Europhys. Lett., **39** (5), pp. 503-508 (1997)

Experimental study of a submerged fountain

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(received 11 April 1997; accepted in final form 17 July 1997)

PACS. 47.35+i – Hydrodynamic waves.
PACS. 47.15Rq – Laminar flows in cavities.
PACS. 47.27Wg – Jets.

Abstract. – We present an experimental study of a vertical planar water jet impinging from below on a water/air interface. Varying the jet velocity and the cavity depth, three regimes are observed: at small velocities or high cavity depths, the jet is stable and the surface bump vertically above the jet is stationary. Increasing the velocity, the bump starts oscillating along the free surface at a well-defined frequency. This motion corresponds to the destabilization of the jet confined in the bulk of the cavity to a self-sustained oscillation regime, characteristic of the behavior of confined jets. Increasing further the velocity induces a transition to a behavior with more complex frequency spectrum. This paper presents a detailed study of the self-sustained oscillation regime. The frequency at the onset is studied as a function of the cavity depth and we show an unusual behavior of the frequency with the distance from the threshold.

Introduction. – The free jet is convectively unstable, which means that all frequency perturbations are amplified; it is also called noise amplifier. However, the free jet is usually characterized by the so-called preferred mode whose frequency corresponds to the higher response of the system [1], [2]. This oscillation mode with f frequency is characterized by the Strouhal number $\mathrm{St} = fd/U$, where d is the nozzle width and U the jet velocity. For a two-dimensional jet at sufficient jet velocities, a constant value for the Strouhal number has been obtained around $\mathrm{St} = 0.3$ [2], [3]. In many configurations, the destabilization of a confined jet has been observed [4]-[6]. The instability becomes absolute, which means that the confined jet presents a robust oscillation dynamics. In this latter case, the system selects a well-defined wavelength and frequency depending on the boundary conditions. If the wavelength of the free jet preferred mode is related to the nozzle width, the wavelength corresponding to self-sustained oscillations in a confined jet is always connected to the impingement length. Usually, the value of the corresponding Strouhal number is decreased [7]-[9].

In the present work we consider a two-dimensional vertical water jet issuing from a nozzle into a rectangular cavity with a water/air interface. The interface induces a confinement effect of the vertical jet in the cavity. To characterize the system, we study the behavior of the surface

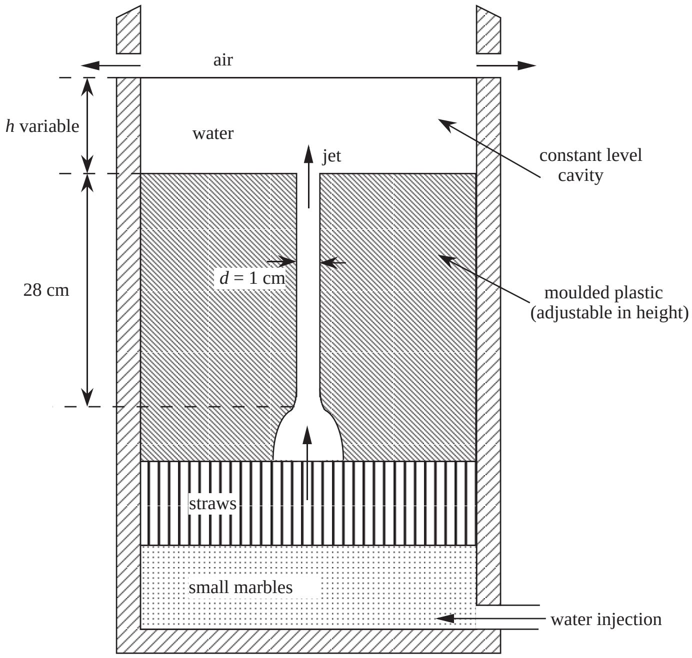
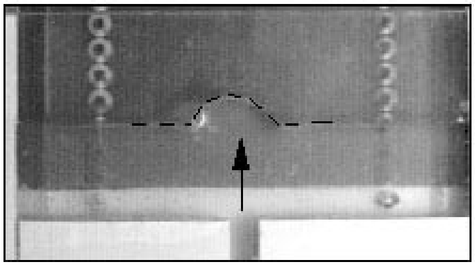


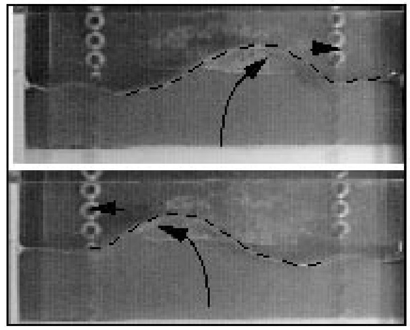
Fig. 1. – Experimental set-up.

bump, that is the materialization at the surface of the confined jet instability in the bulk of the cavity. A stationary bump corresponds to a stable jet and the bump oscillation occurs when the bidimensional jet oscillates in a sinuous mode. In an axisymmetric configuration, Houard *et al.* [10] observed a spiral wave generated from the bump and corresponding to the helicoidal mode of the axisymmetric jet. We present in this paper a detailed study of the self-sustained oscillation regime. The phase diagram is presented as a function of the cavity depth and the jet velocity. We then described the variation of the frequency at the onset of instability varying the cavity depth; these results are compared to those obtained by Madarame *et al.* [11] in a similar configuration. Above the onset, we show an unusual behavior of this systems, where the frequency decreases when the distance from the threshold increases. This behavior has also been observed by Daviaud *et al.* in an axisymmetric configuration [12].

Experimental set-up and phase diagram. – The experimental set-up is shown in fig. 1. The water comes from below where small marbles and multiple pipes are placed to stabilize the flow. The flow rate is regulated with needle valves and measured with a rotameter placed at the entrance. The rotameter has an accuracy of 5% full scale. The jet is created in a 28 cm long by 1 cm wide vertical pipe and penetrates a cavity of 16.5 cm width. The bottom of the cavity is delimited by two pieces of moulded plastic which are adjustable in height in steps of 1 cm. The surface of the water cavity remains at a constant level thanks to outlets in the walls: the cavity depth varies from 2.5 to 8.5 cm and is obtained with an accuracy of around 2%. The whole set up is bidimensional with a thickness equal to 1 cm. The flow patterns were recorded using a charge-coupled device video camera and a digital imaging process. The oscillations were characterized using a spatio-temporal representation. In this representation, the image intensity along a chosen line is recorded at successive times, so that the horizontal axis corresponds to the stored line and the vertical axis to the time.



a)



b)

Fig. 2. – a) Stable regime for $U = 0.5$ m/s and $h = 2.5$ cm. b) Unstable regime: oscillation of the surface bump for $U = 1$ m/s and $h = 3.5$ cm.

Figure 2 shows the flow patterns observed when the control parameters are varied: the cavity depth h (between 2.5 and 8.5 cm) and the mean jet velocity U (between 50 cm/s and 150 cm/s) based on the jet section (1 cm^2) and on the flowrate. Figure 3 shows the corresponding phase diagram. At small velocities or high cavity depths, we observe a stable regime where the surface bump is stationary (in fig. 2 a) for $U = 0.5$ m/s and $h = 2.5$ cm). Increasing the jet velocity or decreasing the cavity depth induces a transition to an oscillatory state (in fig. 2 b) for $U = 1$ m/s and $h = 3.5$ cm). This regime is characterized by the self-sustained oscillation of the bump with a well-defined frequency. From fig. 3, it appears that the oscillation occurs when the Froude number, $\mathrm{Fr} = U^2/gh$, becomes greater than 1, which means that the jet (with inertia $\sim \rho U^2/h$) is sufficiently strong to overcome gravity ($\sim \rho g$). When the velocity is increased further, self-sustained oscillations disappear: the bump still oscillates but the motion becomes irregular (this region of irregular motion is delimited by a curve fitted with $U^2 = 1.5 + 6h$).

Study of the self-sustained oscillation regime. – In the self-sustained oscillation regime, the period is obtained using a spatio-temporal representation as shown in fig. 4. This line is

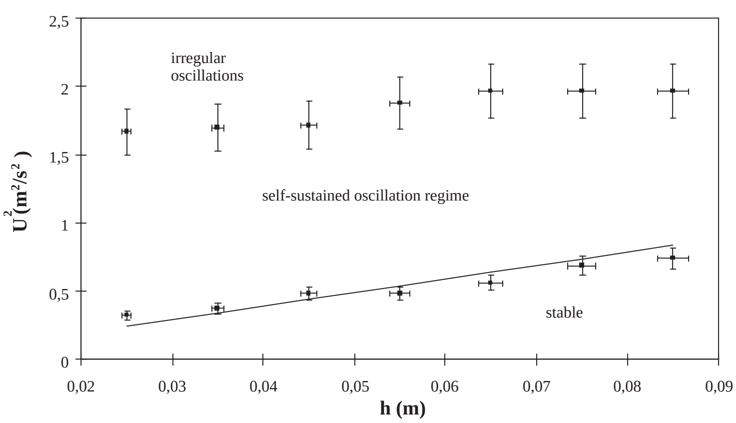


Fig. 3. – Phase diagram (the plain line corresponds to $\mathrm{Fr} = 1$).

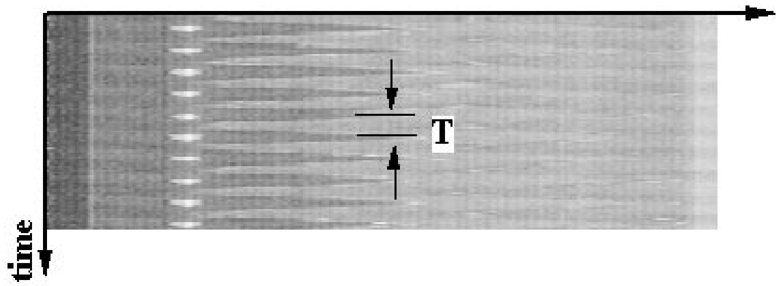


Fig. 4. – Spatio-temporal representation of a line crossing the surface bump at around the half maximum in the self-oscillation regime.

chosen to intercept the bump at around the half maximum and the oscillatory motion is given by the contrast between the water bump and the surrounding air. The measured periods are obtained by determining the number of pixels for 10 periods averaging in fig. 4. We observe a variation of approximately 2 pixels for 10 periods (approximately 100 pixels) for different measurements resulting in an error of the order of 2%.

Frequency f_0 at the onset of instability. – In various systems, the wavelength λ depends on the characteristic distance h of confinement: $h = (n + \epsilon)\lambda$, where n is an integer (usually called mode n) and $\epsilon < 1$ is the so-called end correction. Maurel *et al.* [13] have shown the influence of the jet size that gives a characteristic size to the unstable structures but no universal law has been established. On the other hand, it is widely accepted that the unstable structures are advected at a velocity $U/2$ by the flow [7], [14]. A general law of the form $U = Khf$ can be written, where K is a constant characteristic of the system and we expect that the frequency at the onset of instability varies as $f_0 = (1/K)\sqrt{g/h}$. Figure 5 shows f_0 as a function of the cavity depth h. From this curve, K is found to be close to 6, which suggests that the selected wavelength is equal to 3 times the cavity depth. In other words, the mode 0 would be selected with an end correction equal to 1/3. This result is in good agreement with those obtained by Madarame [11] in a similar configuration, where he observes that $f_0 = (1/2\pi)\sqrt{g/h}$.

Variation of the frequency f with the distance from the onset. – In the self-sustained oscillation, the jet velocity has been changed. Figure 6 shows a non-dimensional

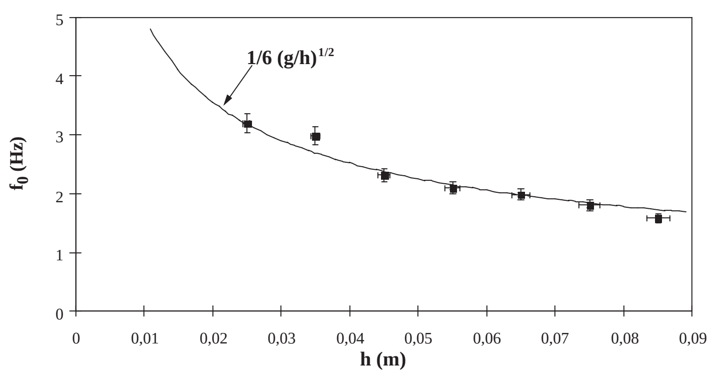


Fig. 5. – f_0 as a function of the cavity depth h.

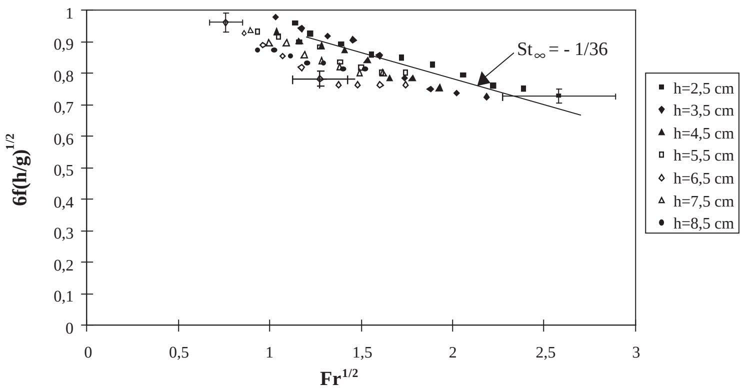


Fig. 6. – Frequency as a function of the jet velocity.

frequency as a function of the square root of the Froude number for various cavity depths. We underline here an important difference between our system and classic oscillators. In this case, the frequency decreases with increasing velocity. This behavior, unusual for a self-sustained oscillation, has been confirmed by Daviaud [12] in an axisymmetric case. In fig. 6, the linear dependence of $f\sqrt{h}$ on $U/\sqrt{h}$ suggests that a good control parameter should be the Strouhal number $\mathrm{St} = fh/U$ which is often used to characterize a self-sustained oscillator. In fact, writing the linear dependence of the frequency $f = f_i + aU$ (solution of the weakly nonlinear Landau-Stuart equation with complex coefficients, where f_i is the frequency extrapolated at $U = 0$), we obtain $\mathrm{St} = \mathrm{St}_\infty + f_i h/U$. The term $f_i h/U$ is often neglected when the experiments are performed at high velocity. In our configuration, this term is dominant and St varies as $1/U$.

The extrapolated value St_∞ of St to U infinite is given by the slope of the curve in fig. 6. We obtain a negative value of St_∞ ($\mathrm{St}_\infty \sim -1/36$). We do not have any explanation for the decrease of the frequency as the velocity. Indeed, it is well known that the confinement effect induces a decrease of the Strouhal number from the free jet situation but the frequency usually still increases with the distance from the onset.

Conclusion. – We have studied the dynamics of a vertical confined jet impinging from below on a water/air interface. This configuration belongs to a class of flows susceptible of generating self-sustained oscillations. The characterization of this oscillator is the first step to fully understand more complex behaviors as the transition to a dynamics with large frequency spectrum or the dynamics of coupled jets network studied by Houard *et al.* [10] in an axisymmetric configuration. In our bidimensional geometry, we have shown that the generator of the instability is the jet inertia while the gravity plays a stabilizing role. The form of the frequency selection at the onset of instability has been established for various cavity depths. Ultimately, we have underlined the unusual behavior of the frequency, which decreases with the distance from the onset. Further works should include the study of the surface perturbation, in terms of height and amplitude, to fully explain the destabilization mechanism and to give some information about the non-linear behavior as the perturbation growths.

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