Far-field acoustic characteristics of supersonic jet from conical, Rao and Double Parabolic Nozzles – an experimental investigation

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Abstract

Purpose – This paper aims to compare the far-field acoustic characteristics of the recently designed contoured Double Parabolic Nozzle (DPN) with the conventional contoured Rao nozzle and conical CD nozzle.

Design/methodology/approach – Each nozzle is designed and fabricated with a design Mach number of 1.6. Two cases of all three nozzles, flanged (lip thickness = diameter of nozzle exit) and unflanged (lip thickness = 0.04 mm), have been analyzed at the design NPR of 4.25, as well as under various overexpanded and underexpanded NPR conditions, at different polar locations ranging from 25 degrees to 105 degrees from the downstream jet axis.

Findings – The results show that the DPN's Overall Sound Pressure Level (OASPL) values are 2.22–4.5 dB lower than those of the Rao nozzle and quieter than the conical nozzle by 3.21 to 5.42 dB. In addition, the screech tone of the DPN is lower in over-expanded and under-expanded conditions and is absent at the design NPR, whereas the other two conventional nozzles exhibit screech tones even at the design condition.

Research limitations/implications – The acoustic data provide sufficient information to characterize the aero- acoustic performance of each nozzle. However, flow visualization techniques like Schlieren or shadowgraph will support the explanation of the shock cell structure and thus the acoustic behavior.

Practical implications – The design of contoured converging-diverging (CD) nozzles has a significant role in the supersonic and hypersonic regimes. CD nozzles with reduced acoustic signatures are preferred by the aerospace industry.

Social implications – The findings support the development of quieter, fuel-efficient supersonic jet nozzles, helping to reduce noise pollution and environmental impact in aerospace applications.

Originality/value – To the best of the authors' knowledge, this work presents the first in-depth study of how internal nozzle contouring affects far-field supersonic jet noise, offering novel insights for acoustic optimization in supersonic nozzle design.

Keywords Contoured nozzles, Double parabolic nozzle, Feedback loop, Far-field acoustics, Screech, Supersonic jet noise

Paper type Research paper

Nomenclature

A^* = Nozzle throat area (mm^2);
Ae = Nozzle exit area (mm^2);
D = Nozzle exit diameter (mm);
Ti = Temperature of flow at inlet (K);
Ta = Ambient Temperature (K);
t = Flanged nozzle lip thickness (mm); and
tb = unflanged lip thickness (mm).

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Introduction

The worldwide boom in commercial space companies, spaceports and the demand to design and produce supersonic speed-spanned aircraft increases the design and application of supersonic nozzles. To launch rockets, maneuver military aircraft, fly commercial supersonic aircraft, and more, supersonic nozzles are necessary. They are also employed in industries for various tasks, including fuel injection, material cutting, jet mixing, etc. However, during operation, the noise—particularly the jet noise—adversely affects the surrounding environment. The launch vehicle structure and its

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surroundings experience large vibroacoustic loads as a result of the extremely high acoustic energy produced during rocket launch. Since the noise environment during the liftoff stage is extremely difficult to predict, over 60% of satellite launches fail on the first day due to vibroacoustic loads (Griffin *et al.*, 2000). The studies on the environmental impact of jet noise in the residential areas near the launch pad (Gee *et al.*, 2024), airports (De Framond and Brumm, 2022) and military bases (Wicki *et al.*, 2024) show the importance of jet noise reduction methods for supersonic flows. For more than 70 years, jet noise studies have focused on designing supersonic nozzles with low acoustic signatures. However, the internal nozzle contour effect on aeroacoustic characteristics has not yet been studied properly. This paper experimentally investigated the characteristics of a supersonic jet emanating from three different contoured converging-diverging (CD) nozzles with the same area ratio operating at the same conditions.

In the early 1950s, jet noise studies were initiated in response to the development of the turbojet engine, which produced an unprecedented level of "roaring" noise. Lighthill (1952) built the foundations on subsonic jet aeroacoustics and derived a mathematical model to explain how the turbulence in the flow acts as a source of noise. Later on, based on this, Alan Powell conducted several experiments on edge tone and its associated phenomena in high-speed jets (Powell, 1953a; Powell, 1961) and on choked jet noise (Powell, 1953c; Powell, 1953b) and characterized the supersonic jet noise as a combination of three major components:

1 turbulent mixing noise;
2 broadband shock-associated noise (BBSAN); and
3 screech tones.

Tam and his associates provide a comprehensive explanation of turbulent mixing noise by conducting a series of experiments on supersonic jet flow at off-design conditions (Tam, 1971; Tam and Burton, 1984) and at the perfectly expanded conditions (Tam and Chen, 1994). According to Tam, turbulent mixing noise is generated by the interaction of small convected disturbances from the internal flow of the nozzle with the instability waves in the shear layer just outside the nozzle lip. Small eddies or disturbances from different nozzle contours will vary significantly; thus, the excitation of shear layer instability waves also differs in nature. Here, we experimentally analyzed the difference in the excitement of shear layer instability waves from three different contoured CD nozzles.

Harper-Bourne (1973) conducted a study on BBSAN from a contoured converging nozzle operating above the critical pressure ratio. He reported that the point where each shock cell ends (in the shock cell structure) is the source of BBSAN. Seiner *et al.* (1979) expanded this study to CD nozzles. They modified the relation to find the peak frequency of BBSAN. More recently, Tam (2022) proposed that "broadband shock associated noise" has two components: one is the already known noise, caused by the interaction of instability waves with shock cell structure; the second, termed as 'broadband shock cell noise', arises from interaction of small turbulent spots in the jet plume with each shock and expansion fan.

Screech tone, a special case of shock-associated noise, arises due to the acoustic-wave feedback loop. It's the resonance noise that occurs when the frequency of the feedback loop formed with (i) the downstream propagating instability waves, (ii) the upstream traveling acoustic waves generated by the interaction of instability waves and shock cells and (iii) the acoustic reflected waves from the nozzle exit lip traveling downstream become equal to the natural frequency of the system. 50 years ago, Powell, with the help of experiments, explained the generation of the screech tone and gave a simple relation for the screech frequency formula (Powell, 1953b).

The reduction of high-frequency intense screech tones and jet noise using various techniques has become an important area for many researchers over the past years. In the passive jet noise reduction methods, researchers worked with chevrons (PS Tide and Srinivasan, 2009; Lopez Rodriguez *et al.*, 2022), tabs (Ahuja, 1993; Ambily *et al.*, 2021), beveled cross-sectional area (Tide and Srinivasan, 2009; Wei *et al.*, 2022), or placing reflectors (Y.-K. Kweon *et al.*, 2005; Y.-H. Kweon *et al.*, 2006; Vinoth *et al.*, 2011; Alapati and Srinivasan, 2024; PN *et al.*, 2022) at the nozzle exit, etc. In a recent study, Periyasamy and Natarajan (2024) introduced a cross-wire placed at the exit of a CD nozzle to suppress screech tones and achieved up to a 5 dB reduction in OASPL under both over-expanded and under-expanded conditions. Manikanta and Sridhar (2024) studied the effect of near-wall interactions on shock cell structure and jet decay for a supersonic rectangular jet. All these cases alter the nozzle exit lip's geometry to increase jet mixing and reduce jet noise. In the active jet noise reduction methods, fluidic inserts (Morris *et al.*, 2013; Powers, 2015) are given to the primary nozzle flow to enhance the jet mixing and thus reduce the noise. Changes in the internal nozzle flow geometry or the nozzle exit shape compromise the thrust output in both active and passive cases.

Researchers have conducted a substantial body of work on jet noise and its correlation with supersonic nozzles from the early 1950s to the present day. However, there is a scarcity of research regarding various internal nozzle geometries and their impact on jet acoustics. Callaghan and Coles (1956) conducted a far-field noise study on converging, converging-diverging, and plug-type nozzles with circular, square, rectangular, and elliptical cross sections having the same area and operating at the same nozzle pressure ratios. They concluded that the CD nozzle exhibits a reduction in jet noise when compared to the converging one. Their primary areas of focus were the impact of the nozzle's cross-sectional area on jet acoustics and the comparison of the jet acoustics behavior between converging and CD nozzles. The first researchers to examine the jet noise behavior of various contoured nozzles were Seiner *et al.* (1979). At a design Mach number of 1.5, they investigated both contoured (designed by the method of characteristics) and conical CD nozzles, delivering about the same thrust. They discovered that, under the same operating conditions, the contoured nozzle had lower noise signatures than the conical one. According to Kim *et al.* (2011), contoured CD nozzles consistently exhibit a shock-free flow under design operating conditions, which results in lower far-field acoustic signatures - even the discrete frequency tones are missing. Almost the same result has been reported by Cuppoletti *et al.* (2014). They compared the acoustic behavior of a biconical CD nozzle (with a sharp throat) and the thrust-optimized nozzle (splined nozzle). A number of researchers has been performed the nozzle contour optimization. For example, Zocca *et al.* (2023), carried out the optimization using the Non-Ideal Method of characteristics, specifically to study the behavior of complex flows; however, no attention was paid to the resulting acoustic effects.

The literature review mentioned above shows that the supersonic jet noise varies with the internal contour profiles of the nozzles. However, there aren't many studies that highlight this criterion; this is one of the few experimental investigations that examines how different contoured nozzle profiles affect the far-field jet noise spectrum. This paper investigates the jet acoustic characteristics of two contoured and one conical CD nozzle. The conventional Rao nozzle and the newly designed Double Parabolic Nozzle (DPN) are selected as contoured nozzles. Mubarak and Tide (2019) conceptualized and developed DPN, a Thrust Optimized Parabolic (TOP) nozzle. Their findings indicated that the DPN exhibits superior thrust performance and improved efficiency compared to traditional Rao and conical nozzles while maintaining identical throat diameter and length. The present study also highlights an additional advantageous feature of the DPN, specifically its superior aeroacoustic performance compared to conventional nozzle designs, as evidenced in the following sections.

Experimental methodology

The flowchart for the complete methodology is shown in Figure 1(a). Each section is elaborated in the subsequent paragraphs.

Nozzle geometry

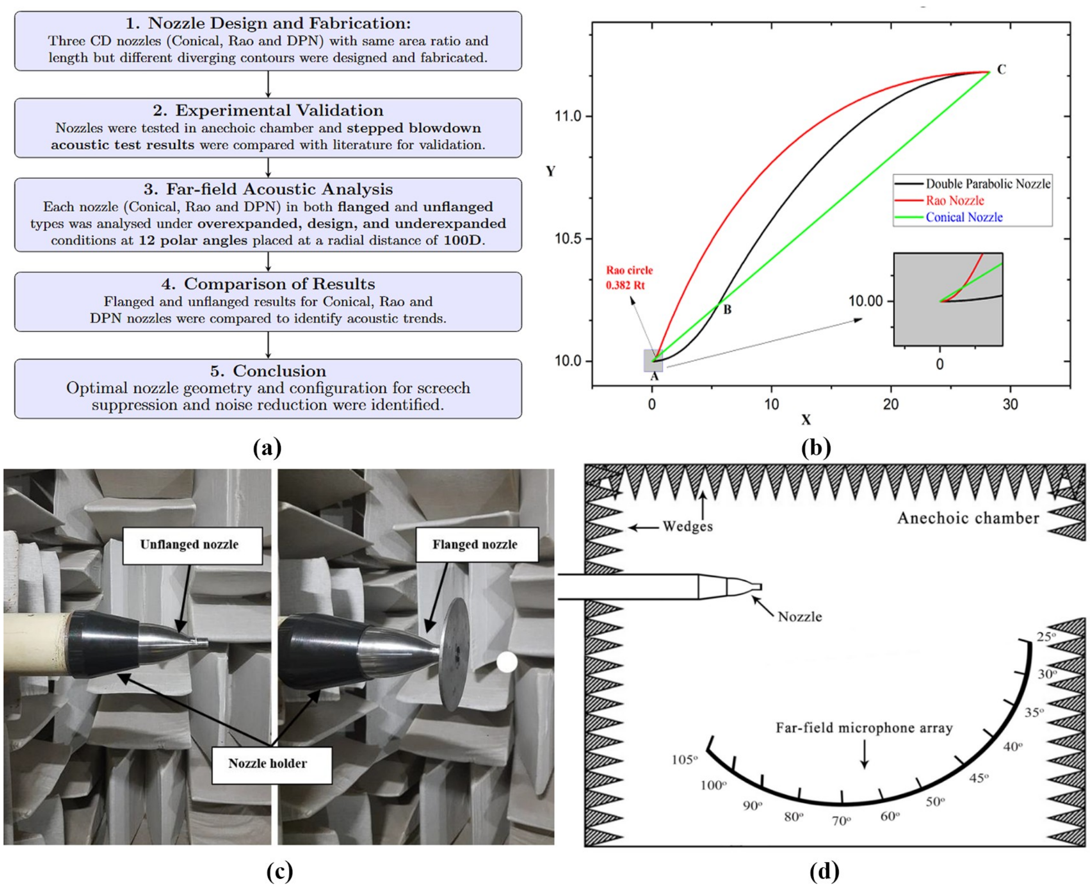
The acoustic experiments are performed with the following three different supersonic CD nozzles:

1 Conventional conical nozzle;
2 Rao nozzle; and
3 Double Parabolic Nozzle (DPN).

All three nozzles have the same design Mach number of 1.6. They share an identical converging section and the same diverging section length but differ in the contour profiles of their diverging sections. The converging section profile was derived from coordinate data provided by Panda and Seasholtz (1999), who had designed two CD nozzles with design Mach numbers of 1.4 and 1.8. From these, the Mach 1.4 nozzle was selected to extract the converging section profile, which was then subjected to geometric similarity and non-dimensional scaling to achieve the desired throat dimensions. For the three nozzles considered, the throat diameter and area ratio, based on the final design specifications, are 20 mm and 1.25, respectively.

The DPN is a TOP nozzle, similar to the Rao nozzle; however, it was not developed using the Method of Characteristics (MOC). This TOP nozzle was designed by Mubarak and Tide (2019) using the Generalized Reduced

Figure 1 (a) Flowchart-methodology, (b) diverging section contours of Conical, Rao and DPN, (c) unflanged and flanged nozzles in the anechoic chamber and (d) nozzle and microphone arrangements



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Gradient (GRG) nonlinear solver with the central difference scheme method to acquire the diverging section coordinates with the desired diverging length.

The motivation behind the selection of DPN for the acoustic study is its greater thrust production capacity than that of conventional nozzles when operating under the same conditions (Mubarak and Tide, 2019; Mubarak and Tide, 2018). While acoustic studies have been performed on several conical and MOC nozzles, the same for this TOP nozzle (DPN) is missing in the literature.

The diverging section contour of the conical nozzle is a straight line designed in such a way that it matches the design Mach number and length of the diverging section of the optimized DPN. The diverging section profile of the Rao nozzle is also a Thrust-Optimized Parabolic section and is designed by MOC (Rao, 1960; Sreenath and Mubarak, 2016), keeping the same diverging section length as the DPN. All three nozzles' diverging section contours are shown in Figure 1(b).

The nozzles were fabricated using stainless steel (SS 316) with a surface finish of 0.4 microns. The flanged (lip thickness is given by t/D = 1) nozzles and the unflanged (lip thickness t_b = 0.04 mm) nozzles are used for testing.

Acoustic test facility

The experiments are conducted at the anechoic chamber facility under the Aerodynamics Laboratory of the Department of Aerospace Engineering, IIT Bombay. The setup ensured a low-turbulence, clean, supersonic and subsonic jet supply through a regulated system into a plenum chamber, followed by the nozzle test section inside the anechoic chamber. Acoustic measurements were performed using two 1 / 4" Brüel & Kjær 4939 (B&K 4939) free-field condenser microphones connected to a B&K 2970 amplifier. Acoustic data was acquired using a National Instruments PCI-4462 DAQ card at a sampling frequency of 150 kHz for 10 s and LabVIEW software. The spectral analysis of the data from LabView software is done by using a Python code.

For the acoustic measurements, the microphones are placed at 12 polar locations at a distance of 100D (Ahuja *et al.*, 1987) from the nozzle exit center with a positioning error of 10 mm. Polar angles are measured from the downstream jet axis, and they vary from 25 to 50 degrees at intervals of 5 degrees, from 50 to 100 degrees at intervals of 10 degrees, and the last location is at 105 degrees. Figure 1(c) shows the flanged and unflanged nozzles inside the anechoic chamber, and (d) shows the schematic microphone arrangement inside the anechoic chamber at different polar angles.

Each nozzle is operated with a cold jet at over-expanded, design, and under-expanded NPR conditions. NPRs 3, 3.5, and 4 are in the over-expanded condition; NPR 4.25 is the design condition; and 4.5, 5, and 5.5 are the under-expanded NPRs. Each NPR value corresponds to the jet Mach number M_j, i.e. NPR varies from 3 to 5.5 as the jet Mach number varies from 1.34–1.77 through the design Mach number of 1.6. The far-field acoustic measurements are taken at each NPR and at each polar location.

Results and discussions

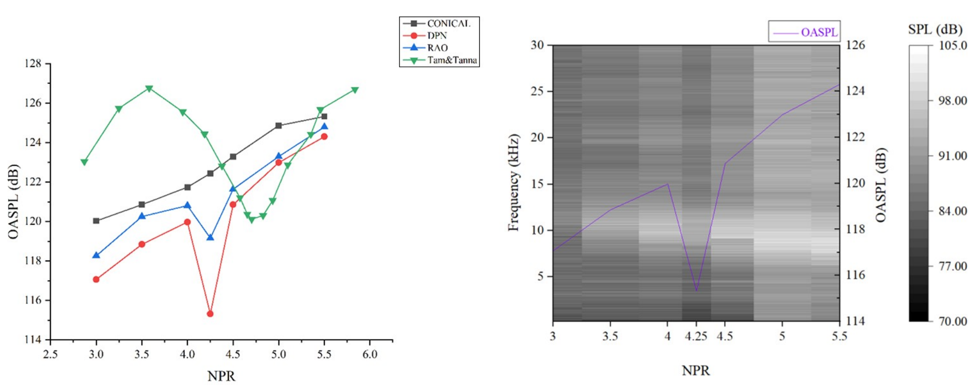
The first part of this section describes the validation of the experimental setup by placing the microphone at a sideline polar angle of 90 degrees and analyzes the results using the readily available literature. The next section describes the directivity pattern of jet noise by placing the microphones at 12 different polar locations. The subsequent section explains the far-field spectra of the noise at each microphone location under various NPR conditions.

Experimental validation through the stepped blowdown test

To validate the acoustic measurements, the variation of OASPL with Mach number is analyzed through the stepped blowdown test. In this test, the compressed air at 9 bars is allowed to expand through the nozzles until it matches each NPR condition under consideration in steps. At each operating NPR, the acoustic pressure data is collected through the microphone. For blowdown tests, the microphone is located at a 100D radial distance from the nozzle exit at the polar angle of 90 degrees measured from the downstream jet axis.

Figure 2 displays the results of the stepped blowdown study for the unflanged nozzles. The variation in the OASPL values with the Mach numbers of the unflanged nozzles is plotted in

Figure 2 (a) OASPL variation of unflanged nozzles under the stepped blowdown study and (b) color contour plot of unflanged DPN under stepped blowdown study



(a) (b)

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Figure 2(a). Figure 2(a) also displays the validation of the curve trend using Tam *et al.* (1982). Since both the current study and Tam and Tanna's study are focused on far-field acoustic analysis, the results used for validation are taken from their experimental study for a CD nozzle at a design NPR of 4.73 with a cold jet ($T_i/T_a = 1.0$). According to their results, the converging-diverging nozzle has a larger noise reduction of about 9 dB than the converging nozzle with the same thrust generation near the design operating conditions. This occurs because the shock waves are significantly weakened or absent both inside and outside the nozzle under the design conditions, which leads to a substantial suppression of shock-associated noise (BBSAN and screech). However, for a converging nozzle, the situation is different; the OASPL value increases as the Mach number increases. In the case of under-expanded jets, the strength of the shock cells increases monotonically with NPR, and so shock-associated noise increases monotonically. But, in the case of over-expanded jets, there are two competing mechanisms. With an increasing degree of over-expansion (i.e. decreasing NPR), the shock cells increase in strength, but the mixing noise decreases as it is proportional to the jet speed. Subsequently, as NPR decreases from the design condition, there is an initial rise of noise followed by a monotonic decrease.

Figure 3 Stepped blowdown study results: (a) Comparison of OASPL for all three flanged nozzles and (b) color contour plot of flanged DPN

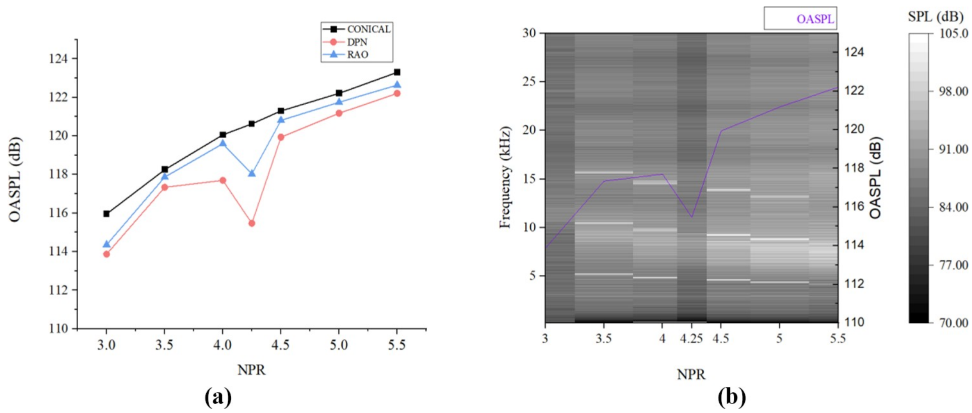

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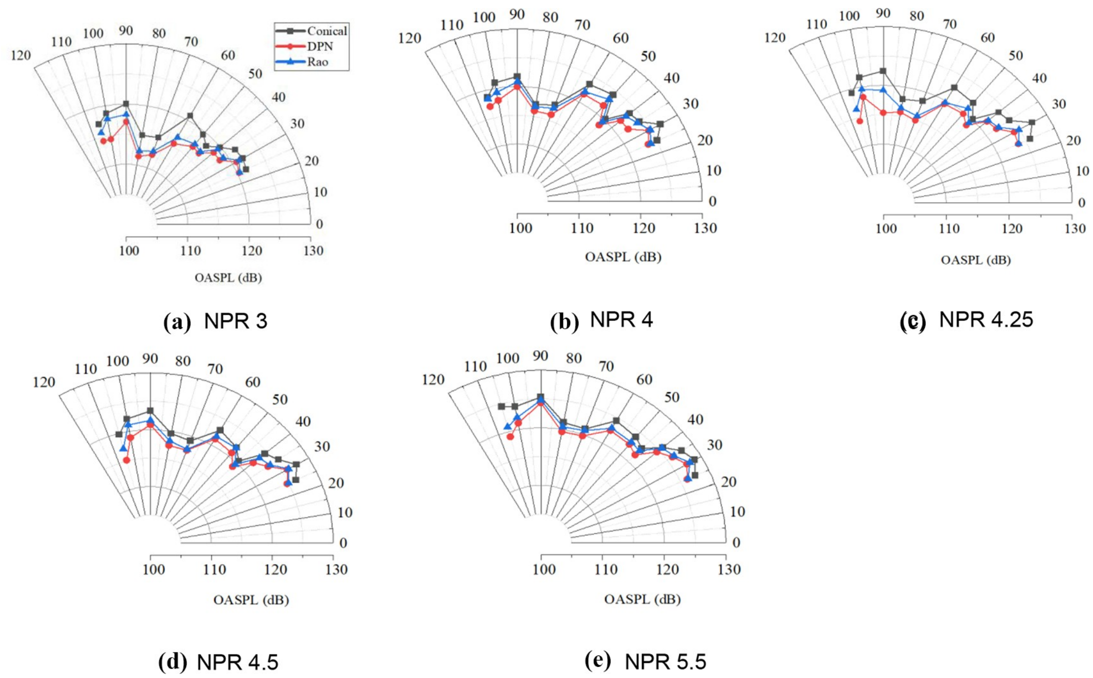
Figure 4 Directivity pattern of unflanged nozzles measured at various microphone locations under different NPR



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In Figure 2(a), similar to the results of Tam and Tanna, both Rao and DPN nozzles show increasing noise (with an average positive slope of 6 and 3 respectively) with NPR up to just below the design value, due to shock cells in the over-expanded conditions. Thereafter, the OASPL drops sharply, (with a negative slope of 6.5 and 15) reaching a minimum at the design NPR, where shock strength diminishes; then, because of the presence of shock cells in the under-expanded conditions, OASPL again increases with NPR (with positive slopes of 6 and 20). Here, the conical nozzle almost behaves like a converging nozzle due to the unavoidable existence of strong shock waves at the sharp nozzle throat, even at the design condition, so the typical OASPL is not seen in the plot. Furthermore, there is a reduction of 3–5 dB of OASPL generated by DPN in comparison with conical nozzles; *vis-à-vis* the Rao nozzle, DPN exhibits a reduction of 2–3 dB of OASPL at or near the design Mach number. Figure 3(b) shows the DPNs' color contour plot of frequency spectra with the OASPL values under the blowdown study. The frequency spectra at NPR 4.25 clearly show a decrease in SPL values and thus the OASPL value. Therefore, the combination of Figures 2(a) and (b), validates the experimental setup for further analysis.

Figures 3 (a) and (b), present the stepped blowdown results of the flanged nozzle to illustrate the variation in screech receptivity, as the thickness of the unflanged nozzle lip is insufficient for generating the acoustic feedback loop and consequently producing the screech tone. Figure 3(b), in particular, shows the contour plot of the DPN under the blowdown study. The white lines in the color contour show the presence of screech tones at each NPR; it is also evident that near the design NPR, the screech tone is absent.

Directivity results

The Overall Sound Pressure Level (OASPL) of all three unflanged nozzles has been measured at different polar angles ranging from 25 degrees to 105 degrees from the downstream jet axis at various NPR conditions. Figure 4 shows the directivity patterns of the two over-expanded nozzles, the two under-expanded nozzles, and the design NPR conditions. Out of the three nozzles, both the contoured nozzles exhibit lower OASPL compared to the conical nozzle, as expected. The maximum directivity of all the nozzles lies between 30 and 45 degrees. In the over-expanded conditions, the DPN shows a maximum of 5 dB reduction in OASPL compared to the conical nozzle and a 3 dB reduction concerning the Rao nozzle.

Compared to the Rao nozzle, there is an overall reduction in jet noise of about 4 dB, and compared to the conical nozzle, the reduction is 7.12 dB. When comparing the DPN with the Rao nozzle, the maximum reduction in OASPL is found in the combination of 4.25 NPR and a 90-degree microphone location; for the DPN and the conical nozzle, it happens in the combination of 4.25 NPR and a 100-degree microphone location. According to Powell (1953c), when NPR increases from over-expanded conditions to under-expanded conditions, the turbulent mixing noise and shock-associated noise are also increased, except at and near the design NPR. Thus, in the current study, the drop in OASPL for DPN implies a reduction in shock cell strength and the associated noise.

The study of directivity patterns for flanged nozzles follows the same trend as that for unflanged nozzles. However, the OASPL values of the flanged nozzles are lower than those of the unflanged nozzles at a particular NPR and at a particular microphone location, as shown in Figure 5. This result is in good agreement with the experimental theory on the effect of reflectors on the supersonic jet by Y. Kweon *et al.* (2005). According to their finding, the downstream shock cell structure is disturbed by the acoustic waves reflected from the nozzle lip; this in turn increases the jet mixing rate and thus the noise reduction. Under these conditions, the screech component adds an extra noise element; however, its contribution is significantly smaller compared to other noise components. The next section provides a detailed discussion on this topic and presents the results of the spectral analysis.

Spectral analysis

The far-field noise spectra will give more emphasis on the jet noise components. Because the lip of the unflanged nozzles is very thin, it cannot reflect the upstream traveling acoustic waves, resulting in a complete absence of screech tones. This was mentioned in the context of the sideline spectra presented earlier (in Figures 2(b) and 3(b)); here, this behavior is demonstrated at other polar angles too. Figure 6(a) shows the variation of far-field spectra for unflanged and flanged DPN under different NPR conditions at a particular microphone location of 25 degrees. Figure 6(b) completely outlines the idea of the screech developed for the case of unflanged and flanged

Figure 5 Comparison of OASPL for unflanged and flanged nozzles

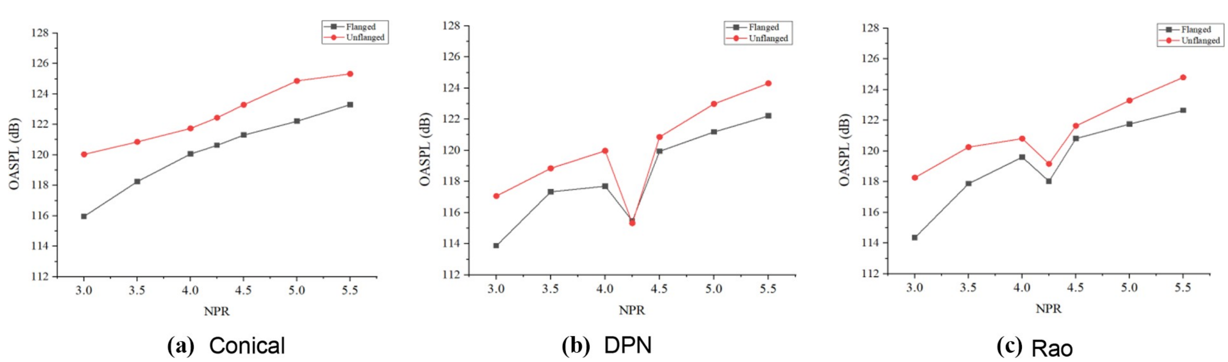

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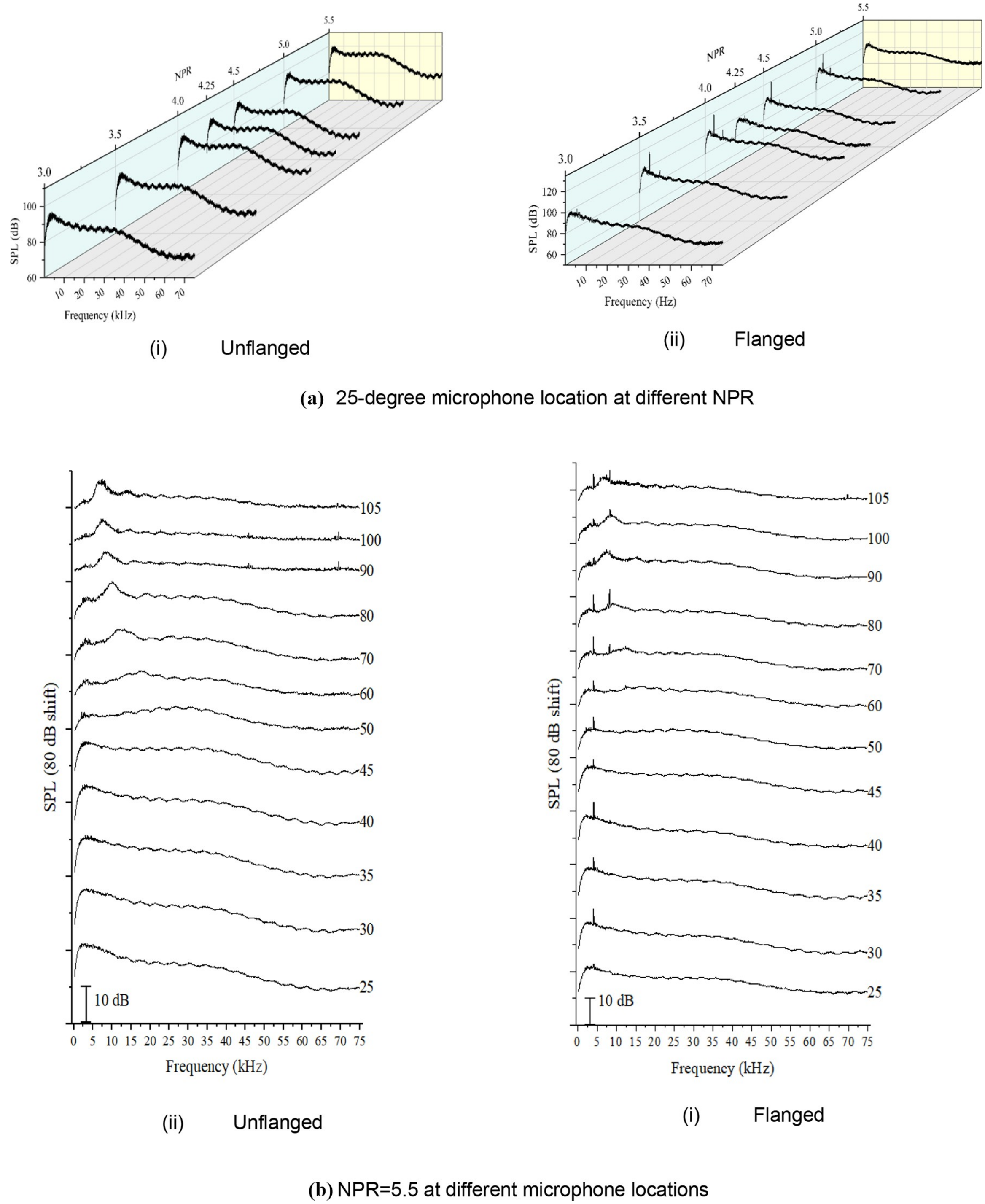
Figure 6 Far-field noise spectra of unflanged and flanged DPN at various (a) NPRs and (b) microphone locations



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DPN at various microphone locations at a particular NPR of 5.5. At over-expanded conditions except NPR 3, the jet produces a screech at all microphone locations. Furthermore, at the polar location, the spectra from 70 to 105 degrees show second harmonics, as shown in the figures. For the design condition, the screech tone is not present due to the absence of shocks in the jet. A comparison of the spectral characteristics of the three unflanged nozzles at a particular NPR of 4.25 and a microphone location of 90 degrees is shown in Figure 7. The second figure indicates that DPN doesn't generate any screech tone at the design NPR condition, but the other two nozzles generate screech tones even at the design condition. This, in turn, reveals that both Rao and conical nozzles are not free from the presence of shocks at the design NPR. This finding is consistent with the experimental observations of Aoki *et al.* (2006), who reported that a conical converging-diverging nozzle generates screech tones at n-design conditions. However, for the case of nozzles with a continuous gradual contour and without a sharp throat in the diverging section, screech tones are not observed under design operating conditions.

The maximum screech tone SPL value in dB for flanged DPN, Rao, and Conical nozzles under different microphone locations is shown in Table 1 under three different conditions: one over-expanded (NPR 3.5), design (NPR 4.25), and one under-expanded (NPR 5.5). The decrease in screech tone SPL values for the DPN in comparison to the other two nozzles is evident. At the design NPR, the screech tone produced by DPN is almost absent.

Conclusion

Far-field acoustic analysis of supersonic jets emanating from three CD nozzles with varying contours has been performed across various nozzle pressure ratios ranging from 3 to 5.5 and at 12 polar microphone locations spanning 25 to 105 degrees. The three nozzles used are the Double Parabolic Nozzle (DPN), the Rao nozzle, and the conical nozzle. All three are designed and fabricated at a design NPR of 4.25 with the same exit diameter and the same nozzle length. Two cases Three nozzles are employed: the conical nozzle, the Rao nozzle, and the Double Parabolic Nozzle (DPN). The exit diameter and nozzle length of all three are identical, and they are designed and fabricated at a design NPR of 4.25. Two variants of each nozzle are examined: unflanged (nozzle with a base lip thickness of 0.04 mm) and flanged (nozzle exit diameter = lip thickness).

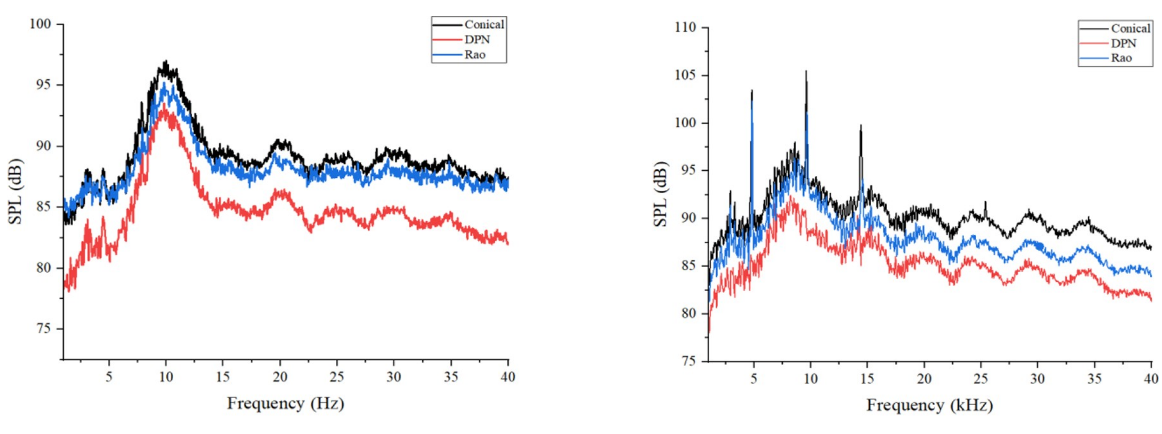
The blowdown studies indicate that both the unflanged DPN and the unflanged Rao nozzles exhibit similar acoustic characteristics in comparison to unflanged conical nozzles. When lip thickness increased, that is, for the flanged nozzles, screech tone became evident in most of the conditions. Far-field spectra show that the screech tone amplitudes and OASPL values for DPN are lower than those of the other two, both in the over-expanded and under-expanded conditions. The OASPL reduction is 2.22 to 4.5 dB more than the Rao nozzle and 3.21 to 5.42 dB more than the conical nozzle.

At the design NPR, the DPN does not exhibit any screech characteristics, whereas the Rao and conical nozzles demonstrate strong screech tones even under these conditions. Since this phenomenon does not depend on any other parameters, it reveals the effect of nozzle contour on shock cell structures and the generated acoustic signatures. This suggests that the DPN operates essentially shock-free in the design condition (in agreement with the results of Mubarak and Tide (2019)), but the conical and Rao nozzles contain shocks. The demonstrated noise reduction with the DPN highlights its potential for practical implementation in next-generation supersonic aircraft, suggesting benefits for environmental noise mitigation, operational efficiency, and community acceptance.

Further work

In this study, the effect of nozzle contour design on acoustic signatures and interpretations of the jet flow structures have been demonstrated solely through acoustic measurements. While this provides useful insights, it remains an indirect approach. Building on the present acoustic tests, future work can incorporate flow visualization techniques, such as Schlieren imaging or the shadowgraph technique to provide qualitative visualization of shock structures. Furthermore, high fidelity computational simulations could offer detailed modeling of the flow and acoustics, providing robust benchmark against experimental results. Thus, a more comprehensive picture of the flow–acoustic interactions can be obtained by integrating

Figure 7 Comparison of far-field spectra of unflanged and flanged conical, DPN and Rao nozzles at NPR 4.25 and 90-degree polar angle



(a) Unflanged nozzles **(b)** Flanged nozzles

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Table 1 Comparison of screech tone SPL (dB) of flanged nozzles under various microphone locations and NPR conditions

Mic. Locations	Over-expanded			Design			Under-expanded		
in deg.	DPN	Rao	Conical	DPN	Rao	Conical	DPN	Rao	Conical
25	Nil		117.77	Nil	103.13	114.65	107.33	119.29	
30	107.17	110.04	114.24	Nil	107.24	118.86	112.45	119.28	120.82
35	101.21		108.39	Nil		114.09	105.51	115.4	117.4
40	104.39	110.01	115.06	Nil	98.43	120.61	113.94	118.89	123.89
45	99.33	103.107	103.51	Nil	107.17	108.05	105.62	106.19	107.65
50	103.22	107.92	105.45	Nil		109.83	103	106	110.86
60	100.9	102.8	103.67	Nil	103.52	107.16	102.17	105.14	111.73
70	95.14	99.64	104.74	Nil	105.85	111.6	102.62	106.33	108.84
80	100.04	101.82	102.18	Nil	106.84	108.99	104.91	106.29	107.23
90	101.34	103.14	113.03	Nil	105.75	109.5	102.36	111.07	105.46
100	105.55	106.74	110.17	Nil		100	104.17	122.17	111.67
105	99.55	101.12	111.09	Nil	116.7	116.77	105.78	111.07	115.006

Source(s): Authors' own work

these approaches which will also help to validate the indirect inferences made here.

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