

Investigation of Physical Mechanisms for Jet Noise Reduction by Plug Nozzle Porosity

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This paper presents the results of a computational study on porous-plug nozzles for their eventual application in reducing landing and takeoff (LTO) noise levels for supersonic civil transport. The study explores a wide range of porous-plug geometries, encompassing variations in hole size, plug length and porosity. Computational fluid dynamics (CFD) analyses are employed in concert with an advanced automated mesh refinement (AMR) scheme, Sketch-to-Solution (S2S), to investigate porous plug nozzle design strategies that may diminish shock strength, broad-band shock noise (BBSN), flow separation, and other undesirable characteristics associated with high takeoff noise levels. A selected subset of the porous-plug nozzles that were analyzed computationally were manufactured at subscale using stereolithography 3D printing. These nozzles were tested experimentally, obtaining far-field noise spectral data and schlieren flow visualization pictures. Detailed comparisons between CFD predictions and experimental results were conducted. These comparisons focus on gaining a better understanding of the underlying physical mechanisms responsible for noise reduction with the porous plugs relative to corresponding solid plugs.

I. Nomenclature

A. Variables

C	= circumference
D	= diameter
L	= length
LF	= plug length factor
M	= Mach number
MJ	= jet Mach number
n	= number of holes per quarter plug
NPR	= nozzle pressure ratio
NTR	= nozzle temperature ratio
P	= pressure
r	= radius
R	= FUN3D residual
s	= hole spacing
T	= static temperature
w	= wall thickness

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x	= axial distance from nozzle crown
y^+	= dimensionless wall distance
ζ	= shock diamond strength marker
ρ	= density
θ	= azimuthal angle
φ	= plug porosity

B. Subscripts

$1-5$	= related to the flow variable residuals within FUN3D
6	= related to the turbulence model residual within FUN3D
a	= ambient conditions
$actual$	= actual value of a variable
$axis$	= denoting a primary axis
$BBSN$	= relating to broad band shock associated noise
c	= cowl
cav	= cavity
CB	= centerbody
d	= drag
Dv	= viscous drag
$hole$	= porous shell hole
k	= index
l	= lift
My	= moment about the y-axis
$norm$	= normalized
rel	= relative to freestream conditions
$target$	= targeted value of a variable
tip	= plug tip
θ	= azimuthal station

II. Introduction

One major obstacle to both regulatory compliance and community acceptance for proposed supersonic commercial vehicles is excessive airport noise [1]. Takeoff noise levels for such vehicles are generally dominated by jet noise [2]. This can reach unacceptably high levels due to takeoff thrust requirements and the low bypass ratio turbofan engines needed for efficient cruise operation. In addition to operational strategies such as engine derating and variable noise reduction systems [3], several technologies have been investigated to reduce takeoff jet noise for these vehicles; such technologies include chevrons and other mixing enhancement devices [4], mechanical shielding [3], multi-stream nozzles [4], mixer-ejectors [5], and plug nozzles [6][7]. While all these technologies have shown some promise in historical research efforts, none have been found to provide sufficient noise reduction for regulatory compliance while avoiding undesirable characteristics such as excessive mechanical complexity or loss of propulsive efficiency [1].

One potential noise reduction technology that has been relatively unexplored to date is the porous external plug nozzle. In such a nozzle, a series of small holes between the plug aft surface (downstream of the throat) and an internal cavity are employed to passively promote circulation between the cavity and exhaust stream, potentially leading to some reduction in strength of shocks that form between the plug surface and nearfield mixing layer. These shocks are a consequence of imperfectly expanded exhaust flow, as is typically found at takeoff conditions around any plug nozzle designed for high efficiency at cruise. For non-porous plug nozzles, a conical shock (in overexpanded operation) or expansion fan (in underexpanded operation)

propagates from the cowl lip to the plug surface and may subsequently be reflected multiple times between the outer mixing layer and the plug surface or the separated shear layer from the plug surface. The resulting shock train can produce various parasitic noise components. In particular, the broadband shock associated noise (BBSN) can be a dominant contributor to jet noise, and therefore to the total aircraft noise during takeoff and initial climb. In a recent experimental study by Zaman et. al. [6], promising results were demonstrated for single-stream conical porous plug nozzles operating at takeoff-relevant conditions. For a conic plug with half-angle 10° and a jet Mach number (MJ) of 1.38, a large decrease in BBSN was observed, and schlieren images showed a dramatic reduction in the strength of reflected shocks across the nearfield jet region. However, the effectiveness of plug porosity (ϕ), defined as open area due to the holes per unit area of plug surface, on BBSN reduction was found to be strongly dependent on factors including plug shape and jet Mach number (or, equivalently, nozzle pressure ratio), and a more recent study by Zaman et. al. [7] has shown further strong sensitivities to cowl shape and other geometric parameters.

This paper presents a computational assessment of geometric sensitivities related to the effectiveness of porous plug nozzles for reducing BBSN. Building on earlier experimental work [6][7][8][9], it aims to systematically evaluate sensitivity to geometry parameters while investigating flowfield characteristics. The ultimate goal is to explore and explain the physical mechanisms behind BBSN reductions in porous-plug nozzles, contributing to advancements in nozzle design as a potential solution to airport noise challenges for commercial supersonic flight. Previous Reynolds-averaged Navier-Stokes (RANS) simulations, conducted with the FUN3D CFD package [10] and Fidelity Pointwise meshes [11], assess various geometric configurations under conditions consistent with previous experiments. This study expands on results from Korth [8], which presented an optimized nonporous plug nozzle design for propulsive efficiency during takeoff and cruise. Zaman et al. [9] experimentally obtained thrust coefficient data supporting the designs based on Korth's optimized geometry.

III. Geometry

All porosity pattern and hole geometry changes are applied to a fixed nozzle geometry with an internal cowl radius (r_c) of 1 in., focusing exclusively on the porous section from the plug crown to the tip, with the upstream section and cowl geometry left unchanged. Plugs at three different length factors (LF) were generated: the nominal length factor ($LF = 1.0$) which comes from a previous study on optimizing such contours in 2D using CFD-informed design space querying [8]. Shorter ($LF = 0.7$) and longer ($LF = 1.3$) profiles were created by linearly... to "...the nominal length factor ($LF = 1.0$), which comes from a previous study on optimizing such contours in 2D using CFD-informed design space querying [8], a shorter length factor ($LF = 0.7$), and a longer length factor ($LF = 1.3$). The shorter and longer profiles were created by linearly scaling the nominal profile ($LF = 1.0$) in the x-dimension according to the specified LF values. Figures 1 through 3 give a detailed look at the geometry to be studied via CFD and experiment. Figure 1 illustrates the side view of the test and simulation geometry, showcasing a generic porosity pattern. In the following study, the term 'centerbody' refers to the solid portion within the plug internal cavity seen shaded blue in Figures 1 and 3. Figures 2 and 3 provide a more detailed look at definitions for hole placement and geometry. Each hole pattern was a result of the chosen target porosity (ϕ_{target}) and hole radius (r_{hole}). For each case, a target porosity of 0%, 5%, 10%, or 15% was selected, and hole spacing was iteratively adjusted to achieve the closest possible value to the target porosity for a given hole size. Due to the chosen pattern allowing only an integer number of holes and enforced quarter symmetry, the porosity is not infinitely variable. Target hole spacing was allowed to vary and actual hole spacing was determined by the hole pattern rules set in Fig. 2, the chosen ϕ_{target} , and r_{hole} . This resulted in small discrepancies between ϕ_{target} and ϕ_{actual} for each case, the magnitude of which is on average 0.31% and no more than 0.52%.

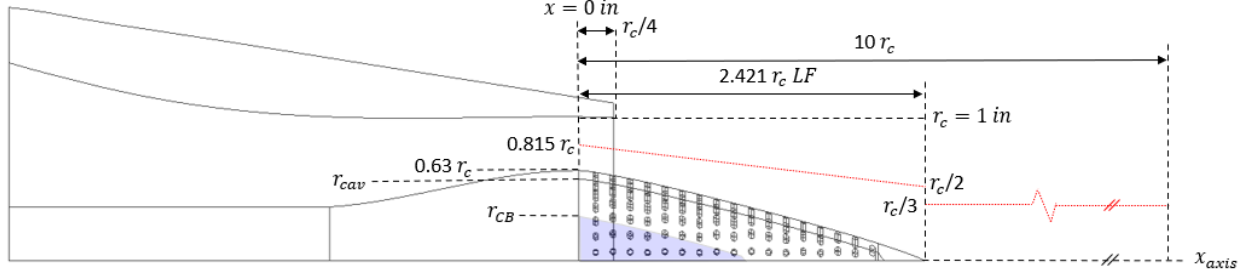


Fig. 1: Side and front view of a sample porous plug nozzle geometry at experimental scale; $s_{target} = 0.115$ in., $n = 82$, $r_{hole} = 0.0185$ in., $\phi_{actual} = 6.30\%$, with the “off body” (left) and “downstream” (right) CFD data extraction lines shown in red.

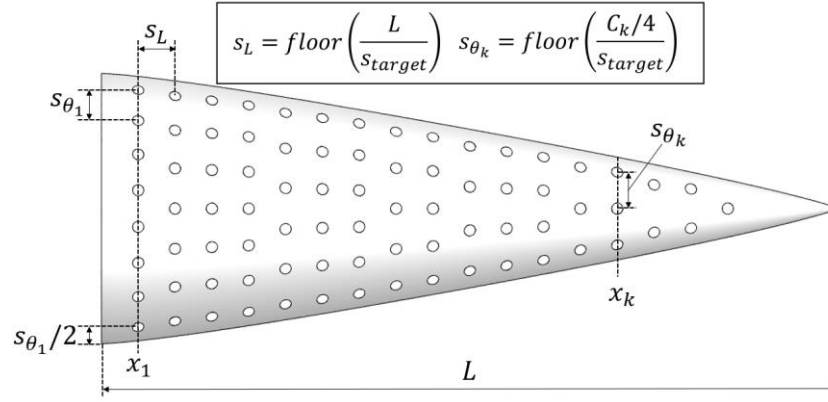


Fig. 2: Detailed look at porosity hole pattern geometry definition.

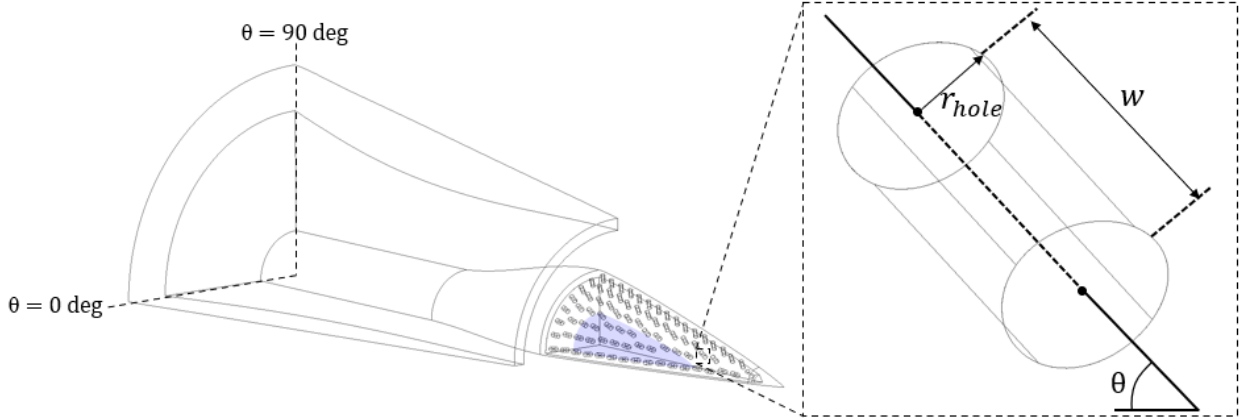


Fig. 3: Detailed look at individual hole geometry definition.

IV. CFD Study of Parametric Sensitivities

A. Meshing

The primary limitation on mesh resolution in previous CFD studies of this nature was the memory capacity of the local machine used for meshing. To overcome this, enhance throughput and solution quality, and reduce human error, the Sketch-to-Solution (S2S) framework [12] with automated meshing and Adaptive Mesh Refinement (AMR) via FUN3D was adopted. Utilizing S2S increases both case throughput and maximum mesh size by approximately an order of magnitude each, improves solution quality with highly

stretched, feature-aligned tetrahedral cells for precise capture of the complex or discontinuous flow features shown in Fig. 4, and enables a fully automated CAD-to-solution workflow. The S2S framework also inherently includes a mesh independence study for each case to confirm that variations across plug configurations are unaffected by continued mesh refinement. A final mesh size of 372M cells was selected, as key quantities stabilized at this level without notable changes in further refinement. Final mesh sizes ranging from 45M to 1.48B cells were also evaluated, revealing a relative pressure ($P_{rel} = P/P_a - 1$) difference of less than 0.05% between the chosen 372M cell mesh and the next refinement level of 744M cells across most of the domain. However, localized differences of up to 1% were observed near shock waves, caused by variations in shock resolution and alignment rather than substantial solution changes. For the complex flows seen around porous plug nozzles, achieving full “mesh independence” is challenging, as continuous refinement, especially in AMR schemes, better approximates discontinuous and chaotic features (e.g., shocks, turbulence, separation) which can never be perfectly modeled via discrete cells. Nonetheless, AMR typically provides higher solution quality than fixed meshes of equivalent or larger size. Recent findings by Galbraith et al. [13] suggest that for the SA turbulence model [14] and its siblings, including ‘sa-neg’ [15], y^+ values below 20 do not necessarily impact model accuracy when error-based mesh adaptation is applied. While some sources advocate $y^+ \approx 1$ for optimal accuracy, others, such as Galbraith et al., argue that lower values do not always correlate strongly with numerical accuracy, especially when boundary layer gradient resolution is sufficient off the wall. Moreover, y^+ targets can vary significantly based on the specific flow problem, grid distribution, and adaptation methods used. Accordingly, the appropriateness of any particular y^+ threshold depends on the model requirements and error tolerance of each application. For the S2S meshes in this study, a target y^+ of 5 was chosen as a balance between accuracy and computational cost.

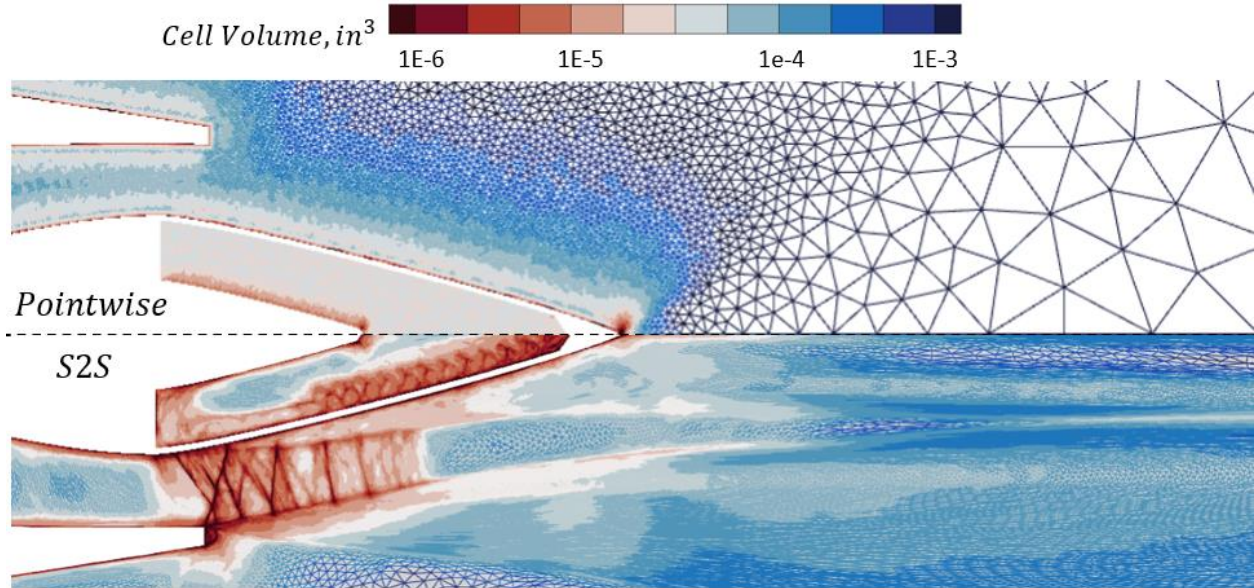


Fig. 4: Meshes for a typical manually generated static 45M cell mesh (top) and Sketch-to-Solution adapted 372M cell mesh (bottom), colored by cell volume.

B. CFD Test Matrix and Simulation Methodology

Through the preliminary CFD studies, including nine cases for general design space exploration, it was determined that plug length factor (LF), target plug porosity (ϕ_{target}), and plug hole radius (r_{hole}) would be the independent variables of interest, while plug centerbody radius normalized by plug cavity inner wall radius (r_{CB}/r_{cav}) and plug wall thickness (w) would remain fixed at 0.5 and 0.04 in., respectively. A preliminary cavity volume study simulating r_{CB}/r_{cav} values of 0 (i.e., no centerbody), 0.5 and 0.8 found minimal impact on plug surface P_{rel} contours. P_{rel} deviations due to r_{CB}/r_{cav} were limited to a maximum

of 1.54%. While both the medium-sized ($r_{CB}/r_{cav}=0.5$) and no-centerbody configurations displayed nearly identical contours, the largest centerbody (i.e., the smallest cavity) caused a slight difference. Similarly, a wall thickness study evaluating w values of 0.01 in., 0.04 in. and 0.08 in. showed a maximum deviation in plug surface P_{rel} contours of 2.1%, also at the jet separation point. Both findings suggest centerbody volume and wall thickness have limited influence on the combined extraction line pressure signature, supporting their use as fixed parameters in subsequent analysis. The simulated ranges of the variables of interest are all permutations of LF values (0.7, 1.0, and 1.3), r_{hole} values (0.015 in., 0.0225 in., and 0.03 in.), and ϕ_{target} values (5%, 10%, and 15%), amounting to 27 unique geometries. An additional 3 solid plugs (0% porosity) and one porous plug with closed holes were also simulated, bringing the total unique geometries to be simulated via FUN3D/S2S to 31. Table 1 presents a summarized run matrix, listing each case name identifier along with actual plug porosity values (ϕ_{actual}) and the number of holes (n) within the simulated quarter-plug domain. Note that all dimensions in the experiment were scaled down by a factor of 25.4 relative to the dimensions used in CFD simulations.

Table 1: Run matrix for porous plug nozzle CFD study

<i>Case</i>	<i>LF</i>	<i>r_{hole}, in.</i>	<i>φ_{target}</i>	<i>φ_{actual}</i>	<i>n</i>
a.00	0.7	0	0.00%	0.00%	0
b.00	1	0	0.00%	0.00%	0
c.00	1.3	0	0.00%	0.00%	0
b.10.m.c	1	0.0225	0.00%	0.00%	91
a.05.s	0.7	0.015	5.00%	5.19%	72
b.05.s	1	0.015	5.00%	5.05%	100
c.05.s	1.3	0.015	5.00%	5.09%	131
a.10.s	0.7	0.015	10.00%	10.10%	140
b.10.s	1	0.015	10.00%	10.20%	202
c.10.s	1.3	0.015	10.00%	10.14%	261
a.15.s	0.7	0.015	15.00%	15.58%	216
b.15.s	1	0.015	15.00%	15.50%	307
c.15.s	1.3	0.015	15.00%	15.38%	396
a.05	0.7	0.0225	5.00%	5.36%	33
b.05	1	0.0225	5.00%	5.00%	44
c.05	1.3	0.0225	5.00%	5.16%	59
a.10	0.7	0.0225	10.00%	10.55%	65
b.10	1	0.0225	10.00%	10.34%	91
c.10	1.3	0.0225	10.00%	10.40%	119
a.15	0.7	0.0225	15.00%	14.77%	91
b.15	1	0.0225	15.00%	14.77%	130
c.15	1.3	0.0225	15.00%	15.38%	176
a.05.L	0.7	0.03	5.00%	5.48%	19
b.05.L	1	0.03	5.00%	5.66%	28
c.05.L	1.3	0.03	5.00%	5.13%	33
a.10.L	0.7	0.03	10.00%	11.26%	39
b.10.L	1	0.03	10.00%	10.50%	52
c.10.L	1.3	0.03	10.00%	10.26%	66
a.15.L	0.7	0.03	15.00%	15.01%	52
b.15.L	1	0.03	15.00%	16.16%	80
c.15.L	1.3	0.03	15.00%	15.54%	100

For each geometry outlined in Table 1, five CFD runs were performed at nozzle pressure ratios (NPR) to attain bulk jet Mach numbers (MJ) of 1.1, 1.2, 1.3, 1.4, and 1.5, outlined below in Table 2, based on 1D isentropic relations [16]. All runs were performed with a static-to-total nozzle temperature ratio (NTR) of 1.68 with adiabatic walls. It should be noted that while the experimental NTR is effectively 1.00, a more flight relevant NTR of 1.68 was chosen for consistency with past CFD efforts. Further sensitivity studies on NTR are planned for future.

Table 2: Flow condition run matrix.

MJ	NPR	NTR
1.1	2.135	1.68
1.2	2.425	1.68
1.3	2.771	1.68
1.4	3.182	1.68
1.5	3.671	1.68

All FUN3D simulations were conducted assuming quarter-symmetry with the same meshing and refinement procedure via the S2S framework, with consistent farfield parameters: flight Mach number 0.1, Reynolds number 53.4k/in., and temperature 72.9°F. The simulations were performed at a 25.4× scale relative to the experimental models presented in subsection V for possible relevance to future flight hardware. Experimental hardware have an internal cowl diameter of 2 in., correlating to a CFD internal cowl diameter of 50.8 in. Each simulation employed the improved one-equation Spalart-Allmaras turbulence model with negative handling (sa-neg) [15], the Low-Diffusion Flux-Splitting Scheme (ldfss) [17] with the H-Van Leer flux limiter (hvanleer) [18] for accuracy and stability, and the Hierarchical Adaptive Nonlinear Iterative Method (HANIM) non-linear solver [19] for speed and robustness. Initial volume meshes consisted of approximately 3M cells, which were refined via 22 mesh adaptations, culminating in 372M cells. The Mach Number Hessian field, i.e. $\nabla^2 M$, was the adaptation metric used for the S2S mesh adaptations. At each mesh size, 500 sub-iteration steps were executed. To prevent adverse reactions near the farfield domain boundaries, artificial mesh coarsening at 80% the maximum farfield distance from the nozzle was applied. In total, 11k iterations were completed per simulation. Previous solution interpolation was disabled to enhance solution robustness, as speed of convergence was not a priority. Each simulation ran on the NAS supercomputer [20] for 28 hours using 20 nodes, with 28 cores/node. Despite disabling solution interpolation, the HANIM solver's aggressive nature stabilized the metrics of interest within 1% of the nominal end value after approximately 200 iterations per mesh adaptation (Fig. 5, right). All CFD cases showed convergence behaviors consistent with that of prior S2S FUN3D cases, seen in Fig. 6.

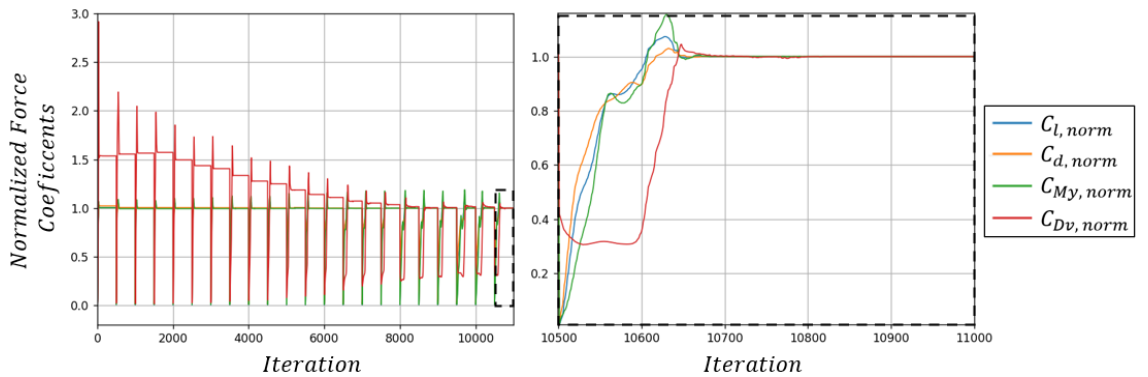


Fig. 5: Force coefficients, normalized by average value of the final 100 iteration, case b.10, $MJ = 1.3$, for entire simulation (left) and final (22nd) mesh adaptation (right).

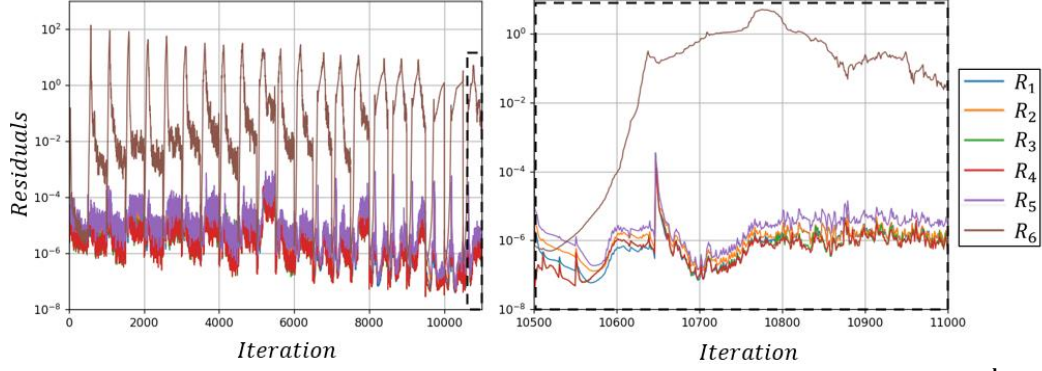


Fig. 6: CFD residuals for case b.10, $MJ = 1.3$, for entire simulation (left) and final (22nd) mesh adaptation (right).

Similarities in the flowfield across all evaluated geometries make it challenging to discern qualitative and quantitative differences among the 155 cases analyzed. To clarify the impact of altering key geometric variables on flow structures in CFD simulations, a summary of each modification and its resultant changes will precede the examination of specific cases related to noise reduction from plug nozzle porosity.

C. Effects of Hole Size

By investigating (experimental equivalent) hole radii of 0.015 in., 0.0225 in., and 0.03 in., the effect of hole size can be isolated and qualitatively assessed using “pseudo-schlieren” contour plots, which depict numerically obtained $\|\nabla\rho\|$. Figure 7 illustrates the effect of varying r_{hole} on the flow structures. To attain the same level of porosity, there is an inverse relationship between r_{hole} and n . As n increases, the number of “shocklets” from each row of holes increases, leading to smoother schlieren contours and transitioning from discrete compression events to a more continuous phenomenon. In the extreme case of infinite number of holes, the plug would resemble a pumice.

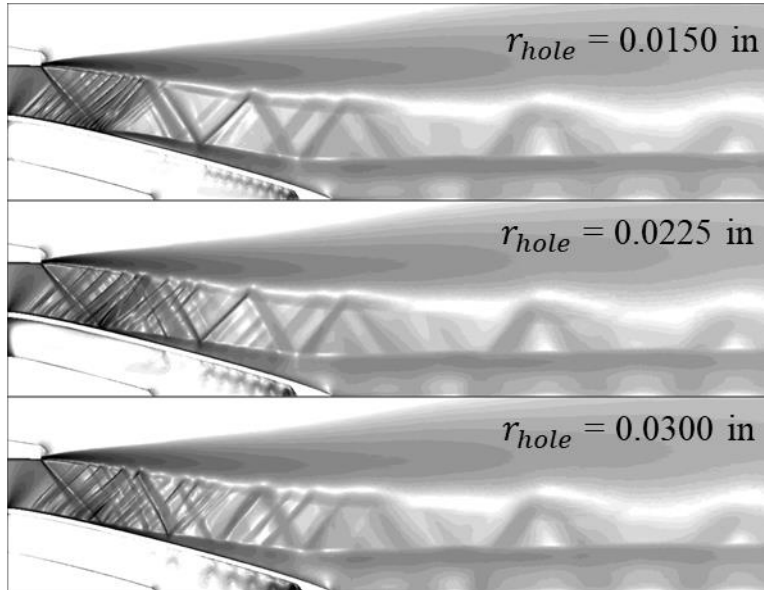


Fig. 7: Pseudo-schlieren contour plot illustrating the effect of changing hole radius, $LF = 1.0$, $\phi_{target} = 10\%$, $MJ = 1.3$.

Figure 8 shows downstream relative pressure signals as hole size is varied on each plug length. These signals on the combined extraction line (Fig. 1) show no meaningful change between small (red), nominal (blue) and large holes (black) as hole size is varied, reinforcing the observation of similarity in downstream shock structure qualitatively seen in the pseudo-schlieren images. Figure 9 shows radial massflow through the holes, normalized by the peak outward massflow attained in any of the 155 CFD runs. Because ϕ_{target} is held constant at 10%, there is a clear independence of hole massflow to hole pattern, number of holes, and hole radii.

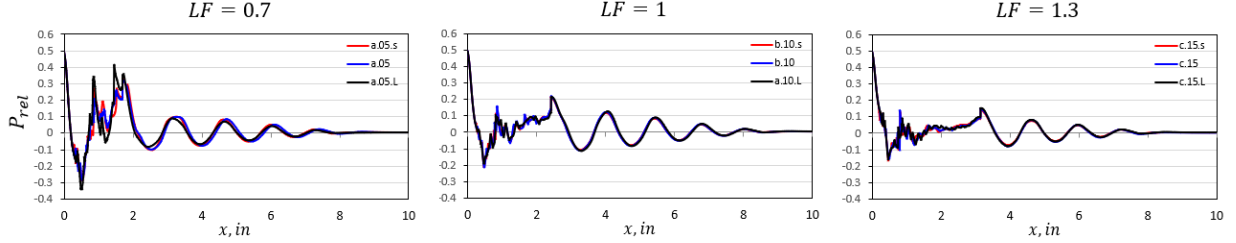


Fig. 8: Relative pressure plots on the combined extraction line at $MJ = 1.3$, $\phi_{\text{target}} = 5\%$ and $LF = 0.7$ (left), $\phi_{\text{target}} = 10\%$ and $LF = 1$ (middle), $\phi_{\text{target}} = 15\%$ and $LF = 1.3$ (right).

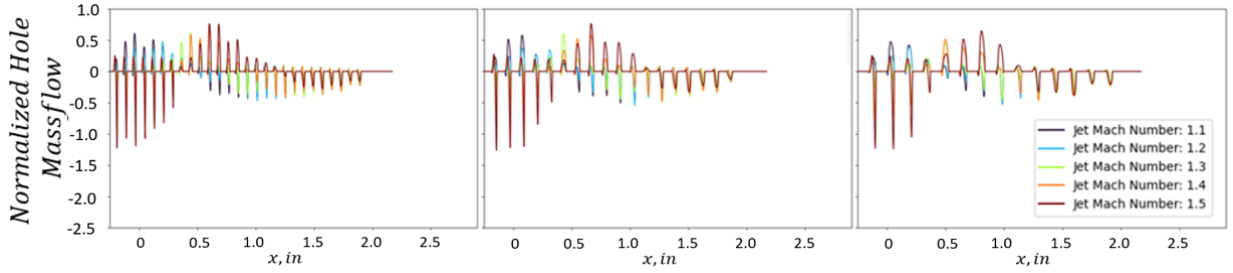


Fig. 9: Normalized hole massflow for each hole radii; 0.015 in. (left), 0.0225 in. (middle), and 0.03 in. (right) for $\phi_{\text{target}} = 10\%$, $LF = 1.3$.

The pseudo-schlieren contours show minimal qualitative changes across varying hole sizes. Clear groupings in the downstream relative pressure signals are observed by porosity, irrespective of hole size. Additionally, there is a pronounced similarity in mass flow characteristics through the holes for a given porosity and bulk jet Mach number. These observations together suggest that r_{hole} will have little to no effect on BBSN.

D. Effects of Plug Length

Pseudo-schlieren plots are shown in Fig. 10 for three cases for which the plug length factor LF is varied, all with the same jet Mach number, porosity, and hole size. A key trend observed in the plots is that as LF increases, the internal jet shear layer, originating at the separation point on the plug surface, moves down the plug and closer to the jet axis. In other words, a longer plug shifts the separation point downstream and toward the axis, narrowing the associated subsonic region. Some related differences in the pattern of reflected shocks between the internal jet shear layer and outer mixing layer are also observed in Fig. 10, with potential consequences for downstream shock propagation and BBSN. Differences in reflected shock patterns are further illustrated in Fig. 11, where relative pressures along the combined extraction line are compared among the three length factors at fixed porosity and jet Mach number. In all three plots, pressure is found to vary strongly with LF , and phase differences in the shock-induced pressure oscillations are clearly displayed for both $MJ = 1.3$ and 1.5. These phase differences may be attributed to variation with LF in the spacing between the internal jet shear layer and outer mixing layer. It is interesting to note that, due at least in part to differences in shock angles with MJ , the phase change with LF seems to be considerably greater at $MJ = 1.3$ than at 1.5

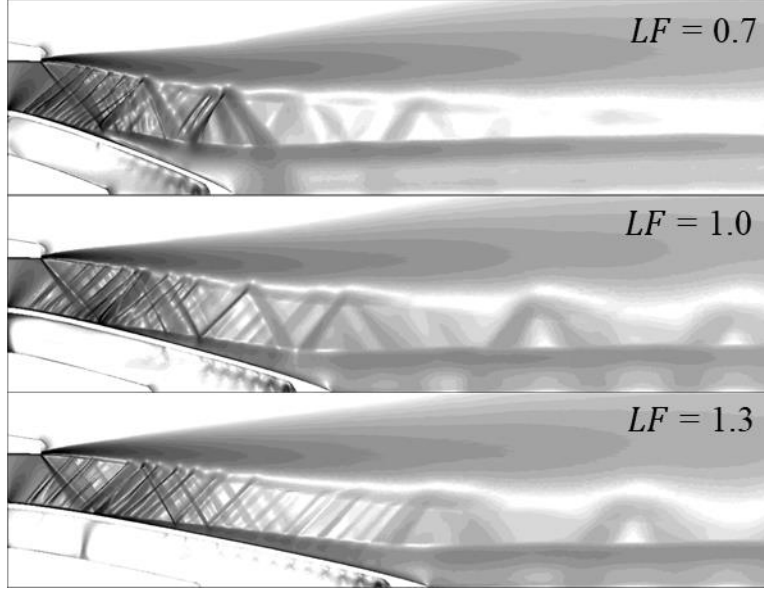


Fig. 10: Pseudo-schlieren contour plot illustrating the effect of changing plug length factor, $r_{hole} = 0.0225$ in., $\phi_{target} = 10\%$, $MJ = 1.3$.

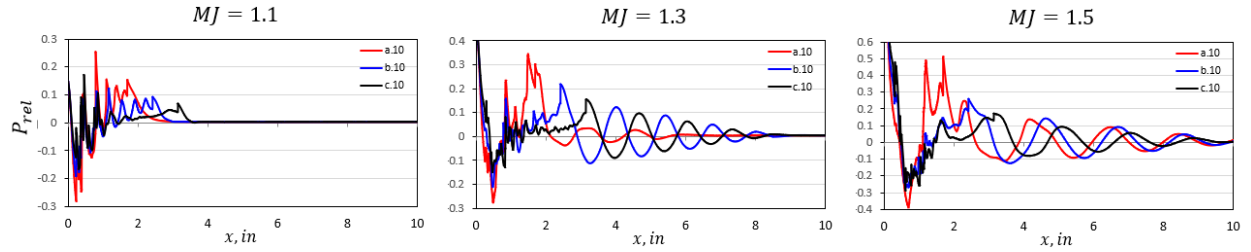


Fig. 11: Relative pressure plots on the combined extraction line for $MJ = 1.1$ (left), $MJ = 1.3$ (middle), $MJ = 1.5$ (right), $\phi_{target} = 10\%$, $r_{hole} = 0.0225$ in.

Figure 12 shows normalized mass flow rates through the holes for the same geometries as in Fig. 10, with varying LF while other inputs remain constant. Each of the three plots displays results for the five MJ values from Table 1, with uniform LF per plot. Similar to Fig. 9, upward and downward spikes indicate trends in inward or outward flow. For example, $MJ = 1.5$ shows primarily inward flow near the upstream plug region, reversing downstream, then returning to inward flow near the plug tip. These trends largely reflect pressure variations along the plug surface due to factors like shock impingement and boundary layer separation. While trends vary with MJ , there is minimal qualitative dependence on LF .

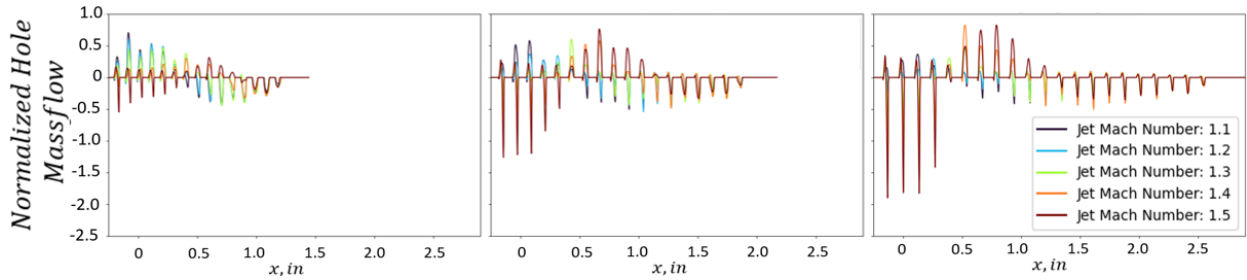


Fig. 12: Normalized hole massflow for each plug length factor 0.7 (left), 1.0 (middle), and 1.3 (right), $r_{hole} = 0.0225$ in., $\phi_{target} = 10\%$.

E. Effects of Plug Porosity

Pseudo-schlieren plots are presented in Fig. 13 for cases with $MJ = 1.3$ and $LF = 1$, and with porosities varying from 0% to 15%. As porosity increases, the separation point on the plug surface moves upstream, due at least in part to a reduction in effectiveness of the Coanda effect [21] associated with differences in viscous entrainment between boundary and free layers on opposite sides of any wall-bounded jet. The Coanda effect tends to promote attached flow and delayed separation in the presence of an adverse pressure gradient, as is found near the impingement location of the cowl lip shock. The effect is weakened by a porous surface due to outward flow (i.e., blowing) through the surface, that apparently also counters entrainment in the outer shear layer. With upstream movement of the separation point, the interior shear layer in the jet – which forms a boundary between the supersonic region containing shock diamonds and the partially subsonic region nearest to the plug tip – tends to move radially outward away from the axis. Another impact of porosity shown in Fig. 13, with potential relevance to BBSN, is a significant weakening of the shock diamonds downstream of the plug tip. This trend may be partly explained by the fact that, as the interior shear layer extends further outward with increasing porosity, the jet in effect becomes less overexpanded, and weaker expansion fans are consequently formed at the intersection of outward-propagating oblique shocks and the edge of the subsonic mixing layer.

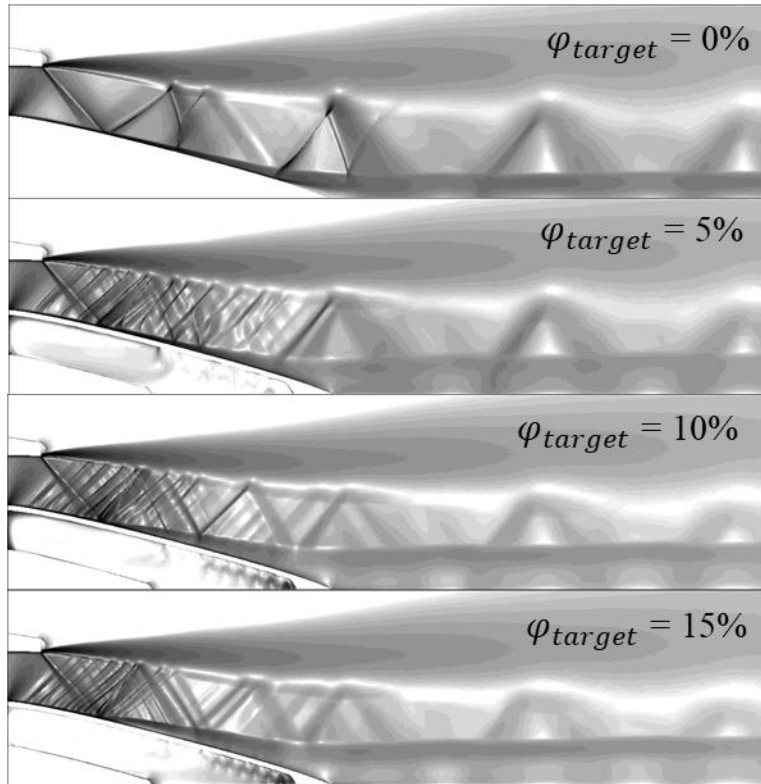


Fig. 13: Pseudo-schlieren contour plot illustrating the effect of varying target plug porosity (ϕ_{target}), $LF = 1.0$, $r_{hole} = 0.0225$ in., $MJ = 1.3$.

The same tendency for reduced shock diamond strength with increasing porosity can be found in some – but not all – of the plots presented in Figures 14 through 16. Results for input parameter combinations ($LF = 0.7$, $MJ = 1.1$), ($LF = 0.7$, $MJ = 1.3$) and ($LF = 1.3$, $MJ = 1.5$) show an especially strong impact of porosity. Large pressure oscillations are found for the nonporous plug cases, whereas pressure is nearly uniform within a small distance of the plug tip for cases with 15% porosity. Smaller benefits of porosity are observed in these figures for ($LF = 1.0$, $MJ = 1.3$) and for ($LF = 1.0$, $MJ = 1.5$). In a few cases, however, pressure oscillations are found to grow with increasing porosity. A positive correlation between oscillation strength and porosity is most clearly seen for ($LF = 1.3$, $MJ = 1.3$). This counter-trend appears to defy a simple

explanation, but may be at least partially due to effects of constructive interference between the main reflected shocks and the weak compression waves (or “shocklets”) originating at individual holes along the plug surface. Also of note, the addition of porosity of 10% or higher effectively eliminates any shock diamonds aft of the plug tip for jet Mach numbers below 1.3 for the shortest plug ($LF = 0.7$), seen in Figures 14 (left) and 15 (left).

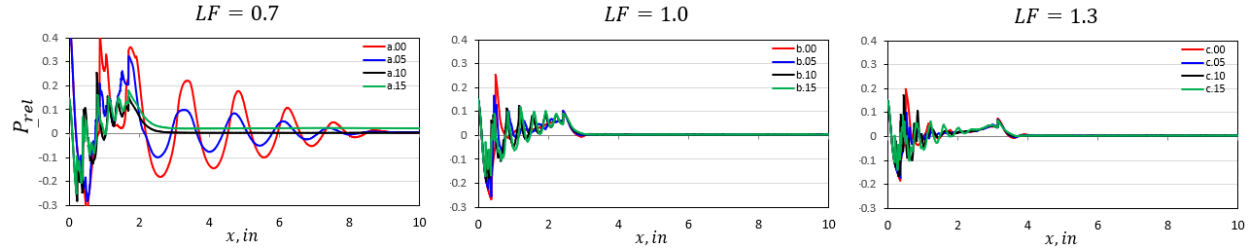


Fig. 14: Effect of porosity on relative pressure on the combined extraction line for $LF = 0.7$ (left), $LF = 1.0$ (center) and $LF = 1.3$ (right), $r_{hole} = 0.0225$ in., $MJ = 1.1$.

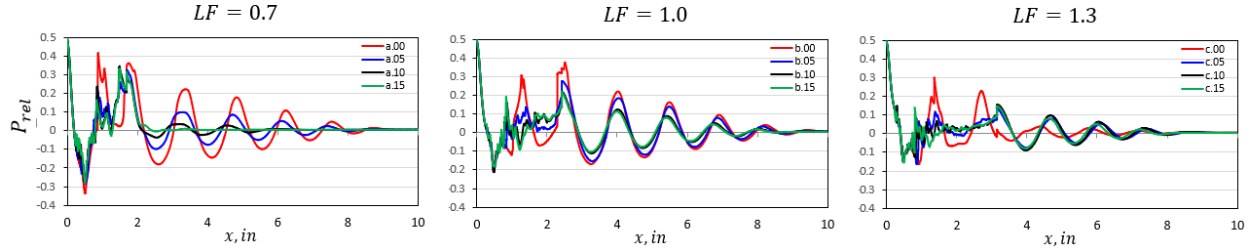


Fig. 15: Effect of porosity on relative pressure on the combined extraction line for $LF = 0.7$ (left), $LF = 1.0$ (center) and $LF = 1.3$ (right), $r_{hole} = 0.0225$ in., $MJ = 1.3$.

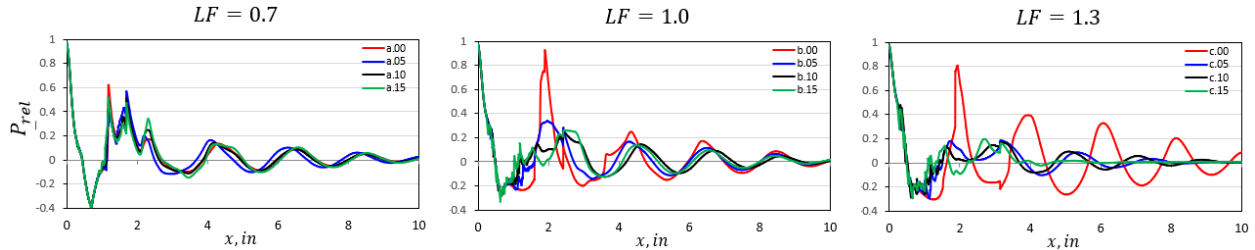


Fig. 16: Effect of porosity on relative pressure on the combined extraction line for $LF = 0.7$ (left), $LF = 1.0$ (center) and $LF = 1.3$ (right), $r_{hole} = 0.0225$ in., $MJ = 1.5$.

F. Effects of Bulk Jet Mach Number

The effect of MJ on the flowfields was found to be relatively complex, with some unique characteristics observed at specific Mach numbers for each LF . Simulations were conducted for Mach numbers ranging from 1.1 to 1.5 in 0.1 increments, with corresponding nozzle NPR and NTR as presented in Table 2. Across the 31 nozzle configurations examined, several consistent trends in overall flowfield characteristics emerged with increasing Mach number. As expected, the average angle of both primary shocks and shocklets from the holes increased, correlating with stronger individual shocks, while the expansion fan propagating from the cowl lip corner grew in angular width and strength. A distinct separation region typically formed where the aft end of the cowl lip expansion fan intersected the plug surface. As a consequence of this separation, the forward movement of the separation point on the plug with increasing Mach number lead to a reduction in the downstream jet width, affecting both the phase and strength of shock reflections off the shear layers originating from the cowl and plug surface. Generally, the strength of shock diamonds increased with Mach number, particularly for non-porous plugs; however, exceptions were observed in cases such as high-porosity and long-length plugs (configuration c.15), where the weakest

shock diamonds occurred at the highest Mach number. These findings highlight the complex nature of plug nozzle flowfields and the significant influence of Mach number on their behavior. Pseudo-schlieren contour plots at all jet Mach numbers for configuration b.10 can be seen below in Fig. 17 and associated relative pressure signals along the combined extraction line are shown below in Figures 18 through 21.

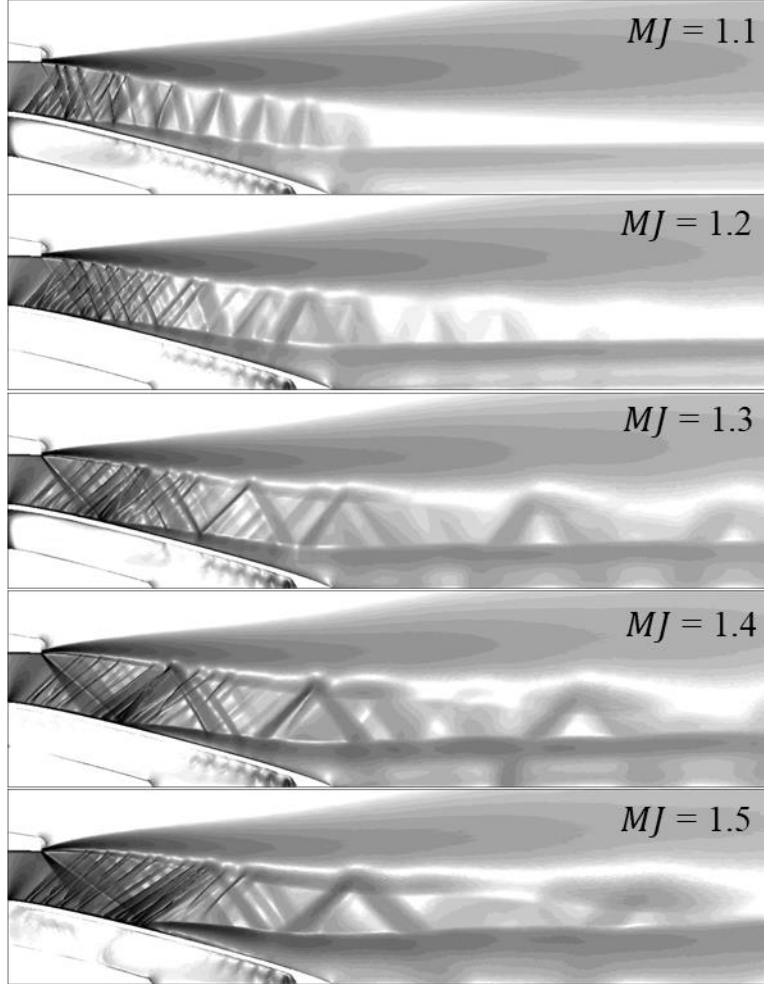


Fig. 17: Pseudo-schlieren contour plot illustrating the effect of changing bulk jet Mach number, $LF = 1.0$, $\phi_{target} = 10\%$, $r_{hole} = 0.0225$ in.

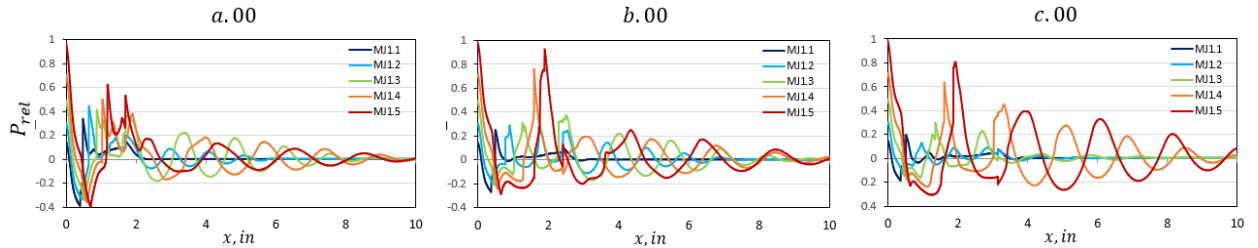


Fig. 18: Effect of jet Mach number on relative pressure on the combined extraction line for $LF = 0.7$ (left), $LF = 1.0$ (middle) and $LF = 1.3$ (right), $r_{hole} = 0.0225$ in., $\phi_{target} = 0\%$.

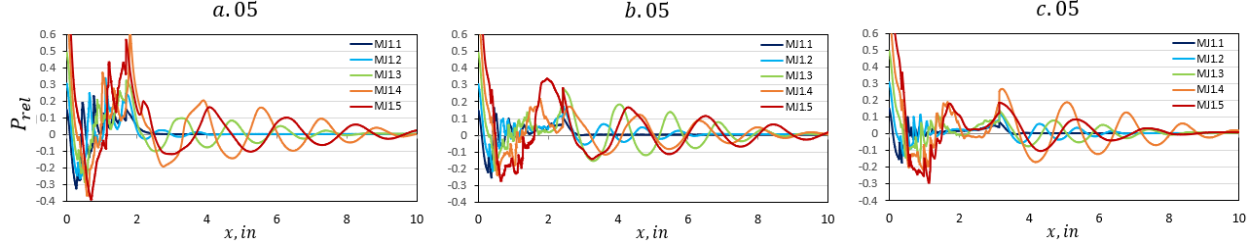


Fig. 19: Effect of jet Mach number on relative pressure on the combined extraction line for $LF = 0.7$ (left), $LF = 1.0$ (middle) and $LF = 1.3$ (right), $r_{hole} = 0.0225$ in., $\phi_{target} = 5\%$.

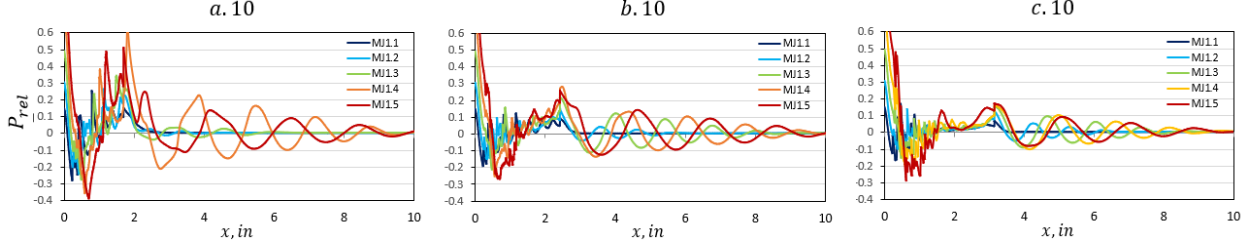


Fig. 20: Effect of jet Mach number on relative pressure on the combined extraction line for $LF = 0.7$ (left), $LF = 1.0$ (middle) and $LF = 1.3$ (right), $r_{hole} = 0.0225$ in., $\phi_{target} = 10\%$.

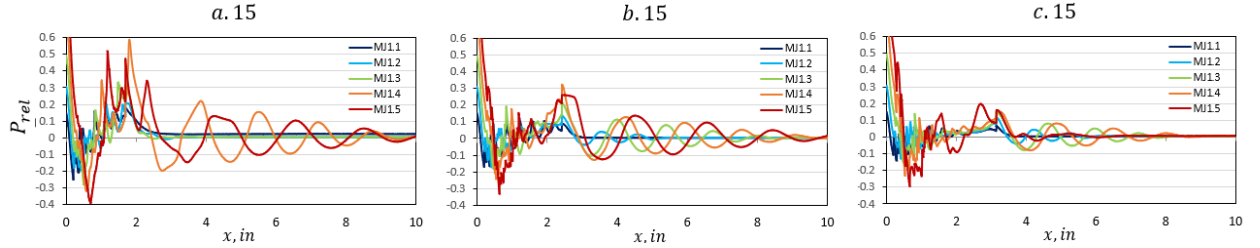


Fig. 21: Effect of jet Mach number on relative pressure on the combined extraction line for $LF = 0.7$ (left), $LF = 1.0$ (middle) and $LF = 1.3$ (right), $r_{hole} = 0.0225$ in., $\phi_{target} = 15\%$.

A RANS-based metric (ζ_{BBSN}) for shock-diamond strength was formulated in Eq. 1 by integrating the square of the pressure over the combined extraction line. This metric is shown graphically in Fig. 22 for all medium hole size cases. Stronger shocks are presumed to produce higher shock-associated noise, as demonstrated by Zaman et al. [6]. Thus, a larger value of this metric, particularly in the jet's downstream region, is expected to result in elevated BBSN levels. A comparative analysis of the short plug cases for $MJ = 1.3$ reveals a distinct correlation between ζ_{BBSN} and the strength of shock diamonds downstream of the plug. Specifically, the a.00 case exhibits the highest ζ_{BBSN} , while a.10 and a.15 are both relatively low. The a.05 case occupies an intermediate position, with the trend reversing around $MJ = 1.4$. This observation aligns closely with the noise data of [6], suggesting a direct link between shock diamond intensity, i.e. ζ_{BBSN} , and noise. This effect, as elaborated further in the following, is particularly notable within the intermediate MJ range of 1.2-1.4, in agreement with Zaman et. al [6], who found “... a dramatic reduction in shock strength for the porous case in the mid-MJ range”. To elucidate noise reduction mechanisms, two extreme cases of porosity-induced ζ_{BBSN} reduction, a.00 vs a.10 and c.00 vs c.10, were analyzed. From these cases, general hypotheses on noise reduction strategies were formulated, to be validated through a comprehensive analysis of all remaining data points.

$$\zeta_{BBSN} = \int_{x_{tip}+r_c}^{x_{tip}+10r_c} P_{rel}^2 dx \quad (1)$$

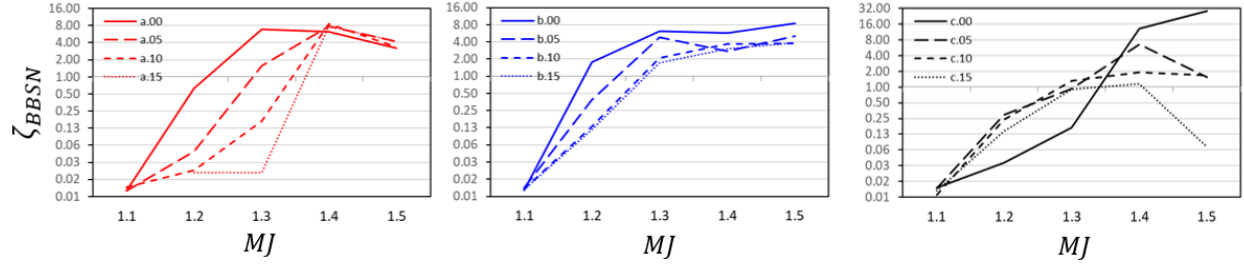


Fig. 22: X-integral of the combined relative pressure signals from 1 to 10 in. aft of the plug tip, short plug (left), nominal plug length (middle), long plug (right).

The characteristics of the massflow through the holes in a porous plug nozzle can be greatly affected by jet Mach number. At lower jet Mach numbers, the flow is primarily entering the plug holes near to the throat, and exiting nearer to the plug tip. As the Mach number is increased, the flow has a greater tendency to enter the plug nearer the throat, exit in the middle (where the primary expansion fan is impinging on the plug surface), and enter the plug in the separation region downstream of the aft end of the impinging expansion fan emanating from the cowl lip trailing edge. Intermediate Mach numbers tend to smoothly blend those two behaviors, from a clear two zone, “in-out” behavior at $MJ = 1.1$ and clear 3-zone “in-out-in” behavior at $MJ = 1.5$, illustrated in Fig. 12.

V. Experimental Results and Comparison to CFD

A. Experimental Setup

The experiments were conducted in the open-jet facility at NASA Glenn Research Center. The experimental setup, shown in Fig. 23, was utilized to acquire noise data and schlieren images. Flow from the main plenum chamber was directed through four U-shaped tubes to a 5 in. diameter ‘floating plenum’ mounted on a linear bearing, allowing axial thrust measurements. A plug nozzle was attached to the downstream end of the floating plenum, featuring a cowl with a 2 in. exit diameter. A fixed stem, with a diameter of 0.75 in. and supported centrally within the nozzle by x-shaped struts, housed a screw mechanism used to attach interchangeable plugs. Sound pressure spectrum data were obtained using overhead microphones. Further details of the experimental configuration are available in previous studies e.g., [9].

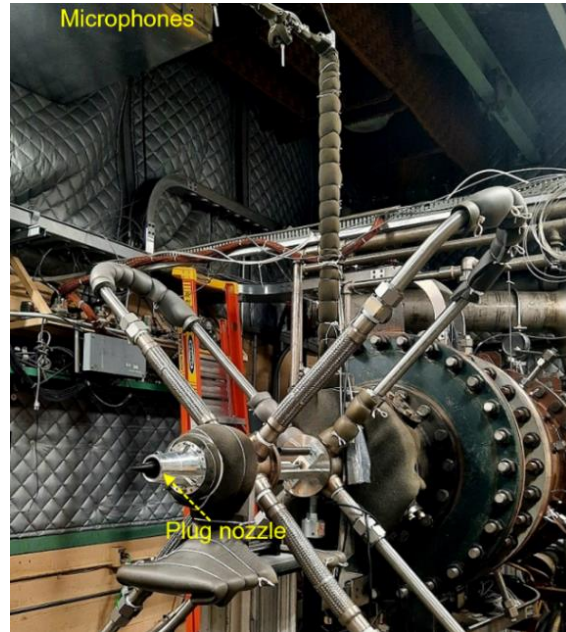


Fig. 23: Experimental setup of the CW-17 open jet facility.

A focusing schlieren system with a lens-and-grid technique was used for flow visualization, projecting a source grid onto a retro-reflective screen and imaging it onto a cut-off grid to produce the schlieren effect, as detailed in [22]. A 5-watt xenon flashlamp with a 1-microsecond pulse illuminated the flow. Density gradients cause light rays to refract, and by using a cut-off grid similar to the "knife-edge" in classical schlieren systems, these disturbances are visualized as light and dark regions in images captured by a scientific-grade CCD camera. Optical components and the camera were enclosed in a light-tight box on one side of the jet, with a 30 in. x 24 in. retro-reflective screen on the opposite side, providing a 10 in. field of view along the streamwise direction and 3.5 in. vertically around the jet centerline. The camera captured 30 images at 3 frames per second, averaging them over a 10-second period to improve image quality with background subtraction and contrast enhancement. Fig 24. shows a system schematic.

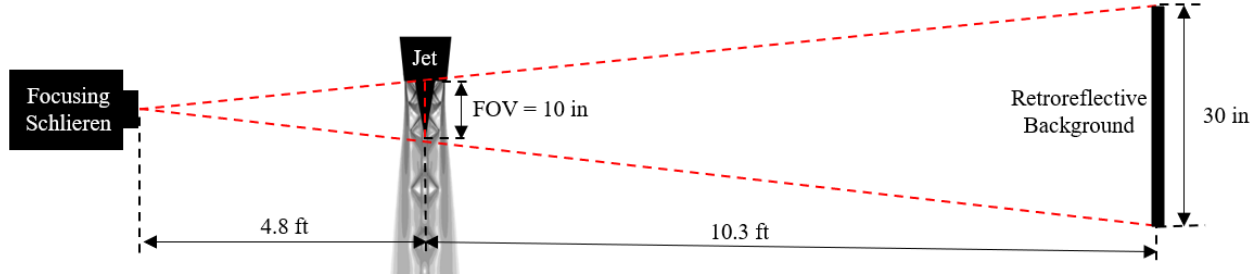


Fig 24: Overhead view schematic of the focusing schlieren layout in the CW-17 free-jet facility.

Experimental and pseudo-schlieren images show good overall agreement, though the experimental schlieren images differ due to a thicker focal plane spanning about 2 in. This setup causes measurements to be a ray-integrated representation of $\partial p / \partial x$ across the focal length, contrasting with the CFD-extracted, infinitesimally thin plane used in pseudo-schlieren images. This thin plane, extracted from the volume solution, provides higher resolution of local flow features but limits direct comparability, as illustrated in Fig. 25. Furthermore, experimental images are time-averaged and are affected by shock oscillations, turbulence, and measurement noise, while CFD yields instantaneous pseudo-schlieren contours. In Fig. 25, qualitative alignment is evident, with contour levels for pseudo-schlieren plots adjusted to a gradient scale of -2.5 to 2.5 1/in. for better comparison with experimental data.

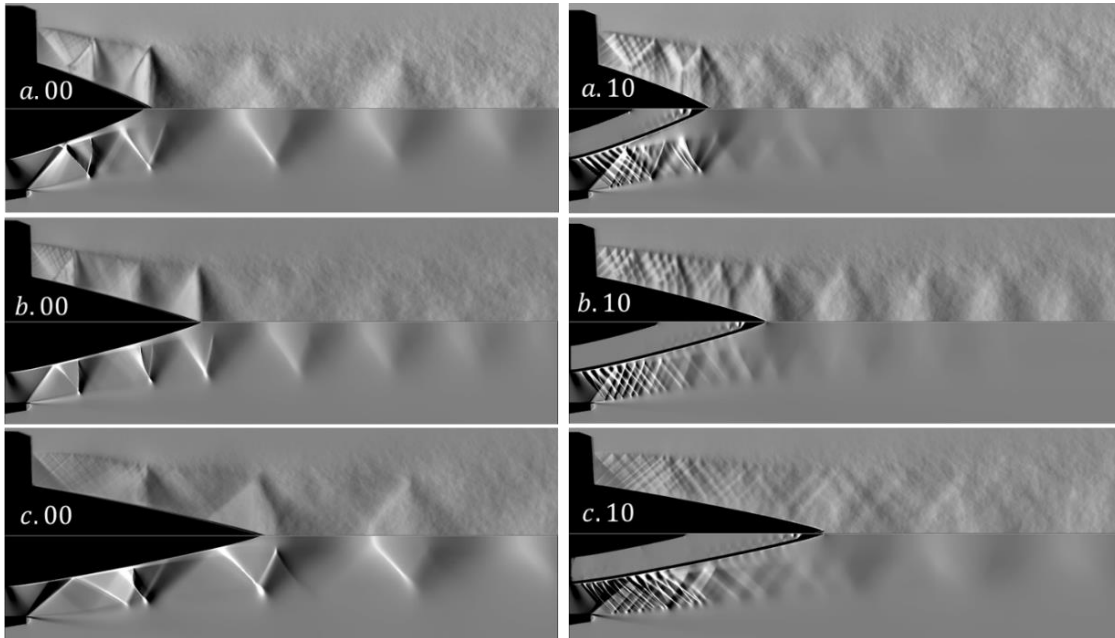


Fig 25: Comparison of experimental (top) and pseudo-schlieren (bottom) images for short, medium, and long plugs (top to bottom), with non-porous (left) and $\phi_{target} = 10\%$ (right) configurations.

B. Noise Data

Noise data was only consistently taken across all geometries for $MJ = 1.2$, $MJ = 1.3$ and $MJ = 1.4$, as the largest differences in porosity-induced relative pressure signals were seen in those ranges computationally. The data for all relevant test configurations, namely a.00 through a.15, b.00 through b.15, and c.00 through c.15 for jet Mach numbers 1.2, 1.3 and 1.4 can be seen below in Figures 26 through 28.

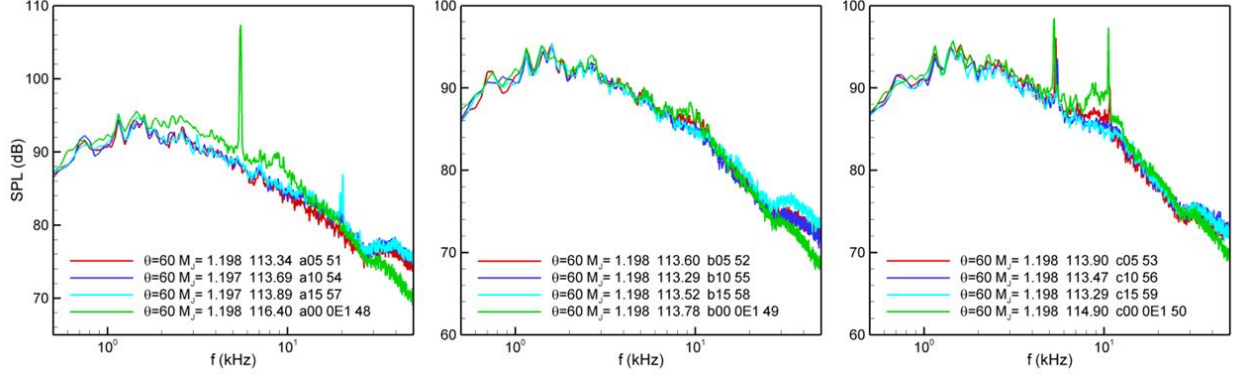


Fig. 26: Noise spectra for non-porous (green), $\phi_{target} = 5\%$ (red), $\phi_{target} = 10\%$ (blue) and $\phi_{target} = 15\%$ (cyan), for $LF = 0.7$ (left), $LF = 1.0$ (middle) and $LF = 1.3$ (right), at $MJ = 1.2$.

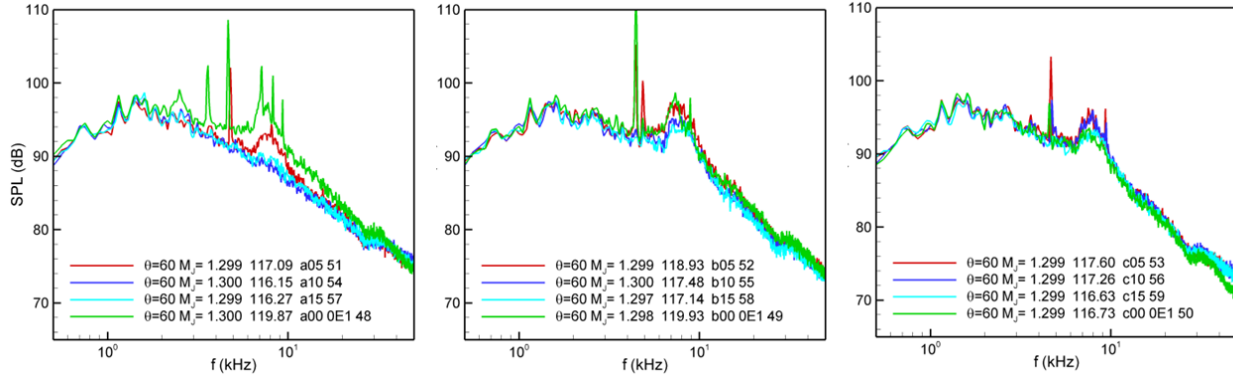


Fig. 27: Noise spectra for non-porous (green), $\phi_{target} = 5\%$ (red), $\phi_{target} = 10\%$ (blue) and $\phi_{target} = 15\%$ (cyan), for $LF = 0.7$ (left), $LF = 1.0$ (middle) and $LF = 1.3$ (right), at $MJ = 1.3$.

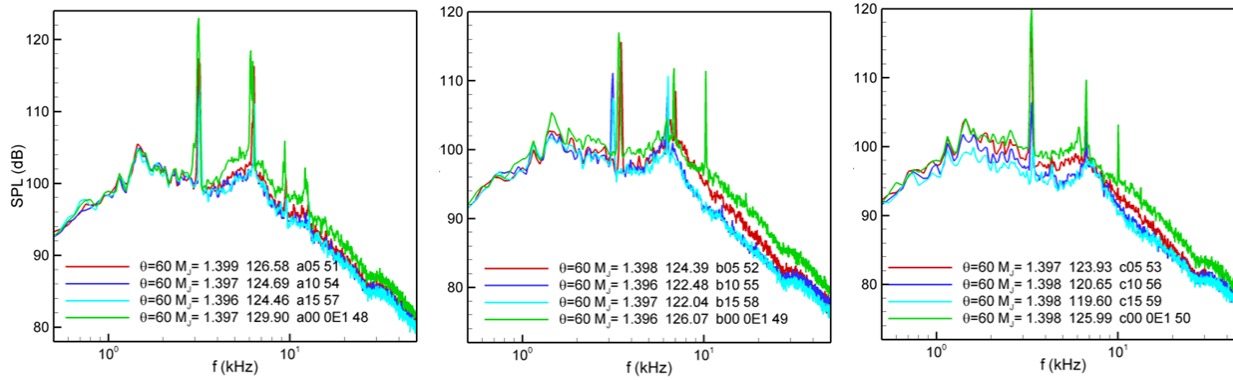


Fig. 28: Noise spectra for non-porous (green), $\phi_{target} = 5\%$ (red), $\phi_{target} = 10\%$ (blue) and $\phi_{target} = 15\%$ (cyan), for $LF = 0.7$ (left), $LF = 1.0$ (middle) and $LF = 1.3$ (right), at $MJ = 1.4$.

A conclusion from the noise spectra in Figures 26 through 28 is that at lower jet Mach numbers (e.g., $MJ = 1.2$ in Fig. 26), reductions in broadband shock noise at mid-frequencies due to plug porosity are often accompanied by a corresponding increase in high-frequency broadband noise. The high frequency noise is apparently due to the 'shocklets' from the holes. The high frequency noise may present challenges in scaled up configurations for perceived noise to human hearing. Adopting to smaller sized holes might alleviate this concern but it needs to be evaluated further.

VI. Investigation of Mechanisms for Jet Noise Reduction

As described in Subsection IV.E, increasing plug porosity can significantly reduce the strength and persistence of shock diamonds, thereby reducing BBSN. However, these effects are highly sensitive to various factors, such as the jet Mach number and plug geometry. A simple physical mechanism is insufficient to fully explain the observed trends, but a partial explanation may be inferred from certain cases, illustrated below in Figures 29 through 32, where the impact of porosity is especially favorable. In these cases, porosity causes a clear weakening or even elimination of shock diamonds within a short distance from the plug tip. One plausible explanation for this trend is that for a non-porous plug ($\phi_{\text{target}} = 0\%$), the Coanda effect typically prevents or reduces boundary layer separation around shock reflection points on the plug surface, such as at the reflection of the cowl lip shock in the overexpanded conditions studied here. A porous plug surface reduces the effectiveness of the Coanda effect because flow through the surface counters the radially inward forcing due to mixing layer entrainment, diminishing the plug's ability to resist boundary layer separation. As porosity increases, the separated region grows and moves upstream, causing a radially outward displacement of the separation-induced free shear layer within the jet. It's outward shift constricts the adjacent jet region containing shock diamonds, effectively reducing the degree of overexpansion within the jet. As overexpansion decreases—specifically, as the pressure variation across the inward-directed expansion fans at the junction of oblique shocks and the mixing layer edge is reduced—the shock diamond pattern cannot propagate as far downstream. This explanation is consistent with observations in the cases shown in Figures 29 through 32.

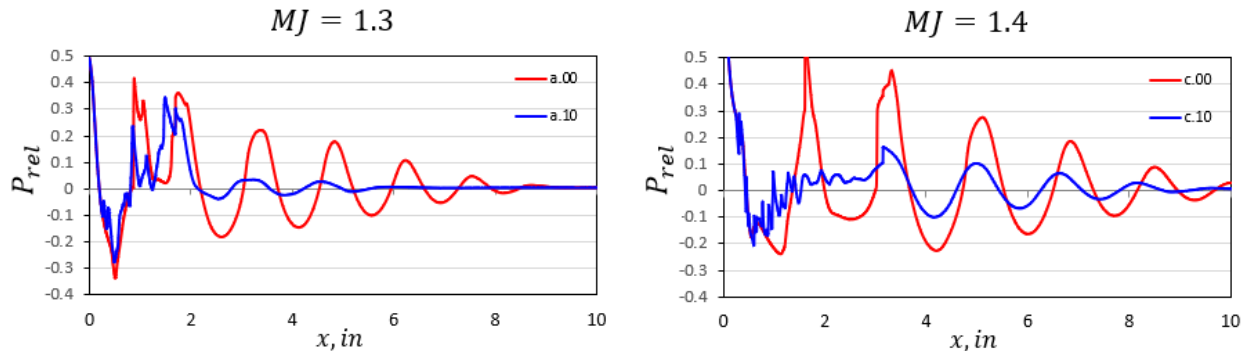


Fig. 29: Relative pressure signals for the combined extraction line for cases a.00 vs a.10 at $MJ = 1.3$ (left) and c.00 vs c.10 at $MJ = 1.3$ (right).

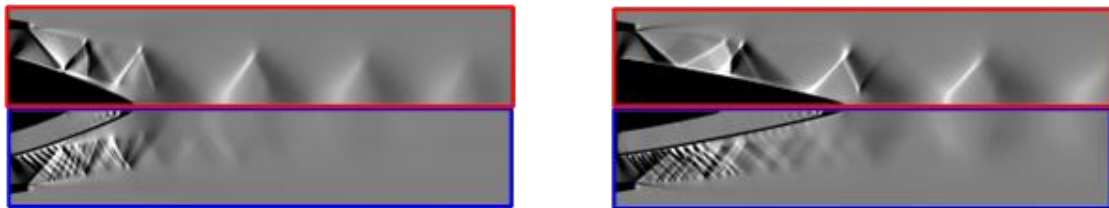


Fig. 30: Pseudo-schlieren contour plots for a.00 (red) vs a.10 (blue) at $MJ = 1.3$ (left), c.00 (red) vs c.10 (blue) at $MJ = 1.4$ (right).

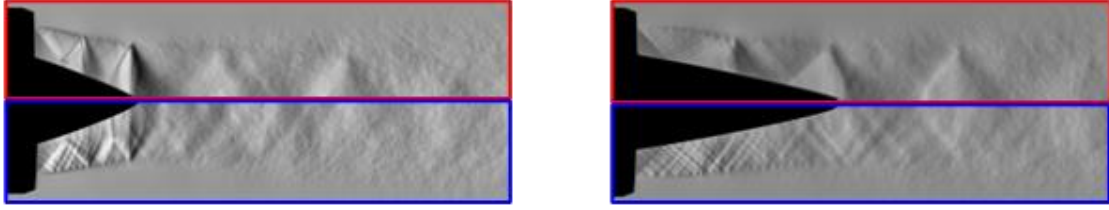


Fig. 31: Experimental schlieren images for a.00 (red) vs a.10 (blue) at $MJ = 1.3$ (left), c.00 (red) vs c.10 (blue) at $MJ = 1.4$ (right).

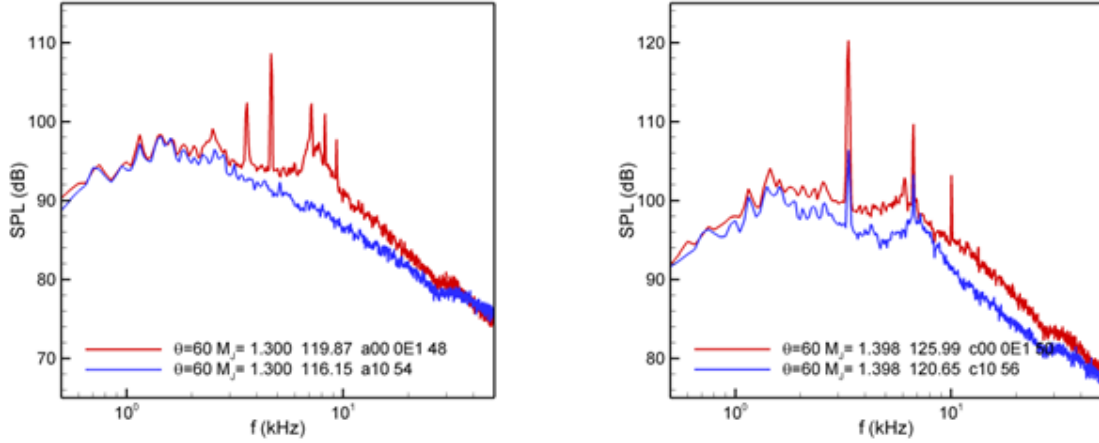


Fig. 32: Noise spectra for a.00 (red) vs a.10 (blue) at $MJ = 1.3$ (left), c.00 (red) vs c.10 (blue) at $MJ = 1.4$ (right).

In other cases, the effect of plug porosity on shock diamond persistence is less favorable. For some cases, the shock diamonds are even stronger with a porous plug compared to an equivalent nonporous plug, for example a.00 vs a.10 for $MJ = 1.4$ and c.00 vs c.15 for $MJ = 1.3$, seen below in Figures 33 through 36. Note that these two cases, chosen for their minimal or even adverse effect on shock diamond strength, are directly adjacent in the case matrix to the two cases discussed in Figures 29 through 32, which show some of the strongest reduction in shock diamond strength. This indicates that the design choices that lead to a significant reduction in BBSN via the advantageous effects of plug porosity may have none, or even adverse effects on BBSN noise levels at a value just slightly off the “design” condition at which porosity-induced benefit is the greatest. Further confirmation of this reversal in porosity effects on shock diamond strength can be seen in Fig. 22, subsection IV.F, as a crossing of the lines representing solid and 10% porosity between $MJ = 1.3$ and $MJ = 1.4$ for both the short and long plugs. This suggests that other physical mechanisms also contribute significantly to the effect of porosity.

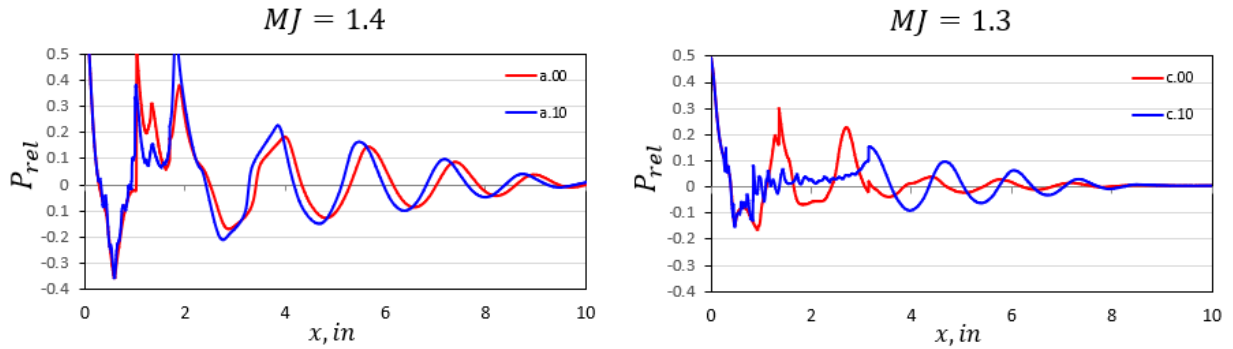


Fig. 33: Relative pressure signals for the combined extraction line for cases a.00 vs a.10 at $MJ = 1.4$ (left) and c.00 vs c.10 at $MJ = 1.3$ (right).

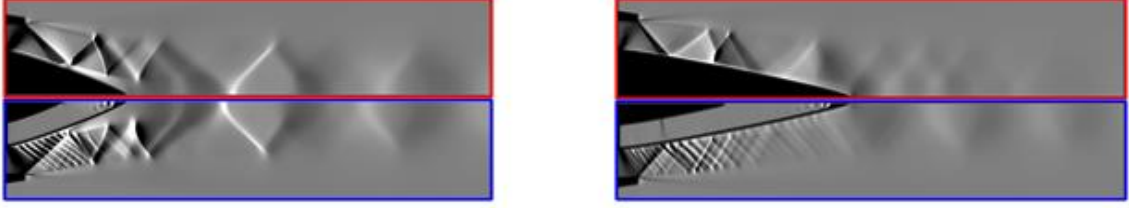


Fig. 34: Pseudo-schlieren contour plots for a.00 (red) vs a.10 (blue) at $MJ = 1.4$ (left), c.00 (red) vs c.10 (blue) at $MJ = 1.3$ (right).

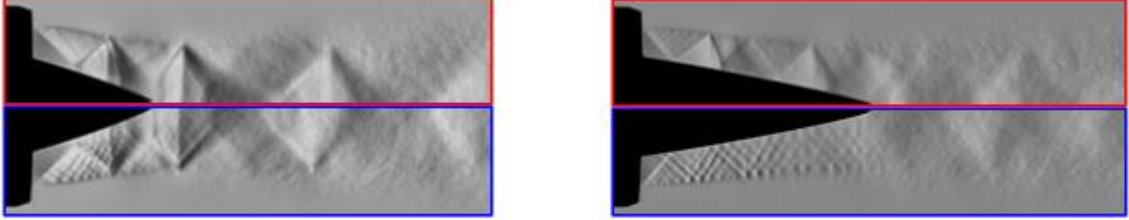


Fig. 35: Experimental schlieren images for a.00 (red) vs a.10 (blue) at $MJ = 1.4$ (left), c.00 (red) vs c.10 (blue) at $MJ = 1.3$ (right).

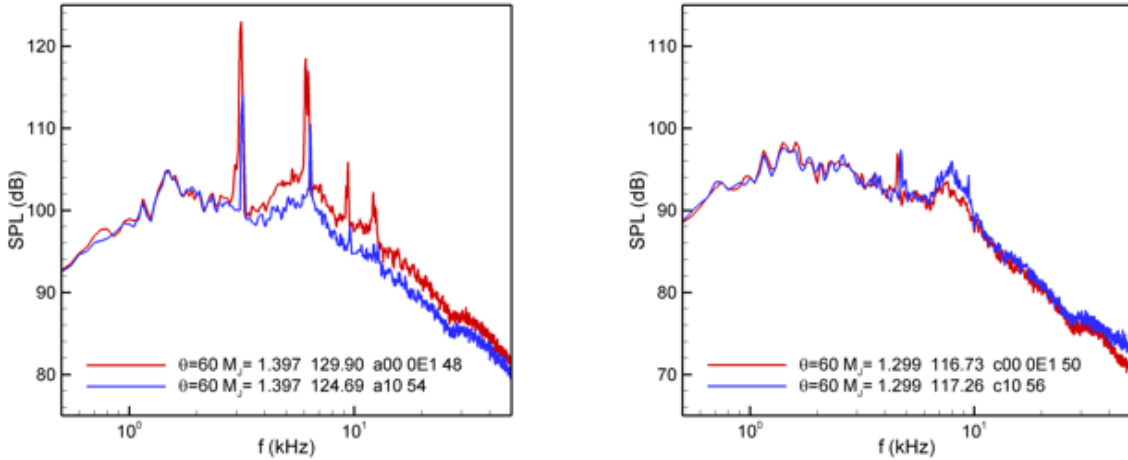


Fig. 36: Noise spectra for a.00 (red) vs a.10 (blue) at $MJ = 1.4$ (left), c.00 (red) vs c.10 (blue) at $MJ = 1.3$ (right).

The “switching” of porosity-induced effects on the shock diamonds, from advantageous to adverse, as MJ is increased, may be explained partially by the relative impact of competing effects changing at different rates as a function of MJ . For example, shock-shock interactions may lead to either constructive or destructive interference, strengthening or weakening the primary shock reflections [23]. In particular, weak shocklets generated from individual holes interact both with one another and with reflections from the cowl lip shock, potentially leading to constructive interference that amplifies shock strength and intensifies local flow disturbances. This interaction can lead to increased complexity in the shock structure, as overlapping shock waves merge, reinforcing each other and creating a more prominent, high-pressure shock front. As the jet Mach number increases, the likelihood and strength of such interactions rise, intensifying the pressure gradients and contributing to more pronounced shock-boundary layer interactions and downstream effects on the flow field. Additional complexity arises from factors such as the recompression shock forming at the plug tip and the transmission and attenuation of shocks through the separation-induced shear layer.

VII. Conclusions

This study investigates the potential of porous plug nozzles to reduce aircraft noise during landing and takeoff (LTO) conditions for low-bypass turbofan engines. Building on previous experiments and expanding the scope to cover a wide array of geometric configurations, this study uses Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) simulations to examine 31 porous plug nozzle designs across jet Mach numbers from 1.1 to 1.5. An automated mesh refinement (AMR) technique, known as Sketch-to-Solution (S2S), is employed to precisely capture complex and discontinuous flow features. The CFD results, combined with experimental testing of 15 subscale stereolithography-printed nozzles, reveal several noise-reduction mechanisms.

The primary mechanism at low jet Mach numbers, particularly relevant to LTO conditions, is a diminished Coanda effect. This reduction results in an expanding jet that has less tendency to adhere to the plug surface, effectively behaving as a less overexpanded jet. A secondary mechanism, induced by the primary effect, involves the destructive interference between porosity-induced shocklets and primary flow structures. As the Coanda effect weakens and the separation point shifts upstream, the radial extent of the internal shear layer increases, narrowing the effective jet core width. This shift alters the phase and relative strength of the shocks, enabling stronger shocks to traverse the internal shear layer while weaker ones reflect back into the jet, leading to increased shock interactions that may facilitate beneficial destructive interference between shock waves and fan structures.

However, the general noise characteristics of shocks in supersonic jets seem to diminish or negate the effects of plug porosity as the Mach number increases, a trend exacerbated by shorter plug lengths. Further research is necessary to determine the relative impact and magnitude of these isolated effects, as well as to identify mechanisms that can be optimized at LTO-relevant conditions to mitigate the community noise impact of commercial supersonic civil transport. Although RANS provides some insights into BBSN levels, a direct correlation between RANS indicators and nozzle noise levels remains unestablished. Existing RANS-based noise prediction methods for BBSN are primarily limited to free jets without nearby surfaces. Nonetheless, these methods could be adapted to predict noise changes resulting from modifications in shock cell persistence downstream of the plug, such as those influenced by porosity. Future research should focus on optimizing flightweight porous plug nozzle designs, enhancing correlations between high-fidelity AMR RANS CFD solutions and experimental noise measurements, isolating noise reduction mechanisms, and conducting studies at lower jet Mach values (0.98 to 1.1). Additional work is also needed on optimized designs and gas dynamics that are more relevant to landing and takeoff, including higher-fidelity noise measurements and tailored experimental testing.

VIII. Acknowledgements

Support for this work was provided by the NASA Commercial Supersonic Technology (CST) project. The authors extend their thanks to several individuals at NASA Glenn Research Center, including James Bridges for his continuing leadership and contributions to the original porous plug nozzle design, as well as Stewart Leib, Will Banks, Julie Dudek and Evan McFadden for their ongoing contributions, discussions, and advice. Special thanks also go to Bil Kleb from NASA Langley Research Center for his detailed and ongoing assistance with high-fidelity CFD and automated mesh refinement schemes, and to Lori Ozoroski for her support and oversight as the CST Project Manager.

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