Jet instabilities producing the slot-tone

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Introduction

In the present paper, the nature of the jet instability governing the slot-tone is identified experimentally. The slot-tone is a class of self-sustained tones created by the impingement of a free jet on a slotted plate (Figure 1) [1,2,3]. The studied configuration presents the particularity that the tones are the result of a direct feedback path for the lower Reynolds numbers whereas, above $Re \sim 1 \cdot 10^4$, the resonances of the flow supply duct are excited and the indirect feedback path created is then dominant [4,5].

A free jet has two main instabilities. The first, the shear layer natural instability, is dominant upstream the extremity of the potential core (4 to 6 times the jet height [6]) and its frequency, f_n, is calculated, for a hyperbolic velocity profile, with the following relation [7]:

$$St = \frac{f_n \cdot \theta}{U_{0\max}} \approx 0.017 , \quad (1)$$

where U_{0max} is the maximal flow velocity and θ the momentum thickness [7]. The second instability, the jet column mode governs the global oscillation of the jet and is dominant downstream the potential core. Its frequency, f_j, is calculated with the following relation [8], where H is the jet height:

$$St_j = \frac{f_j \cdot H}{U_{0\max}} \approx 0.25 . \quad (2)$$

Ziada [3] made the assumption that, for the slot-tone, the instability governing is the shear-layer natural instability, as opposed to the edge-tone, result of the amplification of the column mode of the jet [9]. Recent works [10] showed for flue instruments that both flow instabilities can be responsible of the tones production, depending on the distance from the flue channel to the labium: for shorter distances, the shear layer instability and, for greater distances, the global oscillation of the jet.

Experimental apparatus

After a settling chamber, a flow produced by a fan follows a duct with a rectangular section (9x19 cm) made of 5 mm thick aluminium and a 20 cm contraction nozzle (Figure 1); it creates then a 1 cm high and 19 cm wide subsonic free jet. A 5 mm thick aluminium 25x25 cm plate is fitted with a bevelled slot with the same dimensions that the nozzle outlet and carefully aligned with it. The experimental set-up was designed to permit the variation of the following dimensionless geometrical and flow parameters: L/H, the distance of the plate ($0<L/H<8$) and the jet Reynolds number: $Re = U_0 H/\nu$ (where U_0 is the average velocity of the flow at the nozzle with U_0<32 m/s, $Re<2 \cdot 10^4$ and $M_0=U_0/c<0.1$).

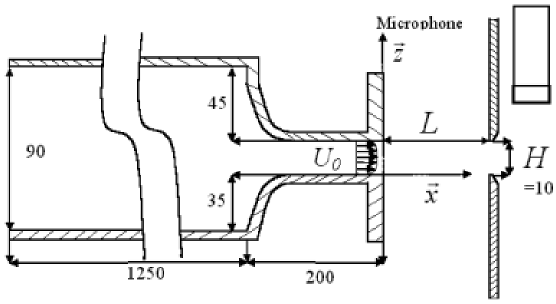

Figure 1: sketch of the experimental set-up (in mm).

The flow velocity is measured at the nozzle outlet by a 55R04 Dantec hot wire anemometer and the sound pressure level with a 7013 ACO Pacific microphone placed behind the plate to avoid hydrodynamic disturbances. As the tones are not pure, their fundamental frequency is defined as the frequency of maximum sound intensity.

Results and discussion

Firstly, velocity profiles without the plate are completed at x=3 mm for a range of Reynolds numbers. Figure 2 shows a typical velocity profile (○) and a hyperbolic approach (dotted line).

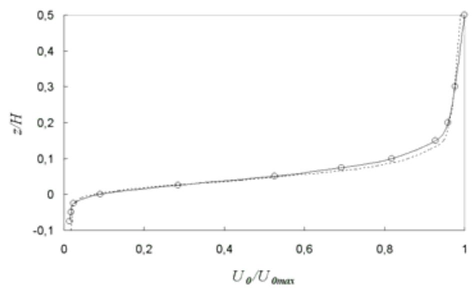

Figure 2: Half experimental velocity profile (○) and hyperbolic tangent profile approach (--); ($Re=9.9 \cdot 10^3$).

The good agreement between the experimental data and the hyperbolic profile allows one to use relation (1) to calculate f_n from θ (solid line in Figure 3). Moreover, the jet column mode frequency f_j is evaluated with relation (2) (dotted line). Then, the minimal (△) and maximal (□) tone fundamental frequencies searched for any plate position at a given Reynolds number. It's found that the highest frequencies are emitted for small distance of the plate (L/H<2) while the lowest are obtained for L/H greater than 4. Both frequencies are reported in Figure 3.

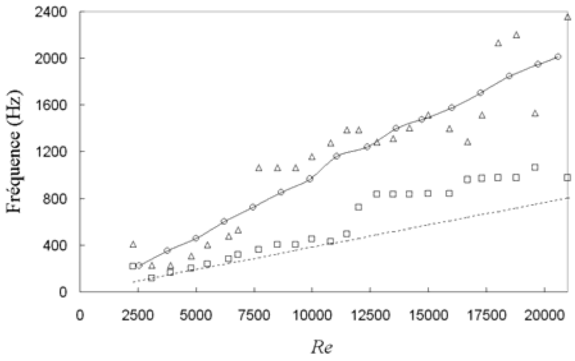

Figure 3: Evolutions of the natural shear-layer (○), the jet column mode frequencies (- -) and the lowest (△) and the highest (□)tone frequencies as a function of the Reynolds number.

The frequency of both instabilities defines the frequency domain of the self-sustained tones. The lowest frequencies of the tones, obtained when the plate is placed downstream the end of the potential core, are the result of the amplification of the column mode frequency. Tones with a frequency lower than the jet column mode frequency are rarely observed. On the other hand, the maximal frequency of the tones, obtained when the plate is situated upstream the end of the potential core, is close to the natural shear-layer frequency. For a dominant indirect feedback path, Figure 4 plots, the highest tone frequency (a, △) the sound pressure at this frequency (b, solid line) and the maximal sound pressure level (b, dotted line), obtained for any plate distance at the same Reynolds number.

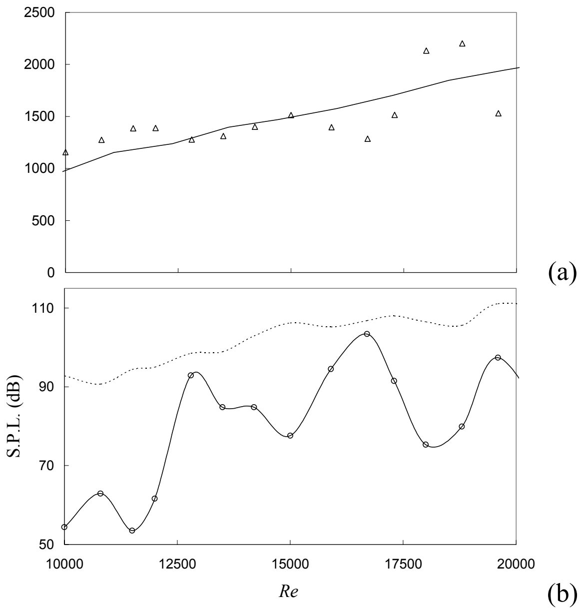

Figure 4: (a) Evolutions of the natural shear-layer frequency (——) and of the highest self-sustained tone frequency (△); (b) evolution of the sound pressure level at the highest frequency (——) and the highest sound pressure level (- -) as a function of the Reynolds number.

When the tone frequency is higher than the natural shear-layer frequency, the sound pressure level produced is about 20 dB below the maximum sound pressure level measured at the same Reynolds number. On the other hand, when the tone frequency is inferior to the natural shear layer frequency, the two sound pressure levels are close. Similarly, Blevins [11] showed for the vortex shedding from a cylinder in a flow that the coupling between the shear layer instability and an acoustic excitation is much better when the excitation frequency is inferior to the shear layer frequency. It confirms the prominent role of the shear-layer instability in the self-sustained tone process for the highest frequencies.

Conclusions

The nature of the instability governing the self-sustained tones produced by a low Mach number plane jet impinging on a slotted plate, known as slot-tone, is identified experimentally. For a given Reynolds number, the natural shear-layer and the jet column mode frequencies of the free jet delimit the values of the measured slot-tone operating frequencies. The oscillations at lower frequencies emitted when the plate is situated downstream the extremity of the potential core are the result of the amplification of the jet column mode. Conversely, those at higher frequencies are obtained the plate is placed upstream the end of the potential core and correspond to the shear layer instabilities.

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