Experimental investigation of the vibration of a slotted plate and the acoustic field in a plane impinging jet

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The impinging jet is a flow configuration in which a fluid issuing from a simple geometry hits a wall (perpendicular or with angle). Impinging jet exhibits rich phenomena in terms of vortex structures and fluid-structure interaction. These phenomena become more complicated if the obstacle (a plate in this study) has a slot and are accompanied in some cases by a high level of noise due to the installation of a loop of self-sustained tones. Several parameters influence these phenomena such as the Reynolds number and the plate to nozzle distance. Therefore, we consider a plane jet issuing from a rectangular nozzle and a slotted plate. The sound pressure and the plate vibration are respectively measured using a microphone and accelerometers mounted on the plate. The spectra of both sound and vibration signal and the corresponding coherences are presented. This study brings out the correlation between the plate vibration and the acoustic field in a plane impinging jet for two Reynolds numbers (Re = 12350 and Re = 18200).

1 Introduction

The dynamics of fluid flow can be a source of noise when a transfer of energy occurs between the aero-dynamic and the acoustic fields. The generated noise can have a large spectrum when it concerns the flow turbulence or a spectrum of high energy when the flow is organized as in the case of a jet impacting on a slotted plate.

Actually, in the case of an impacting jet on a slotted plate, the interaction between the flow and the obstacle near the slot, under certain conditions, generates a perturbation which travels the flow and controls its detachment at the out of the nozzle. The disturbance thus produced by this feedback loop optimizes the transfer of energy between the aero-dynamic field of the jet and the radiated acoustic field. The generated noise is known as the self-sustaining tones.

Self-sustaining tones were studied and their mechanism of production was described in several reviews [4, 7, 9, 10]. Understanding the dynamics of the vortex structures involved in the production of these tones, its synchronization with the sound field and the coupling between the sound source and the resonances of the blow pipe were studied and analyzed by Glesser [1].

The study presented here concerns the vibrations of a slotted plate impacted by a rectangular jet and the acoustic field associated [5, 6]. Thus, the objective of this work is to study the relationship between the acoustic field radiated by the flow and the vibration of the plate. Results are presented for two Reynolds numbers: Re = 12350 and Re = 18200. The spectra of the acoustic and the vibration of the plate signals are presented and compared with the numerical modes of the plate and the duct.

2 Experimental apparatus

Figure 1 is a diagram of the experimental device designed to allow the variation of the following geometrical and flow parameters: L, the distance between the plate and the nozzle outlet, and U0, the average velocity of the flow at the nozzle. The duct has a rectangular cross-section of 9x19 cm made of 5mm 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. A settling chamber is placed upstream of the duct to ensure acoustic isolation of the duct from the blower. A 5 mm thick aluminum 25x25 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” is equal to 4 in this paper. L is defined with a precision of 0.1 mm.

Experiments were performed using a data acquisition card allowing 16 inputs: National Instruments. Of these, 8 were used as accelerometers to measure the acceleration of the plate on points chosen arbitrarily and one microphone placed behind the plate, away from the hydrodynamic disturbances) to measure the sound pressure.

The accelerometers used were DGB A/24/E piezotronics, 8 mm in diameter, weighing 2 g and with a sensitivity of 0 Hz to 10 kHz. The microphone was a B&K Free-Field 1/2” Type 4189, which has a sensitivity of 6.3 Hz to 20 kHz.

3 Results

To obtain the eigenmodes of the plate, it was modeled numerically using the explicit (FEM). Thus, these modes were calculated for a plate embedded and isolated. The first twenty modes are presented in Table 1

<table>
<thead>
<tr>
<th>Mode Propre</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fréquence propre</td>
<td>130</td>
<td>268</td>
<td>296</td>
<td>338</td>
</tr>
<tr>
<td>Eigen Mode</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Eigen Frequency</td>
<td>604</td>
<td>647</td>
<td>679</td>
<td>881</td>
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</table>
The vibration of the plate was measured using eight accelerometers glued on the plate. Figures 2 (a) and 2 (b) show the spectra provided by one accelerometer for both studied Reynolds. The most representative signal was selected each time after verifying that all accelerometers have the same excited frequencies (but with different contributions depending on the position of each accelerometer).

In Figures 2 (a) and 2 (b), one can see that two exited frequencies are very similar to two modes of the plate, the 9th at f = 920 Hz for both Reynolds and the 12th at f = 1460 Hz and 1450 Hz for Re = 12 350 and Re = 18 200 respectively.

The excited frequencies, f = 858 Hz in Figure 2 (a) (Re = 12 350) and f = 855 Hz in Figure 2 (b) (Re = 18 200) are similar to the longitudinal resonance frequencies of the duct. Theirs harmonic 2f ~ 1720 Hz is also present in the spectrum. The longitudinal modes of the duct are calculated numerically [1] and are presented in Table 2.

Table 2: Numerical modes of the duct

<table>
<thead>
<tr>
<th>Mode Propre</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</thead>
<tbody>
<tr>
<td>Fréquence propre</td>
<td>85</td>
<td>207</td>
<td>336</td>
<td>467</td>
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<table>
<thead>
<tr>
<th>Eigen Mode</th>
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<th>7</th>
<th>8</th>
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<tbody>
<tr>
<td>Eigen Frequency</td>
<td>597</td>
<td>726</td>
<td>853</td>
<td>974</td>
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<tr>
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<th>11</th>
<th>12</th>
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<tr>
<td>Eigen Frequency</td>
<td>1081</td>
<td>1179</td>
<td>1288</td>
<td>1407</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Eigen Mode</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigen Frequency</td>
<td>1529</td>
<td>1648</td>
<td>1765</td>
<td>1880</td>
</tr>
</tbody>
</table>

In Figures 3 (a) and 3 (b), the spectra of the pressure signals measured by the microphone are presented for two Reynolds. One can notice the existence of the 12th mode of the plate at 1455 Hz (f = 1447 Hz for Re = 12350 and f = 1462 Hz for Re = 18200). This excited mode of the plate has a very low energy. The 9th mode of the plate is not present in the spectrum of the acoustic signal in contrast to the spectrum of the vibration signal.

For both Reynolds, in Figure 2 which shows the spectra of the accelerometer signals of the plate and in Figure 3 which shows typical spectra of self-sustaining sounds [2], the frequencies f1 = 1039 Hz for Re = 12350 and f2 = 1202 Hz for Re = 18200 and theirs harmonics 2f are excited. A sub-harmonic f/2 and a harmonic 3f/2 (due to nonlinear interactions between the modes) are also present.
We define the Strouhal number $St$:

$$St = \frac{f L}{U_0}$$  \hspace{1cm} (1)

where $U_0$ is the velocity in the center of the flow near the nozzle and $L$ is the distance between the outlet of the jet and the plate.

For both Reynolds, we calculate the Strouhal number of the self-sustained tones (using the highest frequency found in the energy spectrum). We find $St \approx 2.5$ and $St \approx 1.43$ respectively for $Re = 12350$ and $Re = 18200$.

The evolution of the Strouhal number obtained through the most energetic frequencies found from the sound and the vibration spectra is consistent with the work of Billon [3] where it was shown that this evolution of the Strouhal number follows three steps according to the Reynolds number.

Figures 4 (a) and 4 (b) show the coherences between the measured pressure and the vibration of the plate for both Reynolds. The evolution of the coherences is shown during the acquisition time (five seconds). In both cases, for $Re = 12350$ and $Re = 18200$, we can notice that the coherences present continuous horizontal lines showing high coefficients of coherence between frequencies $f_1$ and $f_2$ of the acoustic and the vibration signals.

In Figure 4 (a), the coherence reaches a maximum of 0.98 at the frequency $f_1 = 1202$ Hz and 0.86 at the frequency $2f_1$.

In Figure 4 (b) the coherence reaches a maximum of 0.78 at the frequency $f_2 = 1040$ Hz, 0.62 at the subharmonic $2f_2/2$ and 0.54 at the harmonic $2f_2$. One may note that other modes have significant coefficients of coherence for example at $f = 920$ Hz, $1460$ Hz and $f = 3f/2 = 1556$ Hz.

5 Conclusion

In this study we investigated the coupling between the vibration of the plate exposed to the impact of a plane jet and the acoustic field radiated for two Reynolds number, $Re = 12350$ and $Re = 18200$.

The comparison between the numerical eigenmodes of the plate and the acoustic signal measured for both Reynolds shows that the eigenmodes of the plate does not control the fundamental mode of the self-sustaining tones, however, the 12th mode of the plate ($f = 1460$ Hz) has a low contribution in the spectra of acoustic signals.

The diagrams of coherence show a strong coefficient between the most energetic frequencies (the fundamentals $f_1$ and $f_2$) present in the acoustic and the vibration spectra as well as their harmonics $2f_1$ and $2f_2$.

Other frequencies have significant coefficients of coherence, particularly the sub-harmonics and harmonics ($f_1/2, 3f_1/2, f_2/2$ and $3f_2/2$) and two other modes of the plate at $f = 920$ Hz and $f = 1460$ Hz.
References


