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Suppression of High Mach Number Rocket Jet Noise by Water Injection

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The present work experimentally investigates suppression of the sound level from an underexpanded jet of Mach number 2.8 by water injection. The jet is produced by a solid rocket motor being static test fired. Water is injected from a radial distance of 5.2 jet diameters, at different axial locations from the exit of the nozzle, at two different angles of injection relative to the downstream jet axis. The ratio of mass flow rates of water to the nozzle exhaust gas (referred to as the mass flow rate ratio) and the injection pressure are varied independently. Acoustic measurements are performed at a radius of 30 jet diameters, over angles in the range of 30–130 deg, relative to the downstream jet axis. Sound levels continuously decrease by 10 dB with the increase in the angle of observation. With water injection, higher levels of reduction in sound are observed in the upstream quadrant. Injection closer to the nozzle exit leads to better reduction, mainly due to suppression in the high-frequency range when observed from downstream, but it is almost in the entire frequency range as observed at the upstream locations. At intermediate mass flow rate ratios, an optimum injection pressure exists for maximum noise suppression, due to the penetration of water to the potential core and its evaporation there at high injection pressures. The results affirm that the validity of many past studies obtained on water injection to suppress noise levels on simulated jets can be extended to an actual rocket situation.

I. Introduction

LAUNCH vehicles experience vibroacoustic stress during liftoff due to high-intensity noise sources in the rocket exhaust. Thus, it is essential to suppress overall acoustic levels from rocket exhausts, containing various noise sources. Three fundamental mechanisms of noise generation are known to exist in supersonic jets; namely, turbulent mixing noise, Mach wave radiation, and shock noise [1]. Lighthill's acoustic analogy [2] for subsonic jet noise results in the V^8 law, where V is the jet exit velocity. This was extended by Ffowcs Williams and Hawkings [3] for supersonic jet noise (V^3 law), considering the supersonic convection of large-scale eddies relative to the ambient (Mach wave radiation). In imperfectly expanded jets, additional noise is generated due to the presence of shocks, leading to broadband shock noise on account of shock–turbulence interaction [4] and screech tones. In hot jets, sudden expansion of cold ambient air leads to crackle [5] as part of the mixing noise.

A semi-empirical prediction method based on source allocation techniques was proposed by Eldred and Jones [6]: the so-called NASA method. Recently, Varnier [7] carried out a series of static tests on rocket engines and suggested several improvements to the NASA method. Many improvements to the theoretical models of jet noise have been recently proposed in the literature (for example, the work of Tam [8], Tam et al. [9], Tanna [10,11], and others).

Various techniques for jet noise reduction have been evolved, mainly in the perspective of developing jet noise suppressors in aircraft [12–23]. These techniques can be broadly classified as those that modify the flow at its origin (or passive noise mitigation methods) and those that act on the exhaust flow (or active methods). Major passive techniques are in the form of modified nozzles, such as serrations in the lip (e.g., chevrons) [17], lobed and beveled nozzles [19], coaxial flows (e.g., turbo fan engines) [12,13], and jet rotation [16]. Different mechanisms involved in these are the modification of the mixing region, the potential core length, the Mach disk and the elimination of the Mach wave radiation, or the weakening of the internal shock strength (thereby reducing the cell length and decreasing the screech noise). In active methods, secondary injection on the jet (such as injection of water), wire or mesh devices, and acoustic mufflers are commonly adopted. Water injection affects the mixing and shock noise sources, which effectively break the shock-cell structure [20–23]. Wires/meshes reduce the shock strength and consequently suppress the noise [15].

Although the motivation for aircraft jet noise suppression is linked primarily to environmental regulation, suppression of rocket exhaust noise is important for the launch vehicle, payload structure, and ground support equipment. The strong noise directivity of hot supersonic jets makes the characteristics of suppression directionally dependent. Contrary to the perceivable aircraft noise requiring reduction in the downstream direction of the jet, launch vehicles require significant reduction in the upstream direction during liftoff. Therefore, passive methods adopted in aircraft for regulatory compliance, such as beveled nozzles deflecting the bulk of the noise skyward, cannot be adopted in launch vehicles. Passive methods tend to penalize the efficiency of the propulsion system, whereas active methods require additional subsystems that are more conveniently employed in a relatively stationary noise environment (such as on a launch pad) as opposed to being carried onboard the vehicle. Therefore, active methods are more suitable to the launch vehicle liftoff environment.

Water injection into the rocket exhaust during liftoff in huge quantities, with typical water-to-gas mass flow rate ratio (MFR) of 3–4, is a proven suppression technique in launch pads. It has been reported that the water injection system deployed by NASA and ESA for their launch pads can attenuate the sound levels by 8–12 dB [24–32]. The optimal injection parameters were generated based on studies with cold and hot gas models. Water injection attenuated all three components of jet noise: the turbulent mixing noise, the Mach wave radiation, and the broadband shock noise. The magnitudes of

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attenuation for the different components were dissimilar and depended on the injection parameters and the angle of observation.

Norum [20] and Krothapalli et al. [21,22] investigated water injection as applicable to aircraft nozzles. The effect on mixing noise, broadband shock noise, and screech tone were studied independently over a range of operating conditions of the nozzle, with MFR of 0.19–3.4. A low MFR was found to be sufficient for disrupting the phase relation of successive shock cells with the convected turbulence, and it brought down the broadband shock-associated noise considerably [20]. It was the same with screech tones. Comparatively, a high MFR was required for significant reduction of low-frequency mixing noise, which was evident from the downstream acoustic measurements. An optimum reduction up to 12 dB was achieved. The observation of higher reduction levels in the upstream quadrant where the shock-associated noise dominated, as compared with the downstream quadrant where the large-scale mixing noise dominated, had a beneficial effect in launch vehicle noise suppression.

Krothapalli et al. [21,22] and Krothapalli and Washington [23] used a very low MFR, which were typically called microjets. These jets produce fine atomized water droplets and were injected directly into the jet shear layer. With the aid of particle image velocimetry, the unsteady flowfield and far field acoustic measurements were correlated. The reduction levels estimated by substituting turbulence measurements in the Philips equation [22] were matched with the far field acoustic measurements. The flow visualization provided significant insight into the flowfield modification by water droplets. The effect of water injection was to reduce the flapping motion of the jet, the size of the large-scale vortical structures, and the magnitude of the eddy size. The transverse turbulence levels were also reduced without affecting the mean flow structure. On the whole, it was evident that the effect of water injection was to lower turbulence intensities and shear stress in the jet.

Experiments by Marble and Candel [24] showed that there could be attenuation in excess of 5 dB/m for plane waves while passing through a cloud containing water droplets. Kandula [25] recently showed that jet mixing noise reduction could be predicted theoretically by involving the dimensionless ratios of droplet diameter to jet exit diameter and droplet Reynolds number to jet Reynolds number. It was pointed out by Kandula [25] that the effect of microjet injection in reducing jet noise was mainly by turbulence modification with no appreciable changes in the mean flowfield (velocity and temperature), and that water injection at relatively high MFR reduced jet noise by reducing the jet mean velocity and temperature. The prediction of turbulent jet mixing noise reduction with water injection [25] was recently extended to broadband shock noise [33]. Also, the spectral attenuation of sound with regard to turbulent jet mixing noise was investigated [34].

A series of studies on hot and cold gas models were conducted at the Martel facility of the Centre National d'Etudes Spatiale in Poitiers, France and the facility at the Ecole Centrale de Lyon in Ecully Cedex, France, to find to find the optimal water injection parameters for implementation in launch pads [27–32]. Zoppelari and Juvé [31,32] used an MFR of 3–4. The two attenuation mechanisms observed were decrease of jet velocity by momentum transfer between liquid and gas phase and reduction of jet temperature due to partial vaporization of the injected water. The need to have sustained water injection near the rocket nozzle exit during the liftoff phase was recently reported by Ignatius et al. [35]. In fact, multistage water injection was found to be very effective in the launch scenario.

The optimal water injection parameters that have evolved out of several studies could be summarized as follows:

1) Injection close to the nozzle induced fast mixing and effective momentum transfer in the peak noise-producing region (tip of the potential core). Also, it affected all of the shock cells involved in the noise generation process.

2) At higher injection angles (close to 90 deg, perpendicular to the jet), penetration of the water jet was higher, yielding faster mixing; but, it also produced low-frequency impact, drag, and obstacle noise. Hence, as a compromise between significant penetration and low impact noise, injection angles in the range of 45–60 deg were preferred.

3) Atomized water drops induced faster mixing with less impact and drag noise.

4) An optimum MFR (3–4) existed, beyond which there was no effective momentum transfer and noise reduction. For hot jets due to evaporative loss of injected water, relatively higher MFR was required for maximum reduction.

The objective of the present work is to obtain experimental data on the mitigation of high-temperature full-scale rocket exhaust jet noise by water injection. When compared with the models, the actual rocket motor exhaust mass flow rate and temperature are very high. Also, it has the additional complexity of the afterburn of fuel-rich products. Although water injection as a means of suppression of rocket exhaust noise has been studied with scale models, reports of full-scale tests are scarce in the literature. Moreover, the effect of injection pressure, independent of the MFR, has not been clearly explored so far. The present test setup of static test firing a solid rocket motor is similar to the experiments by Varnier [7], but with a toroidal water injection system capable of varying the injection parameters (such as location, angle, pressure, and MFR). A polar scan of the acoustic pressure level spanning upstream and downstream quadrants relative to the nozzle exit is performed to deduce the directionality of the attenuation due to water injection in this scenario.

II. Experimental Details

The experimental setup is exclusively designed for measuring the acoustic levels from an underexpanded open jet of a horizontal rocket exhaust with and without water injection. A solid rocket motor based on a typical composite propellant made of hydroxyl-terminated polybutadiene, aluminum, and ammonium perchlorate is fired in the horizontal position, on a swing bench compression-type thrust measurement system, in an open field. The experimental setup is shown in Fig. 1. A convergent–divergent nozzle with a throat diameter D_t of 62.8 mm, an exit diameter D_e of 144 mm, and a divergence angle of 15 deg conforming to an area ratio A_e/A_t of 5.26 is used. The exit Mach number M_e is 2.8, and the exit pressure ratio is 1.2. The fully expanded jet Mach number M_j corresponding to the nozzle pressure ratio of 40 is $M_j \sim 3.05$. Table 1 lists the thermophysical parameters of the rocket motor used in the present study.

Water is injected using a toroid with 32 orifices at the required angle of injection, as shown in Fig. 1. The toroid can be located at any desired axial location from the nozzle exit. It is connected to a water tank, which is pressurized through a regulator to the desired level by a bank of nitrogen cylinders.

Acoustic measurements are made at six locations using calibrated half-inch microphones of a piezoelectric type (Endevco Model 2510, San Juan Capistrano, CA), having a flat frequency response up to 10 KHz and an amplitude measurement range of 80–180 dB, with an accuracy of plus or minus 0.5 dB in the 120–160 dB range. The microphones are located at an r/D_e of 30 from the center of the nozzle exit at various angles θ, in the range of 30–130 deg (relative to the jet direction), and face the nozzle exit irrespective of their angles

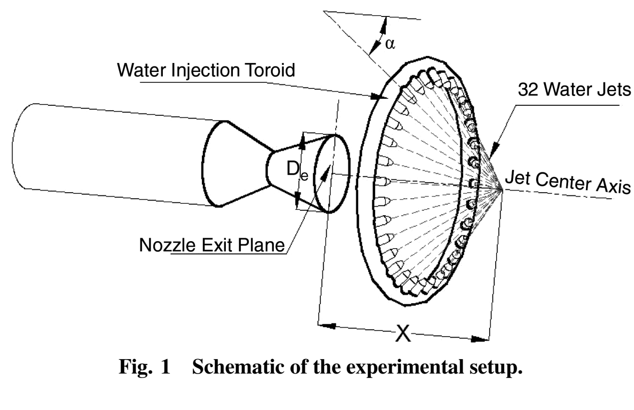


Fig. 1 Schematic of the experimental setup.

Table 1 Thermophysical properties of the solid rocket motor.

Thermophysical properties	Parameters
Chamber stagnation pressure p_o	≈40 bar
Chamber stagnation temperature T_o	3415 K
Specific heats ratio γ	1.2
Nozzle exit diameter D_e	144 mm
Nozzle throat diameter D_t	62.8 mm
Area ratio AR	5.26
Nozzle exit pressure p_e	1.2 bar (Absolute)
Nozzle pressure ratio p_o/p_e	≈33.33
Fully expanded jet Mach number M_j	≈3.05
Nozzle exit temperature T_e	1900 K
Mass flow rate (average)	8.1 kg/s
Jet exhaust Mach number M_e	2.81
Jet exhaust velocity U_e	2270 m/s

(Fig. 2). The microphones are deployed in the horizontal plane, passing through the nozzle central axis at $\sim 10D_e$ above the ground. Although this distance is comparable with other similar tests reported earlier [7], because the floor is not acoustically treated, the reflections from the ground would contaminate the measurements. However, this is considered acceptable because the relative reduction of sound by water injection is of primary interest in the present study.

The acoustic data are acquired at the rate of 40 kilosamples/s per channel for 6 s duration and processed for the root mean square amplitude and spectral analysis using a dynamics signal analyzer (Focus II model, Ling Dynamics, London, U.K.). Fast Fourier transform was performed on the data set with 512 bins with a frequency resolution of 40 Hz and averaged.

The axial location of the water injection X/D_e was varied as 2, 2.5, 3, 4, and 5. Two angles of injection α with respect to the jet axis were tested: 60 and 85 deg. The injection pressure of water p_w was varied in the range of 2–10 bar in steps of 2 bar. The mass flow rate of water relative to that of the jet MFR was varied in the range of 2–5 in steps of 0.5 by varying the size of the orifices on the toroid in the range of 5–8.5 mm. The water injection pressure and the mass flow rate were varied independently in some tests.

III. Results and Discussion

A. Effect of the Injection Location

The directivity of the overall sound pressure level (OASPL) without and with water injection is shown in Fig. 3. Focusing on the case without any water injection first, it can be seen that the OASPL reduces progressively from the downstream direction to the upstream direction, with a locally insensitive region above 90 deg. This is consistent with most previous studies that show the dominance of supersonic convection of eddies, and the Mach wave radiation are the major cause of high noise levels in the downstream region. Tanna [10] has, in fact, reported the local insensitivity around 90 deg is due to the noise being free from convective effects. Attempt has not been made in the present study to isolate crackle as a distinct source of sound within the large-scale mixing noise because it is primarily observed in the downstream region due to convection, whereas the region of interest in the present application is upstream.

In the same figure (Fig. 3), the typical case of water injection (here, $X/D_e = 2$, $\alpha = 60$ deg, MFR = 2, and $p_w = 4$ bar) is shown for comparison with the no-injection case discussed previously. The momentum ratio of the exhaust gas to water jet is ~38 in this case. It can be seen from Fig. 3 that the reduction in the noise level due to water injection is small in the rear arc (~2 dB), whereas significant reduction is observed in the forward arc (~4 dB). First, this is important in the rocket launch scenario, as mentioned earlier. Next, this also suggests that the water injection is not as effective in tackling the mixing noise as much as the shock noise.

The effect of injection location X/D_e can be observed in Fig. 3 for the case of $\alpha = 60$ deg, $p_w = 4$ bar, and MFR = 2. For this variation of X/D_e, it is estimated that the water jets may penetrate the shear layer well within the length of the potential core, within the second shock cell up to $X/D_e = 4$, and in the third shock cell for $X/D_e = 5$ [1]. It can be seen in Fig. 3 that the reduction in the noise level due to water injection is less sensitive to X/D_e in the downstream region than in the upstream. It is known that the major noise source near the tip of the potential core is significantly affected by injection within the core [35]. Because the present range of X/D_e is well within the potential core length, the reduction in the mixing noise is nearly insensitive to the injection location, as observed in the downstream direction. Regarding the noise suppression in the direction normal to the jet axis (~90 deg), the closest injection locations yield substantial reduction.

Looking at the spectra obtained only at extreme X/D_e and observation angles for the sake of brevity (Fig. 4), the downstream observation location clearly shows the substantial decrease in the noise in the mid-to-high frequency range due to water injection (Fig. 4a). Here, the frequency is nondimensionalized in terms of the Strouhal number $St = fD_e/U_e$, where f is frequency and U_e is nozzle exit velocity. Injection closer to the nozzle exit is quite effective in the midfrequency and high-frequency ranges, implying its effect on shock noise as well as the fine-scale mixing noise. This is observed to a greater extent at the upstream observation location (Fig. 4b). The large-scale mixing is relatively unaltered by the injection location. Interestingly, significant low-frequency impact noise is observed in the downstream region. Because of this, the major effect on the shock noise and fine-scale mixing noise by water injection contributes to the lower OASPL observed upstream rather than downstream.

The spectral data (Fig. 4 and others which follow) indicate that there is no screech noise observed for the underexpanded jets considered here. This is perhaps due to the relatively large value of the parameter $\beta = 2.88$, where $\beta = \sqrt{M_j^2 - 1}$. It is known from experiments on underexpanded jets that at values of β in excess of about 1.2 at relatively high pressure ratios, the regular shock structure is disrupted and a Mach disc is formed [4,11], leading to reduced noise intensity due to the presence of subsonic flow downstream of the Mach disc.

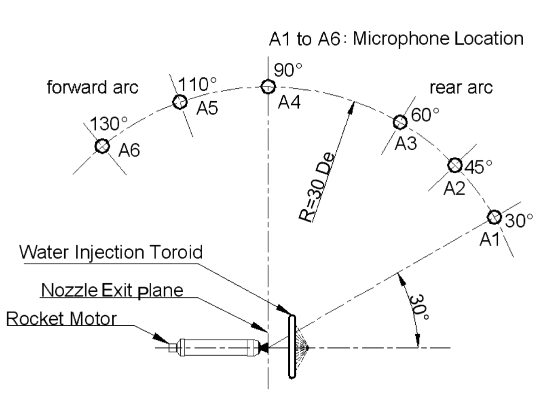


Fig. 2 Sound measurement scheme.

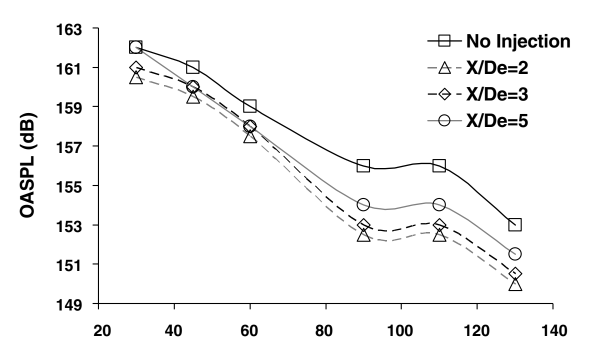
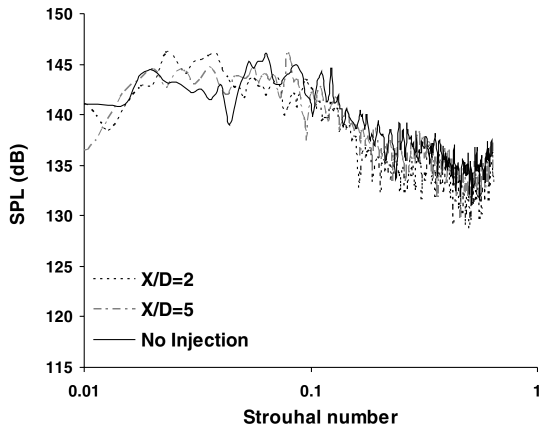
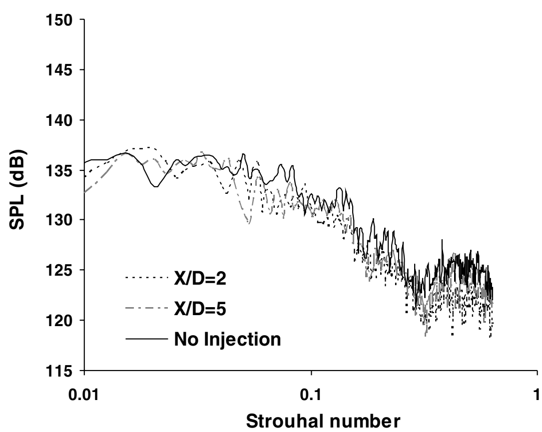


Fig. 3 Effect of the location of water injection X/De on noise suppression ($\alpha = 60$ deg, $p_w = 4$ bar, and MFR = 2).



a) $\theta = 30°$



b) $\theta = 130°$

Fig. 4 Comparison of noise spectra with water injection at two axial locations, as observed from two different directions ($\alpha = 60$ deg, $p_w = 4$ bar, and MFR = 2).

B. Effect on the Strouhal Number

Figure 5 shows slices of the sound pressure level (SPL) spectra at specific values of the Strouhal number. This is intended to clarify the effect of water injection on the low-frequency mixing noise versus the shock noise, as suggested by the previous OASPL plot (Fig. 3). The values of the frequencies observed at the selected Strouhal numbers are 120, 600, 1000, 2000, 5000, and 8000 Hz, which are representative of different frequency ranges for which different noise sources are prominent. Figure 5a shows the comparison of the SPL observed at different directions without and with water injection at the lowest frequency considered. Sound level reduction is observed at almost all directions up to ~ 5 dB, except the downstream octant of less than 50 deg, where it is lower. At this frequency, the mixing noise due to the large-scale structures is the most prominent, and hence this shows that the water injection does not address this noise source as effectively as others, as anticipated previously. In fact, at a higher frequency (Fig. 5b), the downstream octant registers a more increased SPL with water injection than without. This can be attributed to the impact and drag noise due to water injection interacting with the rocket exhaust, mentioned earlier. The sound level reduction in the remaining region of greater than 50 deg is correspondingly lower than in the previous case at $\sim$4 dB. The reduction in the sound level in the midfrequency range (Figs. 5c–5e) is mainly in the 90–110 deg direction up to $\sim$7 dB, but it is only mild in the upstream direction and marginal in the downstream direction. This is a frequency range for which the large-scale mixing noise overlaps with the broadband shock-associated noise. The former is highly directional, mostly toward the downstream, and the weak reduction in that direction confirms that the water injection at this pressure and MFR is insufficient to suppress it, but it is quite effective on the latter when looking at the direction normal to the flow. The

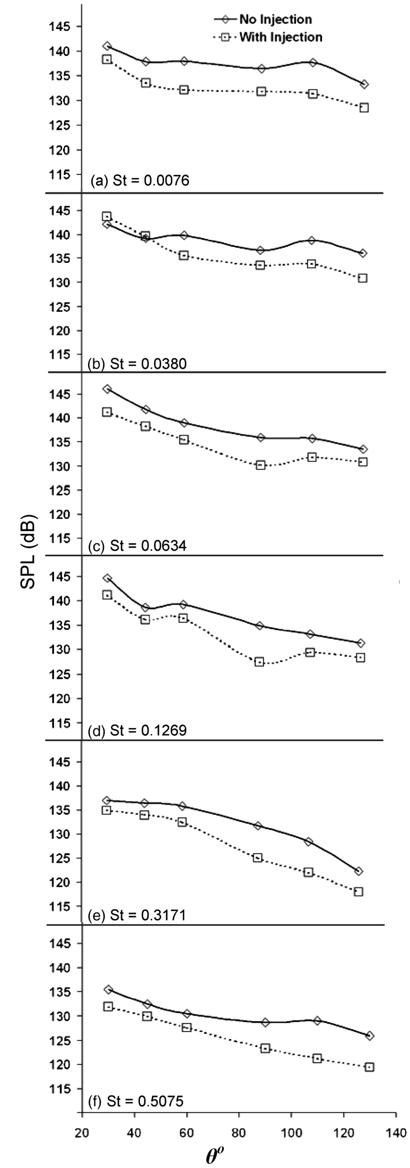


Fig. 5 Directivity of SPL at different frequencies (in terms of the Strouhal number) without and with water injection ($X/D_e = 2$, $\alpha = 85$ deg, $p_w = 6$ bar, and MFR = 5.5).

high-frequency noise (Fig. 5f) is from the fine-scale mixing, and its reduction by water injection is significant from 60 deg downstream. Because this source is convective, and hence directional, the previous observation shows that, unlike the marginal effect on the large-scale mixing, the water injection does alter the fine-scale mixing.

C. Effect of the Injection Angle

Figure 6 compares the OASPL directionality for the two injection angles tested. The conditions are $X/D_e = 2$, $p_w = 4$ bar, and MFR $= 2$, as before. The spectral details are presented in Fig. 7 for the upstream and downstream observation locations. The lower angle $\alpha = 60$ deg is effective in noise reduction as observed from all angles, but it is more effective in the upstream region than the downstream (Fig. 6), as has been reported in past work [31]. Looking at the spectra (Fig. 7), the major differences between the two injection angles are the impact noise at low frequency observed particularly in the rear arc (Fig. 7a) and the consistently greater reduction of the fine-scale mixing noise by injection at $\alpha = 60$ deg. At the lower angle, the water jets affect the mixing region surrounding the potential core and hence effectively curb the mixing noise, whereas at the higher angle, the water jets possibly penetrate the potential core and evaporate, because the gas jet is hot, which is ineffective in suppressing mixing noise.

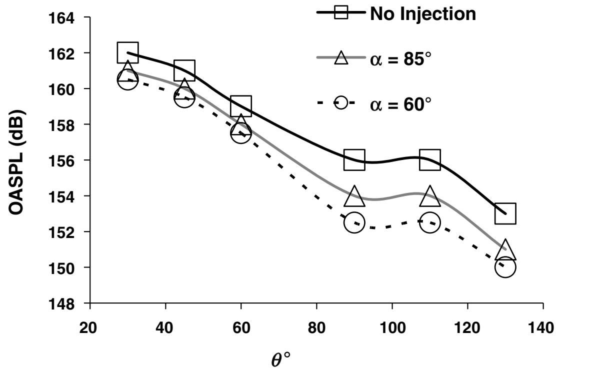
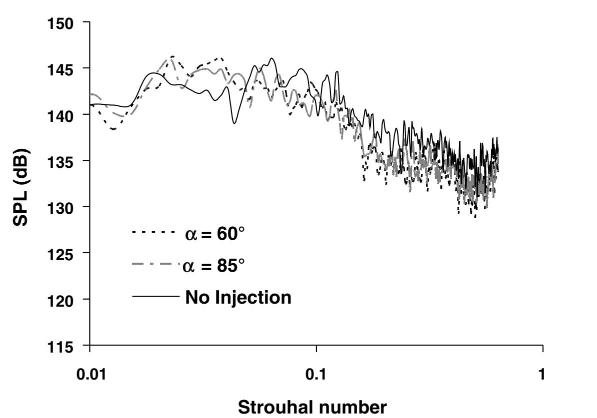
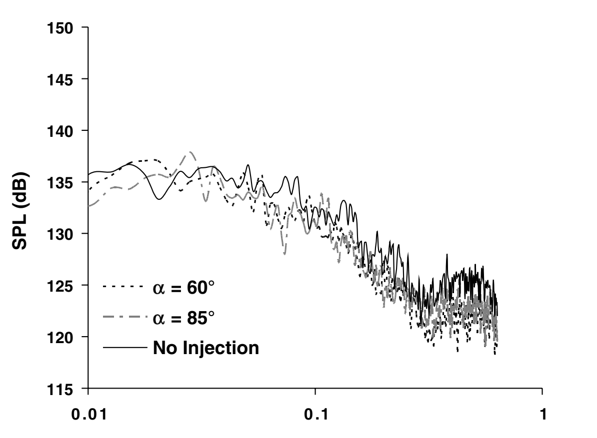


Fig. 6 Effect of the angle of water injection α on noise suppression ($X/D_e = 2, p_w = 4$ bar, and MFR = 2.1).



a) $\theta = 30°$

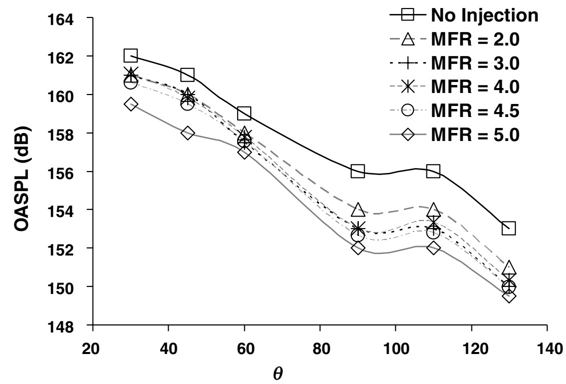


b) $\theta = 130°$

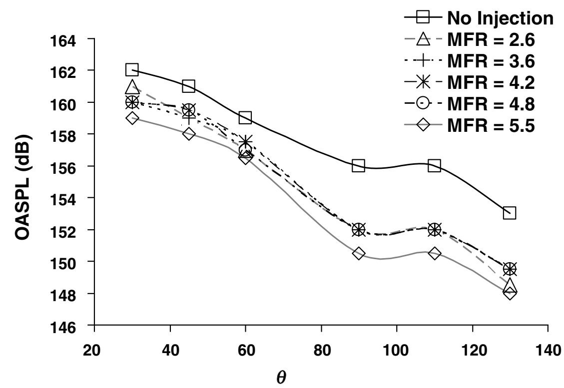
Fig. 7 Comparison of noise spectra with water injection at two injection angles, as observed from two different directions ($X/D_e = 2$, $p_w = 4$ bar, and MFR = 2.1).

D. Effect of the Mass Flow Rate Ratio

The MFR is varied in the present work at keeping the injection pressure constant. Varying the orifice diameter of the injector varies the MFR at constant pressure. Tests are performed over a range of MFR for two injection pressures; namely, 4 and 6 bar. The directionality of the OASPL for the two injection pressures and different MFR levels is shown in Fig. 8. It can be seen that, at $p_w = 4$ bar (Fig. 8a), there is a consistent trend of increased noise reductions with the increase in the MFR at all observation angles. Note that the earlier expectation of greater reduction with increased MFR, as observed downstream, is borne out by the present result. As expected, the reduction is more in the upstream regions. The most



a) $p_w = 4$ bar



b) $p_w = 6$ bar

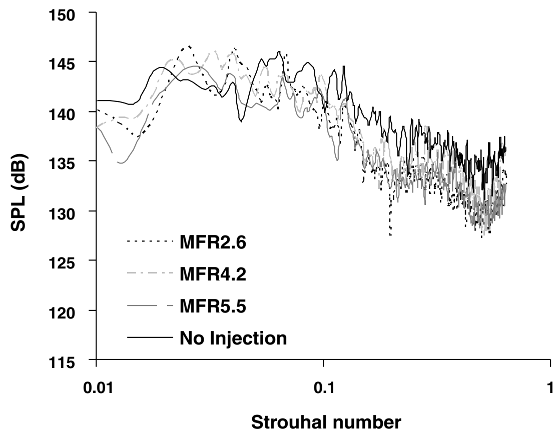
Fig. 8 Effect of the MFR of water injection on noise suppression at two injection pressures ($X/D_e = 2$ and $\alpha = 85$ deg).

important observation is in Fig. 8b, in which significant noise reduction is observed over all the MFR levels tested at $p_w = 6$ bar, but most of these are insensitive to the MFR except at the highest level tested (i.e., MFR = 5.5). This shows that when the injection pressure is sufficiently high, even smaller mass flow rates can cause substantial noise reduction; conversely, still higher noise reduction requires quite high mass flow rates at high injection pressure.

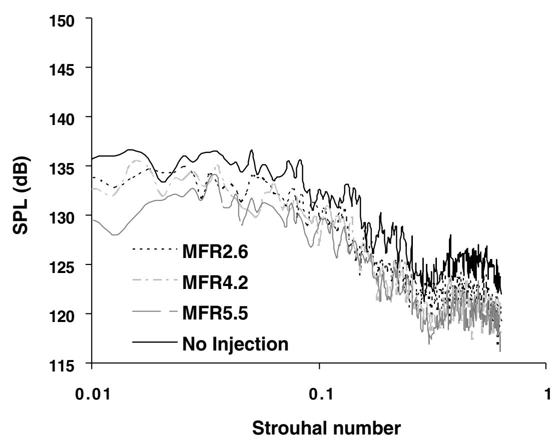
Figure 9 compares the spectra for water injection at three MFR levels across the test range and $p_w = 6$ bar with the no-injection case, as observed downstream and upstream. There is a distinct difference in the spectra when observed from the two directions. Significantly higher MFR than in the 2.6–4.2 range is required for appreciable noise reduction in the low frequency range, but the noise at higher frequencies is unaffected even at high MFR when observed from downstream. The impact noise is perceptible at $St \sim 0.04$ for all MFRs. On the other hand, the sound reduction is sensitive to the MFR in the entire spectrum when viewed from upstream. The impact noise offsetting the sound reduction in the downstream quadrant is not noticed when viewed from this direction.

E. Effect of the Injection Pressure

The sensitivity of sound reduction to injection pressure rather than MFR is clearly observed in the present work when the injection pressure is increased, allowing for the water mass flow rate to increase proportionately. However, the effect of injection pressure alone, at a fixed mass flow rate, is the appropriate aspect to investigate, and it has not been considered in past works. This is presented in Fig. 10. The figure clearly shows the existence of an optimum injection pressure beyond which there is actually a decrease in the noise reduction. In this case, over the test range of p_w being 2–8 bar, the optimum pressure is 6 bar. This is also the case with slightly higher MFR(=3.6) tested but not shown here. This is clearly understood from the spectra shown in Fig. 11 for three injection pressures and compared with the no-injection case observed from downstream and upstream. In the downstream direction (Fig. 11a),



a) $\theta = 30°$



b) $\theta = 130°$

Fig. 9 Comparison of noise spectra with water injection at different MFRs, as observed from two different directions ($X/D_e = 2$, $\alpha = 85$ deg, and $p_w = 6$ bar).

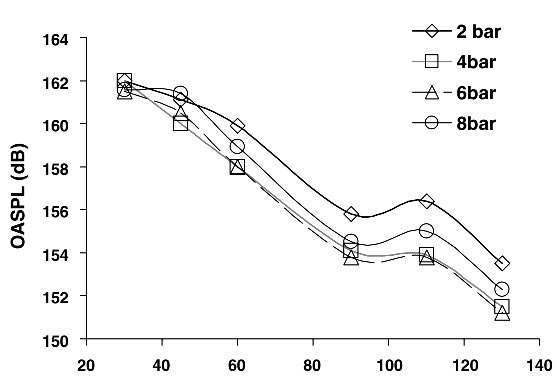
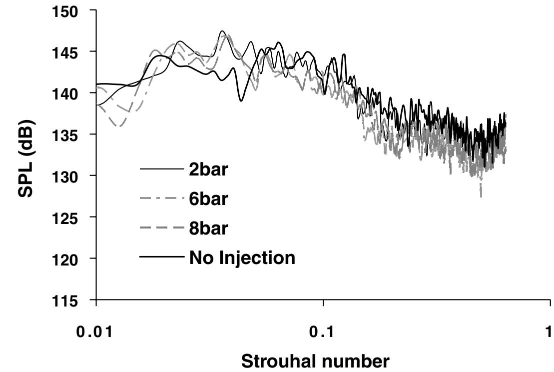
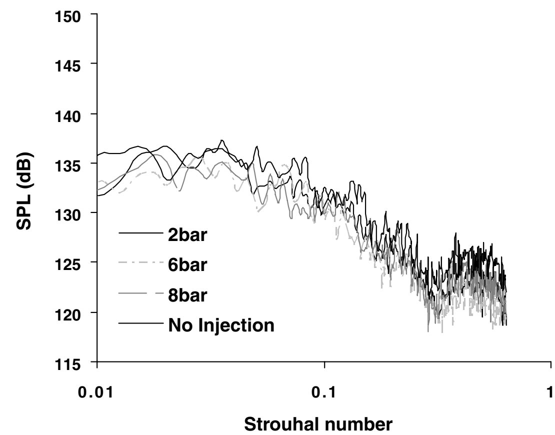


Fig. 10 Effect of the pressure of water injection p_w on noise suppression ($X/D_e = 2$, $\alpha = 85$ deg, and MFR = 3).

the impact noise is observed in equal measure at low frequency ($St \sim 0.04$) for all injection pressures. The low-frequency mixing noise sensed prominently in this direction is also insensitive to the pressure of water injection. The broadband shock-associated noise at midfrequency clearly shows a decrease with increase in the water injection pressure. However, it is the high-frequency noise that shows the preference for an optimum injection pressure, also prominent in this observation direction. With the injection angle being 85 deg at $X/D_e = 2$ in these tests, the water penetration into the potential core is higher at a higher injection pressure, which is inimical to effective curbing of the high-frequency mixing noise, because the water tends to evaporate in the hot jet and does not significantly affect the fine-



a) $\theta = 30°$



b) $\theta = 130°$

Fig. 11 Comparison of the noise spectra with water injection at different pressures, as observed from two different directions ($X/D_e = 2$, $\alpha = 85$ deg, and MFR = 3).

scale mixing. Looking from the upstream direction (Fig. 11b), the impact noise being absent and the low-frequency mixing noise being imperceptible leads to an overall reduction in the sound level across all of the low-to-mid frequency range for injection pressure greater than 2 bar, but comparably between 6 and 8 bar. Again, the midfrequency broadband shock-associated noise is observed to be monotonically sensitive to injection pressure, but the optimal role of injection pressure is determined by suppression in the high-frequency fine-scale mixing noise, as observed downstream.

The relationship between the optimum injection pressure and MFR for sound level reduction by water injection can be summarized as shown in Fig. 12. It indicates that the MFR required for suppression of broadband shock noise is relatively low at 6 bar injection pressure (constant reduction of 4 dB from MFR of 2 to 4.8) and a slightly higher MFR is required in the case of 4 bar injection pressure. This confirms the earlier results by Norum [20] on broadband shock noise reduction by water injection. With further increase in the MFR,

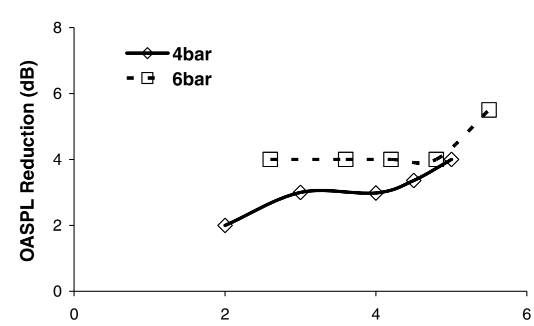


Fig. 12 Effect of the MFR of water injection on OASPL reduction ($X/D_e = 2$, $\alpha = 85$ deg, $\theta = 90$ deg, and $p_w = 4$ and 6 bar).

it can be observed that the reduction increases appreciably, due to the effect of water injection on the low-frequency mixing noise.

IV. Conclusions

On the whole, examining the reduction in the SPL by water injection and in different frequency bands where different noise sources predominate and their contribution to the OASPL reduction is observed in different directions, the view emerges that the water injection adopted in the present study does not significantly affect the low-frequency mixing noise, but it suppresses the midfrequency broadband shock-associated noise and appreciably influences the high-frequency fine-scale mixing. Injection of water closest to the nozzle leads to significant reduction of OASPL in the normal and upstream directions, mainly through action on broadband shock noise sources and fine-scale mixing. In the downstream direction, an insignificant effect on large-scale mixing and a contribution from impact noise in the low frequency range leads to OASPL reduction that is insensitive to the injection locations tested here, because they are all well within the potential core. Water injection penetrating into the potential core of the hot jet evaporates the water and does not appreciably influence the fine-scale mixing, signifying an optimum injection pressure. This also necessitates lower injection angles. Given the optimum injection pressure, the noise reduction is insensitive to MFR over a wide range. For rocket exhausts, a moderate MFR at the optimum injection pressure and injection angle is conducive for effective suppression of almost all noise sources in the upstream direction, which is important from the viewpoint of securing the structure and the electronic packages in the payload and the guidance and control of the vehicle.

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