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Energy Reports

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Elsevier

Suggested Citation: Assoum, Hassan H. et al. (2020) : Turbulent Kinetic Energy and self-sustaining tones in an impinging jet using High Speed 3D Tomographic-PIV, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 2, pp. 802-806, <https://doi.org/10.1016/j.egy.2019.12.018>

This Version is available at:

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The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019),
September 20–23, 2019, Okinawa, Japan

Turbulent Kinetic Energy and self-sustaining tones in an impinging jet using High Speed 3D Tomographic-PIV

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Received 2 October 2019; accepted 19 December 2019

Abstract

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 produced by aero-acoustic coupling can occur in impinging jets when a feedback loop develops between the jet exit and the surface of impact. (Powell, 1964) developed an analogy that takes into account the sound sources created by vortices, and (Howe, 1975) was the first to use this analogy in the case of a near-wall flow. Howe's energy corollary makes it possible to calculate acoustic power using three quantities: vorticity, flow velocity and acoustic velocity, using experimental or numerical data and taking the aerodynamic field to be the main source of energy. In this study, the velocity and the acoustic fields in a rectangular jet impinging on a slotted plate were measured simultaneously using High Speed 3D Tomographic time-resolved particle image velocimetry (Tomographic-PIV) and a microphone. The 3D Tomographic time-resolved has the advantage of providing three components of velocity in a volume. Thus, we inspect the interaction between turbulent energy produced by the flow and the acoustic field in the presence of self-sustaining tones in order to have a better comprehension of the aero-acoustic coupling. Results were obtained for a Reynolds numbers $Re = 5294$ and $Re = 5956$ which are configurations that induces acoustic tones. The spectrum of the Turbulent Kinetic Energy (TKE) had peaks of frequencies such that the period of the acoustic signal was smaller than that of the TKE in presence of self-sustaining tones. The findings of this work may serve to develop new techniques of control to reduce the acoustic generation.

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: Aero-acoustic coupling; Impinging jet; Tomographic-PIV; Turbulent Kinetic Energy

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<https://doi.org/10.1016/j.egy.2019.12.018>

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1. Introduction

Jets are very important due to their many industrial applications. They can differ in terms of their form (two-dimensional, axisymmetric, elliptic, lobed, etc.), regime (laminar, transient, turbulent), their confinement (lateral, transversal, etc.), the shape of the blowing device (nozzle, orifice, tube, convergent, etc.), and the temperature and nature of the fluid (density, compressibility).

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 [1,2] showed that the Strouhal number relative to the frequency transmitted depends both on the distance between the jet outlet and the slotted plate, and on the speed of the jet, while remaining within the upper and lower limits of the velocity range that corresponds to the appearance of self-sustaining sounds. Chanaud and Powell [3] noted the presence of pure and harmonic sounds in a laminar regime (between $Re = 1000$ and $Re = 2500$). Ziada [4] considered cavity noise and noted in his work the presence of self-sustaining tones from $Re = 3000$ to $49\,000$.

The acoustic field is related to the irrotational part of the velocity field [5]. Howe's energy corollary [6] can be used to evaluate the acoustic power generated or absorbed in a flow. It is used for low Mach number flows and a periodic acoustic field of period T_0 . It is written:

$$P = \iint_S \langle \vec{I} \cdot \vec{n} \rangle dS = \iiint_V \langle f_0 \cdot u_a \rangle dV = - \iiint_V \rho_0 \langle (\omega \times v) \cdot u_a \rangle dV \quad (1)$$

where P is the acoustic power flux across a surface S which surrounds the domain V and \vec{n} is the normal to the surface S . The three terms ω , v and u_a (where ω , v and u_a are the vorticity, the velocity and the acoustic velocity, respectively) must be obtained using experimental data (difficult to access the acoustic velocity) or numerically, as was the case in the study by Glessler [7], Hourigan et al. [8].

Few studies have examined the Turbulent Kinetic Energy derived from Tomographic-PIV velocity fields [9–11] for impinging jets when a self-sustaining tones is set in the jet. Thus, in this work, we investigated the correlation between the Turbulent Kinetic Energy (denoted by TKE in this paper) derived from High Speed 3D Tomographic-PIV measurements, and the acoustic signal measured with a microphone. Our main objective was to investigate the optimal conditions for the transfer of energy between the aerodynamic and the acoustic fields.

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 aluminum 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 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 aluminum plate was fitted with a beveled 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 impinged 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).

2.2. High speed 3D Tomographic-PIV and acoustic measurements

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 $40 \times 60 \times 10$ mm³ following the reference system (X-axis, Y-axis, Z-axis). Three Phantom V711 cameras with 1280×800 pixels were used.

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 to 20 kHz. This microphone has an uncertainty value of 0.2 dB.

3. Results

As shown in Table 1, the acoustic level decreased 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.

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

Re	SPL (dB)	F_0 (Hz)
5294	97.3	164
5956	93.7	168

As shown in Table 1, the fundamental frequencies (F_0) of the acoustic signals are $F_{0,Re=5294} = 164$ Hz and $F_{0,Re=5956} = 168$ Hz.

Fig. 1 illustrates the 3D iso-contours of the vorticity and the distribution of the average normalized TKE. As can be seen for $Re = 5294$ and $Re = 5956$ (Fig. 1a and b), TKE was highest near the surface of impact, where the deformation of vortices occurs. Moreover, there was a symmetric mode for $Re = 5345$. However, an antisymmetric mode was found for $Re = 5956$ (see the vorticity and velocity vectors). The change of aerodynamic mode (from symmetric to antisymmetric, as in our case) may be followed by a deterioration in the optimal conditions for energy transfer, which could be related to the local acoustic peak at $Re = 5294$.

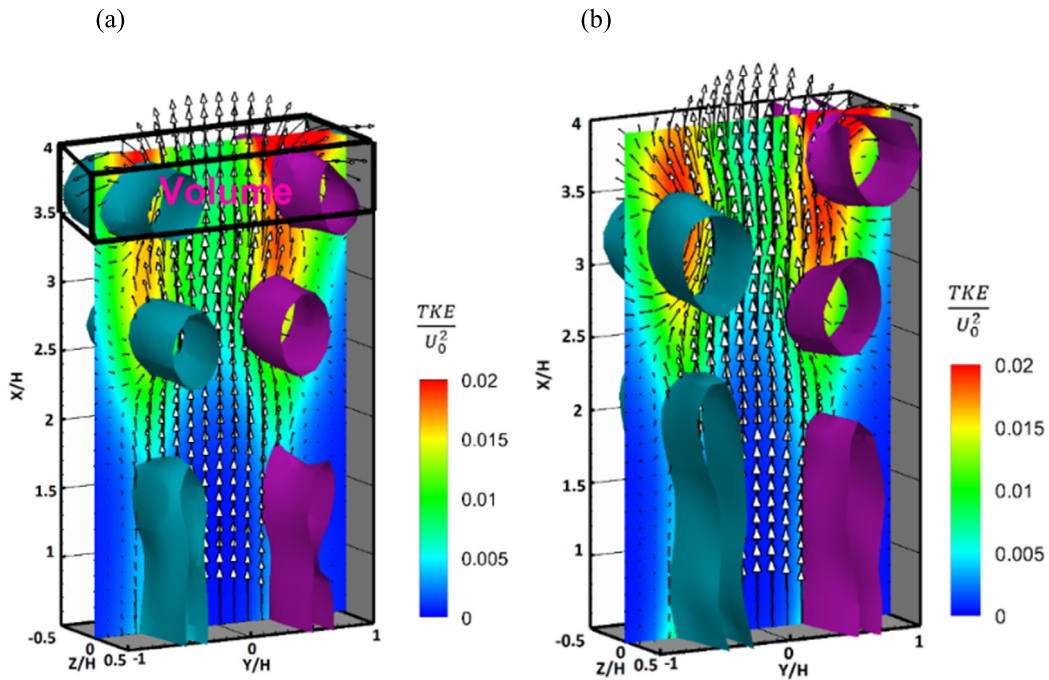


Fig. 1. Vorticity 3D iso-contours and TKE field. (a) $Re = 5294$ and (b) $Re = 5956$.

The volumetric TKE (with $TKE = \frac{u'^2 + v'^2 + w'^2}{2}$) in Fig. 1 was calculated on each voxel of the Tomographic-PIV images in a selected volume as shown in Fig. 1b, where U , V and W are the velocity components in X , Y and Z directions, respectively ($U = U_{mean} + u'$, $V = V_{mean} + v'$ and $W = W_{mean} + w'$). The Turbulent Kinetic Energy was normalized by the square of the maximum streamwise velocity U_0^2 : $\frac{TKE}{U_0^2}$. Therefore, the change as a function of time of TKE was calculated in the volume shown in Fig. 1b in such a way that it contained the vortices which hit the wall, as described previously by Assoum et al. [12]. Therefore, the sum of $\frac{TKE}{U_0^2}$ in this volume, ($3.5 < \frac{X}{H} < 4$, $-1 < \frac{Y}{H} < 1$ and $-0.5 < \frac{Z}{H} < 0.5$) was divided by the volume considered. By performing this calculation for successive PIV images, we obtained the normalized TKE per unit of volume as a function of time.

Time was normalized by the acoustic period obtained from the acoustic period given in Table 1 ($T = 1/F_0$); the volumetric normalized TKE was obtained as function of the acoustic period.

In the present work, 3D High Speed Tomographic-PIV was performed at a sampling rate of 2 kHz. The main flow vortices frequencies were below 0.4 kHz. Since TKE is very sensitive and can thus fluctuate a lot with time, we were mainly interested in the spectrum of this fluctuation and the frequencies which could be excited in the presence of self-sustaining tones.

Fig. 2 is a plot of the power spectra of TKE for each Reynolds number. The power spectra of the TKE had peaks at $f_{Re=5294} = 148$ Hz and $f_{Re=5956} = 152$ Hz and harmonics $2 * f$ (for $Re = 5294$). Interestingly, all the excited frequencies were lower than the frequency of the acoustic signal $F_{0,Re=5294} = 164$ Hz for $Re = 5294$ and $F_{0,Re=5956} = 168$ Hz for $Re = 5956$ (Table 1). This may indicate that self-sustaining tones occur when the period of TKE is larger than the period of the acoustic signal, enabling a better transfer of energy from the aerodynamic to the acoustic field.

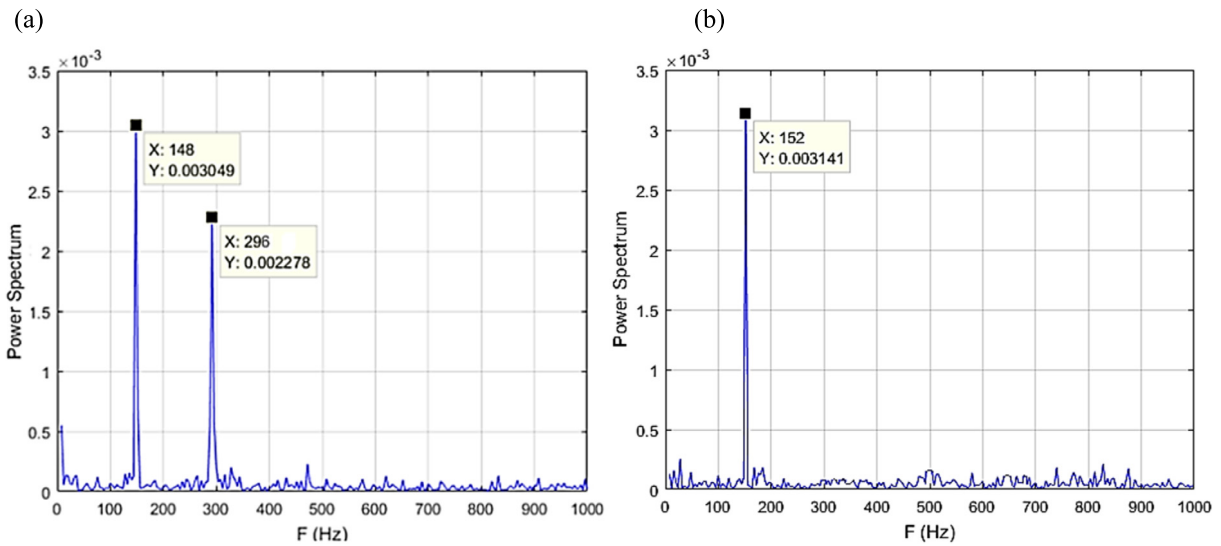


Fig. 2. (a) Power spectrum of normalized TKE (a) $Re = 5294$ and (b) $Re = 5956$.

In Table 2, the cross-correlations coefficients calculated between the acoustic signal and TKE for each Reynolds number are given. For $Re = 5294$ the cross-correlation showed a negative peak with a correlation coefficient $C_{Re=5294} \approx -0.25$. However, for $Re = 5956$, positive peaks of correlation were obtained with correlation coefficients of $C_{Re=5956} = 0.33$. The negative peak of correlation for the optimal self-sustaining tones configuration ($Re = 5294$, local peak of the acoustic level) may suggest that both acoustic and TKE fields should be in opposition of phase for an optimal transfer of energy.

Table 2. Coefficient of cross correlation between $TKE/(U_0^2 * Volume)$ and the acoustic signal as a function of the Reynolds number (Re).

Re	C_{Re}
5294	-0.25
5956	0.33

4. Conclusion

For different Reynolds number, the Turbulent Kinetic Energy (TKE) 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. It was found that the spectrum of TKE had peaks of frequencies such that the period of the acoustic signal was smaller than that of the TKE for the two Reynolds numbers with self-sustaining tones. Actually, in such configurations the acoustic cycle was covered by the TKE period, which may indicate that the conditions were adequate for the transfer of energy from the aerodynamic to the acoustic field. We also obtained a negative peak of

correlation between the acoustic signal and TKE for $Re = 5294$ (a configuration with a local peak of the acoustic level), which may suggest that the acoustic and TKE fields should not be in phase in order to obtain an optimal configuration for energy transfer. Experiments with more Reynolds numbers should be investigated in the future for better understanding of these phenomena.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors wish to thank FEDER and the region of Nouvelle Aquitaine for its financial support.

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