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Experimental study of the vortex organization in a rectangular impinging jet in the presence of self-sustained tones

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Abstract

Impinging jets could be used in the terminal elements of ventilation systems to ensure a better air mixing in the residential buildings. However, under certain configurations, these jets could be accompanied by a whistling tone. This whistling tone is amplified when the jet encounters a slotted obstacle in its flow. Usually, for a given Reynolds number, these tones are characterized by a single frequency. In this study, we represent the jet behavior for a Reynolds number Re=5900 where two different frequencies are obtained in the spectrum of the whistling tone signal. This unusual aspect is related to an altered vortex organization as we will show using Stereoscopic PIV (SPIV) measurements.
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Keywords: Impinging jet, vortex, self-sustaining tones, Stereoscopic PIV (SPIV).

1. Introduction

Impinging jet on a slotted plate has multiple uses. In particular, for the cooling of parts by accentuating thermal exchanges. Similarly, to ensure the aeraulic comfort in the air renewal systems in living enclosures. Thus, we introduce air grilles which improve the mixture and reduce the feelings of air currents. These terminal elements behave like an impinging jet on a slotted plate. But these jets generate, in certain configurations, noise pollution which can be intensified by the installation of self-sustaining tones (Rayleigh (1896)). These self-sustaining tones are manifested by whistling, which deteriorates the acoustic comfort (Alkheir (2020); Alkheir et al. (2019); Assoum et al. (2014, 2013)). Note that, the self-sustaining tones are only installed for well-defined blowing conditions. During their

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installation, the conditions of energy transfer from the turbulent kinematic field to the acoustic field are optimized (Alkheir et al. (2019); Assoum et al. (2019); Edgington-Mitchell et al. (2014); Hamdi et al. (2019); Chanaud and Powell (1965)). Typically, for each Reynolds number, we have a specific selfsustained tones (Alkheir et al. (2020); Ho and Nosseir (1981); Rockwell and Naudascher (1978)). Powell (1964) has studied the noises emitted by the vortex structures. In 1975, Howe (1975) has deposed his formulation of the acoustic power generated by a self-sustaining tones. This acoustic power is a mixed product of the vorticity, the convection velocity of vortex and the acoustic velocity. Thus, we note that the acoustic wave production is relied to the dynamic structures of the flow. The main objective of this article is to study the aeroacoustic behavior of a rectangular impinging jet on a slotted plate for a Reynolds number Re = 5900. Simultaneous measurements of the instantaneous kinematic fields and the radiated sound fields were carried out. Thus, the dynamics of the flow, from the outlet of the jet to the slotted plate, were obtained thanks to Stereoscopic Particle Image Velocimetry (SPIV) measurements. The processing and analysis of the data made it possible to visualize the vortex activity and calculate correlations between velocities and acoustic signal. Monitoring vortex structures have allowed us to understand the origin of the acoustic frequencies that emerge in the spectra. On the first hand, the analysis of the results highlights an atypical and remarkable dynamic behavior. On the other hand, following a statistical study, this atypical behavior was explained.

2. Methodology

The air is initially compressed via a compressor and then directed to a stabilization chamber. After that, the air passes in a duct of 1250 mm in length where a honeycomb is installed to reduce its turbulent aspect. The flow is finally ejected through a rectangular convergent of height H = 10 mm and a width L_z = 190 mm. A slotted plate placed in face of the jet intercept the flow (Fig. 1). The impinging distance between the nozzle of the jet and the slotted plate is denoted by "L" and could be adjusted via a displacement system. Note that the Reynolds number is given by $Re = (U0.H)/\nu$, with U_0 is the flow average velocity at the outlet of the jet and ν is the kinetic viscosity. The kinematic field of the flow is calculated from measured field via the Stereoscopic Particle Image Velocimetry technique (SPIV). This technique is based on illuminating a flow seeded by small particles of oil by a laser sheet. Two cameras Phantom V711 are installed to take photos of the illuminated flow. For the PIV acquisitions, the sampling frequency was 2500 Hz. Pressure measurements were taken simultaneously with the photos using a B&K4189 microphone. For the acoustic acquisitions, the sampling frequency was 15000 Hz.

Based on the Shannon theorem, to detect a frequency f, sampling frequency must be equal $f_e = 2 \times f$. Due to the high SPIV data's volume, the frequency 2500 Hz is selected different than 15000 Hz. This frequency detects all dynamics occurrences under 1250 Hz. In raison of the dynamic fields affect the acoustic fields and the acoustic data is not voluminous, the acoustic frequency was set at 15000Hz, to verify that there is any other occurrence between 1250 Hz and 7500Hz.

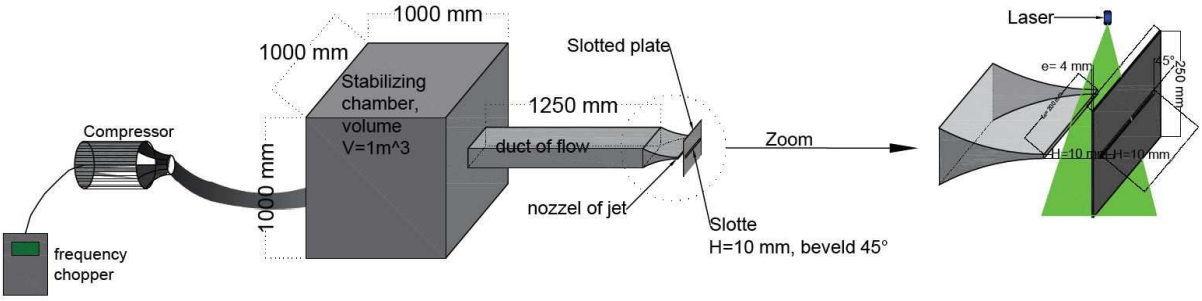

Fig. 1. Experimental device.

3. Results

Fig. 2 represents the acoustic spectrum obtained by the microphone for a Reynolds number $Re = 5900$. One can see that two peaks of frequency are present at $f = 160\ Hz$ and $f = 320\ Hz$ (Fig. 2). As we mentioned before, this spectrum represents an atypical behavior of a whistling tone loop which show only one peak of frequency usually.

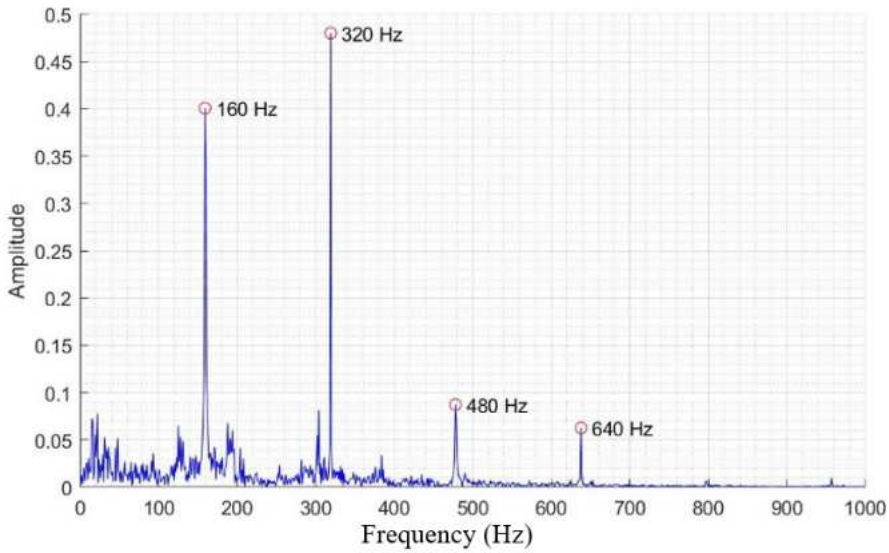

Fig. 2. Acoustic frequency spectrum, for Re=5900 and L/H=4.

This result therefore suggests two vortex organizations for this same Reynolds number Re = 5900. The spectrum also shows other much less energetic harmonics at 480 Hz and 640 Hz.

Since the acoustic signal is triggered by the impingement of vortices on the slotted plate, this unusual aspect pushes us to visualize the flow in order to understand what happened at the level of the flow dynamics. On Fig. 3 we represent a raw field obtained via the cameras of SPIV system. Analysis of all the images over a period of 1 s shows an atypical behavior of the dynamic behavior of this flow. Indeed, the vortex dynamics of the flow presents a symmetrical organization (Fig. 3 (a)), then following instabilities in the shear layer, the vortex dynamics changes behavior to become antisymmetric (Fig. 3 (b)). This alternating behavior of the vortex dynamics continues to follow one another over time.

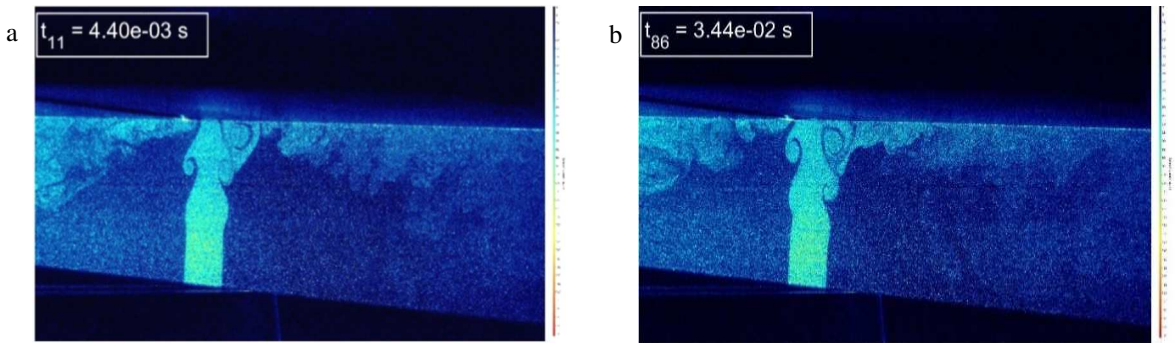

Fig. 3. (a) Symmetric organization (t = 4.4 ms); (b) Antisymmetric organization (t = 34.4 ms).

Thus, the flow presents a behavior with symmetrical and antisymmetric vortex organizations. The transition time between these two organizations is of the order of 1 ms much less than the periods of the frequencies of the self-sustaining tones installed in the flow (160 Hz and 320 Hz).

This result (which will be confirmed by other approaches) explains the existence of the frequencies of 160 Hz and 320 Hz which reflect the two different organizations of the vortex dynamics in the flow. It should also be noted that the self-sustaining tones at the fundamental frequencies 160 Hz and 320 Hz follow each other (do not appear at the same time) which conforms to the definition of self-sustaining tones. As it has been shown from the raw field that for the Reynolds number Re = 5900 with an impact ratio L/H = 4, the flow represents two alternating vortex organizations. In order to identify the vortices structures, we have calculated the λ_2 criterion that are based on the minimum of local pressure.

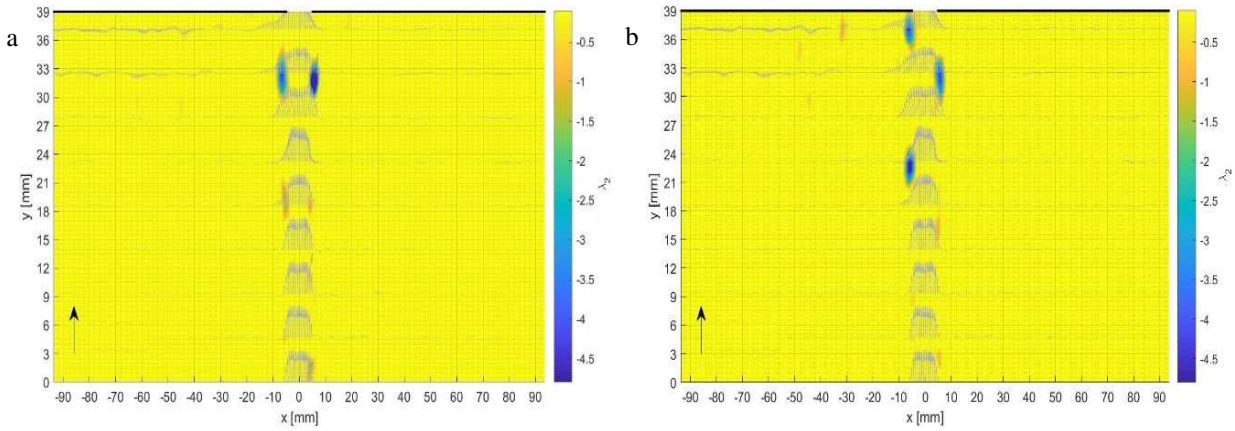

Fig. 4. (a) λ_2 criterion for symmetric organization ($t = 4.4\ ms$); (b) λ_2 criterion for antisymmetric organization ($t = 34.4\ ms$).

Fig. 4 (a) shows the symmetrical organization of the vortex structures detected by the criterion λ_2, and Fig. 4 (b) shows the antisymmetric organization of the vortex structures detected by the criterion λ_2, for a Reynolds number Re=5900 and an impact ratio L/H = 4.

Fig. 4 (a), shows that when the vortex structures are symmetrical with respect to the axis of the jet, they are in phase from their birth until their impacts at the level of the slotted plate. The phase shift calculated between the vortices of the bottom of the jet (left side) and that of the top of the jet (right side) shows an almost zero value (0.03 rd); which confirms that the vortices are in phase on either side of the axis of the jet.

After a certain moment, the flow will be destabilized for a very short time (less than one millisecond) and a new organization of the vortex structures takes place: the vortex structures take on an antisymmetric organization as shown in Fig. 4 b). Thus, during this vortex arrangement, the phase shift between the vortices at the bottom of the jet and that at the top of the jet is of the order of 3 rd.

In order to verify the correlation between symmetric/antisymmetric modes of the flow and the two peaks of frequency in the acoustic spectrum, we consider a point of the field where the vortices are convected ($X = 5\ mm, Y = 33\ mm$) and we represent the spectrum of the transversal velocity at this point on Fig. 5.

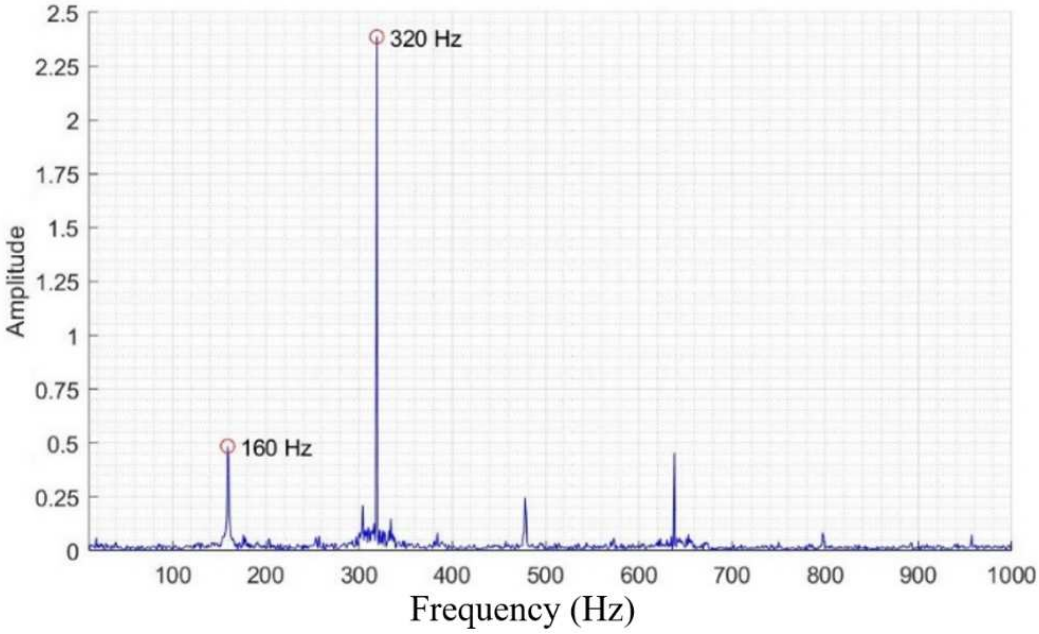

Fig. 5. Velocity frequency spectrum for ($X = 5\ mm$; $Y = 33\ mm$), $Re = 5900$ and $L/H = 4$.

The transversal velocity spectrum shows also two peaks of frequency which are the same of the acoustic signal (160 Hz and 320 Hz). Note also that the spectrum shown in Fig. 5 tells us only about the frequency of the vortex dynamics at the chosen point. Indeed, the amplitudes of the frequencies of the spectrum depend on the amplitudes of the measured transverse speeds which in turn depend on the point chosen to detect the vortex passage. Furthermore, the calculation of the convection velocity of the vortex structures and of their phase shift showed that the symmetric vortex organization is installed at 160 Hz and the antisymmetric vortex organization is installed at the frequency of 320 Hz.

To understand this atypical alternating vortex dynamic which is responsible for the appearance of self-sustaining tones alternating in turn between the frequencies 160 Hz and 320 Hz, the trajectories of the vortex structures will be followed. For this purpose, the vortices detected by the criterion λ_2 will be superimposed for all acquisition instants (1 s) including all the phases of their formation until their impacts on the slotted plate. Thus, Fig. 6 represents the trajectories of the vortex structures during 1 second.

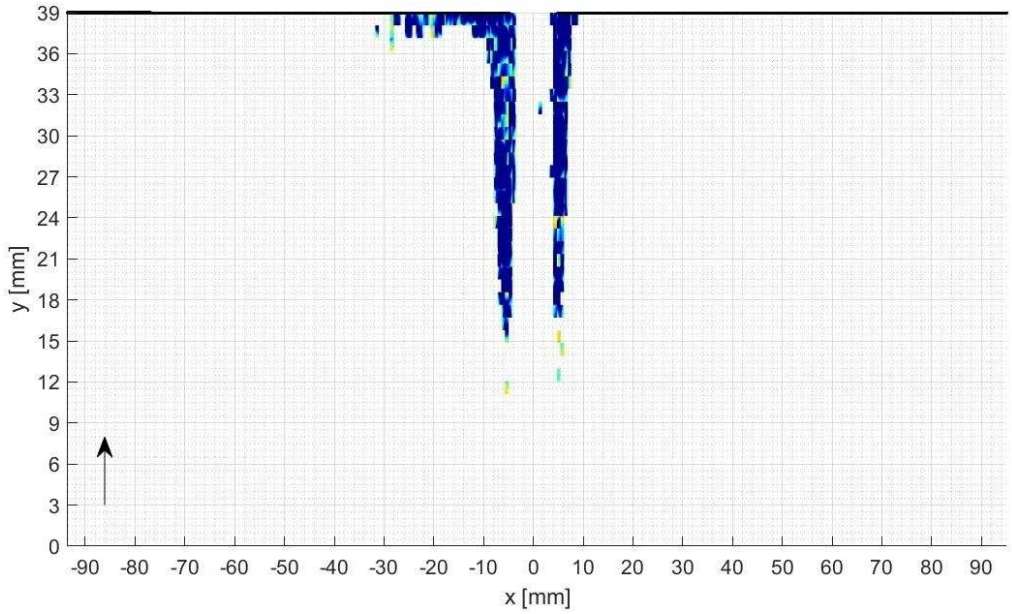

Fig. 6. Trajectories of vortices detected by the criterion λ_2, for a Reynolds number $Re = 5900$ and an impact ratio $L/H = 4$.

From this figure (Fig. 6), we can notice that the vortices resulting from the organization of symmetrical vortex structures at the $160\ Hz$ frequency and antisymmetric at the $320\ Hz$ frequency follow almost the same path. As we approach the slot, a small portion of the vortex structures at the bottom of the jet (left side) passes through the slot. This explains why there is a fairly sustained vortex activity on this side of the plate. However, the vortex structures at the top of the jet (right side) almost all pass through the slot. This asymmetry could be attributed to the instabilities of the flow, which cause the alternation between the symmetrical and the antisymmetric organization of the vortex structures. On the other hand, this behavior could also explain the energy difference of the acoustic frequencies $160\ Hz$ which represents the symmetrical behavior of the vortex activity and that of $320\ Hz$ which reflects the behavior of the antisymmetric activity of the flow. Indeed, the vortices which pass through the slot optimize more the energy transfer towards the acoustic field.

We seek to learn about the persistence over time of the two symmetrical and antisymmetric vortex organizations which alternate in the flow. Thus, when following the vortex structures of the flow over time, image by image, we find that the antisymmetric mode organization is more persistent in time than that of the symmetric vortex organization. These different vortex organizations are represented in Fig. 7.

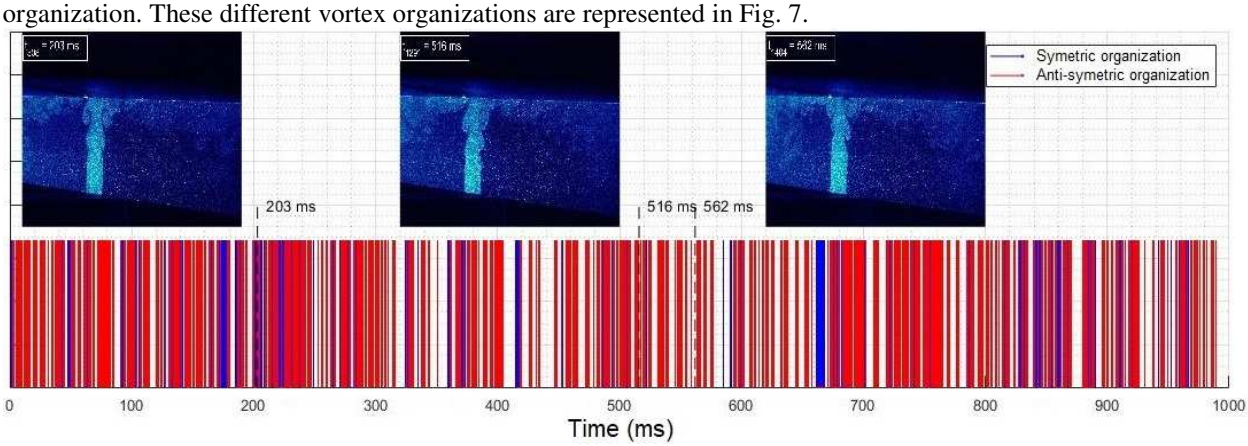

Fig. 7. Succession of vortex organizations as a function of time for $Re = 5900$ and $L/H = 4$.

This figure (Fig. 7) shows the following:
Peaks in blue indicate a symmetrical vortex organization for 0.01 seconds (1.6 periods of the $160\ Hz$ frequency, for example ($t = 203\ ms$)).
The peaks in red indicate an antisymmetric vortex organization for 0.005 seconds (1.6 periods of the $320\ Hz$ frequency, for example ($t = 516\ ms$)).
That the antisymmetric organization (red peaks) is more present in the flow than the symmetric organization (blue peaks).
That the alternation of symmetric and antisymmetric vortex organizations in the flow is random. That the white spaces where there is no peak on the curve correspond to a transition time from one organization to another (for example, ($t = 562\ ms$)).

From the Fig. 7, a statistical approach was used to know the duration of persistence over time of each of the two vortex organizations. The number of blue peaks that indicate symmetric organization is equal to 394, when the number of red peaks that indicate the presence of an antisymmetric vortex organization is equal to 1121:
During one second of acquisition, the time of persistence of the symmetrical organization in the flow is equal to: $\tau = 0.26\ s$.
During one second of acquisition, the time of persistence of the antisymmetric organization in the flow is equal to: $\tau = 0.74\ s$.

This approach confirms the quantitative observations made from the analysis of images from the SPIV. This persistence explains the energetic difference between the frequencies $160\ Hz$ and $320\ Hz$ in the obtained spectra of the transversal velocity and that of the acoustic field.

4. Conclusion

In this study, we considered a rectangular jet impinging on a slotted plate for a Reynolds number $Re = 5900$, two whistling tones have been met at the frequencies of $160\ Hz$ and $320\ Hz$. Thanks to SPIV measurements, we have shown that the acoustic frequencies of $160\ Hz$ and of $320\ Hz$ are generated respectively by symmetric and antisymmetric vortex organizations who alternates randomly in time. In addition, we have noticed that the vortices of the symmetrical organization and those of the anti-symmetric organization follow almost the same trajectories. The statistical study of the vortex organization has shown that the vortex organization is antisymmetric and more persistent (74%) than that of the symmetrical vortex organization (26%). Likewise, the flow switches from the symmetrical vortex organization to the antisymmetric vortex organization in a random manner and during a switching time of the order of $1\ ms$. In future works, another nozzle to plate distances should be tested. A thin cylinder could also be introduced in the trajectory of the flow to observe its effect on the flow organization and its acoustic generation.

Acknowledgments

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