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Oscillating acoustic streaming jet

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The present paper provides the first experimental investigation of an oscillating acoustic streaming jet. The observations are performed in the far field of a 2 MHz circular plane ultrasound transducer introduced in a rectangular cavity filled with water. Measurements are made by Particle Image Velocimetry (PIV) in horizontal and vertical planes near the end of the cavity. Oscillations of the jet appear in this zone, for a sufficiently high Reynolds number, as an intermittent phenomenon on an otherwise straight jet fluctuating in intensity. The observed perturbation pattern is similar to that of former theoretical studies. This intermittently oscillatory behavior is the first step to the transition to turbulence. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4901319>]

Eckart acoustic streaming denotes flows induced by acoustic wave propagation far from lateral walls. Many experimental investigations have been made in this configuration with circular plane acoustic sources.^{1–5} These experimental observations, all made in the laminar regime assuming quasi steady flows, were motivated by the need to better understand this type of flows and by the existence of several actual or potential applications.^{5–12} Fully turbulent acoustic streaming jets have also been observed and theoretically analyzed.^{13,14} However, no oscillatory behavior has ever been reported and hardly anything is known about the laminar to turbulent transition in acoustic streaming jets.

In contrast, such behavior has already been seen for other kinds of jets as confined jets or plume flows. For instance, the mechanism which causes the transition to turbulence for a natural convection plume flow was studied by Kimura and Bejan.¹⁵ Likewise, Maurel *et al.*¹⁶ have recently performed an experimental study of self-sustained oscillations in a confined jet. A specificity of Eckart acoustic streaming is that a controlled external volumetric force is applied within a given fluid volume at any time. Therefore, our contention is that studies carried out in the acoustic streaming configuration can shed new light on this intricate stability problem. The present paper provides thus the first experimental observation of an oscillating acoustic streaming jet. As the observed oscillations amplify and exhibit non-linear behavior leading to a disordered state, the present study may also be the first step on the transition to turbulence in acoustic streaming jet.

The experiments are performed in a rectangular cavity filled with water (see Figure 1). A 2 MHz ultrasonic circular plane transducer from ImasonicTM, with a diameter of 29 mm, is used to generate the acoustic beam. Such acoustic beam includes a near field and a far field.⁴ The present work focuses on oscillating flows occurring in the far field. This far field zone is delimited by two sound absorbing plates, one positioned close to the Fresnel length ($L_f = 274$ mm) and the other placed along the end-wall opposite to the acoustic source. The first plate is drilled with a 63 mm hole,

which is covered with a thermo retractable plastic film, in order to let the ultrasound waves enter the investigation area, but provide a rigid wall condition for the flow driven by acoustic streaming. The second plate is intended to avoid reflected waves. The domain of investigation, between the two plates, has dimensions of $470 \times 180 \times 160$ mm³ (length \times width \times height) and it is situated 285 mm far from the transducer surface.

The measurements are performed within xy horizontal and xz vertical middle planes (see Figure 1). The investigation area is in the end-part of the domain and extends from $x = 605$ mm to $x = 755$ mm (i.e., until the end wall) in the longitudinal direction and from -17 mm to $+17$ mm in the transverse horizontal and vertical directions (distance to the axis beam).

A LavisionTM Particle Image Velocimetry (PIV) system is used to obtain two-component velocity fields. It includes a double cavity Nd:Yag pulsed laser and a 12 bits PCO SensicamTM CCD camera with a resolution of 1280×1024 pixels. The used de-ionized water is seeded with $5 \mu\text{m}$ PSP particles from DantecTM with density 1030 kg/m^3 . In our measurements, we use a double frame mode with a frequency of 3.75 Hz. The water temperature is 23°C .

When observing the jet near the end-wall, meandering oscillations are clearly seen over a duration of a few seconds. They take the form of initially very small waverings, travelling towards the end-wall, transiently amplified until a clearly non-linear regime, before being damped and vanishing. Figures 2(a) and 2(b), respectively, provide instantaneous fields of axial and transverse velocity in the xy horizontal plane, once the onset of oscillations has occurred. A video, made from these PIV measurements, can be found in the online version of the paper.¹⁷ Note that when the waverings reach their biggest amplitude, the flow becomes very complex. It can be seen as a disorder state localized in both space (in the vicinity of the end wall) and time (few seconds), so that this video might be the first observation of the transition to turbulence in an acoustic streaming jet. In the axial velocity snapshots (Fig. 2(a)), the meandering oscillations of the jet in the end part of the cavity (at a distance $l_0 \approx 350$ mm

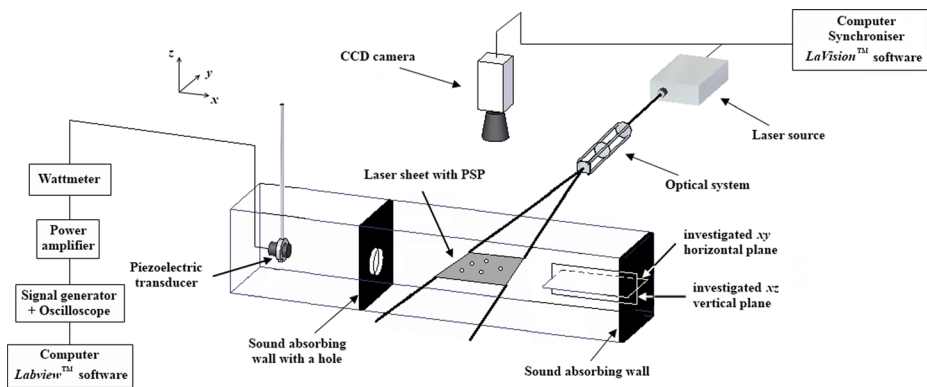


FIG. 1. Experimental setup for the visualization of acoustic streaming jet oscillations in the far field zone. The origin of the Cartesian frame is set at the middle of the transducer plane surface: the x -axis coincides with the propagation direction, the y and z axes are horizontal and vertical, respectively. The corresponding velocities are u , v , and w .

from the upstream wall) are clearly visible. The observation of the transverse velocity snapshots (Fig. 2(b)) is also interesting as they represent perturbations with respect to the straight jet configuration. These perturbations appear as alternating positive and negative values of the transverse velocity located along the jet axis and moving downstream with time. From these transverse velocity snapshots, the temporal period of the oscillations is estimated at about 1.33 s (five time intervals); the spatial wavelength λ is about 4 cm, which gives a 3 cm/s wave celerity.

Figure 3 shows time evolutions of the transverse and axial velocities at $x = 720$ mm on the beam axis. During this 4 min measurement, the jet oscillations reported in Figure 2 are the only ones to occur. Actually, the jet oscillates during a very short time (15–20 s) and then comes back to a quieter state, i.e., a horizontal laminar jet, as indicated by the far smaller transverse velocities obtained after the oscillation burst (Fig. 3(a)). It must be noted, however, that this horizontal laminar jet features a high frequency noise component. As can be seen in Figure 3(b), it is in addition unsteady on larger timescales, ranging from 10 to 100 s. These low frequency velocity variations appear on the PIV snapshots as global variations of the jet axial velocities which are transported downstream. The corresponding range of variation of this component is large: from less than 2 cm/s up to 7 cm/s. In contrast, the high frequency noise variation around this low frequency variation is far smaller. From the signal given in Figure 3(b) and taken between $t = 670$ and

750 s, the standard deviation due to the high frequency noise is estimated to be around ± 0.13 cm/s. The axial velocity in the horizontal jet state obtained outside the oscillation bursts is shown in Figure 4 at $t = 582$ s and $t = 613$ s, respectively, before and after the oscillation burst. Compared to those of Figure 2(a), the jets in Figure 4 are really straight. Before the burst ($t = 582$ s), the jet intensity is strong and quite uniform in the investigation area (plateau of high axial velocities, Figure 3(b)). In contrast, after the burst ($t = 613$ s), the intensity is smaller and less uniform along the jet. The smaller intensity is in agreement with the smaller axial velocities observed at this time at $x = 720$ mm in Figure 3(b). The non-uniformity can also be expected from this figure, as the axial velocity at $x = 720$ mm is about to strongly decrease as a result of low velocity upstream zones flowing downstream. Note finally that, according to Figure 3(b), a very small intensity is observed around $t = 650$ s.

The same type of oscillatory behavior was observed in similar experimental conditions in the xz vertical plane. The measurements were longer, namely, 25 min. During this period of time, several jet oscillation sequences occur, separated by periods of straight jets with low frequency intensity variations. One of these jet oscillation sequences, lasting more than 30 s, is presented in Figure 5 as a spatio-temporal diagram showing the vertical velocity component measured along the x -axis as a function of time. The period, obtained as the average on a sequence of 12 oscillations, is 1.36 s and the wave velocity, obtained as the slope of the perturbation

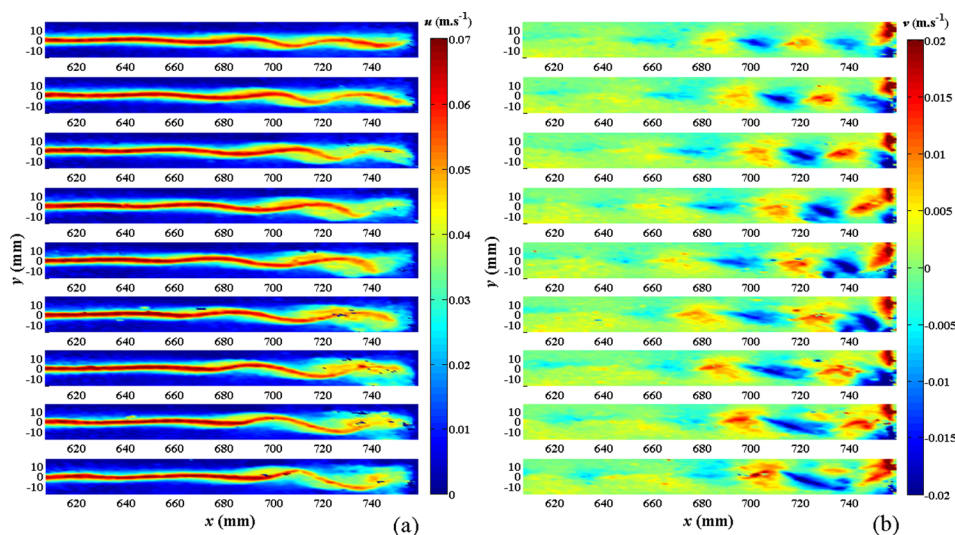


FIG. 2. Instantaneous fields of (a) the axial velocity u and (b) the transverse velocity v in the investigated xy horizontal plane. Time increases from top to bottom; the first snapshot is taken at 588 s after the transducer is switched on (at $t = 0$) and the following snapshots are acquired with a frequency of 3.75 Hz. The right end of the snapshots corresponds to the sound absorbing wall at the end of the cavity.

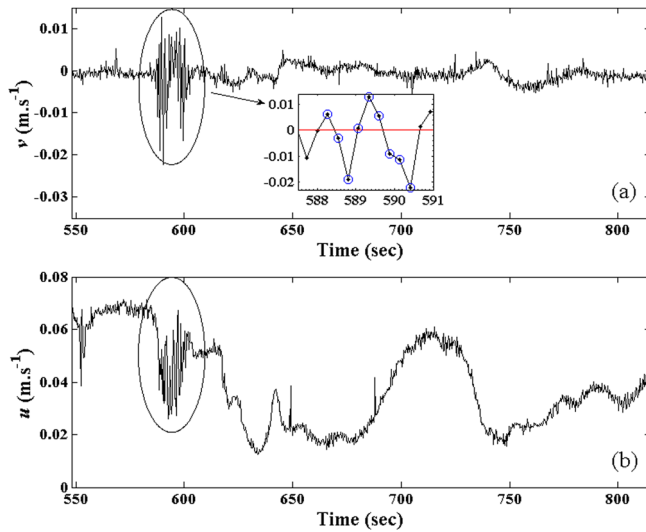


FIG. 3. Time evolutions of (a) the transverse velocity v and (b) the axial velocity u on the acoustic beam axis at $x = 720$ mm from the transducer, obtained by PIV measurements in the xy horizontal plane. The origin of the time is taken when the transducer is switched on. An enlargement of the signal between 587 and 591 s is also given as inset in (a), where the blue circles correspond to the times at which the snapshots in Figures 2(a) and 2(b) are taken.

trajectories in this plot, is 3.09 cm/s. The wavelength is thus 4.2 cm. These characteristics are close to those more roughly estimated from the former measurements in the xy horizontal plane.

As shown previously, jet oscillations do not appear as a first instability of a steady state straight jet, but as an intermittent phenomenon occurring on an already noisy jet. However, it has already been found to appear as a first instability in a one-dimensional theoretical model featuring analytical base velocity profiles assuming a uniform intensity straight acoustic beam.¹⁸ Moreover, preliminary stability results obtained with the same acoustic model in a two-dimensional cavity indicate that the transition to jet oscillations occurs through an eigenvector corresponding to counter-rotating rolls only present in the downstream part of the jet. In both cases, these perturbation rolls have the shape of an arrow head oriented in the upstream direction (see Figure 16 in Ref. 18).

To have a better idea of the perturbations involved in the experiment during the oscillation bursts, a Proper Orthogonal Decomposition (POD) treatment is applied on the sample of nine snapshots of Figure 2. The combination of the first two

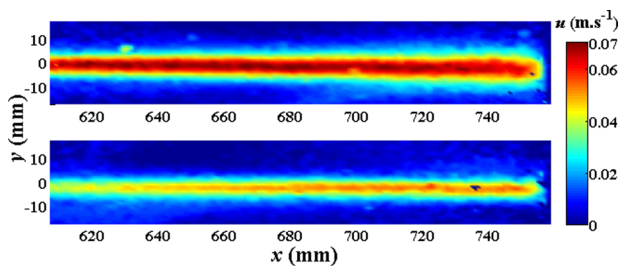


FIG. 4. Instantaneous fields of the axial velocity u in the investigated xy horizontal plane at two instants, $t = 582$ s (top view) and $t = 613$ s (bottom view), respectively, before and after the oscillation burst described in Figure 2.

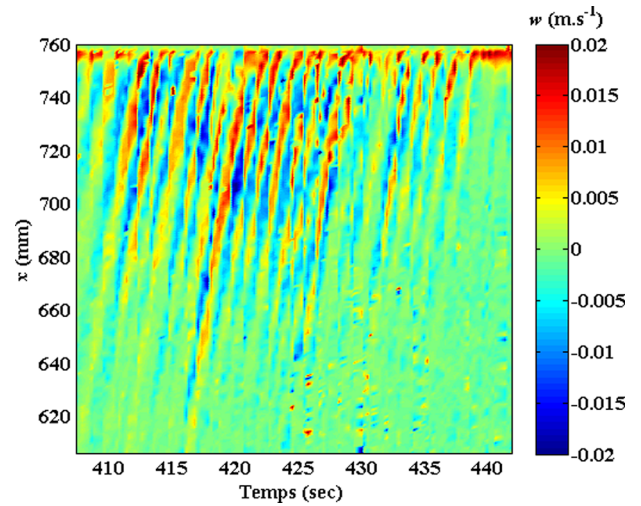


FIG. 5. Spatio-temporal diagram showing the vertical velocity w during an oscillation burst observed by measurements in the xz vertical plane.

POD modes (30.3% and 25.5% of the fluctuating energy, respectively) representing the basic perturbation of the jet is shown in Figure 6 at three instants separated by 0.8 s. Similar to the former stability analyses, we see that the counter rotating rolls have rather an arrow head shape than a circular shape, particularly close to the right end boundary.

These results seem thus to indicate that the observed dynamics of the jet corresponds to an unsteady straight jet pulsating in intensity with dominant low frequency variations and smaller fluctuations with higher frequencies. From time to time, unsteady variations lead the system, in the phase space, close to a cycle corresponding to regular oscillations

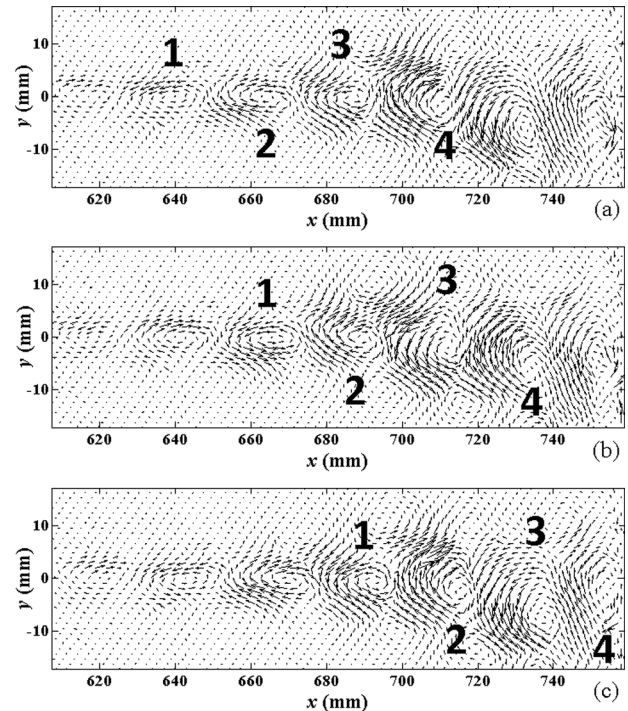


FIG. 6. Reconstruction of the fluctuating velocity field in the investigated xy horizontal plane from the first two POD modes obtained from the snapshots shown in Figure 2. These fluctuating velocity fields are presented at different times corresponding to (a) the third snapshot, (b) the sixth snapshot, and (c) the ninth snapshot.

of the jet. In contrast with the stability studies in simplified situations, these oscillations have not been found as a stable oscillatory state, for smaller intensities of the jet, in the experiment.

A detailed interpretation of the observed results is of course outside the scope of the present letter, but it is remarkable to note that the oscillations appear at a Reynolds number (based on the maximum axial velocity and the acoustic source diameter) $Re \approx 2000$, a value far higher than, for instance, the threshold for the transition to turbulence in a round jet ($Re \approx 30$).¹⁹ Such a large difference is likely due to a strongly stabilizing effect of the acoustic force; more work would be necessary to clarify the physical basis for such an effect. On the other hand, the ratios of the instability wavelength to the jet diameter ($\lambda/\phi_{\text{jet}} \sim 1.5$) and of the oscillation onset distance to the wavelength ($l_0/\lambda \sim 8$) are similar to those of buckling flows as given by Kimura and Bejan.¹⁵ In any case, our results could serve as reference data for model validation.

Finally, as for the confined jet in Maurel *et al.*¹⁶ or the plume flow in Kimura and Bejan,¹⁵ it seems that the acoustic streaming jet undergoes two dimensional, in-plane, oscillations, which we have observed successively in the horizontal middle plane and in the vertical middle plane. Other orientations of the oscillations can, however, be expected, as we can think that there are no preferential orientations in this circular jet.

Our experimental investigation of the oscillating motion of an acoustic streaming jet in water has yielded a number of general conclusions. The oscillations occur in the end-part of the jet at a Reynolds number around 2000. They appear as a 2D wave pattern, with wavelength of about 4 cm, period of about 1.4 s, and downstream advection speed of about 3 cm/s, which has been observed successively in the horizontal and vertical middle planes. These oscillating jet events appear as bursts, lasting a few dozens of seconds, and occurring on an otherwise unsteady straight jet with dominant low frequency variations and smaller high frequency fluctuations. The observed perturbation pattern is similar to the one observed in former simplified theoretical studies:¹⁸ it is restricted to the downstream part of the jet and the velocity perturbations feature an arrow-head shape.

The flow observed in this investigation thus features several time and length scales: those of the acoustic forcing (0.5 μ s, 0.7 mm), those of these oscillating events (1 s, 4 cm), and those of the unsteady flow featuring slow variations (dozens of seconds and centimeters). This picture strongly contrasts with the usual idea of acoustic streaming flows seen as simple steady flows driven by acoustic waves. The present study is also the first to describe a possible step in the transition to turbulence for an acoustic streaming jet. A more systematical parametrical study of this transition should be the subject of further investigations in the near future.

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¹⁷See supplementary material at <http://dx.doi.org/10.1063/1.4901319> to visualize the video on the oscillating acoustic streaming jet.

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