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Correlations between density fluctuations and acoustic far field in free jets using Rayleigh scattering

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ABSTRACT

The mixing noise of a subsonic jet at $M_j = 0.9$ and of an ideally expanded supersonic jet at $M_j = 1.32$ is experimentally investigated. The time-resolved density fluctuations are measured by a Rayleigh scattering based apparatus, and confronted to the acoustic pressure measured by a microphone in the far-field. High levels of coherence are found between the flow downstream the end of the potential core of the jets, and the acoustics measured along the downstream direction. The average event of density responsible for the radiation of acoustics in the downstream direction is also extracted by using a conditional processing.

1. INTRODUCTION

The identification of noise sources in turbulent jet remains a research topic. A commonly used way to identify a source is to seek for connections between turbulent events and far-field acoustic noise. This has been applied to the noise generated by the region of the flow downstream the end of the jet potential core by means of correlation between density fluctuations and acoustics in Panda and Seasholtz [5], or between schlieren images and acoustics in Veltin et al. [6]. Approach based on correlations provided statistical results, but does not offer a precise view of the flow field. For this reason, another used technique is the conditional averaging found to successfully describe flow features from hot wire measurements in Juvé et al. [1] or Zaman and Hussain [7] among others. Nevertheless, those studies used intrusive measurement devices and this may induce spurious noise sources unacceptable for aeracoustics surveys of high speed flows.

For this reason, a Rayleigh scattering method has been developed and implemented in the large anechoic wind tunnel located in the Laboratoire de Mécanique des Fluides at École Centrale de Lyon. This method provides a time resolved, non-intrusive, and local measurement of the density resting upon the intensity of light scattered by the molecules of the gas flow. Correlations, and conditional averages obtained on two ideally expanded jets at Mach numbers 0.9 and 1.32 are presented in the following. Those results are complementary with those proposed for the same experiment in Mercier et al. [2].

2. METHODOLOGY

A continuous-wave 5 W laser and a dedicated optical arrangement permit to define a probe volume in the flow, whose dimensions are of the order of 1 mm wide (in two dimensions) and 0.3 mm high. In this case, the amount of scattered light power is very small, which prevents an evaluation of this quantity by use of a classical powermeter; the intensity of the collected scattered light is thus determined by photon counting using photo-multiplier tubes.

After having validated the consistency of this Rayleigh scattering bench (Mercier et al. [4]) using the physical properties of Rayleigh light scattering (linear dependency to the input laser beam intensity and to $\sin^2(\phi)$, with ϕ the polarization angle between the laser light electric field and the observer), the method is now used for studying jet aeroacoustics. Two different jet flows are considered here; first, a $M_j = 0.9$ subsonic jet from a converging nozzle, and a $M_j = 1.32$ ideally expanded jet from a converging-diverging nozzle. These jets are surrounded by a secondary stream which is necessary to limit the presence of dust particles in the flow and makes the density measurements achievable. The experimental set-up used is shown in Fig.1. Thirteen 1/4" PCB IEPE microphones are located in the acoustic far field of the jet. Microphone measurements are carried out at the acquisition rate of 204.8 kHz and synchronized with photon counting signals. Density fluctuations spectra can be deduced from Rayleigh scattering measurements after having applied a dedicated post-processing to limit the influence of shot noise on these results. The post-processing formerly proposed by Panda and Seasholtz [5] required two independent and simultaneous density measurements of the same region. An adaptation of this post-processing that requires only a single density measurement is proposed in Mercier et al. [3], and will serve at computing the fluctuation spectra presented in the following, that will themselves be used to normalize coherence spectra.

3. RESULTS

Density fluctuations spectra have been measured on the jet centerline at different axial positions around the end of the jet potential core; the results obtained at the axial location $z/D = 8$ are illustrated in Fig. 2 for the two considered jets. High levels of density fluctuations are typically obtained in the range $St_j \in [0.05; 0.4]$, and a straight decay is observed at higher frequency.

Density signals were recorded at different axial locations, between $z/D = 5$ and $z/D = 10$, and radial locations, $y/D = 0$ (jet centerline) and $y/D = 0.25$ simultaneously with acoustic signals along 30° with respect to the downstream jet axis. The coherence spectrum γ^2 between density and acoustic signals is determine following

$$\gamma^2 = \frac{|P_{\rho' p'}|^2}{P_{\rho'\rho'} P_{p'p'}} \quad (1)$$

where the cross spectrum $P_{\rho' p'}$ is normalized by the density spectrum $P_{\rho'\rho'}$, and the pressure spectrum $P_{p'p'}$. An example of coherence between the density measured at $z/D = 8$ and the far-field acoustic at 30° is given in Fig. 3. for both jets, the level of coherence are significant at low frequencies, and orders of magnitude larger than the residual coherence due to the shot noise obtained at higher frequencies. The level of coherence is larger for the $M_j = 0.9$ jet than for the $M_j = 1.32$ jet but over a smaller frequency range. In both case, the level at $St_j = 0.1$ is representative of the maximum coherence. The evolution of the coherence at $St_j = 0.1$ with the axial location z/D is presented in Fig 4. Large values of coherence are obtained on the centerline downstream of the end of the potential core, whereas they are significantly lower along the line at $y/D = 0.25$. To better understand the reason of this observation, averages of the density signal conditioned by the far-field acoustic pressure events are computed for the $M_j = 0.9$ jet.

The method used to estimate the conditional averaging of the density measurements is described in Fig. 5, and consists first in analyzing the pressure signal to detect the pressures peaks that are above a given threshold. Then, for each pressure event, a time windows from which density signal is extracted is defined. The window is shifted in time using the propagation delay of the acoustic wave from the jet to the microphone. All the density signal extracts are therefore in phase with a pressure event, and the average $\tilde{\rho}$ of all these extracts is the signature of the mean density event that produces noise in the far-field acoustic. A detailed analysis of the effects of the threshold level on the results, and a characterization of the pressure events is provided in Mercier et al. [2].

The conditional averages are obtained for $M_j = 0.9$ at different axial positions ranging from $z/D = 5$ and $z/D = 10$ along the centerline and the line at $y/D = 0.25$. Results are plotted on Fig. 4. They depict the convection of the mean density event which consists of a density drop followed by a positive overshoot. Upstream the end of the potential core that occurs near $z/D = 6$, the event is stronger on the $y/D = 0.5$ line. It then arises on the centerline for $z/D = 7$. The maximum amplitude is observed at $z/D = 8$ where the coherence is also found high. It is noticeable that signatures in the density field of events detected along the $y/D = 0.25$ line at the axial location $z/D = 5$, are retrieved more downstream on the axis ($y/D = 0$ line). The correlation length downstream of the potential core being expected to be of the order of the jet diameter, it is likely that these signatures recorded at different radial locations correspond to large flow structures or interactions between large flow structures that complementary measurements should point out.

4. CONCLUSION

Aeroacoustic sources identification requires the use of non-intrusive probes. This issue is here addressed by the use of a Rayleigh scattering based measurement apparatus. Coherence between the hydrodynamic field and the far-field acoustics are calculated for two jet at $M_j = 0.9$ and $M_j = 1.32$. A high level of coherence is found but with a strong spatial dependency. The study is completed for $M_j = 0.9$ by a conditional averaging of the density based of events on the acoustic pressure measured in the far-field. A mean density event is observed and tracked in the region downstream of the jet potential core without exhibiting the same spatial dependency as for the coherence.

ACKNOWLEDGMENT

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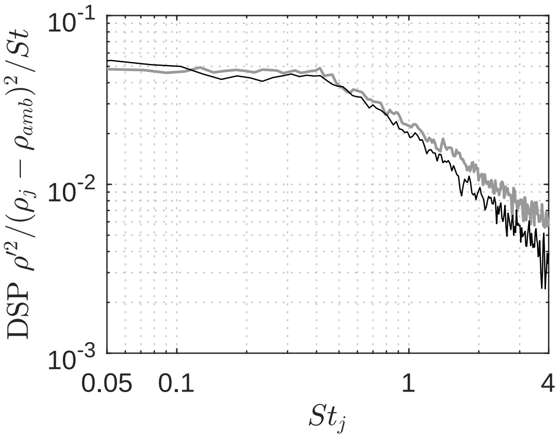

Figure 2: Density fluctuation spectra measured on the centerline of a $M_j = 0.9$ (—) and a $M_j = 1.32$ (—) at $z/D = 8$.

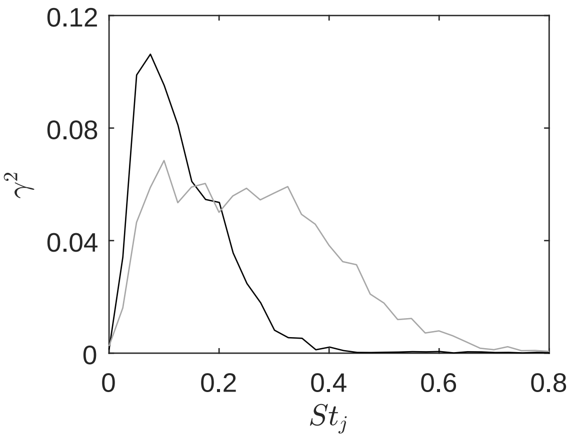

Figure 3: Coherence between the far field acoustic signal at 30° and density measured on axis at $z/D = 8$ for $M_j = 0.9$(—) and $M_j = 1.32$(—).

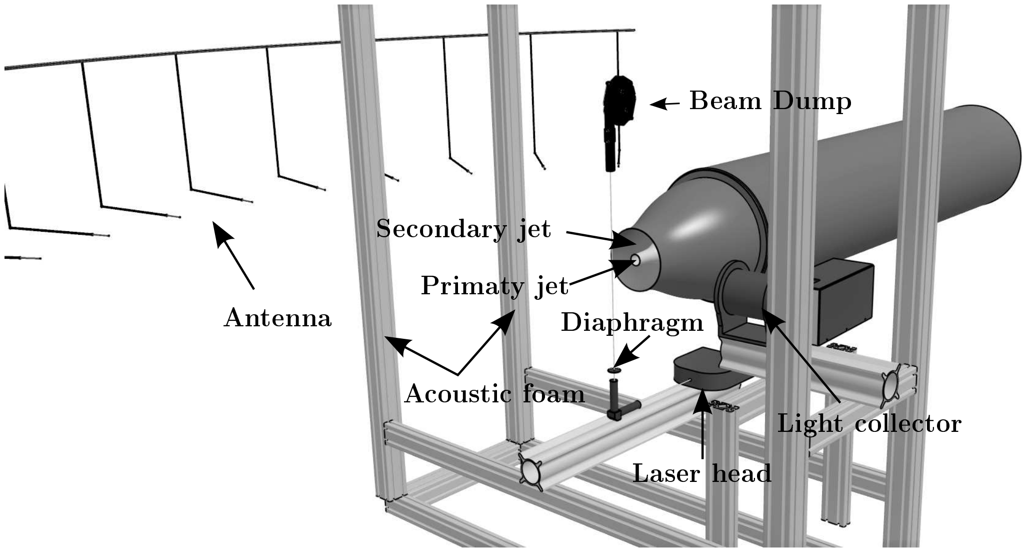

Figure 1: Sketch of the Rayleigh scattering apparatus in the wind tunnel, and of the microphone antenna.

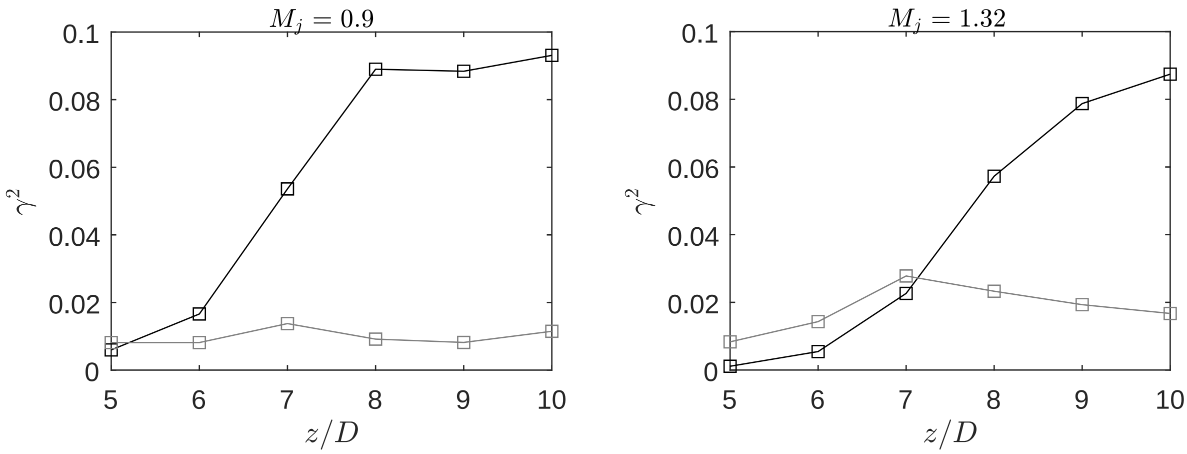

Figure 4: Coherence at $St_j = 0.1$ between the far field acoustic signal at 30° and density measured along the lines $y/D = 0$ (—) and $y/D = 0.25$ (—).

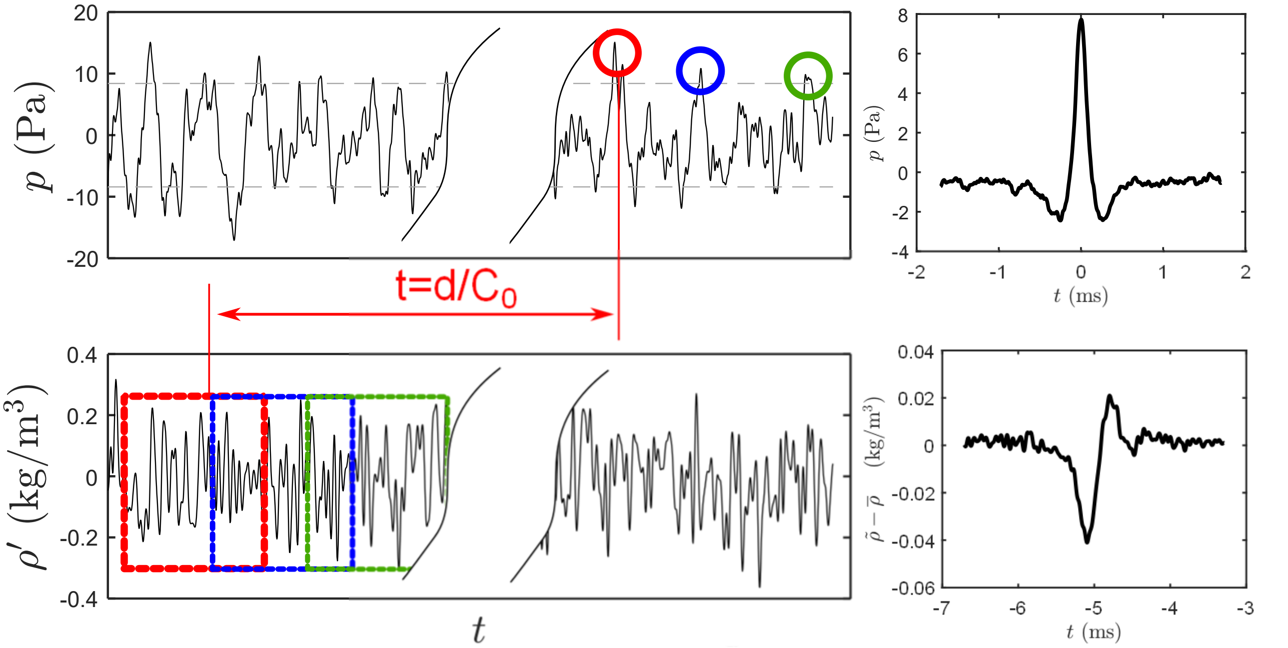

Figure 5: Description of the method for the calculation of the conditional averages. Left: time signal of the acoustic pressure and the density. Right: Conditional average of the pressure and the density. – – – threshold for pressure event detection.

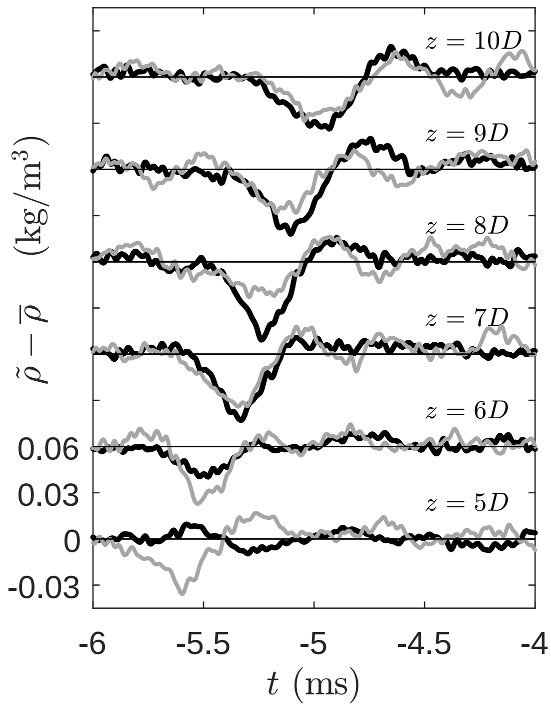

Figure 6: Density averaged with respect to positive pressure peaks in the far-field acoustic signal of the $M_j = 0.9$ jet for different position of density measurements. — $y/D = 0$, — $y/D = 0.25$.