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Technical Notes

Shock Oscillations in a Supersonic Jet Exhibiting Antisymmetrical Screech

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I. Introduction

THIS contribution follows a Technical Note published by the authors in *AIAA Journal* [1], in which a shock-tracking algorithm was applied to a screeching underexpanded jet. It was shown that the shocks oscillate at the screech frequency, in a symmetrical or antisymmetrical manner, according to the screech mode. The temporal signals of two diametrically opposed near-field microphones were also considered. At a nozzle pressure ratio (NPR) of 2.54, corresponding to a flapping mode B, both microphones showed a simultaneous modulation of the screech amplitude at a frequency of the order of $1/1000$ of the screech frequency. A schlieren video was extracted from the complete recording for each one of the weak and strong screech spells. The tracking algorithm was applied on the resulting movies, and it was deduced that the shock oscillation amplitude increases with an increase in the screech level, which is in agreement with the analytical model proposed by Panda [2].

The picture of the flapping screech viewed by two diametrically opposed microphones appears, however, too simplistic, and a property of screech that remained unseen at that time is highlighted in the present work.

Screech is a tonal component of shock-associated noise arising in incorrectly expanded supersonic jets. It was first studied by Powell [3], who already mentioned the existence of modes. Of particular importance for the present study is the flapping mode B, whose pressure signal in the near field is antisymmetrical about a plane. The modal behavior of screech was later extensively studied, especially by Powell et al. [4] as well as Ponton and Seiner [5], who noted that the plane of antisymmetry can slowly rotate or oscillate. This feature, referred to in the following as plane rotation, was investigated in some detail by the authors [6] using a near-field azimuthal microphone antenna comprising 18 transducers located every 20 deg. It was shown that the plane rotation was related to the simultaneous presence of two counter-rotating helices of slightly different frequencies in the screech azimuthal-mode content. It was also explained that the screech level is minimum near the plane of antisymmetry and maximum perpendicular to that direction. In light of [6], it is believed that the strong amplitude modulation in time of the microphone signals in the original study [1] was caused by the rotation of the plane of antisymmetry. The plane rotation was then interpreted as a time modulation of screech strength due to the small number of microphones used.

The identification of the plane rotation in the acoustic field has suggested a possible rotation of the plane of antisymmetry of the shock motion. This question is considered in the present paper. The experimental facility is first presented. Then, results for two cases of flapping screech are discussed.

II. Experimental Setup

The supersonic jet is unheated and exhausts through a 38-mm-diam contoured convergent nozzle into an anechoic room. The wall static pressure is measured 15 nozzle diameters upstream of the exit. Stagnation pressure is then retrieved from the static pressure value through the estimate of the local Mach number in the measurement section.

Two schlieren systems are mounted, as sketched in Fig. 1a, on a frame downstream of the nozzle exit. One is a Z-type system, essentially consisting of two $f/8$, 203.2-mm-diam parabolic mirrors. The off-axis setting is limited to $2\alpha = 10$ deg. Because of a place constraint, the second schlieren apparatus is a double-pass system, including a beam splitter and a single spherical $f/12$, 203.2-mm-diam mirror. Both arrangements also use a light-emitting diode, a knife edge, and a high-speed Phantom V12 camera. The Z-type system is oriented so that the parallel light beams cross the jet horizontally. A vertical slice of the shock can thus be viewed, as shown in Fig. 1b (shock tips 1 and 2). The optical axis of the double-pass apparatus is set vertical. It thus gives a horizontal view of the jet (shock tips 3 and 4).

A circular near-field azimuthal microphone antenna, consisting of 18 6.35-mm-diam PCB Piezotronics condenser microphones located every 20 deg, is set in the nozzle exit plane approximately three nozzle exit diameters from the jet center. The antenna is also shown in Fig. 1a. The angle ϕ_m denotes the position of the microphones. The transducers located at $\phi_m = 0$ and 180 deg are directly above and under the shock tips visualized by the Z-type schlieren system. The transducers located around $\phi_m = 90$ and 270 deg are set to the left and right of the shock tips visualized by the double-pass schlieren system.

The frame rate of both cameras is 62,015 Hz, while the pressure signals are sampled at 102,400 Hz. One common trigger is used for both cameras and the sampling card so that all acquisitions are synchronized. Owing to the 4 GB RAM embedded in the cameras and the area of the sensors used, about 1.77 s can be recorded by the cameras at a time. According to the geometrical configuration and the objectives used on each camera, the Z-type and double-pass systems have spatial resolutions of 0.107 and 0.120 mm/pixel, respectively.

III. Shock Motion Features

In the following, a jet at a fully expanded Mach number of 1.50, corresponding to an NPR of 3.67, is visualized. The screech at this operating condition corresponds to a flapping mode, as documented in [6]. It was neither fully stable nor unstable so that a recording associated with a quiescent plane of antisymmetry and another one corresponding to a rotating plane have been performed. The present study focuses on the motion of the first shock.

A. Stable Screech

The stable case is considered here. The shock-tracking algorithm presented previously [1] has been applied to the movies recorded by

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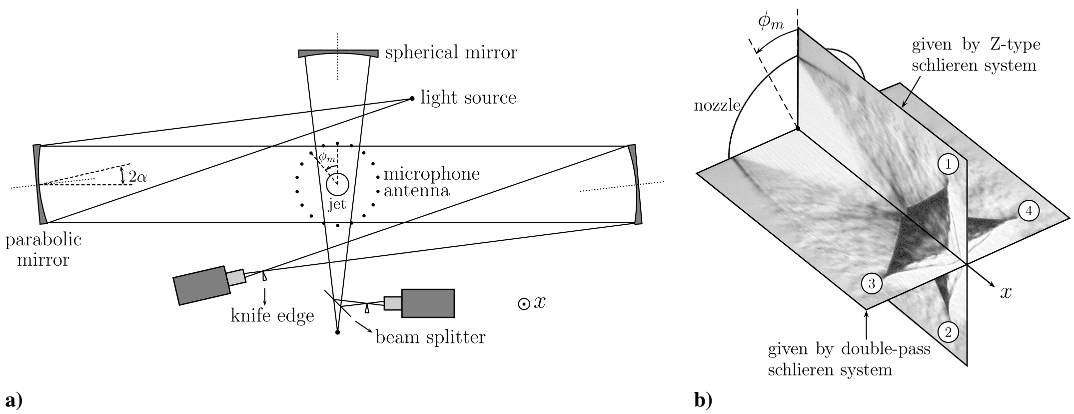

Fig. 1 a) Sketch of the schlieren apparatus with azimuthal microphone antenna (not to scale); b) representation of the two planes examined and definition of the shock tips.

each camera. This allows the position along the jet axis of each shock tip represented in Fig. 1 to be determined. Time traces of the results are displayed in Fig. 2 along with the temporal signal of the microphones located at $\phi_m = 0$ and 100 deg. It is apparent that the two microphones do not sense the same level of screech, which is typical of flapping screech modes, as recalled in Sec. I. Viewed along the direction of weak screech ($\phi_m = 0$–180 deg), the first shock motion has a weaker amplitude than when it is looked at along the direction of strong screech ($\phi_m = 90$–270 deg). The power spectral density of the shock motion signal shows that the shock oscillates exactly at the screech frequency. Phase averaging has been performed, and the shock-tracking algorithm has been applied to the averaged images (see [1]). The shock on the recording from the Z-type system has a magnitude of oscillation of 0.37 ± 0.05 mm, whereas the one of the shock on the double-pass recording is 1.2 ± 0.06 mm. Comparing these two figures gives a ratio of about 3. This is to be linked to the 3.7 ratio of root-mean-square pressure fluctuations between the corresponding microphones. It seems then that the near-field sound pressure level pattern associated with the flapping screech mode is imprinted in the jet and that the shocks are oscillating about the direction of the acoustical plane of antisymmetry, which would thus also be the plane of antisymmetry for the shock motion.

B. Unstable Screech

Another recording at a jet Mach number of 1.50 has been performed while the plane of antisymmetry of screech was rotating. The time trace of the acoustic signal at $\phi_m = 0$ deg is displayed in Fig. 3a. It features bursts similar to Powell et al.'s observation [4]. The spectra of the near-field microphone signals as well as that of the shock displacement data show a double peak, which can be associated to two counter-rotating helices of different frequencies (see [6]). The plane of antisymmetry therefore rotates, inducing the periodical vanishing of the screech signal measured at each azimuthal location.

A visualization of the rotation can be obtained as follows. To extract the time envelope of the bursts, the root-mean-square values of the pressure signals have been computed over 15 screech periods throughout the entire recording. The time period from 1.2 to 1.75 s is then selected from the plot in Fig. 3a because the bursts are there seen to be regular. For each azimuthal microphone, the mean phase angle

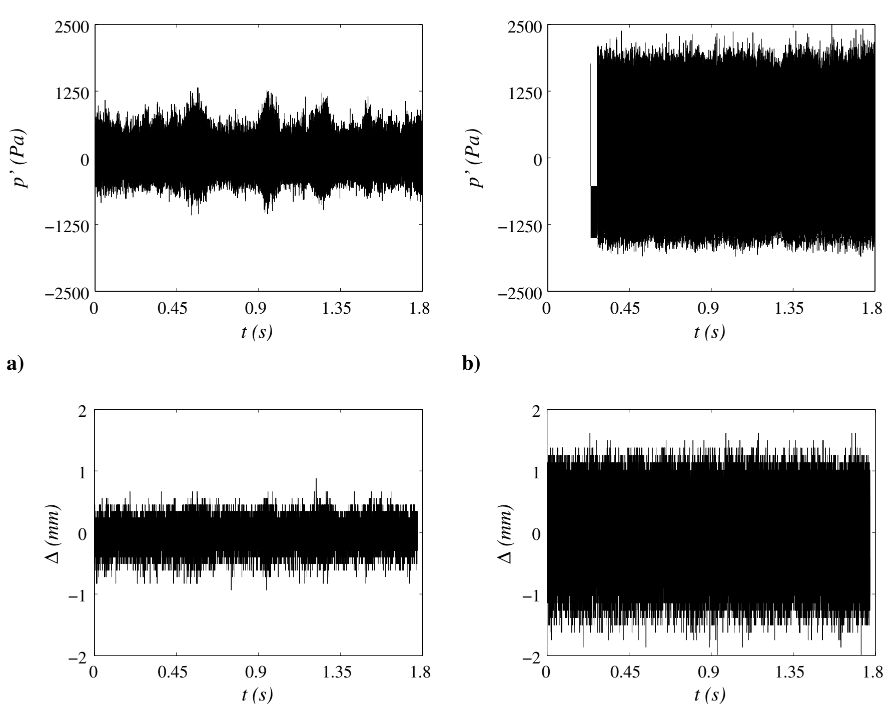

Fig. 2 Time trace of microphone signal at a) $\phi_m = 0$ deg, and b) $\phi_m = 100$ deg. Time trace of Δ, the shock axial displacement from its mean location, for c) tip 1, and d) tip 3.

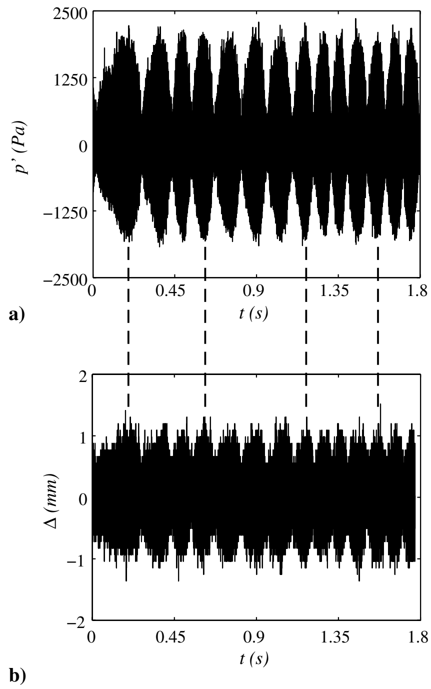

Fig. 3 Time traces of a) microphone signal at $\phi_m = 0$ deg, and b) location of the shock tip 1.

difference to the reference microphone located arbitrarily at $\phi_m = 0$ deg has been computed from the time delay yielding the maximum cross correlation between each pair of envelopes. The results are displayed in Fig. 4. The phase relations, written as $\Delta\psi$, are expressed as a fraction of the time period of the envelopes. Thus, $\Delta\psi = 0$ means that the bursts are in phase, whereas $\Delta\psi = \pm 0.5$ stands for an opposite phase relation. The evolution of the phase relations between envelopes is linear with the azimuthal angle, which reflects the stable rotation speed of the plane of antisymmetry.

The shock motion for shock tip 1 is presented in Fig. 3b. Here again, the oscillatory characteristics of the shock are closely linked to the pressure signal measured in the same plane because the bursts on both acoustic and shock motion signals are seen to be in phase.

This link is now investigated in greater detail by considering the motion of all shock tips. Envelopes for the shock motion signals have also been computed and are displayed for a time extract in Fig. 5, along with that of the microphones located at $\phi_m = 0$ and 100 deg. The envelopes of the shock displacement for the vertical view and of the microphone signal at $\phi_m = 0$ deg are in phase, as already noted in Fig. 3. The same statement holds true for the horizontal view of the shock with the microphone at $\phi_m = 100$ deg, although the phase matching is only approximate in this case because this microphone is not exactly in the plane of view of the double-pass schlieren system. Furthermore, the bursts for the two orthogonal schlieren views are in opposite phase relation, as are the associated pressure signals.

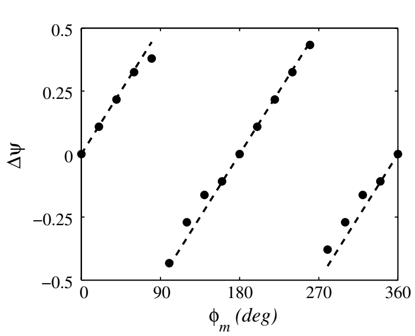

Fig. 4 Phase relation between each microphone of the azimuthal antenna and the microphone at $\phi_m = 0$ deg, represented by solid dots. Linear phase variation with 180 deg periodicity, represented by dashed lines.

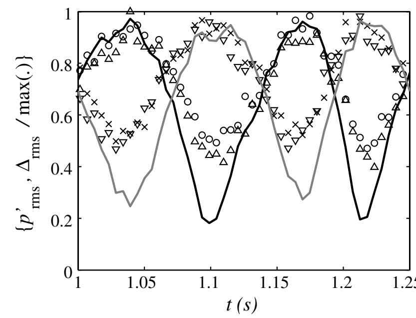

Fig. 5 Envelopes of pressure signal at $\phi_m = 0$ deg (black line), pressure signal at $\phi_m = 100$ deg (gray line), shock tip 1 (Δ), shock tip 2 (∘), shock tip 3 (×), and shock tip 4 (∇).

The conclusion drawn in Sec. III.A is thus confirmed here; in the case of a flapping screech mode, the shocks inside the jet plume also flap about the same plane. When the acoustical plane rotates, so does the plane of antisymmetry inside the jet.

IV. Conclusions

The shock oscillations in an underexpanded supersonic jet at a fully expanded Mach number of 1.50 have been investigated by means of two schlieren systems set orthogonally to one another. At this operating condition, the screech is flapping. Two recordings of a stable as well as an unstable screech case have been performed. The instability is here the consequence of a rotating plane of antisymmetry arising from the coexistence of two counter-rotating helices of different frequencies. The shock motion has been tracked using the same algorithm as previously reported by the authors.

In the case of the stable flapping screech, the vertical and horizontal views of the first shock have shown very different oscillation amplitudes, which can be linked to the properties of the near acoustic pressure field. The similarity goes on when the plane of antisymmetry rotates; the modulation of screech strength in time at $\phi_m = 0$ deg exactly corresponds to a similar modulation of shock oscillation amplitude in the vertical view, whereas the bursts of the shock motion in the horizontal view are in opposite phase relation, as are the horizontal pressure signals. This emphasizes that the plane of antisymmetry of the shock motion rotates just like the acoustical plane of antisymmetry and that both planes are in fact only just one.

It is demonstrated here that the oscillation pattern inside the jet is an exact replica of that of the acoustic field, which should not be so surprising, owing to the causality relation linking the two. With a usual, two-dimensional view of the flow and of the acoustic pressure field, only a projection of the plane rotation on the viewing direction is observed, which does not permit all the dynamics of the shock oscillation and associated pressure fluctuation patterns to be unveiled.

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