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AEROACOUSTIC COUPLING OF A MISALIGNED JET-SLOT-OSCILLATOR WITH NON-PLANAR MODES OF A RESONATOR

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ABSTRACT
The impingement of a plane jet on a slotted plate produces a “jet-slot oscillator” emitting acoustic tones. The coupling of such tones with high-order acoustic resonances of the flow-supply duct (i.e., above the first transverse mode cut-off frequency) is studied experimentally , in the particular case where the jet-exit and the obstacle are misaligned in the spanwise direction. An experimental set-up based on microphones and hot-wire probes is used to investigate the effect of the slot angle on the sound production mechanism. The aligned jet-slot oscillator is first studied, showing that the parallelism between the jet exit and the slot imposes the excitation of planar modes of the resonator only. Conversely, the misaligned jet-slot oscillator appears to be coupled with a combination of planar and transverse modes. The induced spanwise variation of the acoustic field phase has two consequences. First, it compensates the difference of vortices convection time in the spanwise direction, due to the obstacle misalignment. Second, it enhances the spanwise coherence of the aeroacoustic source produced by the jet-slot interaction: the vortex-tubes are shed in an oblique direction which tends to be parallel to the obstacle.

INTRODUCTION
Self-sustained tones can be produced when a sheared flow impinges on a downstream obstacle. The self-sustained acoustic oscillations have been extensively studied over the past fifteen years and their mechanism is globally well known [4, 8, 3]. The interaction of the jet and the obstacle produces a strength on the fluid, which gives rise to (i) an aeroacoustic source and (ii) a flow perturbation directly fed-back 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 indirect feedback path). The perturbations due to the dominant feedback path are amplified by the jet instabilities and interact again with the obstacle; a self-sustained loop is created. When a constructive phase relationship is met along this loop, tones are generated [3].

The configuration under study is the jet-slot oscillator. It consists of a plane jet impinging on a slotted plate [10, 11, 2]. Billon et al. show that for a Reynolds number Re, based on the jet height, smaller than 10000, the tones produced are the result of a dominant direct feedback path [1, 2]. The emitted sound level is then below 80 dB. On the opposite, 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 level can reach 115 dB. In this case, the vortex shedding is synchronized with the acoustic velocity fluctuations induced at the jet exit by the resonance. The duct resonances control the emission frequency and enhance the emitted sound level. The frequencies reported in the experiments of Billon et al. correspond to high-order modes (up to the order of 16) of the flow supply duct [2]. Moreover, acoustic phase measurements permit to verify, in no-flow condition, that the flow-supply duct is susceptible to propagate the first transverse mode for the measured emission frequencies. However, the excitation of this transverse mode by the aeroacoustic source has not been confirmed in operating conditions, even when the emission frequency is above the cutoff frequency of this first transverse mode.

A study of the effect of the edge misalignment on the production of the edge-tone has been proposed by Kiya et al. [6]. It shows that the emitted sound level drops down after a critical angle of inclination 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 avoid the tones production [5, 9]. But the influence of such three-dimensional geometrical modifications on the aeroacoustic coupling of self-sustained tones with a resonator have been previously few studied. The aim of this paper is then to show that a three dimensional jet-slot oscillator, produced by the inclination of the slot with respect to the jet spanwise direction, can enhance the first transverse resonant acoustic mode of the flow-supply duct. The coupling between such a misaligned jet-slot oscillator with non-planar modes of the resonant flow-supply duct is then studied experimentally.

The experimental set-up used is presented in a first part. The second part presents the results. A discussion is given in a third part before a general conclusion.

MATERIAL AND METHODS

Set-up

An air flow, produced by a blower, passes through an expansion volume and a duct (of dimensions $1250 \times 190 \times 90$ mm in the coordinate system of Figure 1) ended by a nozzle creating a $H = 10$ mm-high and $L_y = 190$ mm-wide free jet (Figure 1). The flow-supply duct, constituted by the constant-section duct and the nozzle, can be acoustically resonant when coupled with the jet-slot oscillator. Based on a half-wavelength resonance, the cut-off frequency of the duct's first transverse mode in the spanwise direction y is found to be 895 Hz. The jet impinges on a 4 mm-thick slotted aluminum plate. In the standard configuration (Figure 2a), the plate slot, bevelled with a 45° angle, is aligned with the jet exit and has the same dimensions. In the so-called misaligned configuration (Figure 2b), the obstacle is rotated with an angle 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. U is the maximum value of the jet velocity at the exit.

A 4944-A B&K 1/4" microphone is located behind the obstacle to measure the radiated tones frequency f_0, *i.e.* the most energetic component of the pressure-signal power spectrum, and the emitted sound level. Air velocity measurements are carried out by using two hot-wire probes (Dantec 55R01 and 55R04).

A Reynolds number of 18000 ($U = 28$ m/s) and a distance $L/H = 2.5$ insuring a dominant indirect feedback path are used for the results given in this study. However the phenomena reported are also observed for other values of the Reynolds number and the distance L/H, provided that a flow-supply duct resonance is coupled with the jet-slot oscillator.

In-flow measurement of the spanwise acoustic phase pattern

The spanwise acoustic phase pattern is measured at the nozzle exit to assess the planar or non-planar nature of the resonance. Since microphonic in-flow pressure measurements are quite intrusive and could disturb the aeroacoustical coupling, acoustic velocity measurements by using hot-wire probes are preferred.

Principle. The potential core of the jet is very weakly turbulent, the velocity fluctuations recorded in this area are thus mainly due to the acoustic velocity generated by the flow-supply-duct resonances.

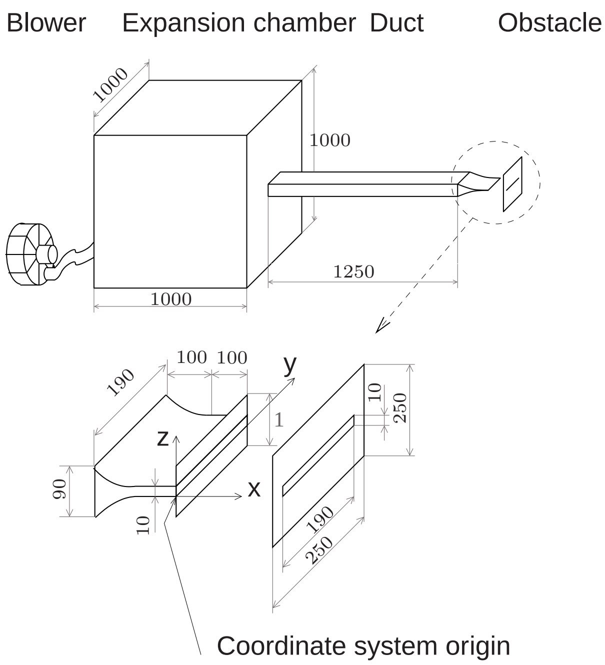


Figure 1: Overall view of the experimental set-up (dimensions in mm).

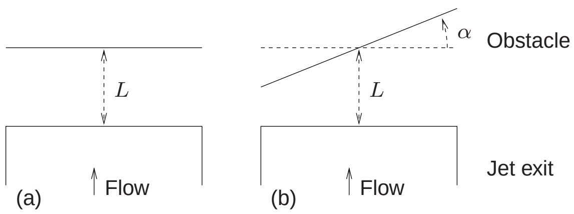


Figure 2: Upper view of the jet exit and of the obstacle, (a) standard jet-slot oscillator, (b) mis-aligned jet-slot oscillator.

Acoustic phase pattern measurement. 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 fluctuations signal $u_f(t)$ 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, for 5 mm$< y < 185$ mm; it measures a signal $u_m(t)$. In order to evaluate the phase difference between these two signals at the tones' operating frequency, their cross-spectrum ($S_{mf}(f) = U_m(f)U_f^*(f)$, where $U_m(f)$ and $U_f(f)$ are the Fourier transforms of $u_m(t)$ and $u_f(t)$, respectively) are computed by averaging over 20 segments of 2048 points. The signal is sampled at 5kHz. The phase difference is measured for different spanwise positions of the mobile probe to evaluate the acoustic transverse phase pattern (along y).

Vortex-tubes morphology measurement

A mobile hot-wire probe is located in the inner side of the upper shear layer ($z = 9$ mm, see Figure 1). The passage of the successive vortices gives rise to a quasi-sinusoidal velocity fluctuation $u_p(t)$ at the probe location. This can be understood by the simple model proposed by Nelson et al. [7]: given the rotation of the vortices (counter-clockwise in the upper shear-layer), the vortex passing involves a local increase of the velocity measured by this probe.

The static probe is kept in the jet potential core, recording the acoustic velocity signal used as a phase reference. The mobile probe is moved along a mesh of 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 due to the convection of the vortices. The phase difference between the two signals at the vortex shedding frequency is measured (again by using estimates of the signal cross-spectrum) for each location of the mobile probe, providing a phase map of the aerodynamic velocity fluctuations at the sheding frequency. The vortex-tubes spanwise morphology can be identified in this phase map by the phase isolines, the successive vortices being separated by a phase of 2π and a distance of U_cT_0, $U_c = 0.6U$ being the vortices convection velocity [3].

RESULTS

Tones emission characterization. The tones frequency and the emitted sound level are measured as a function of the misalignment angle α between the jet exit and the obstacle (Figure 3). Globally, the sound level decreases as the angle is increased, until the tones disappear at about $|\alpha| = 6°$. For $|\alpha| > 6°$, some broadband noise is emitted. The frequency and amplitude behavior is almost symmetric around $\alpha = 0°$. For $|\alpha| < 3°$, the tones frequency is equal to about 1250 Hz, and for $|\alpha| > 3°$, the tones frequency jumps to about 1600 Hz. This frequency jump is associated with a slight increase of the emitted sound pressure level.

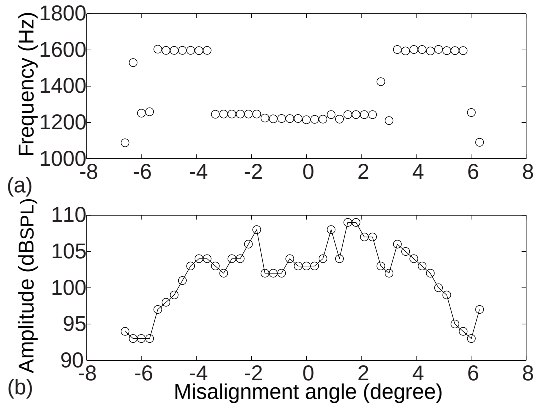


Figure 3: Tones frequency (a) and emitted sound level (b) as a function of the misalignment angle α between the jet-exit and the obstacle, for $Re = 18000$ and $L/H = 2.5$.

Acoustic phase pattern. The acoustic phase pattern in the spanwise direction is measured at the tones frequency, as explained previously, for different angles α. The results are plotted in Figure 4.

The phase pattern exhibits some spanwise variations of the acoustic phase of about $180°$, which indicates that the first transverse acoustic mode is propagated in the duct; the acoustic resonant field is then the result of the superimposition of a planar mode and of the first transverse mode. The sign of the spanwise phase shift depends on the orientation of the obstacle. Conversely, for $|\alpha| < 3°$ (tones at frequency 1250 Hz), the spanwise acoustic phase pattern is flat (an example for $\alpha = 0°$ is plotted in Figure 4); this indicates the propagation in the duct of a planar mode only. Additional measurements at different Reynolds numbers and distances jet-exit/obstacle have also shown a similar phase pattern.

Vortex-tubes morphology. A phase map of the aerodynamic velocity is measured in the inner part of the upper shear layer for misalignment angles of 0° and 3.3° (Figure 5). The phase has been interpolated and the color scale has been adjusted to make a grey-level map for easier interpretation. From the phase isolines (the map isocolors in the figure), it is possible to deduce the spanwise morphology of the vortex-tubes.

For the standard jet slot oscillator ($\alpha = 0°$), the vortex-tubes have a rectilinear spanwise shape and are convected parallely from the jet exit to the obstacle (Figure 5a). For the misaligned jet slot oscillator ($\alpha = 3.3°$), the map shows that the vortex-tubes have a bended-shape in the spanwise dimension (Figure 5b).

It is possible to interpret the vortices spanwise shape by using the acoustic phase pattern at the jet exit plotted in Figure 4, and by using the assumption that the non-planar resonant acoustic velocity at the jet exit controls the vortex shedding. If the acoustic phase difference $\Delta\theta$ between

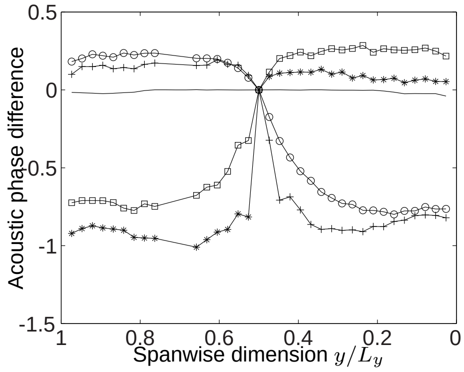
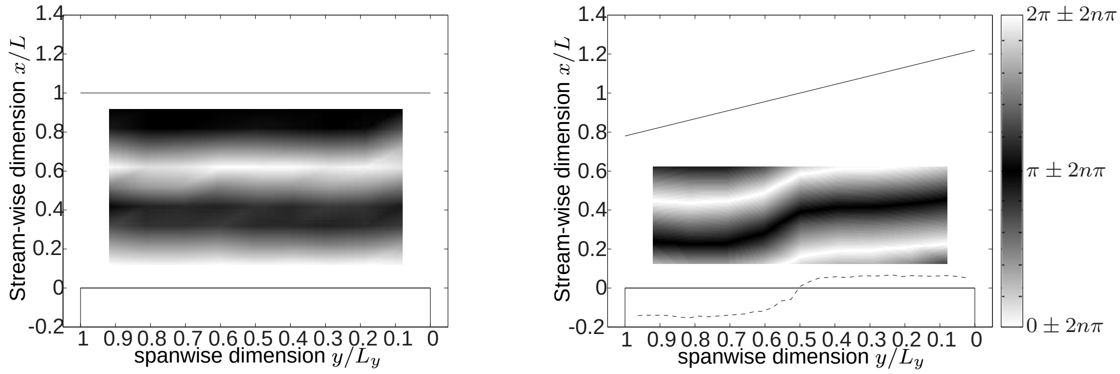


Figure 4: Acoustic phase pattern, in the spanwise dimension, at the exit of the flow supply duct, for $Re = 18000$ and $L/H = 2.5$, (−) $\alpha = 0°$ (+) $\alpha = -5.1°$, (o) $\alpha = -3.6°$, (□) $\alpha = 3.3°$, ($*$) $\alpha = 5.1°$.

a spanwise location y_1 and the center y_0 of the jet is positive, it means that the acoustic signal in y_1 is in advance with respect to the signal in y_0. It also means that the vortex is shed earlier in y_1, and that the vortex at y_1 has already covered some distance Δx when it is shed at y_0. This distance Δx can be expressed as follows as a function of the spanwise position y:

$$\Delta x(y) = \frac{\Delta\theta(y)}{2\pi f_0} U_c, \qquad \text{(Eq. 1)}$$

where $U_c = 0.6U$ is the vortices convection speed. It is plotted in dashed line in Figure 5b. The vortex-tubes spanwise morphology obtained experimentally and the one obtained from the acoustic phase pattern exhibit a great similarity. This confirms that the acoustic velocity at the duct exit triggers locally the vortex shedding, controlling the vortex-tubes spanwise morphology. It is also observed that the vortex tubes orientation tends to be parallel to the obstacle.



(a) 0° misalignement angle

(b) 3.3° misalignement angle

Figure 5: Phase map measurements for $Re = 18000$ and $L/H = 2.5$.

DISCUSSION

The previous results show that even if the tones frequency is higher than the cut-off frequency (895 Hz) of the duct's first transverse mode, this mode is not excited by the aeroacoustic source when the jet exit and the obstacle are aligned in the transverse dimension (Figure 4). Indeed the excitation of this mode would involve substantial spanwise acoustic-velocity phase variations that are not observed experimentally. The vortices, which shedding is controlled by the acoustic resonant field, have therefore a rectilinear-tube-like shape parallel to the spanwise axis, as confirmed by the rectilinear phase isolines observed in Figure 5a. The whole vortex tube impinges simultaneously on the obstacle.

Nevertheless, the results confirm that self-sustained tones coupled with the flow-supply duct can be produced until a jet exit / obstacle misalignment angle $|\alpha|$ equal to $6°$ (Figure 3). For $|\alpha| <$

$3°$, the tones frequency of the aligned jet-slot oscillator is preserved. The mode involved in the aeroacoustic coupling is a planar mode. A change of behavior of the jet-slot oscillator is observed for $|\alpha| \approx 3°$. For $|\alpha| > 3°$, the tones frequency changes, and the first transverse mode of the flow-supply duct is propagated, involving $180°$-phase spanwise variations of the resonant acoustic field. As a consequence, the vortex-tubes are shed obliquely with respect to the y axis (see the dashed curve in Figure 5b). It is verified by the aerodynamic velocity measurements which clearly show the oblique direction of the vortex-tubes (Figure 5b). The vortex-tubes become as parallel to the obstacle as the maximal spanwise phase shift of $180°$ permits.

In this way, whatever the misalignement angle, the whole vortex-tube tends to impinge simultaneously on the obstacle for all spanwise positions y. The spanwise coherence of the aeroacoustic source produced by the jet-slot interaction is then maintained

CONCLUSION

Self-sustained tones can be produced by the coupling between a jet-slot oscillator and the resonant acoustic modes of the flow-supply duct. The influence of the slot inclination with respect to the jet spanwise direction on the acoustic modes nature (planar or non-planar) has been examined. When the inclination angle is under 3°, the aeroacoustic source is coupled with planar modes of the resonator only. On the opposite, for higher inclination angles, non-planar modes of the resonator are excited by the aeroacoustic source. This behavior tends to enhance the spanwise coherence of the aeroacoustic source produced by the jet-slot interaction, as the vortex-tubes are shed in a transverse direction (planar for the standard jet-slot oscillator and oblique for the misaligned jet-slot oscillator) which tends to be parallel to the obstacle.

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