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Mitigation of under-expanded supersonic jet noise through stepped nozzles

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Abstract

An experimental investigation into noise reduction of supersonic jets through nozzle trailing-edge modifications was conducted, whereby far-field acoustic measurements were captured for two different stepped nozzles under two distinct under-expanded conditions. When compared to a baseline nozzle, results show that stepped nozzles lead to significant noise reductions at certain polar and azimuthal angles. In particular, a maximum noise reduction of 6dB is observed for the longest stepped nozzle at a nozzle-pressure-ratio of 4 and 0° azimuthal angle. Spectral analysis shows that the noise reduction is mainly due to reduction in broadband shock associated noise and elimination of jet screech phenomenon. Abrupt changes in nozzle lip lengths of the stepped nozzles appear to disrupt acoustic feedback loop, thus resulting in screech cessation. Qualitative schlieren imaging and quantitative schlieren measurements were subsequently performed to correlate the shock structures and density gradient fields with the resulting noise components. Unlike those produced by the baseline nozzle, shock structures generated by the stepped nozzles are highly irregular and the jet plumes undergo discernible deflections. The reduction in broadband shock associated noise is related to the lower shock strengths, as demonstrated by the density gradient profiles.

Keyword: Supersonic jet; jet noise; noise reduction; schlieren imaging; calibrated schlieren

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Nomenclatures

D	Nozzle exit diameter
D_j	Jet plume mean diameter
f	Frequency
f_{BSAN}	Broadband shock associated noise peak frequency
f_c	Jet plume characteristic frequency
Δf	Frequency resolution
I	Broadband shock associated noise intensity
L_s	Shock cell length
Ma	Mach number
M_d	Design Mach number
M_j	Jet plume Mach number
P_t	Reservoir total pressure
P_∞	Ambient pressure
r	Radial distance from centreline
Re	Reynolds number
T_t	Stagnation temperature
u_c	Convective velocity of large-scale turbulent structures
u_j	Jet plume mean velocity
w_{sh}	Normalized characteristic width of the fundamental spectral component of broadband shock associated noise
X, Y, Z	Cartesian coordinates
β	Shock strength parameter
γ	Specific heat ratio
δ	Refractive index difference of the test medium
ε_y	Light ray angular deflection
θ	Azimuthal angle as measured from shorter lip plane
ϕ	Polar angle as measured from downstream axis
dB	Decibel scale using a reference pressure of 20 μ Pa
BSAN	Broadband shock associated noise
C-D	Converging-diverging (nozzle)
CFD	Computational fluid dynamics
FFT	Fast Fourier Transform
FPS	Frames-per-second
LDV	Laser Doppler Velocimetry
NPR	Nozzle-pressure-ratio (ratio of reservoir total pressure to ambient pressure)
OASPL	Overall sound pressure level
PIV	Particle Image Velocimetry

SPL	Sound pressure level
SPL _p	Peak amplitude value of broadband shock associated noise
St	Strouhal number
St _p	Peak Strouhal number of broadband shock associated noise

1. Introduction

Significant efforts have been expended in the last few decades to achieve a better understanding of jet noise emissions and their underlying sources, such that noise reduction techniques may be systematically developed. In particular, supersonic jets operating at off-design pressure ratio conditions often have two other important components beside turbulent mixing noise, namely jet screech and broadband shock associated noise [1]. While both components are generated through interactions between large-scale turbulent flow structures and quasi-stationary shock systems, the former component involves a feedback loop that noise produced at a certain downstream location travels upstream and interacts with nozzle lip to excite new instability waves [1, 2]. In contrast, broadband shock associated noise (hereafter referred to as “BSAN”) does not involve any acoustic feedback loop. Harper-Bourne and Fisher [3] were the first to develop a model for predicting the frequency and intensity of BSAN and they regarded each intersection of the shock cells and the jet shear layer as a noise source radiating with relative phasing determined by the time lag between them. Subsequently, Tam and Tanna [4] proposed a new wave model for explaining BSAN generation and radiation, in which the shock noise is generated by weak interactions between the shock structures and the downstream propagating large-scale turbulent structures. They subsequently employed a stationary wave pattern to model the shock cell structures and instability waves to model the large-scale turbulent structures [4]. It should also be noted that both jet screech and BSAN have the strongest emissions towards the upstream direction of the supersonic jet.

Various jet noise reduction techniques have been proposed and developed over the years, such as plasma actuators [5], micro fluid injection [6, 7], Mach wave elimination [8, 9], wire device [10], jet nozzle exit geometry modifications [11-13]. Among these, modifying jet nozzle exit geometry represents a potentially viable approach, due to very low penalties upon the jet thrust

and system weight. In earlier studies, the effects of chevron nozzles with various geometric parameters on noise levels were investigated by Callender et al. [14, 15]. Far-field measurements demonstrate that the chevron nozzles lead to 3 to 6 dB noise reductions at aft polar angles, where low-frequency noise emission is dominant. Furthermore, near-field measurements show that peak noise is shifted towards the upstream region and its intensity decreases spatially. However, chevron nozzle could impose thrust loss and weight increase and the penalties highly depend on the nozzle geometric parameters, such as the number and penetration of the chevrons [16]. Heeb et al. [17] studied the combined effects of fluidic injection and chevron nozzle designs on jet noise mitigation. The experimental and computational study indicates that significant noise reduction is achieved through suppression of low-frequency turbulent mixing noise and shock associated noise. Additionally, flow field measurements indicate that shock strength can be reduced by more than 50% and shock cell spacing shortened by around 10%.

Bevelled and tabbed nozzles for suppressing jet noise were also investigated by Wlezien and Kibens [18]. Their experimental results show that the acoustic characteristics are radically changed by these asymmetric nozzles at nozzle-pressure-ratio (NPR) of 4 and overall sound pressure level (OASPL) is sensitive to the exact nozzle trailing-edge design and azimuthal angle (i.e. noise level is reduced at certain angles while augmented at others). Subsequently, Viswanathan [12] and Viswanathan and Czech [13] conducted detailed acoustic measurements on bevelled nozzles with various bevel angles. Their results show that bevelled nozzles generate significant noise reductions at aft polar angles where peak noise emissions occur, and especially in the plane of the longer nozzle lip. Through these earlier studies, the fundamental principle underpinning the effectiveness of bevelled nozzles appears to be the manipulation of jet mixing effects and shock structure intensities by the asymmetric trailing-edge designs.

In the present study, the acoustic emissions and flow fields for two different stepped nozzles are investigated to further explore the efficacy of using unique asymmetric nozzle designs to control supersonic jet noise emissions. While such nozzles had been observed by Wlezien and Kibens [18] to produce noise reductions at certain azimuthal orientations, the influence of certain flow and acoustic parameters remains lacking and this motivated the present study. In the present work, the effects of different stepped nozzle geometries on under-expanded supersonic noise features, such as noise spectrum, overall noise level, BSAN and jet screech are studied based on microphone measurements. On the other hand, shock system formations and their quantitative details such as shock spacings and shock strengths, are investigated through quantitative schlieren technique.

2. Experimental setup and procedures

2.1 Facility

Noise measurements were performed in the aeroacoustics test facility at Temasek Laboratories, National University of Singapore. The test facility consists of a jet rig and a 2350 mm $\times$ 2350 mm $\times$ 2350 mm anechoic chamber, which was internally covered by polyurethane foam acoustic wedges (SONEX super) with approximately 500 Hz cut-off frequency. Compressed air from gas tank with a 68.95 bar maximum working pressure was piped into the jet chamber through a series of regulators and control valves, and a series of perforated plates were fitted within the jet rig to reduce turbulence before the jets exhausted from it. Additionally, a pressure gauge was employed to monitor the instantaneous pressure of the air flow before it entered the nozzle apparatus. More complete information about the jet rig can be found in [19]. Lastly, the uncertainty in the jet velocity is approximately within $\pm 1.9\%$ of the target value at 95% confidence level.

Fig. 1 Geometries of baseline and stepped nozzles

2.2 Nozzle geometries

The geometries of the circular baseline and stepped nozzles are shown in Fig. 1. The baseline nozzle (which is used as a basis for comparisons in the acoustic and flow fields here) comprised of a convergent-divergent section with an exit-to-throat area ratio of 1.144, followed by a straight section. The junction between the two sections had been smoothed and optimized to minimize shock formations, so as to avoid them contaminating the resulting jet flows. More details on the baseline nozzle design can be found in Wu and New [20]. The two stepped nozzles were actually designed based on the same baseline nozzle such that the longer and shorter nozzle lips coincide with 30° and 60° inclinations about the nozzle mean height, as illustrated in Figs. 1(b) and 1(c) respectively. Such a design approach would ensure that the mean-heights of all nozzles here remain similar and consistent to that adopted by earlier studies by Wlezien and Kibens [18, 21] and Longmire et al. [22]. For the sake of brevity, these two stepped nozzles will be known as S30 and S60 nozzles respectively here onwards.

To ease identification of the measurement planes, a Cartesian coordinate system is defined such

Table 1 Jet operating conditions

NPR	M_d	M_j	u_j (m/s)	D_j/D	Re_j	T_t (K)
4	1.45	1.56	444	1.03	7.66×10^5	300
5	1.45	1.71	471	1.09	9.59×10^5	300

that the origin is consistently located along the cylindrical axis indicated by the red dots. As such, the plane connecting the longer and shorter lips is known as XY plane while the orthogonal plane is known as XZ plane. All the three nozzles have the same internal diameter of $D=12.7$ mm and 0.5 mm wall thickness, as well as possessing the same design Mach number of $M_d=1.45$. Lastly, all test nozzles were fabricated using stainless steel and the internal surface was carefully polished to minimize flow issues due to wall roughness.

2.3 Jet operating conditions

The jet operating condition is dictated by the NPR and defined as the ratio of reservoir total pressure (P_t) to ambient pressure (P_∞) as shown in Eq. (1). The jet Mach number (M_j) is determined by using the equation with the assumption that the jet is fully expanded:

$$\text{NPR} = \frac{P_t}{P_\infty} = \left(1 + \frac{\gamma - 1}{2} M_j^2\right)^{\frac{\gamma}{\gamma - 1}} \quad (1)$$

In the current study, two under-expanded conditions were chosen to investigate how stepped nozzles affect jet screech and BSAN radiation. Table 1 outlines the operating conditions along with the jet Mach number, M_j , jet velocity, u_j , fully-expanded diameter to design diameter ratio, D_j/D , Reynolds number, Re_j and stagnation temperature, T_t . For the present baseline supersonic jet configuration, Wu and New [20] observed that perfect jet expansion occurs at NPR=3.4. Lastly, while the initial baseline nozzle wall boundary layer was not measured during the study, simulations conducted by Zang et al. [23] on the same nozzle, jet apparatus and flow condition at NPR=4 indicated that they are most likely to be turbulent here.

Fig. 2 Side-view schematic of the far-field acoustic arrangements.

2.4 Far-field acoustic measurements

A 1/8inch Brüel & Kjær (B&K) Type 4138-A-015 pressure-field microphone was vertically mounted on a pivot system and set at grazing incidence to acquire far-field acoustic measurements. The circular arc of the microphone locations as shown in Fig. 2 was centred at the nozzle origin with a radius of $48D$. Note that Viswanathan [24] had earlier suggested that a microphone distance of approximately $35D$ is sufficient for fair-field jet noise measurements, and that distances ranging from $47D$ to $49D$ for relatively similar far-field measurements have been adopted by Wlezien and Kibens [18], Heeb et al. [25] and Munday et al. [26] previously. To ensure accuracy, the circular arc was aligned using a laser-based director and the error in the microphone position was approximated to be $\pm 0.001^\circ$. Furthermore, the polar angle of the arc, ϕ , was measured from the downstream jet axis. A circular traverse controlled using National Instruments LabVIEW™ software was developed to precisely control the pivot system at locations from $\phi=30^\circ$ to 115° . The polar angle measurement interval was $\Delta\phi=10^\circ$,

Fig. 3 Schematics illustrating the polar angle, ϕ , and azimuthal angle, θ . Azimuthal angles $\theta=0^\circ$ to 180° at 30° intervals at an arbitrary polar angle, ϕ , are shown as an example.

with the exception of the last location at 115° where wall restriction limited it to $\Delta\phi=5^\circ$. The azimuthal angle, θ , was measured along the YZ plane around the nozzle circumference at intervals of $\Delta\theta=30^\circ$, where $\theta=0^\circ$ and 180° correspond to the shortest and longest nozzle lips as shown in Fig. 3. Lastly, the microphone was calibrated by a Model 4231 B&K acoustic calibrator prior to the measurements, which is able to generate acoustic wave at 94 dB at 1 kHz frequency. According to the free-field correction curve, the microphone can provide a flat response up to 30 kHz and an accuracy within ± 1 dB between 30 kHz to 100 kHz. Additionally, the overall uncertainty of the measurement is approximately ± 1.1 dB of the target value at 95% confidence interval [27].

Microphone signals were acquired by a National Instruments PXI-6143 data acquisition board installed in a National Instruments PXIe-1082 chassis at a sampling rate of 200 kHz with 3 s sampling time per measurement. A MATLAB[®] code based on the approach described by Kuo et al. [28] was used for data post-processing. Firstly, the raw data was converted from voltage values to pressure values through the microphone calibration constant. Secondly, the data was high-pass filtered at 500 Hz by a 4th-order Butterworth filter to avoid the signal being contaminated by environmental or electronic noise. Thirdly, the data were fed into 199 4096-

point blocks and a Hanning window function with 50% overlap was used. Subsequently, the data for each block were passed through a Fast Fourier Transform (FFT) to generate narrow-band spectra of sound pressure level (SPL) in decibel scale (dB) using a reference pressure of 20 μPa with a frequency resolution of 48.8 Hz. Finally, spectra derived from all blocks were averaged and were subsequently non-dimensionalized to arrive at the SPL per Strouhal number as calculated by Eq. (2):

$$SPL/Strouhal = \underbrace{SPL(f)/bandwidth}_{raw\ SPL} - \underbrace{10 \times \log_{10} \Delta f}_{scaling\ to\ 1Hz\ bandwidth} + \underbrace{10 \times \log_{10} f_c}_{Strouhal\ number\ scaling} \quad (2)$$

The Strouhal number is defined in Eq. (3) as:

$$St = f/f_c \quad (3)$$

where f_c is the characteristic frequency of the jet plume.

The total energy contained in the noise spectrum, OASPL, was calculated by using Eq. (4) to evaluate the overall sound pressure level radiated from the three test nozzles across different polar or azimuthal angles:

$$OASPL = 10 \log_{10} \left[\sum \left(10^{\frac{SPL(f)/bandwidth}{10}} \right) \right] \quad (4)$$

2.5 Schlieren imaging and measurements

Due to laboratory space constraints, a modified Z-type schlieren system was used for both qualitative and quantitative purposes in the present study [20, 29]. The schlieren system consists of optical components that include a source aperture, two 300 mm focal length parabolic mirrors, a knife-edge, and an IDT NX4-S1 high-speed camera with a 105 mm, $f/2.8$ lens. An LED light source was used to provide 200 W broadband light, which was then reflected and collimated by the two parabolic mirrors, before passing through the test section

where the supersonic jets issued. Subsequently, a vertical knife-edge was used at the focal plane which produced schlieren images that revealed the refractive index gradient in the test medium on the camera. The exposure time of the camera was set at 30 μs with a capturing frame rate of 1000 FPS. For the refractive index of an axisymmetric flow, the Snell's Law can be written as:

$$\varepsilon_y = 2y \int_r^\infty \frac{d\delta}{dy} \frac{dr}{(r^2 - y^2)^{0.5}} \quad (5)$$

where ε_y is the angular deflection of the light ray, y is the location of displaced transverse ray, δ is the refractive index difference and r is the radial distance from the centreline. The light intensity of “zero refraction” which corresponded to ambient condition was obtained by extracting the pixel intensity value along a line in the image background. Subsequently, well-established Abel transformation was used for Eq. (5) to calculate the density gradients in the supersonic jet flows. The details of the set-up, the calibration and data processing can be found in Mariani et al. [29] and Hargather and Settles [30].

3. Results and discussion

3.1 Acoustics

During the present investigation, a significant number of acoustic measurements were taken at different combinations of polar and azimuthal angles for all three test nozzles. However, only noise spectrum and OASPL comparisons at azimuthal angle $\theta=0^\circ$ and other polar angle combinations are shown here, as results at other azimuthal angles exhibit relatively similar trends. In particular, noise spectra at polar angles $\phi=30^\circ, 50^\circ, 70^\circ, 90^\circ$ and 110° are presented as noise spectra are observed to be more sensitive towards polar angle variations. Figure 4(a) shows the noise spectra of all three nozzles at different polar angles and NPR=4 flow condition. Starting from a polar angle of $\phi=30^\circ$, it can be discerned that noise radiated from all three

Fig. 4 Noise spectra of baseline and stepped nozzles at $\phi=30^\circ, 50^\circ, 70^\circ, 90^\circ$ and 110° and $\theta=0^\circ$, taken at (a) NPR=4 and (b) NPR=5.

nozzles are dominated by turbulent mixing noise, due to the relatively smooth spectra curves [31, 32]. However, as the polar angle gradually increases from $\phi=50^\circ$ to 110° , the baseline nozzle produces a broadband “hump” in the spectra that becomes increasingly prominent in the upstream region. This “hump” is related to broadband shock associated noise (BSAN), which has been extensively investigated in many previous studies [4, 33]. There is a persistent reduction of the dominant frequency associated with the “hump” as the measurement location moves progressively upstream as well.

In contrast, the two stepped nozzles generate significantly lower BSAN levels as compared to the baseline nozzle as the measurement locations moves progressively upstream. Figure 4(b) shows similar trends under NPR=5 flow condition, though the overall amplitudes of the spectra

Fig. 5 OASPL comparisons of baseline and stepped nozzles at various ϕ and $\theta=0^\circ$, taken at (a) NPR=4 and (b) NPR=5.

are discernibly higher due to the greater under-expansion of the jet flows. The figure also shows a distinct sharp frequency peak other than that associated with the BSAN “hump” from $\phi=50^\circ$ onwards. Furthermore, the frequency of the sharp peak remains invariant at approximately $St=0.25$, which is consistent with a value of approximately $St=0.24$ in [28]. It is also always lower than that associated with the BSAN, regardless of the polar angle. This discrete peak is associated with the screech tone and the above observations are consistent with studies reported previously [34, 35]. Note that no discernible screech tone is observed at NPR=4 for the baseline nozzle, presumably due to the use of thin nozzle lip walls here [35]. In contrast, the spectra of the two stepped nozzles display lower overall BSAN levels relative to the baseline nozzle. More importantly, they do not produce any observable jet screech at all, which demonstrates that the imposition of simple step configurations upon a conventional baseline nozzle here could mitigate jet screech effectively.

Figure 5(a) shows a comparison of baseline and stepped nozzles OASPL at various polar angles under NPR=4 condition. It is unsurprising that all three nozzles possess relatively similar overall noise levels at $\phi=30^\circ$, as they share comparable turbulent noise level at both low and

high frequencies as shown in Fig. 4(a) earlier. However, it can also be observed that both stepped nozzles lead to increasingly significant noise reductions as the polar angle increases to $\phi=110^\circ/115^\circ$. Specifically, S30 nozzle produces a maximum noise reduction of 4.8 dB at $\phi=115^\circ$, while S60 nozzle leads to a maximum noise reduction of 6 dB at $\phi=110^\circ$. At NPR=5 condition shown in Fig. 5(b), note that there are drastic fluctuations in the OASPL of the baseline nozzle between $\phi=30^\circ$ to 50° . Closer inspection of their noise spectra (not shown here) reveals that the reduction from $\phi=30^\circ$ to 40° is due to large-scale turbulent noise transiting to fine-scale turbulent noise. However, the presence of significant screech tone and broadband shock noise at $\phi=50^\circ$ leads to an increase, before it decreases again. Regardless, similar to NPR=4 condition, the two stepped nozzles exhibit comparable overall noise level relative to the baseline nozzle at $\phi=30^\circ$ with progressively larger noise reductions from $\phi=50^\circ$ to 115° . However, it should be highlighted that S60 nozzle leads to higher noise reduction than its S30 counterpart at NPR=5. As a comparison, S30 nozzle produces a maximum noise reduction of 3.5 dB at $\phi=100^\circ$, while S60 nozzle produces a reduction of 5.2 dB at the same azimuthal angle. Lastly, a closer re-examination of Fig. 4(b) shown earlier reveals that S60 nozzle is more effective in BSAN suppression as compared to S30 nozzle at certain polar locations, which in turn leads to variations in noise reduction efficacies.

3.2 Azimuthal directivity

As the stepped nozzle shapes are asymmetric, noise emissions will vary with the exact polar and azimuthal locations. Acoustic measurements were taken at different azimuthal angles to investigate the azimuthal directivity of the noise emissions. Note that it has been previously established that turbulent mixing noise and shock noise dominate at downstream and upstream regions respectively [1, 33], which has also been demonstrated by the present results depicted in Fig. 4 earlier. Hence, the microphone is positioned at $\phi=30^\circ$ and 90° respectively, which

Fig. 6 Azimuthal acoustic directivity of all test nozzles at NPR=4 condition along (a) $\phi=30^\circ$ and (b) $\phi=90^\circ$ polar planes.

represent the different noise emission regions, and then rotated to various azimuthal locations to map out the azimuthal characteristics systematically. As all test nozzles are symmetric about the XY plane, measurements were conducted from $\theta=0^\circ$ to 180° at 30° intervals, such that measurement data were acquired at seven different azimuthal angles for each polar angle on one side of the symmetry plane.

Figure 6 presents the azimuthal noise measurement results of all test nozzles at NPR=4 condition. At $\phi=30^\circ$ shown in Fig. 6(a), S30 nozzle produces moderate noise reduction levels relative to the baseline nozzle across all azimuthal angles. In contrast, S60 nozzle produces slightly higher noise levels across all azimuthal angles as compared to those of the baseline nozzle. Interestingly, S30 nozzle leads to maximum and minimum noise levels along the shortest and longest lip regions (i.e. $\theta=0^\circ$ and 180° respectively). On the other hand, such relationships are not observed for the S60 nozzle. As large-scale turbulent mixing noise is dominant along $\phi=30^\circ$ plane as shown in Fig. 4(a), the noise directivity of S30 nozzle is likely to be caused by the variations in the jet shear layer mixing effects along different azimuthal planes.

Fig. 7 Azimuthal acoustic directivity of all test nozzles at NPR=5 condition along (a) $\phi=30^\circ$ and (b) $\phi=90^\circ$ polar planes.

Moving to a larger polar angle plane along $\phi=90^\circ$ as shown in Fig. 6(b), both stepped nozzles produce significant noise reductions across all azimuthal locations. In this case, S30 nozzle exhibits a relatively symmetrical noise distribution about $\theta=90^\circ$ location, while S60 nozzle produces a minimum noise level at $\theta=0^\circ$. In particular, while noise levels for both stepped nozzles are closer between $\theta=0^\circ$ to 90° , that for the S60 nozzle incurs a moderate increase over the S30 nozzle test case between $\theta=120^\circ$ to 150° . As such, azimuthal directivity of S60 nozzle along $\phi=90^\circ$ plane can be mostly attributed to the azimuthal variations in the shock structures and strengths according to the spectrum analysis (not shown here).

Figure 7 shows azimuthal acoustic comparison of the three nozzles under NPR=5 condition. At a polar angle of 30° , the two stepped nozzles produce noise levels that vary azimuthally as shown in Fig. 7(a). In particular, they possess moderate noise reduction between $\theta=40^\circ$ to 110° , while produce relatively similar noise levels as compared to the baseline nozzle at other azimuthal angles. Additionally, the noise levels of S30 and S60 nozzles are quite close across all azimuthal angles and they both incur maximum noise reductions at approximately $\theta=90^\circ$. This is likely due to enhanced mixing effects within the jet shear layer along this location, caused by additional small-scale flow structures generated by the sharp steps at this azimuthal

plane. In fact, these small-scale flow structures can be visualized in the schlieren results presented later. In contrast, moving to polar angle of 90° , significant noise reduction is achieved while exhibiting negligible noise variations across different azimuthal angles as shown in Fig. 7(b). Furthermore, S60 nozzle produces slightly lower noise level than S30 nozzle across all azimuthal angles. In general, the above observations demonstrate that the noise radiation of stepped nozzles is less uniform azimuthally, and likely to be related to how the flow and shock structures are asymmetrically arranged. More importantly, Figs. 6 and 7 demonstrate that the noise reduction effectiveness of these stepped nozzles is sensitive towards many factors, such as polar and azimuthal angles and the NPR of supersonic jet flows, where non-optimal conditions may lead to noise increments seen in Fig. 6(a) instead. Due to the interplay of complex modifications to the flow fields and noise generation mechanisms by using stepped nozzles, there will be changes in the dominant noise components at different polar and azimuthal angles as well. In particular, both the flow fields and shock systems are significantly distorted to become highly asymmetric along the XY plane, which result in noise radiations that are highly complex.

3.3 Broadband shock associated noise

As seen in the previous section, the stepped nozzles can reduce noise levels at both NPR=4 and 5 conditions by suppressing the amplitude of the shock noise components significantly along the side and upstream quadrants. S30 nozzle will be more effective at NPR=4 while both stepped nozzles will be effective at both NPRs. Additionally, the noise reduction abilities have also been observed to depend upon azimuthal locations. Therefore, it will be insightful to document and compare the amplitudes and Strouhal numbers of the shock noise components based on the nozzle configurations and azimuthal angles.

Fig. 8 Example of how the peak amplitude and Strouhal number of shock noise components were extracted from a narrowband noise spectrum for the baseline nozzle at NPR=5 and $\phi=90^\circ$. The peak frequency and corresponding amplitude are indicated by circles.

To illustrate, Fig. 8 shows an example of how the peak amplitude and Strouhal number of shock noise components were extracted from a narrowband noise spectrum for the baseline nozzle at NPR=5 and $\phi=90^\circ$. Firstly, the jet screech tone was isolated from the noise spectrum by a peak locating algorithm. Secondly, a spectra function provided by Kuo et al. [36] was chosen over simple Gaussian distribution [37, 38] to extract the fundamental characteristics of BSAN as shown by the red curve in Fig. 8, due to its ability to fit the non-symmetric broadband spectral peak better. This was undertaken to exclude any screech harmonics from the determination of BSAN characteristics. The spectra function used here can be expressed as:

$$SPL(St) = SPL_p + 10 * \log_{10} \left[e^{-\left(\frac{St_p}{St} - 1\right)^2 / w_{sh}^2} \right] \quad (6)$$

where SPL_p and St_p are the values of BSAN peak amplitude and corresponding peak Strouhal number respectively and w_{sh} is the normalized characteristic width of BSAN spectral component. Since jet screech has not been observed for the two stepped nozzles even at NPR=5, only the amplitudes and Strouhal numbers of BSAN at various azimuthal locations have been documented. Furthermore, plausible explanations for screech elimination by stepped nozzles will be discussed in the following section.

Fig. 9 Comparison of BSAN peak amplitudes at NPR=4 and 5 along $\phi=90^\circ$ polar plane.

After the above-mentioned procedures had been implemented upon the relevant measurement results, Fig. 9 shows a comparison between the measured BSAN amplitudes. At both under-expanded NPR=4 and 5 conditions, it is clear that the use of stepped nozzles can suppress BSAN peak amplitudes significantly. It should be highlighted that BSAN amplitude increases with NPR regardless of nozzle configuration or azimuthal orientation, as shock strength naturally increases as the NPR deviates further away from the design condition [3, 4]. It is also interesting to observe that the S60 nozzle is better than S30 nozzle in reduction of BSAN amplitudes at NPR=5. In contrast, that is not the case at NPR=4, where sensitivity towards azimuthal location is higher. In particular, while S60 nozzle produces a larger amplitude reduction than S30 nozzle at $\theta=0^\circ$, the opposite behaviour occurs at $\theta=90^\circ$ and 180° .

Peak frequency associated with BSAN has been extensively studied in many earlier studies. In particular, Harper-Bourne and Fisher [3] and Tam and Tanna [4] made use of the following expression to evaluate f_{BSAN} :

$$f_{BSAN} = \frac{u_c}{L_s(1 - M_c \cos\phi)} \quad (7)$$

where u_c is the convective velocity of large-scale turbulence structures, L_s is the shock cell length, M_c is u_c normalized by the ambient sound speed and ϕ is the polar angle. According to

Fig. 10 Measured BSAN peak Strouhal number as function of NPR value at $\phi=90^\circ$.

the equation, BSAN peak frequency will continuously decrease if the microphone is gradually shifted from a downstream location to an upstream one, which can also be observed in Fig. 4(a).

Figure 10 shows a comparison between BSAN peak Strouhal numbers determined at various azimuthal angles. It can be readily discerned from the figure that BSAN peak Strouhal numbers associated with the two stepped nozzles are generally significantly higher than that of the baseline nozzle at NPR=5, especially the case for S60 nozzle. In contrast, at NPR=4, the two stepped nozzles tend to produce slightly lower BSAN Strouhal numbers, with the exception of the S30 nozzle producing a significantly higher BSAN Strouhal number than the other test configurations at $\theta=90^\circ$. Intriguingly, this particular test configuration produces the lowest Strouhal number gain at NPR=5, as compared to other test configurations. Hence, current results suggest that the noise reduction behaviour of stepped nozzles may not be consistent with variations in the NPR, at least for the test configurations used here.

Figure 11 compares the BSAN peak Strouhal numbers as a function of the polar angle at NPR=4 and 5 with those predicted by Eq. (7) (assuming $u_c=0.7u_j$). The comparison shows that the measured Strouhal numbers of the present baseline nozzle under both operating conditions

Fig. 11 BSAN peak Strouhal numbers at (a) NPR=4 and (b) NPR=5 for the present baseline nozzle as a function of polar angle, and their comparison with Eq. 7 derived from Tam and Tanna [4]

are in good agreement with the formula. Additionally, Fig. 11(b) demonstrates that results from Kuo [39] agree well with the formula and the present measurements as well. Closer examination will show that the peak BSAN Strouhal numbers determined by Kuo [39] are slightly higher than the current results at various polar angles, that would be due to the minor differences in the nozzle geometries used. From the two plots, it also can be observed that the Strouhal numbers of stepped nozzles at 90° polar angle remain close to the predicted values by the formula, even though they vary slightly with the azimuthal angle as compared to those of the baseline nozzle.

3.4 Schlieren imaging

Schlieren images of supersonic jets issuing from all the test nozzles at NPR=4 and 5 are presented in Fig. 12(a) and 12(b) respectively. For the baseline nozzle shown in Figs. 12(a)(i) and 12(b)(i), axisymmetric quasi-periodic diamond pattern shock cells are formed within the jet columns. However, it can also be noticed that when the NPR value is increased from 4 to 5, the shock cells become visibly more persistent and the shock cell length increases from

Fig. 12 Schlieren images captured for all test nozzles along XY-planes at (a) NPR=4 and (b) NPR=5. Camera exposure time was set to $30\mu\text{s}$ with the knife-edge oriented vertically.

approximately $1.26D$ at NPR=4 to $1.68D$ at NPR=5. The longer shock cell length leads to a lower BSAN peak Strouhal number value [4, 33], which is consistent with the acoustic observations in Fig. 10 earlier.

For the S30 nozzle schlieren images taken along the symmetry plane shown in Figs. 12(a)(ii) and (b)(ii), it is observed to produce three different shock systems that originate from different parts of the nozzle. The first shock system is induced along the shorter nozzle lip due to static pressure mismatch within and without the jet column. This can be better appreciated in Fig. 13(a), where a close-up view of the shock cell structures and interactions at NPR=5 is presented. The second shock system emanates from the inner walls of the nozzle and likely to be

Fig. 13 Shock structures and interactions for (a) S30 and (b) S60 nozzles along XY-planes at NPR=5. Camera exposure time was set to $30\mu\text{s}$ with the knife-edge oriented vertically.

associated with the asymmetric boundary layer distribution along the nozzle inner wall. It intersects the first shock system near the shorter nozzle lip, where it subsequently reflects off the upper jet shear layer towards the lower jet shear layer, from which it will continue to be reflected within the jet column. Lastly, the third shock system is produced along the longer nozzle lip, where it intersects with the first and second shock systems, before being reflected within the jet column. Hence, it can be seen that more complex, asymmetric and multiple shock systems are formed when stepped nozzles are used.

Corresponding schlieren images taken along the symmetry plane for S60 nozzle at NPR=4 and 5 are shown in Figs. 12(a)(iii) and (b)(iii) respectively. The three different shock systems observed for S30 nozzle previously are essentially reproduced here. However, the exact shock patterns are slightly different, since the length difference between the shorter and longer nozzle lips is much more significant for S60 nozzle than for S30 nozzle. Take for instance, the first shock system originating from the shorter nozzle lip is initially reflected by the lower nozzle wall before proceeding to be reflected within the jet column as it propagates downstream. The behaviour of the second shock system that emanates from the inner wall of the nozzle, as well as that of the third shock system that originates from the longer nozzle lip, remains relatively

similar to what have been observed for the S30 nozzle. At $\text{NPR}=5$, the shock system produced by the shorter nozzle lip will be reflected right at the longer nozzle lip due to the elongation of the shock cell when NPR increases, leading to a situation whereby it will merge with the shock system produced off the longer nozzle lip to form a thin shock band shown in Fig. 13(b).

In general, the resulting shock system becomes more intense as the NPR increases from $\text{NPR}=4$ to 5, which would explain the increase in the BSAN amplitudes with the NPR in Fig. 9 earlier. It should also be noted that stepped nozzles lead to vectoring of the jet columns towards the shorter nozzle lip regions, particularly when the NPR increases to $\text{NPR}=5$. This observation has been observed by the authors earlier for asymmetric bevelled nozzles [20, 40] and in-line with notion that there is a pressure relief lag between the longer and shorter nozzle lips for such asymmetric nozzles [41, 42].

Lastly, schlieren images taken along XZ-plane (i.e. orthogonal to XY-plane) for both stepped nozzles are presented in Fig. 14(a) and 14(b). Along this plane, the jet flows are more symmetrical about the nozzle cylindrical axes. Due to the partial blockage of the jet flows by the longer nozzle lips, it is difficult to distinguish shock system origins and formations associated with the shorter nozzle lips. However, it can be inferred from the overlapping but symmetrical shock structures that they do not differ too much from the diamond-shaped shock structures observed in the baseline nozzle earlier on. However, in this case where there is a length discrepancy between the shorter and longer nozzle lips, the shock systems produced by the former and latter will form earlier and later respectively, thus leading to overlapping shock cell structures as shown in Fig. 14.

Equally interesting, the two stepped nozzles possess wider jet spreads than the baseline nozzle

Fig. 14 Schlieren images captured for all test nozzles along XZ-planes at (a) NPR=4 and (b) NPR=5. Camera exposure time was set to $30\mu\text{s}$ with the knife-edge oriented vertically.

along the XZ-plane. This can be clearly observed in Fig. 15 where additional schlieren images taken using a shorter camera exposure time of $1\mu\text{s}$ in conjunction with horizontal knife-edge orientation are presented – the shorter exposure time render the jet shear layer clearer than those shown in Fig. 14 earlier. The wider jet spreads are likely due to additional small-scale flow structures induced by the sharp steps between the shorter and longer nozzle lips, which have been visualized partially in Fig. 13 earlier as dark lines emanating from the sharp nozzle steps. Other than improving the mixing between the jets and the ambient through wider jet spreads (i.e. evident in the increased narrowing of the jet column when the sharp step occurs earlier for S60 nozzle), the formation of these flow structures and associated flow disruptions appear to mitigate jet screech tone as well. Firstly, it is plausible that flow changes conferred upon conventional circular supersonic jets by the nozzle steps disrupt the aeroacoustic feedback loop occurring at the nozzle lip [4]. Note that similar behaviour has also been observed by Raman [35] and André et al. [43]. Secondly, the sharp mismatch between the nozzle-lip lengths could have also contributed towards disrupting the aeroacoustic feedback loop that leads to jet

Fig. 15 Close-up views of schlieren images captured along XZ-plane for all test nozzles at NPR=5 with $1\mu\text{s}$ camera exposure time in conjunction with horizontal knife-edge orientation to better highlight the jet spreads.

screech. Lastly, unlike the case for the baseline nozzle, it is difficult to establish a direct quantitative relationship between the shock cell length and the resulting BSAN behaviour for stepped nozzles, due to the complex shock formations and jet vectoring. Nevertheless, qualitatively speaking, the shock cell lengths do appear to be lengthened when the NPR increases from NPR=4 to 5.

3.4 Quantitative calibrated schlieren

It is well known that BSAN is caused by interactions between large-scale turbulent structures and shock structures within the jet potential core. Harper-Bourne and Fisher [3] were among the first to predict BSAN characteristics by relating shock strength to a parameter β that relates

to jet velocity and found that the intensity (I) of BSAN is proportional to the parameter raised to the power of four. To be specific, the relationship can be expressed as

$$I \propto \beta^4, \text{ where } \beta = \sqrt{M_j^2 - 1} \quad (8)$$

Subsequently, Tam and Tanna [4] provided a new theoretical model for BSAN generation and radiation, where the parameter β was modified to

$$\beta_{(M_d \neq 1)} = \sqrt{M_j^2 - M_d^2} \quad (9)$$

for a convergent-divergent nozzle. Apparently, the parameter β is insufficient to evaluate shock strengths when the shock structures are altered by asymmetric nozzle geometries (such as the stepped nozzles used here). Furthermore, quantitative information on shock strengths obtained through experimental measurements are rather limited, and this lack of quantitative experimental data has compelled many studies to compare between numerical simulation results to qualitative schlieren visualization [20, 23, 44]. One of the reasons for the lack of experimental data on shock strengths is due to the limitations of conventional experimental techniques. Take for instance, the use of intrusive Pitot tubes or hot-wire probes for supersonic flow measurements will inevitably modify the original shock structures such that the original acoustic field becomes distorted [45].

While partial success has been achieved through laser Doppler velocimetry (LDV) for time-average velocity measurements [46, 47], various problems associated with beam steering effects from sharp density gradients (in dual-beam implementations) and seed particles passing through shock waves render LDV implementations challenging. Particle image velocimetry (PIV) also has similar problems associated with seeding particle distributions as well [48, 49]. As such, the present study made use of non-intrusive quantitative calibrated schlieren technique to measure the density gradients of the supersonic jet flows here, such that shock strengths and

Fig. 16 Density gradient contours along XY-plane for all test nozzles at (a) NPR=4 and (b) NPR=5.

BSAN amplitudes may be better correlated. The technique has recently been used successfully by Mariani et al. [29] and readers are referred to that paper for more details. For the results presented here, experimental data was processed about the baseline nozzle centreline and reflected to obtain the full density gradient results. As for the stepped nozzles, the full density results were obtained by processing the top and bottom halves of the experimental data, before stitching together along the nozzle centreline. This accounts for the discontinuous nature of the contours along the nozzle centreline and is due to the implementation of the Abel transformation used here, where either the top- or bottom-half of the experimental data could only be processed at a time. As such, these results should be used for comparisons of the broad trends here only.

Figure 16 shows the density gradient contour results determined for the three nozzles along the symmetric XY-plane. In the figure, negative and positive contour regions represent expansion and compression regions respectively, and the ranges of the density gradient magnitudes are kept constant throughout for ease of comparison. For the baseline nozzle, an alternating and regular sequence of expansion and compression regions within the jet column at the two NPRs can be observed. As the jet static pressure is higher than the ambient pressure, expansion occurs at the nozzle lip immediately after the supersonic jet was exhausted. This leads to a regular series of expansion and compression regions captured through the present calibrated schlieren measurements, as well as diamond-like shocks to propagate within the jet column progressively downstream. It should also be mentioned that the shock cell lengths for the baseline nozzle at NPR=4 and 5 are consistent with those discerned from the qualitative schlieren images presented earlier.

In contrast, the resulting expansion and compression regions for stepped nozzles are more complicated. Closer inspections of their density gradient results shown in Fig. 16 show that they are highly asymmetric. In particular, it would appear that the shocks emanating from the longer nozzle lips dominate with a resulting “zig-zag” shock pattern reflecting within the jet column. As with the baseline nozzle, the shock strength increases with an increase in the NPR as well. Figure 17 presents corresponding density gradient contour results for the stepped nozzles but taken along XZ-plane. In this case, the shock patterns are much more regular and symmetric about the nozzle centreline. While it appears that the results seem to have more expansion and compression regions as compared to the baseline nozzle, this is not the case as they merely reflect the earlier comment on the overlapping of the two shock systems produced by the shorter and longer nozzle lips. Schlieren imaging is a light-integration technique and hence, both shock systems will be visualized and therefore quantified through calibrated

Fig. 17 Density gradient contours along XZ-plane for stepped nozzles at (a) NPR=4 and (b) NPR=5.

schlieren approach.

To compare the average shock strengths between the baseline and stepped nozzles quantitatively, density gradient profiles were extracted at $0.2D$ radially away from the jet centreline. This location was selected to better identify the shock structures, especially for the stepped nozzles. Due to the stepped nozzles undergoing prominent jet plume deflections along the XY plane, canted jet centrelines approximated from earlier schlieren images were used instead. Density gradient distributions of the baseline nozzle at NPR=4 and 5 at $0.2D$ radially away from the jet centreline were extracted and presented in Fig. 18. It can be observed that the density gradient magnitude oscillates about the centreline in a highly regular manner, due to the formation of regular shock diamonds within the jet column. When the NPR increases from 4 to 5, the amplitudes and frequency of the density gradient oscillations can be seen to increase and decrease respectively. Since the average shock strength can be evaluated by averaging difference between adjacent peak and valley amplitudes [25, 50], the average peak-

Fig. 18 Density gradient profiles of the baseline nozzle along radial distance $0.2D$ off jet centreline at NPR=4 and 5.

valley amplitude difference was estimated and can be seen to increase from 249 kg/m^4 to 637 kg/m^4 when NPR increases from 4 to 5. Hence, this provides direct evidence that the average shock strength increases with the NPR. More interestingly, this is consistent with the BSAN amplitude of baseline nozzle increasing with NPR as previously shown in Fig. 9 earlier.

Figure 19 presents a comparison of density gradient profiles between baseline, S30 and S60 nozzles at different azimuthal planes. The results indicate that the density gradient profiles of the two stepped nozzles do not demonstrate regular oscillatory patterns, which is considered to be a direct consequence of the asymmetric shock cell structures found in the jets. To compare further, the shock strengths associated with the three test nozzles were estimated based on earlier procedures. Results show that the stepped nozzles can significantly reduce the shock strengths at various azimuthal angles at both NPRs. In addition, it can also be discerned that the S60 nozzle tends to be more efficient in shock strength reduction than the S30 nozzle at various azimuthal angles under NPR=5 condition. For instance, at NPR=5 and $\theta=180^\circ$, the average peak-valley amplitude difference of the baseline nozzle is 637 kg/m^4 , while those of the S30 and S60 nozzle are 440 kg/m^4 and 291 kg/m^4 respectively. In contrast, the situation is more complex at NPR=4. In particular, S60 nozzle produces a slightly lower average peak-

Fig. 19 Density gradient profiles of baseline and stepped nozzles at $0.2D$ away from the jet centrelines at various azimuthal angles (0° , 90° , 180°) under (a) $NPR=4$ and (b) $NPR=5$ conditions respectively.

valley amplitude difference at $\theta=0^\circ$ than its S30 counterpart, while the opposite is true at $\theta=90^\circ$ and 180° . Generally speaking, these average shock strength results agree well with the earlier observations on BSAN amplitude trends for all three test nozzles. It should be highlighted that many earlier studies found that large screech amplitude reductions can lead to amplification of the BSAN level [43, 51]. In the present study however, both stepped nozzles manage to

eliminate screech tone and suppress BSAN level at the same time. This observation suggests that shock strength reduction could play a more important role than jet screech in determining the BSAN amplitude, at least for the nozzles investigated here.

4. Conclusions

Acoustic measurements have been conducted for a circular baseline and two stepped nozzles at underexpanded NPR=4 and 5 conditions and results demonstrate that stepped nozzles can alter supersonic jet noise generation and radiation significantly. Specifically, stepped nozzles produce significant noise reductions relative to their baseline counterpart at high frequencies along the sides and forward polar quadrants. Close examinations of their noise spectra reveal that noise reductions can be mainly attributed to BSAN suppression and jet screech elimination. Major differences in OASPL at different polar and azimuthal angles are also observed, where stepped nozzles can significantly reduce the overall acoustic energy radiated. For instance, at NPR=4 condition and azimuthal angle of 0° , the maximum noise reductions produced by S30 and S60 nozzles are 4.8 dB and 6 dB respectively.

BSAN amplitudes and Strouhal numbers at different azimuthal angles along 90° polar angle are studied based on curve-fitting Gaussian distributions. The amplitude is observed to increase with NPR progressively regardless of nozzle configuration or azimuthal orientation. At both NPRs, stepped nozzles always lead to significant reductions in the BSAN amplitudes with the extent of reduction dependent upon the azimuthal angle. Subsequent quantitative schlieren results show that changes to the BSAN amplitudes correlate well with the variations observed in the mean shock strengths, where lower shock strengths lead to lower BSAN levels. In contrast, mitigation of jet screech is postulated to result from the disruption of the aeroacoustic feedback mechanism occurring at the nozzle lips by the step geometries.

On the other hand, the present results do not show consistent trends between BSAN Strouhal numbers, NPR value and azimuthal angle. At NPR=5, Strouhal numbers of the stepped nozzles are apparently higher than those of the baseline nozzle at various azimuthal angles. However, the behaviour is fundamentally different at NPR=4. In particular, both stepped nozzles produce slightly lower BSAN Strouhal numbers, with the exception of the S30 nozzle at an azimuthal angle of $\theta=90^\circ$. Qualitative schlieren visualizations show that stepped nozzles produce wider jet-spreads and while the baseline nozzle produces prominent quasi-periodic shock cells that are symmetric about the jet centreline, those by stepped nozzles intersect in a complex, non-periodic and asymmetric manner along their incline-planes. This suggests that it may not be possible to directly correlate between the BSAN Strouhal numbers and shock cell lengths.

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