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Two feedback paths for a jet-slot oscillator

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Abstract

The coupling between a subsonic jet-slot oscillator (usually referred to as a slot-tone) and acoustical resonances of the flow supply duct is investigated experimentally. The aspect ratio of the jet height H to the slot stand-off distance L is varied in the range $0 \leqslant L/H \leqslant 8$. The Reynolds (Re) number based on the jet height is varied in the range $0 \leqslant \mathrm{Re} \leqslant 2 \times 10^4$. The acoustical pressure measured at the back of the slot-plate at a distance of 75 mm from the slot edge reaches whistling values to the order 10^{-2} of the stagnation pressure (or 115 dB SPL). Two types of oscillation behavior have been observed depending mainly on Re. For lower Re values, a hydrodynamic oscillator (edge-tone like) is generated, while for $\mathrm{Re} \geqslant 10^4$, the oscillator is coupled to the resonances of the flow supply duct. This resonant duct creates an indirect feedback path (organ-pipe like) that controls the tone frequency and reinforces their amplitude. An important result is that this lock-in phenomenon involves very high-order nonplanar acoustical modes (up to the 32nd). The introduction of damping foam in the flow supply duct induces a decrease of the emitted levels reaching 25 dB for the emitted levels, but the oscillation behavior remains dependent on the duct resonance. This indicates that purely hydrodynamical behavior cannot be studied without a special design of the flow supply.

1. Introduction

Several configurations in which a shear layer interacts with an obstacle can generate self-sustained tones. This article deals with the impingement of a free jet with a rectangular section and a large aspect ratio on a slotted plate (Fig. 1) and its coupling with high-order acoustic modes. This configuration produces a class of self-sustained tones known as ''slot-tones'' (Rockwell and Naudascher, 1979; Ziada, 1995, 2001). In the case of an axisymmetric geometry this is called a hole-tone (Rockwell and Naudascher, 1979; Blake, 1986).

Without acoustic resonance effects, the self-sustained oscillations are created by a direct (or hydrodynamic) feed-back loop (edge-tone like): the distortion of the vorticity upon flow impingement is fed back upstream, where new disturbances are induced at the separation location (Rockwell, 1983). For the hole-tone, the frequency of the oscillations is then dependent on the Strouhal number based on the stand-off distance (Sondhauss, 1854). With increasing flow speed, this Strouhal number describes increasing stages, linked with the hydrodynamic mode of the jet. Moreover, the tones are observed for a laminar jet (Chanaud and Powell, 1965) or when it becomes turbulent (Matta,

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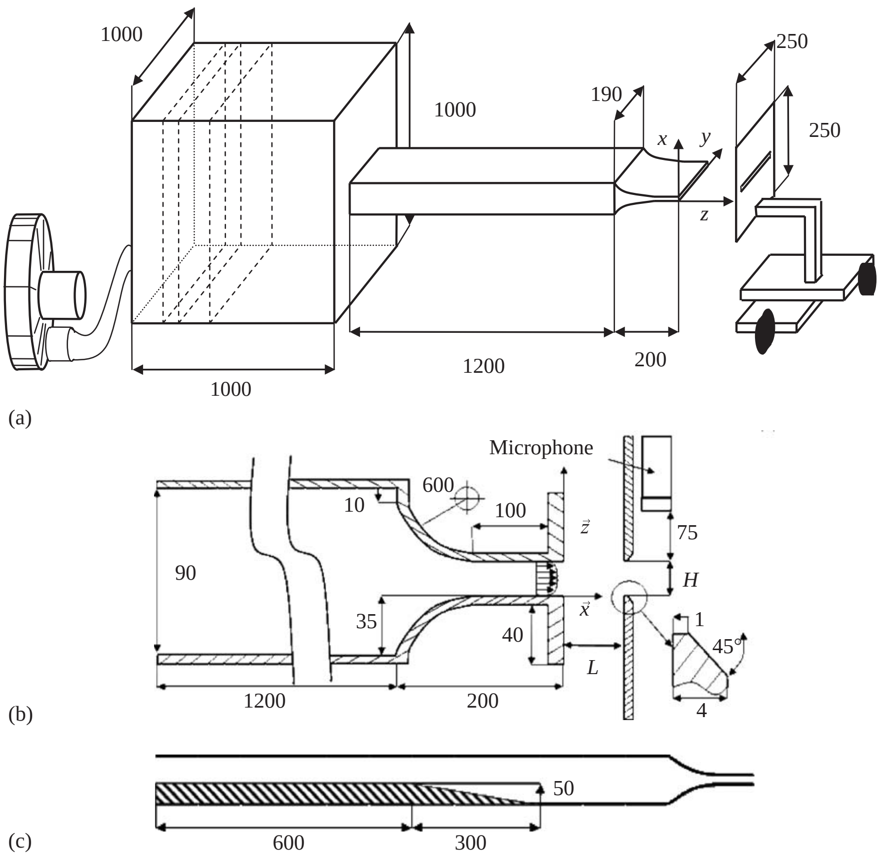

Fig. 1. (a) Experimental set-up; (b) test section; (c) configuration with damping foam (distances are given in mm).

1973). For turbulent jets and high sonic speeds, Chanaud and Powell reported that a much less clear sound was emitted, unless some confinement around the slot is added (Ziada, 1995).

The excitation of an acoustic resonance, creating an indirect (or acoustic) feedback path, can reinforce the level of the tones and control their frequency. This phenomenon has many applications (recess noise, organ pipe …) and has been extensively studied. Nevertheless, the interaction of the self-sustained oscillations with the acoustical resonances of the cavity from which the jet flows out has rarely been studied. Wilson et al. (1971) reported a noteworthy sound pressure level increase when the tone frequency was close to a resonance of the flow supply duct. Moreover, the frequency of the pipe-tone (Anderson, 1953, 1954, 1955) or of the whistler nozzle (Hill and Greene, 1977; Hirschberg et al., 1989) is controlled by the longitudinal resonant modes of the pipe. For two baffles in tandem in a duct, Huang and Weaver (1991) thus showed that the same resonance of the duct can be excited by different hydrodynamic modes of the jet, depending on the flow velocity. The Strouhal number then describes decreasing stages with increasing Reynolds number. The lowest Strouhal stage, i.e. the simplest hydrodynamic mode, usually corresponds to the highest sound pressure (Rienstra and Hirschberg, 2002). Identical results were obtained by Nomoto and Culick (1982), Isaacson and Marshall (1981) and Hourigan et al. (1990). However, in all these studies only the first few acoustical modes of the excited cavities were observed.

The object of this paper is to investigate the effect of resonances of the flow supply duct on the slot-tone production. This kind of a phenomenon can be encountered in air conditioning applications. After a presentation of the experimental setup (Section 2), the operating ranges of these tones are described in Section 3. Then, in Section 4, the influence of two control parameters (the plate distance and the jet velocity) on the tone frequency is studied. Section 5 shows that two feedbacks can control the self-sustained oscillations: one direct, and the other one indirect, resulting in the excitation in high-order resonances of the flow supply duct. The effects of the introduction of acoustic damping foam in the duct are reported in Section 6.

2. Experimental set-up

The experimental set-up, shown in Fig. 1, was designed to allow the variation of the following geometrical and flow parameters: L, the distance between the plate and the nozzle outlet (or stand-off distance), and U_0, the average velocity of the flow at the nozzle. The duct has a rectangular cross-section of 9×19 cm made of 5 mm thick aluminum and is followed by a 20 cm contraction nozzle. It creates a 1 cm high and 19 cm wide free jet. The jet height is denoted by H and its width (in the y-direction) by L_y. A settling chamber is placed upstream of the duct to ensure acoustic isolation of the duct from the blower. A 5 mm thick aluminum 25×25 cm plate is fitted with a beveled slot of the same dimension as the nozzle outlet and is carefully aligned with the nozzle using a gauge and a displacement table. The dimensionless distance between the nozzle outlet and the slot, L/H, called ‘‘length parameter’’ in this paper, may vary between 0 and 8. L is defined with a precision of 0.1 mm.

A Dantec hot wire anemometer 55R04 is used to measure the velocity of the flow at the nozzle outlet. The average velocity U_0 may vary from 0 to 32 m/s (Mach number lower than 0.1). For later use, we can define a Reynolds number linked to the jet dynamics $\mathrm{Re} = U_0 H/v$, where v is the kinematic viscosity of the air. During slot-tone operation, a 7013 ACO Pacific microphone, placed behind the plate and at 75 mm of the slot to avoid hydrodynamic disturbance, measures the near-field-radiated pressure fluctuations, and another one is flush-mounted at the duct wall. We call the fundamental frequency of the tones, denoted by f_0, the frequency at maximum sound intensity. We can now define a Strouhal number linked to the jet-slot oscillations $\mathrm{St}_L = f_0 \times L/U_0$, constructed from the nozzle/plate distance. For all the results presented and in order to allow judgment of the oscillation intensity at different test conditions, the r.m.s. value of the pressure variation $P_{\mathrm{r.m.s}}$ is normalized by the dynamic head of the jet, i.e.,

$$\bar{P} = P'_{\mathrm{r.m.s}} / \tfrac{1}{2}\rho U_0^2. \tag{1}$$

In preliminary tests, the frequencies of the resonant modes of the combined aluminum duct with a constant rectangular section and the contraction nozzle have been measured. An external source excited the duct without any flow or obstacle and its response was measured by a set of microphones flush-mounted at different locations along the duct. The results are presented in Fig. 2(a). Due to the shape of the duct followed by the convergent section, the resonant mode frequencies have no equal spacing, even when only planar modes are propagating. The frequency of the first resonant longitudinal mode was measured to be equal to 85 Hz and the first transverse mode equal to 905 Hz. Above this frequency, the resonance density increases and the resonances observed in the duct are a superimposition of longitudinal resonances and the first transverse resonance. For instance, Fig. 2(b) plots the pressure phase along the y (spanwise)-axis for two resonant frequencies above the first transverse mode cut-off frequency, just at the nozzle exit. The 22nd mode (1118 Hz) contains mainly the planar mode (no phase variation along the span of the nozzle exit), while the 17th and 27th modes (respectively, 967 and 1270 Hz) are significantly affected by transverse resonance. Indeed, when the plane wave mode and the first transverse mode are both propagated, the phase change along the span can take on any value between 0° (plane wave mode alone) and 180° (transverse mode alone), according to the relative values of the amplitudes of these two modes. Moreover, the spanwise phase pattern of the acoustic pressure is not necessarily symmetric with respect to $y = 0.5$, as shown in Fig. 2(b). It will be seen in the following that such high-order modes can be excited in the tone generation. For later use, acoustic damping foam is added within the duct (Fig. 1(c)) to further observe its effect on the slot-tone (Section 6). In this configuration, the duct resonances are greatly damped above 400 Hz.

3. Operating range of the self-sustained tones

To define the operating range of the slot-tone the self-sustained oscillations are investigated with the microphone placed behind the slotted plate according to both control parameters. The two control parameters, the Reynolds number and the length parameter, are, respectively, increased by steps of 800 for Re and of 0.3 for L/H over their respective ranges ($0 \leqslant \mathrm{Re} \leqslant 2 \times 10^4$, $0 \leqslant L/H \leqslant 8$). Fig. 3 shows the dimensionless sound pressure as a function of both control parameters.

Domains 2–4 correspond to the domain where self-sustained tones are emitted (each domain will be defined in Section 5). For Reynolds numbers higher than 2.4×10^3 and for $1.3 < L/H < 7.5$, harmonic tones appear and the sound pressure level rises significantly with Re, reaching -20 dB (1% of the stagnation pressure). These maximum levels correspond to 115 dB if the SPL is normalized with the reference pressure 2×10^{-5} Pa. The minimum stand-off distance decreases slightly with increasing jet velocity as reported in previous works (Chanaud and Powell, 1965), but a disappearance of the tones is not observed, the flow velocity obtainable with the blower being too low.

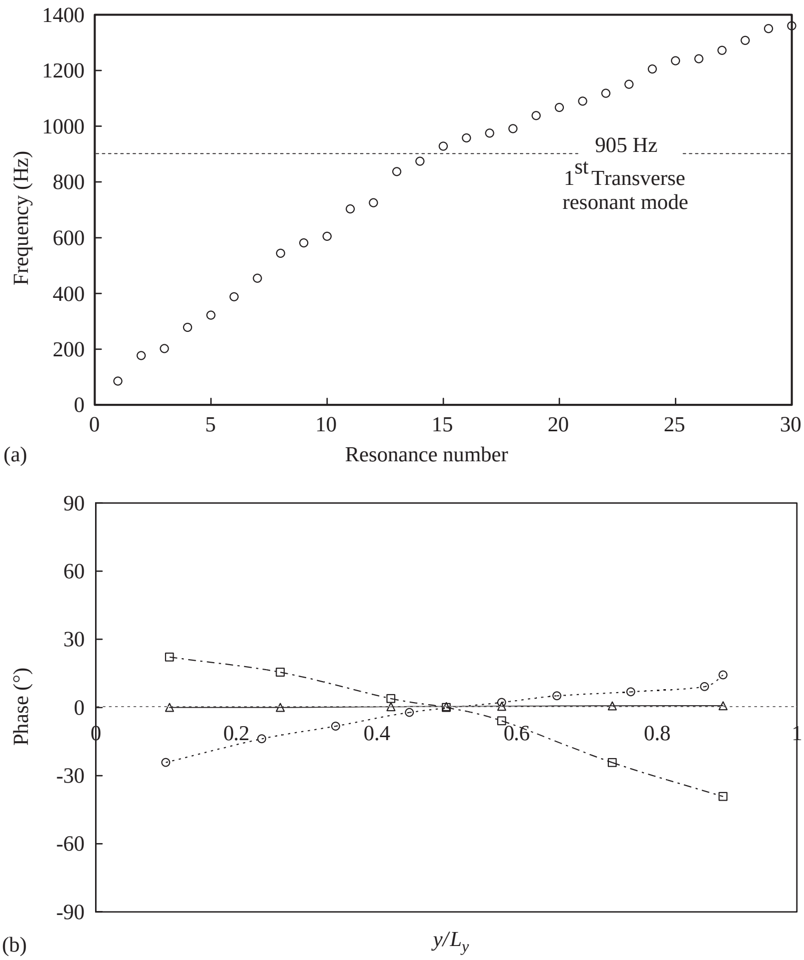

Fig. 2. (a) Frequency of the measured acoustic resonances of the duct. (b) Transverse pressure evolution in the convergent section (○, 967 Hz; △, 1118 Hz; □, 1270 Hz).

Domain 1 corresponds to the domain where broad-band noise is measured. Below $\mathrm{Re} \simeq 2.4 \times 10^3$ and $L/H = 1.3$, a wide-band noise with a low level is emitted without any discrete frequency, similar to the one produced by the jet without the obstacle but with a higher level (around 5–10 dB). For $L/H > 7.5$, harmonic tones disappear and the sound pressure level decreases significantly. Self-sustained tones are observed only when the jet becomes turbulent ($\mathrm{Re} > 2 \times 10^3$), whereas Chanaud and Powell (1965) reported clear tones with a laminar jet for a hole-tone. These discrepancies may be due to the geometrical differences between both devices.

Fig. 4 shows a typical power spectrum of the pressure signal of the self-sustained tones produced. It exhibits a fundamental frequency f_0 at 1182 Hz, a subharmonic $f_0/2$, as well as a harmonic and a nonlinear interaction between the sub-harmonic $f_0/2$ and the fundamental f_0 at frequency $3f_0/2$. In the following sections, we will concentrate on the behavior of the fundamental frequency of the tones in domains 2, 3 and 4 of Fig. 3.

4. Evolution of the tones with the control parameters

4.1. Evolution of the tone frequency with nozzle/plate distance (L/H)

Here we investigate here the evolution of the tone fundamental frequency f_0 with the length parameter L/H, by considering the Strouhal number ($\mathrm{St}_L = f_0 L/U_0$). Results for two Reynolds numbers which exhibit different behaviors

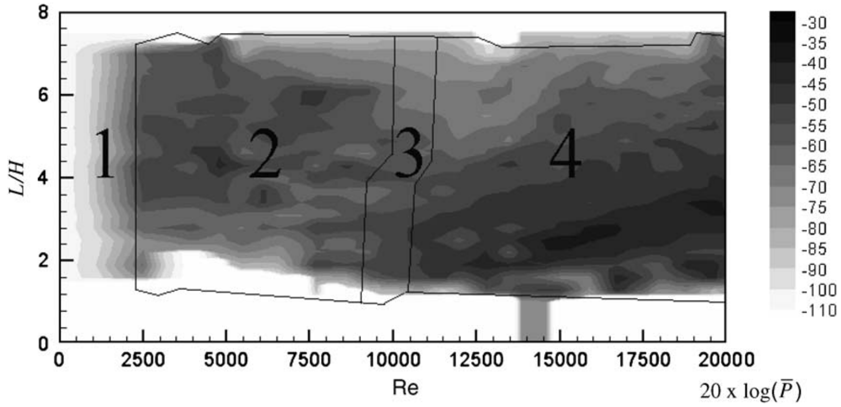

Fig. 3. Dimensionless sound pressure level as a function of L/H and the Reynolds number (1: broad-band noise; 2: hydrodynamic feedback; 3: both feedbacks; 4: acoustic feedback).

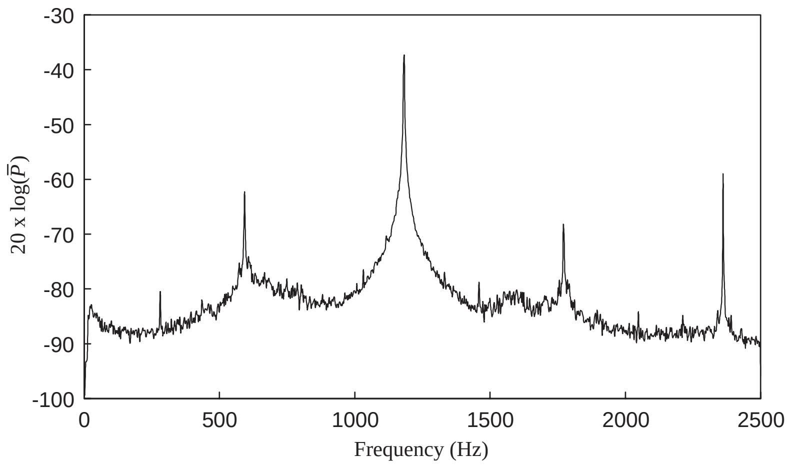

Fig. 4. Example of noise spectrum ($L/H = 3.0$, $\mathrm{Re} = 1.9 \times 10^4$).

are as follows : $\mathrm{Re} = 6.5 \times 10^3$ ($U_0 = 10\,\mathrm{m/s}$) and $\mathrm{Re} = 1.18 \times 10^4$ ($U_0 = 18.1\,\mathrm{m/s}$). The plate has been first moved downstream (open circles in Fig. 5), from 0 to 7 L/H, and then back in the upstream direction (open triangles in Fig. 5). Fig. 5 shows the Strouhal number of the tones as a function of the length parameter.

The overall evolution of the two curves shows some similarities. They are formed by a succession of stages with abrupt jumps that are often associated with hysteretic effects, typical of self-oscillating systems. The general behavior of Fig. 5(a) is in good agreement with both the results of Matta (1973) and Von Gierke (1950) for a hole-tone device without acoustic resonance. For both curves, each stage corresponds to a certain number of vortices present at the same instant between the nozzle outlet and the plate. Whereas each stage of the Strouhal number is somewhat smooth and continuous in Fig. 5(a), it is characterized by a succession of small notches in Fig. 5(b). The notches represent stages of nearly constant frequency over a certain distance, indicating that the self-sustained tones lock on specific acoustic resonances. The strong correlation between the pressure fluctuations at the slot and in the pipe confirms this (Fig. 7(b)). When the plate distance is further increased ($L/H > 4.2$), i.e. when the slot is situated downstream of the end of potential core of the jet [between 4 and 8H (Weir et al., 1981)], the Strouhal number reduces dramatically to half its value and remains almost constant. More explanation on these two behaviors will be given in Section 5 and, for this purpose, Points A and B have been marked in Fig. 5.

4.2. Evolution of the tone frequency with the jet velocity (Re)

We now focus on the influence of the jet velocity on the tone frequency. The length parameter is set to $L/H = 3.0$ and the jet velocity is increased from $\mathrm{Re} = 2 \times 10^3$–$2.1 \times 10^4$ ($U_0 = 32\,\mathrm{m/s}$). In Fig. 6 the Strouhal number St_L (a, open

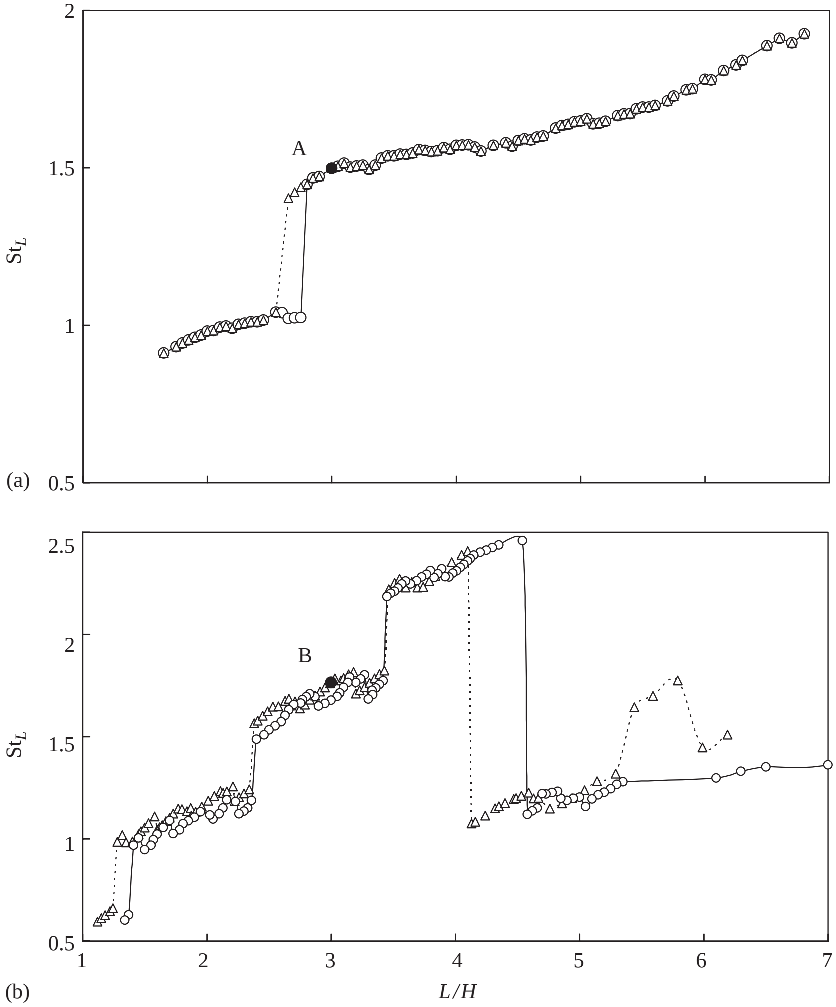

Fig. 5. Evolution of the Strouhal number with L/H: (a) $\mathrm{Re} = 6.5 \times 10^3$; (b) $\mathrm{Re} = 1.18 \times 10^4$; (○, downstream shifting; △, upstream shifting).

circles) and the dimensionless radiated sound pressure level (b, solid line) are plotted as functions of the Reynolds number.

Fig. 6(a) shows that the Strouhal number evolution forms four successive stages with increasing Reynolds number. The transition from the first ($\mathrm{St}_L \sim 1.10$) to the second stage ($\mathrm{St}_L \sim 1.60$) appears to be characteristic of the behavior of a self-oscillating system with a dominant hydrodynamic feedback path, as reported for the edge-tone for instance. A Strouhal number increase indicates a transition to a higher hydrodynamic mode, as shown by Matta (1973) for the hole-tone: the number of vortices present between the nozzle outlet and the plate increases. Nevertheless, the phenomenon is somewhat unstable, as the Strouhal evolution for $8 \times 10^3 < \mathrm{Re} < 1 \times 10^4$ shows that the oscillator often shifts from one to the other mode. In Section 5, the sound pressure level peaks in Fig. 5(b), at $\mathrm{Re} = 3.2 \times 10^3$ and 5.3×10^3, will be commented upon.

Conversely, the transition from the third stage ($\mathrm{St}_L \sim 1.76$) to the fourth stage ($\mathrm{St}_L \sim 1.23$) of Fig. 6(a) is associated with a decrease of the Strouhal number with increasing Reynolds number, typical of a dominant acoustic feedback path [e.g., Nomoto and Culick (1982)]. Moreover, the third and fourth stages exhibit notches indicating that the tones lock on a specific acoustical resonance as in Fig. 5(b), indicating the dominance of an acoustic feedback.

Under this assumption, the transition from the second to the third stage at $\mathrm{Re} \sim 1 \times 10^4$ seems to be due to the excitation of an acoustic resonator. In this study, the only part of the experimental setup which can act like an acoustic resonator is the flow supply duct. The increase of the tone frequency at $\mathrm{Re} = 1 \times 10^4$ is associated with an increase in

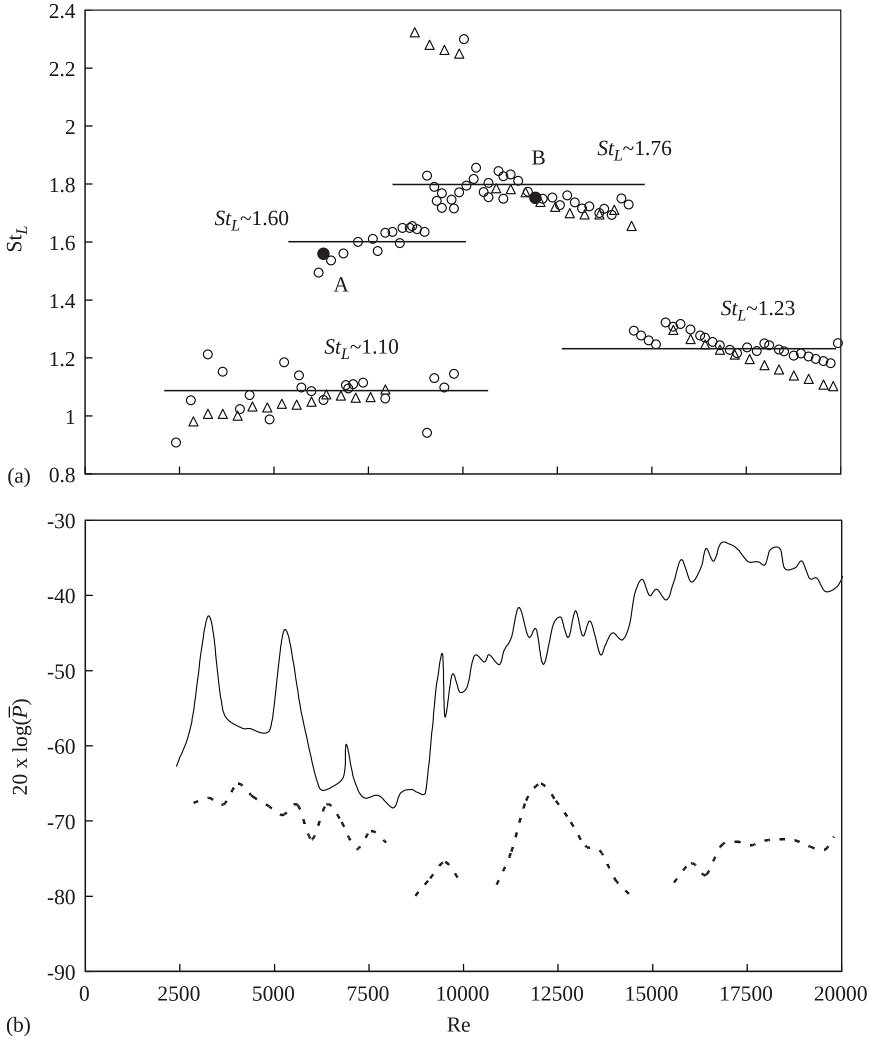

Fig. 6. (a) Strouhal number and (b) dimensionless sound pressure level as a function of the Reynolds number ($L/H = 3.0$); (○, solid line: normal configuration; △, dotted line: damped configuration).

the sound pressure level of about 20 dB, which is a consequence of an improvement of the feedback loop efficiency through the resonance of the duct.

To verify the assumption of a dominant hydrodynamic feedback path for the first and second stages and a dominant acoustic feedback path for the third and fourth stages, we shall focus in the next section on the acoustic behavior of the duct and its coupling with the slot-tone.

5. Coupling with the duct resonances

To evaluate the coupling between the acoustic field within the duct and the radiated acoustic field, an experiment is reported in which both acoustic fields are compared. For this purpose, a first microphone is placed just after the plate, measuring the sound pressure radiated from the slot-tone oscillator, called an 'outer signals' in the following. A second one is flush-mounted at the wall of the duct at different locations along the center of the pipe ($y/L_y = 0.5$) and measures the acoustic field inside the duct (inner signal). The length parameter is set to $L/H = 3.0$, and the two mean jet velocities that were used were the following: $\mathrm{Re} = 6.5 \times 10^3$ (corresponding to point A of Figs. 5(b) and 6(a), location of the flush-mounted microphone $x/H = -83$) and $\mathrm{Re} = 1.18 \times 10^4$ (point B, Figs. 5(b) and 6(a), location of the flush-mounted microphone $x/H = -85$). Fig. 7 gives the spectra of the signals of the inner (top) and outer (middle) microphones and their coherence (bottom). The left and right figures depict, respectively, the results for points A and B.

For point A, the outer pressure signal exhibits a well-defined frequency, whereas the inner one shows that several resonant modes are excited but none is preponderant. No standing wave pattern is observed in the duct. The coherence between the inner and outer acoustic fields is low at the tone frequency (607 Hz). The pipe does not create any feedback path; thus the hydrodynamic feedback is dominant in the self-oscillating system.

For point B, the tones emitted are more powerful. Both inner and outer spectra are similar and exhibit a broad peak of coherence at the tone frequency (969 Hz). Besides, at the tone frequency, a regular pattern of the sound pressure level distribution in the direction of the duct is observed, characteristic of standing waves in ducts. Fig. 8 presents the evolution of the pressure along the center of the duct in Pa (P_{in}) normalized to the pressure of a radiated field in Pa (P_{out}) (to remove pressure fluctuations that could occur during the experiments) as a function of the location along the duct for two different length parameters and Reynolds numbers. The spatial period of the observed patterns along the x-direction in the duct is close to the wavelength of the acoustic field radiated by the slot-tone. In this case, the pipe acts

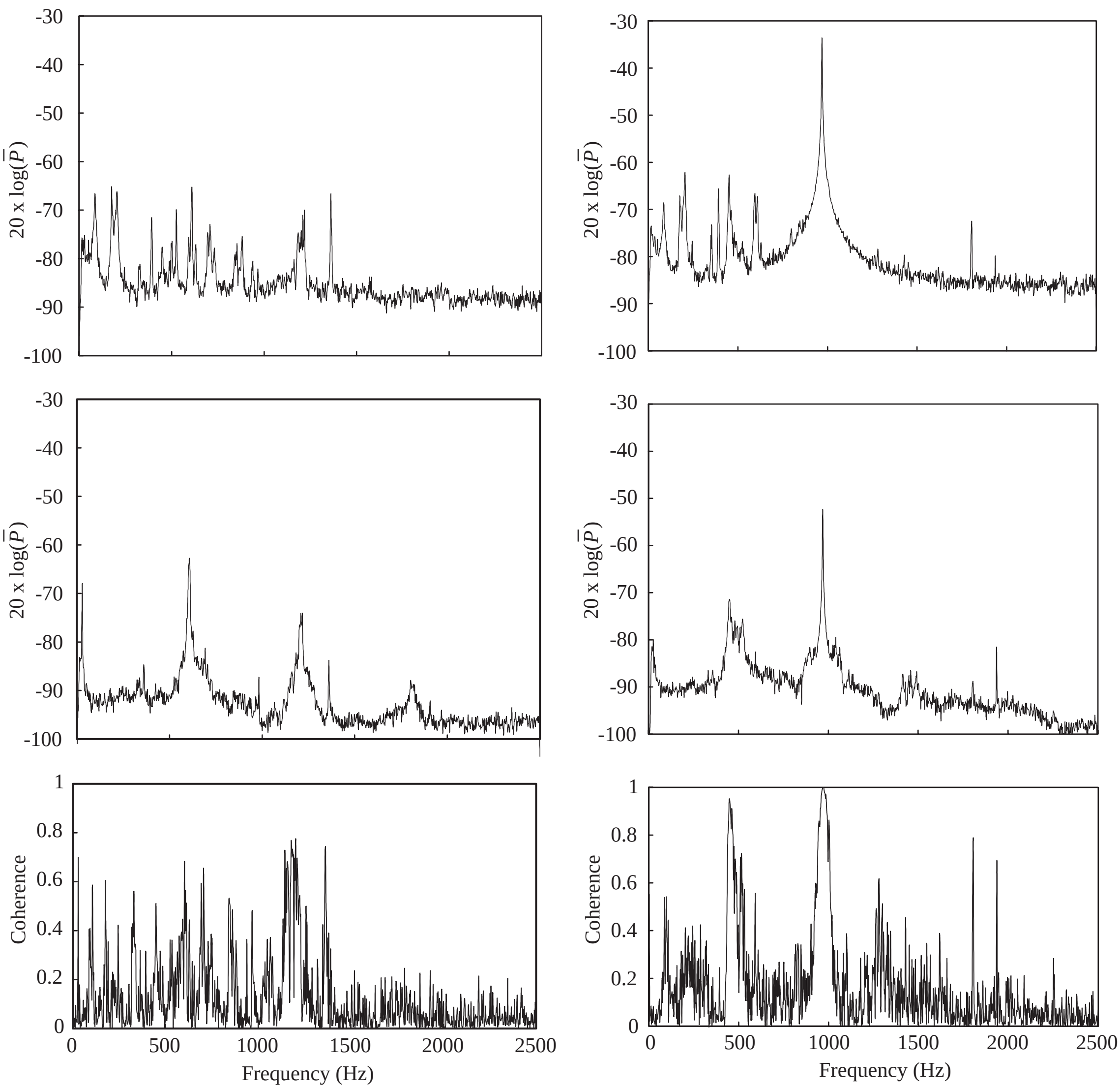

Fig. 7. Spectra of the inner (top) and the outer pressure signals (middle) and their coherence (bottom); left: point A; right: point B of Fig. 5.

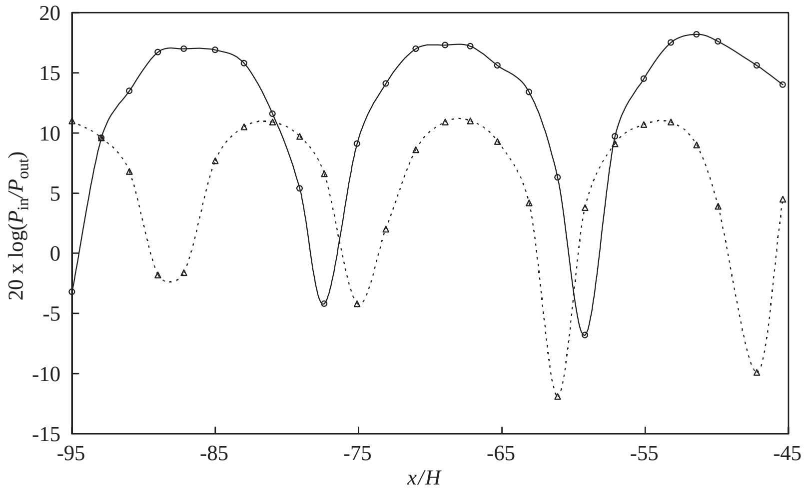

Fig. 8. Evolution of the acoustic pressure within the duct normalized by the pressure of the radiated acoustic field along the x-axis of the duct; (○, $\mathrm{Re} = 1.73 \times 10^4$, $L/H = 2.3$, $f_0 = 1270\,\mathrm{Hz}$; △, $\mathrm{Re} = 1.08 \times 10^4$, $L/H = 5.3$, $f_0 = 967\,\mathrm{Hz}$).

as an excited acoustic resonator creating an indirect feedback path, which reinforces and controls the self-oscillation phenomenon. To better evaluate the influence of the coupling with the duct resonances, Fig. 9(a) presents the results of Fig. 5(b) when the plate is moved downstream in terms of frequency together with the resonant frequencies of the duct, and Fig. 9(b) presents the dimensionless sound pressure level for the same experiment.

It is seen in Fig. 9 that the self-sustained oscillations occur at frequencies of high-order modes of the duct until $L/H = 4.2$, ranking from the 32nd to the 17th. After this point, the most excited resonance of the duct is still the 17th one, corresponding to 962 Hz, but the radiated frequency decreases to 481 Hz with a strong component at 962 Hz. The acoustical coupling presented in Fig. 9 thus occurs over the whole spatial range of existence of the self-sustained tones. The successive decreases of the SPL indicated in Fig. 9(b) (dashed horizontal lines) correspond to successive shifts to higher hydrodynamic modes (i.e. increasing Strouhal number stages in Fig 5(b)). Indeed, as mentioned in Section 1, the simplest hydrodynamic modes are often the most energetic ones (Rienstra and Hirschberg, 2002).

Fig. 3 summarizes the evolution of the dominant feedback path; the occurrence of a duct resonance allows one to systematically assess the nature of the feedback. As explained in Section 3, Domain 1 corresponds to a domain where broad-band noise is emitted. Domains 2, 3 and 4 correspond to the area where the self-sustained tones occur. In Domain 2, consisting of the lower Reynolds numbers ($\mathrm{Re} < 9 \times 10^3$) for a given geometry ($L/H$ fixed), the frequency increases continuously with the Reynolds number and the sound pressure level is low: the self-oscillations are not acoustically resonant and result from the hydrodynamic feedback. However, localized intervals of coupling can occur, as in Fig. 6(b) at $\mathrm{Re} = 3.2 \times 10^3$ and 5.3×10^3. They correspond to the excitation of low-order resonances (here, the 3rd and the 5th) of the duct over a short range of Re. For higher Reynolds numbers (Domain 4), the vorticity of the shed structures increases and makes the excitation of an acoustic resonance of the flow supply duct possible. The resonant duct then creates an indirect feedback path (acoustic feedback) which controls the self-sustained oscillations and increases the sound pressure level radiated. The resonant field inside the duct and the radiated field are highly coherent, and the tone frequency jumps from one resonant mode of the duct to another when Re is varied. Domain 3 (Re between 9×10^3 and 12×10^3) is a transition area where both feedback paths can occur.

The excited resonances at higher Reynolds numbers correspond to very high-order modes, with a frequency above the frequency of the first transverse mode (905 Hz). This important result means that nonplanar high-frequency modes are able to control the self-sustained oscillations via acoustic feedback. Indeed, transverse modes are propagative only at high frequencies, but have a sufficiently high-quality factor to control the emitted tones. It is also noticeable that both high-order modes with no standing waves in the y-direction (e.g. the 22nd mode, see Fig. 2(b)), and modes with a transverse resonance (e.g. the 17th and 27th modes, Fig. 2(b)) can be excited. Hence, the occurrence of standing-waves in the spanwise direction is not directly correlated with the excitation or nonexcitation of a given mode (e.g. the 18th or the 21st modes are never excited). Moreover, as explained in Section 2, the excited high-order modes are not generally pure transverse modes but result from a superimposition of planar and transverse modes. Only the first transverse mode alone is 180° out of phase in the spanwise direction. As a result, the excitation of the jet is not generally out of phase on either side of the nozzle outlet, and the excitation of high-order modes can still produce an intense sound.

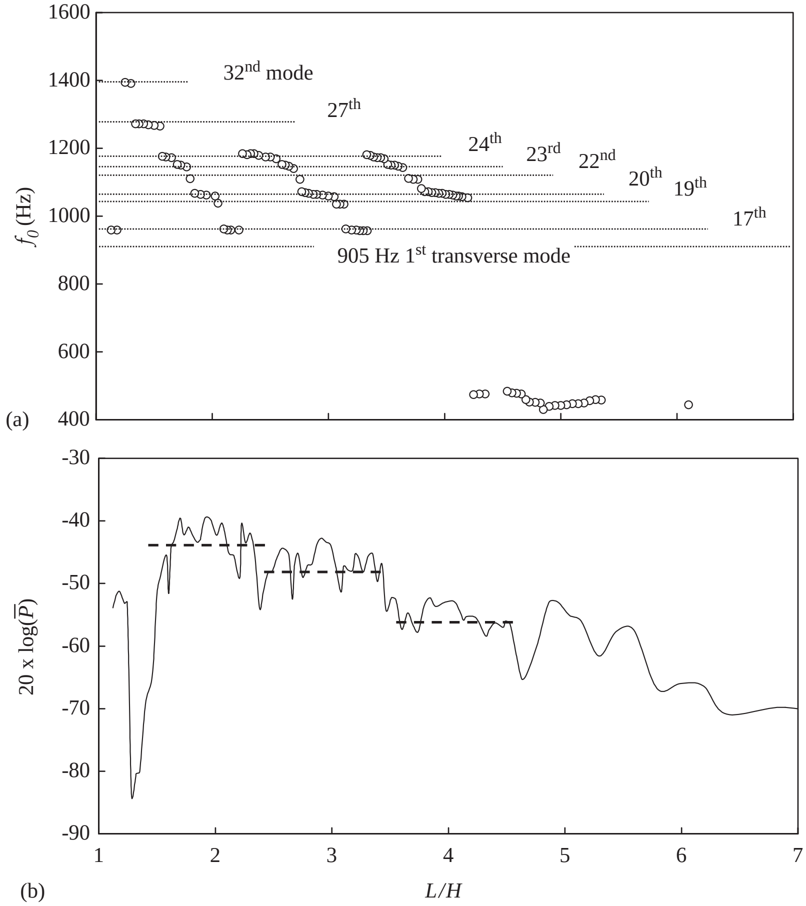

Fig. 9. (a) Tone frequency compared with the resonant modes of the duct and (b) dimensionless sound pressure level as a function of L/H ($\mathrm{Re} = 1.18 \times 10^4$).

Some further experimental data (not reported in this paper) did not show a clear correlation between the spanwise pressure phase variation and the spanwise velocity phase fluctuation at the nozzle outlet, in the case of transverse mode excitation. It is possible that the finite width of the jet produces extra spanwise effects which complicate the excitation mechanism of the shear layer. The excitation of slot-tones by transverse modes certainly deserves a more dedicated study.

6. Effect on the tones of the addition of damping materials in the duct

In industrial applications, the usual and easiest solution for reducing or suppressing the disturbances created by flow-tones is to add acoustic damping materials around the aeroacoustic source or the excited resonator. Moreover, to study the purely hydrodynamic behavior of an experimental flow-oscillator, the flow supply system resonances must be avoided. Some melamine foam is thus placed in the duct (representing 30% of the total duct volume) in order to reduce the coupling between the slot-tone and the duct resonances, while not excessively disrupting the flow (Fig. 1(c)). The same measurements as in Section 4.2. (Fig. 6) are conducted. The length parameter is set to $L/H = 3.0$ and the jet velocity is increased from $\mathrm{Re} = 2 \times 10^3$ to 2.1×10^4: the Strouhal number (open triangles) and the dimensionless radiated sound pressure level (dotted line) are plotted in Fig. 6 (a) and (b), for comparison with the results without the damping material (Fig. 6 (a) open circles for the Strouhal number, and Fig. 6 (b) solid line for the SPL).

The overall evolution of the Strouhal number is similar for both configurations, but a decrease of the dimensionless sound pressure level is observed, due to the damping foam. Whereas this decrease lies between 5 and 10 dB for the lowest Reynolds numbers (apart from $Re = 3.2 \times 10^3$ and 5.3×10^3 where low-order resonances are excited without the damping material), this reduction reaches 25–30 dB above $Re \sim 1 \times 10^4$. Nevertheless, for this range of higher Reynolds numbers, the duct is still resonant: the pressure spectrum inside the duct exhibits a main sharp peak, but the energy of this peak is highly attenuated by the foam. However, the duct resonance still controls the frequency of the emitted tones, with a high coherence between the inner and outer pressure fields at this frequency. Interestingly, the tone frequency evolution with Re is quite continuous; as noticed in Fig. 6(a), the Strouhal number does not display notches anymore at high Re with the damping foam. Thus, to observe the purely hydrodynamic behavior of a low-speed flow-tone, the flow supply duct must be very carefully designed to avoid acoustic resonances.

7. Conclusions

The coupling between a subsonic jet-slot oscillator (usually referred to as a slot-tone) and acoustical resonances of the flow supply duct is investigated experimentally. The apparatus consists of a jet flowing out from a duct and impinging on a slotted plate. The ratio of one jet height H to the slot stand-off distance L is varied in the range $0 \leqslant L/H \leqslant 8$. The Reynolds (Re) number based on the jet height is varied in the range $0 \leqslant Re \leqslant 2 \times 10^4$. The acoustical pressure measured at the back of the slot-plate at a distance of 75 mm from the slot edge, reaches up to whistling values of the order 10^{-2} of the stagnation pressure (or 115 dB SPL).

Two types of oscillation behavior are observed, depending mainly on Re. For the lower Re, a hydrodynamic oscillator (edge-tone like) is generated, while for $Re \geqslant 10^3$ the oscillator is coupled to the resonances of the flow supply duct. This resonant duct creates an indirect feedback path (organ-pipe like) that controls the tone frequency and reinforces the oscillation amplitude. An important result is that this lock-in phenomenon involves very high-order acoustical modes (up to the 27th), in the present case nonplanar pipe modes. The introduction of damping foam in the flow supply duct induces a decrease of the emitted levels, reaching 25 dB, but the oscillation behavior remains dependent on the duct resonance. This indicates that purely hydrodynamical behavior cannot be studied without a special design of the flow supply. Also, in industrial applications such as air-conditioning systems one could expect such coupling to be important.

Acknowledgments

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