Shear-layer noise generation in an excited jet

Vincent Fleury [1] **Christophe Bailly** [2]
vincent.fleury@ec-lyon.fr christophe.bailly@ec-lyon.fr
Daniel Juvé [3]
daniel.juve@ec-lyon.fr
[1] [2] [3] Centre Acoustique, Ecole Centrale de Lyon
36 avenue Guy de Collongue, 69134 Ecully cedex, France

Abstract

The noise generated by an excited low Mach number jet shear-layer is investigated. Fluctuations are organized according to the frequency of the excitation and its subharmonics, in following Kibens [5]. Two different radiated subharmonic pressure fields have been observed. At low Reynolds number, the pattern is typical of the vortex pairing noise reported by Bridges [2]. An extinction angle around 85° to the jet axis is then noticed. On the other hand, at moderate Reynolds number, the subharmonic radiation is strongly oriented downstream and is superdirective, in agreement with the experiments of Laufer & Yen [6]. The initial conditions of the boundary layer at the nozzle exit seem to be the discriminating parameter and more precisely, the presence or not of the second subharmonic along the shear-layer.

Keywords: excited jet, vortex pairing noise, superdirectivity

1 Introduction

For a supersonic jet, the strong Mach wave noise radiation downstream is mainly generated by instability waves as shown by Tam & Burton [8]. It is very attractive to extend this aeroacoustic mechanism to subsonic jets. Recent studies have shown that the radiation in the downstream direction of a subsonic jet is directly linked to the dynamics of coherent structures at the end of the potential core, and that the directivity pattern is quite similar to the radiation of instability waves, see for instance Bogey, Bailly & Juvé [1]. The study of excited jets may help to deal with this issue by simplifying broadband fluctuations in a few discrete structures. In the present work, the shear-layer of a low Mach number and low to moderate Reynolds number jet is controlled by an external tone acoustic disturbance. The noise generated by the subharmonic structure of the excitation is investigated. Two directivity patterns are to be distinguished, namely the vortex pairing noise reported by Bridges [2] and the superdirective emission observed by Laufer & Yen [6]. In this study, these two emission kinds have been measured on the same facility and the discriminating flow characteristics have been identified.

2 Shear-layer fluctuations

A round jet of diameter $D = 5$ cm has been investigated in an anechoic chamber of the École Centrale de Lyon (6.10 m × 4.60 m × 3.80 m). Two velocities were considered, $U_j = 20$ m/s and $U_j = 40$ m/s. For the first case, the shear-layer at the nozzle exit is laminar and for the second case, transitional. This results of the increasing Reynolds number Re_D from 6.7×10^4 to 1.3×10^5 respectively, as pointed out by Zaman [9]. A device of 4 identical loudspeakers and cavities opened at the nozzle exit by a 1 mm wide circular slot generates an axisymmetric acoustic perturbation of the initial shear-layer. The frequency of the excitation f_{ex} is taken close to the frequency of the most-unstable axisymmetric instability wave of the natural shear-layer, see the works of Freymuth [4] and Michalke [7]. For $U_j = 20$ m/s, velocity fluctuations in the shear-layer are then mostly reduced to the fundamental component f_{ex}, the first subharmonic $f_{s1} = f_{ex}/2$, the second subharmonic $f_{s2} = f_{ex}/4$ and their non-linear interactions. This dynamic follows the experimental results of Kibens [5]. However, for $U_j = 40$ m/s, the excitation effect is not as efficient to organize the shear-layer and the component f_{s2} is not observed.

The axial variation along the center of the shear-layer of the fluctuating velocity $\overline{u^2_{f_{ex}}}$, $\overline{u^2_{f_{s1}}}$ and $\overline{u^2_{f_{s2}}}$ of the components f_{ex}, f_{s1} and f_{s2} respectively, are shown in Fig. 1. For $U_j = 20$ m/s, the fundamental $\overline{u^2_{f_{ex}}}$ has a fast initial growth up to its saturation in X_{ex}. In addition, maxima of the first and second subharmonics are observed in $X_{s1} = 2X_{ex}$ and $X_{s2} = 4X_{ex}$ respectively. These saturations give rise to energy transfers toward harmonics. Hence, the harmonic $2 \times f_{s2} = f_{s1}$ of f_{s2} is fed in X_{s2}, where the amplitude $\overline{u^2_{f_{s1}}}$ of the component f_{s1} has a second maximum. For $U_j = 40$ m/s, the variation of the first subharmonic fluctuating velocity in the center of the shear-layer is basically different. Only one maximum is observed, which is implied to the absence of a time-correlated second subharmonic f_{s2} fluctuation. The total fluctuating velocity u' is overlaid as well. As $X < 1D$, u' is mainly composed of these few discrete fluctuations and the peaks of u' can be related to the maxima of these components.

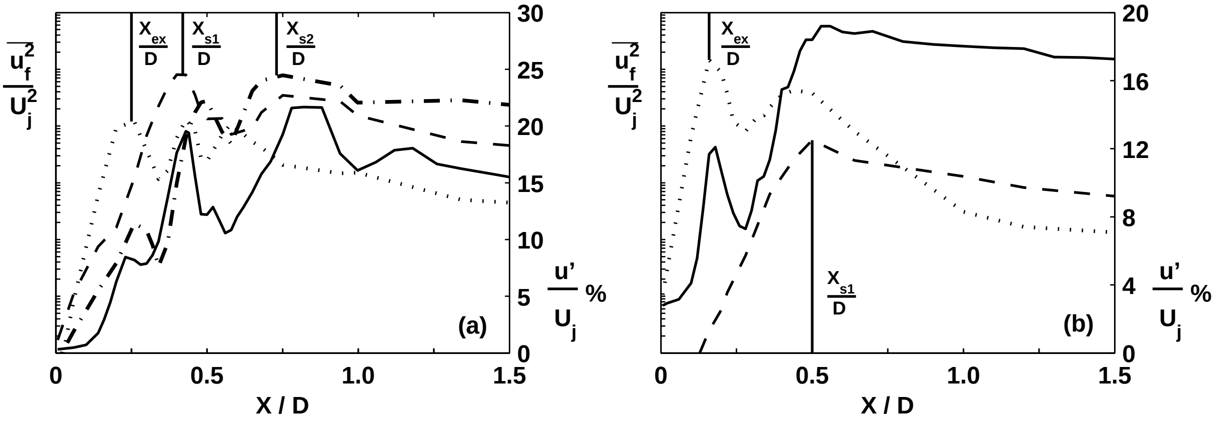

Figure 1: Axial evolution of the fundamental and subharmonic fluctuating velocity in the center of the shear-layer $r = D/2$. The total turbulence intensity is displayed as well. (a): $U_j = 20$ m/s; (b): $U_j = 40$ m/s. ···· $\overline{u^2_{f_{ex}}}/U_j^2$; – – – $\overline{u^2_{f_{s1}}}/U_j^2$; – · – $\overline{u^2_{f_{s2}}}/U_j^2$; —— u'/U_j.

3 Near pressure field

The pressure field was measured along the shear-layer, slightly outside the jet, at roughly $D/5$ from the jet radius. The microphone was traveled in a 10° direction to the jet axis in order to follow the flow spreading. The axial variation of the first subharmonic pressure $p_{f_{s1}}$ is characterized by its amplitude $|p_{f_{s1}}|$ and phase its $\phi(X)$, $p_{f_{s1}} = |p_{f_{s1}}| \exp(i\phi(X))$.

The amplitude is reported in Fig. 2a. For $U_j = 20$ m/s, two strong peaks are noticed around X_{s1} and X_{s2}, as previously for the velocity $\overline{u^2_{f_{s1}}}$ in the center of the shear-layer. A similar two-lobe distribution of the near pressure field was measured by Bridges & Hussain [3]. On the other hand, for $U_j = 40$ m/s, a Gaussian pattern is observed, which is in agreement with the results of Laufer & Yen [6] :

$$|p_{f_{s1}}| \propto \exp\left\{-\left(\frac{X - X_m}{\sigma_e}\right)^2\right\} \tag{1}$$

where σ_e is the length-scale of the Gaussian and X_m is the location of the maximum pressure, found around X_{s1} for $U_j = 40$ m/s, see Fig. 1b.

The phase ϕ of $p_{f_{s1}}$ was determined by comparison to a reference microphone. The length-scale of the fluctuation λ_{s1} could then be calculated as $\lambda_{s1} = 2\pi/(d\phi/dX)$. Though not constant over the involved domain, a mean λ_{s1} value can be roughly determined and has been found around $0.5D$ for $U_j = 20$ m/s and $0.3D$ for $U_j = 40$ m/s.

The acoustic length-scale λ_{ac} of the radiated pressure is evaluated with the relation $\lambda_{ac} = c_\infty/(2\pi f_{s1})$ and is found far larger than both the axial and the radial range of the near subharmonic pressure field, namely $9.1D$ for $U_j = 20$ m/s and $3.8D$ for $U_j = 40$ m/s. Thus, this pressure field is acoustically compact.

4 Directivity pattern

The far-field radiation of $p_{f_{s1}}$ was measured at 40D from the nozzle exit for different angular positions θ to the jet axis. The result is plotted in Fig. 2b. For $U_j = 20$ m/s, an extinction angle is found around $\theta = 85°$ and the directivity pattern is typical of vortex pairing noise as reported by Bridges [2]. On the other hand, for $U_j = 40$ m/s, a monotonic angular evolution of the acoustic pressure is observed. The radiation is moreover strongly oriented downstream and a far higher range of the acoustic pressure is found, around 25 dB with respect to about 15 dB for $U_j = 20$ m/s. This emission collapses fairly well with the distribution given by Laufer & Yen [6], see Fig. 2b, and known as superdirectivity :

$$|p_{f_{s1}}| \propto \exp\left\{-\frac{45}{2}\left(1 - M_p\cos\theta\right)^2\right\} \tag{2}$$

where $M_p = (\lambda_{s1} f_{s1})/c_\infty = \lambda_{s1}/\lambda_{ac}$ is the phase Mach number of the fluctuating pressure in the near-field. This parameter is found around $0.7M_j$, with $M_j = U_j/c_\infty$ the jet Mach number.

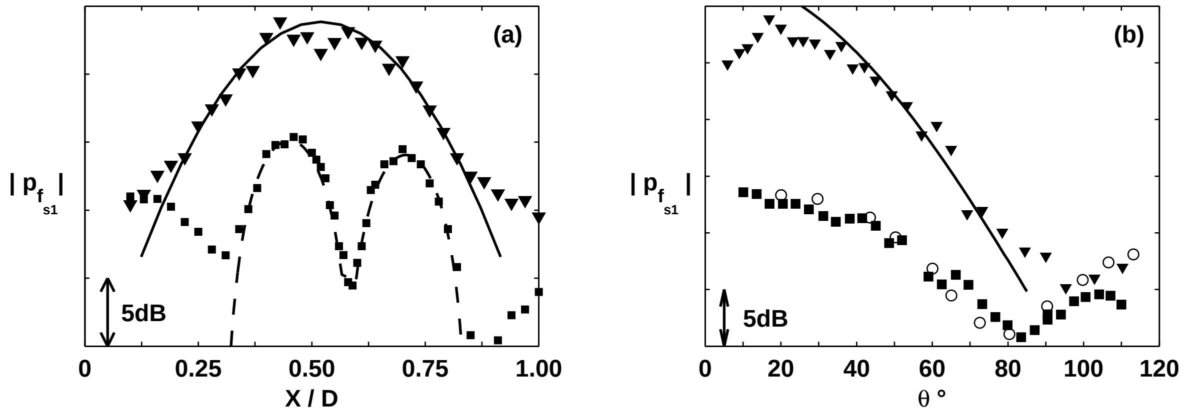

Figure 2: Near pressure field (a) and directivity pattern (b). ■ $U_j = 20$ m/s; ▼ $U_j = 40$ m/s; − − − sinusoidal distribution; ○ Bridges [2] (Fig. 2.7, doubly stable pairing configuration, component $f_{ex}/2$); —— Gaussian distribution (1) and superdirective pattern (2).

5 Conclusion

In this paper, the acoustic radiation generated by the subharmonic fluctuation in an excited shear-layer was investigated. A far pressure field conformed to the vortex pairing noise reported by Bridges [2] has been observed for a low Reynolds number configuration, while a superdirective radiation is measured at moderate Reynolds number in agreement with Laufer & Yen [6]. The discriminating feature is the condition of the boundary-layer at the nozzle exit and more precisely, the presence or not of the second subharmonic fluctuation along the shear-layer.

References

[1] Bogey C., Bailly C. & Juvé D., Noise investigation of a high subsonic, moderate Reynolds number jet using a compressible LES, Theoretical and Computational Fluid Dynamics, vol. 16, no. 4, pp. 273-297, 2003.

[2] Bridges J. E., Application of coherent structure and vortex sound theories to jet noise, *Ph.D. Dissertation*, University of Houston, 1990.

[3] Bridges J. & Hussain F., Direct evaluation of aeroacoustic theory in a jet, *J. Fluid Mech.*, vol. 240, pp. 469-501, 1992.

[4] Freymuth P., On the transition in a separated laminar boundary layer, *J. Fluid Mech.*, vol. 25, pp. 683-704, 1966.

[5] Kibens V., Discrete noise spectrum generated by an acoustically excited jet, *AIAA Journal*, vol. 18, no. 4, pp. 434-441, 1980.

[6] Laufer J. & Yen T.-C., Noise generation by a low-Mach-number jet, *J. Fluid Mech.*, vol 134, pp. 1-31, 1983.

[7] Michalke A., On spatially growing disturbances in an inviscid shear layer, *J. Fluid Mech.*, vol. 23, pp. 521-544, 1965.

[8] Tam C.K.W. & Burton D.E., Sound generated by instability waves of supersonic flows, Part 2, axisymmetric jets, *J. Fluid Mech.*, vol. 138, pp. 273-295, 1984.

[9] Zaman K. B. M. Q., Far-field noise of a subsonic jet under controlled excitation, *J. Fluid Mech.*, vol. 152, pp. 83-111, 1985.