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Effect of a tab on the aerodynamical development and noise of an underexpanded supersonic jet

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A B S T R A C T

Mechanical tabs are often used as a screech-suppressing device in order to study broadband shock-associated noise (BBSAN). In this study, various experimental methods are used to characterise the effect of a tab on the development and noise of an underexpanded supersonic round jet. It is shown that the jet development is considerably modified by the introduction of the tab in that the shock spacing is shortened and the shock-cell pattern loses axisymmetry and strength. Moreover, the broadband shock-associated noise radiated by the tabbed jet is compared to that of a jet in which screech was suppressed by means of a notched nozzle. The peak frequency of BBSAN for the tabbed jet approximately matches that of the notched counterpart, but the amplitude of this noise component was seen to be smaller for the former jet. More importantly, the axisymmetry of the acoustic field is lost when using a tab, resulting in a dependence of measurements on the location of the tab relatively to the microphones. It is concluded that the use of a tab should be avoided to remove screech when studying broadband shock-associated noise.

1. Introduction

An imperfectly expanded supersonic jet contains a shock-cell pattern arising from the pressure difference between jet and ambient medium at the nozzle exit [1]. As a consequence of the interaction of the mixing layer turbulence with the shock-cell structure, two shock-associated noise components can be emitted: a tonal one, referred to as screech, and a broadband one. Screech has been extensively studied since Powell's pioneering work [2]. Powell explained with some success the generation of this tone by an acoustic feedback loop between the nozzle and an array of acoustic sources coincident with the shocks in the mixing layer. Broadband shock-associated noise (BBSAN) is linked with screech [3], since it also arises from shock–turbulence interaction. BBSAN has been studied since Martlew [4]. Harper-Bourne and Fisher [5] proposed the first model for BBSAN by adapting Powell's stationary source array model. Subsequently, Tanna [6] performed extensive acoustic measurements to evaluate this semi-analytical model. Recently, the aeronautical industry's interest for BBSAN has renewed. Indeed, a commercial aircraft powered by turbofan engines exhausts imperfectly expanded supersonic jets at cruise. Moreover, the use of composite materials in the fuselage of the next-generation aircraft, inducing smaller sound transmission losses than classical metallic structures, makes noise levels in the cabin a potential issue.

While BBSAN comes alongside screech in model laboratory jets, the latter does not seem to be observed in the practical, full-scale problem. But screech is known to have a strong impact on the jet dynamics, for instance on the shock motion [7,8]

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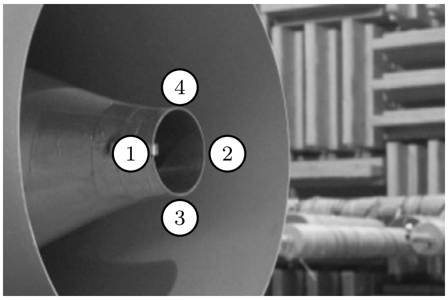

Fig. 1. Definition of the tab positions. The far-field microphone antenna is visible on the right behind the nozzle.

or on the large-scale jet motion [9], leading to a completely different jet development and decay [10,11]. As a consequence, efforts have been devoted from the start to suppressing screech for the study of BBSAN. Harper-Bourne and Fisher [5] eliminated screech by designing a projection on the nozzle lip that penetrated into the jet, following similar earlier tries by Westley and Lilley [12] and Powell [13]. This technique proved very efficient to disrupt the feedback loop and was often used afterwards, see Refs. [6,14,15], for instance. The dimensions of Tanna's tab [6], as quoted by Norum and Seiner [15], are $0.125D$ (width) times $0.063D$ (protrusion), where D is the nozzle exit diameter. Bryce and Pinker [14] already mentioned an effect of the tab on the jet. They noticed from pressure measurements a reduction of the shock-cell length alongside a quicker decrease of this length with downstream distance. They also identified on shadowgrams acoustic waves emanating from the tab. Seiner and Norum [16] formulated some serious doubts about the use of the tab as well as on the relevance of suppressing screech for the study of BBSAN. Although they noticed that the tab noise is not a concern in the case of a converging nozzle, the difficulties introduced by the tab had them abandon this technique. However, the best way to deal with screech remained quite unclear, since the same authors later alternatively used data obtained with and without tab [15,17]. Later, complementary aerodynamical studies on the effects of a tab on a supersonic jet were performed, without particular reference to the noise emission properties of the jets. Ahuja and Brown [18] carried out total pressure and total temperature measurements. They showed that the mixing of the jet with the ambient air was greatly enhanced by the tab, leading to an accelerated decay of the jet. They also suggested the idea of a reorganisation of the large-scale turbulent structures within the mixing layer. Samimy et al. [19] visualised the evolution of the supersonic jet mixing layer in cross sections by Mie scattering. They deduced that the effect of a tab still persists far downstream in the case of underexpanded jets, owing to the long-lived pair of streamwise vortices generated by this device, and that the shock-cell structure is *drastically* altered.

These considerations led some researchers to find less intrusive ways to suppress screech. Nagel et al. [20] and Norum [21] used a baffle mounted upstream of the nozzle exit to cancel screech by an interference effect. The first authors could then relate the shock spacing reduction mentioned above to the tab itself and not to the screech suppression and recommended the use of their cancellation technique instead of a tab. Recently, a different kind of nozzle lip alteration was designed at NASA [22] to suppress screech without modifying the jet structure too much. The idea was to cut many shallow notches into and around the lip so as to make the disturbance smaller and axisymmetrical. This strategy has been tested in [23] and it has been confirmed that a notched nozzle is successful in suppressing screech non-intrusively.

The goal of the present paper is to complement the past studies mentioned above by gathering various experimental data on the effect of a tab on underexpanded supersonic jets. The impact of the tab on BBSAN itself is also characterised. Since screech has an effect on BBSAN [23], it is desirable to compare the acoustic emission by the tabbed jet with that of a configuration where screech is *non-intrusively* suppressed. The notched nozzle is then used to provide this reference. The experimental facility is first presented. Then, the effects of the tab on the jet shock-cell structure are discussed before assessing its acoustical effects.

2. Facility and experimental techniques

The supersonic jets are unheated and exhaust into an anechoic room. In the following, the operating conditions will be expressed in terms of the fully expanded Mach number M_j. Values of M_j up to 1.50 can be obtained.

The tab used here is of rectangular form, with a width of approximately $0.126D$ and a penetration length of $0.065D$ (corresponding to a geometry very close to that of Tanna [6]). It can be fixed on a 38.25-mm-diameter contoured convergent nozzle. Tests with various tab geometries have been performed to try and reduce the protrusion, but it appeared that a smaller size of tab also diminished its efficiency. Different azimuthal positions of the tab are considered in the following. They are located every 90° and are labelled in Fig. 1 for future reference. The notched nozzle employed is contoured and convergent, has a diameter of 38.7 mm, and shows 24 notches of 1 mm width times 4 mm depth.

Far-field acoustic data are obtained from eleven 6.35-mm-diameter PCB condenser microphones fixed on a circular, polar antenna 2020 mm from the centre of the nozzle. They are set every 10° from 30° to 130°. In the following, polar angles are written θ and measured from the downstream jet axis.

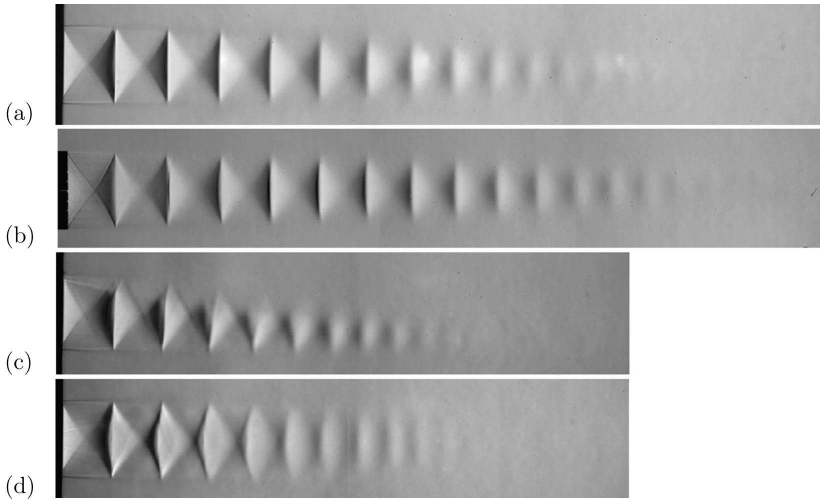

Fig. 2. Mean schlieren pictures, $M_j = 1.15$. (a) Baseline jet, (b) notched jet, (c) tabbed jet with tab located in 4, (d) tabbed jet with tab located in 1 (refer to Fig. 1).

A Z-type schlieren system, mounted on an axial traverse downstream of the nozzle exit, has been used to visualise the flows exiting both nozzles. It consists of a light-emitting diode as light source, two f/8, 203.2-mm-diameter parabolic mirrors, a straight knife-edge set perpendicular to the flow's direction and a high-speed numerical camera.

Static pressure measurements have been performed by means of two short static probes, one being a flat boundary layer probe and the other based on a design by Pinckney [24]. It was checked that both probes gave similar results.

Axial flow velocity is measured by a laser Doppler velocimeter. An argon ion Spectra-Physics 2017 laser operates on the green line of wavelength 514.50 nm with a power of 100 mW. The optical arrangement provides a measurement volume of approximately 90 μm diameter and 1.5 mm length, with the long dimension set perpendicular to the jet axis. The receiving optics collects the forward scattered Doppler bursts approximately 30° off axis. The Doppler signals are finally processed by a BSA F80 processor with a clock frequency of 180 MHz. The flow is seeded with olive oil by means of Laskin nozzle generators. The mean particle size is known to be around 1 μm. No seeding of the jet surroundings has been set up, but the measurements presented next mostly remain within the jet potential core and the first two nozzle diameters, so this is not expected to lead to velocity overestimations.

3. Aerodynamical effects of the tab

The jet without tab or notches is referred to as *baseline jet* in the following, as opposed to the *tabbed jet* and the *notched jet*.

3.1. Schlieren visualisations

First, the aerodynamical impact of the tab is visualised on mean schlieren images. The schlieren assembly leads to a vertical plane of view (containing tab positions 3 and 4 of Fig. 1). Mean schlieren images of the baseline, notched and tabbed jets are displayed in Figs. 2 and 3 for $M_j = 1.15$ and 1.35, respectively. The images have been recorded with different cutoffs and subsequently treated so that the grayscale levels cannot be directly compared between the cases. Comparing the baseline jet to the notched jet, it is clear that the shock-cell system extends further downstream when screech is suppressed. This comes from the quicker damping of the shock-cell structure induced by strong screech tones pinpointed in [23]. This effect is more obvious at $M_j = 1.35$: six shock cells are visible in the baseline jet plume, whereas approximately 12 can be identified with the notched nozzle. Moreover, the shock spacings are practically not modified by the notched nozzle. Comparing the notched jet to the tabbed jet, it stands out that the number of shock cells visible is reduced in the latter. At $M_j = 1.35$, nine shock cells can be observed with the tab, against 12 in the notched jet. Hence, the extension of the shock-cell pattern is a function of two parameters: the screech level and the nozzle type (tabbed or notched). It is more adequate to compare the tabbed case to the notched case, since both are non-screeching. The effect of the tab on the jet plume is then seen to be a reduction of the extension of the shock-cell structure. Moreover, it is clear that the shock spacing is reduced as compared to the baseline and the notched cases. These observations are in agreement with the enhanced mixing introduced by the tab and the accelerated decay mentioned in the Introduction.

Consider now the schlieren pictures of the tabbed jet. Viewed in the plane containing the tab (Figs. 2c and 3c), the shocks appear twisted, while viewed in a plane orthogonal to the tab (Fig. 2d), they are straight again. So, the axisymmetry of the plume is destroyed by the tab. These results are similar to those of Nagel et al. [20].

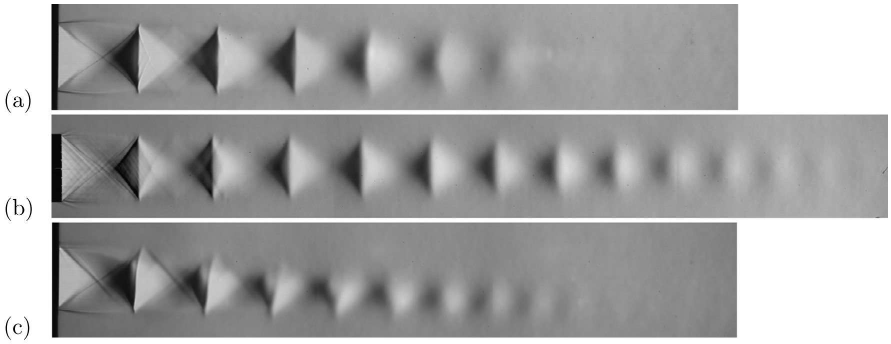

Fig. 3. Mean schlieren pictures, $M_j = 1.35$. (a) Baseline jet, (b) notched jet, (c) tabbed jet with tab located in 4.

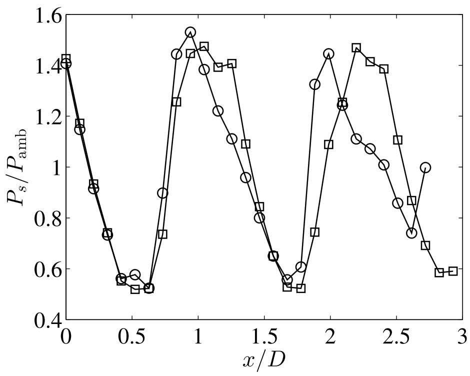

Fig. 4. Centreline profiles of static pressure P_s, $M_j = 1.35$. □ Baseline jet, ○ tabbed jet. P_{amb} is the ambient pressure.

3.2. Static pressure measurements

Shock-cell structures are often characterised by centreline static pressure profiles. Such measurements have been performed both with and without tab for $M_j = 1.35$, as shown in Fig. 4. It has to be mentioned that even without tab, no screech tones are emitted by the jet, because of the introduction of the probe into the plume. Several effects of the tab stand out. Firstly, the shock spacing is shorter in the tabbed jet. Secondly, the oscillations of static pressure have lost their symmetry with tab. Thirdly, the oscillations are attenuated in the case with tab, meaning that the strength of the shock-cell structure is reduced. These conclusions are in agreement with the schlieren visualisations presented before as well as with Bryce and Pinker [14] and Norum and Seiner [15].

3.3. Laser Doppler velocimetry results

Axial velocity measurements have been performed, with and without tab for $M_j = 1.15$, with a laser Doppler system. The conclusions that can be reached from the axial profiles shown in Fig. 5 are in total agreement with those coming from the static pressure measurements. The measurement volume has also been traversed radially along a jet diameter containing the tab, located at $x/D \approx 0$, $y/D = -0.5$. Three radial profiles measured inside the first shock cell are shown in Fig. 6. The three stations correspond to the expansion region, the middle of the cell, and the compression region of the jet without tab. The wake of the tab is clearly visible on these profiles as a velocity drop toward the tab radial location. It is thus obvious, as it was observed from the schlieren images, that the axisymmetry of the jet plume is destroyed. At $y/D \approx 0.5$, the velocities are coincident, since the tab-induced perturbations do not reach the other side of the jet in the first cell. Note that the small velocity deficit on the centreline of the tabbed traverse displayed in Fig. 6a as compared to the baseline profile, not visible on the axial traverse in Fig. 5, can arise from a small variation of the axial locations between both radial traverses. The high velocity gradients present in the flow then change any small variation into a noticeable velocity difference.

4. Acoustical effects of the tab

The adequacy of using a tab for studying broadband shock-associated noise without screech is estimated now. The effects of the tab on BBSAN will be characterised from comparisons with the noise emitted by the notched jet, in the same way as for the analysis of the schlieren visualisations. The fully expanded Mach numbers investigated are 1.10, 1.15, 1.35 and 1.50; each condition sustains a distinct screech mode [9].

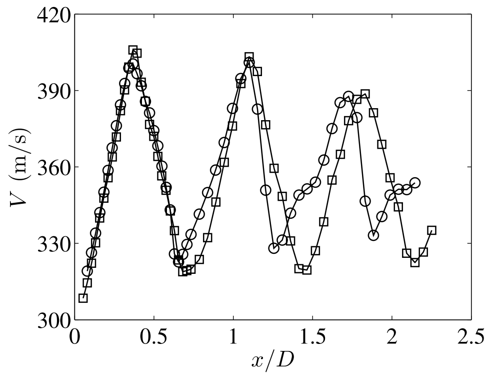

Fig. 5. Centreline axial velocity profiles measured by laser Doppler velocimetry (LDV), $M_j = 1.15$. □ Baseline jet, ○ tabbed jet.

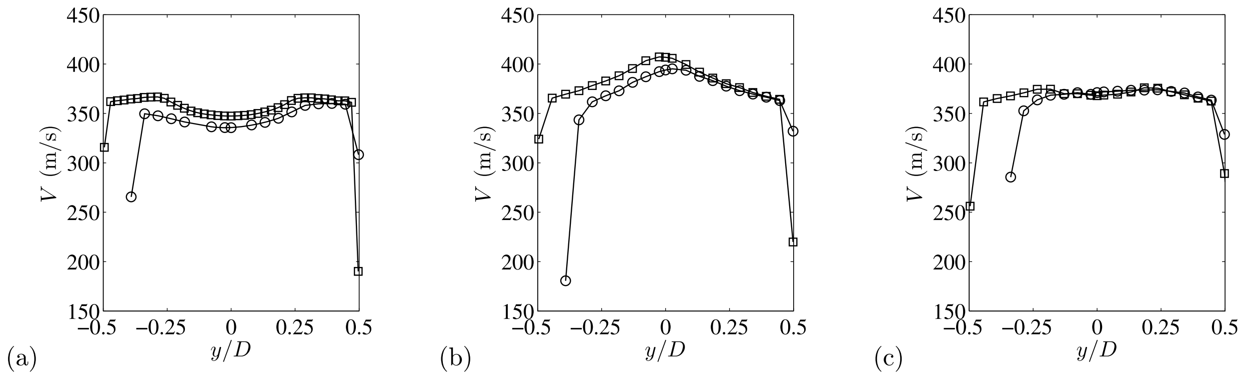

Fig. 6. Radial profiles of axial velocity measured by LDV, $M_j = 1.15$. (a) $x/D = 0.16$, (b) $x/D = 0.34$, (c) $x/D = 0.52$. □ Baseline jet, ○ tabbed jet. The tab is located at $x/D \approx 0$, $y/D = -0.5$.

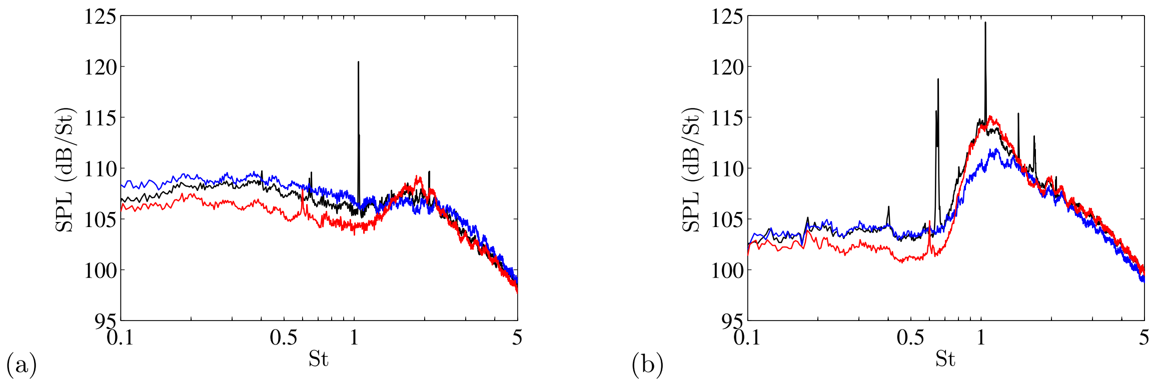

Fig. 7. Far-field acoustic spectra, $M_j = 1.15$. (a) $\theta = 70°$, (b) $\theta = 110°$. — Baseline jet, — tabbed jet, — notched jet. $\mathrm{St} = fD/U_j$, with f the frequency and U_j the perfectly expanded velocity. Colour available online.

4.1. Tab effects on the BBSAN characteristics

For all results of this paragraph, the tab is located in position 1, *i.e.* opposed to the polar microphone antenna. Some spectra are displayed in Figs. 7 and 8 for $M_j = 1.15$ and 1.35, respectively. Both suppression methods work equally well at these two operating conditions, hence any difference on the spectra cannot come from the presence of a residual screech tone in either case. The fundamental broadband hump is shifted toward higher frequencies for both techniques, but by a larger amount for the tabbed jet. Moreover, the amplitude of the hump seems to be reduced in the jet with tab, as compared with the jet exiting the notched nozzle.

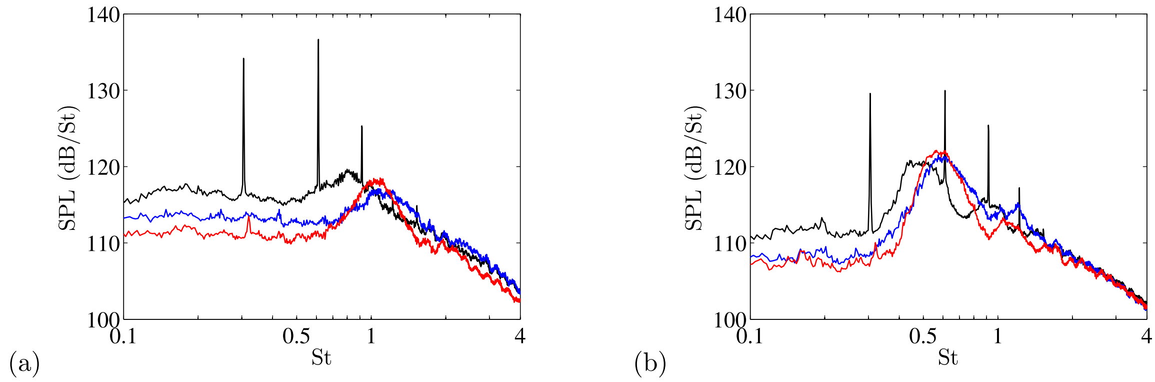

Fig. 8. Far-field acoustic spectra, $M_j = 1.35$. (a) $\theta = 70°$, (b) $\theta = 110°$. — Baseline jet, — tabbed jet, — notched jet. Colour available online.

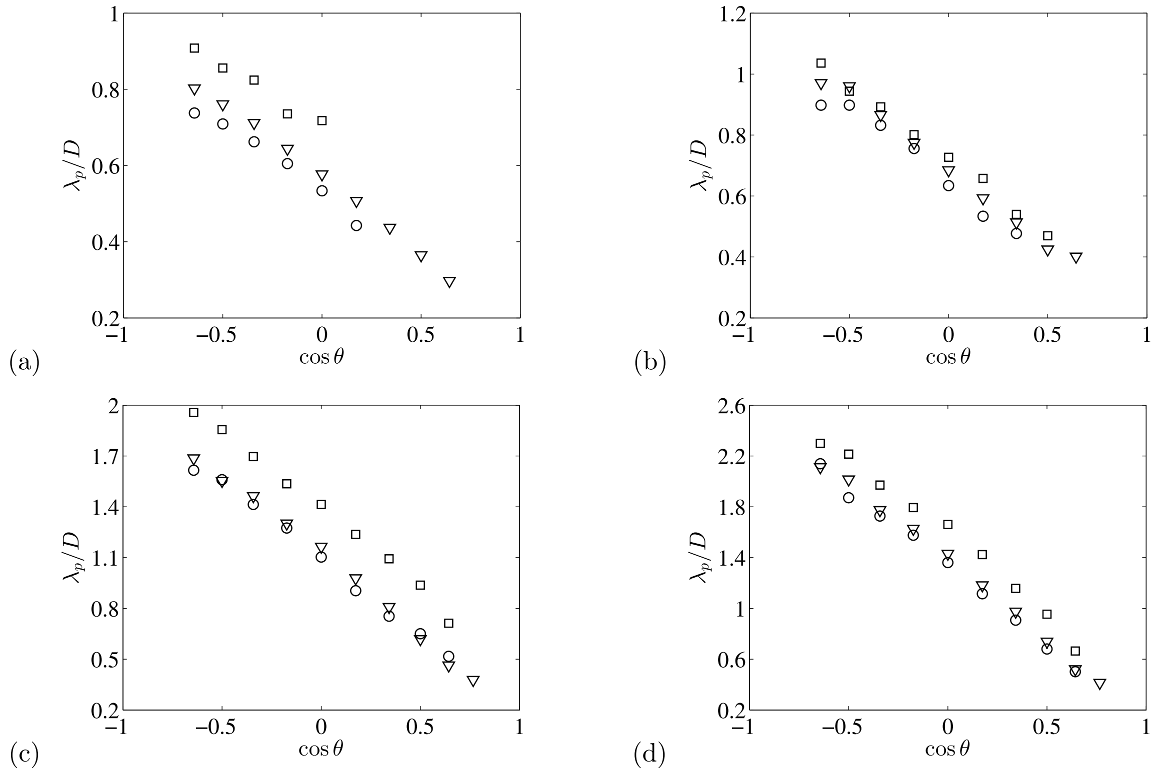

Fig. 9. Evolution of λ_p/D *versus* $\cos\theta$. $\cos\theta$ near one corresponds to the downstream direction. (a) $M_j = 1.10$, (b) $M_j = 1.15$, (c) $M_j = 1.35$, (d) $M_j = 1.50$. □ Baseline jet, ○ tabbed jet, ▽ notched jet.

In order to analyse the acoustic spectra in a standardised and objective manner to extract the fundamental characteristics of BBSAN, Gaussian curves are fitted to the spectra to best represent the broadband hump. These fits are written:

$$A \exp\bigl(-(f - f_p)^2/\bigl(2\sigma^2\bigr)\bigr)$$

where f is the frequency, A is the maximum amplitude of the hump, f_p is its peak frequency and σ is a measure of the hump half-width.

The evolution of the peak wavelength λ_p and amplitude A with θ are displayed in Figs. 9 and 10, respectively, for $M_j = 1.10$, 1.15, 1.35, and 1.50. λ_p corresponds to c_∞/f_p, with c_∞ the speed of sound in the ambient medium. These curves confirm and quantify the preliminary conclusions drawn from the spectra. f_p is indeed slightly higher for the tabbed jet than for the notched one, corresponding to a smaller λ_p. Comparing the peak wavelengths with that of the baseline case, the agreement between the tabbed and the notched jet is nonetheless surprisingly good. This agreement is fortuitous though. The higher BBSAN peak frequency in the tabbed jet probably comes from the shock-cell shortening due to the protrusion, while with the notched jet, it comes solely from the screech suppression (see Ref. [23]).

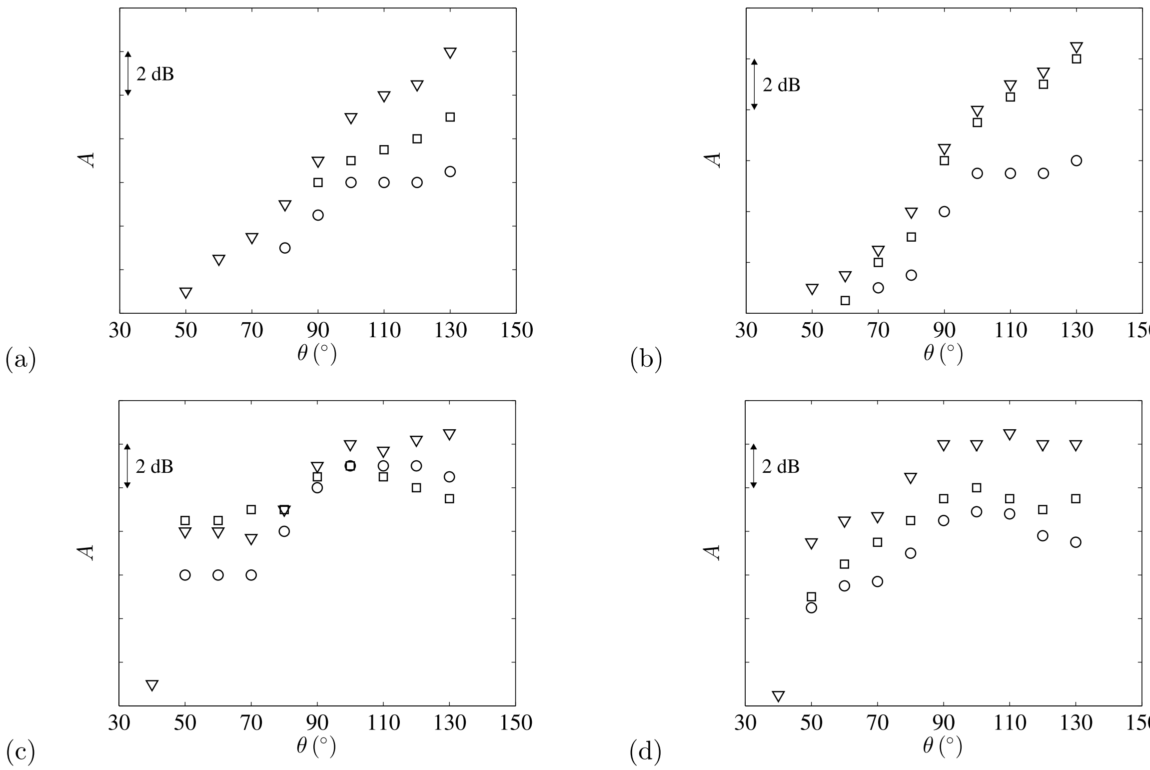

Fig. 10. Evolution of the broadband hump maximum amplitude *versus* θ. (a) $M_j = 1.10$, (b) $M_j = 1.15$, (c) $M_j = 1.35$, (d) $M_j = 1.50$. □ Baseline jet, ○ tabbed jet, ▽ notched jet.

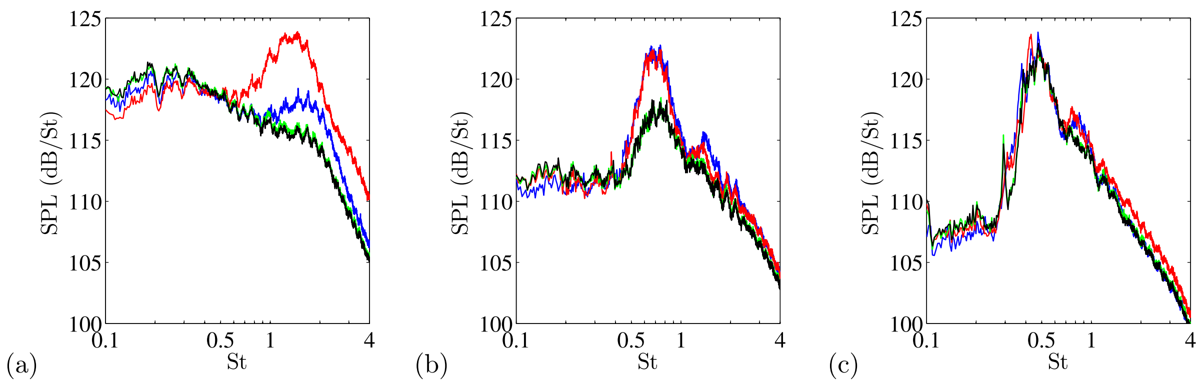

Fig. 11. Far-field acoustic spectra, $M_j = 1.40$. (a) $\theta = 50°$, (b) $\theta = 90°$, (c) $\theta = 130°$. Tab located in position —1, — 2, — 3, — 4. Colour available online.

The broadband hump amplitude is reduced with tab for all M_j and θ considered. The evolution of σ, not shown here, is similar to that of f_p: σ decreases when θ increases, accounting for the well-known fact that the hump narrows in the upstream direction. Furthermore, σ is higher for the tabbed jet than for the notched jet. It is as if M_j were smaller with tab, as compared to the operating condition reigning with the notched nozzle: for a given angle, the broadband hump is weaker, and the peak frequency as well as the width is higher. This parallel is consistent with the shock-cell shortening and weakening due to the tab, shown in Section 3.

4.2. Influence of the position of the tab

The influence of the tab position relatively to the far-field microphones has been investigated at $M_j = 1.40$. Some spectra are displayed in Fig. 11. The hump of BBSAN and its evolution with the polar angle are strongly dependent on the tab position, as already noted by Ahuja et al. [25]. For example, the amplitude evolves weakly with θ when the tab is located in 2, whereas it strongly increases when moving upstream for locations 3 and 4. Note that the spectra for the latter two positions are virtually identical for all values of θ, which is expected considering the symmetrical character of these locations with respect to the microphone antenna. Finally, the differences between spectra vanish upstream ($\theta = 130°$ in Fig. 11), which is similar to the observation of Wlezien and Kibens [26] in their study of acoustic emission from asymmetrical nozzles. It is possible that the asymmetrical development of the jet with tab affects the downstream microphones in a more pronounced way due to their more favourable exposure, compared to the upstream microphones.

5. Concluding remarks

The effect of a mechanical tab on the jet development and the acoustical emission of underexpanded supersonic jets has been investigated experimentally. It has been shown that the tab had a strong effect on the plume's shock-cell structure. An asymmetry and a reduced extension of the latter as well as a decrease of shock spacing and shock strength have been observed by means of schlieren visualisations and velocity and static pressure measurements. These effects can be related to the enhanced mixing induced by the tab. The characteristics of the fundamental hump of broadband shock-associated noise have been compared between the tabbed jet and a jet exiting a notched nozzle, effective in non-intrusively suppressing screech. The reduction of the shock spacing due to the tab induces a shift of the peak frequency of BBSAN to higher frequencies, which fortuitously mimics the real effect of screech suppression. The observed tab-induced shock-cell weakening however entails lower shock-associated noise levels. The most disturbing problem associated with employing a tab is deemed to be the broadband hump dependence, both for level and peak frequency, on the tab position relatively to the far-field microphones. This arguably makes any conclusion on BBSAN with screech suppressed by a tab dependent on the measuring system. Because of this, and considering the simplicity of implementation of the notched-nozzle method, we suggest that the latter technique be used for screech suppression in order to study broadband shock-associated noise.

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