

Flow and noise from supersonic plug nozzles

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Nozzles with external plugs are candidates for propulsion of future supersonic aircraft. A model-scale experimental study is conducted exploring the flow and noise characteristics of various plug nozzles. For a given outer nozzle, the plug geometry is varied from conic with various half-angles (lengths) to plugs designed by the method of characteristics (MoC) as well as truncated and porous plugs. So far, noise characteristics and schlieren flow visualization data have been acquired. Limited numerical simulations have also been done addressing thrust performance. The simulations show that the MoC plugs out-perform the conic cases, especially around high Mach number cruise conditions. The experimental data, however, show that the MoC plugs are noisy relative to the conic cases at low Mach number landing and takeoff (LTO) conditions. The increased noise (with MoC at LTO) is accompanied by unsteady turbulent structures and increased jet spreading, as seen in schlieren pictures. At LTO, the longest conic plug is found to be the least noisy. Furthermore, a porous surface on the long conic plug effectively suppresses broadband shock associated noise (BBSN) at higher Mach numbers. Thus, a dilemma remains. MoC design gives best thrust performance at cruise but it is noisy at LTO. A long conic plug, on the other hand, is quieter at LTO but may have unacceptable thrust at cruise.

I. Introduction

A review of plug nozzle research over the past eight decades was given recently in [1]. Early experimental studies established that the thrust coefficient of a plug nozzle can be as good as that achieved by full expansion of flow with a convergent-divergent (C-D) nozzle [2-7]. The fact that a plug nozzle could achieve as much thrust as a C-D nozzle, while offering advantages such as reduced hardware complexity, was attractive. Added to this was the attribute of 'altitude compensation'. A plug nozzle maintained the thrust at pressure ratios lower than design, a condition (overexpanded) that would occur at low altitudes. Comparatively, a C-D nozzle at low altitude suffered drastic thrust loss. These observations led to a flurry of studies in the 1950's and 1960's.

Soon it was found that an external stream had a detrimental effect on plug nozzle performance [5, 6, 8]. The design of an 'isentropic' plug involved a sharp inward bend of the outer cowl so that the 'throat' was placed at the exit. This caused low pressures over the bent surface of the cowl and large boattail drag. The problem was acute in transonic flow when an expansion fan occurred at the beginning of the bend exacerbating the low pressures. Furthermore, even though the plug nozzle offered advantages in terms of reduced design complexity and part count, it added weight and required cooling. These disadvantages dampened the initial enthusiasm. The drop in research in the 1970's is reflected by scant publications on the topic in the 1980's. The interest picked up again in the 1990's due to the advent of the Single Stage to Orbit (SSTO) program and its X-33 demonstrator that adopted the plug nozzle due to certain advantages [9, 1].

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Flow mechanisms and the altitude compensation attribute of plug nozzles were addressed in various publications [5, 9-11]; the reader may look up [1] for further discussion. Starting from a basic plug nozzle geometry, however, there was room for improvement. A gentle taper of the cowl minimized boattail drag. Hollow plugs not only saved weight but also allowed effective routing of coolant flow. The plug could be truncated to save weight. A truncated plug was found to perform well with minimal thrust loss [7, 12, 13]. Detailed geometries of the plug and the nozzle and their relative placement were critical for optimum performance. These aspects have remained topics of further research. CFD and optimization tools could help. Much of the research in the area since the 1990's has been numerical [e.g., 14-19]. Model-scale experiments could also provide valuable insight and guidance in designs. Examples of such experiments include Refs. [11, 20-22].

Another benefit of a plug nozzle is possible reduction in noise emission [23-26]. It is this potential that motivated the present study. The need for noise attenuation during landing and take-off of an aircraft remains a challenge. It is currently the focus of various research efforts including the 'Airport Noise' element of NASA's Commercial Supersonic Technology Project. The current study is being conducted in support of this Project.

Runkel [23] in early 1960's recognized the need for LTO noise attenuation without compromising cruise performance. A sea-level static test was conducted in the late 1960's comparing the noise characteristics of four candidate nozzles for supersonic vehicles [24]: (1) a 10° half-angle conical plug nozzle, (2) a variable flap ejector nozzle, (3) a variable-area convergent nozzle and (4) an auxiliary inlet ejector nozzle. At military power the sound power level was found to be the lowest with the plug nozzle; the other nozzles were louder in the order listed.

Noise reduction with plug nozzles was also noted by Stone et al. [25] with the comment, "the simplest way to achieve a small level of noise reduction is through the use of a plug nozzle." It was conjectured that the plug taper decelerated the jet and reduced the shear between the jet and the ambient and thereby reduced the noise. Data were provided for variations in the annular passage height of a plug nozzle and 1 to 2 EPNdB reduction was noted consistently over various operating conditions. Reference [26] also reported noise reduction in experiments with small-scale plug nozzles ($D_{eq}=0.89''$). Several plug cases were tested, at a nozzle pressure ratio (NPR) of 1.94, using helium to simulate high temperature. With a long plug, noise reduction was noted at all polar angles. At the given NPR there should not be significant shocks and thus the noise reduction must have been due primarily to a reduction of mixing noise. Authors attributed shielding and suppression of turbulence due to boundary condition imposed by the plug, as mechanisms for the reduction in the noise. Furthermore, they demonstrated that a shaped (flattened) plug produced asymmetric directivity which could be taken advantage of by placing the low noise side towards the observer.

From the review of literature it became apparent that for noise reduction with supersonic flows the focus should be on minimization of shocks, attempting to reduce shock associated noise. Porosity and other changes in the texture of the plug might offer further benefit besides shock minimization such as some absorption of noise generated in the shear layer.

In a novel effort, Maestrello [27] used porous plugs to demonstrate the possibility of noise reduction. He used plug-to-nozzle diameter ratios of 0.833 and 0.55 and the two cases had exit areas with equivalent diameters of 2" and 3", respectively. The plugs were 27" and 9.84" long and were hollow inside. Sound pressure spectral amplitudes reduced significantly with the plug cases relative to corresponding convergent nozzle cases. At NPR=3.04 there was screech with the convergent case; the plug suppressed them making the reduction in overall sound pressure level (OASPL) dramatic. At another NPR=3.72, there was no screech

yet significant OASPL reduction occurred due to suppression of broad-band shock associated noise (BBSN). Plugs with 2% porosity did better than plugs with 1.2% porosity.

Maestrello's work was followed up by a few investigations using porous plugs [28-30]. At McDonell Douglas Research Laboratories [28], tests were conducted with a 14% scale model of GE CF6-50 engine exhaust. Plug configurations, with a porosity ratio of 2.7%, yielded large OASPL reduction (e.g., over 7 dB at 90°, at NPR=2.2). While even higher reductions occurred at high NPR (some due to suppression of screech), minimal reductions were noted at subsonic conditions (NPR=1.6). The large noise reductions were accompanied by about 2% reduction in thrust coefficient. In a subsequent publication, Kibens and Wlezien [29] commented that the inward and outward flow through the holes on the plug surface reduced the pressure differentials and a self-correcting adjustment of the shocks occurred. The weakening of the shock cells led to the reduction in the noise.

Following the work of [27], the effect of porous plugs was also investigated at Syracuse University [30]. Relative to a solid conical plug, 2 to 3 dB noise reduction was noted with porous plugs. The noise characteristics of a short porous conical plug was found to be comparable to that of a solid MoC design plug. Interestingly, smaller (4%) porosity resulted in a better noise reduction than larger (10%) porosity. With 10% porosity, closely spaced shocks, originating from the pores and visible in the schlieren data, apparently led to an increased noise.

Unfortunately, in all work with porous plugs cited above, sometimes screech tones occurred that made it difficult to assess actual reduction in mixing noise and broadband shock associated noise. The latter noise components are of interest in typical applications since screech tones seldom occur in large-scale practical jets. Many questions remain unanswered about the efficacy of the porous plugs. Kibens and Wlezien [29] advocated for more data to determine if porosity per se led to flow modification or the size and distribution of surface holes played a role in weakening the shock cells to cause the noise attenuation.

Unanswered questions and potential for improvements in thrust and reduction in noise with basic plug nozzles provided the motivation for the present study. It is a fundamental study conducted in a relatively small facility with a simple configuration where parameters could be varied easily. For a given nozzle a multitude of plug geometries was explored. The ongoing effort involved close collaboration with numerical simulations by colleagues. Key results obtained so far, on noise and flow field characteristics, are presented in the following.

II. Experimental Facility

The experiments are conducted in an open jet facility at NASA Glenn Research Center (GRC), which is shown in Fig. 1(a). Compressed air passes through a 30" diameter plenum chamber before exhausting through the nozzle into the ambient of the test chamber. Further description of the facility may be found in earlier publications, e.g., [31, 32]. Overhead microphones (Fig 1a) are used to measure radiated noise. The test cell is not fully anechoic; however, relative variations in the noise spectrum with variation of parameters can be evaluated. This proved to be valid for identifying various acoustic phenomena on many occasions in the past. (That is, phenomena first identified in this facility were confirmed later by accurate noise measurements in acoustically cleaner facilities, e.g., in [32]). In this paper all noise data presented pertain to a microphone location of 90° to the jet axis from the nozzle exit.

The plug nozzle is attached to the end of the plenum chamber. A cross-sectional view of the nozzle assembly is shown in Fig.1(b). In the experiment, the nozzle remains fixed. It is convergent with 2" exit diameter (D) hav-

ing a lip thickness of 0.050". The center plug is held with X-shaped struts. The strut leading edges have serrations to suppress possible resonances induced by vortex shedding [31]. The upstream cylindrical part of the plug has a diameter of 0.75". A threaded rod fixed to the cylindrical part is used to attach the plug end pieces, facilitating various plug geometries. Also, spacers placed at the junction between the end piece and the cylindrical part allow for variation of the axial location (Δx) of the plug crown relative to the nozzle lip (Fig. 1b).

Three conical plugs with half angles of 10°, 16° and 22° (denoted as 'P10', 'P16' and 'P22') are shown in Fig. 1(c). Also shown are two plugs designed by the method of characteristics (MoC) – one pointed (denoted as 'MOC') and another truncated (denoted as 'MCT'). The approximate MoC method given in Ref. [33] is used to design these plugs; the MoC designed portion of these two plugs are shown in Fig. 1(d). The diameter at the starting point (throat) of the calculated contour was taken as 1.50". It turns out that this diameter and the length of the plug, for a given nozzle, are dictated by the design Mach number. In order to obtain the specified starting diameter (1.5"), with the 2" nozzle, the design Mach number for the pointed and truncated plugs had to be 2.036 and 1.978, respectively. On the upstream end, the plug contour was faired up to a crown diameter of 1.54" before fairing it down to 0.75" diameter to match the upstream cylindrical part. The downstream base diameter of the truncated plug is 0.5".

All porous plugs were fabricated by additive manufacturing process (3D print). Five of the porous plugs are shown in Fig. 1(e). The notations and general characteristics of several plugs are listed in Table 1; additional plugs not listed will be described with the data. Figures 1(f) and (g) show CAD drawings for the exterior and the interior of the PRS6 porous plug (it corresponds to the solid P10 case). The pore pattern, 28 rows of pores, each 0.037" diameter, cut on the 0.063" thick skin can be seen in the exterior view. The interior view, with the pores suppressed for clarity, shows crossed-shape struts that support the skin. The hollow interior is divided into four compartments that do not communicate with one another. The openness ratio for the PRS6 plug is 6% of the total surface area of the conical portion. The number of pores, pattern as well as pore size are varied to achieve specific openness ratios with other porous plugs (Table 1). In one set of experiment, only a few rows of pores with the PRS6 case, just downstream of the crown, were left open while the rest were closed with cellophane tape. The tape had to be wrapped carefully and its intactness was checked at end of data acquisition.

All plugs used in this study have a nominal crown diameter of 1.54". Some of the 3D printed porous plugs turned out to have slightly larger crown diameter of 1.55". Note that the annular gap width between the plug and the nozzle (throat) depends on the axial location of the crown. The average gap width for most of the cases discussed in the following was roughly the same, yielding an equivalent diameter of about 1.28". All plugs, after installation, were also found to have some non-concentricity relative to the nozzle exit; the gap width variation in the azimuthal direction was typically 5% and was different for the different plugs. These differences are thought to have minimal effect on the results presented in the following.

With supersonic flow the plug nozzle often involved screech tones that made comparisons of the sound pressure level spectra difficult. Various techniques were tried to suppress screech and eventually two triangular shaped 'delta tabs' were found most effective. Each tab had 0.175" base width, with 90° angle at the apex, and placed at 45° to the streamwise direction. A picture of the nozzle with the two tabs, placed on diametrically opposite sides, is shown in Fig. 1(h); the total area blockage due to the tabs was about 0.9% of the annular exit area. In the results section, data are first presented without the tabs but the rest of the data starting with Fig. 7 are for the tabbed configuration.

The primary diagnostic used for the flow field is schlieren flow visualization. A dedicated focused schlieren system exists with the facility (Fig. 1a). The microphone data acquisition is done using National Instruments A/D card and Labview™ software. Sound pressure level spectral analysis is done typically over 0-50kHz with

a bandwidth of 50 Hz, using a data rate of 100 kHz and a 50 kHz low-pass filter. The nozzles were tested with unheated air, varying the plenum pressure ratio. As the onset of broadband shock-associated noise is a critical component of jet noise, the jet Mach number is the defining parameter of the problem, with LTO conditions likely to be slightly below $M_j = 1$ and cruise conditions to be closer to $M_j = 2$. The jet Mach number is defined based on the plenum pressure, p_o , and the ambient pressure, p_a , and given by,

$$M_j = \left(\left(\frac{p_o}{p_a} \right)^{(\gamma-1)/\gamma} - 1 \right)^{1/2}, \text{ where } \gamma \text{ is the ratio of specific heats for air. As all data were acquired}$$

with unheated flow, the total temperature was the same everywhere as in the ambient. Note also that all data are for 'static' conditions without the presence of an external flow.

III. Results

3.1 Effect of plug shape: In Fig. 2, sound pressure level (SPL) spectra are presented for the MOC and the P16 plugs, while varying the crown location. Data for two jet Mach numbers (M_j) are shown as indicated. By using combinations of spacers, the crown location Δx (Fig 1b) is varied from -0.30" (upstream) to 0.20" (downstream) relative to the nozzle exit. For both plugs the upstream locations of $\Delta x = -0.30''$ and $-0.18''$ yield minimum noise levels while a substantial increase in the levels occurs as the plug is drawn downstream. In the legends of this and subsequent figures the values M_j and overall sound pressure level (OASPL, dB) are listed in the last two columns. At higher supersonic conditions the data are found to involve screech tones.

By comparing the data in Figs. 2(a) and 2(c), it is noted that the amplitudes are generally larger for the MOC case relative to the P16 case. This is demonstrated clearly in Fig. 3 by direct comparison of the data, for $\Delta x = -0.18''$. At the lower M_j 's of 0.9 and 1.10 (LTO conditions), the MOC is clearly noisier with an OASPL difference of about 5 dB. At the highest M_j , as cruise condition is approached, the trend reverses and the broadband noise levels for the MOC case become less. However, the occurrence of screech makes the comparisons difficult.

Schlieren flow visualization pictures are compared for the MOC and P16 cases in Fig.4, for the same M_j values of Fig. 3. One finds that the flow for the MOC case, at lower M_j 's, is marked by larger scale turbulent structures and a faster jet spread. The root cause possibly traces to unsteady shock motions. The flow here is overexpanded. This is similar to observations made in [32] with C-D nozzles. Overexpanded flows from C-D nozzles also lead to 'excess broadband noise', due to unsteady shock motions. At the highest M_j ($=1.61$), the flow field has less spread for the MOC plug. This is accompanied by less or comparable broadband spectral levels relative to the P16 case (Fig. 3d).

Figure 5 compares SPL spectra for different plug shapes, at two values of M_j ; for most cases data at several M_j were obtained, however, only few cases are shown for brevity. At $M_j = 0.9$, again one finds that the MOC and MCT cases have higher noise levels. The three conic plugs (P10, P16 and P22) behave similarly. At the higher M_j ($=1.38$) the data are beset with screech tones making the comparisons difficult. At this point an effort was undertaken to get rid of the screech so that meaningful comparisons could be made for the broadband noise. Eventually, two triangular tabs proved to be effective without significant blockage (see section 2, Fig. 1h). The effect of the tabs in eliminating screech tones is demonstrated in Fig. 6 for three plug cases at two M_j . Apart from screech, BBSN spectral peaks (around 10 kHz) are also altered although not eliminated. Unfortunately, screech was not suppressed for all plugs at all M_j ; such cases will be either avoided or pointed out in the following.

The SPL spectra for the tabbed jets are now compared for four plugs at four values of M_j in Fig. 7; (hereon, all data pertain to cases with the two tabs.) The MOC plug still exhibits high noise levels at LTO conditions ($M_j = 0.9$ and 1.10); the MCT plug produced some screech even with the tabs and are not shown for clarity. Among the four cases in Fig. 7, overall, the longest conic plug (P10) is found to have the least noise levels although differences with other conic cases are not large.

3.2 Effect of plug porosity: The effect of plug porosity is now examined. As stated in the Introduction porous plugs in earlier works [27-30] often involved screech tones that cast doubt on the benefit of the porosity. Note that the presence of screech not only adds to the noise by itself but also may cause an increase in the broadband levels. Here, by using the two tabs screech tones are practically suppressed making it easy to study the relative effects on the broadband levels. Figure 8 compares SPL spectra for the solid and porous versions of the P16 plug. The porous case (PRS2, second from left in Fig. 1e) has 0.037" diameter pores having a total openness ratio of 6%. The pores communicate with the four quadrants of the hollow interior (Fig. 1g). Data for four values of M_j are shown in Fig. 8. At the lowest M_j ($=1.10$) there is hardly any effect of porosity. However, at higher values of M_j there is a clear change in the spectral levels, the most significant being at $M_j = 1.38$. BBSN-like spectral components (around 10 kHz and above) are significantly reduced leading to a drop in OASPL by 3.9dB. At higher M_j 's there is similar effect but not as pronounced.

Schlieren pictures corresponding to three cases of Fig. 8 are shown in Fig. 9 (these are time-averaged pictures that seemed to show the shocks more clearly). It is apparent that the shocks in the porous case are altered over the plug. At $M_j = 1.38$ the shocks are seen 'splintered' into multiple cells apparently caused by the pores. A similar observation was made in [30]. BBSN is generated by reinforcement of noise originating from the interaction of a turbulent structure with successive shock cells. This reinforcement is apparently disrupted with the splintered shock cells. This might have partially led to the reduction in BBSN. However, with splintering of shocks by large pores in Ref. [30] there was an increase in noise instead (a similar effect with the MOC case is discussed shortly). Note that the shocks at the higher M_j 's (Fig. 9) are somewhat weakened downstream. There is also flow in and out of the hollow interior. Both these factors may have contributed to noise reduction, however, the full mechanism remains from clearly understood.

Porosity effect on the P10 plug is shown in Fig. 10. So far, the best noise reduction with porosity was observed with this plug. Spectral data are presented for six values of M_j . The porous case (PRS6) involved 0.037" diameter pores with 6% openness. More than 5.5 dB reduction in OASPL has taken place at $M_j = 1.38$ and 1.43 . The reduction is achieved by suppression of BBSN-like components in the spectra. Corresponding schlieren pictures for a few M_j are shown in Fig. 11. The splintering of the shock cells in the porous case is more conspicuous here. There is also a dramatic reduction in shock strength for the porous case in the mid- M_j range. These factors must have contributed to the observed noise reductions. The OASPL reduction, as a function of M_j , is captured in Fig. 12. In the entire supersonic regime there is significant reduction, the largest occurring in the M_j range of $1.2 - 1.5$.

Corresponding porosity effect data for the MOC plug is shown in Fig. 13. There is a mild reduction in the spectral levels at the lower Mach numbers. There does not appear to be any effect at $M_j = 1.43$ and, somewhat surprisingly, there is an adverse effect at the highest M_j (1.61). It is unclear why the noise increases. Recall the data of Ref. [30] discussed earlier. Somehow the alteration of the shock cells here caused a reinforcement to accentuate BBSN. It appears that the shock strength downstream is somehow enhanced by porosity in this case, as seen in the schlieren pictures of Fig. 14. The shocks downstream of the plug tip, especially at $M_j = 1.38$, appear enhanced relative to corresponding solid cases on the left.

For the P16 and P10 cases, the porosity was varied systematically. The pore diameter was varied keeping the openness ratio the same. On the other hand, for same pore diameter the openness ratio was varied by varying the number of pores. SPL spectra for various porosity at $M_j = 1.38$ are shown in Figs. 15(a) and (b) for P16 and P10 cases, respectively. For the porous plugs, pore diameter (inches), openness ratio (%) and OASPL are listed in the legend of each figure. It should be apparent that for either case, the 0.037" pores with 6% openness ratio resulted in best noise reduction. The difference in the effectiveness due to the pore geometry is quite pronounced in the P10 case.

One other exploration was done with the porous plugs. It was speculated that perhaps, only a portion of the plug, such as near the crown (where the shock strength is maximum) needed to be porous to produce the effect. This was explored with the PRS6 plug. Cellophane tape was wrapped to block off all pores downstream while leaving only a few rows open near the crown. Data for 3- and 6-rows open are compared with all-open and the solid cases (Fig. 16.) Results for two values of M_j are shown. An inspection reveals that all pores need to be open for effective noise reduction. Leaving only 3 or 6 rows open is not anywhere near as effective. For example, at $M_j = 1.38$, while OASPL is reduced by 5.79 dB with all pores open, the reduction is only 1.36 and 2.26 dB with 3- or 6-rows open, respectively.

3.3 Preliminary numerical studies: Numerical studies were performed earlier for the solid plug geometries and reported in Ref. [1]. An important set of results is shown in Fig. 17. The plug geometries, shown in Fig. 17(a), are the same as in this experiment (There is a truncated P10 case for which experimental noise data have not been acquired). The thrust coefficient results are shown in Fig. 17(b) as a function of M_j . Two-dimensional axisymmetric simulations were performed using 'Ansys Fluent', a finite-volume unstructured Reynolds-Averaged Navier-Stokes solver. The results show that the MoC plugs clearly perform better over a wide range of M_j relative to the conic cases. A similar result was reported in [15]. The difference in Fig. 17 is especially pronounced around the design Mach number (≈ 2) and above. Note that the truncated plug designed by MoC had thrust performance just as well as the corresponding pointed one. The conic case with the smallest half-angle (P10) has performed the worst.

Limited and independent calculations by colleagues (Jonathan Burt using 'FUN3D' software, private communication, and by the third coauthor using 'Solidworks' flow solver) agreed with the trends shown in Fig. 17(b). Furthermore, a preliminary numerical study was conducted by Jonathan Burt with the porous plugs. With the internal flow through the plug cavity the porosity is expected to incur thrust loss. The simulation with the PRS6 configuration at $M_j = 1.38$ showed a loss in thrust coefficient by about 0.5%. Thus, the 5.8dB OASPL reduction came at the expense of 0.5% loss in thrust coefficient. The results need confirmation and further exploration over wider parametric ranges. These numerical results, together with experimental confirmation of thrusts, will be reported in the future.

Thus, we have a conflicting result at hand. The P10 case (especially the porous version) does best in terms of noise characteristics at LTO conditions; however, its thrust performance at cruise is compromised and likely unacceptable. The MoC designs considered herein, on the other hand, have the best thrust coefficient around cruise but they are noisy at LTO conditions. Various adaptive (variable) plug geometries are being explored currently to maintain low LTO noise while not compromising cruise thrust. So far this has been a challenge.

IV. Conclusions

A model-scale experimental study was conducted exploring the flow and noise characteristics of various plug nozzles. Plug geometries explored includes conic plugs with various half-angles (lengths), plugs designed by the method of characteristics (MoC), plugs that are truncated, as well as porous plugs. So far,

noise characteristics and schlieren flow visualization data have been acquired. From these static measurements the following observations are made:

- (1) The plug crown needs to be located somewhat upstream of the nozzle exit for least noise. For the given nozzle, a crown location of $\Delta x \approx -0.1D$ relative to the nozzle exit appears to work best. This is observed with a 16° conic as well as an MoC plug. When the crown is placed at or downstream of the nozzle exit the flow is noisier.
- (2) The MoC plug is noisier relative to conic cases at low Mach number (LTO) conditions. Schlieren pictures show that the flow for the MoC is characterized by large-scale turbulent structures and a faster jet spread.
- (3) With screech tones suppressed by tabs, the longest conic case (10° half angle) is found to be the least noisy among the various plugs over most of the Mach number range covered in the experiment.
- (4) Porous plugs suppress BBSN-like spectral components at supersonic conditions. This is true especially for the 10° conic case; OASPL is reduced by over 5dB. Noise suppression by porosity is insignificant at LTO conditions and appears to diminish also as cruise condition is approached.
- (5) Intermediate size pores with about 6% total surface openness ratio yielded the best noise suppression with the conic cases. Smaller or larger diameter pores as well as smaller or larger openness ratio yielded poorer noise suppression.
- (6) Preliminary CFD results for the best suppression case with the 10° conic plug show that a 5.8dB OASPL reduction comes with about 0.5% penalty in thrust coefficient.
- (7) CFD results suggest that the MoC plug outperforms any of the conic plugs in terms of thrust performance, especially near cruise condition. Thus, an MoC design appears to be the best for supersonic aircraft concepts since thrust at cruise is of prime importance. Unfortunately, as stated in item 2 above, the MoC plug is noisy around LTO conditions. Thus, a successful plug geometry may have to be adaptable, i.e., variable between the two shapes depending on the flight condition. In the model-scale experiments implementation of this so far has proven to be a challenge.

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Table 1 Plug geometry.

Notation	Description	Tip	Porosity
P10	Conic	10° half angle	Solid
P16	Conic	16° half angle	Solid
P22	Conic	22° half angle	Solid
MOC	MoC design $M_D=2.036$	Pointed tip	Solid
MCT	MoC design $M_D=1.980$	Truncated	Solid
PRS1	Conic	16° half angle	Porous 0.020" pores 6% open
PRS2	Conic	16° half angle	Porous 0.037" pores 6% open
PRS3	Conic	16° half angle	Porous 0.070" pores 6% open
PRS4	Conic	16° half angle	Porous 0.050" pores 3% open
PRS5	Conic	16° half angle	Porous 0.024" pores 12% open
PRS6	Conic	10° half angle	Porous 0.037" pores 6% open
PRS7	Conic	22° half angle	Porous 0.037" pores 6% open
PRS8	MoC design $M_D=2.036$	Pointed tip	Porous 0.032" pores 6% open

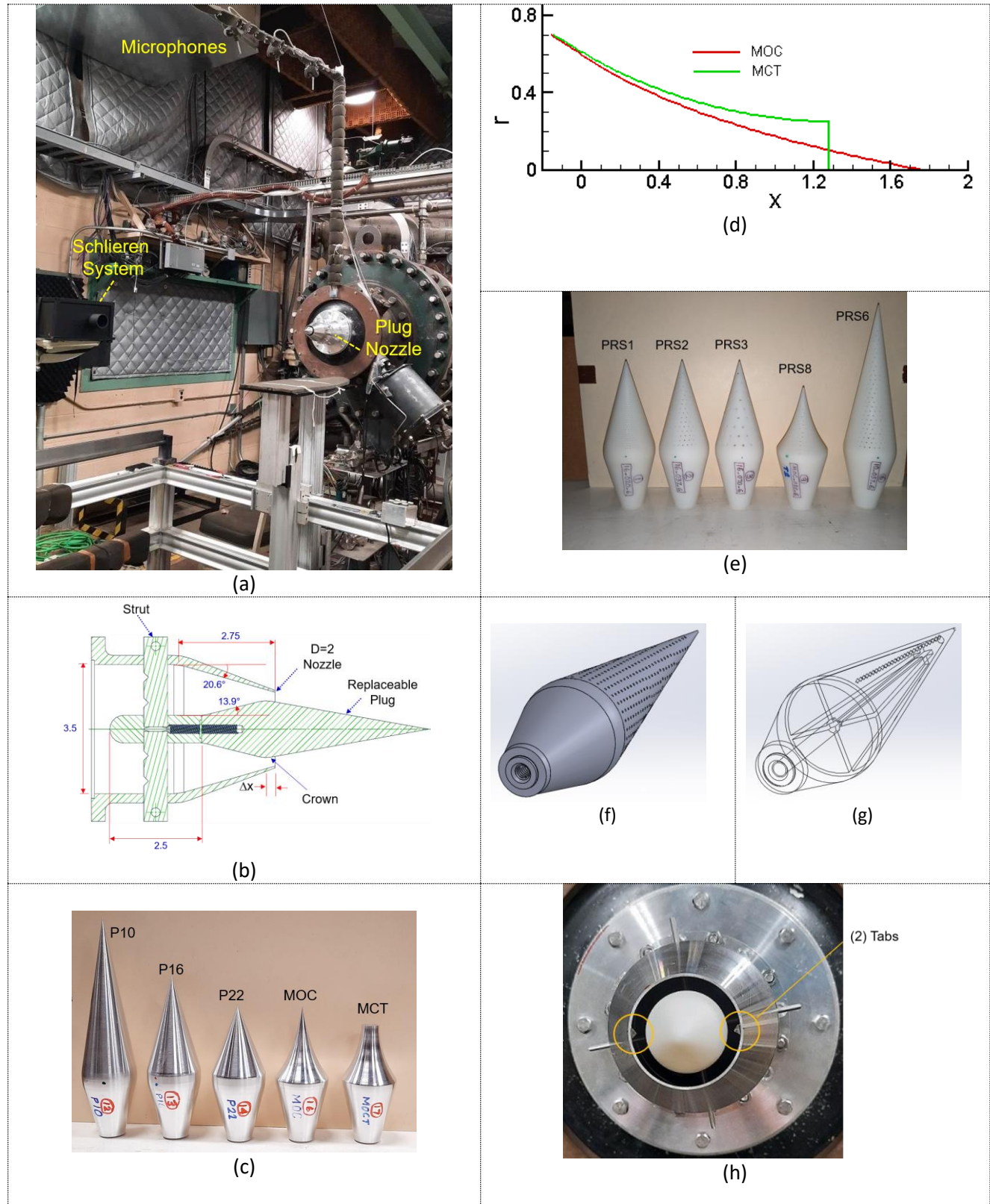
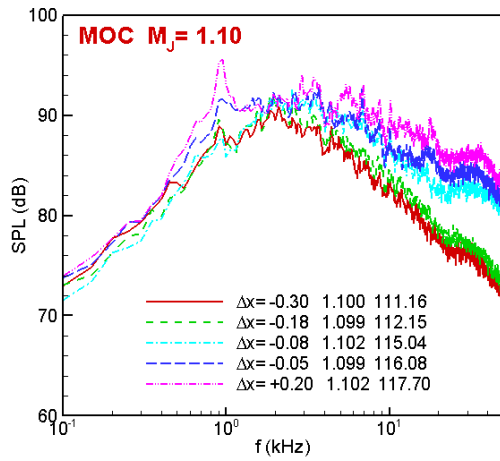
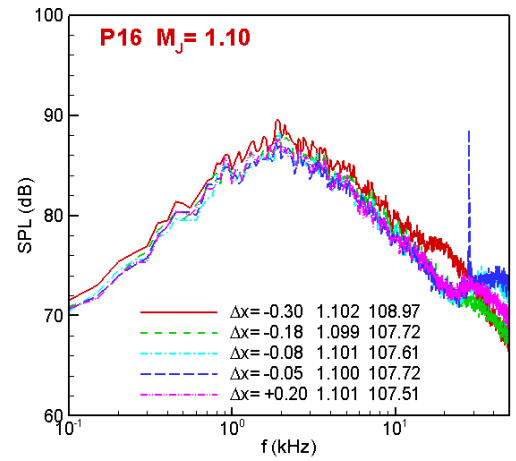


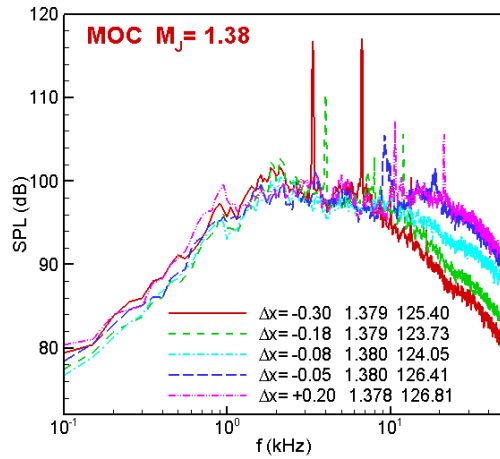
Fig. 1 Experimental Facility. (a) Picture of jet rig, (b) drawing of plug nozzle, (c) picture of several solid plugs, (d) contours of MOC and MCT plugs, (e) picture of several porous plugs, (f) CAD drawing of PRS6 exterior, (g) CAD drawing of PRS6 interior, and (h) picture of nozzle fitted with two tabs.



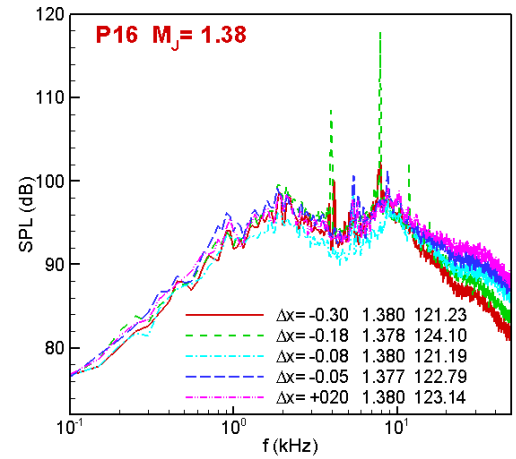
(a)



(c)

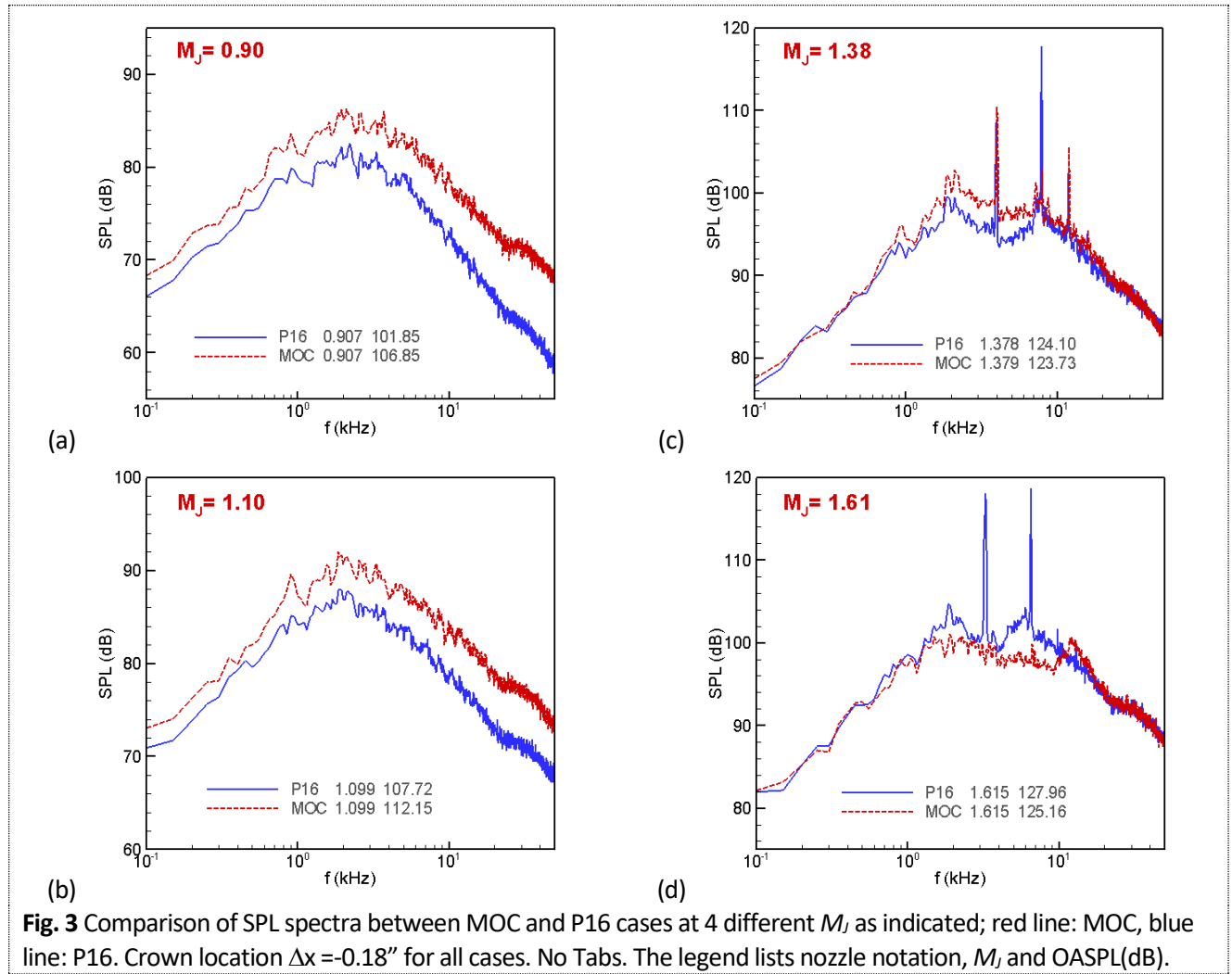


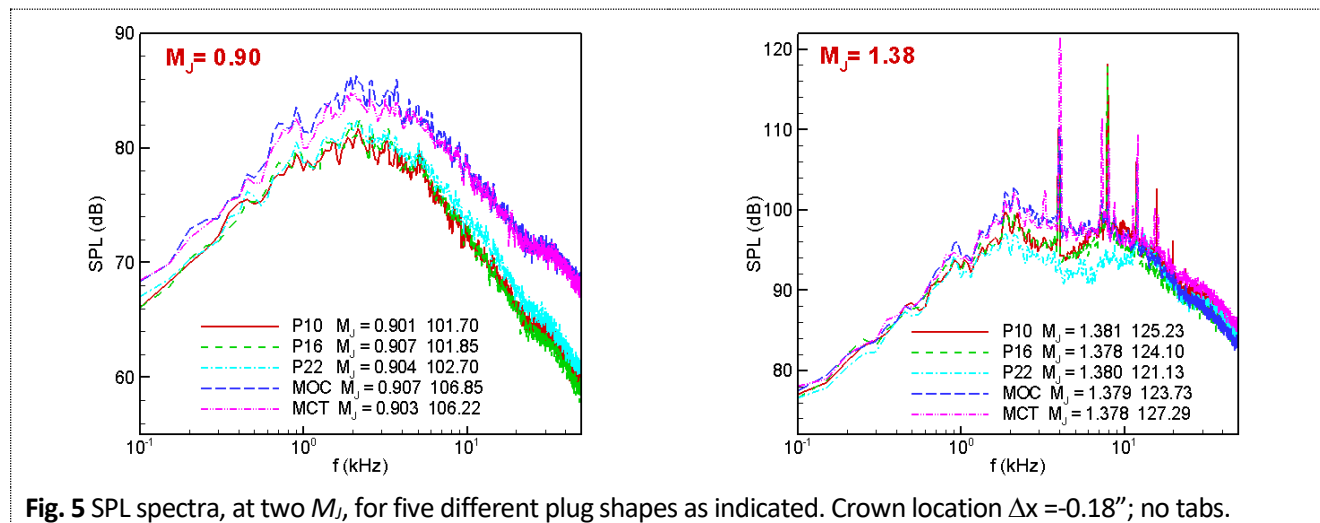
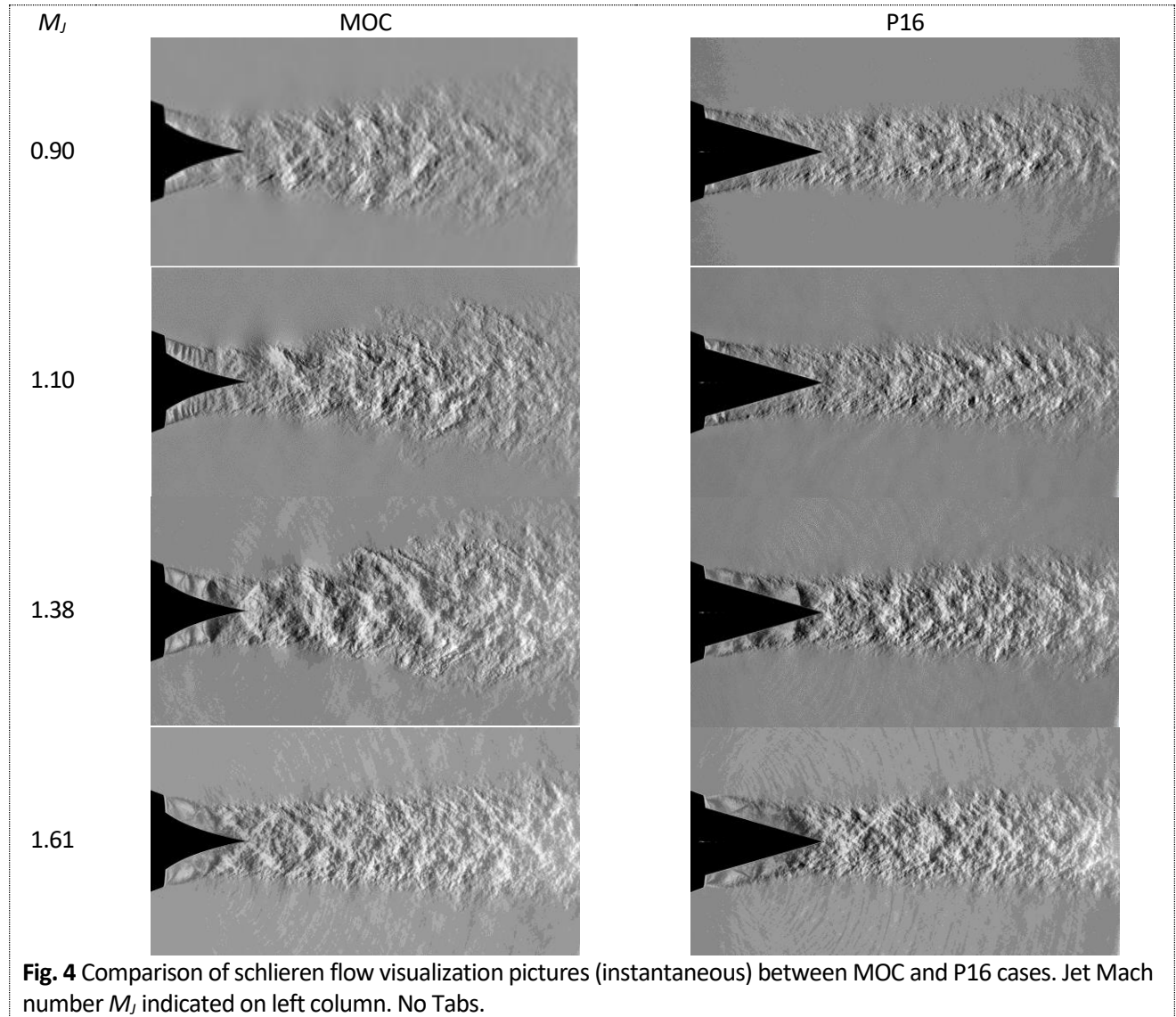
(b)



(d)

Fig. 2 Sound pressure level (SPL) spectra for varying crown location Δx (Fig. 1b); Δx , jet Mach number M_j and OASPL (dB) shown in legend. (a), (b): data for MOC case; (c), (d): corresponding data for P16 case. No Tabs. The legend lists Δx , M_j and OASPL (dB).





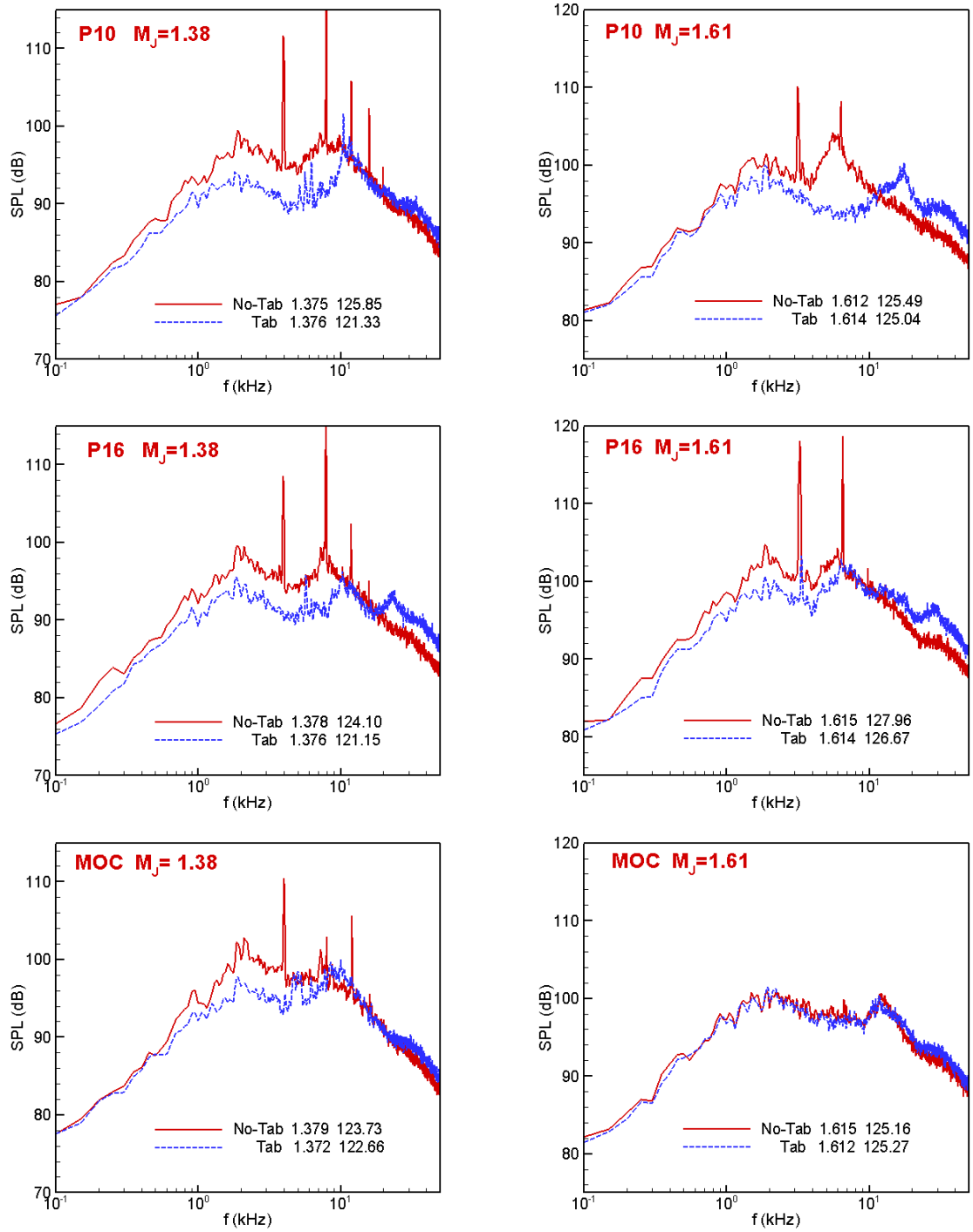
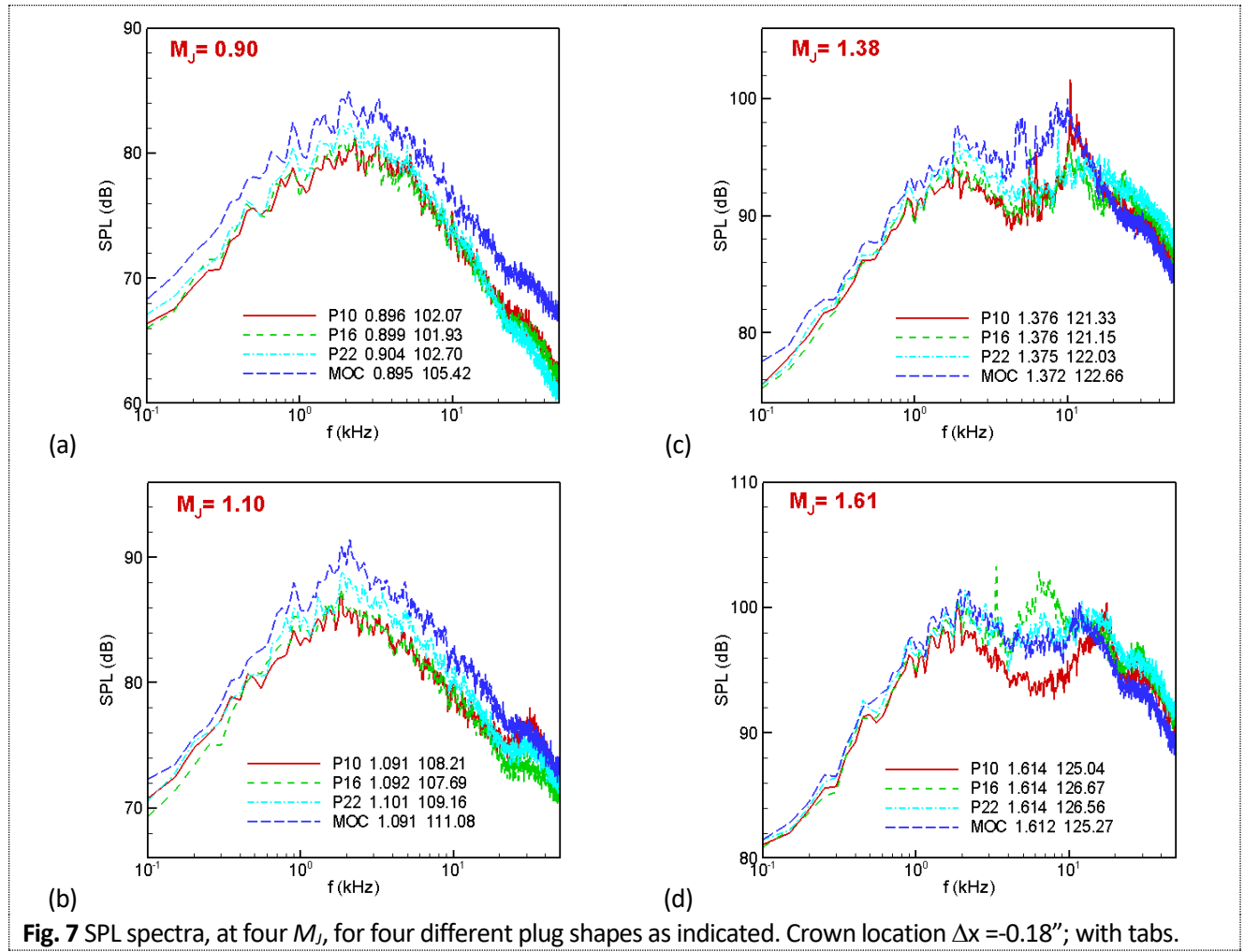
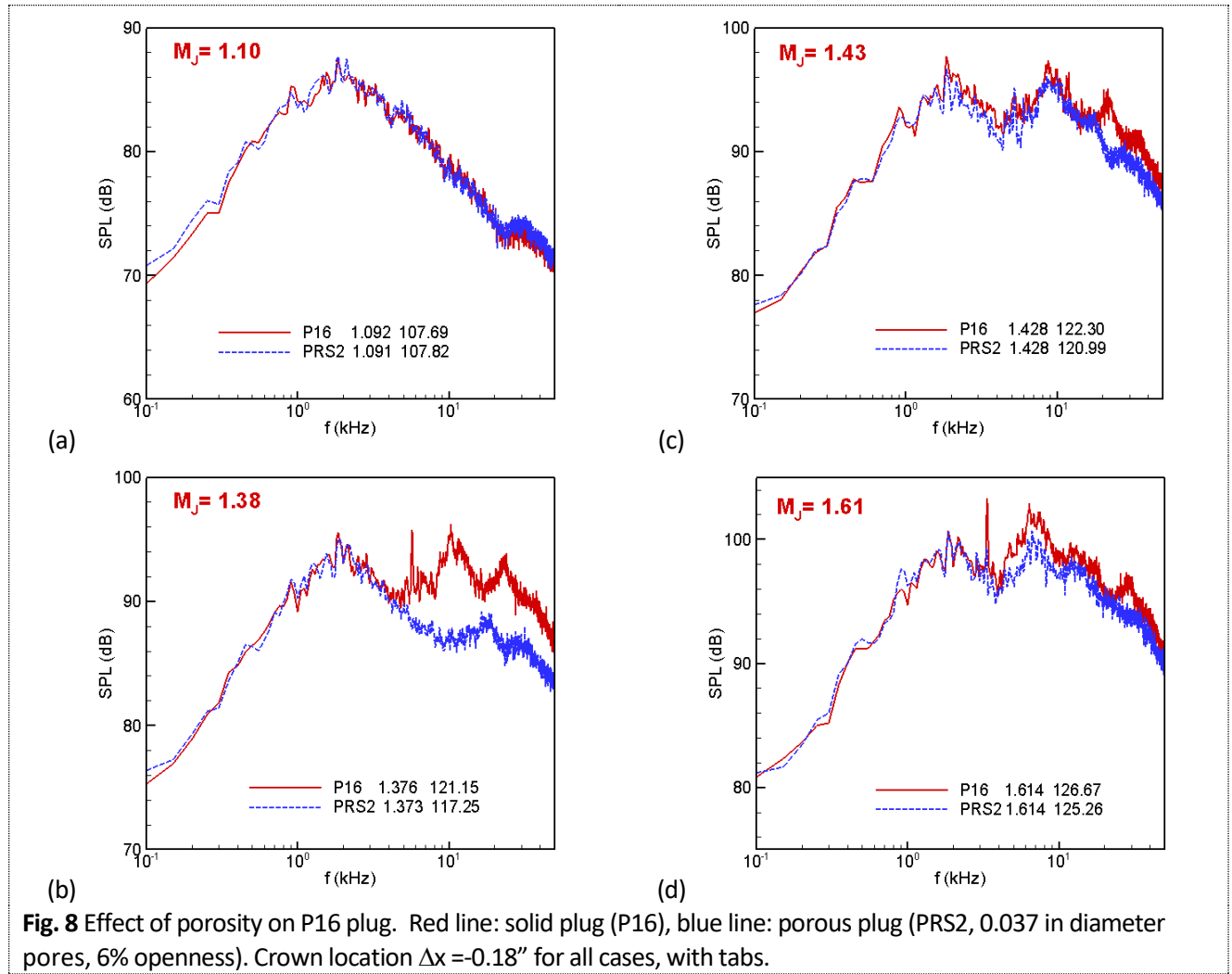
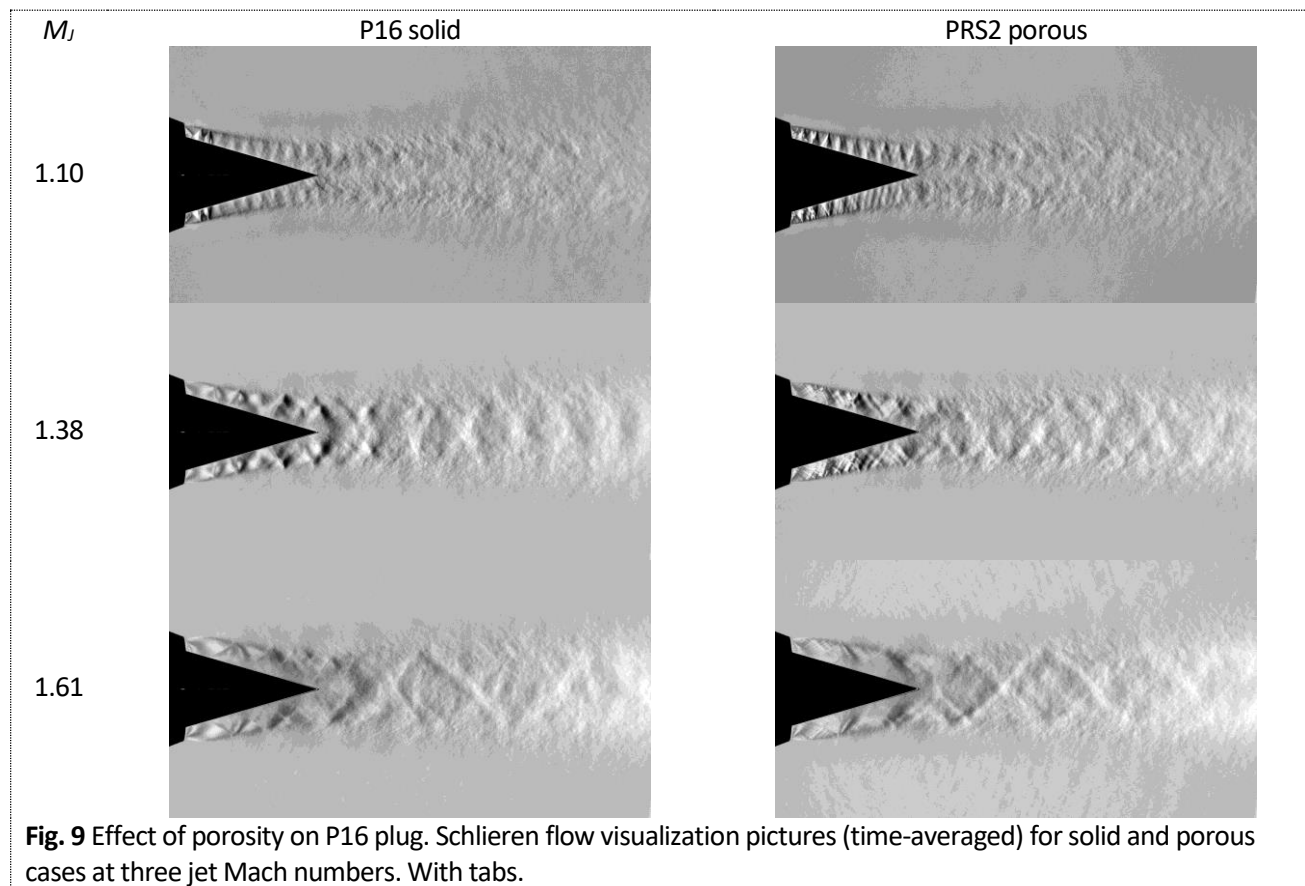


Fig. 6 SPL spectra with and without tabs (Fig. 1c) for three different plugs at two jet Mach numbers; red line: without tabs, blue line: with tabs.







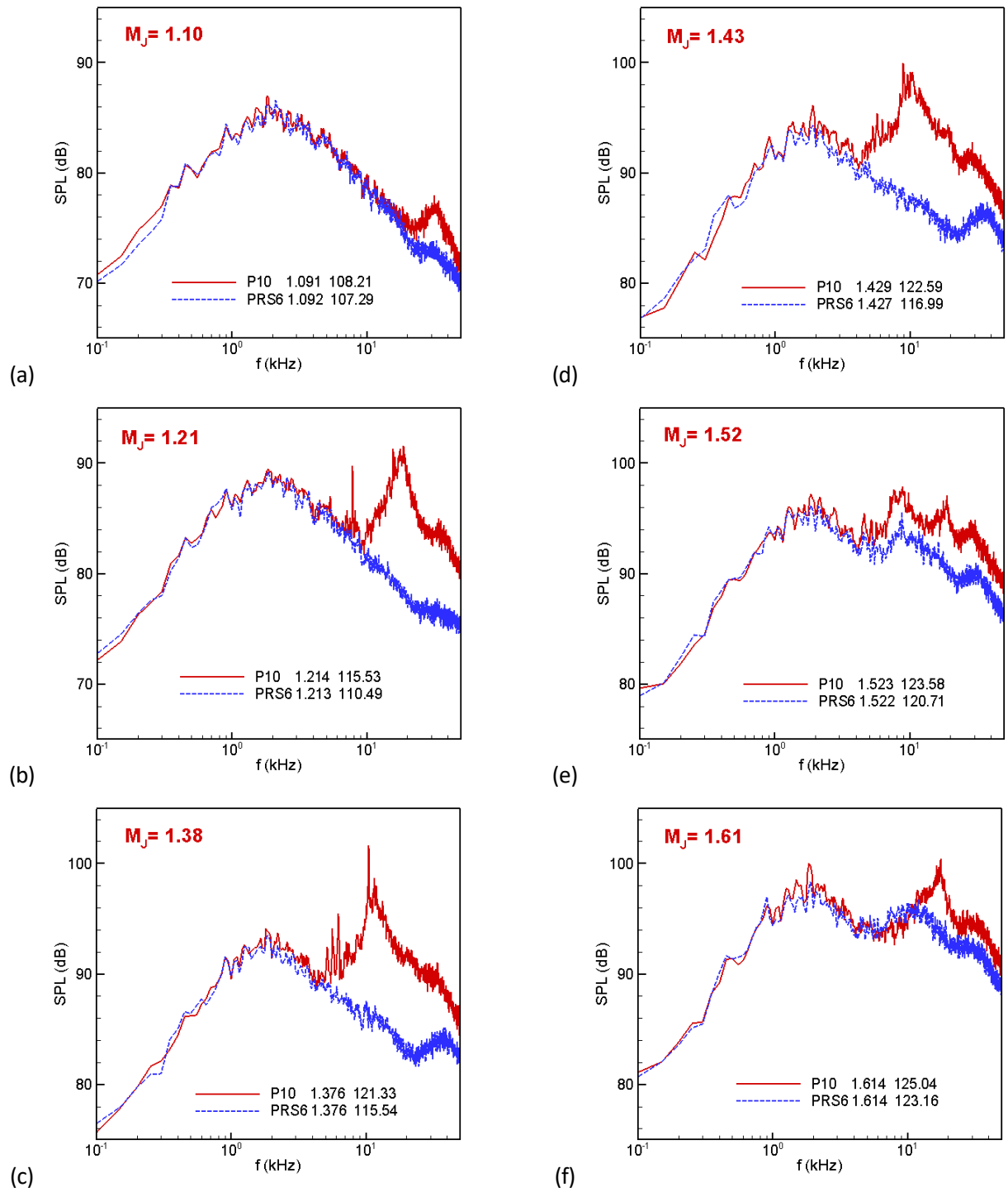


Fig. 10 Effect of porosity on P10 plug. Red line: solid plug (P10), blue line: porous plug (PRS6, 0.037 in diameter pores, 6% openness). Crown location $\Delta x = -0.18''$; with tabs.

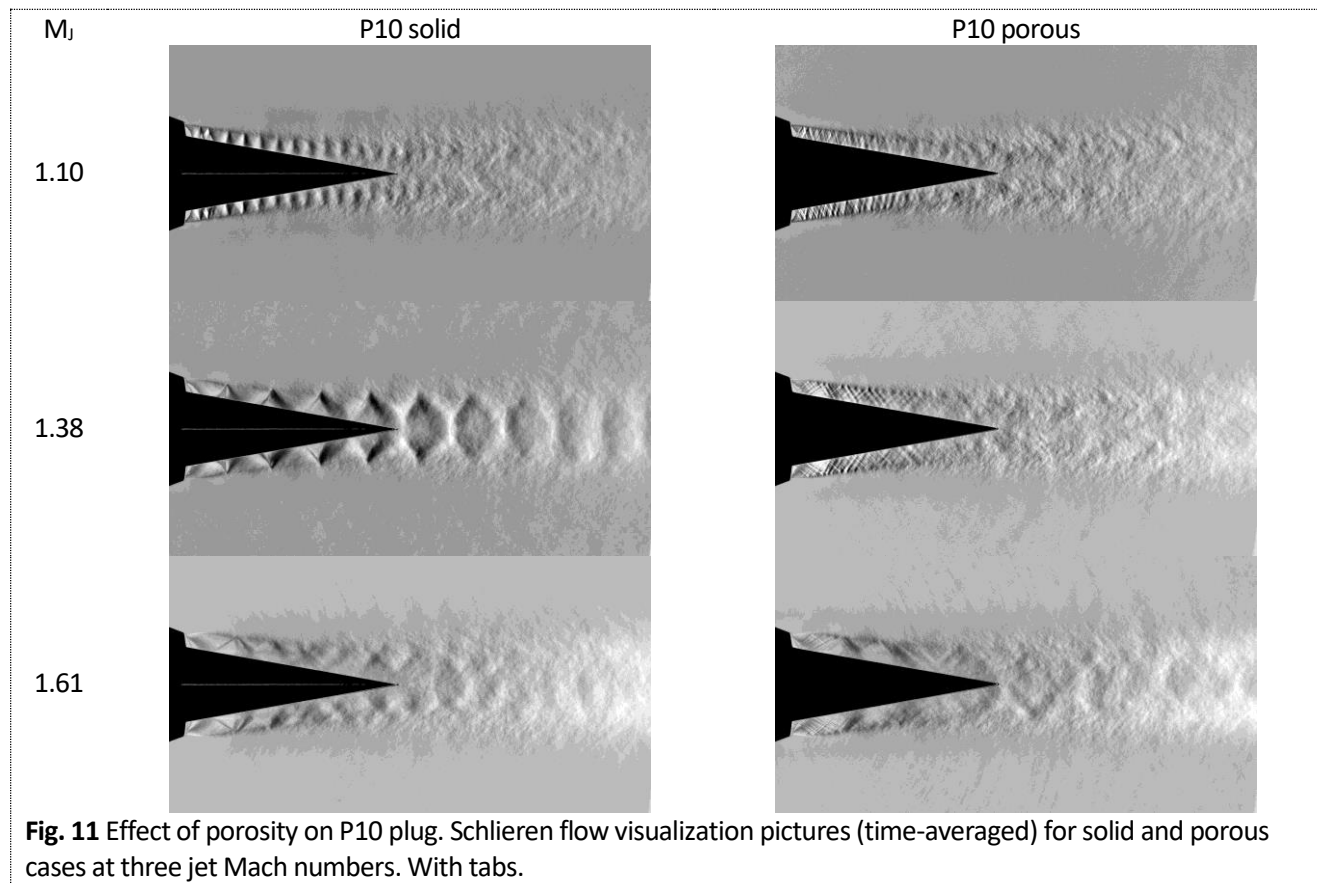


Fig. 11 Effect of porosity on P10 plug. Schlieren flow visualization pictures (time-averaged) for solid and porous cases at three jet Mach numbers. With tabs.

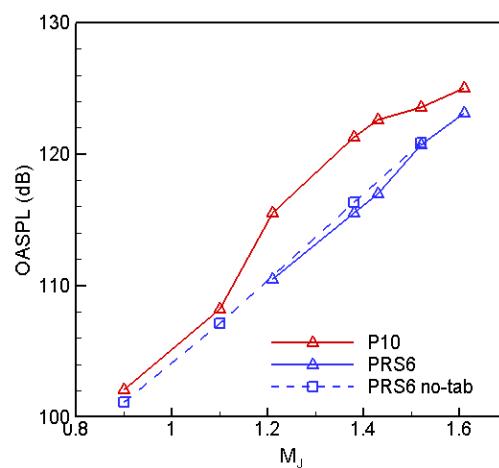
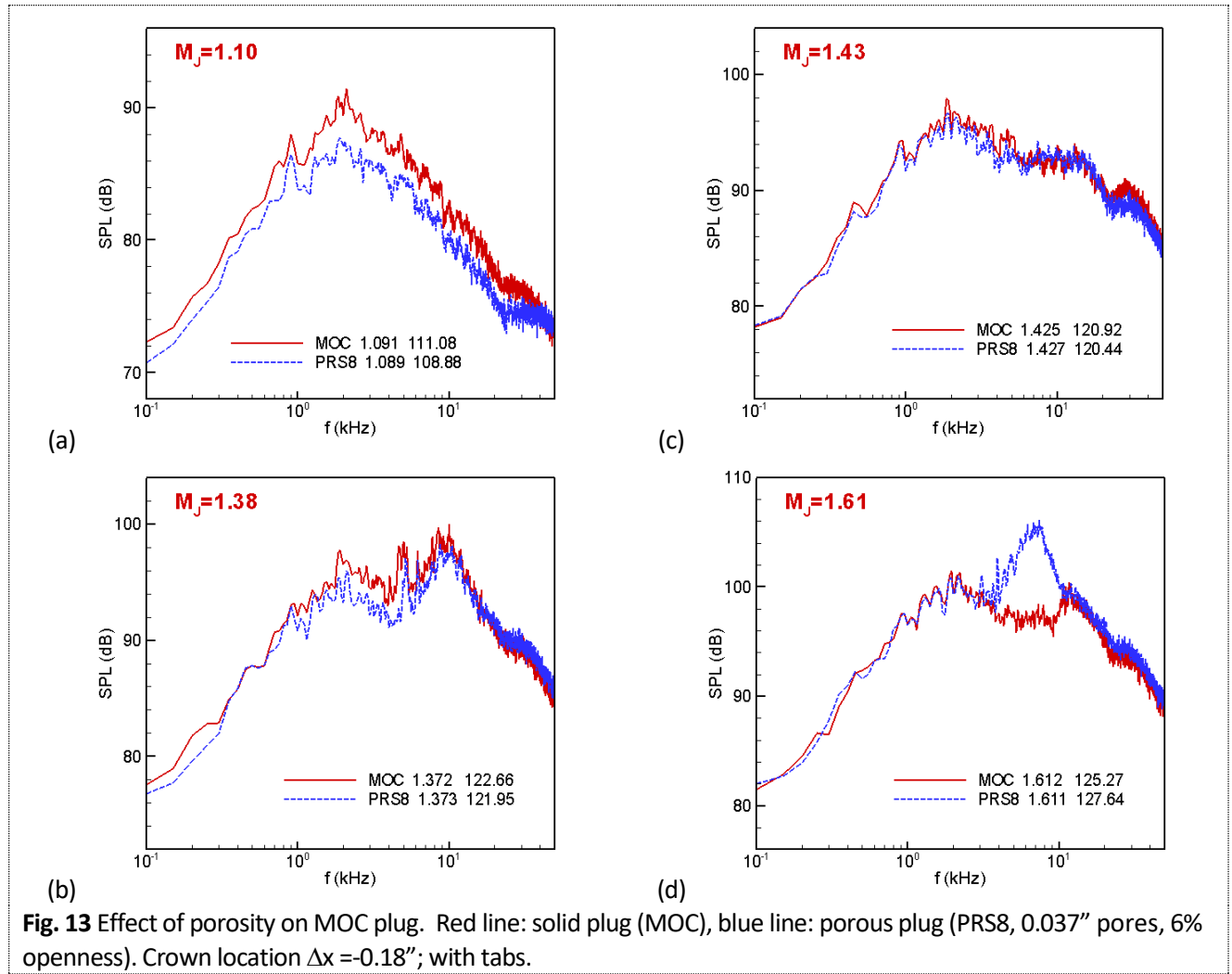


Fig. 12 Effect of porosity on overall sound pressure level. Red line: P10 solid case, Blue lines: PRS610 porous case; (dashed blue line for no tab case, others are with tabs).



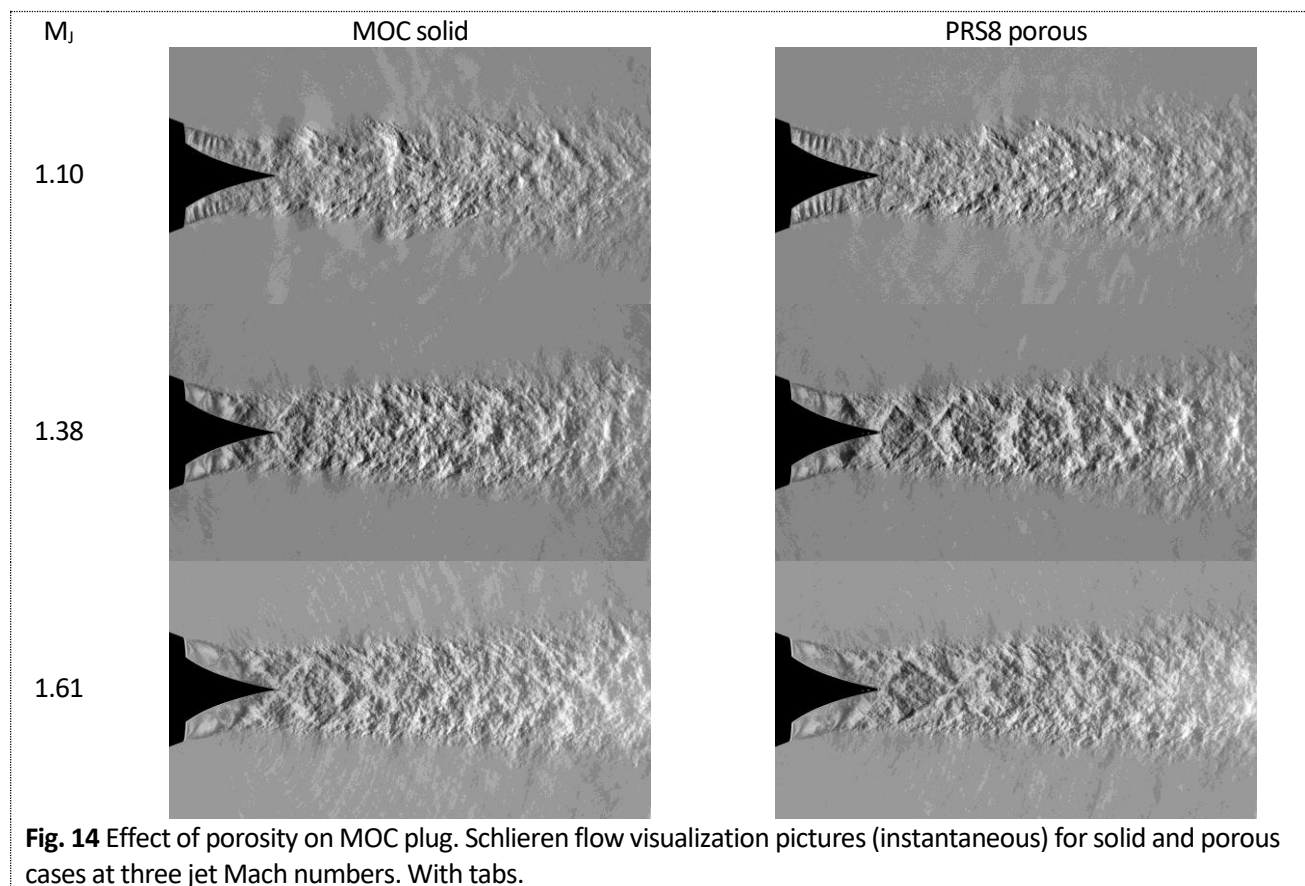


Fig. 14 Effect of porosity on MOC plug. Schlieren flow visualization pictures (instantaneous) for solid and porous cases at three jet Mach numbers. With tabs.

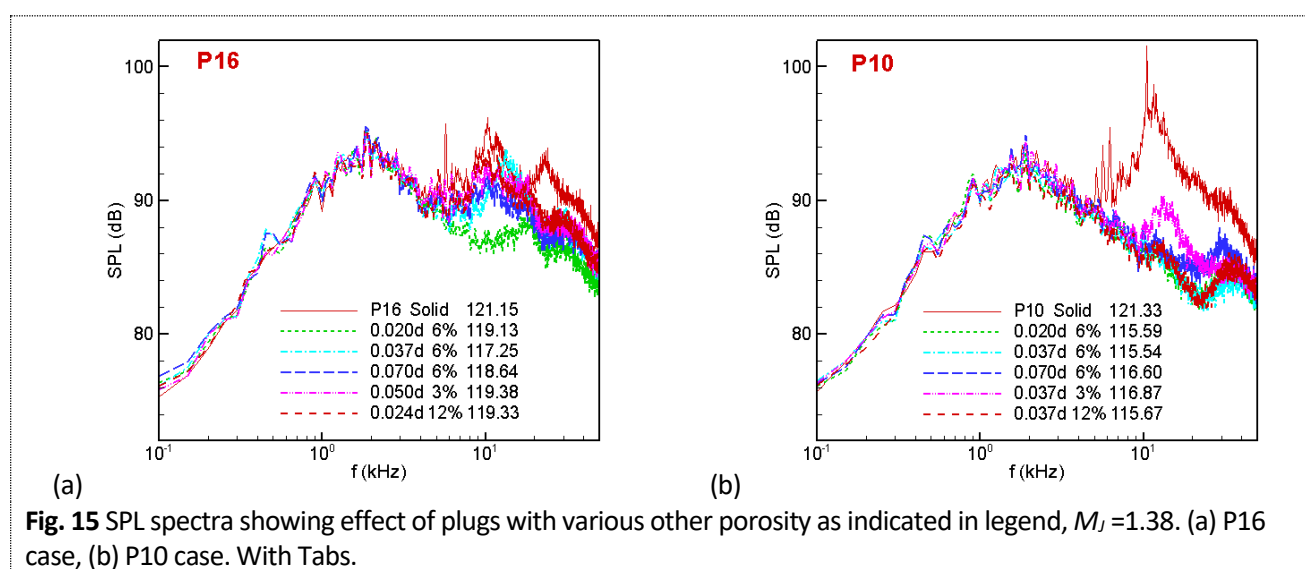


Fig. 15 SPL spectra showing effect of plugs with various other porosity as indicated in legend, $M_j = 1.38$. (a) P16 case, (b) P10 case. With Tabs.

