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FREQUENCY HALVING DUE TO VORTEX PAIRING FOR A JET-SLOT OSCILLATOR

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Abstract

At the outlet of the HVCA systems, whistling can occur, due to self-sustained oscillations. In this study, the ventilation outlet is modelled by a free plane subsonic jet impinging on a slotted plate, leading to self-sustained tones production; this configuration is known as the jet-slot oscillator.

The tone's frequency can be predicted through the vortex dynamics within the flow. For jet velocities higher than 16m/s, the tones couple with the flow-supply-duct's resonances. These resonances control the vortex dynamics and reinforce the sound production, of about 20dB. Moreover, when the distance from the jet exit to the plate is increased and reaches 4.5 times the jet height, the fundamental frequency of the tones is suddenly halved due to some vortex pairing occurring at the end of the potential core of the jet.

In this paper, the vortex pairing is observed with three different experimental techniques. Firstly, comparison between the radiated and the in-duct acoustic fields is conducted. Then the energy transfer from the fundamental to the sub-harmonics of the shear layer's velocity fluctuations is observed with anemometric measurements. Finally high speed flow visualizations are performed and allow to link the vortex impingement on the plate to the sound production.

INTRODUCTION

When a sheared flow impinges on an obstacle, whistling can be produced. These whistling own to the self-sustained oscillations family. The jet-slot oscillator results thus from the impingement of a free plane jet on a slotted plate [1,2]. In this configuration, the oscillation's frequency domain is bounded [3], for the highest frequencies, by the natural most instable frequency of the shear layer [4] and, for the lowest frequencies, by the jet column mode [5]. The ratio between both frequencies, at a given Reynolds number, is close to 2, characteristic of a tuned jet [6]. Ho and Huang [7] showed that, in this configuration, the jet column mode is the result of successive vortex pairing and characterized the non-linear energy transfer from the fundamental excitation to the subharmonics occurring. In the previous studies of self-sustained oscillators, the phenomenon is commonly observed in the impingement of a high-subsonic circular jet (Mach number superior to 0.6) on a plate [8] and, seldom, when a shear layer impinges on a wedge [9]. When some coupling with a resonator occurs, the excited resonant mode can trigger successive pairings allowing the tone's production through the excitation of the shear layer natural instability for different flow velocities [10] whereas, for the jet-slot oscillator, the tone frequency halving occurs even when the flow supply duct resonances are not excited [11] depending only on the plate distance.

The aim of this investigation is then to present three different experimental evidences of the occurrence of vortex pairing. After a presentation of the experimental set-up and procedures in Section 2, results obtained using three experimental techniques using acoustic, anemometric measurements and visualizations will be presented in Section 3 and discussed in Section 4.

EXPERIMENTAL SET-UP AND PROCEDURES

The experimental set-up, shown in Fig. 1(a), was designed to permit variations of the following geometrical and flow parameters: *L*, the distance between the plate and the nozzle outlet and U_0, the flow velocity at the nozzle outlet. After a settling chamber, a free jet is created by a rectangular cross-section (9x19 cm) duct (1.2 m length) made of 5 mm thick aluminium followed by a 20 cm-long contraction nozzle. This jet can reach 32 m/s, a low subsonic speed. A characteristic Reynolds *Re* number can be then calculated based on *H*, the jet height. The jet impinges on a 4 mm thick aluminium plate (25x25 cm dimensions) fitted with a bevelled slot aligned with the nozzle outlet. The dimensionless distance between the nozzle outlet and the slot L/H may vary between 0 and 10.

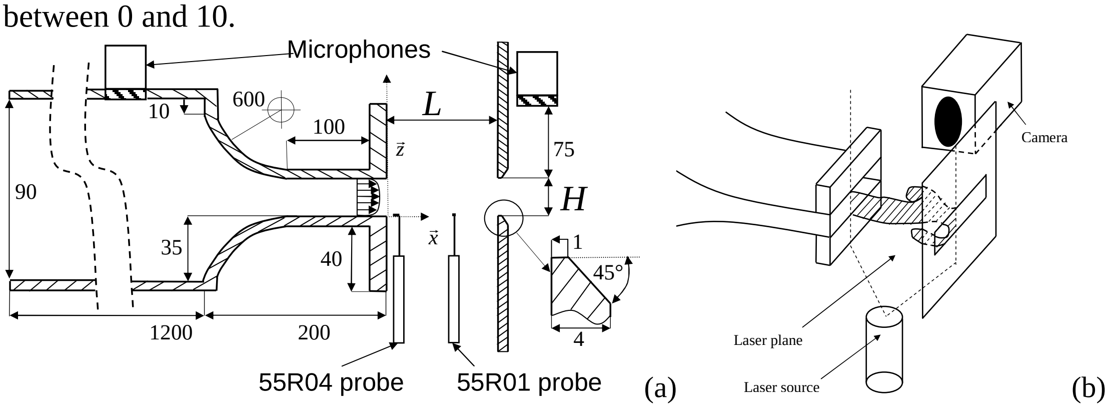

Figure 1 - (a) Experimental set-up (dimensions in mm). (b) Visualization set-up.

A 4189-A-021 B&K microphone is placed behind the plate 75 mm above the slot to avoid hydrodynamic disturbances, and measures the radiated near-field pressure fluctuations (called radiated acoustic signal in the following). Another is flush-mounted at the duct's wall and measures the pressure fluctuations within the duct and its signal is called in-duct acoustic signal. A characteristic Strouhal number of the oscillations St_L is defined by: $St_L = f_0 \cdot L / U_0$, where f_0 is the most energetic frequency in the power spectrum of the radiated pressure field.

Two Dantec hot wire anemometers, a 55R04 probe located in the shear layer at the nozzle outlet and a movable 55R01 probe are used to measure the flow velocity. The second probe is moved in the shear layer along the streamwise direction with 1 mm steps; for each position the amplitude of the velocity fluctuations and the phase difference with the fixed probe is estimated. For the visualizations, the flow is seeded with hot paraffin droplets and lighted with a laser plane parallel to the flow main direction, created using a Nanopower 4W/795 nm laser (see Fig. 1(b)). Pictures are then recorded using a high-sensibility camera Nanosense MKII 5kHz.

RESULTS

Firstly, the radiated pressure field (measured behind the slot, see last section) is measured for a Reynolds number fixed at 11800 when the plate is moved downstream.

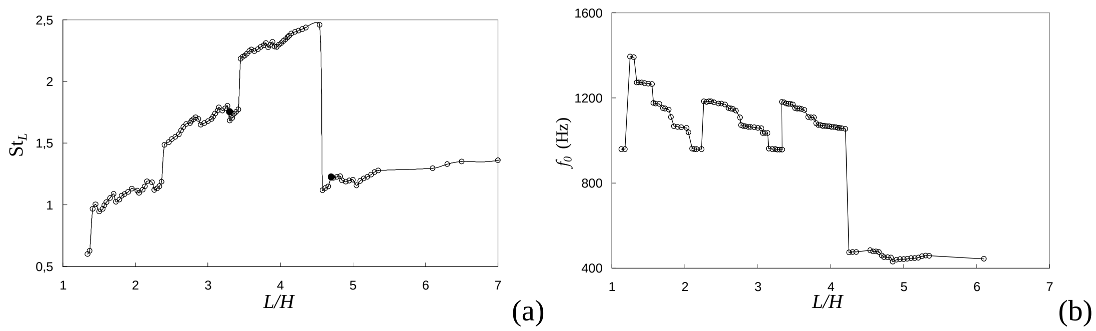

Figure 2 - Evolution of the fundamental frequency (a) and of the Strouhal number (b) as a function of the plate distance; Re=11800 [11].

For the shortest plate distances, the evolution of the Strouhal number (Fig.2 (a)) describes increasing stages, i.e. the number of vortices present at the same instant between the nozzle outlet and the plate grows until *L/H*=4.2. At this point, the Strouhal number is halved from 2.5 to 1.2 and remains almost constant until the tones disappear: the number of vortices is divided by two. Moreover, at the Reynolds number under consideration, the vortex shedding frequency is controlled by a flow supply duct resonance [11]. The measured tones most energetic frequency for *L/H*≥4.2 (around 480Hz, Fig. 2(b)) does not correspond to any resonant mode frequency of the duct, the closest being 454 Hz and 544 Hz. Figure 3 plots the power spectra of the radiated and in-duct acoustic signals for *L/H*=4.6.

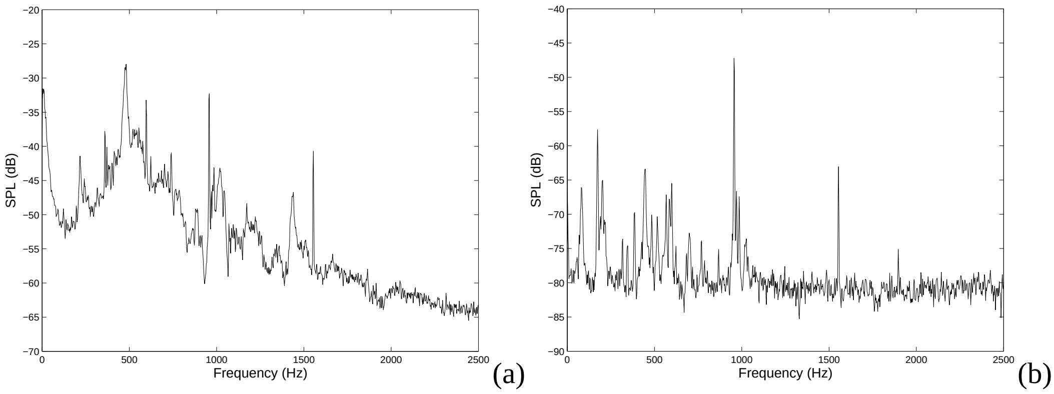

Figure 3 - Power spectrum of the radiated (a) and in-duct (b) acoustic signals; L/H=4.6, Re=11800.

The power spectrum of the radiated signal (Fig. 3(a)) exhibits a dominant peak at 480 Hz and a lower one at 956 Hz (this frequency corresponding to a resonant mode of the flow supply duct) whereas the inner power spectrum shows a strong excitation at 956 Hz. The other duct's resonant modes are only weakly excited.

The flow structure is now investigated in terms of velocity fluctuations between the nozzle outlet and the plate in the shear layer. For *L/H*=4.4 and *Re*=11800, the amplitude (a) and the phase (b) of the velocity fluctuations at 956 Hz (Δ) and 480 H (o) are depicted in Fig. 4 as a function of the probe location.

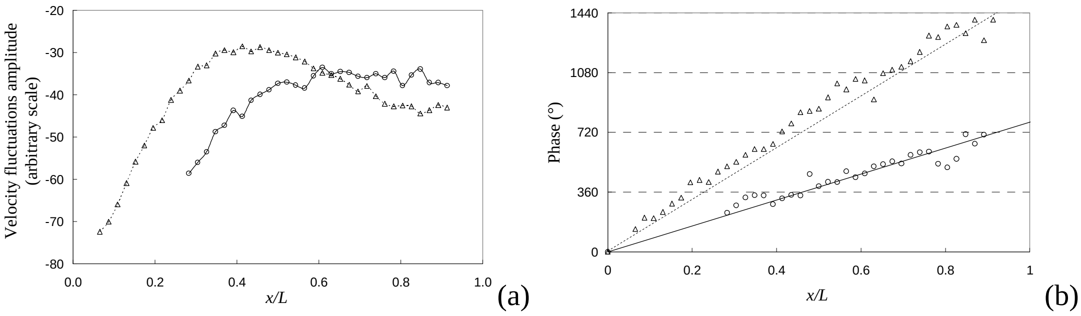

Figure 4 - Evolution of the amplitude (a) and phase (b) of the velocity fluctuations at 956 Hz (Δ) and 480 Hz (o) as a function of the movable probe position; L/H=4.4, Re=11800.

The fluctuations magnitude (Fig. 4 (a)) at 956 Hz increases up to *x/L*=0.4 and then diminishes progressively whereas the magnitude at 480 Hz appears later (*x/L*=0.3), exceeds the 956 Hz amplitude's fluctuations at *L/H*=0.6 and rises until saturation farther downstream (*x/L*=0.8). These results are in good agreements with those of Ho and Huang [7] for an excited free jet. The growth of the subharmonics (480 Hz) amplitude is associated with a decrease of the fundamental's (956 Hz) one, showing energy transfer from the fundamental frequency to its subharmonics frequency.

Moreover, as each 360° phase variation corresponds to the presence of one vortex between the nozzle outlet and the plate, Fig. 4(b) implies the possible presence of four vortices at 956Hz (St_L=2.4) and two at 480Hz (St_L=1.2). Therefore, the anemometric measurements show that the halving of the Strouhal number stage in Fig. 2(b) is induced by vortex pairing.

For *Re*=118000 and *L/H*=4.6, flow visualizations (see Fig. 1 (b)) have been carried out at different instants of an acoustic period *T*=2.1 ms (f_0=480Hz); the nozzle outlet is situated on the left (slotted plate on the right) with the flow going from left to right.

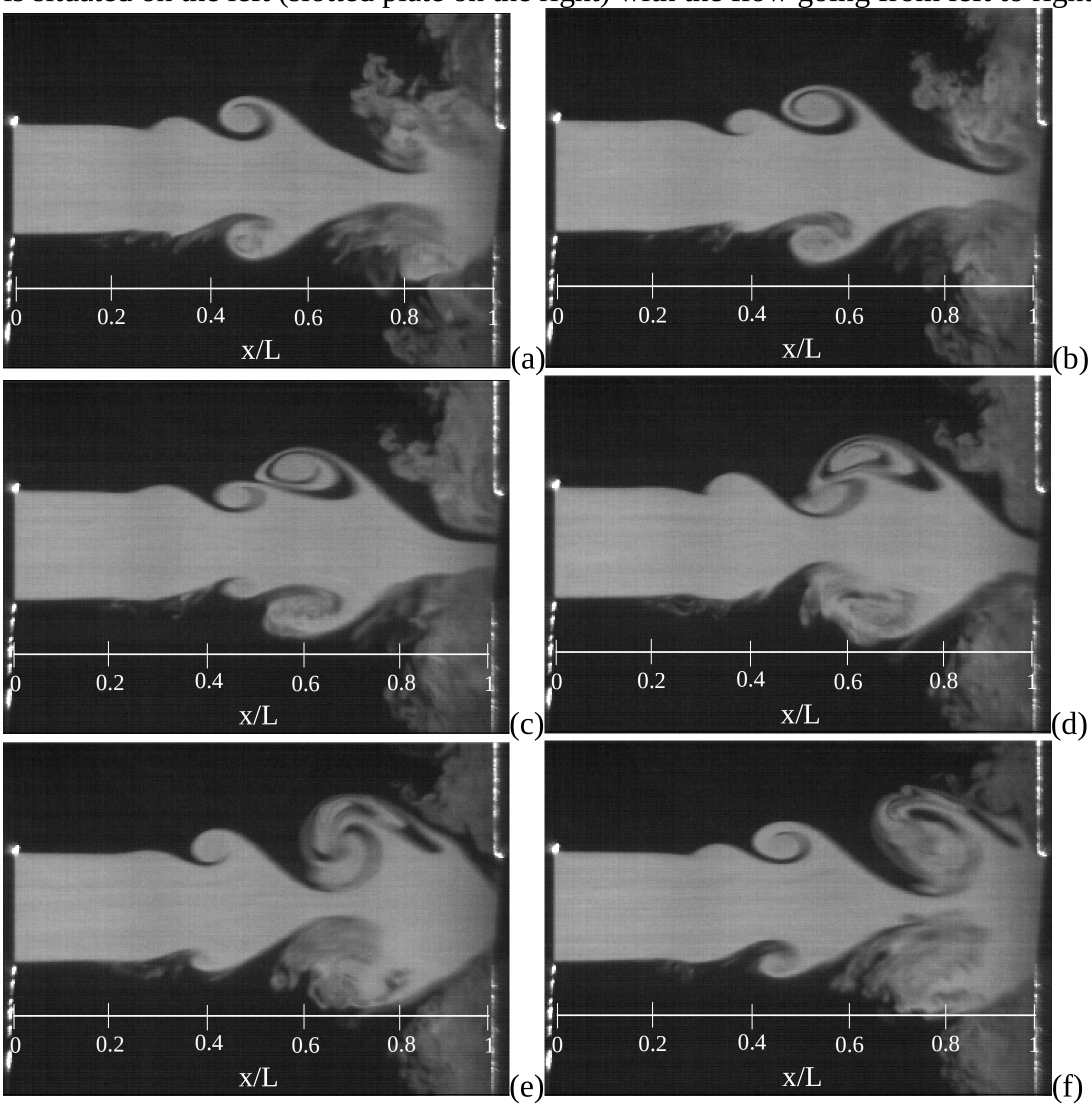

Figure 5 -. Flow visualizations of vortex pairing at Re=11800 and L/H=4.6; (a) t=0, (b) t=T/5.5, (c) t=2T/5.5, (d) t=3T/5.5, (e) t=4T/5.5, (f) t=5T/5.5.

On each side of the shear layer, two vortical structures are recognizable (Fig. 5(a) and (b)). At *L/H*=0.6, the structures get closer (Fig. 5(c)) and start to merge (Fig. 5(d)). These visualisations are in agreements with the velocity fluctuations measurements reported in Fig. 4(a): *L/H*=0.6 corresponds to the location where the magnitude of the subharmonic velocity fluctuations becomes greater than those at the fundamental. Afterwards, the merging occur between *L/H*=0.6 and 0.8 (Fig. 5(e)). For *L/H*>0.8, only a bigger structure can be observed (Fig. 5(e)) which later impinges on the obstacle. The frequency at the impingement is divided by two compared to the vortex shedding frequency. These visualisations allow one to observe the main stages of the vortex pairing and confirm qualitatively the anemometric measurements (Fig. 4).

DISCUSSION

In the near field of the obstacle, where the aeroacoustic sound source is situated, the frequency of the most energetic flow instability is then 480 Hz (Fig. 4). The vortex sound theory [12] involves that the dominant frequency of the radiated pressure waves must be the same, which is confirmed by the acoustic measurements (Figure 3(a)). On the other hand, 480 Hz does not correspond to any resonant frequency of the flow supply duct; this component of the acoustic field cannot excite a duct resonance and is then destructed by interference inside the duct [13]. The second component (956 Hz), less energetic, corresponds to a resonant mode frequency and can excite a flow supply duct resonance (Fig. 3(b)). This component controls then the vortex shedding (Fig. 4 and 5). This mechanism is different from the one reported by Vétel et al. [10]: the successive vortex pairings occurs as the flow velocity is increased allowing the natural instability of the shear layer to be excited by the same resonant mode. Otherwise, in the present configuration, when the plate is moved farther downstream, no other pairing occurs. The observed vortex pairing defines the inferior limit of the emitted tone’s fundamental frequency.

SUMMARY

Anemometric measurements and visualizations allow one to study a vortex pairing phenomenon occurring in the particular configuration of a low subsonic free plane jet impinging on a slotted plate coupled to its flow supply resonances. This pairing explains why the main component of the radiated acoustic field is 480 Hz whereas the vortex shedding frequency is found to be equal to 956 Hz; it is responsible for a sudden drop of the emitted tone frequency when the obstacle distance is increased. Moreover, this pairing defines the inferior limit of the emitted tone fundamental frequency. The better understanding of the physical features of jet-slot oscillator will make the development of a predictive numerical model.

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