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Experimental Investigation of the Aeroacoustic Coupling Between the Non-Planar Modes of a Resonator and the Misaligned Jet-Slot Oscillator

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Summary

The jet-slot oscillator is a source of aeroacoustic self-sustained tones resulting from the impingement of the vortical structures of a plane jet onto a slotted plate. The coupling of this type of aeroacoustic source with high-order acoustic resonances of the flow-supply duct is experimentally studied, in the particular case where the jet-exit and the obstacle are misaligned in the spanwise direction. An experimental setup based on microphones and hot-wire probes is used to investigate this coupling. It is shown that: (i) the misaligned jet-slot oscillator can be coupled to non-planar (transverse) modes of the flow-supply duct, (ii) the vortex tubes spanwise morphology is governed by the phase pattern of the excited modes, and (iii) the impingement of the vortices on the inclined obstacle tends to occur in phase in the spanwise direction, in order to enhance the coherence of the interaction along the slot. An investigation of the excited modes as a function of the plate inclination angle and of the streamwise slot position was then conducted. For small inclination angles, the coupling involves a planar mode or a combination of planar and transverse modes. For higher misalignment angles the coupling involves transverse modes or "opposite-transverse" modes, generating vortices with an inclination angle opposite to the plate inclination angle. The influence of the coupling nature on tone production (emission frequency and SPL) was thus evaluated.

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1. Introduction

Self-sustained tones can be produced when a sheared flow impinges on a downstream obstacle. These self-sustained acoustic oscillations have been extensively studied over the past fifteen years and overall their mechanism is well known [1, 2, 3, 4, 5, 6, 7]. The interaction of the jet and the obstacle produces a force on the fluid which gives rise to (i) an aeroacoustic source and (ii) a perturbation of the flow which is fed back directly to the jet exit, leading to a direct feedback path. If an acoustic resonator is located in the vicinity of the flow structure interaction domain, its excitation by the aeroacoustic source can also perturb the jet birth, creating a second feedback path called the indirect feedback path. The perturbations due to the dominant feedback path are amplified by the jet instabilities and again interact with the obstacle; a self-sustained loop is created. When a constructive phase relationship is met along this loop, high energy tones are generated [4].

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The configuration under study is the jet-slot oscillator (Figure 1), consisting in a plane jet impinging on a slotted plate [8, 9, 10]. This configuration experimentally models an HVAC air vent. Billon *et al.* [11, 9] observed the occurence of two different feedback paths, depending on the Reynolds number Re (based on jet height H). For values of Re smaller than 10000, the tones produced are the result of a dominant direct feedback path. The emitted sound pressure level, measured behind the obstacle, is then below 80 dB. In contrast, for $Re > 10000$, the indirect feedback path is dominant: the self-sustained oscillations are coupled with the acoustic resonances of the flow supply duct, and the sound pressure level can reach 115 dB. In this case, vortex shedding is synchronized with the acoustic velocity fluctuations induced at the jet exit by the resonance [4]. The duct resonances control the emitted tone frequency and enhance the emitted sound pressure level. The tone frequencies reported in reference [10] correspond to high-order longitudinal modes (up to the order of 16) of the flow supply duct, and can exceed the first transverse mode cut-off frequency. However, its excitation by the aeroacoustic source has not been observed in operating conditions [10].

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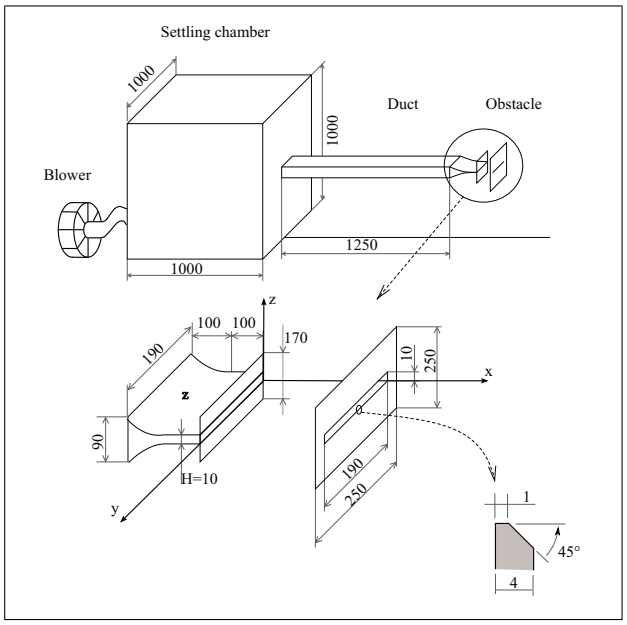

Figure 1. Overall view of the experimental setup (dimensions in mm).

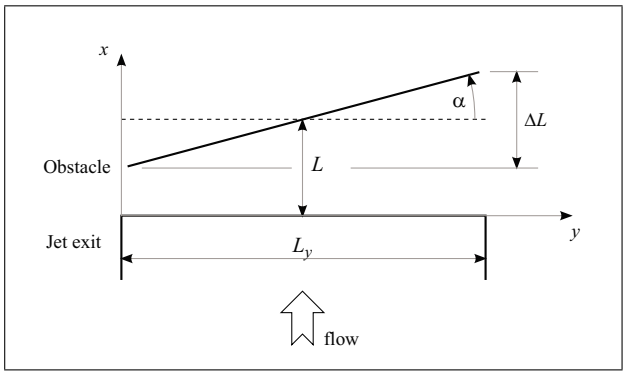

Figure 2. Upper view of the jet exit and of the obstacle.

Previous studies on self-sustained tones were mainly focused on two-dimensional or axisymmetric geometric configurations. However, the effect of edge misalignment on the production of the edge tone was studied by Kiya *et al.* [12]. Their results showed that the emitted sound pressure level drops beyond a critical inclination angle of the edge axis of about 4° with respect to the streamwise direction. Three-dimensional modifications of the geometry can also be used to modify the flow pattern and then to limit or avoid tone production [13, 14]. Nevertheless, the influence of three-dimensional geometrical modifications on aeroacoustic coupling between self-sustained tones and a resonator have rarely been studied.

In this paper, our experimental study focuses on a configuration called "misaligned jet-slot oscillator". It consists of a jet-slot configuration, the obstacle being misaligned with respect to the spanwise dimension. In particular, the consequence of this misalignment on aeroacoustic coupling with the flow-supply duct is studied. The paper is divided in two main parts: the first presents the experimental setup and the metrological techniques. The second presents and discusses the results obtained. Preliminary measurements first identifies the acoustic consequences of obstacle misalignment. The hydrodynamic conditions governing aeroacoustic coupling are then examined. A detailed exploration of the coupling conditions is provided in a third subsection and a generalization with a set of conclusions are given at the end.

2. Materials and methods

2.1. Setup

An air flow, produced by a blower, passes through a settling chamber and a duct (of dimensions 1250 × 190 × 90 mm in the coordinate system of Figure 1) ending in a nozzle creating a $H = 10$ mm-high and $L_y = 190$ mm-wide free jet (Figure 1). The jet impinges on a 4 mm-thick slotted aluminum plate. In the standard configuration, the plate slot, bevelled downstream at a 45° angle, is aligned with the jet exit and has the same dimensions. The maximum value of the jet velocity at the exit is U. The flow-supply duct, consisting of the constant-section duct and the nozzle, can be acoustically resonant when coupled with the jet-slot oscillator. The closest reflecting surface is the ground situated 1.5 m away from the nozzle exit. This prevent the occurence of direct sound path back-reaction produced by spurious reflexion. A Reynolds number of 18000 ($U = 28$ ms^{-1}), ensuring a dominant indirect feedback path, was used in this study [11, 9]. Based on a half-wavelength resonance, the cut-off frequency of the duct's first transverse mode in the spanwise direction y is 895 Hz. In the so-called misaligned configuration (Figure 2), the obstacle is rotated at an angle of α with respect to the spanwise direction. The jet exit/obstacle distance, measured at the middle of the spanwise dimension of the jet ($y = 95$ mm) and normalized by the jet height H, is noted L/H.

A 4944-A B&K 1/4" microphone was placed behind the obstacle ($x = L + 50$, $y = 85$, $z = 135$, in mm) to measure the radiated tone frequencies f_0, *i.e.* the highest energy component of the pressure-signal power spectrum, and the emitted sound pressure level (SPL). Velocity measurements were carried out by using two hot-wire probes (Dantec 55R01 and 55R04).

2.2. In-flow measurement of the spanwise acoustic phase pattern

The spanwise acoustic phase pattern was measured at the nozzle exit to assess the planar or non-planar nature of the resonance. Since microphonic inflow pressure measurements are quite intrusive and could disturb the aeroacoustic coupling, hot-wire measurements of the acoustic velocity at the duct exit were preferred.

As the potential core of the jet is very weakly turbulent [15], the velocity fluctuations recorded in this area are mainly due to the acoustic velocity generated by the flow-supply-duct resonances [10]. This assumption was verified using coherence measurements between an in-duct

microphonic signal and a velocimetric signal delivered by a probe placed in the potential core.

The first hot-wire probe is kept static in the potential core of the jet ($x = 0$, $y = 135$ mm, $z = H/2$) and measures the velocity fluctuation signal $u_r(t)$, which is used as a reference. The mobile probe is also located in the potential core ($x = 0$, $z = H/2$) but can be moved in the spanwise direction y in the range [5 mm; 185 mm]; it measures a $u_a(t)$ signal. Both signals were sampled at 5 kHz, the typical tone frequency being around 1 kHz. In order to evaluate the phase difference between these two signals at the oscillation frequency, their cross-spectrum ($S_{ar}(f) = U_a^*(f)U_r(f)$, where $U_a(f)$ and $U_r(f)$ are the Fourier transforms of $u_a(t)$ and $u_r(t)$ respectively) were computed by averaging over 20 segments of 2048 points. The phase difference $\Delta\theta(y)$ was measured for different spanwise positions of the mobile probe to evaluate the acoustic transverse phase pattern (along y).

2.3. Vortex tube morphology measurements

In the plane jet configuration, disregarding the lateral edge effects, the vortices shed at each lip of the nozzle have a "tube" shape (equivalent to the vortex-ring shape in axisymmetric configurations). Two hot-wire probes were used to evaluate the spanwise vortex morphology in this study.

The static probe was kept in the jet potential core, recording the acoustic velocity signal used as a phase reference. A mobile hot-wire probe was placed in the inner side of the upper shear layer ($z = 9$ mm, see Figure 1). At the probe location, the passage of successive vortices gives rise to a quasi-sinusoidal velocity fluctuation $u_h(t)$ at the emission frequency f_0 [10]. This mobile probe is moved along a mesh in the $z = 9$ mm-plane with 20 mm steps in the spanwise direction y and 2.5 mm steps in the streamwise direction x, measuring the aerodynamic velocity fluctuations due to the convection of the vortices. The phase difference between the two signals at the vortex shedding frequency was measured (again by using estimates of the signal cross-spectrum) for each location of the mobile probe, providing, in a horizontal plane, a phase map of the aerodynamic velocity fluctuations at the vortex shedding frequency. The spanwise morphology of the vortex tubes can be identified in this phase map by the phase isolines, the successive vortex cores being separated by a phase of 2π and a distance of U_cT_0, $U_c = 0.6U$ being the vortex convection velocity [10].

3. Results and discussion

3.1. Preliminary measurements

The acoustic phase pattern at the duct exit in the spanwise direction was measured at the tone frequency (as indicated in section 2.2) for both the standard jet-slot oscillator configuration and the misaligned configuration (Figure 3). This allows an estimation of the nature of the resonant mode of the flow-supply duct excited by aeroacoustic coupling. The following configuration was arbitrarily chosen for this purpose: $L/H = 2.5$, $Re = 18000$.

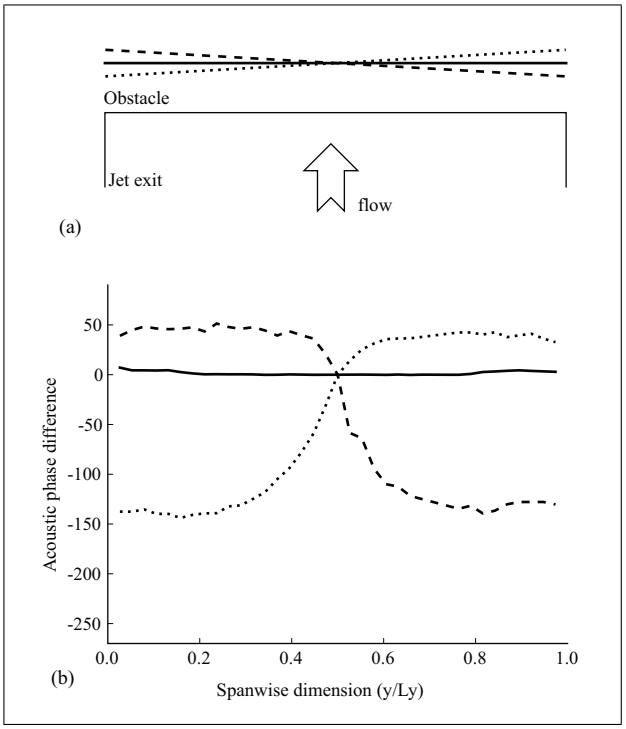

Figure 3. Acoustic phase pattern for $Re = 18000$, $L/H = 2.5$ and (—) $\alpha = 0°$, (· · ·) $\alpha = 3.3°$, (– –) $\alpha = -3.3°$. (a) obstacle inclination, (b) measurements.

The standard (aligned) configuration produced a tone at 1250 Hz. The phase pattern was flat and the phase difference remained within the range [−7°; 5°]; this confirms the propagation, in the duct, of a planar mode only [10]. Additional measurements at different Reynolds numbers and jet-exit/obstacle distances showed a similar phase pattern for the standard case, even if the emission frequency was higher than the duct's first transverse mode cut-off frequency (895 Hz).

The inclination of the obstacle with respect to the spanwise direction results in a modification of the tone frequency. For the configuration depicted in Figure 3 ($\alpha = \pm 3.3°$), the tone frequency was equal to 1600 Hz. In this case, the acoustic phase exhibits some spanwise variations, indicating that the first transverse acoustic mode is also propagated in the duct.

As a first conclusion, these preliminary measurements show that, in the standard jet-slot oscillator, only planar modes are excited. Conversely, the misaligned jet-slot oscillator appears to be coupled to the resonator in a combination of planar and transverse modes when some of the latter are cut-on.

3.2. Hydrodynamic conditions governing aeroacoustic coupling

Velocimetric measurements were used to describe the phenomenon governing the aeroacoustic coupling in the misaligned case. The spanwise shape of the vortex tubes was

estimated (as explained in section 2.3) by plotting the hydrodynamic velocity phase distribution (Figure 4a). This distribution showed that the vortex tubes have a bent shape in the spanwise dimension (Figure 4b).

As stated in the introduction, the acoustic fluctuations trigger vortex shedding at the jet exit. Their phase variation in the spanwise direction should then mould the spanwise morphology of the vortex-tubes. Indeed, the spanwise acoustic phase difference $\Delta\theta(y)$ depicted in Figure 3 can be interpreted in terms of the relative distance $\Delta x(y)$ covered by the vortices during their convection,

$$\Delta x(y) = \frac{\Delta\theta(y)}{2\pi f_0} U_c, \tag{1}$$

where f_0 is the tone frequency. The distance $\Delta x(y)$ obtained from equation (1) is plotted as dashed lines in Figure 4a. The spanwise profile of $\Delta x(y)$ exhibits a strong similarity with the vortex tubes spanwise morphology obtained from the hydrodynamic phase distribution. This confirms the triggering of vortex shedding by the acoustic velocity at the duct exit even when non-planar modes of the resonator are excited.

It is then concluded that the aeroacoustic coupling gives the vortex a bent morphology. The vortex tube orientation tends to match the inclination of the obstacle, the whole vortex tube impinging almost simultaneously along the obstacle. In this way the oscillating system maintains an optimal phase relationship around the feedback loop for all spanwise positions y by accommodating the nature of the acoustic resonance of the flow-supply duct.

The nature of the excited acoustic resonant mode (and, as a consequence, the spanwise morphology of the vortices) is therefore imposed by the following hydrodynamic condition: the vortices must impinge on the obstacle almost in phase in order to keep the spanwise coherence of the interaction along the slot.

3.3. Aeroacoustic coupling

In this section, the consequences of this hydrodynamic condition on aeroacoustic coupling are studied in terms of tone frequency, emitted sound pressure level (SPL) and excited resonant mode.

3.3.1. Detailed study for $L/H = 2$

The tone frequency, the emitted sound pressure level and the velocity fluctuations in the potential core u' (normalized by the jet speed U) were measured as a function of the misalignment angle α for $L/H = 2$ and $Re = 18000$ (Figure 5). The aligned jet-slot oscillator ($\alpha = 0°$) produced tones at 1300 Hz with an amplitude of 115 dB. The SPL decreased linearly as α increased in the range $[0°; 3.5°]$. The tone frequency was equal to 1310 Hz in this range. In the range $[3.5°; 4.5°]$, the SPL decreased more quickly and the tone frequency varied slightly. Lastly, for $\alpha = 5°$, a sudden change of frequency ($f_0 = 1250$ Hz) was associated with an increase in SPL of 10 dB. The ratio u'/U is in the range [0.1% ; 0.3%] which corresponds to the values

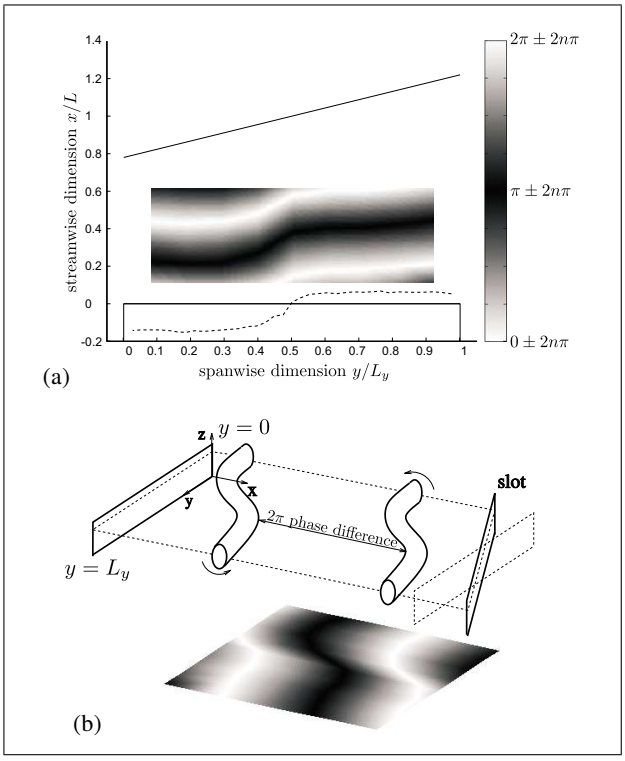

Figure 4. Phase map measurements for a misaligned jet-slot oscillator, for $\alpha = 3.3°$, $Re = 18000$ and $L/H = 2.5$.
(a) (*grayscale*) phase map (- -) vortex tube spanwise morphology calculated from the acoustic phase pattern data of Figure 3.
(b) Diagram of the vortex tubes.

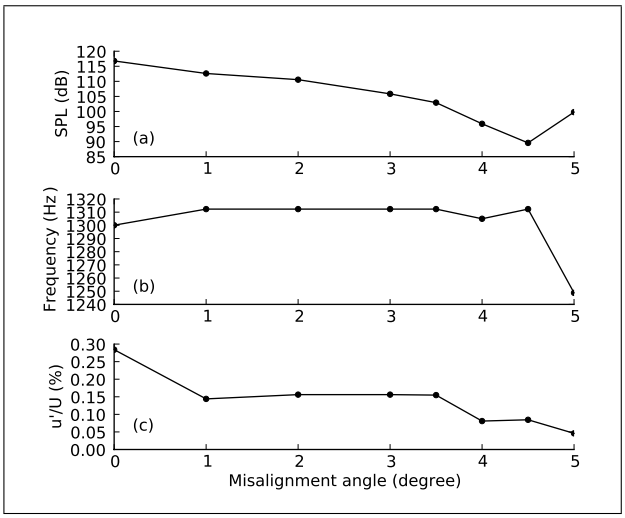

Figure 5. Sound pressure level (a), frequency (b) of emitted tones, and relative velocity flucutations in the potential core (c) as a function of the misalignment angle α between the jet exit and the obstacle, for $Re = 18000$ and $L/H = 2$.

measured for an indirect coupling condition in reference [10], ensuring that the flow-supply duct is resonant.

The measured acoustic phase pattern in the spanwise direction is shown in Figure 6 for different misalignment angles in the range $[0°; 3.5°]$. The observed pattern suggests the propagation of a superimposition of a planar mode and

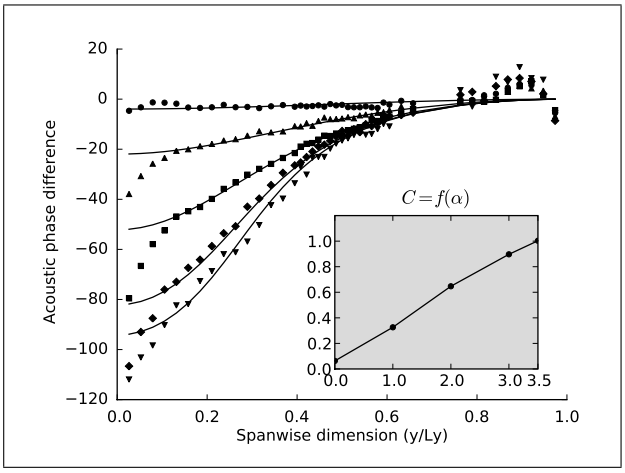

Figure 6. Acoustic phase pattern measured in the spanwise dimension, at the exit of the flow supply duct, for $Re = 18000$ and $L/H = 2$ and for: (•) $\alpha = 0°$, (▲) $\alpha = 1°$, (■) $\alpha = 2°$, (♦) $\alpha = 3°$, (▼) $\alpha = 3.5°$. The theoretical phase pattern (obtained by tuning the relative amplitude C of the transverse mode in equation (2) to fit the experimental data) are plotted as solid lines. The inset figure depicts the relative amplitude C of the transverse mode as a function of the misalignment angle α.

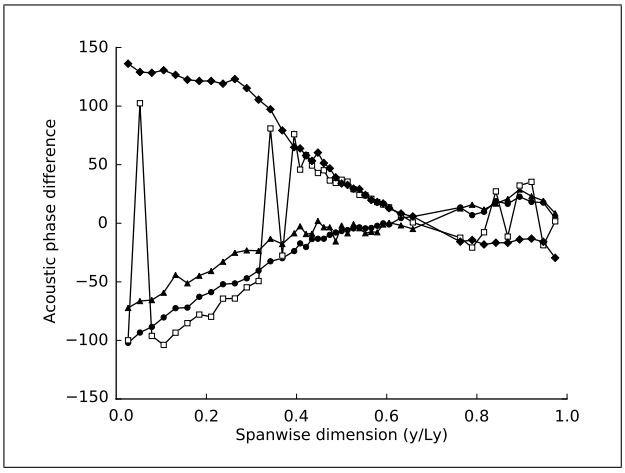

Figure 7. Acoustic phase pattern measured in the spanwise dimension, at the exit of the flow supply duct, for $Re = 18000$ and $L/H = 2$ and for: (•) $\alpha = 3.5°$, (▲) $\alpha = 4°$, (□) $\alpha = 4.5°$, (♦) $\alpha = 5°$.

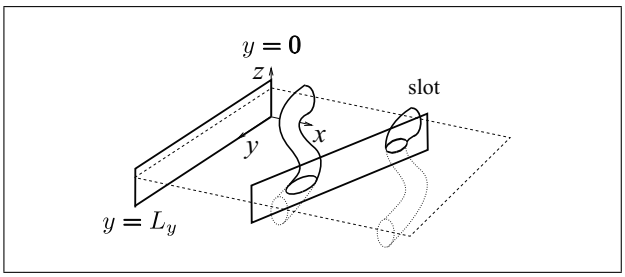

Figure 8. Diagram of the vortex tubes in the "opposite-transverse mode" coupling condition.

of the first transverse mode. In such a case, the acoustic pressure in the duct can be written as follows,

$$p(x, y, t) = \cos(k_0 x - \omega t) + C \cos\left(\frac{\pi y}{L_y}\right) \cos(k_1 x - \omega t), \quad (2)$$

where $k_0 = \dfrac{\omega}{c}$, (3)

and $k_1 = \left(\dfrac{\omega^2}{c^2} - \dfrac{\pi^2}{L_y^2}\right)^{1/2}$, (4)

are the planar and transverse mode wave-numbers respectively [16]. The experimental data of Figure 6 can be fitted by tuning the ratio C between the transverse and planar mode amplitudes (C being a real quantity). However, the value of x can not be predicted: it has then been chosen so that the obtained phase patterns exhibit the highest similarity with the experimental pattern (the x value remains identical for all the simulated patterns). The theoretical acoustic phase patterns are plotted as solid lines in Figure 6. The experimental and theoretical patterns are in very close agreement, except near the jet sides, for y/L_y close to 0 and 1 (due to the finite width of the nozzle). Furthermore, the inset plot of Figure 6 shows that the value of the ratio C is a quasi-linear function of the misalignment angle. This suggests that, for a given misalignment angle in the range $[0°; 3.5°]$, the system adapts the ratio between the planar and the transverse mode to accommodate the hydrodynamic condition (section 3.2).

For higher misalignment angles α ($\alpha > 3.5°$), the measured acoustic phase patterns in the spanwise direction are plotted in Figure 7 for the same values of Re and L/H (measurements could not be made for $\alpha > 5°$ as the space left between the slot and the duct end was not sufficient to move the probe). The acoustic phase pattern for $\alpha = 3.5°$ already shown in Figure 6 is recalled in Figure 7. For $\alpha = 4°$, the coupling conditions were modified: the orientation of the acoustic phase pattern no longer followed the obstacle inclination. For $\alpha = 4.5°$ the system shifted between two acoustic phase patterns. Lastly, for $\alpha = 5°$, a sudden change of the tone frequency (as reported in Figure 5) was associated with a new coupling condition: the acoustic phase pattern inclination was the opposite of the obstacle inclination. This mode will hereafter be called "opposite-transverse mode". The acoustic phase difference depicts a 180° variation in the spanwise direction.

The modification of the coupling conditions occurred close to a critical misalignment angle α_c for which the streamwise interval ΔL_c created by the misalignment (see Figure 2) was equal to a hydrodynamic wavelength λ_h (corresponding to the distance between two successive vortices):

$$\lambda_h = \frac{U_c}{f_0}. \quad (5)$$

The critical misalignment angle can be expressed as follows:

$$\alpha_c = \operatorname{atan}\left(\frac{\Delta L_c}{L_y}\right) = \operatorname{atan}\left(\frac{U c}{f_0 L_y}\right), \quad (6)$$

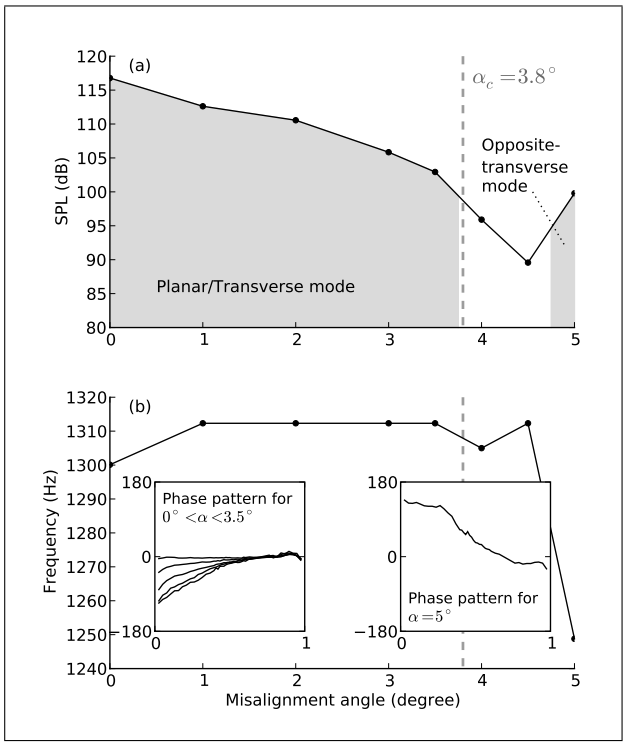

Figure 9. Sound pressure level (a) and frequency (b) of the emitted tones as a function of the misalignment angle α between the jet exit and the obstacle, for $Re = 18000$ and $L/H = 2$. The inset figures depict the acoustic phase patterns measured for two sets of misalignment angles.

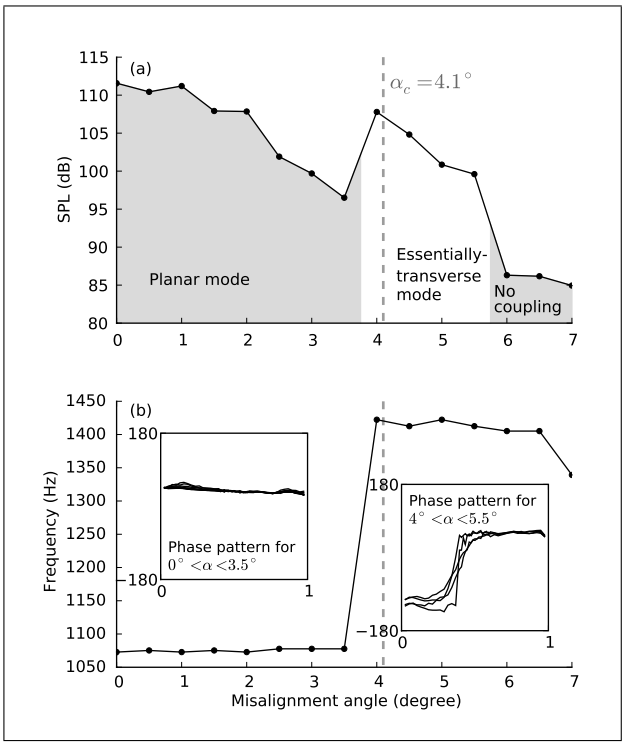

Figure 10. Sound pressure level (a) and frequency (b) of emitted tones as a function of the misalignment angle α between the jet exit and the obstacle, for $Re = 18000$ and $L/H = 2.75$. The inset figures depict the acoustic phase patterns measured for two sets of misalignment angles.

and is equal to 3.8° in the configuration of Figure 7. It has been stated that vortex impingement must occur almost simultaneously along the obstacle in the spanwise direction to ensure an optimal coupling condition. When the misalignment angle exceeds this critical angle, the vortices can't be sufficiently inclined. As a consequence, the SPL decreases faster when the misalignment angle exceeds the critical angle α_c (see Figure 5). For $\alpha = 5°$, the opposite-transverse mode is excited and the inclination of the vortices allows the simultaneous impingement of a vortex left-portion and the following vortex right-portion (as schematically represented in Figure 8). This condition enhances coupling by accommodating better the hydrodynamic condition and allows an increase in the emitted level by 10 dB (see Figure 5).

3.3.2. Generalisation

The measurements from section 3.3.1 (summarized in Figure 9) have been reproduced for a set of distances between the jet-exit and the obstacle. Unfortunately, the system did not exhibit a predictable behaviour, in terms of the coupling conditions, as a function of this distance. The results for $L/H = 2.75$ are given in Figure 10, as they showed two other coupling conditions.

In this configuration, the critical angle α_c evaluated by using relation (6) was equal to 4.1°. The aligned jet-slot oscillator produced tones at 1075 Hz with an amplitude of 111 dB. In the range [0°; 3.5°], the SPL decreased almost linearly as α increased. The tone frequency remained unchanged in this range and coupling occurred with the resonator in planar mode. At $\alpha = 4°$, close to the critical angle, a sudden change of frequency ($f_0 = 1410$ Hz) occurred and was associated with a SPL increase of 10 dB and a change in the nature of the coupling. In the range [4°; 5.5°], a 180° phase-shift along the spanwise direction was observed, indicating a coupling with a mode called "essentially-transverse mode". The SPL decreased again as α increased in this range. Finally, a drop of 15 dB in SPL was recorded for $\alpha > 6°$. For these angles, coherent acoustic phase patterns could not be measured, indicating that the aeroacoustic coupling no longer occurred.

These results identified two other coupling conditions for a larger jet-slot-distance, and are difficult to analyse. Nevertheless, it can be argued that the twisted vortex filament produced by a transverse mode generates both streamwise and vertical components of the vorticity vector, that should tend to make the vortex filament go off the horizontal plane. This could explain a less clear behaviour of the jet-slot oscillator for larger jet-slot distances.

Overall, for the other distances L/H investigated, the following coupling conditions were observed: (i) for misalignment angles weaker than the critical angle there was a coupling with the resonator in planar modes or a combination of planar and transverse modes by tuning the ratio between the mode amplitudes, and (ii) for misalignment angles exceeding the critical angle there was a coupling with the resonator in "essentially-transverse" modes or with "opposite-transverse" modes. Nevertheless, the measure-

ments show that the behaviour of the system for a given distance L/H and misalignment angle is difficult to predict.

4. Conclusion

Self-sustained tones can be produced by the coupling of a jet-slot oscillator to the high-order resonant acoustic modes of the flow-supply duct. The influence of the slot inclination (with respect to the spanwise jet direction) on aeroacoustic coupling was examined. It was shown that only the resonator planar modes were excited when the obstacle was aligned with respect to the jet exit, but that non-planar modes could be excited when the obstacle was misaligned.

The system behaviour was carefully described and interpreted for one configuration ($L/H = 2$). The spanwise phase pattern of the acoustic resonant mode, imposing the morphology of the vortices, was shown to be imposed by a hydrodynamic condition: the vortices must impinge almost in phase along the obstacle in order to keep the spanwise coherence of the jet-slot interaction. Moreover, a simple analytical model of the resonant acoustic field showed that the ratio of transverse and planar excited modes was tuned by the system in order to keep this coherence at a maximum. The existence of a so-called "opposite-transverse mode" was also shown, generating vortices with an inclination angle that was the opposite of the plate inclination angle. The study of the system behaviour for other slot positions L reveals a general trend in the nature of the modes involved in the coupling as a fonction of the obstacle inclination. Higher-order modes (possibly cut-off) could be involved in the coupling process and have a local influence in the vicinity of the nozzle edges. This could be taken into account in further studies to improve the description of the coupling process.

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