

Article

Flowfield and Noise Dynamics of Supersonic Rectangular Impinging Jets: Major versus Minor Axis Orientations [†]

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Abstract: The current study explores the flowfield and noise characteristics of an ideally expanded supersonic (Mach 1.44) rectangular jet impinging on a flat surface. The existing literature is primarily concentrated on axisymmetric jets, known for their resonance dominance, pronounced unsteadiness, and acoustic signatures. In contrast, non-axisymmetric jets remain relatively less understood, particularly those impinging on a ground surface. By employing Schlieren imaging, high-frequency pressure measurements using high-bandwidth transducers, and particle image velocimetry (PIV), this research comprehensively examines the flow-acoustic phenomena. Schlieren imaging revealed distinct, coherent structures and strong acoustic waves, while pressure measurements at the impingement surface exhibited high-amplitude fluctuations, peaking at approximately 186 dB. Acoustic analysis identified multiple high-amplitude tones with unique directional characteristics, suggesting the potential for multiple simultaneous modes in rectangular jets. Furthermore, the PIV data elucidated differences in the jet shear layer and wall jet development attributed to the nozzle orientation. These findings contribute to a deeper understanding of non-axisymmetric jet behavior, offering insights relevant to fundamental flow physics and practical applications such as vertical takeoff and landing aircraft.

Keywords: supersonic jets; flowfield; jet noise; impinging jets



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1. Introduction

Axisymmetric supersonic impinging jets under specific operating conditions are known to exhibit high unsteadiness and pronounced acoustic fluctuations due to the feedback mechanism [1–7]. This dynamics is largely attributed to a mechanism where Kelvin–Helmholtz instabilities within the jet shear layer give rise to vortical structures which grow as they convect downstream. Upon impinging on a surface, these structures induce significant pressure fluctuations, which manifest as upstream-traveling acoustic waves that subsequently excite the shear layer at the nozzle lip, thus perpetuating the feedback loop. The extent of unsteadiness and noise generated by these jets is modulated by various parameters, which include the distance of the nozzle to the ground plane, presence of adjacent jets, momentum, Mach number, nozzle pressure ratio (NPR), and temperature ratio (TR) of the jet [8–11]. Figure 1 describes the two modes of feedback loop mechanisms associated with supersonic jets. Powell [12,13] developed a theoretical model to predict the frequencies associated with the feedback loop of round impinging jets.

Despite extensive investigations into axisymmetric jets, the study of non-axisymmetric jets, particularly those emanating from rectangular nozzles, remains relatively sparse. Rectangular jets are distinguished by their enhanced mixing rates with the ambient environment compared with their axisymmetric counterparts, attributed to their distinct

geometric configuration [14–18]. Previous research has delved into the flowfield evolution and three-dimensional characteristics of rectangular jets, identifying three primary regions within these jets: a potential core, a self-similar decay region along the minor axis, and an axisymmetric decay region where the velocity decay is inversely proportional to the axial distance. Notably, non-axisymmetric jets exhibit a phenomenon known as axis switching [15,18,19], where the size of the jet along its minor axis surpasses the one along its major axis at a certain downstream distance. Previous studies utilizing particle image velocimetry (PIV) and acoustic measurements in rectangular jets have revealed the impact of corner and streamwise vortices on the generation of self-induced excitation, commonly referred to as the screech tone [18,20–22]. Similar findings have also been reported in various numerical studies (see, for example, [23,24]).

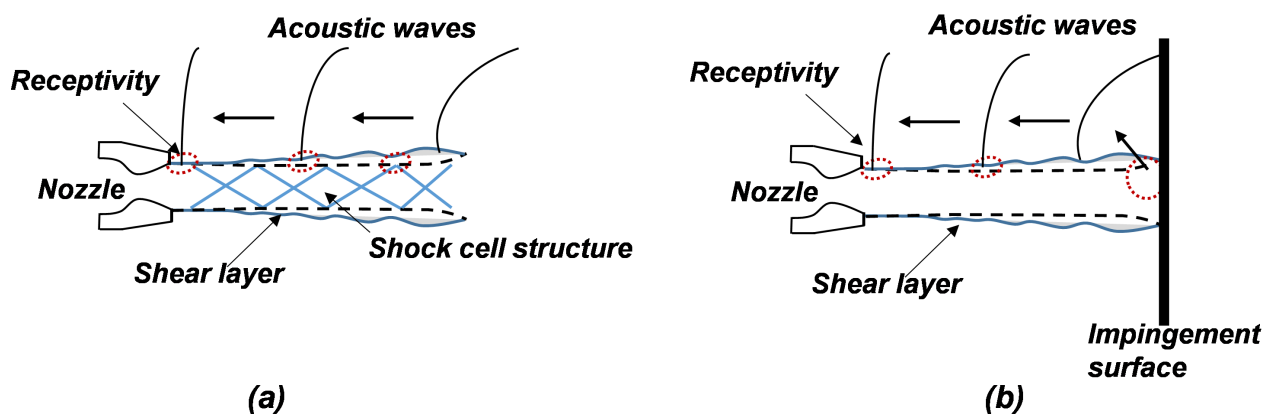


Figure 1. Feedback loop mechanism in a supersonic (a) screeching jet and (b) impinging jet.

The interaction of such jets with a surface introduces additional noise components, characterized by both discrete (impingement tones) and broadband elements. Early foundational work by researchers, such as Krothapalli [25], shed light on the fundamental features of rectangular impinging jets, identifying the dominant tones associated with screech and impingement. Subsequent studies [26–30], including detailed investigations into acoustic behavior such as multiple tones and flow oscillations of rectangular jets, have furthered our understanding of these complex phenomena.

However, much of the existing literature has focused on off-design, screech-dominated conditions, with limited exploration of the impact of the impingement distance on the flowfield evolution at the ground surface and its consequent acoustic signature. In addressing this gap, the present study aims to elucidate the effects of the impingement distance on ground-level unsteady pressures and nearfield acoustics as well as examine variations in the flow and acoustic fields along the major and minor axes of the rectangular nozzle. Through this investigation, we seek to answer two pivotal scientific questions. (1) What is the effect of the impingement distance on the unsteady pressures on the ground and the nearfield acoustics of jets exhausting from rectangular nozzles? (2) How do the flow and acoustic fields vary about the two axes (i.e., major and minor axes) of the rectangular nozzle?

2. Experimental Set-up and Conditions

2.1. Test Facility

All experiments were carried out in the short take-off and vertical landing (STOVL) facility at the Florida Center for Advanced Aero Propulsion located at the FAMU-FSU College of Engineering. The compressed air for this facility was supplied through a set of tanks with a capacity of 110 m³ which could supply air at a maximum pressure of 3450 kPa. The facility has the capability of supplying a maximum absolute pressure of 827 kPa and stagnation temperature of 750 K, which are controlled by high-pressure valves and an inline 192 kW electric heater to achieve the desired nozzle pressure ratio and temperature ratio, respectively.

A series of honeycomb straighteners and meshes were installed upstream of the nozzle to streamline and condition the flow. A ground plane, which was positioned perpendicular to the nozzle axis, was attached to a traverse mechanism. This mechanism was connected to a stepper motor to simulate various distances between the nozzle and the ground. A circular impingement plate insert 266.7 mm in diameter was flush-mounted on the rectangular ground plane to study the impinging jet flows. The impingement plate insert was designed to accommodate unsteady pressure transducers in an array. The plate insert could also be rotated about its axis to change the orientation of the pressure transducer array.

The experiments were conducted with a converging–diverging rectangular nozzle with a design Mach number of 1.44. The nozzle had an aspect ratio of 4:1 with the minor axis of the nozzle ($h = 10$ mm), while the major axis was $w = 40$ mm. The converging part of the nozzle was designed using a fifth-order polynomial, and the diverging section was designed based on the method of characteristics (MOC), which existed only along the minor axis. The major axis was kept straight from the throat to the exit.

2.2. Measurement Techniques and Instrumentation

2.2.1. Schlieren

The flowfield was visualized using a Z-type Schlieren technique. White light from a Luminus Devices 7000K 3A LED source (pulse duration of 1 μ s) was focused onto a pinhole using collimating optics. The beam emerging from the pinhole was directed to a concave mirror (focal length of 2.54 m, $f_{\#} = 8$) through a planar folding mirror. The concave mirror generated a collimated beam of light, while the plane folding mirror was used to overcome spatial constraints within the test facility. The collimated beam subsequently illuminated the region of interest and then traveled to a second identical concave mirror on the other side of the test section. This beam was captured using a Photron FASTCAM SAZ camera after being reflected by a second planar folding mirror. A vertical knife edge was placed at the focal point of the converging beam from the concave mirror, and 500 instantaneous images were acquired at a rate of 60 Hz for the current set of experiments.

2.2.2. Nearfield Acoustics

Nearfield acoustic measurements were performed using two Brüel & Kjaer 4939 free field microphones 6.35 mm in diameter. They were positioned in such a way that they were perpendicular to each other, corresponding to the major and minor axes, and 25.4 h upstream of the plane containing the nozzle exit. A schematic of the microphone locations about the nozzles is shown in Figure 2. Microphones Mic 1 and Mic 2 were placed at a radial distance of $r = 38$ h with respect to the nozzle axes. The microphone signals were first amplified through a B&K 2960 C signal conditioning amplifier at a sensitivity of 3.16 mV/Pa. The signals were then passed through low-pass analog filters (Stanford Systems SR 650) with a cutoff frequency of 50 kHz. Before each set of tests, the microphones were calibrated using a B&K 4228-type pistonphone at a frequency of 250 Hz and an amplitude of 124 dB. Nearby metal surfaces were covered with acoustic foam to minimize acoustic reflections, as the tests were conducted in a non-anechoic environment.

2.2.3. Surface Unsteady Pressure Measurements

The flow-induced pressure fluctuations on the impingement plate were measured with two high-frequency Kulite pressure transducers 1.6 mm in diameter (K1 and K2) (model no. XCE-062-100A) separated by a distance of 54.61 mm (5.46 h) such that K1 was located exactly beneath the impingement point, and K2 was situated in the wall jet, as shown in Figure 2. The pressure transducers were carefully calibrated using a Druck DPI 610 pressure calibrator before the tests.

All unsteady pressure measurements and acoustics signals were synchronized and sampled at a rate of 102.4 kHz for 1 sec at each nozzle-to-ground plate distance. The data were acquired through a National Instruments PCI-4472 acquisition card and were monitored

using LabView software. A frequency resolution of 50 Hz was achieved, and the results were post-processed using the 'Pwelch' function on the MATLAB computing platform.

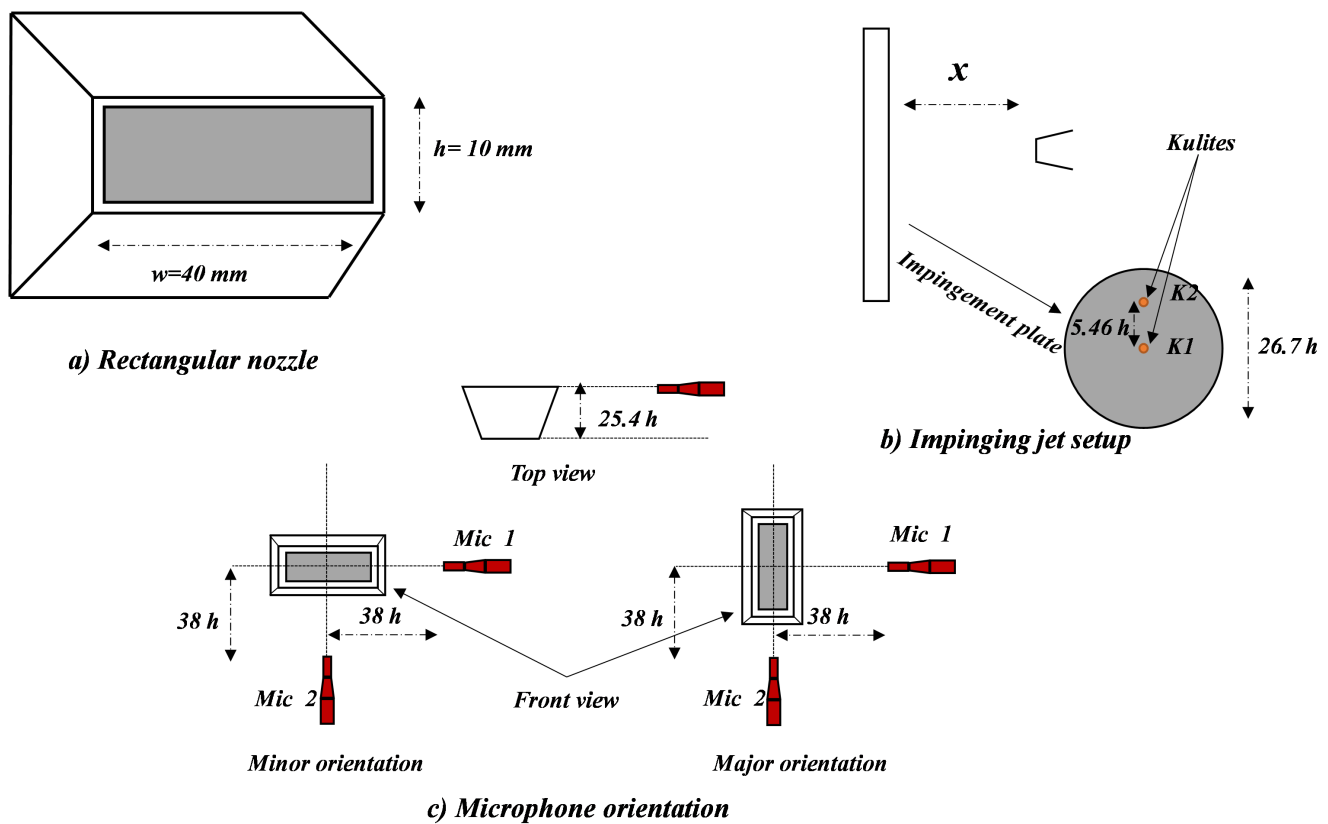


Figure 2. Schematics of the rectangular nozzle, impingement surface, and instrumentation setup.

2.2.4. Planar Particle Image Velocimetry (PIV)

PIV was carried out to quantify the velocity field. The flow was seeded by sub-micron size avocado oil using a Laskin nozzle seeder. A double-pulsed Nd:YAG (200 mJ/pulse) laser was used for illumination of the seed particles. A light sheet with a thickness of about 1 mm was created using a suitable combination of spherical and cylindrical lenses. The time between the two laser pulses was set to 1.8 μ s. Images were acquired at a rate of 15 Hz using a 5.5 megapixel, 2560 $\times$ 2160 pixel sCMOS camera. The processing employed a multi-pass approach. During the initial two passes, an interrogation window of 64 $\times$ 64 pixels with 50% overlap was utilized. In the final pass, an interrogation window of 32 $\times$ 32 pixels with 75% overlap was applied. For each case, 500 instantaneous image pairs were acquired, and the image pairs were processed using LaVision DaVis software.

2.3. Test Conditions and Measurement Uncertainties

The experiments were performed at a nozzle pressure ratio of 3.37, corresponding to the ideally expanded condition. All experiments were performed at a temperature ratio of 1. The nozzle-to-impingement-plate distance was varied from 3 to 20 h in steps of 0.25 h for the acoustics and pressure measurements. The Schlieren, acoustics, pressure transducers, and PIV set-ups were held fixed, and only the nozzle was rotated by 90 degrees to obtain measurements in both (major and minor) orientations. Table 1 summarizes the test conditions for the current set of tests. The NPR and TR values were accurate within ± 0.0375 and ± 0.04 , respectively. The ground-plane-to-nozzle distance uncertainty was ± 3 mm. The data acquisition system used for acoustic and unsteady pressure measurements had a 24 bit analog-to-digital-converter resolution. The measurement uncertainty in the unsteady pressure signals provided by the manufacturer was $\pm 0.5\%$ of the full-scale output. The

velocities measured through planar PIV were found to have uncertainties within 2% of the jet's fully expanded exit velocity in the jet cores and within 5% of the jet velocity in the shear layer. These values were calculated using DaViS software.

Table 1. Test matrix.

Measurement	TR	NPR	x/h	Measurement Location
Unsteady pressure	1.0	3.37	3–20	0–5.46 h
Nearfield acoustics	1.0	3.37	3–20	38 h
Schlieren	1.0	3.37	5, 17, free jet	
PIV	1.0	3.37	5, 17	

3. Results and Discussion

The objective of this study was to characterize the aeroacoustic properties of rectangular impinging jets. As mentioned in the previous section, the results were examined at various impingement distances. However, only pertinent results are included herein. The global flowfield was visualized utilizing the Schlieren technique. Unsteady pressure measurements and nearfield acoustics were employed to characterize the flow's unsteadiness. Finally, the flowfield was quantified and elucidated by employing PIV.

3.1. Qualitative Flow Visualization

The conventional Schlieren technique was employed to visualize the flowfield associated with the impinging jet, with the findings compared against those of free jets under analogous conditions. Instantaneous Schlieren images for three cases are shown in Figure 3 for both the major and minor orientations. The results of the minor axis are illustrated in Figure 3a–c for x/h of 5, 17, and the free jet condition, respectively. At $x/h = 5$ (Figure 3a), the supersonic jet was observed to exit the nozzle, advect downstream, and approach the impingement plate, where it decelerated abruptly. The jet subsequently altered its trajectory, owing to the surface-imposed zero penetration boundary conditions. Post impingement, a wall jet formed and diffused at a certain distance from the impingement point. One can visualize the coherent structures within the jet shear layer, forming a comparatively subdued shock cell structure, and various acoustic wave patterns were discernible. Cylindrical wave patterns were also observed to originate from the jet shear layer. Despite maintaining nozzle pressure conditions conducive to an ideally expanded jet, minor pressure variances, coupled with nozzle imperfections and a finite lip thickness, resulted in a faint shock cell structure.

One can also visualize several waves originating near the impingement point, which correspond to the high-amplitude impingement tones. These tones directly resulted from the aeroacoustic coupling, a self-sustained phenomenon initiated at the nozzle lip by the acoustic waves. As briefly described, these resulted in instabilities close to the nozzle lip, which were amplified and manifested into large-scale coherent structures as they convected downstream. These structures subsequently impinged upon the surface. The resulting impingement led to the generation of pressure fluctuations, leading to high-intensity acoustic waves. The phase relationship of the feedback loop determine a specific frequency to be satisfied. In the noise spectrum, these discrete high-amplitude tones manifest as impingement tones. Detailed analyses of the noise measurements are in subsequent sections. At an increased impingement distance of $x/h = 17$, as depicted in Figure 3b, features such as the shear layer, wall jet, coherent structures, and acoustic waves persisted, albeit with diminished intensity. Previous studies on axisymmetric nozzles suggest that the flowfield at shorter impingement distances is predominantly dominated by resonance [9,10]. In contrast, when the impingement plate is removed, resulting in a free jet scenario, as shown in Figure 3c, the flowfield underwent significant alteration, notably the absence of wall jets and acoustic waves. The jet displayed a flapping mode, yet wave patterns were absent, indicating a weakened feedback loop (screech) between the shock structures and the shear layer.

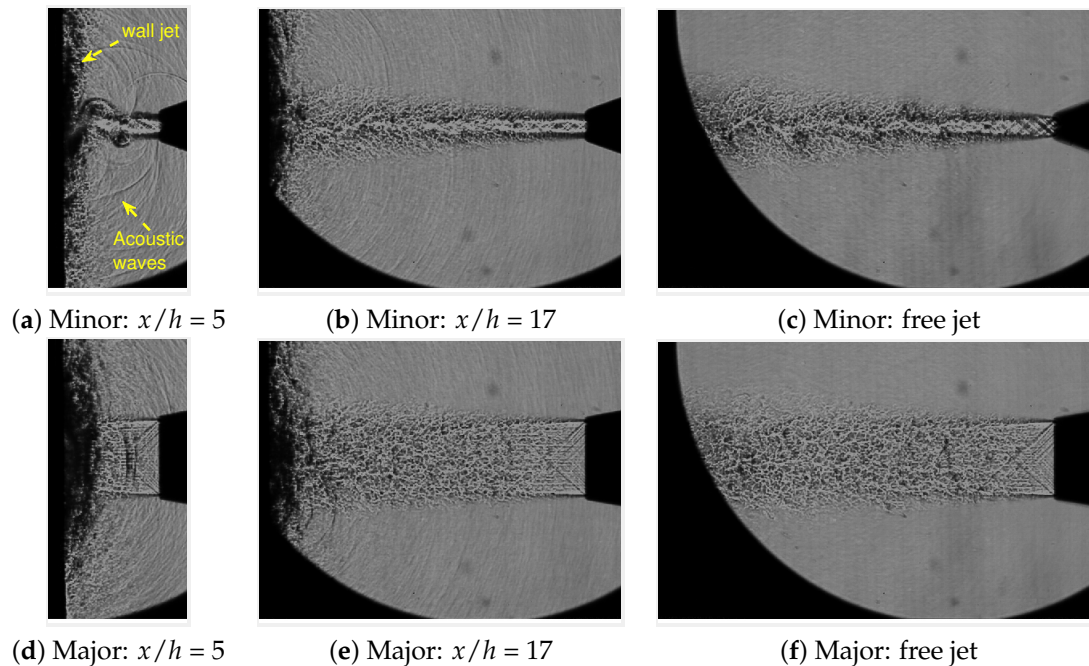


Figure 3. Instantaneous Schlieren images at different nozzle heights for major and minor axes (flow from right to left).

When the nozzle was oriented such that the major axis aligned with the direct line of sight in Schlieren imaging, both similar and distinct features were discerned in comparison with those observed with the minor axis orientation. As depicted in Figure 3d, the presence of a weak shock structure, impingement tones, and unsteady wall jets, akin to those observed in the minor axis configuration, can be identified. An increase in the impingement distance, as illustrated in Figure 3e, led to diminished intensity for the impingement tones, expansion of the shear layer, and persistence of the unsteady wall jets. Comparable to the minor axis scenario, the major axis configuration also revealed analogous characteristics for the free jet condition, as shown in Figure 3f. While the overarching features of the major axis orientation bore resemblance to those of the minor axis orientation, several nuanced distinctions were also observed. Notably, the pronounced vortical structures evident in the minor axis (Figure 3a) at $x/h = 5$ were absent in the major axis configuration. Concurrently, the intensity of the acoustic waves was somewhat reduced, indicating the influence of the nozzle orientation on the behavior of non-axisymmetric jets. Figure 4 delineates the root mean square (RMS) characteristics of the Schlieren images, derived from post-processing 100 instantaneous Schlieren images, to accentuate the flow's fluctuating nature. Figure 4a vividly illustrates the jet's interaction with the impingement surface, showcasing a bright, dense plate shock indicative of a high-velocity jet impinging upon the plate, leading to the typical spread observed in wall jet formation. A comparative analysis across all orientations and impingement distances revealed more pronounced shear layer growth in the minor axis configuration. These observations will be quantitatively elaborated upon in subsequent sections. Overall, the Schlieren findings offer invaluable insights into the dynamics of a supersonic jet, elucidating the influence of the nozzle orientation and standoff distance on the jet spread, shock intensity, and flow structure. These distinctions play a pivotal role in comprehending the jet's acoustic and dynamic behaviors, with significant ramifications for applications in jet propulsion and noise mitigation. The observed non-uniformity in coherent structures and wave emission in rectangular nozzles necessitate further investigation through additional pressure and acoustic measurements, as detailed in the following subsections.

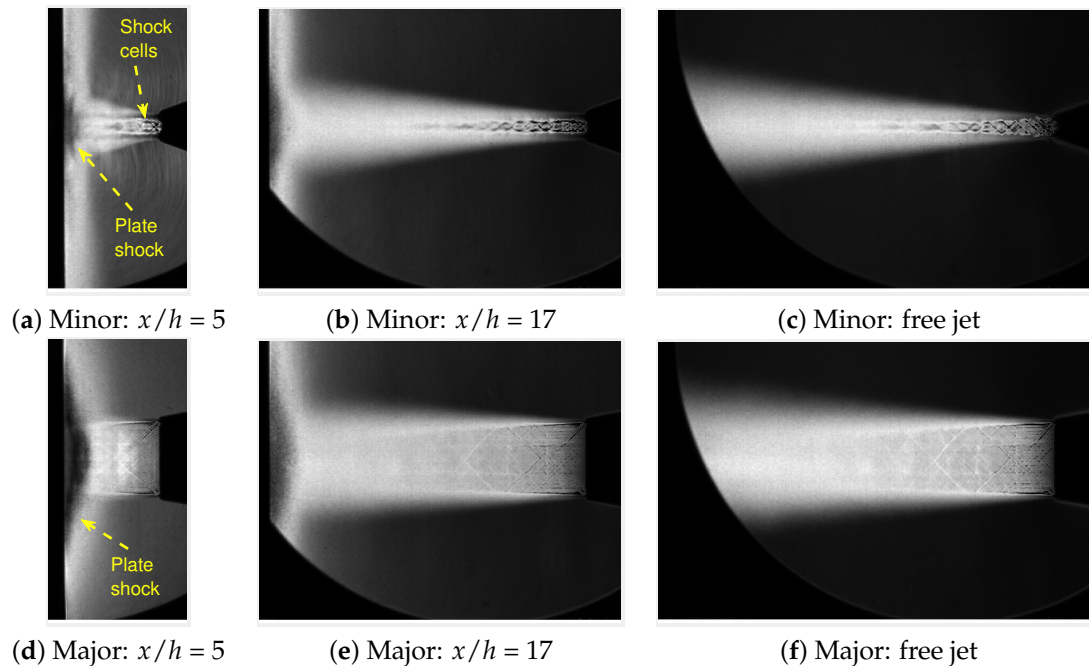


Figure 4. RMS Schlieren images at different nozzle heights for major and minor axes (flow from right to left).

3.2. Unsteady Surface Pressure and Nearfield Acoustics

Unsteady surface pressure and nearfield acoustic measurements were performed using two Kulite pressure transducers flush-mounted on the impingement plate and free field microphones (Mic 1 and Mic 2), respectively, as described in the experimental section (Figure 2). Pressure and acoustics measurements were synchronized to better understand and quantify the flow unsteadiness. The results were obtained for both axes (major and minor) and at different impingement heights as shown in Figure 5. We begin by presenting the overall sound pressure level (OASPL) for two microphones when the nozzle was in the major axis orientation (Figure 5a). Mathematically, the OASPL on a dB scale is defined by Equation (1):

$$OASPL(dB) = 20 \times \log_{10} \left(\frac{P_{rms}}{P_{ref}} \right) \quad (1)$$

where P_{ref} is 20 μ Pa and P_{rms} is the fluctuating pressure component of the pressure. For Microphone 1, it is apparent that the OASPL distribution demonstrated distinct local maxima and minima as a function of the impingement distance, indicating a pronounced dependence on the nozzle standoff distance. An OASPL of 147 dB was recorded at the minimal impingement distance of 3 h. Notably, the OASPL values reached their peak within a 5–6 h distance from the nozzle, suggesting this region was indicative of strong resonance-based impingement tones which substantially contributed to the sound pressure levels. It is widely recognized that such intermediate distances typically exhibit resonance-dominated behavior in axisymmetric impinging jets [1,10]. Interestingly, analogous characteristics were observed in the present study of non-axisymmetric impinging jets. A more detailed analysis of resonance-dominated impingement tones will be conducted subsequently. Beyond $x/h = 6$, the OASPL diminished with an increasing impingement distance, displaying smaller peaks and troughs, which implies that a weaker resonance was maintained even at greater impingement distances. The OASPL value decreased to 137 dB at the maximum distance from the nozzle. Subsequently, the nearfield noise levels measured by Microphone 2 are presented and contrasted with those of Microphone 1.

The trend of the OASPL for Microphone 2 closely mirrored that of Microphone 1, with OASPL values peaking at a specific nozzle height before diminishing markedly as

the distance between the nozzle and the impingement plate increased. Although the qualitative trends showed minimal variation, quantitative differences between the two microphones' results are evident. Primarily, the OASPL magnitude for Microphone 2 was lower than that for Microphone 1 at most locations, indicating a pronounced directivity in non-axisymmetric jets. Previous studies, such as those conducted on axisymmetric single impinging jets, have typically reported symmetric sound emission. However, the current findings indicate a unique directivity pattern in nearfield noise from rectangular impinging jets, which may also correlate with the Schlieren images previously discussed, where the nozzle exhibited a preferential flapping mode along one axis. Notably, the disparity in OASPL amplitudes was more pronounced at shorter impingement distances, diminishing with increased distance from the nozzle and eventually nullifying at $x/h = 20$. This trend could be associated with the attenuation of coherent structures at larger distances, leading to a weakened feedback loop mechanism.

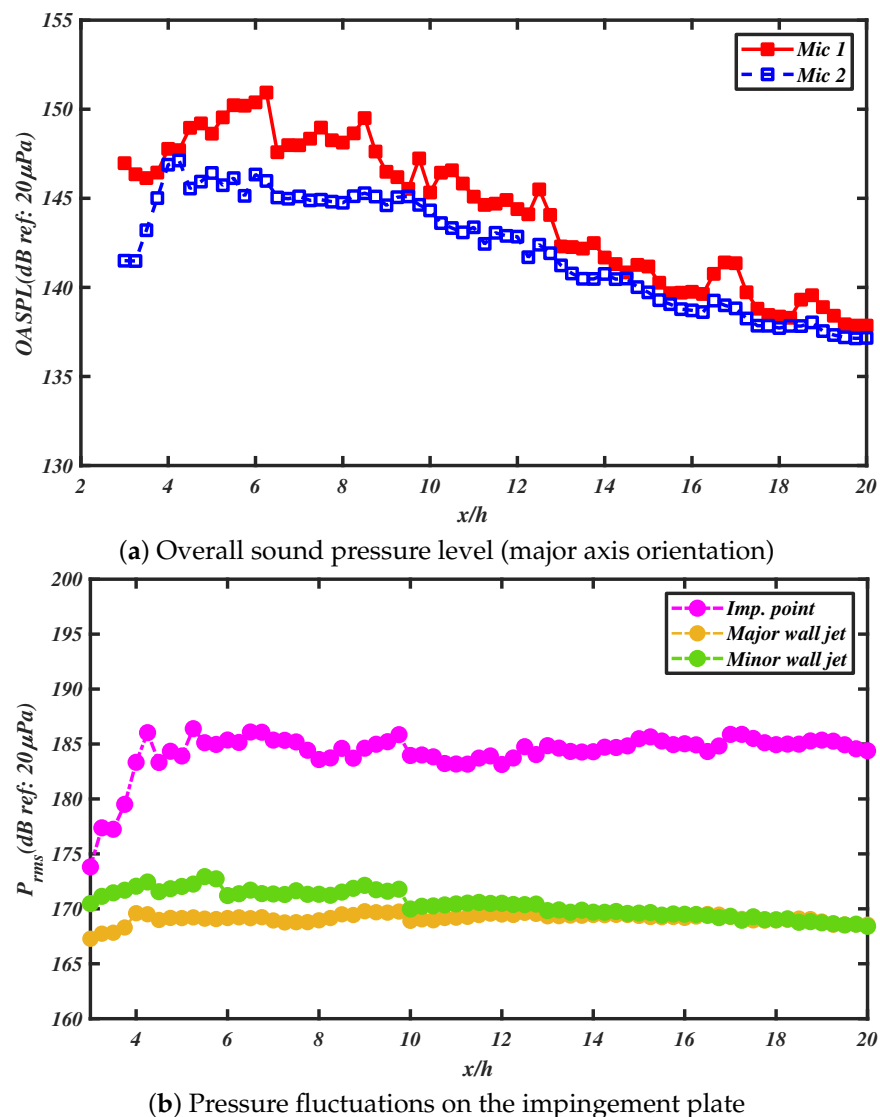


Figure 5. Unsteady characteristics of a rectangular impinging jet.

Further examination was directed toward the unsteady pressures measured at the impingement (Imp.) point and within the wall jets along both the major and minor axes on the ground plane, as depicted in Figure 5b. To assess the wall jet in a different orientation, the nozzle was rotated by 90 degrees, transitioning from the major to the minor view plane. The unsteady pressures, reaching as high as 185 dB at the impingement point, peaked near

$x/h = 5$ and 6, aligning with the resonance-dominated distances akin to the acoustic findings. Beyond this point, the pressure fluctuations surprisingly remained relatively constant, a phenomenon consistent with prior studies on impinging jets from circular nozzles, where impingement point pressure fluctuations reach a peak and then stabilize for most distances. Such elevated pressure fluctuations are commonly observed in supersonic jets. Interestingly, until $x/h = 13$, the unsteadiness in the wall jet differed between the major and minor axis orientations, with higher pressures observed in the minor axis orientation. This could be attributed to the more pronounced coherent structures and rapid shear layer growth in the minor axis orientation, as evidenced in the Schlieren images. Beyond $x/h = 13$, the unsteadiness equalized between the two axes, potentially due to the impingement surface extending beyond the potential core of the jet. Another contributing factor might be the axis-switching phenomenon frequently observed in rectangular jets, where at sufficient distances, the minor axis of the jet begins to expand more rapidly than the major axis [18]. It is hypothesized that at approximately $x/h = 13$, the jet may undergo an axis switch, leading to a more axisymmetric jet shape prior to their eventual convergence further downstream. Comparing nearfield acoustics and unsteady pressure fluctuations revealed that the unsteadiness was global and resonance-dominated, also being influenced by the jet's axis orientation.

We further investigated the acoustic spectra derived from Microphones 1 and 2 at two distinct nozzle standoff distances ($x/h = 5$ and 17), as depicted in Figure 6, with the nozzle oriented along its major axis. The frequency is represented by the x axis, while the y axis denotes the sound pressure level (SPL), calculated with a reference pressure of 20 μPa . As illustrated in Figure 6a, the spectra from Microphone 1 distinctly exhibited multiple discrete high-amplitude impingement tones and their harmonics, indicative of flow-acoustic coupling. Contrarily, previous studies on axisymmetric nozzles typically reported a singular dominant peak or a series of peaks corresponding to either the axisymmetric or non-axisymmetric modes and their harmonics [1,10]. The observed multiplicity of modes and harmonics at a resonant distance of $x/h = 5$ in this study suggests the co-existence of a lower-frequency tone, associated with the symmetric feedback instability wave mode, and a higher-frequency tone, linked to the purely antisymmetric feedback instability wave mode of the jet. Similar findings have been reported in experimental studies by [26,28]. The frequencies of additional peaks, beyond the symmetric and asymmetric modes, equated to the summation and differences, thereby representing combinations of the two fundamental tones. In this study, these fundamental tones were identified at frequencies of roughly 3850 kHz and 8300 kHz. The presence of these additional tones in the spectra is typically attributed to nonlinearities within the jet flow, including nonlinear oscillatory motions of the jet and its interaction with the impingement surface.

Conversely, for Microphone 2, as shown in Figure 6b, there was a notable reduction in the intensity of the impingement tones and a decrease in the number of distinct tones, aligning with the overall reduction in the SPL observed in Figure 5. Furthermore, a diminution in low-frequency broadband noise levels was observed for Microphone 2, indicative of hydrodynamic noise. It is postulated that this variation in noise levels may be related to differences in the shear layer thickness between the two axes, a hypothesis which may be supported by Schlieren imaging analysis. Figure 6b also presents the acoustic spectra for Microphone 1 at an axial distance of 17 h from the nozzle, revealing a significant decrease in the number of impingement tones, akin to observations from axisymmetric studies in which impingement tones were markedly attenuated at greater heights. Additionally, a closer examination suggests alterations in the fundamental frequencies of base tones, likely due to changes in the feedback loop mechanism caused by the varying absolute distances between the initial perturbation location (i.e., nozzle lip) and the impingement plate. There was an observable reduction in the amplitude of the impingement tones. These acoustic spectra outcomes highlight the unique directivity of noise levels in rectangular impinging jets, particularly regarding the tonal content across the two axes.

The narrowband pressure spectra for the unsteady pressures measured at the ground plane at $x/h = 5$ and 17 are illustrated in Figure 7. As shown in Figure 7a, strong multiple

impingement tones and harmonics, mirroring those seen in the acoustic spectra, are evident at a nozzle standoff distance of $x/h = 5$. While the amplitude of these tones varied from the acoustic spectra, the fundamental frequencies remained relatively constant across most tones. Additionally, the low-frequency unsteadiness was heightened due to the direct impingement of the jet on the pressure transducer, contributing to significant unsteady loads on the impingement plate. The wall jet, observed in both major and minor axes, exhibited notable differences in the broadband and discrete tonal contents. Increasing the impingement distance to $17h$, as shown in Figure 7b, resulted in significant attenuation of the impingement tones, consistent with the acoustic findings. Intriguingly, the low-frequency broadband noise increased significantly compared with the shorter impingement distance, potentially due to the increased jet thickness and hydrodynamic noise, which contributed to the low-frequency content. For wall jets, a similar spectral content was observed in both axes across most frequencies, aligning with the unsteady pressure levels depicted as $Prms$ values in Figure 5b.

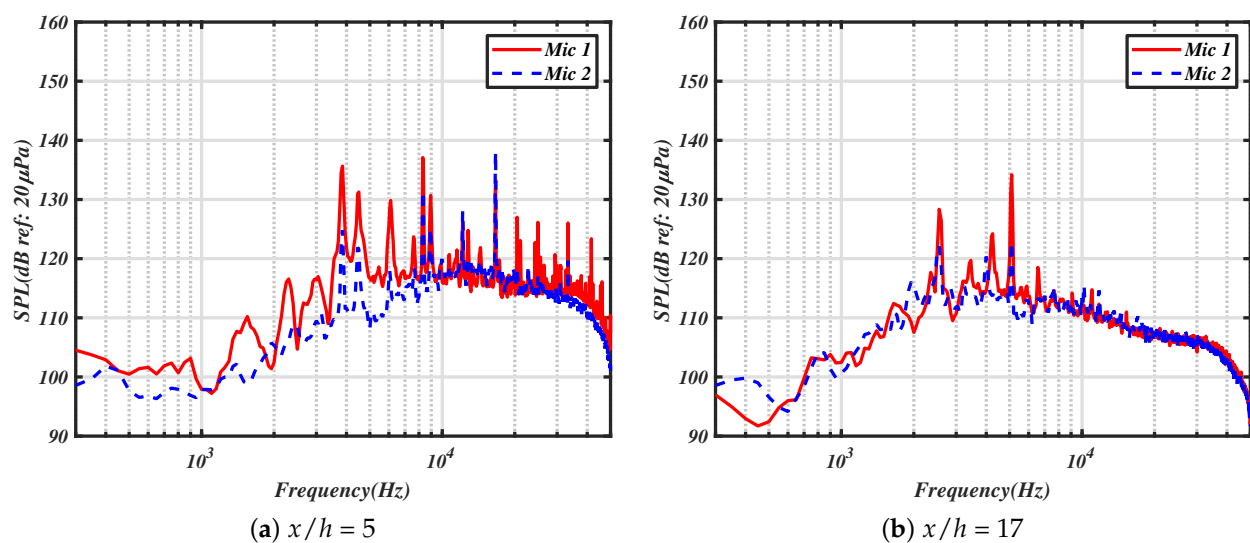


Figure 6. Nearfield acoustic spectra (major axis orientation).

Numerous researchers have extensively documented the feedback loop-related resonance characteristics of high-speed impinging jets for circular nozzles, highlighting a phase-locked process between the nozzle lip and the impingement surface which results in discrete, high-amplitude impingement tones [1,10,31]. These processes are known to be sensitive to variations in the boundary conditions, such as the temperature, pressure, and impingement distance. Moreover, a well-documented staging phenomenon has been observed in axisymmetric impinging jets, where the frequency of the tones gradually decreases with an increase in the impingement distance up to a certain threshold, beyond which any further increase in the impingement distance leads to an abrupt increase in frequency, signifying the transition to a new stage.

The resonance characteristics and staging phenomena for rectangular impinging jets were subsequently examined, as depicted in Figure 8a,b. The spectrogram plots the frequency on the y axis against the impingement distance on the x axis, with the z-axis representing the nearfield acoustics quantified by sound pressure level. In the spectrogram, a lighter grayscale denotes broadband noise or tones of lower magnitudes, while darker lines indicate high-amplitude tones and their harmonics. The frequency of the impingement tones was also estimated using Powell's equation [12], as expressed in Equation (2):

$$\frac{N+p}{f_n} = \frac{h'}{C_{ac}} + \int_0^{h'} \frac{dh'}{C_{st}} \quad (2)$$

where f_n represents the predicted frequency of an impingement tone, h' is the distance between the nozzle and the plate, C_{ac} is the ambient speed of upstream traveling acoustic waves (340 m/s), and C_{st} is the velocity of coherent structures ($0.63 \cdot U_j$), while N is an arbitrary integer denoting different frequency modes and p represents the phase lag, with $p = -0.30$ providing the best approximation for the current tests.

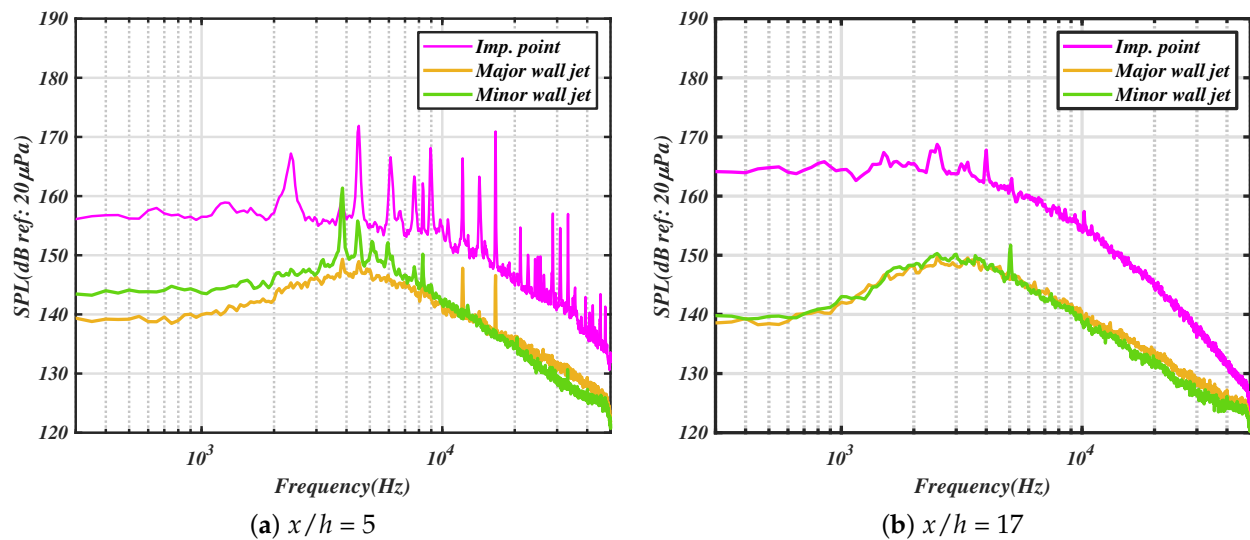


Figure 7. Unsteady pressure measurements at impingement plate (nozzle rotated to obtain both major and minor wall jets).

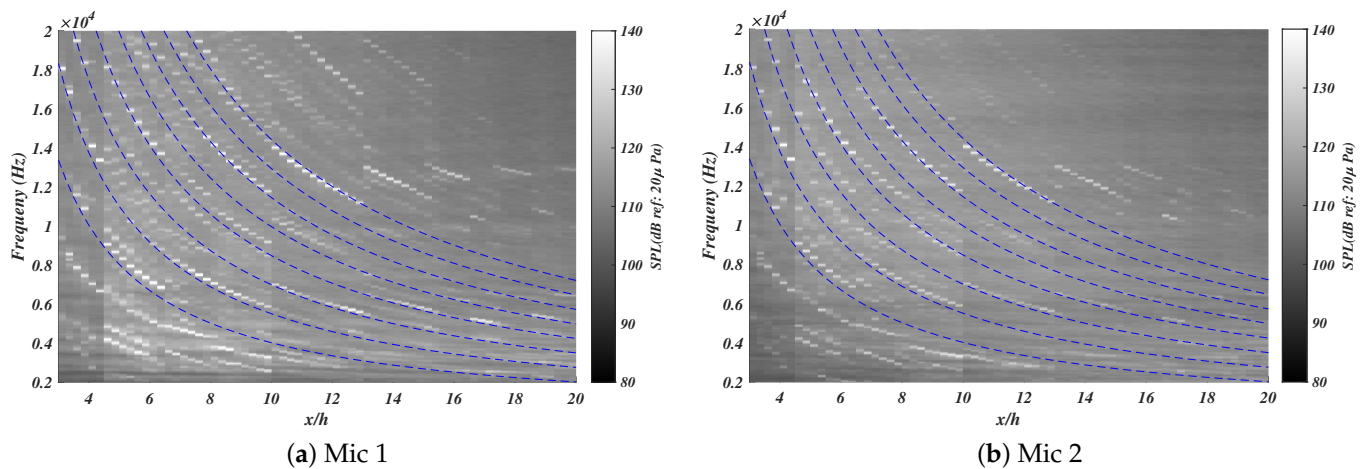


Figure 8. Comparison of impingement tones with Powell's prediction (blue lines) (major axis orientation).

As observed in Figure 8a, the spectrogram displays a plethora of high-amplitude tones across various frequencies and amplitudes. Similar to the findings from axisymmetric studies, the staging phenomenon is evident, with tone frequencies generally decreasing as the impingement height increased to a certain limit, after which the tones transitioned to higher frequencies. The spectrum exhibited a higher number of tones up to $x/h = 10$, beyond which the quantity of tones typically diminishes, although the spectrogram remained rich in tonal content even at larger impingement distances. These experimental findings are in alignment with the theoretical predictions of impingement tone frequencies estimated by Powell's equation, which are superimposed on the spectrogram as a blue dotted line. Similarly, Figure 8b showcases a rich array of impingement tones for Microphone 2, exhibiting similar staging phenomena and in line with the theoretical estimations. While the overall features of the spectrogram remained consistent, Microphone 2 captured significantly fewer

and weaker tones compared with Microphone 1. This discrepancy is briefly discussed in the context of the varying shear layer growth across the two axes, potentially resulting in different mode shapes and thus causing azimuthal variations in the impingement tones.

3.3. Quantitative Flow Visualization

3.3.1. Main Jet Column Properties

Figure 9 shows the mean velocity results as derived from PIV flowfield measurements. The velocity results were non-dimensionalized with the jet exit velocity. Furthermore, due to the surface reflections, some of the data (bad vectors) near the nozzle exit and the impingement plate were trimmed. Starting from the left, the first column represents the contours of the axial velocity, wherein the first two rows (starting from the top) are the results of the major and minor axes orientations at $x/h = 5$. The results in Figure 9a distinctly capture the supersonic jet profile from the nozzle exit extending toward the vicinity of the impingement plate. Notably, in close proximity to the impingement plate, a unique parabolic velocity profile indicative of reduced velocities was observed, which was attributed to the plate shock phenomenon. This phenomenon typically occurs when supersonic jets encounter a solid surface situated within one of its shock cell regions. At this impingement distance, the shear layer growth was not discernible on either the major or minor axes (Figure 9a,d). However, at an increased impingement distance of $x/h = 17$ (Figure 9g,j), the shear layer profiles became evident in both orientations, with the minor axis demonstrating greater growth compared with the major axis. Despite the increased distances, the flow remained supersonic, and the plate shock typically observed at lower heights was absent.

The second column investigates the transverse velocity component for both orientations at varying heights. At an impingement distance of $x/h = 5$, as depicted in Figure 9b,e, the positive and negative velocities indicate the flow direction. The contours clearly differentiated the wall jet from the main jet, with noticeable differences in the thickness of the wall jets between the two orientations, potentially correlating with the variations in wall jet strength. These results suggest that both the shear layer and wall jet growth are influenced by the nozzle's axis orientation, with further analysis of the wall jets provided in subsequent sections. At an impingement distance of $x/h = 17$ (Figure 9h,k), new features emerged, including weak shocks within the main jet column, attributed to slight variations from ideal conditions due to the finite nozzle thickness and minor fluctuations in the nozzle pressure ratio during operation. The increased shear layer growth at this height was more pronounced in the minor axis compared with the major axis, aligning with observations from the Schlieren analysis. The third column presents quantitative data, such as the axial and transverse centerline velocity components. At $x/h = 5$ for the major axis (Figure 9c), the axial velocity distribution demonstrated smooth supersonic flow for most of the measured distance, with a deceleration observed around $x/h = 3.75$, which was attributed to plate shock, as inferred from the Schlieren images and qualitative PIV analysis. The transverse velocity component exhibited a minor peak near $x/h = 2$, possibly resulting from weak shock cells within the jet, with variations being relatively minor (to the order of 0.02 of the exit velocity). Changing to the minor axis orientation (Figure 9f), the axial velocity variation mirrored that of the major axis, while the transverse component displayed slightly enhanced fluctuations. At a nozzle height of $x/h = 17$ (Figure 9i), the axial component remained predominantly supersonic up to approximately $x/h = 10$ –12, beyond which the velocity decreased, indicative of the potential core region and consistent with free jet studies on rectangular jets [18]. The transverse component fluctuations extended from the nozzle exit to the impingement plate with an increase in fluctuation magnitude at higher heights, a trend similarly observed on the minor axis (Figure 9l). The cessation of the core and augmented diffusion contributed to the increase in the transverse component magnitude at greater distances.

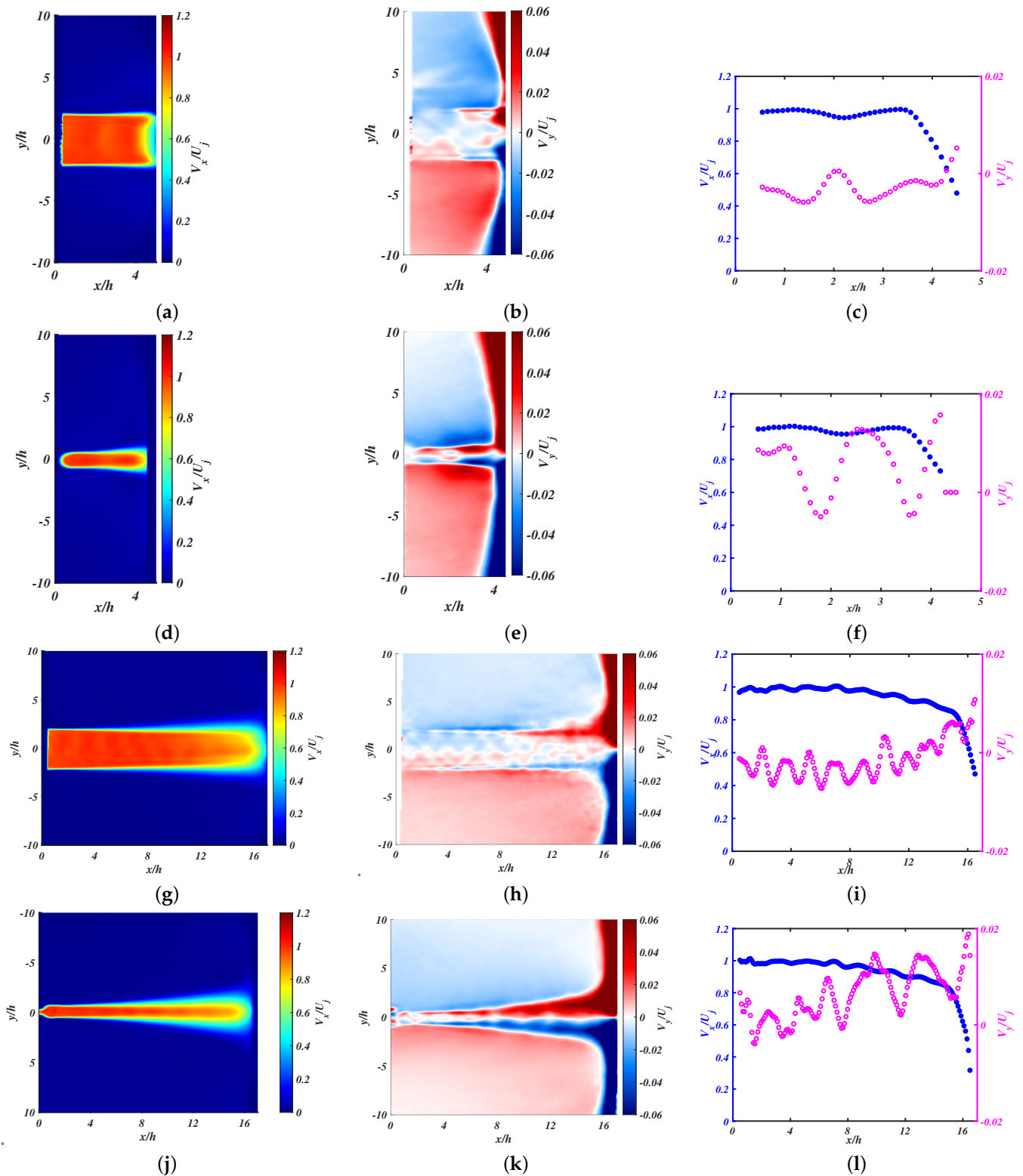


Figure 9. PIV results at different nozzle heights for major and minor axes. The first column (a,d,g,j) represents the axial velocity contours, the second column (b,e,h,k) represents the transverse velocity contours, and the third column (c,f,i,l) represents the centerline axial (blue) and transverse (pink) velocity component (flow from right to left).

Figure 10 depicts the cross-stream velocity profiles for the major and minor axes at various axial locations, with the impingement plate positioned at $x/h = 17$ from the nozzle exit. Near the nozzle exit, the velocity profiles for both orientations exhibited a classical top

hat shape, with the maximum velocity at the center decreasing rapidly toward the radial directions. This trend persisted up to $x/h = 10$ for the major axis, which continued to display a top hat profile. For $x/h = 13$ and 16, the velocity profiles for both axes assumed different shapes, with peak velocities dropping below unity, indicating the end of the potential core. A notable discussion point is the variation in thickness (radial extent) of the major and minor axis profiles. A comparison at different heights reveals that the radial growth of the minor axis outpaced that of the major axis, with convergence occurring at $x/h = 13$. Extrapolating these data suggests that the minor axis thickness may surpass that of the major axis beyond $x/h = 17$, a phenomenon consistent with axis switching observed in three-dimensional jets [15,18]. Further analysis of the shear layer characteristics, including the jet half-width and shear layer spreading rates, will be provided in subsequent subsections.

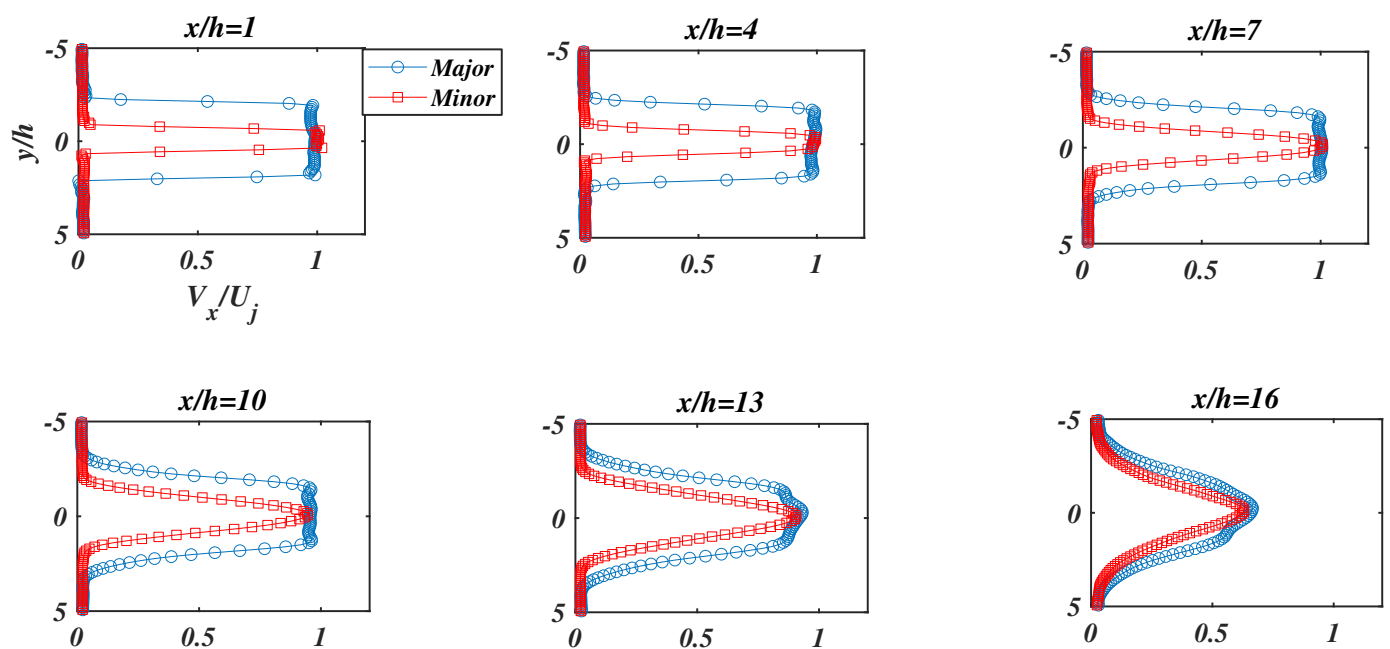


Figure 10. Cross-stream velocity profiles for different axial locations.

3.3.2. Shear Layer Properties

Figure 11a shows the results of the shear layer growth of the jet in major and minor orientations. The results are presented in terms of the jet half-width ($\delta_{0.5}$), which is non-dimensionalized with the width (y-axis) of the jet. The slope of the jet width curve is a representation of the shear layer growth. With the impingement plate fixed at a nozzle standoff distance of $x/h = 17$, the half-width along the major axis exhibited a relatively constant trend, with a minor increment at distances farther from the nozzle. Conversely, the minor axis's half-width displayed a continuous increase throughout the measured range, suggesting a more rapid shear layer expansion compared with the major axis. This variation in the growth rates of the shear layer between the axes until $x/h = 12$ implies a change in the jet's cross-section shape along the x axis. Beyond this point, the growth rates appear to converge with increasing distances. These differences in the shear layer characteristics may be ascribed to the disparate initial boundary layers at the nozzle exit for each orientation, influencing the mixing and entrainment processes and thereby affecting the jet spread. It is hypothesized that the shear layer's spread is intrinsically linked to the flow-acoustic coupling, where the jet impingement generates acoustic waves which propagate upstream, impacting the shear layer and corner vortices differently across the two axes. Given the minor axis's initially larger surface area, the coherent structures within its shear layer expanded rapidly, inducing azimuthal variations in the acoustic properties. These observations are consistent with the pronounced tones discussed in the acoustics section. The current hypothesis posits that the shear layer thickness between the free and

impinging jets under identical conditions would differ, a notion supported by the findings in [32], with the authors noting discrepancies in the shear layer thickness between the free and impinging jets in circular jets operating under ideal conditions.

Figure 11b displays experimental data for a non-dimensional velocity profile in the radial direction of a supersonic rectangular impinging jet. The velocity V_x at various radial positions was normalized by a jet exit velocity. The expression $\eta^* = (y - y_{0.5})/x$ was used to scale the y location from a reference position $y_{0.5}$ (where the velocity was half of the jet exit velocity U_j) normalized by x , which is the distance from the nozzle exit. The plot depicts data collected at different impingement heights corresponding to the potential core (until $x/h = 12$). The results are presented for both the major and minor orientations. The profile shows that the non-dimensional velocity was highest near the center of the jet and decreased toward the edges. Remarkably, all data sets, irrespective of axial distance or orientation, aligned along a single curve, indicating self-similarity in the velocity profile of the flowfield. This convergence of data onto a singular curve suggests that the flow characteristics of the rectangular jet might be encapsulated by a universal profile within the tested experimental conditions and set-up range. The span of these profiles depicted in the figure quantitatively represents the spreading rate of the shear layer in both orientations. This phenomenon, reminiscent of the data collapse observed in [33] for round jets, uniquely captures the spreading behavior of both axisymmetric and non-axisymmetric jets, as demonstrated in the current study.

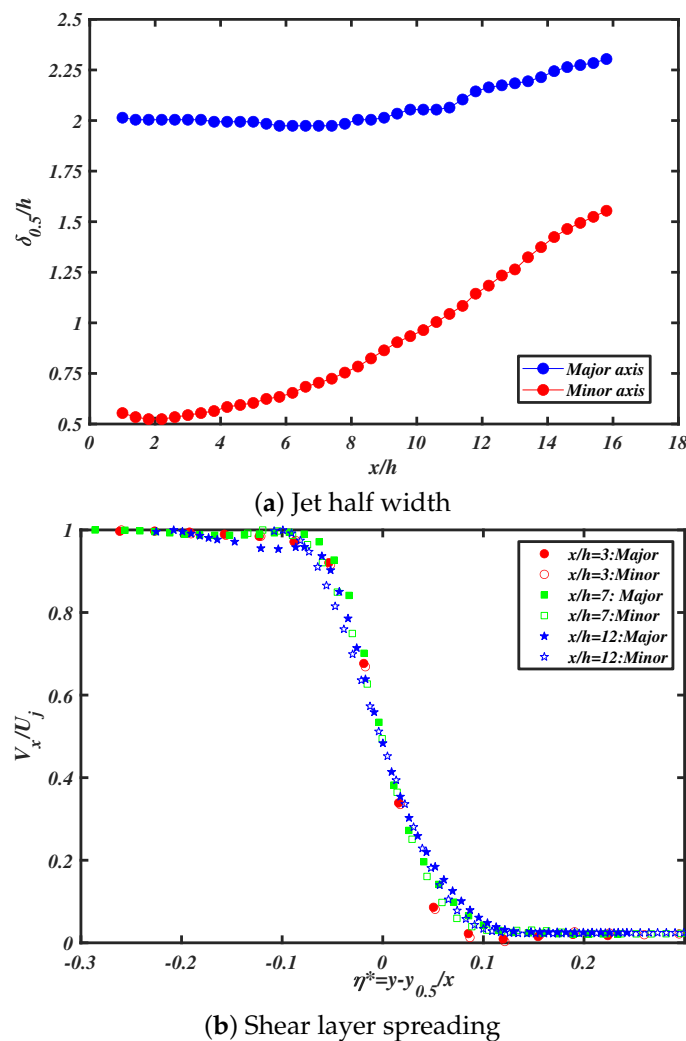


Figure 11. Jet half-width and normalized shear layer spreading at $x/h = 17$.

Figure 12 shows the velocity profiles of the wall jets when the plate was fixed at $x/h = 17$ for the major and minor orientations. The results were extracted roughly $0.1 h$ from the impingement plate, and for brevity, only one half of the wall jet velocity profile (centered at the impingement point) is presented. In general, the minor axis's velocity profile manifested a bifurcation, showcasing two distinct peaks, indicative of a complex flow structure potentially arising from interactions with the boundary layer or other flow features, such as the vortices. Beyond a peak $y/h = 4.8$, the velocity diminished, a natural consequence of jet spreading and diffusion into the ambient surroundings. Conversely, the major axis orientation exhibited a comparatively flatter and lower-magnitude profile, except within the $y/h = 1$ and 3 range. These variations in the wall jet flowfields are attributed to the distinct boundary layer effects in the two orientations, stemming from initial flow perturbations. These findings elucidate that the asymmetric nature of three-dimensional rectangular jets extends beyond the impingement zone, resulting in anisotropic wall jets.

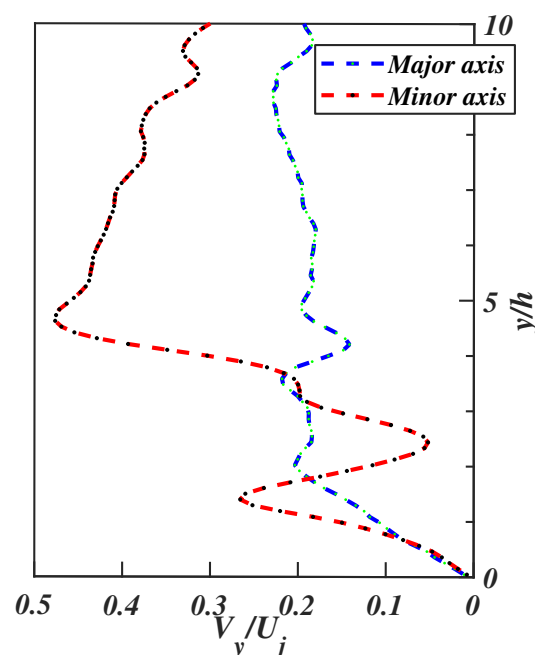


Figure 12. Wall jet velocity profile extracted $0.1 h$ from the plate located at $x/h = 17$.

4. Conclusions

The flowfield of supersonic impinging jets is highly oscillatory and complex in nature. This study delved into the flowfield and noise characteristics of a supersonic rectangular jet issued from a Mach 1.44 nozzle impinging on a surface. The nozzle, with an aspect ratio of 4:1, operated at a nozzle pressure ratio (NPR) of 3.37, corresponding to the design's NPR.

Flow visualization through Schlieren imaging unveiled both instantaneous and unsteady flow features, highlighting large-scale coherent structures and sharp acoustic waves, including impingement tones akin to those documented in axisymmetric supersonic impinging jet studies. These structures and the resultant impingement tones exhibited a distinct directivity, being more pronounced along one axis. This directional behavior can be attributed to the rapid shear layer growth in the minor axis compared with the major axis.

Pressure fluctuations at the impingement point and along the wall jet were measured using a high-frequency response pressure transducer. The root mean square (RMS) fluctuations indicated that unsteady pressures could reach up to 186 dB when the nozzle-to-impingement distance was approximately 5–6 h , remaining roughly constant beyond this range for the present cases.

Nearfield acoustic measurements using microphones placed in two different planes relative to the nozzle exit further elucidated the acoustic characteristics. The acoustic results

revealed multiple strong impingement tones and harmonics, indicating the presence of more than one resonance mode during operation. Other observed tones were combinations of these base modes. The comparison of spectra from different microphones confirmed the hypothesis that the high-amplitude tones exhibited directional behavior. Generally, an increase in the impingement distance led to a reduction in the number of tones, displaying definitive staging behavior similar to that observed in axisymmetric impinging jets.

Additionally, particle image velocimetry (PIV) analysis provided insights into the variation in the shear layer thickness of the main jet and the resulting wall jets across different axes. These variations correlated with the observed acoustic directivity, underscoring a unique asymmetry in the resonance mechanisms of rectangular impinging jets.

Overall, this study presents a comprehensive examination of the flowfield and acoustic properties of supersonic rectangular impinging jets, highlighting the complex interplay between flow structures, pressure fluctuations, and acoustic emissions. The findings emphasize the directional nature of the acoustic tones and the impact of shear layer growth on the resonance characteristics, contributing to a deeper understanding of the behavior of supersonic impinging jets.

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