Further characterization of noise sources in supersonic jets

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Summary Different noise sources in supersonic jets can combine to provide the well-known acoustic signature of these free flows. In addition to the turbulent mixing noise appearing for supersonic as well as for subsonic jets, the structure of underexpanded jets is marked by the shock-cell structure which interacts with turbulence developing in the jet shear layer, inducing complementary noise sources: a tonal noise (screech) and broadband shock-associated noise. These three sources will be considered. The broadband mixing noise is studied on the basis of far-field acoustic/flow density correlation using Rayleigh scattering. The influence of screech on the broadband shock-associated noise, and a closure of the feedback loop at the origin of screech will be proposed.

The underexpanded jet flow structure is marked by the development of a shock-cell structure through which the flow parameters substantially evolve. The jet shear layer is thus submitted to strong and periodic modulations in pressure gradients which result in a periodic interaction between the shock tips protruding in the shear layer and the turbulence developing in the jet shear layer. This interaction gives rise to additional noise sources with respect to the sole broadband mixing noise: a tonal signature called screech at frequency f_s and harmonics, and broadband shock-associated noise (BBSAN). The result of these noise sources can be detected in acoustic far-field noise spectra, for instance, as depicted in Figure 1. To determine the contribution of each noise source to the global spectrum, three different cases can be considered. First, the case of a perfectly expanded $M_j = 1.35$ jet issuing from a convergent-divergent (CD) nozzle constitutes a baseline that only exhibits broadband noise obeying scaling laws similar to that of subsonic jets [1]. This reference spectrum is compared to results from an underexpanded $M_j = 1.35$ jet issuing from a convergent nozzle: this clearly put a stress on the screech phenomenon, responsible for tonal emission at the fundamental frequency of 3.5 kHz and its harmonics - the first harmonic being dominant in the direction normal to the jet $\theta = 90^\circ$. Interestingly, the BBSAN is seen to emerge from broadband mixing noise under the form of regularly-spaced humps. The comparison also depicts a global broadband noise increase, which is reminiscent of the results obtained for subsonic jet excitation by external pure tone noise [2]. The third result to be considered benefits from the intermittent behavior of the screech for this particular M_j. The spectrum presented in Figure 1 was recorded during a phase where the screech tone was temporarily absent. In this very interesting configuration, BBSAN is also retrieved under the form of humps, but centered around characteristic frequencies that differ from the screeching case. This indicates the influence of the screech phenomenon on the BBSAN characteristics and consequently the interest in continuing the efforts made in the last decades for understanding and modelling the different jet noise sources, using here experimental techniques adapted to supersonic flows. The study of turbulent mixing noise sources by use of Rayleigh scattering will be presented. A combination of schlieren and acoustic pressure measurements will be used to allow for identifying the most active shock-cells in terms of screech generation for various M_j conditions; the influence of the screech on BBSAN central frequency will finally be highlighted from pressure measurements.

Turbulent mixing noise/flow correlation using Rayleigh scattering

Rayleigh scattering measurements allow to optically determine the local flow density and ultimately permit the determination of density fluctuation spectra. The time signal of the density is nevertheless very difficult to obtain with this method because the output signals of the measurement devices are inevitably corrupted by a high level of shot noise. Nevertheless, by conditionally-averaging the time traces of density on the basis of specific events in the acoustic pressure measured by a microphone in the far-field near the jet axis ($\theta = 30^\circ$), it is possible to reduce the measurement noise footprint and derive density time signals for a physical interpretation. Such signals are illustrated in Figure 2. The events in the reference acoustic signals triggering the conditional averaging consist in positive peaks above 1.5 times the standard deviation of acoustic pressure signal. It clearly emphasizes that these acoustic events, major contributors to the jet noise level [4], are consecutive of flow events appearing at the end of potential core as expected. They consist in a marked deficit of density over a time duration of several hundreds microseconds, corresponding to a length scale of the order of the nozzle diameter; this flow signature is shown to be convected downstream and reinforces as z/D increases [7]. These results are in line with previous measurements or simulations [3], with the peculiarity of being based on a fully non-intrusive experimental method.

Localization of screech noise sources in underexpanded jets

The extreme narrowness of the screech peak in underexpanded jet noise spectra is the most striking feature of the screech phenomenon. It denotes a substantial value for the quality factor of the resonant loop causing the screech tone. However the physical mechanisms responsible for screech production still need to be precised, in particular the different components of the resonant loop. Experimental evidences of the contribution of multiple shocks have been shown [6], with some shock-cells playing a major role in screech generation. To identify these highly-contributing shock-cells in a

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systematic fashion over a large range of M_j without any assumption on screech modes, near field pressures measurements are analyzed together with high-speed schlieren records of the jet shear layer. The characteristic time scales of the different sequences in the screech loop on the basis of an outer feedback path are established and an estimate of number of screech periods during one screech loop is determined [8]. This estimate is seen to be fully consistent with the different screech stages, and provides a new way to distinguish the different screech modes.

Effect of screech on BBSAN

As visible in Figure 1, screech may influence the characteristics (central frequency, amplitude) of the BBSAN. A systematic study of this phenomenon is proposed here, using two different nozzle configurations. The first one relies on the standard convergent nozzle used in the above-mentioned experiments, the other uses a notched nozzle efficient in greatly reducing or even suppressing screech tone over a large range of M_j. The results presented in Figure 3 compare the first harmonic of the screech frequency ($2f_s$), for which the noise level radiated in the direction normal to the jet ($\theta = 90°$) is maximum [1], with respect to f_p measured in each of the above-mentioned configurations. One striking feature revealed by Figure 3 is the monotonic behavior of f_p with M_j as screech is absent, by contrast with the staging evolution of the same quantity in the presence of screech. Furthermore, for the cases where two screech modes compete (for instance around $M_j = 1.25$), the corresponding stage for f_p lies in-between the screech frequencies. A systematic decrease of the BBSAN central frequency is obtained as screech is present [5].

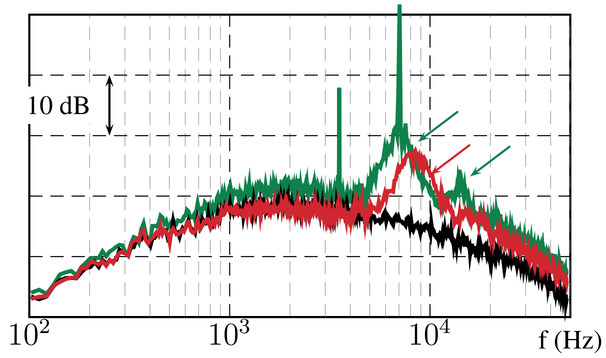

Figure 1: Supersonic jet far-field noise spectra along the direction θ= 90°. M_j=1.35. Jet from converging nozzle, with screech (━), without screech (━); jet from CD nozzle (━). The BBSAN components are indicated by colored arrows

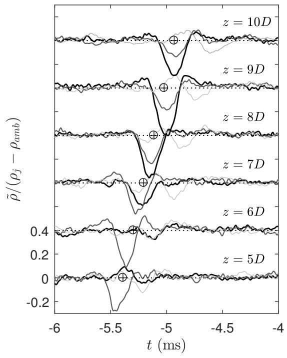

Figure 2: Time evolution of flow density using a conditional-averaging based on the far-field acoustic signal (θ=30°). Convergent/divergent nozzle at M_j=M_d=1.32 . Density measurement radial location: r/D=0 (━), r/D=¼ (━) and r/D=½ (━).

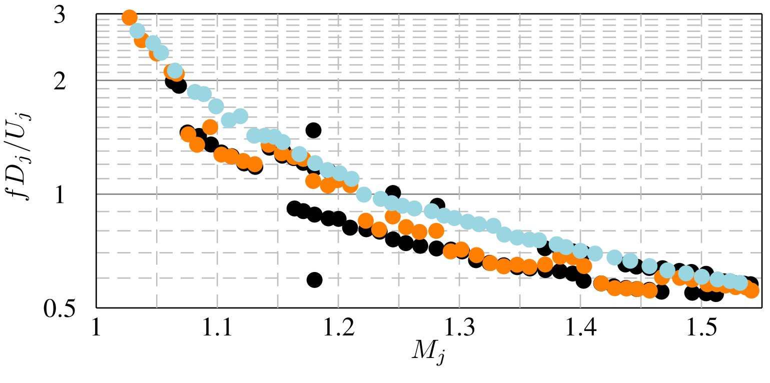

Figure 3: Change with M_j of $2f_s$ (f_s screech frequency) (●) and of BBSAN central frequency f_p in the direction θ=90° in normalized scale. Standard nozzle (●) and screech-suppressing nozzle (●).

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