Open access • Journal Article • DOI:10.1103/PHYSREVE.91.033011

Near-field acoustic streaming jet. — Source link

Brahim Moudjed, Valéry Botton, Daniel Henry, Séverine Millet ...+2 more authors

Institutions: École centrale de Lyon

Published on: 19 Mar 2015 - Physical Review E (American Physical Society)

Topics: Acoustic streaming, Acoustic wave equation, Acoustic wave, Ion acoustic wave and Acoustic source localization

Oscillating acoustic streaming jet

Brahim Moudjed, Valéry Botton, Daniel Henry, Séverine Millet, Jean-Paul Garandet, Hamda Ben Hadid

Submitted to Phys. Rev. L

Oscillating acoustic streaming jet

Brahim Moudjed[1], Valéry Botton[1], Daniel Henry[1], Séverine Millet[1], Jean-Paul Garandet[2] and Hamda Ben Hadid[1]

[1] *Laboratoire de Mécanique des Fluides et d'Acoustique, CNRS/Université de Lyon, Ecole Centrale de Lyon/Université Lyon 1/INSA de Lyon, ECL, 36 avenue Guy de Collongue, 69134 Ecully Cedex, France*

[2] *CEA, Laboratoire d'Instrumentation et d'Expérimentation en Mécanique des Fluides et Thermohydraulique, DEN/DANS/DM2S/STMF/LIEFT, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France*

The present paper focuses on the experimental investigation of an oscillating acoustic streaming jet. The observations are performed in the far field of a 2MHz circular plane ultrasound transducer introduced in a rectangular cavity filled with water. Two acoustically absorbing walls are used to delimit the far field zone and avoid acoustic reflection. Measurements are made by 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.

I. INTRODUCTION

Acoustic streaming denotes flows induced by acoustic wave propagation in fluids. The present work concerns the Eckart configuration where the acoustic waves propagate far from lateral walls. Many experimental investigations have already been made in this configuration with a circular plane acoustic source [1–5]. These experimental observations were made in the laminar regime and quasi steady flows were reported. Conversely, turbulent acoustic streaming jets have been observed and theoretically analyzed [6,7]. Nevertheless, to our knowledge, no oscillating behavior has been yet reported for acoustic streaming jets.

In contrast, such behavior has already been observed 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 *et al*. [8]. Likewise, Maurel *et al*. [9] have more recently performed an experimental study of self-sustained oscillations in a confined jet.

An acoustic streaming jet is a specific jet in the sense that a controlled external volumetric acoustic force is applied all along the acoustic beam at any time. As far as we know, the present paper provides the first experimental observation of an oscillating acoustic streaming jet. This experiment could also give information on the transition to turbulence in an acoustic streaming jet.

II. EXPERIMENTAL SET-UP

The experiments are performed in a rectangular cavity filled with water (see figure 1). A 2 Mhz ultrasonic circular plane transducer from *Imasonic*™, with a diameter of 29 mm, is used to generate the acoustic beam. Such acoustic beam includes a near field and a far field [5]. The present work focuses on oscillating flows occurring in the far field for sufficiently rapid acoustic streaming jets. 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 x 180 x 160 mm (length x width x height) and it is situated at 285 mm from the transducer surface (position of the plastic film).

The main measurements are performed in the end part of this investigation area, within xy horizontal and xz vertical planes including the acoustic beam axis, as depicted in figure 1. These middle planes extend from $x = 605$ mm to $x = 755$ mm (*i.e.* to the sound absorbing wall) in the longitudinal direction and from -17 mm to +17 mm (distance to the axis beam) in the transverse horizontal or vertical directions.

A *Lavision*™ Particle Image Velocimetry (PIV) system is used to obtain two-component velocity fields in these horizontal and vertical middle planes. It includes a double cavity Nd:Yag pulsed laser which emits light at a wavelength of 532 nm. Image acquisition is made with a 12 bits *PCO Sensicam*™ CCD camera with a resolution of

1280x1024 pixels. The used de-ionized water is seeded with 5 µm Polyamid Seeding Particles (PSP) of density 1030 kg/m^3 from *Dantec*™. In our measurements, we use a double frame mode with a frequency of 3.75 Hz. The time between the two images taken within a frame pair is chosen to be 10 or 15 ms, in order to optimize the apparent displacement of the seeding particles. The temperature of the water is about 23°C.

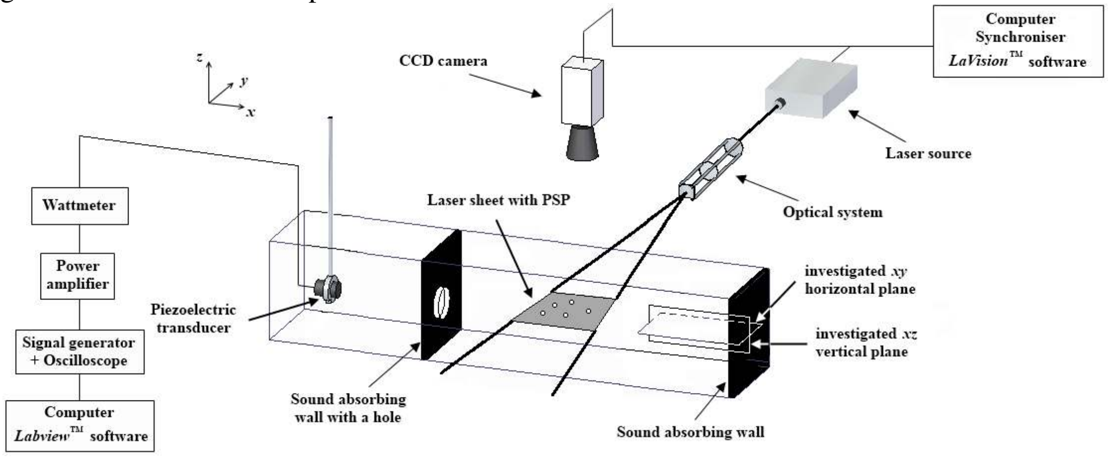
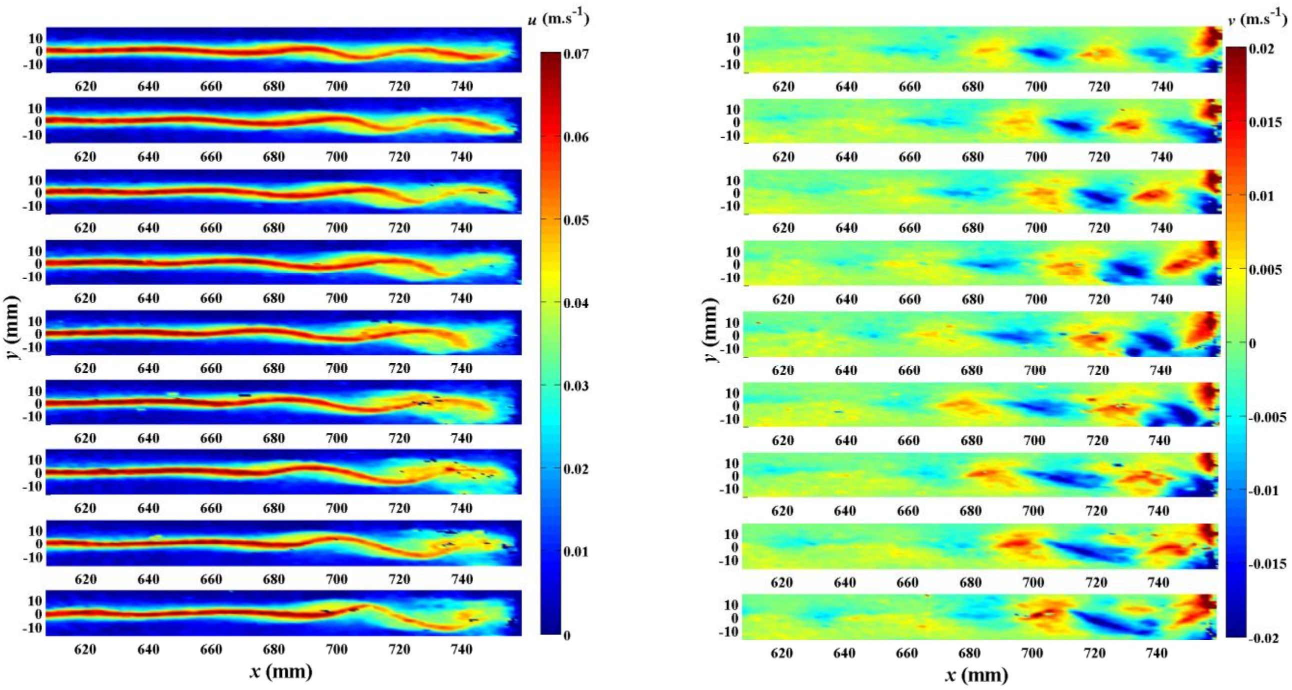


Figure 1: Experimental set up for the visualization of acoustic streaming jet oscillations in the far field zone. The origin of the Cartesian frame is set at the middle of the transducer plane surface: the x-axis coincides with the propagation direction, the y and z axes are horizontal and vertical,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

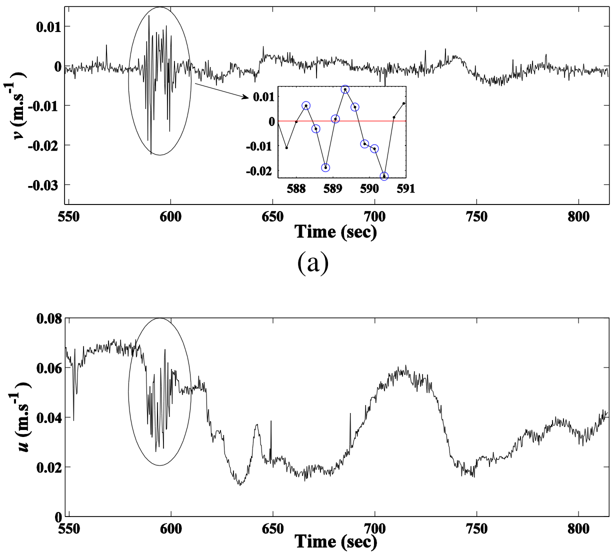


(a) (b)

Figure 2: Instantaneous field 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.

III. EXPERIMENTAL OBSERVATIONS

When attentively observing the jet near the end-wall, meandering oscillations can be clearly seen over a duration of a few seconds. They take the form of initially very small progressive waves, which are 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 investigated 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. From the observation of the axial velocity snapshots (Fig. 2(a)), the meandering oscillations of the jet, which progress as traveling waves in this end part of the cavity (at a distance $l_0 \approx$ 350mm 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 with time. From these transverse velocity snapshots, the temporal period of the oscillations can be estimated at about 1.33 seconds (five time intervals), whereas the spatial wavelength λ is about 4 cm, which gives a wave celerity of about 3 cm/s.



(a)

(b)

Figure 3: Time evolution 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 seconds 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.

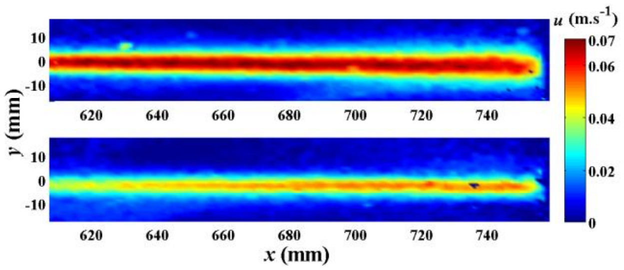


Figure 4: Instantaneous field of the axial velocity u in the investigated xy horizontal plane for two times, $t = 582$ s (top view) and $t = 613$ s (bottom view), respectively before and after the oscillation burst described in figure 2.

The time evolutions of the transverse and axial velocities at $x = 720$ mm on the beam axis are plotted in figure 3. During this 4 minutes measurement, only one occurrence of the oscillations (the one reported in figure 2) was observed. Actually, the jet oscillates during a very short time (15 to 20 seconds) 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 (figure 3(a)). It must be noted, however, that this horizontal laminar jet is somewhat noisy and, as can be seen in figure 3(b), it is also unsteady on larger timescales, ranging from 10 to 100 seconds. These low frequency velocity variations appear on the PIV snapshots as global variations of the axial velocity intensity in the jet. These variations are expected to appear in the upstream part of the jet and, transported by the jet itself, to progressively invade the whole jet domain. The corresponding range of variation of the axial velocity is quite large, from less than 2 cm/s up to 7 cm/s. In contrast, the noisy variation (at higher frequencies) 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 noise is estimated to be around ± 0.13 cm/s. The horizontal jet state obtained outside the oscillation bursts is shown in figure 4, through the axial velocity, at two times, $t = 582$ s and $t = 613$ s, respectively before and after the oscillation burst described in figure 2. Compared to figure 2(a), we see that the jets are really straight jets. Before the burst (at $t = 582$ s), the intensity of the jet is strong and quite uniform in the investigation area (plateau of high axial velocities visible in figure 3(b)). In contrast, after the burst (at $t = 613$ s), the intensity is somewhat 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, meaning that there exist upstream smaller intensity zones which will move towards this point. Note finally that, according to figure 3(b), small intensity jets are obtained around $t = 650$ s.

The same type of oscillatory behavior was also observed in similar experimental conditions by further measurements in the xz vertical plane. The duration of these measurements was longer, namely 25 minutes. 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, which lasts more than thirty seconds, is presented in figure 5 as a spatio-temporal diagram showing the vertical velocity component measured along the $\boldsymbol{x}$-axis as a function of time. The traveling wave character of the oscillating jet is clearly put in evidence with this plot. The characteristics of the wave can also be more easily obtained. The period, obtained as the average on a sequence of 12 oscillations, is about 1.36 s and the wave velocity, obtained as the slope of the perturbation trajectories in this spatio-temporal plot, is estimated at 3.09 cm/s. The wavelength deduced from these values is about 4.2 cm. These characteristics are close to those more roughly estimated from the first measurements in the xy horizontal plane.

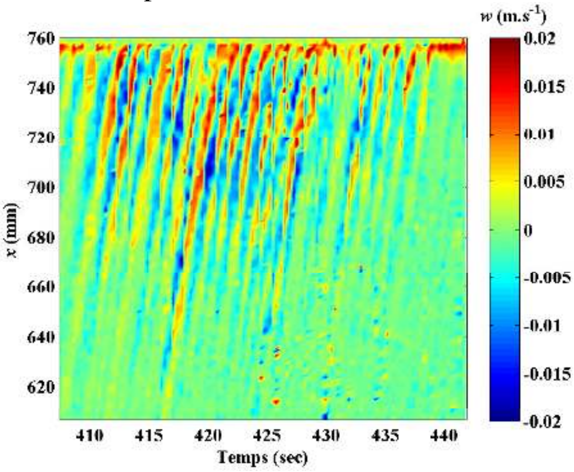
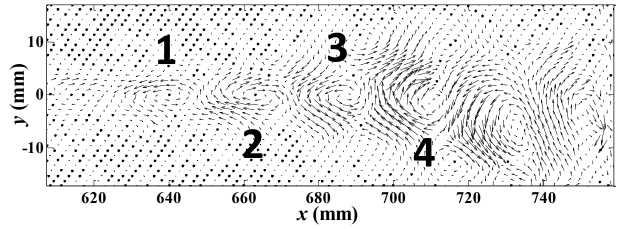
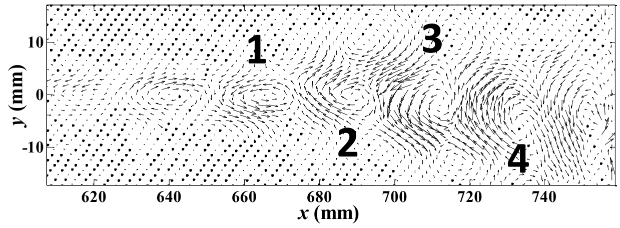


Figure 5: Spatio-temporal diagram showing the vertical velocity w during an oscillation burst observed by measurements in the xz vertical plane.

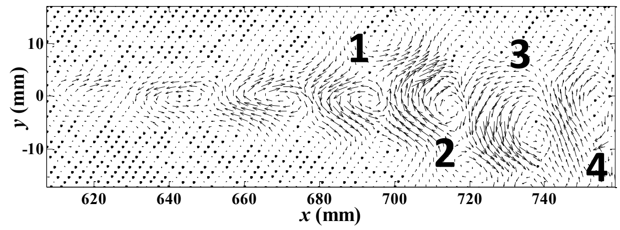
As shown previously, the traveling wave oscillations of the jet do not appear as a first instability of a steady state straight jet, but as an intermittent phenomenon occurring on an already unsteady jet. An estimation of the Reynolds number based on the maximum axial velocity (∼7 cm/s) and the acoustic source diameter gives $Re \approx 2000$, a value far higher than, for instance, the threshold for the transition to turbulence in a round jet given at $Re = 30$ [10]. Such jet oscillations, however, have already been found to appear as a first instability in a one-dimensional theoretical model assuming a constant intensity straight acoustic beam, for which one-dimensional acoustic streaming base profiles can be analytically determined [11]. Moreover, preliminary stability results obtained with the same acoustic model in a two-dimensional cavity indicate that the transition to jet oscillations occur 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 [11]).



(a)



(b)



(c)

Figure 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.

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 shown in figure 2. The combination of the first two POD modes (30.3 and 25.5% of the fluctuating energy, respectively) give a traveling wave structure representing the basic perturbation of the jet, which is shown in figure 6 at three instants successively separated by 0.8 seconds. It is interesting to see that the counter rotating rolls in this traveling flow structure have not a circular shape, but rather an arrow head shape, quite similar to that predicted by the former stability analyses, 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, these unsteady variations lead the system, in the phase space, close to a cycle corresponding to regular oscillations of the jet. In contrast with the stability studies in simplified situations, these oscillations of the jet have not been found as a stable oscillatory state, for smaller intensities of the jet, in the experiment.

Finally, as for the confined jet in Maurel *et al*. [9] or the plume flow in Kimura *et al*. [8], 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. Other characteristics of the jet, such as the wavelength to the jet diameter ratio ($\lambda/\phi_{jet} \sim 1.5$) and the oscillation onset distance to the wavelength ratio ($l_0/\lambda \sim 8$), are similar to those given by Kimura *et al*. [8].

IV. CONCLUSION

The oscillating motion of an acoustic streaming jet created by a circular transducer in water has been experimentally observed by PIV measurements. These oscillations occur in the end-part of the jet at a Reynolds number around 2000. They appear as a 2D traveling wave pattern, which has been observed successively in the horizontal and vertical middle planes. These waves have similar characteristics: a wavelength of about 4 cm, a period of about 1.4 seconds, and a speed, at which they are convected downstream, of about 3 cm/s. These oscillating jet events appear as bursts, with a duration of a few dozens of seconds, which occur on an otherwise unsteady straight jet pulsating in intensity with dominant low frequency variations and smaller high frequency fluctuations.

The acoustic streaming flow observed in this investigation thus features several time and length scales: those of the acoustic forcing (0.5 μs, 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 – to the best of our knowledge – 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.

Funding for this project was provided by a grant, including a doctoral fellowship for Brahim Moudjed, from la *Région Rhône Alpes*.

V. REFERENCES

[1] T. Kamakura, T. Sudo, K. Matsuda and Y. Kumamoto, J. Acoust. Soc. Am. **100**, 132 (1996).
[2] V. Frenkel, R. Gurka, A. Liberzon, U. Shavit and E. Kimmel, Ultrasonics **39** 153 (2001).
[3] H. Mitome, Electron. commun. Jpn. Pt. III - Fundam. Electron. Sci. **81**, 1 (1998).
[4] A. Nowicki, T. Kowalewski, W. Secomski and J. Wójcik, Eur. J. Ultrasound **7**, 73 (1998).
[5] V. Botton, B. Moudjed, D. Henry, H. Ben Hadid, and J.-P. Garandet, submitted to Phys. Fluids.
[6] S. J. Lighthill, J. Sound Vibr. **61**, 391 (1978).
[7] M. C. Schenker, M. J. B. M. Pourquié, D. G. Eskin, and B. J. Boersma, Ultrason. Sonochem. **20**, 502 (2013).
[8] S. Kimura and A. Bejan, Int. J. Heat Mass Transfer **20**, 1515 (1983).
[9] A. Maurel, P. Ern, B. J. A. Zielinska, and J. E. Wesfreid, Phys. Rev. E **54**, 3643 (1996).
[10] A. Bejan, *Convection heat transfer*. John Wiley & Sons, Inc., Hoboken, New Jersey, 4th edition (2013).
[11] W. Dridi, D. Henry, and H. Ben Hadid, Phys. Rev. E **81**, 056309 (2010).