTAINED VISCOUS SOLITONS

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Summary We investigate the generation of wind waves at the surface of a highly viscous liquid. Contrarily to the classical low-viscosity case, we observe the intermittent formation of large localized structures that propagate rapidly downstream, which we call viscous solitons. These strongly nonlinear coherent structures propagate at a velocity given by the balance between the aerodynamic drag in the air and the viscous drag in the liquid. We propose here a model to describe their dynamics based on a subcritical bifurcation governed by the wind shear stress.

INTRODUCTION

When wind blows over water, small disorganized surface deformations, called wrinkles, first appear [1, 2]. These structures, elongated in the direction of the wind, are the random wakes generated by the turbulent pressure fluctuations traveling in the air flow. When the wind velocity is increased above a critical value, these wrinkles evolve into nearly periodic waves propagating in the direction of the wind, with slowly increasing amplitude and wavelength.

This general picture remains unchanged for viscosity up to approximately 100 times the water viscosity. However, for more viscous liquids, the nature of the waves dramatically changes: the initial wave-packet becomes violently unstable and forms a large asymmetrical fluid bump pushed by the wind [3, 4]. While the energy of the disturbance is homogeneously distributed in the low-viscosity case, it is strongly focused in these large bumps at large viscosity. We call these nonlinear objects, first qualitatively described by Francis in 1954 [5], *viscous solitons*. They are illustrated in figure 1 for a liquid of kinematic viscosity $\nu_l = 1000 \text{ mm}^2 \text{ s}^{-1}$ and wind velocity $U_a = 9.6 \text{ m s}^{-1}$. They are typically 2 to 4 mm high, 4 cm in the propagation direction, and 5 to 10 cm in the transverse direction, with a steep rear facing the wind and a weaker slope at the front.

LIFE CYCLE OF VISCOUS SOLITONS

To characterize the viscous solitons, we set up an experiment consisting in a 1.5 m long tank filled with silicon oil of kinematic viscosity $\nu_l = 1000 \text{ mm}^2 \text{ s}^{-1}$, fitted to the bottom of a wind tunnel of rectangular cross-section. Wind is blown at velocity between 0 and 15 m/s, and the depth of the liquid tank h is varied from 20 to 150 mm. The surface deformation is measured by laser sheet profilometry, with a vertical resolution of 0.1 mm.

The life cycle of viscous solitons is characterized using spatio-temporal diagrams, as illustrated in figure 2. Above a critical wind velocity, of the order of 9 m/s, a small-amplitude wave packet of a few wavelengths is first formed at small fetch. This wave packet remains spatially confined but it is temporally unstable (figure 2 (a)): the wave amplitude slowly grows until one of its crests reaches a critical height and rapidly evolves into a viscous soliton. Once formed, the soliton accelerates, leaves the wave packet region, and travels along typically 30-50 cm with constant shape and a slightly decreasing velocity (figure 2 (b)). The initial wave packet disappears after the emission of a soliton, but it reforms after a

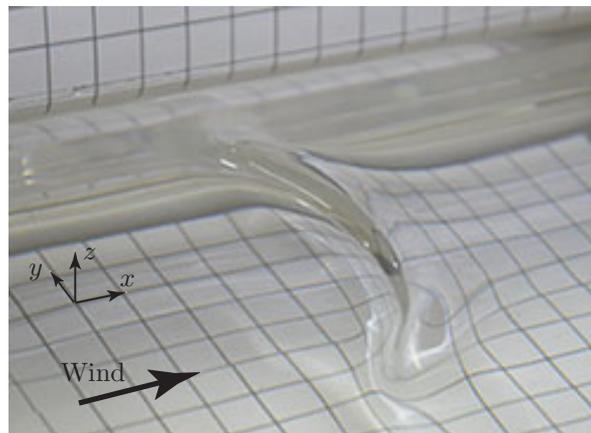


Figure 1: Viscous soliton propagating from left to right, generated by a wind velocity $U_a = 9.6 \text{ m/s}$ at the surface of silicon oil of kinematic viscosity $\nu_l = 1000 \text{ mm}^2 \text{ s}^{-1}$. The size of the grid pattern is 1.3 cm. From Ref. [4].

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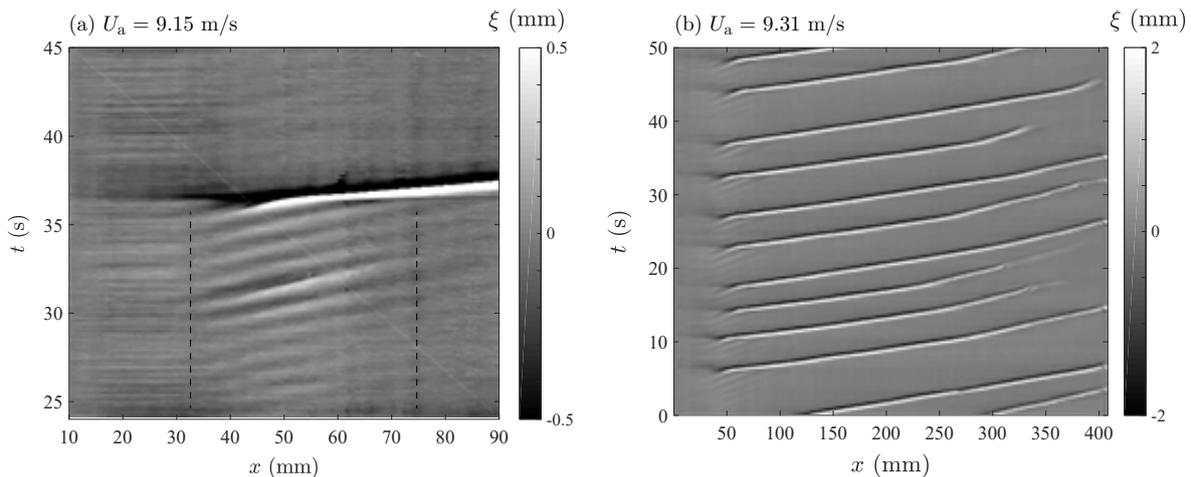


Figure 2: Spatiotemporal diagrams of the surface elevation $\xi(x, t)$ for a liquid depth $h = 35$ mm showing the emission, propagation and decay of viscous solitons. Figure (a) shows a zoom on the generation of a soliton from the instability of the initial wave packet for a wind velocity close to the onset ($U_a = 9.15$ m s $^{-1}$). Figure (b) shows the propagation and interaction of viscous solitons at larger velocity ($U_a = 9.31$ m s $^{-1}$): mature downstream solitons are slowed down because of the sheltering by newly created upstream solitons.

while and the process repeats. The waiting time between solitons is of order of 1 min close to the onset, but it decreases down to about 1 s at larger wind velocity.

The finite amplitude (about 2 mm) of the viscous solitons even close to the critical wind velocity suggests that they result from a subcritical instability. This is confirmed by additional experiments, in which solitons are excited for a wind slightly lower than the natural onset by using a small immersed wavemaker producing a finite-amplitude disturbance.

Systematic measurements of the soliton amplitude as a function of the downstream distance and wind velocity show that their dynamics is governed by the local wind shear stress: In the absence of mechanical forcing, viscous solitons spontaneously emerge from the initial wave packet that forms at small fetch, for a local shear stress above a first threshold $\tau_1 \simeq 0.25$ Pa. Solitons then escape from this initial wavepacket and propagate in the subcritical region over an appreciable distance, but because of the thickening of the turbulent boundary layer, the shear stress decreases with downstream distance and solitons disappear when the shear stress reaches a secondary threshold $\tau_2 \simeq 0.21$ Pa. The return to the base state is either natural, if the soliton is isolated and reaches the distance where the shear stress is below τ_2 , or forced, when the air drag on the soliton is reduced by the nucleation of a new upstream soliton.

Viscous solitons provide a striking example of out-of-equilibrium coherent structures, resulting from a balance between external forcing and dissipation. These observations raise a number of questions: How their nontrivial asymmetric shape is selected by the liquid viscosity and surface tension? What governs the minimum viscosity to switch from the classical weakly non-linear wind-wave regime to the strongly non-linear soliton regime?

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