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Energy transfers between aerodynamic and acoustic fields in a rectangular impinging jet

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Abstract

Ventilation systems in buildings are of vital importance for the provision of acceptable thermal conditions and air quality while meeting stringent energy requirements. When a rectangular jet hits a slotted plate, an acoustic disturbance can be generated and self-sustained tones produced. Self-sustaining tones appear when a feedback loop develops between the surface of impact and the jet instabilities near to the jet exit. In order to control this phenomenon, more attention should be given to the source of energy that amplifies the resulting noise. Few studies have considered the fluctuation of the aerodynamic field using High Speed 3D Tomographic-PIV in the presence of self-sustaining tones. In this work, we investigate energy transfer between the aerodynamic and acoustic fields for different Reynolds numbers ($Re = 5294$ and $Re = 5956$) to better understand the noise generated by a rectangular jet impinging on a slotted plate. High Speed 3D Tomographic-PIV was performed at a sampling rate of 2 KHz and main flow vortices frequencies below 0.4 KHz. It was found that in the case of an optimal configuration for self-sustaining tones, the fluctuation of the Z-component of velocity presented higher amplitudes near the jet exit region.

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Keywords: Impinging jet; Tomographic-PIV; Turbulent kinetic energy; Self-sustaining tones

1. Introduction

Impinging jets are encountered in many ventilation systems, and these can have a major impact on the acoustic environment and energy performance. Self-sustaining tones can be encountered in applications where a feedback loop exists [2].

An impinging jet is a flow configuration in which a flow coming from a jet exit hits a wall (perpendicular or at an angle). An impinging jet is rich in vortex dynamics and fluid–structure interactions and may be accompanied in

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some cases by a high level of noise due to the development of a loop of self-sustaining tones. When a flow hits a wall, a “stress” on the fluid is created in the impingement contact area, generating a disturbance which travels upstream to the point where the vortices originated and regulates their detachment at the same frequency as that of the excitation produced at the obstacle.

Like the parameters of the flow, the geometry of the jet orifice or the nozzle plays a critical role in the production of self-sustaining tones [4,5,7,8,11] and [12]. When a self-sustaining loop is optimized, energy transfer from the aerodynamic field to the acoustic field occurs in a geometric configuration that allows optimal interactions between the acoustic field and the aerodynamic fluctuations. Many studies have been performed to study self-sustaining tones or to estimate the turbulence kinetic energy produced in 2D-PIV [6]. Alekseenko et al. [1] also considered the Turbulent Kinetic Energy in an impinging jet and the authors calculated the dissipation term from instantaneous Stereo-PIV velocity fields in order to compare swirling and non-swirling impinging jets. A few studies, such as those by Schäfer et al. [13], Schneiders et al. [14] and Tokgoz et al. [15], considered the fluctuation of the jet in Tomographic-PIV velocity fields. In this work, we studied the fluctuations of the velocity field in High Speed 3D Tomographic-PIV, and the acoustic signal was measured with a microphone. Our main objective was to investigate the fluctuation of velocity in optimal conditions for the transfer of energy from the aerodynamic to the acoustic field at different Reynolds numbers ($Re = 4632$, $Re = 5294$ and $Re = 5956$). The Reynolds numbers selected had relatively high and low levels of acoustic generation with the presence of self-sustaining tones [2]. This work should be very useful in understanding the energy transfer mechanism in such configurations, which will in turn contribute to the development of noise reduction techniques.

2. Methodology

2.1. Air flow facilities

A jet impinging on a slotted plate was generated in our laboratory at a free stream velocity denoted by U_0 . A 4 mm thick aluminium plate equipped with a 10 mm high slot was set up in order to achieve the configuration of a jet impinging on a slotted plate. The experimental setup of our study is shown in Fig. 1. The airflow is generated by a compressor and then the airflow passes through a 1250 mm long rectangular tube which was extended by a rectangular convergent. Hence, the setup creates a free jet $H = 10$ mm high and $L_z = 190$ mm wide. Parallel to the convergent, a 4 mm thick aluminium plate was fitted with a bevelled slot of the same dimensions as the convergent outlet and perfectly aligned with the latter using a displacement system. The distance from the exit of the convergent to the impinging plate is denoted by L and was set at 40 mm in this study in order to generate high acoustic levels. Note that confinement is defined as the ratio between L and H , i.e., $L/H = 4$. The Reynolds number is based on the dimension of the nozzle $Re = U_0 \cdot H / \nu$ (where U_0 is the maximum stream-wise velocity at the jet exit and ν is the kinematic viscosity of air).

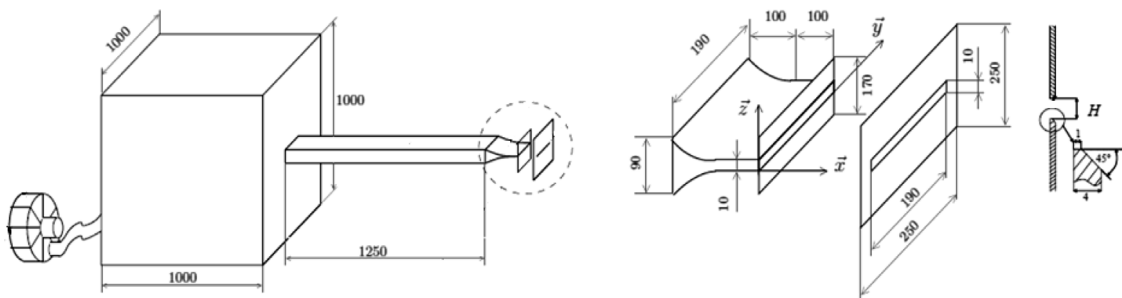


Fig. 1. Experimental setup.

2.2. High Speed 3D Tomographic-PIV

In order to study the characteristics of an impinging jet on a slotted plate for a confinement of $L/H = 4$ and different Reynolds numbers in the presence of self-sustaining tones, a High Speed 3D Tomographic-PIV system was

employed to measure the three velocity components. Time resolved Tomographic-PIV consists in cross-correlating two successive recorded images order to obtain the kinematic field [9].

A 527 nm Nd: YLF LDY 300 Litron laser was used at 30 mJ per pulse, extended with a 1800 mm laser arm. The laser arm was equipped with a volume generator formed by diverging lenses that generate a volume illumination. The volume measured in the present study was $40 \times 60 \times 10 \text{ mm}^3$ following the reference system (X-axis, Y-axis, Z-axis: see Fig. 1). Three Phantom V711 cameras with 1280×800 pixels were used. Two cameras were placed on the right side of the jet exit, one above the other, and the third was placed on the left of the jet at the same level as camera 1 (See the effect of cameras configurations in Elsinga et al. [10]).

2.3. Acoustic measurements

The acoustic pressure was measured simultaneously with the velocity measurements. A microphone was placed behind the plate (away from the aerodynamic disturbances) to measure the radiated sound pressure. The B&K free field $1/2$ inch type 4189 microphone used has a sensitivity range of 7 Hz–20 kHz. For sound field measurements, the sampling frequency was 10 KHz. Microphone signals were processed with a B&K Nexus amplifier/conditioner before being recorded via a National Instruments PXI-6224 acquisition board mounted on a National Instruments PXI 10441 data logger. This microphone has an uncertainty value of 0.2 dB.

3. Results

Self-sustaining tones may be accompanied by very high acoustic levels. The Sound Pressure Levels (SPL) obtained by the jet analysed in this study are shown in Table 1 as a function of the Reynolds number for $L/H = 4$. As shown in Table 1, the acoustic level decreased from by 3.6 dB (from 97.3 dB to 93.7 dB) despite an increase in the Reynolds number from $Re = 5294$ to $Re = 5956$. This Reynolds number ($Re = 5294$) is optimal for the feedback loop of the acoustic excitation, as shown by Assoum et al. [3], and could promote energy transfer from the dynamic to the acoustic field.

Table 1. Sound Pressure Level (SPL) and main acoustic frequency F_0 (Hz) as a function of the Reynolds number (Re).

| Re | SPL (dB) |
|------|----------|
| 5294 | 97.3 |
| 5956 | 93.7 |

Fig. 2 presents the Root Mean Square components V_{rms} and W_{rms} for $Re = 5294$ and $Re = 5956$. For the both Reynolds number, V_{rms}/U_0 started at 0.2 near the surface of impact. Actually, self-sustaining tones are created by a feedback loop that is sustained by an excitation which travels along the jet from the zone of vortex impact and reaches the jet exit, where the flow is very sensitive to any type of perturbation. This perturbation controls vortex generation and energy transfer between the aero-dynamic and acoustic fields. Fig. 2 shows that when $(\frac{Y}{H} \approx \pm 1.5)$ and near the jet exit ($0 < \frac{X}{H} < 1.5$), $\frac{W_{rms}}{U_0}$ is greater, with higher levels ($Level_{maximum} \approx 0.05$) for $Re = 5294$, which is an optimal configuration for self-sustaining tones [3]. For $Re = 5956$, there were lower levels of $\frac{W_{rms}}{U_0}$ in this region of the jet ($Level_{maximum} \approx 0.03$). These lower levels of $\frac{W_{rms}}{U_0}$ in this region may be related to the propagation of the perturbation of control from the impact wall to the jet exit, and could explain why it was stronger when the self-sustaining tones were in optimal conditions, as for $Re = 5294$.

4. Conclusion

The Root Mean Square of the velocity field in a rectangular jet impinging on a slotted plate and the acoustic field generated were investigated experimentally using High Speed 3D Tomographic-PIV and a microphone. Two Reynolds numbers ($Re = 5294$ and $Re = 5956$) with optimal and less optimal configurations for self-sustaining tones were considered. It was found that, in the case of an optimal configuration for self-sustaining tones ($Re = 5294$, local peak of the acoustic level), W_{rms} presented higher amplitudes near the jet exit region. This may be related to the upstream propagation of the perturbation of control created at the impinging wall. This

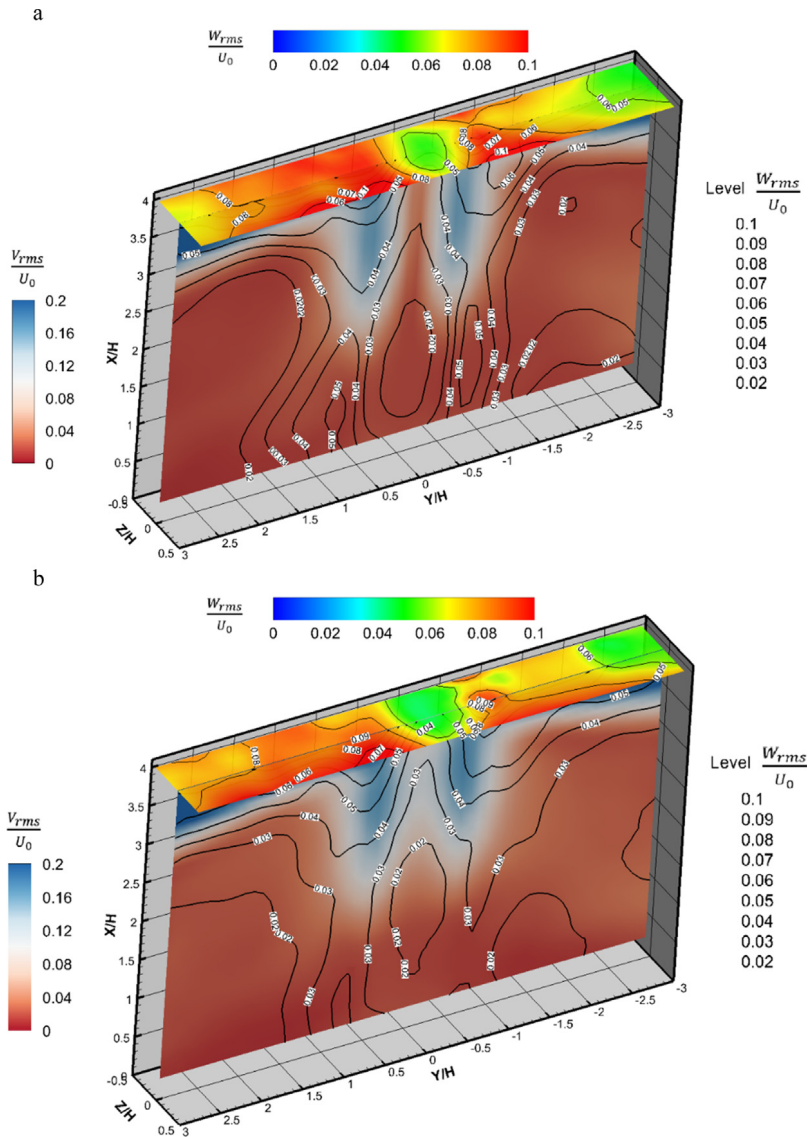


Fig. 2. Root Mean Square components at the centre of the jet. (a) $Re = 5294$ and (b) $Re = 5956$.

perturbation is of high significance in the self-sustaining phenomena by its spatial propagation and effect on the fluctuations of the velocity field. Further work needs to be done on the correlation between turbulent kinetic energy and the acoustic field. This may provide more information regarding the energy source the acoustic field.

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