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D3.1- REPORT ON NOISE IMPACT FROM ACTIVE TECHNOLOGIES (FLUIDIC ACTUATORS/AIR CURTAIN) NUMERICAL SIMULATIONS VALIDATED THROUGH DEDICATED EXPERIMENTS

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Abstract

This document is the main deliverable associated with Subtask 3.1.2 "Assessment of active flow control devices, based on innovative numerical simulations and experiments at a reduced scale". The document discusses the second of two test campaigns which took place in DLR's AWB wind tunnel facility in Braunschweig in Germany. The tests were conducted to assess the air curtain concept as a viable low noise technology for landing gear. The tests took place in March 2023 and this second campaign was the principle of the two campaigns with the primary focus of the tests being on Dassault's GB-TA-MLG1 main landing gear scaled model.

This deliverable must be read in conjunction with both D2.11 (and especially) D2.12 in which full descriptions of the test facility and both the air curtain nozzles and landing gear models are discussed and described.

In summary, both the "Lagoon-*Like*" and the GB-TA-MLG1 models are evaluated with air curtain nozzles located upstream and/or attached locally to the gear, see Fig 1 for a schematic of locations or else Fig 11 and Fig 12 in D2.12. Wind tunnel speeds up to the maximum of 63 m/s are evaluated with metal "choked-flow" air curtain nozzles operating at air pressures of up to 7 bar.

Keywords

Landing gear; Air Curtain; Acoustics

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[1] Use one of the following codes: R=Document, report (excluding the periodic and final reports)

DEM=Demonstrator, pilot, prototype, plan designs

DEC=Websites, patents filing,press & media actions, videos, etc.

OTHER=Software, technical diagram, etc.

[2] Use one of the following codes: PU=Public, fully open, e.g. web

CO=Confidential, restricted under conditions set out in Model Grant Agreement

CI=Classified, information as referred to in Commission Decision 2001/844/EC.

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Glossary

Lagoon LG	Simplified Nose LG defined by Airbus
Lagoon-Like LG	Modified version of the Lagoon LG, such as defined in the present INVENTOR project
CFD	Computational Fluid Dynamics
ATUNNEL	Facility of Technische Universiteit Delft (TUD)
AWB	Wind tunnel facility of Braunschweig DLR
MSLA	Masked Stereolithography
FDM	Fused Deposition Modelling

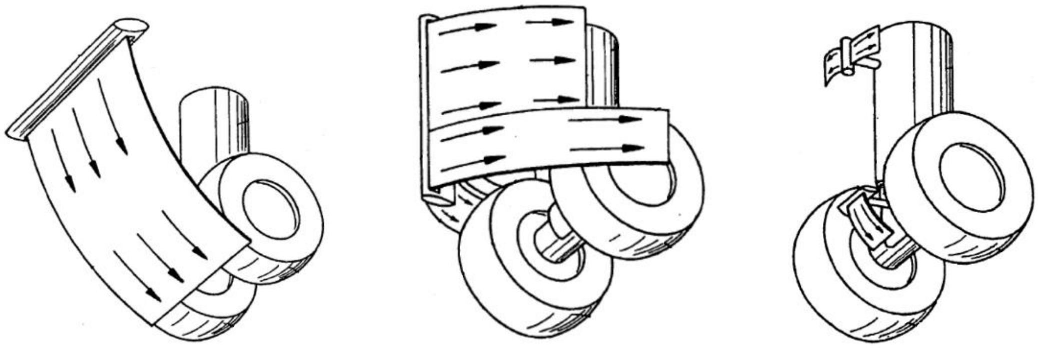
1 Introduction

Landing gear is mechanically complex, primarily designed to support the load of a landing aircraft. Its design, as a priority, is constrained by requirements associated with safety, inspection, and maintenance. This has resulted in a large number of components clustered together in a highly non-aerodynamic shape. Whilst in principle, it should be an easy task to dramatically decrease landing gear noise by fully encasing it in a solid aerodynamic fairing, the overriding requirements of weight and safety (including access for pre-flight inspections and free-fall and tire-burst criteria), and allowing for brake cooling, prevent this obvious solution from being adopted. Therefore, unlike the aeroengine which has been acoustically refined over 50 years, current production aircraft landing gear, except for hub caps in some cases, are almost completely absent of any design or noise abatement technology which might lower its significant acoustic output.

2 Air Curtain Technology

This work considers the use of an "air curtain", which is really a planar jet in crossflow, as a noise reduction technology for aircraft landing gear. To the contributors knowledge, it was first suggested as a technology for landing gear noise reduction in a patent by Wickerhoff and Sijpkes [1] although no further development of this paper-based proposal by the inventors themselves is evident. However, a European Union funded project: TIMPAN, did investigate a simplified geometry of the concept experimentally and measured noise reductions of between 3 dB and 10 dB and concluded that for full models larger noise reductions could be anticipated [2]. The TIMPAN research demonstrated a proof-of-concept to significantly reduce broadband landing gear noise which typically scales with the 6^{th} power of local flow speed. The authors of the TIMPAN work also identified potential obstacles to the adoption of this technology, *viz.* the noise generated from the introduction of the air curtain itself. They found that this additional noise was composed of two separate noise sources: a high frequency jet-mixing noise that scales with the 8^{th} power of the planar jet velocity and a lower frequency lip-noise source found at the planar jet exit slot which scales with the 5th power.

Figure 1 illustrates the concept of how an air curtain in crossflow might reduce the aerodynamic noise from landing gear on approach to landing. Three possible configurations are shown. The first, Figure 1(a), shows how the air curtain issues from the fuselage upstream of the landing gear at some fixed angle relative to the aircraft velocity vector. The air curtain streamlines would subsequently follow a curvature primarily dependent on the angle of emission and the velocity ratio between the planar jet velocity and the local mean velocity over the fuselage. Figure 1(b) shows an alternative configuration where air curtains issue from a vertical strut located upstream of the landing gear and this two-sided lateral blowing set-up is described as being similar to a large streamline cap [2]. The third alternative, shown in Figure 1(c), would route the air supply along the landing gear itself to provide local jets for local shielding.



(a) Fuselage Mounted: Horizontal | (b) Fuselage Mounted: Vertical | (c) Landing Gear Mounted

Figure 1. Air curtain concept for shielding landing gear (Edited from [1])

Each of these implementations have advantages and disadvantages. Figure 1(a), would issue from the fuselage and could provide complete shielding of the landing gear. This could be turned off just upon landing and thus allow essential airflow for brake cooling and not impede visual safety inspection by ground staff. However, it would require the most mass flow supply of air and the high jet velocity required to shield the entire length of leg might result in a significant additional noise source. Figure 1(b) would require a much lower exit velocity being required to only extend to half the width of the gear, at most, but would require a retractable strut to extend from the fuselage. The third implementation, in Figure 1(c), would have the lowest required mass flow, lowest additional noise but would add some complexity to the gear and would only provide partial shielding. However, the shielding could be focused to address the greatest noise sources.

A review of research conducted by TCD in advancing the state of the art in air curtains is provided in a book chapter based on a presentation given by TCD in DLR Braunschweig [3].

3 Experimental Setup

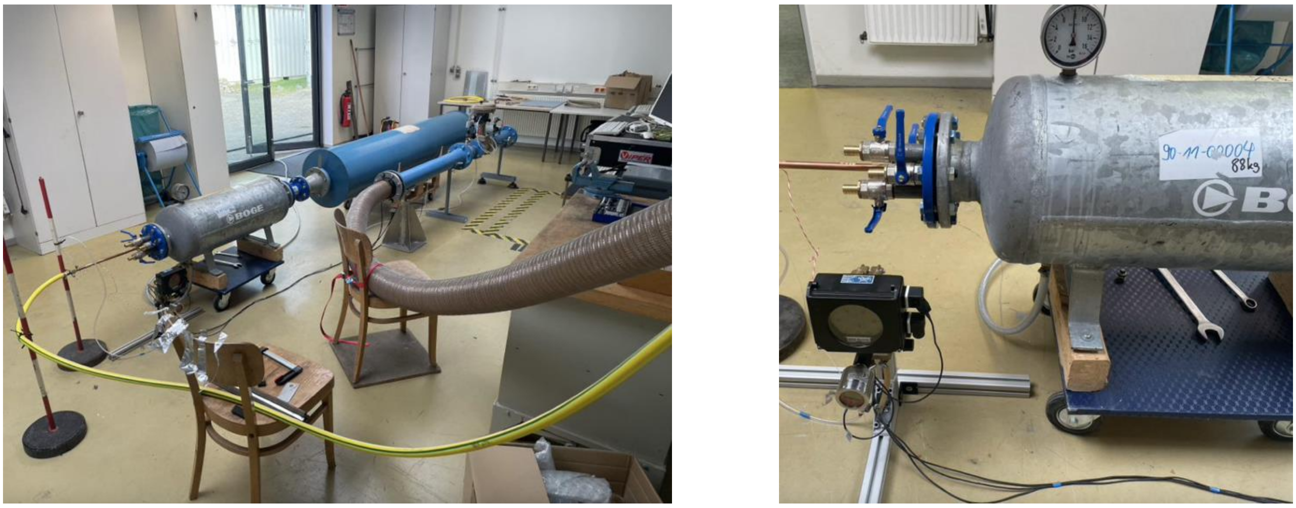


Figure 2. High pressure air supply compressor setup

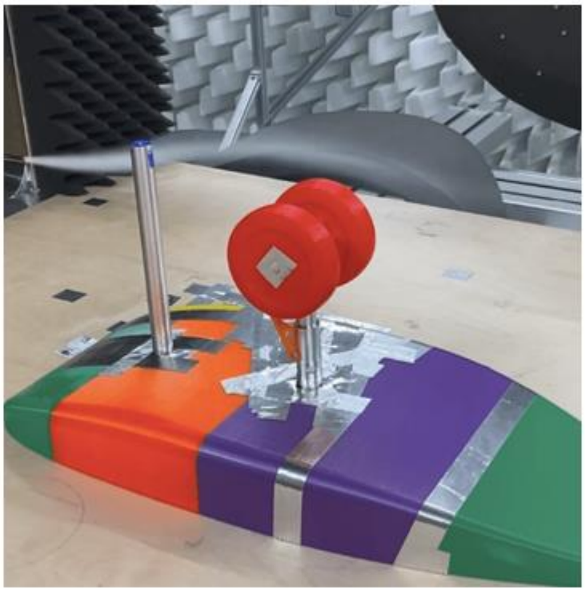
As discussed in the specification document of D2.12, higher pressures and flow rates were required for this second AWB test campaign. Initially air supply was drawn from the NWB tunnel supply but this was inadequate. Alternative measures were taken by DLR to achieve a high-pressure air supply to the wind tunnel, consisting of a compressor, air storage tanks and a silencer, as shown in Figure 2. These measures were successful and enabled the supply of air up to 7 bar gauge pressure and in addition variation of the pressure was possible. Furthermore, the configuration shown was capable of supplying sufficient mass flow rates in accordance with the requirements set out in D2.12, such that no limitation was experienced related to mass flow rate.

All other experimental facilities related to the AWB wind tunnel are consistent with those set out in D2.12.

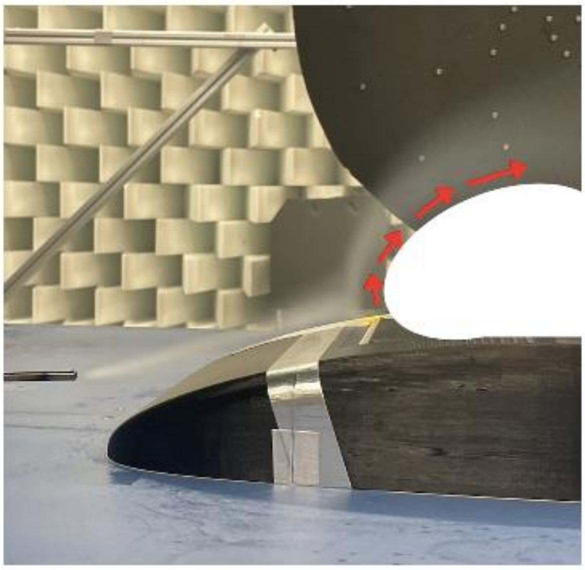
4 Flow Visualization

The Air Tube (AT) and Air Blade (AB) nozzles were examined using a smoke probe so that flow visualisation could be performed. Air pressures of 2 and 7 bar respectively, in a 30 ms^{-1} cross flow were tested. The smoke probe was positioned at various points upstream of the nozzles and the smoke trail was observed.

The visualisation offered insight into the level of flow deflection achieved. Figure 3 (a) shows a significant degree of flow deflection around the upper half of the Air Tube Nozzle, which features three rows of outlet holes to maximise flow deflection around the wheels. While some vortices were observed over the top of the air curtain, the general consensus was that the nozzle was functioning as intended and a sufficient level of shielding was achieved at this cross flow velocity and nozzle air pressure. Figure 3 (b) shows a good level of deflection was also achieved with the Air Blade Nozzle for the given conditions, albeit such flow deflection was not sufficient to fully shield the full height of the landing gear (not shown in image).



(a) AT with 2 bar pressure.



(b) AB with 7 bar pressure.

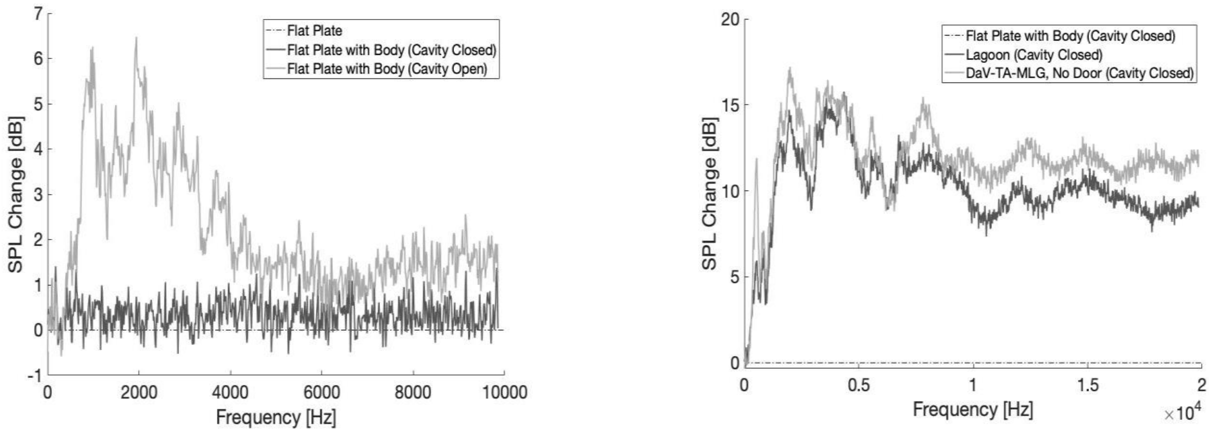
Figure 3. Flow visualisation tests with AT and AB nozzles.

5 Baseline Analysis

5.1 Frequency Spectra

As a first stage in the analysis of the acoustics, it was thought valuable to perform a baseline analysis to gauge the effect of various elements to the overall acoustic profile. Figure 4(a) presents an initial comparison between the acoustic output of the baseline, flat plate mounting system and when the landing gear bay is installed, both with and without cavity closure. This clearly indicates the streamline body of Dassault contributes negligibly to the acoustic profile when the cavity is closed, however the open cavity does produce noise which is not insignificant especially below 4kHz.

Figure 4(b) illustrates the difference in acoustic output of the two landing gears when compared to the flat-plate, cavity closed baseline. As expected, the increased complexity of the GB-TA-MLG1 compared to the Lagoon results in increased noise production. Values of up to 5 dB in difference can be seen for this case when the cavity is closed with the Dassault gear being louder than the Lagoon across the frequency range.

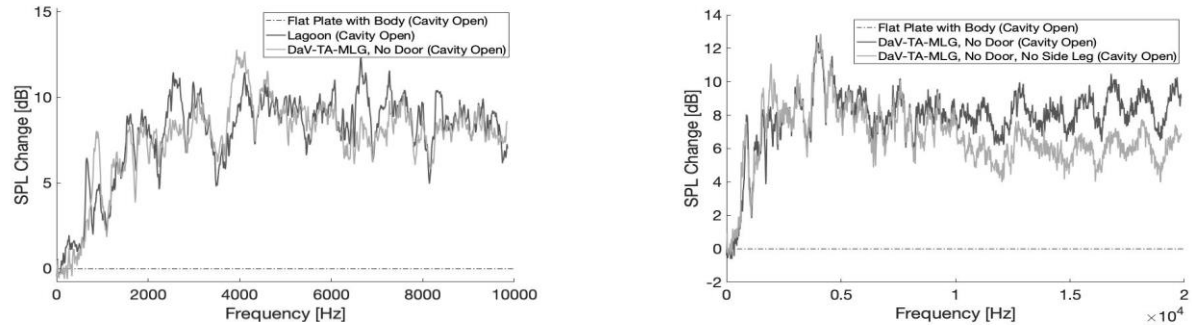


(a) Impact of streamline shape and of the cavity.

(b) Landing gear comparison. Cavity closed.

Figure 4. Baseline comparison at M2 microphone with 63 m/s crossflow velocity

However, analysis of the two landing gears when the cavity is open highlights a relatively small variation between the acoustic spectra in the 0-10kHz range, as shown in Figure 4(a). In this frequency range, either gear can be louder depending on the frequency. A final baseline analysis was performed to analyse the impact of the GB-TA-MLG1 Side Leg which is an additional component not present in the Lagoon landing gear. It was thought this would contribute significantly to the acoustic emissions, and it is shown to do so in Figure 4(b). However, it is clear that the effect of the side leg on the frequency spectrum primarily is at around 2kHz and above 10kHz.



(a) Landing gear comparison with cavity open

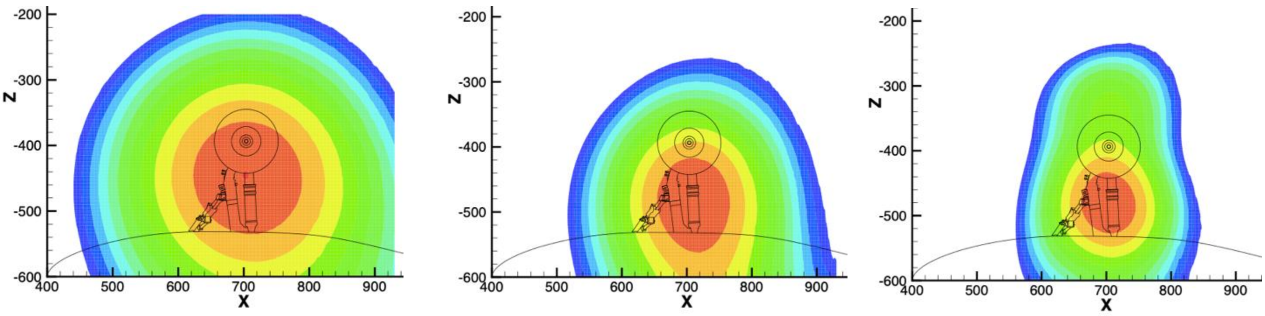
(b) GB-TA-MLG1 side leg analysis. Cavity open.

Figure 5. Baseline comparison at M6 microphone with 63 m/s crossflow velocity

5.2 Beamforming

5.2.1 Dassault

Beamforming results shown in Figures 6 & 7 for the Dassault GB-TA-MLG1 indicate that the primary noise source exists in the region of the main leg close to the knuckle and between the leg and the damper at 63 m/s. At these frequencies and from this view the cavity seems to have little effect. Top view beamforming shown in Figures 9 & 9 indicates that the side leg likely is the source of some noise as it can be observed that the noise source is off centre on the wheel axis. Furthermore, while the cavity open is known to result in higher noise levels at some frequencies, the main noise source was not affected in this analysis by the presence of the cavity. Hence, the landing gear was still the dominant noise source in the cavity open configuration.

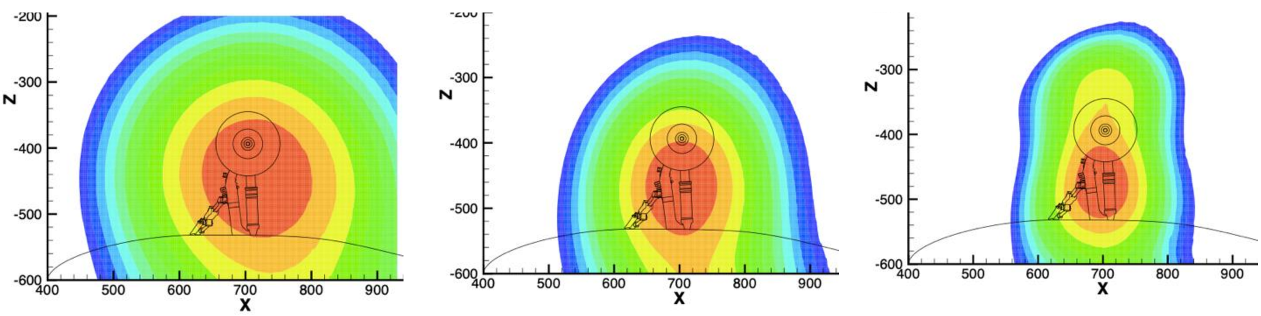


(a) 2500 Hz

(b) 4000 Hz

(c) 6300 Hz

Figure 7. Reference landing gear configuration beam forming results for side array with 63 m/s and cavity open.

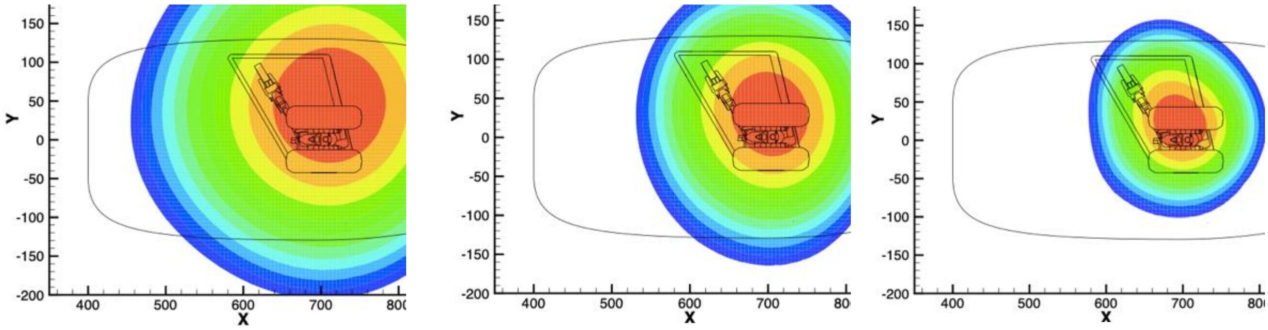


(a) 2500 Hz

(b) 4000 Hz

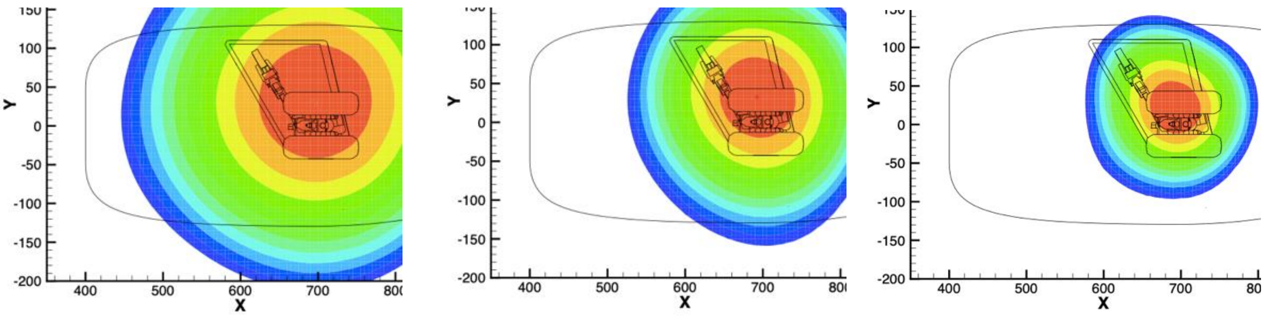
(c) 6300 Hz

Figure 6. Reference landing gear configuration beam forming results for side array with 63 m/s and cavity closed.



(a) 2500 Hz (c) 4000 Hz (b) 6300 Hz

Figure 9. Reference landing gear configuration beam forming results for top array with 63 m/s and cavity open.



(a) 2500 Hz (b) 4000 Hz (b) 6300 Hz

Figure 8. Reference landing gear configuration beam forming results for top array with 63 m/s and cavity closed.

6 Air Curtain Nozzle Analysis

Figures 11 and 12 in D2.12 shows the air curtain nozzles tested in the current test campaign for the Lagoon-like and Dassault landing gears. In general, acoustic data was acquired at 0 m/s, 30 m/s, 45 m/s and 63 m/s although a small number of other velocities were examined also. Variations on the configurations such as testing with or without the cavity or, in the case of the GB-TA-MLG1, with and without the side stay were also examined. In the next sections, the following abbreviations are used: AT- Air Tube, LHD- Local High Density, LLD – Local Low Density, AB- Air Blade.

6.1 Lagoon Landing Gear with Air Curtain Nozzles

Initial tests on the Lagoon-Like LG involving a closed bay cavity with nozzle air pressure of 7 bar showed that none of the tested configurations (AT, AB, LHD Wheel, LHD Wheel & AB) produced noise reductions with 30 ms^{-1} crossflow velocity, as shown in Figure 10. The self-noise of the nozzles was dominant over the aerodynamic noise of the landing gear across the full frequency spectrum at this low crossflow velocity, due to the minimal noise produced by the landing gear.

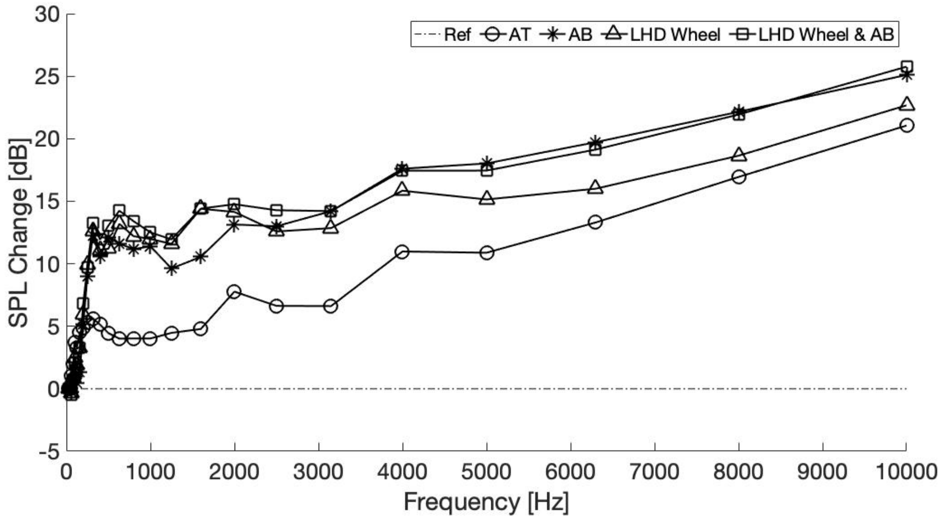


Figure 10. Lagoon-*Like* LG. Change in 1/3 octave bands at M5 microphone for 30 m/s crossflow velocity. Closed Bay.

At higher velocities, the AB, LHD Wheel and LHD Wheel & AB configurations achieved no noise reduction at any crossflow velocity, whereas the AT configuration showed noise reductions at 45 ms^{-1} and 63 ms^{-1} crossflow velocity, with the most significant reduction (up to 5 dB) being achieved at 63 ms^{-1} in the 1.5-8kHz range, as shown in Figure 11. Note that the air supply pressure used was 7 bar. Above 10kHz, all nozzle configurations led to a substantial increase in noise levels.

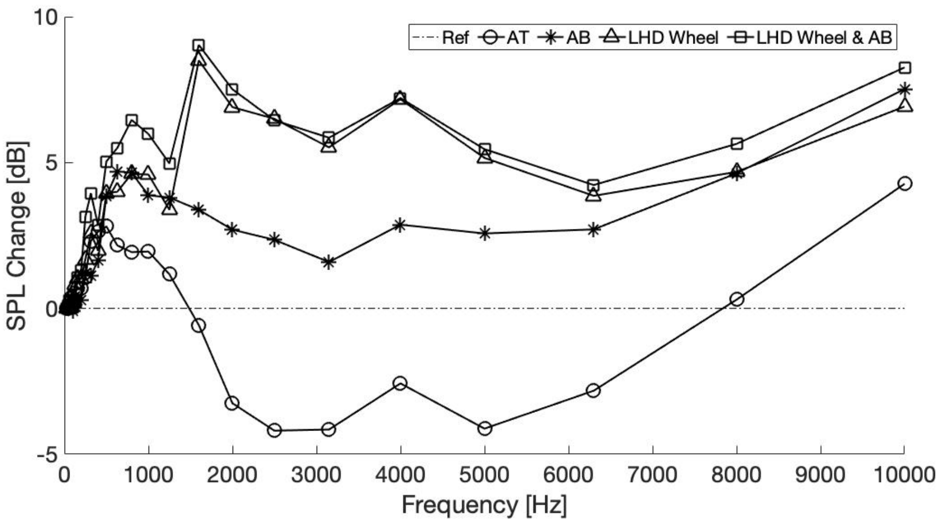
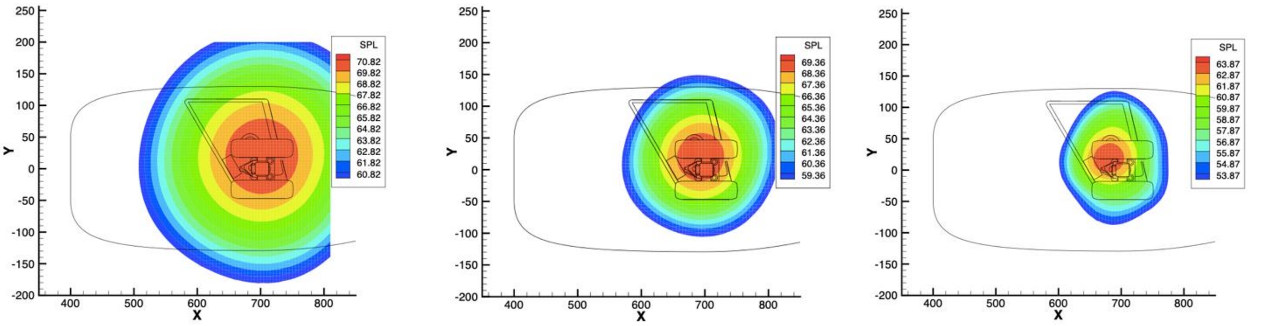


Figure 11. Lagoon-*Like* LG. Change in 1/3 octave bands at M5 microphone for 63 m/s crossflow velocity. Closed Bay.

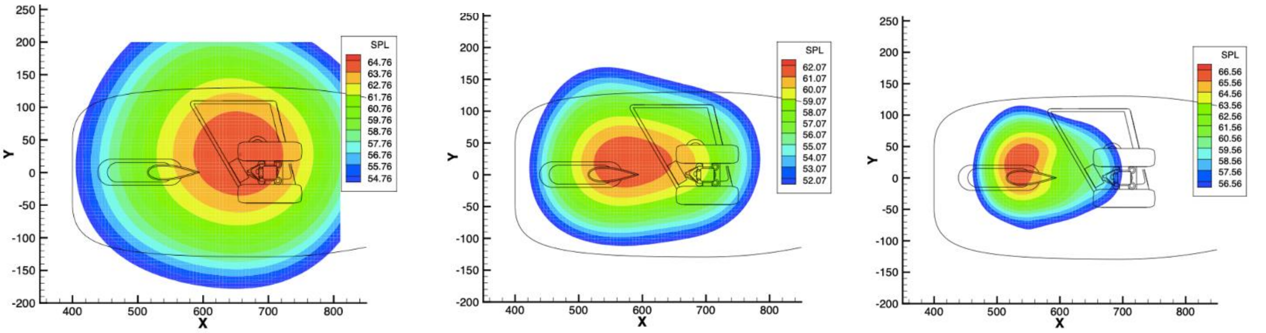
6.2 Air Tube Nozzle

To gain further insight, beamforming results were examined. Beamforming results of the AT test with 7 bar air supply pressure and 63 m/s crossflow show large sound level reductions up to 10kHz, with a maximum reduction of 7.3 dB observed from the top array at the 5kHz 1/3 octave band. Beam forming permitted the visualisation of the noise source and hence the cause of the acoustic changes was studied. A redistribution of the noise source was evident, with the landing gear generating lower levels of noise at all frequencies. Below 10kHz, while the AT did contribute to noise levels, overall noise levels were reduced. Above 10kHz, the AT became the dominant source of noise and was responsible for an increase in overall levels. This analysis is shown for various frequency bands with a top view of the landing gear in Figures 12 & 13 and a side view of the landing gear in Figures 14 & 15.



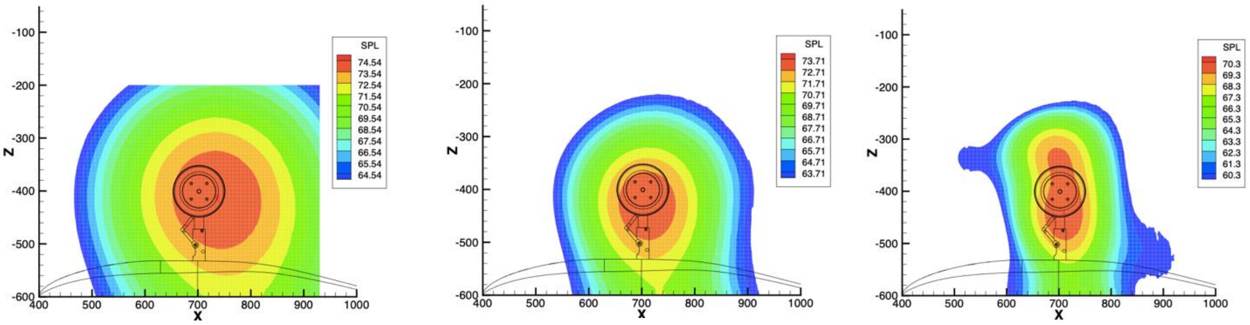
(a) 3150 Hz (b) 5000 Hz (c) 10000 Hz

Figure 12. Reference landing gear configuration beam forming results for top array with 63 m/s and cavity closed



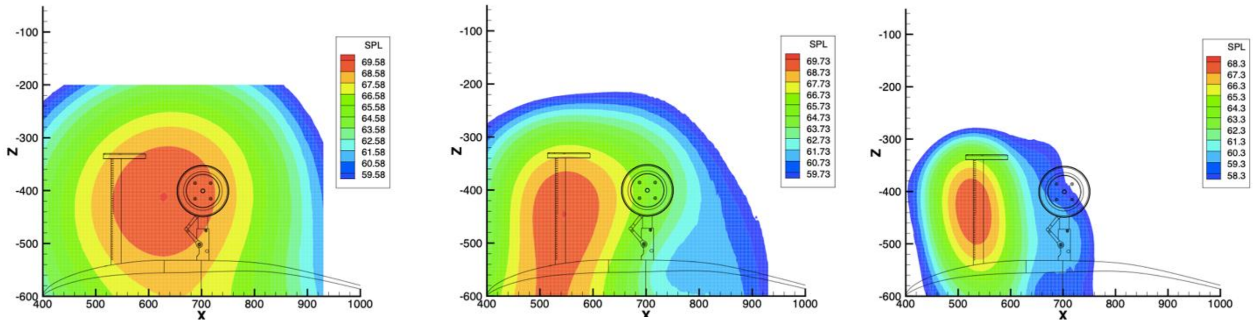
(a) 3150 Hz [-6 dB] (b) 5000 Hz [-7.3 dB] (c) 10000 Hz [+3 dB]

Figure 13. AT landing gear configuration beam forming results for top array with 63 m/s



(a) 2500 Hz (b) 4000Hz (c) 6300Hz

Figure 15. Reference landing gear configuration beam forming results for side array with 63 m/s and cavity closed



(a) 2500 Hz [-5 dB] (b) 4000 Hz [-4 dB] (c) 6300 Hz [-2 dB]

Figure 14. AT landing gear configuration beam forming results for side array with 63 m/s and cavity closed

6.3 Local Nozzles

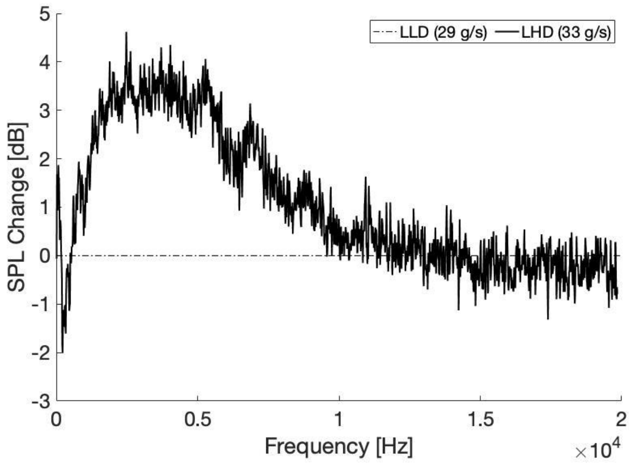


Figure 16. Change in frequency spectra at M2 microphone with 7 bar air pressure and no crossflow.

In D2.12 it was discussed how shielding is a function of momentum and therefore if choked flow could be maintained, that a greater number of holes causing a higher outlet area and therefore mass flow should result in greater shielding. It was unsure at the time, however, if there would be a negative impact on noise. Tests were conducted with the local nozzles, LHD and LLD, to assess the impact of the hole density variation of the two nozzles on acoustic output. For these tests, the nozzles were individually tested in the LLD Main Leg and LHD Main Leg configurations, with no cross flow and 7 bar air pressure. The results of this analysis are presented in Figure 16, indicating that the LHD nozzle produced more low frequency noise while producing similar levels of high frequency noise.

6.4 Air Blade Nozzle

While the AB showed little potential for sound reduction in the tests discussed above for the closed bay, the impact of the AB on noise levels with and without cavity closure was also investigated. Figure 17 illustrates the impact of the AB on noise levels with each of the two bay cavity configurations. The AB showed greater potential for noise reduction with the open cavity configuration, and achieved reductions at multiple frequencies.

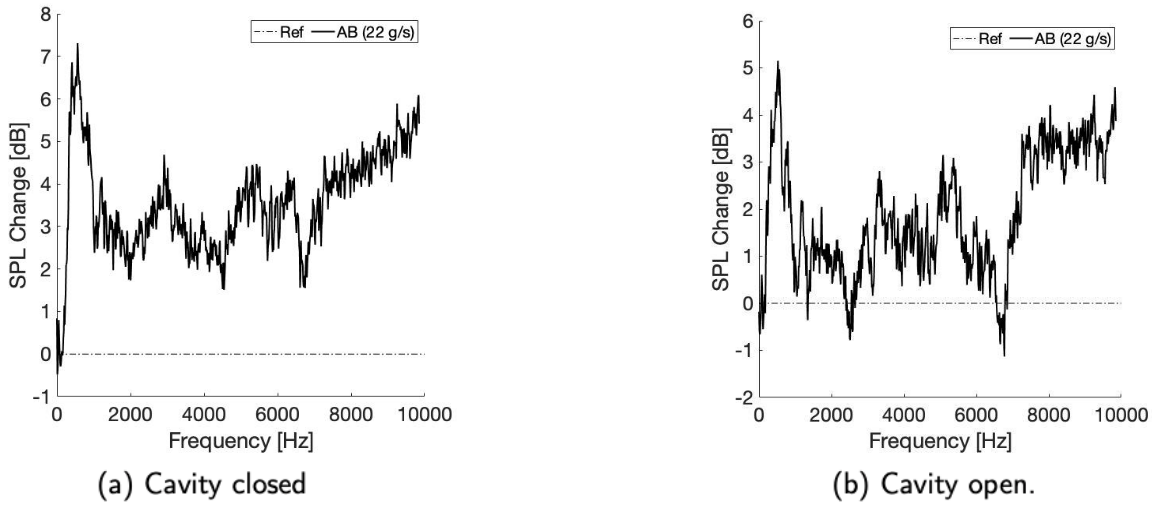
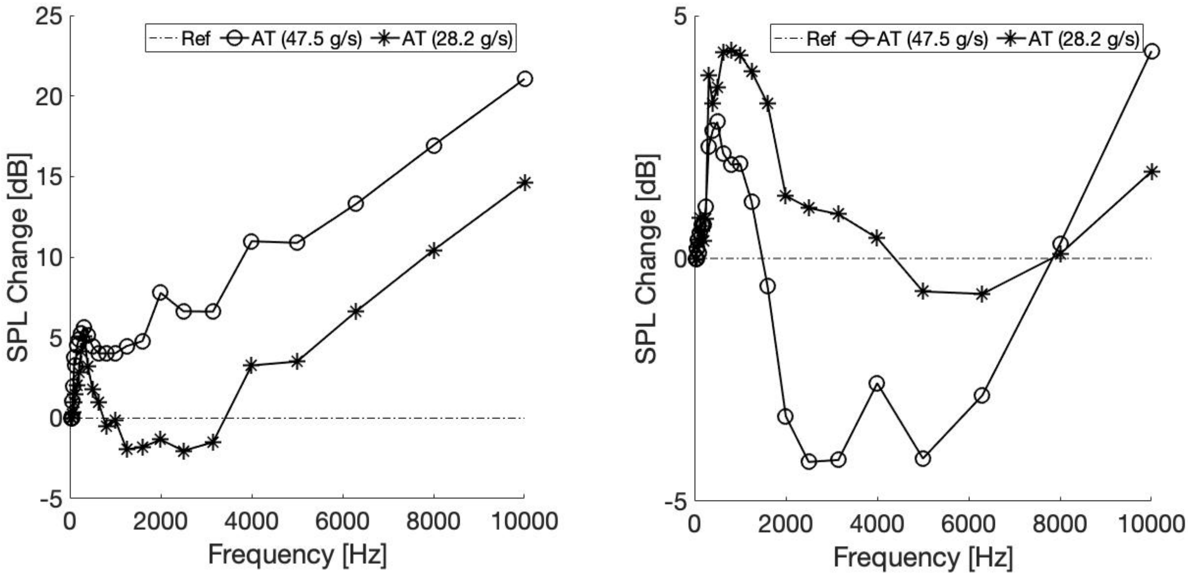


Figure 17. Frequency spectra at M2 microphone for AB cavity open and closed at 63 m/s crossflow velocity.

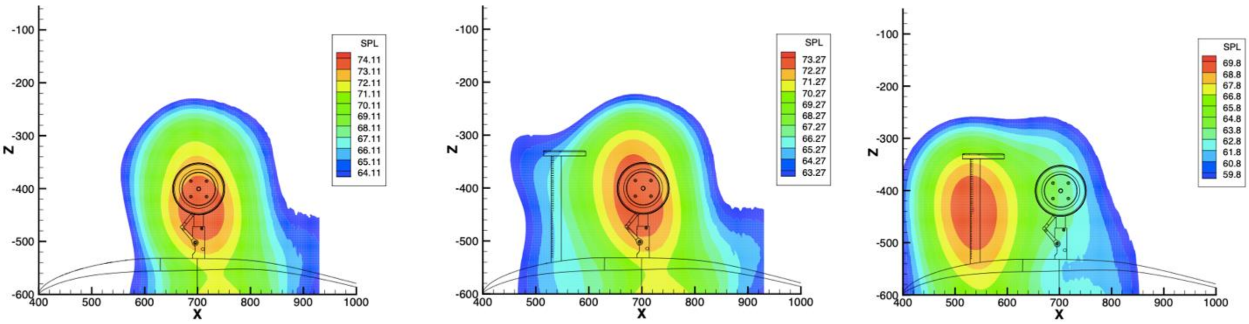
6.5 Mass Flow Rate Influence



(a) 30 m/s (b) 63 m/s

Figure 18. Change in 1/3 octave bands at M5 microphone for varying flow rates and crossflow velocities with AT. Cavity Closed.

Further analysis of the AT configuration was performed in which the nozzle pressure was varied. The AT was supplied with pressures of 2 bar (28.2 g/s) and 7 bar 47.5 g/s), and was subjected to cross-flows of 30 m/s and 63 m/s. The change in the 1/3 octave bands from the reference tests are shown in Figure 18. As previously mentioned, the nozzle supplied with 7 bar did not achieve noise reductions

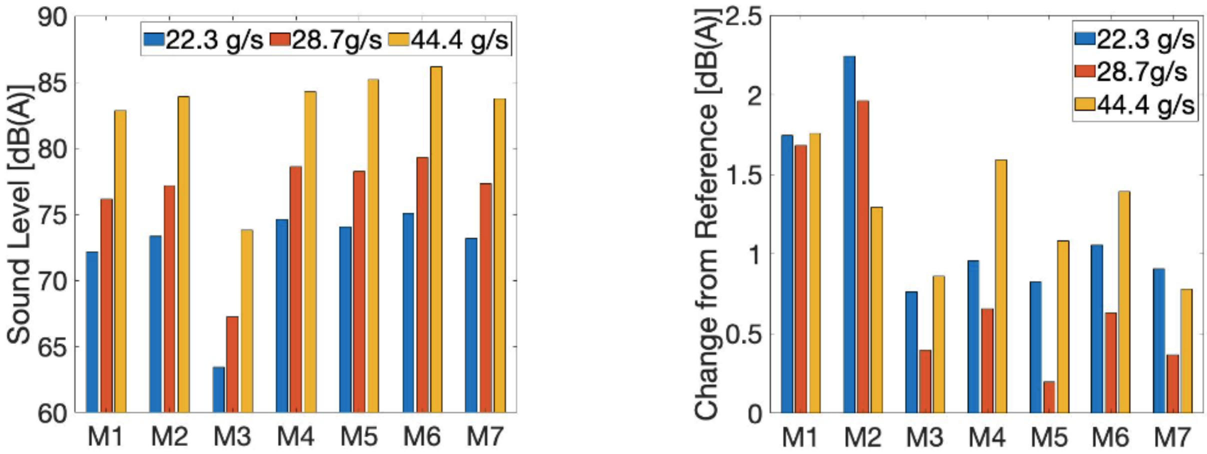


(a) Reference (b) AT (2 bar pressure) (c) AT (7 bar pressure)

Figure 19. Flow rate comparison at 5 kHz for AT with cavity closed and 63m/s crossflow velocity.

at 30 m/s crossflow due to the high self-noise of the nozzle. Interestingly, the AT achieved noise reductions at this crossflow velocity when supplied with 2 bar, as shown in Figure 18(a). However, with 63 m/s crossflow, a far more significant the noise reduction was achieved with 7 bar pressure. Figure 19 provides insight into this, as the side array beam forming results indicate that at the 5 kHz frequency, adequate shielding was not achieved by the AT pressurised at 2 bar (b). Therefore, the dominant noise source in the system was aerodynamic noise of the landing gear, as indicated by the beamforming. When supplied with 7 bar pressure (c), adequate shielding was achieved such that the landing gear was not a dominant source of noise but rather the nozzle, albeit at lower levels as shown by the scale in the figure.

The AB & LHD Wheel combined configuration was used for further analysis of the effect of low mass flow. Nozzle air pressures of 2.7, 3.8 and 6.9 bar were used, yielding mass flow rates of 22.3, 28.7 and 44.4 g/s respectively. In the absence of cross flow, increases in mass flow rate corresponded to increases in self noise levels, as shown in Figure 20(a). When subjected to a cross flow of 63 m/s, higher sound levels were recorded for all microphones compared to the reference, again highlighting the failure of this configuration to effectively reduce noise levels. However, as shown in Figure 20(b), reductions in sound levels were observed across all microphones when the flow rate was increased from 22.3g/s to 28.7 g/s. This would suggest greater shielding was achieved which yielded acoustic performance gains that dominated over the associated increase in self noise. Furthermore, with the exception of the M2 microphone location, further increasing the mass flow rate to 44.4 g/s resulted in an increase in the sound levels. Suggesting increases in self noise dominated over corresponding noise reductions due to the increased shielding effect at this higher flow rate. This indicates an optimum flow rate likely lies between 22.3 and 44.4 g/s in which nozzle self-noise and aerodynamic shielding are balanced.



(a) Sound levels with varying mass flow rate and no cross flow.

(b) Sound level change with respect to the reference in a 63 ms^{-1} cross flow.

Figure 20. Impact of nozzle pressure on sound levels for AB & LHD Wheel configuration.

7 Dassault GB-TA-MLG1 Landing Gear with Air Curtain Nozzles

Consistent with the findings of the Lagoon Landing Gear study, the majority of configurations resulted in noise increases at the majority of frequencies, however, the AT configuration, once again, was effective in achieving meaningful noise reductions, this time in the 1-8 kHz range. Such noise reductions are clearly evident in the 1/3 octave band spectra shown in Figure 21. These plots indicate a clear noise reduction of up to 5 dB across a range of frequencies, with the use of the AT configuration. Above 10 kHz, as in the previous study, self-noise of each nozzle dominated.

Observations of the suppression of noise at a narrow range of frequencies, such as the suppression of a tone, was more commonly observed with this landing gear. Figure 22 demonstrates the presence of low frequency tones in the narrow band frequency spectra in the absence of air curtain nozzles. The tonal frequency is known to scale with the crossflow velocity, and such a phenomenon is clearly present as indicated by the red circles. This occurrence is likely due to the complex geometry of the GB-TA-MLG1 which likely produces a greater number of tones than the Lagoon, due to the greater number of cavities, connections and components. Local nozzles in a range of configurations were successful in supressing such tones, as indicated by the results at 45 m/s in Figure 23. These results indicate that each of the analysed nozzles in the side leg/main leg area were successful.

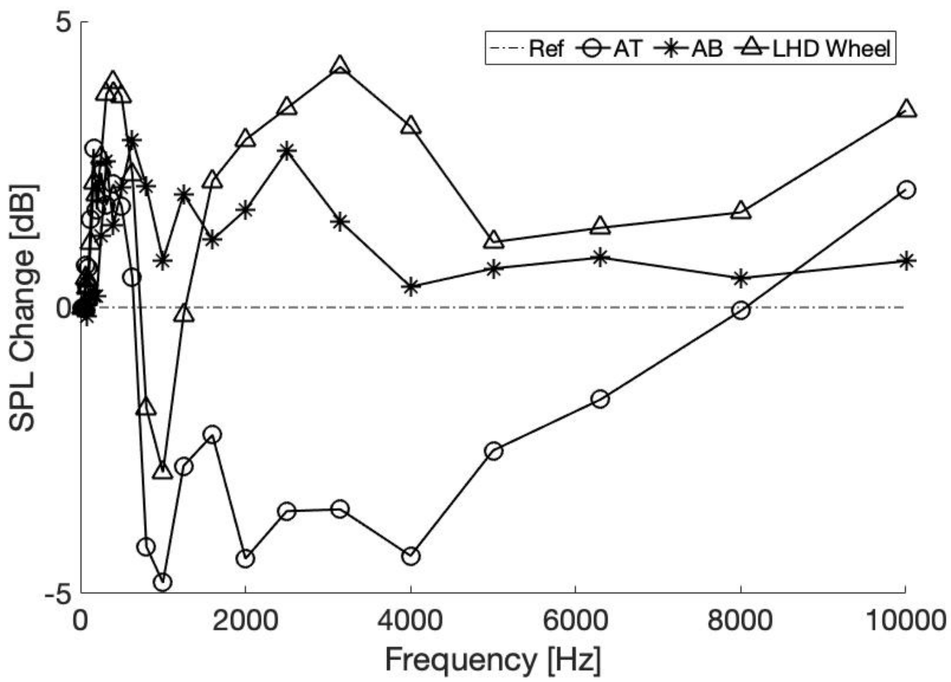
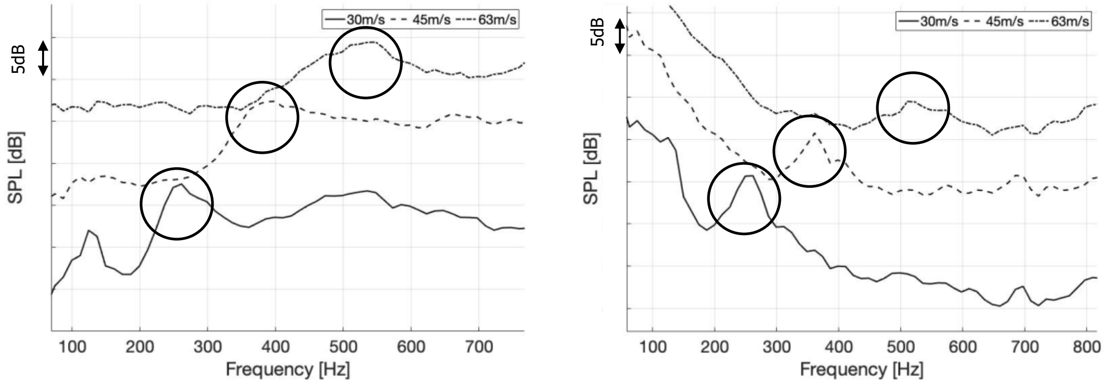
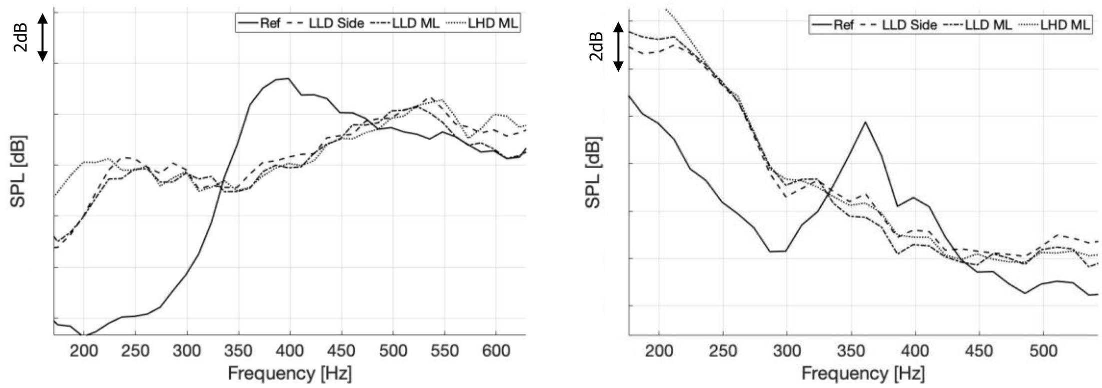


Figure 21. Change in 1/3 octave bands at M4 microphone for 63 m/s crossflow. Cavity Open.



(a) M2 microphone (b) M7 microphone

Figure 22. Analysis of tones at M2 and M7 microphones. Cavity Open.

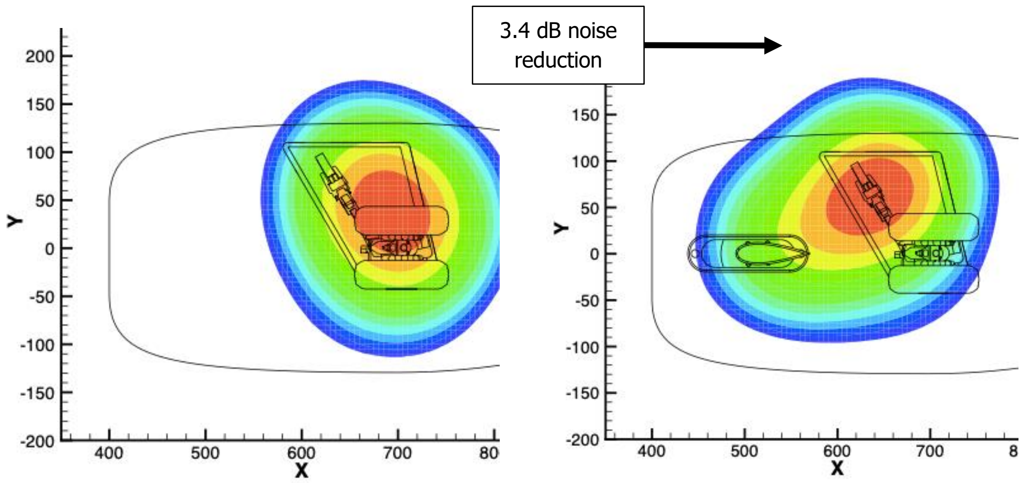


(c) M2 microphone (d) M7 microphone

Figure 23. Suppression of tones at M2 and M7 microphones with 45 m/s crossflow. Cavity Open.

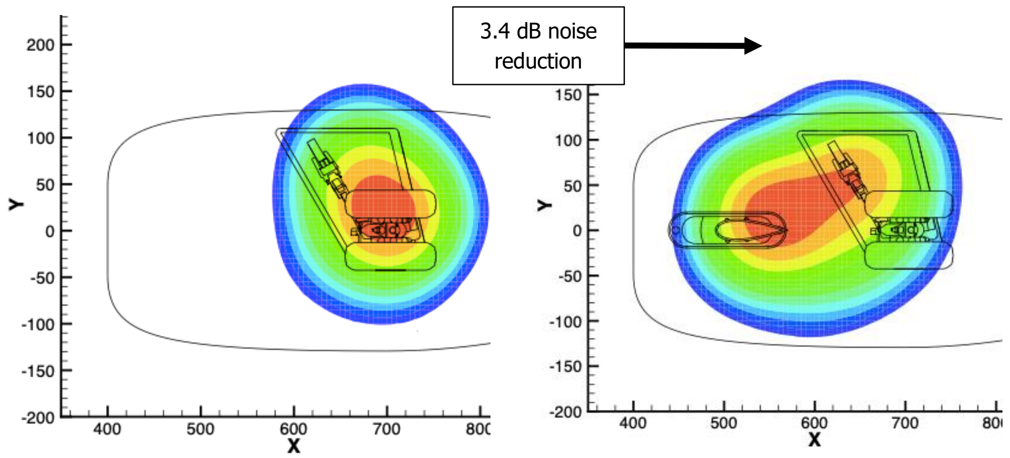
7.1 Air Tube Nozzle

Beamforming plots of the 1/3 octave bands present similar findings to that of the frequency plots presented previously. Figures 24 & 25 present the beamforming results for the 5000 Hz and 6300 Hz frequency bands and indicate noise reductions of approximately 4 dB for the AT configuration with the bay cavity open and 63m/s crossflow velocity. This is consistent with the noise reductions observed in Figure 21 which also referred to a top view of the landing gear (M4 microphone). Beamforming results from the side array indicate greater noise reductions of up to 6 dB in the 3150 Hz and 5000 Hz frequency bands, as shown in Figures 26 & 27. As expected, at the higher frequencies, the self-noise of the nozzle dominates over that of the landing gear and leads to an increase in overall noise levels and a shift of noise source from the landing gear to the nozzle outlet. This effect is shown clearly at the 10 kHz frequency band in Figure 28.



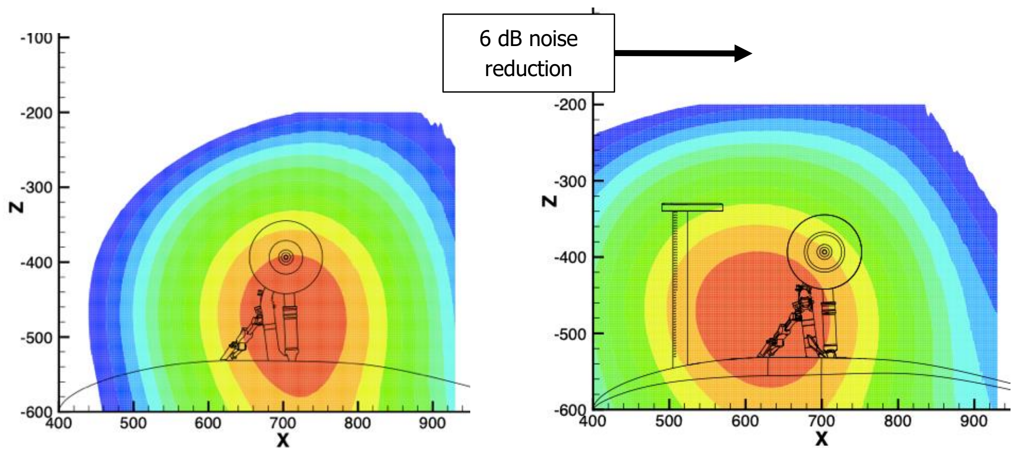
(a) Reference (b) Air Tube

Figure 24. 5000Hz top array results for AT nozzle with cavity open and 63m/s crossflow velocity.



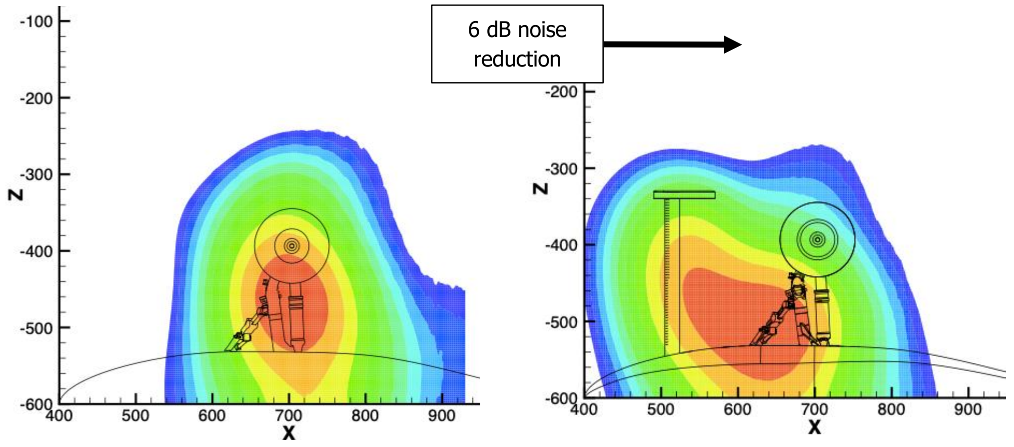
(a) Reference (b) Air Tube

Figure 25. 6300Hz top array results for AT nozzle with cavity open and 63m/s crossflow velocity.



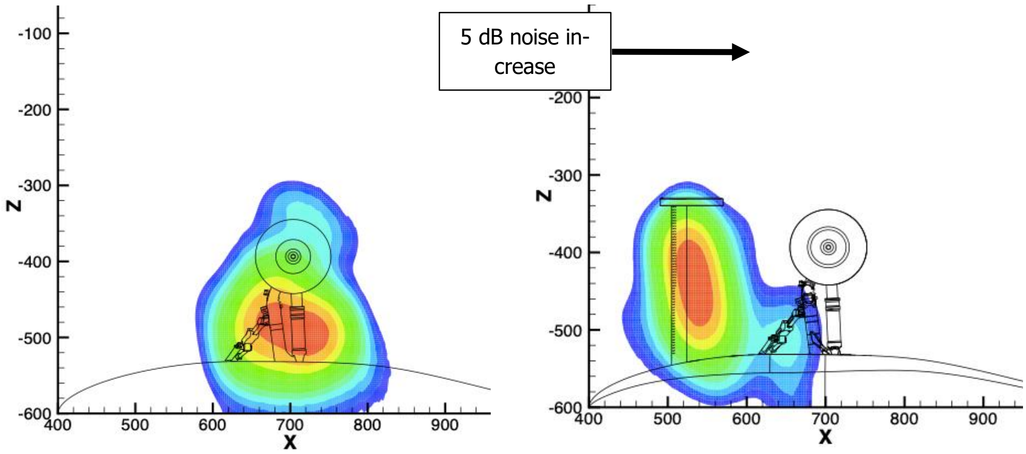
(a) Reference (b) Air Tube

Figure 26. 3150Hz side array results for AT nozzle with cavity open and 63m/s crossflow velocity.



(a) Reference (b) Air Tube

Figure 27. 5000Hz side array results for AT nozzle with cavity open and 63m/s crossflow velocity.

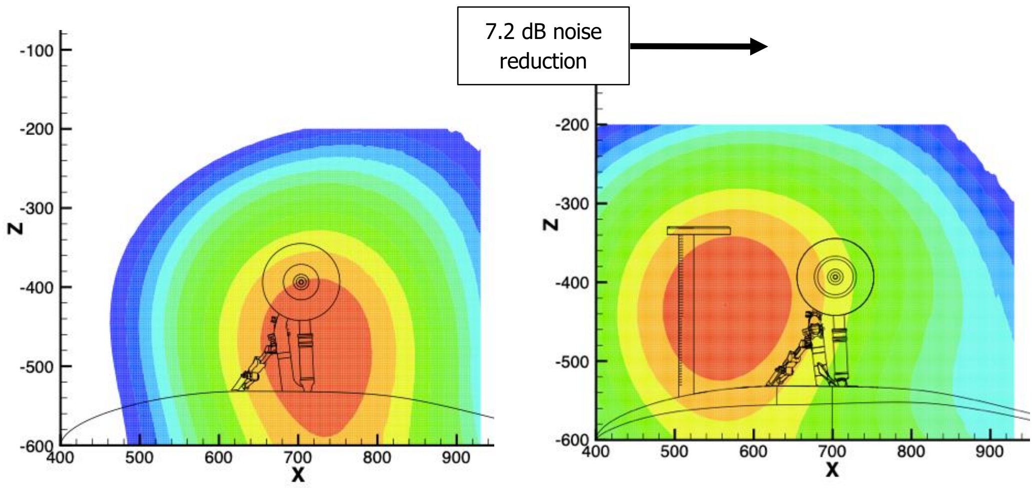


(a) Reference (b) Air Tube

Figure 28. 10000Hz side array results for AT nozzle with cavity open and 63m/s crossflow velocity.

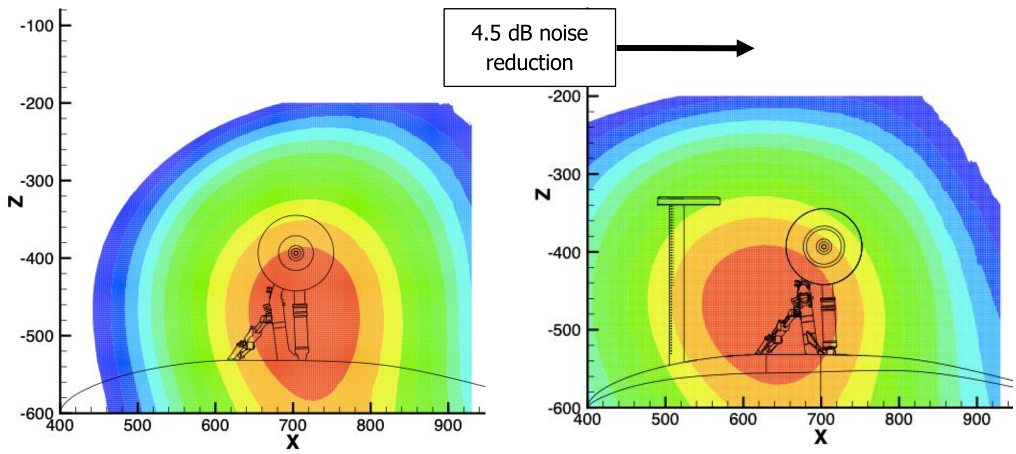
7.1.1 Side Stay

As discussed in the Baseline Analysis section, the side stay did not contribute significantly to landing gear noise in the absence of nozzles, in the 0-10 kHz range which was the primary focus of this study. However, beamforming results indicate that it did interfere with the ability of the AT to reduce noise in this range. Figures 31 & 34 present the results of the 3150 Hz frequency band without and with the side stay respectively. Similarly, Figures 34 to 34 present the equivalent data for the 5000 Hz frequency band. It can be noted that a reduction in noise levels was observed in both cases, however the noise reduction with the side stay was less significant than without the side stay. Hence it was concluded that the extra spanwise shielding requirement presented by the presence of the side stay impairs the ability of the AT to completely shield the full landing gear. It should be noted however that the triple jet geometry of the AT was designed to maximise shielding in the wheel region only. An adapted design featuring triple jet geometry along the full length of the AT on the side stay side may further improve performance with the side stay attached.



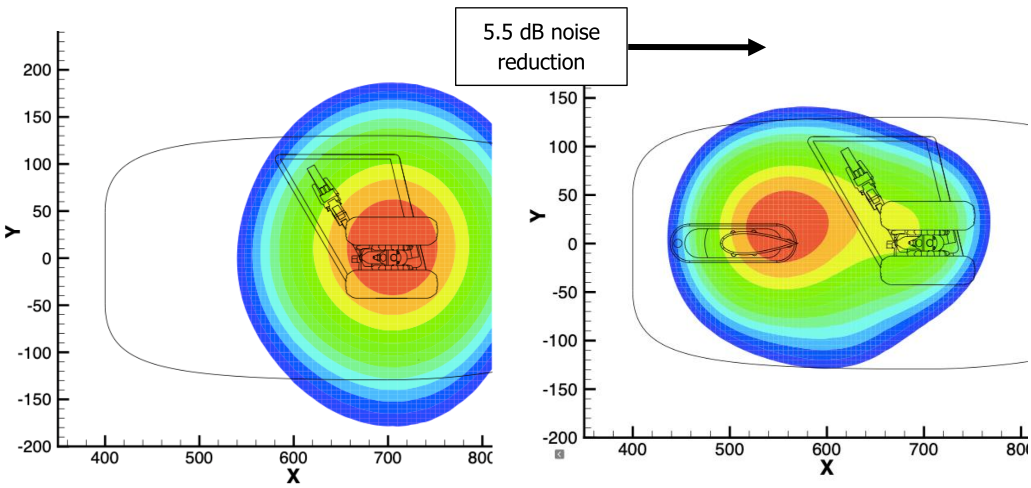
(a) Reference (b) Air Tube

Figure 31. 3150Hz side array results for AT nozzle with cavity closed, no side stay and 63m/s crossflow velocity. (NOTE. The image shows a side stay but none was present for this test)



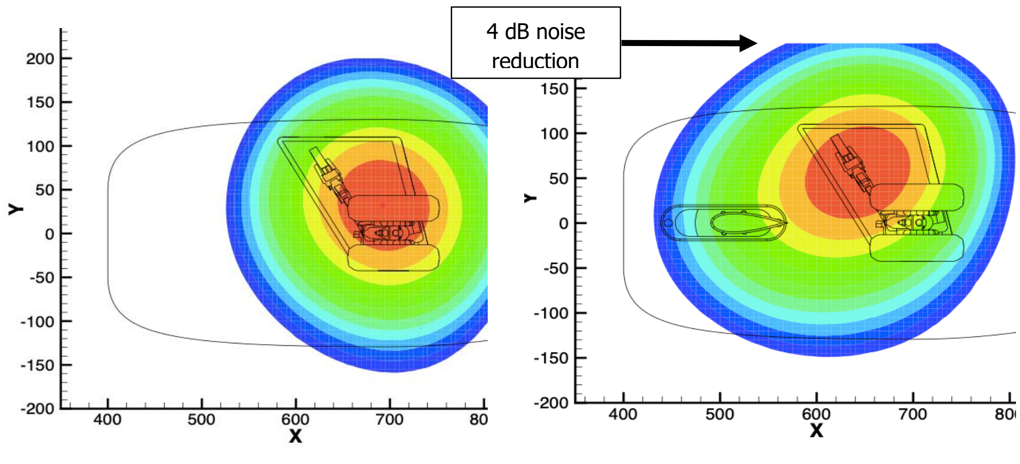
(a) Reference (b) Air Tube

Figure 30. 3150Hz side array results for AT nozzle with cavity closed, with side stay and 63m/s crossflow velocity.



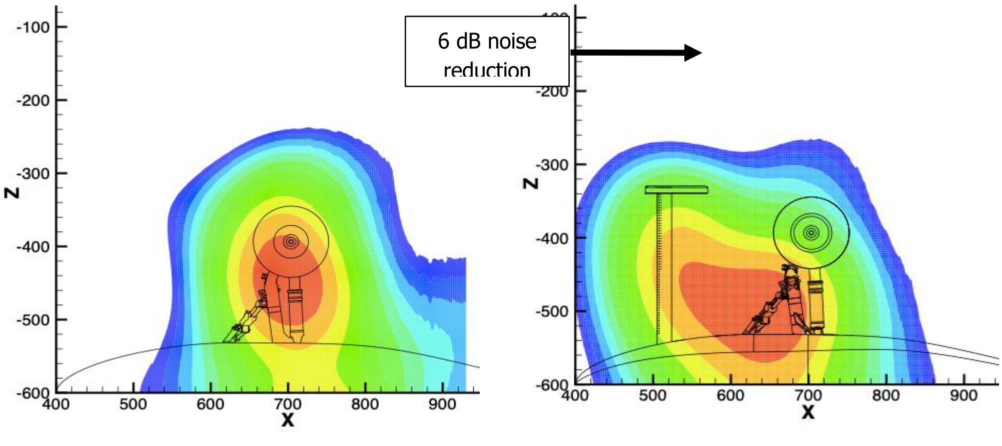
(a) Reference (b) Air Tube

Figure 29. 4000Hz top array results for AT nozzle with cavity closed, no side stay and 63m/s crossflow velocity. (NOTE. The image shows a side stay but none was present for this test)



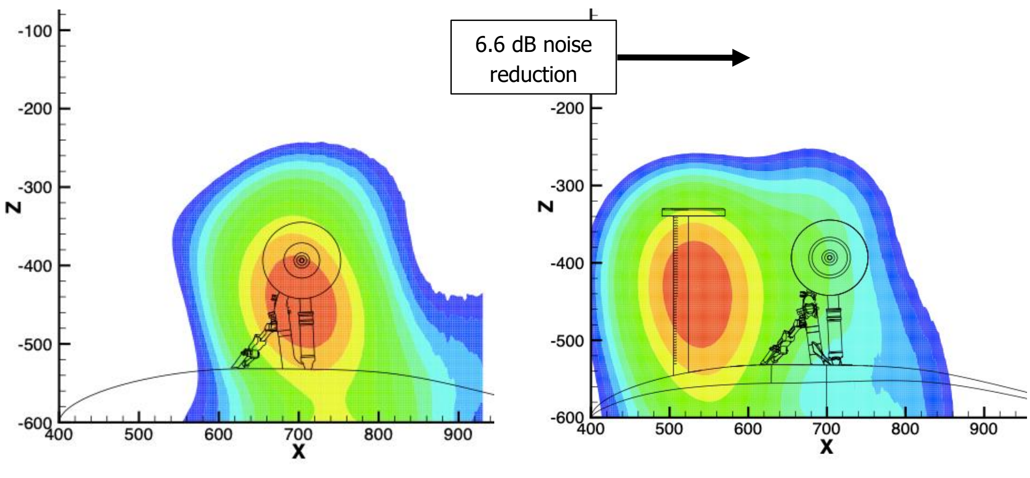
(a) Reference (b) Air Tube

Figure 34. 4000Hz top array results for AT nozzle with cavity closed, <u>with side stay</u> and 63m/s crossflow velocity.



(a) Reference (b) Air Tube

Figure 33. 5000Hz side array results for AT nozzle with cavity closed<u>, with side stay</u> and 63m/s crossflow velocity.



(a) Reference (b) Air Tube

Figure 32. 5000Hz side array results for AT nozzle with cavity closed, <u>no side stay</u> and 63m/s crossflow velocity. (NOTE. The image shows a side stay but none was present for this test)

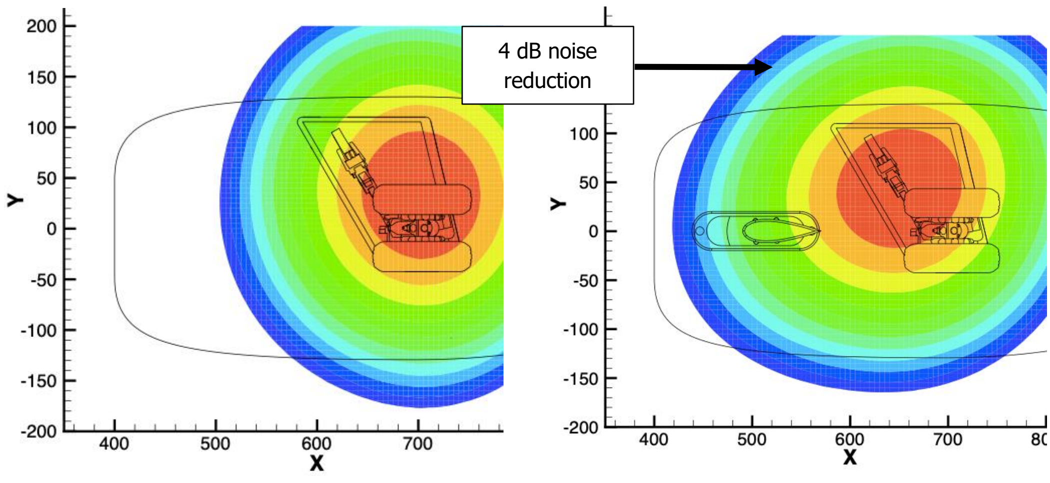
7.1.2 Cavity Open Vs. Cavity Closed

As mentioned in the Baseline Analysis section, the cavity closed configuration presents a noise reduction compared to cavity open, in the absence of air curtains. In the presence of the AT nozzle configuration, the difference between cavity open and cavity closed is minor for frequencies of 5 kHz and above, as would be expected as the noise increase in the baseline tests due to cavity open was most significant in the low frequencies (0-4 kHz). At frequencies below 5 kHz, increases in noise reduction were observed with the cavity open configuration, such as observed at the 3150 Hz frequency band shown in Figures 35 to 38. This finding suggests that a component of the noise reduction with the cavity open can be attributed to cavity noise suppression.

A further analysis of the cavity noise suppression effect is presented in Figure 39, which displays the change in SPL from each configurations respective reference. As expected, the configuration with no side stay presents the greatest noise reduction. In addition, the cavity open configuration exhibits greater noise reduction compared to that of the cavity closed configuration. It must be noted however that these SPL changes are not with respect to the same reference, and the absolute SPL levels of the AT configuration with cavity open are in fact higher. Nonetheless, this offers an interesting opportunity to gain insight into the contribution of the cavity noise to the overall noise reduction capabilities of the AT.

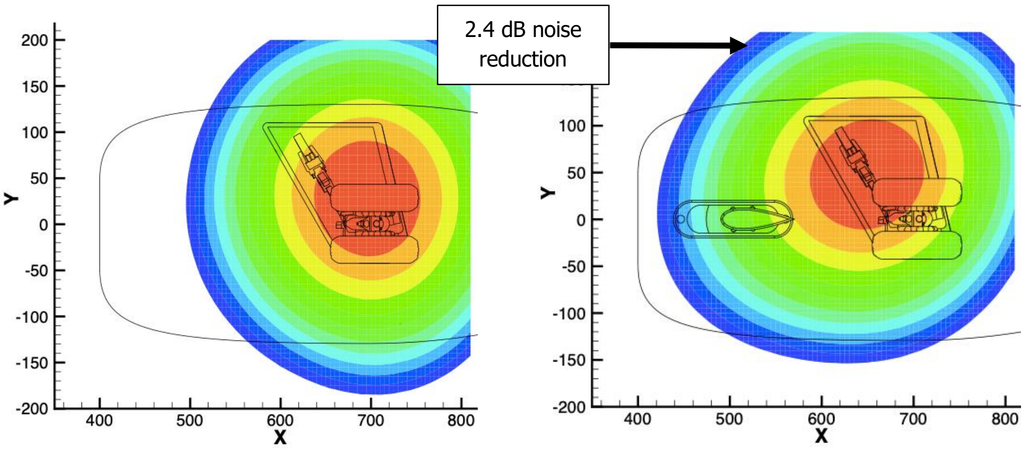
Figure 40(a) illustrates the level of cavity noise present in the 1/3 octave bands. Clearly, this is highest between 500 Hz and 2000 Hz, and the AT reduces the levels by up to 4 dB in some octave bands. Figure 40 (b) illustrates the contribution of cavity noise reduction to total noise reduction with the AT configuration. In the low frequencies (below 2000 Hz), almost the entire noise reduction can be attributed to cavity noise reduction rather than landing gear noise reduction, while at higher frequencies it represents a lesser proportion of total noise reduction.

While this section of the report focuses on the GB-TA-MLG1, it is worth noting that this same analysis was performed on the Lagoon landing gear and the same conclusions could be drawn. A summary of the analysis is presented in Figure 41.



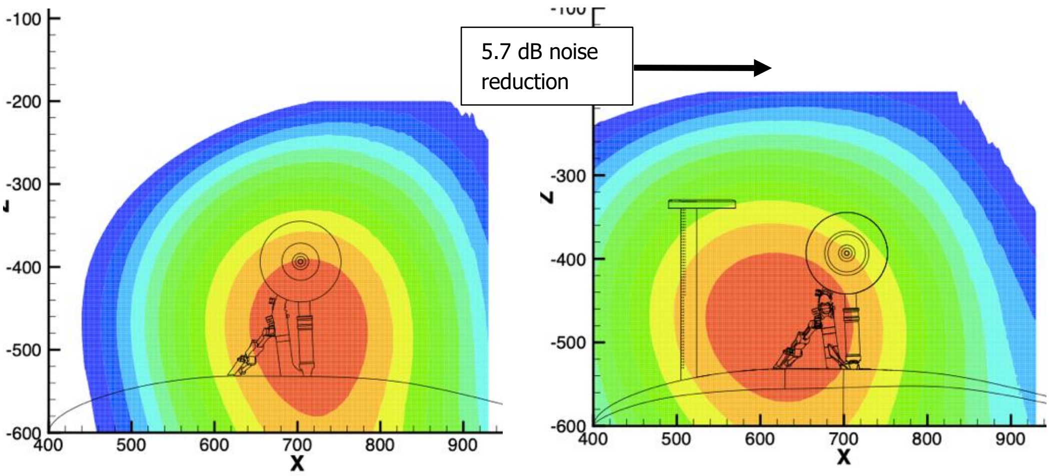
(a) Reference (b) Air Tube

Figure 35. 3150Hz top array results for AT nozzle with cavity open and 63m/s crossflow velocity. With side stay



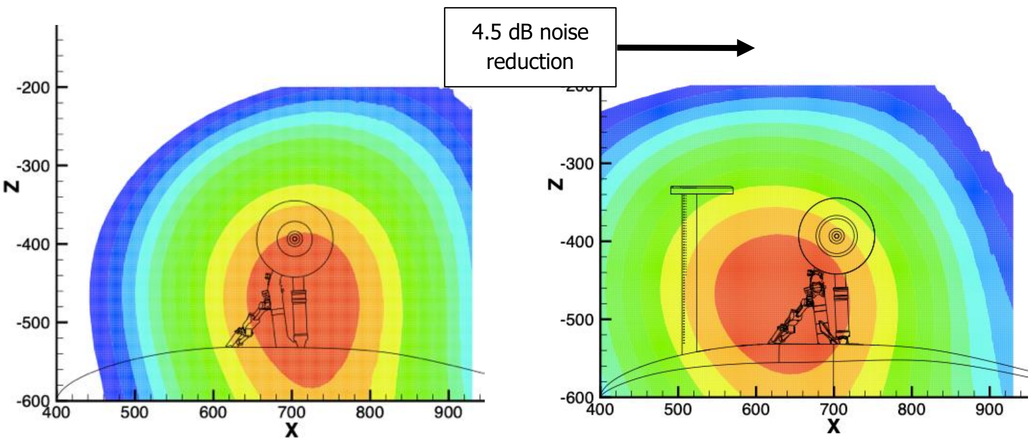
(a) Reference (b) Air Tube

Figure 36. 3150Hz top array results for AT nozzle with cavity closed and 63m/s crossflow velocity. With side stay



(a) Reference (b) Air Tube

Figure 37. 3150Hz side array results for AT nozzle with cavity open and 63m/s crossflow velocity. With side stay



(a) Reference (b) Air Tube

Figure 38. 3150Hz side array results for AT nozzle with cavity closed and 63m/s crossflow velocity. With side stay

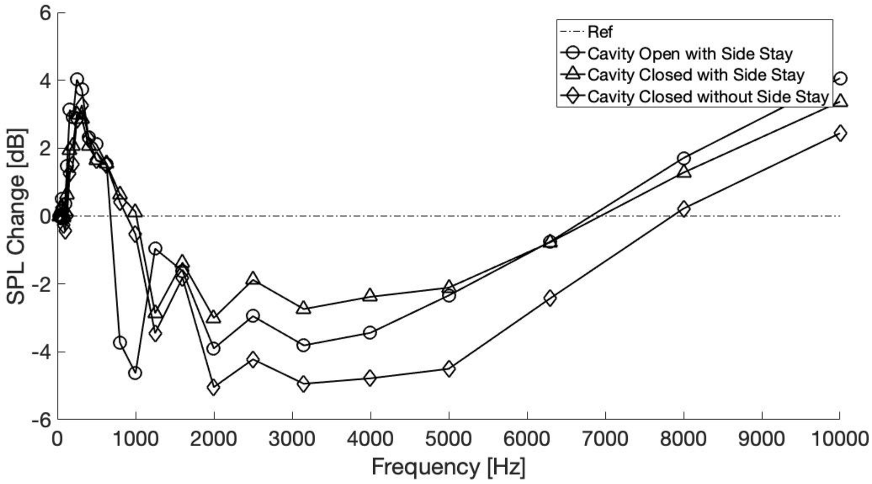
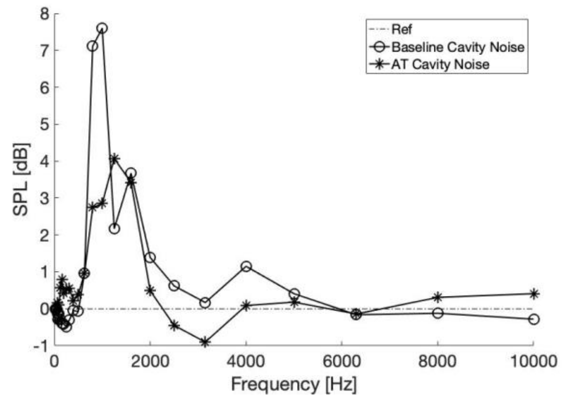
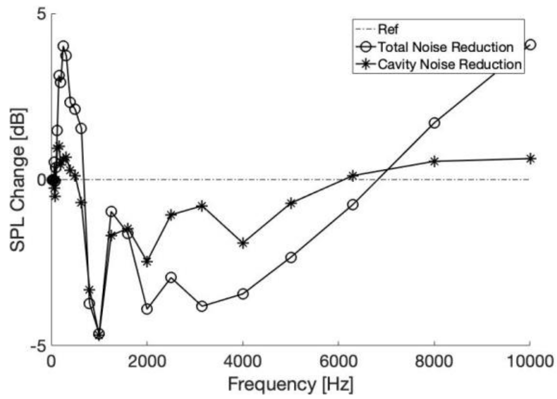


Figure 39. Noise reduction achieved by various AT configurations with mass flow rates of 47-48 g/s at the M6 microphone in 63 m/s crossflow.

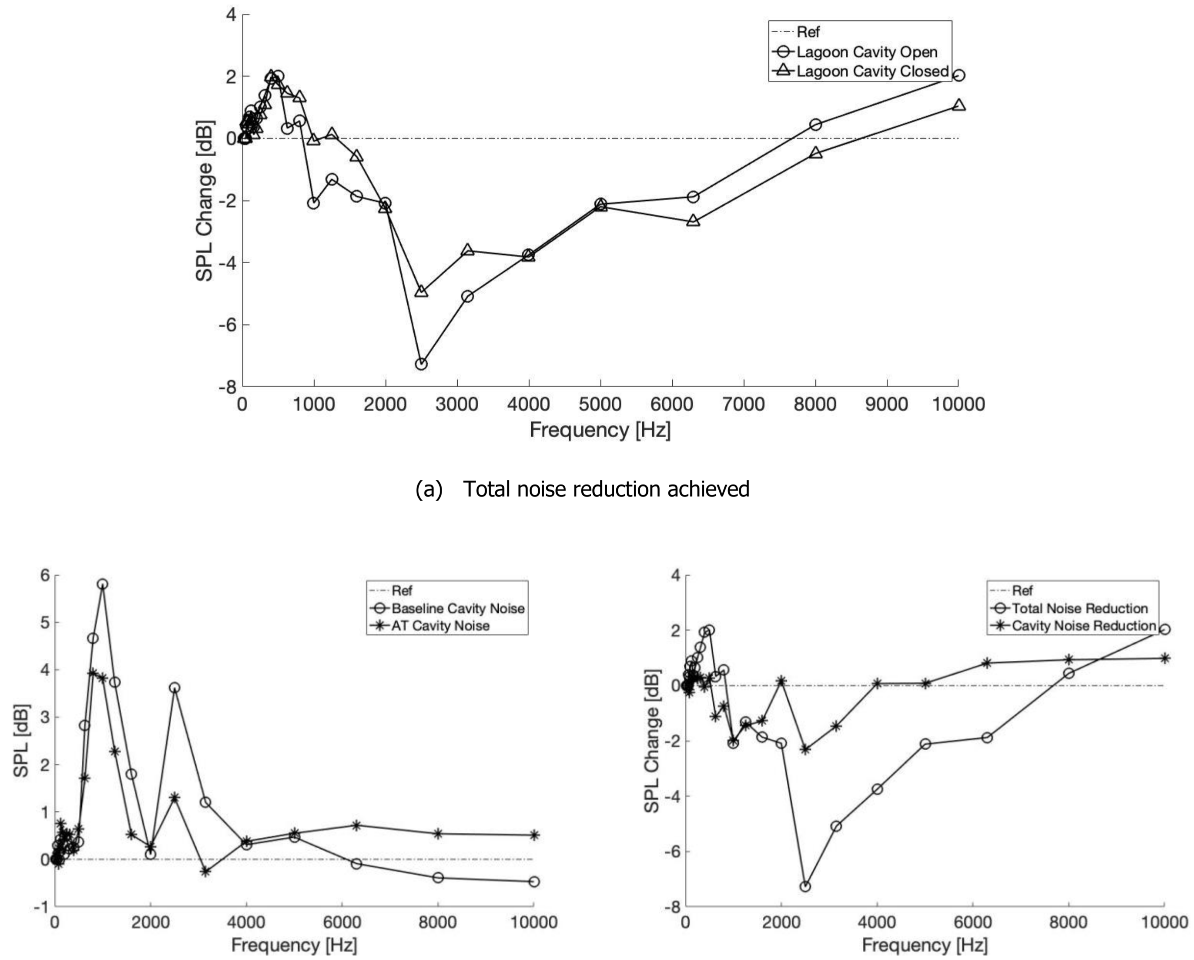


(a) Cavity noise for baseline and AT



(b) Cavity noise reduction contribution

Figure 40. Cavity noise analysis at M6 microphone for AT with 47.3 g/s mass flow rate in 63 m/s crossflow



(a) Total noise reduction achieved

(b) Cavity noise levels

(c) Cavity noise contribution to total

Figure 41. Lagoon landing gear cavity noise analysis with 48 g/s flow rate, at M3 microphone in 63 m/s crossflow

7.2 Air Blade

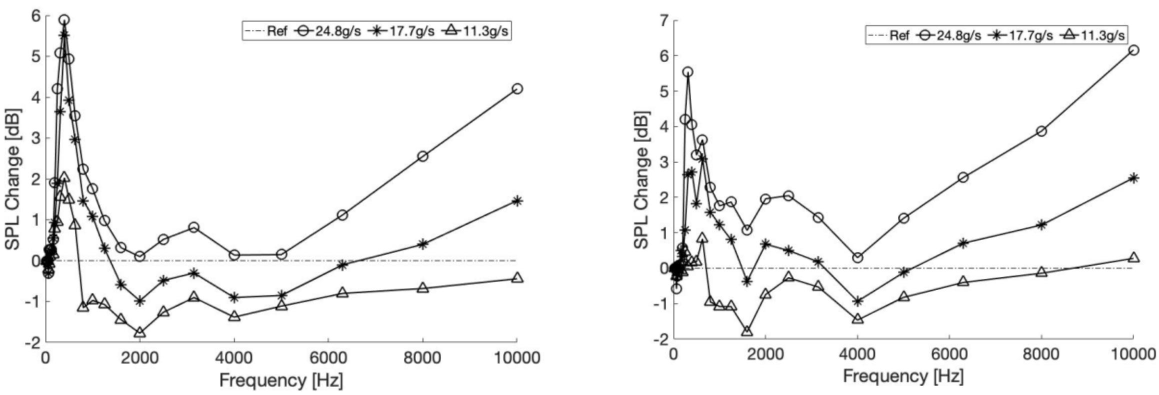
While the Lagoon study found only a limited amount of noise reduction was achieved with the AB configuration, more significant noise reductions were observed with the GB-TA-MLG1. This noise reduction was however highly sensitive to mass flow rate and was only observed when the bay cavity was open. Figure 42 illustrates that a noise reduction was achieved throughout the 0-10 kHz frequency range by the configuration with the bay cavity open and with a low flow rate of 11 g/s. Higher flow rates led to a reduction in noise reduction performance, with the highest flow rate tested leading to a noise increase. This effect is evident from both the top (Figure 42(a)) and the side (Figure 42(b)) microphones, hence highlighting its significance for noise reduction applications. Beamforming plots shown in Figures 44 & 45 also highlight the noise reduction. As flow visualisation experiments and Lagoon tests concluded, the AB does not provide sufficient shielding to completely shield the landing gear, it was hypothesised that this noise reduction was due to the suppression of bay cavity noise rather than landing gear noise. This hypothesis is validated by the results in Figure 43 which indicate that no noise reduction was achieved when the cavity was closed.

Clearly the lowest flow rate yields more favourable acoustic performance than the higher flow rate, seemingly contradictory to previous results which found the AT configuration on the Lagoon landing gear produced more noise reduction at higher mass flow rates.

However, this discrepancy is likely explained by two factors;

- With the bay cavity closed, the configuration was ineffective at achieving noise reduction, suggesting that the noise reduction was in fact the suppression of bay cavity noise as opposed to landing gear noise. Therefore, the fundamental noise reduction mechanism is slightly different and hence the two shouldn't be directly compared.
- It is likely that rather than maximising or minimising flow rate yielding more favourable results, an optimum mass flow rate probably exists whereby the effects of flow deflection and nozzle self-noise are balanced such as to yield a maximum noise reduction.

Nonetheless, these results indicate potential for this configuration and suggest that rather low flow rates may be effective in achieving desirable results.



(a) M2 microphone (top) (b) M6 microphone (side)

Figure 42. 1/3 octave bands for M2 and M6 microphones with bay cavity open and a range of mass flow rates in the AB and 63 m/s cross flow velocity. No side stay.

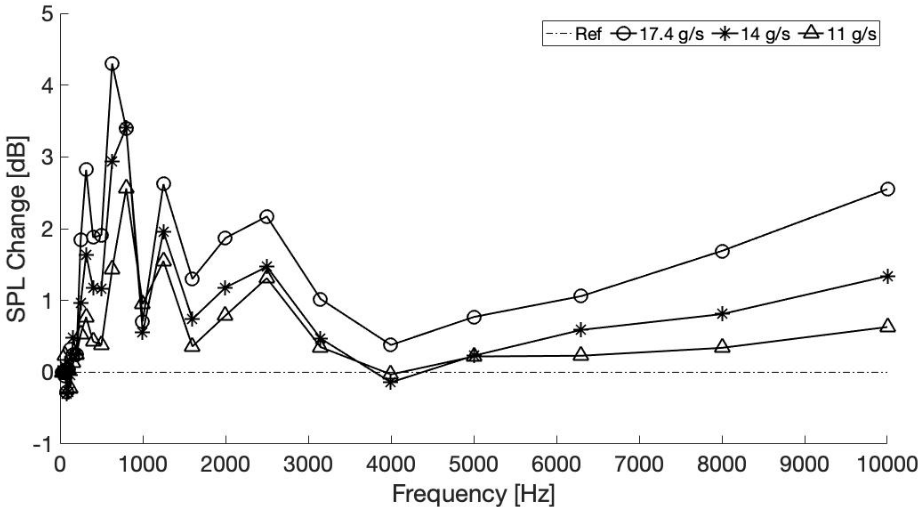
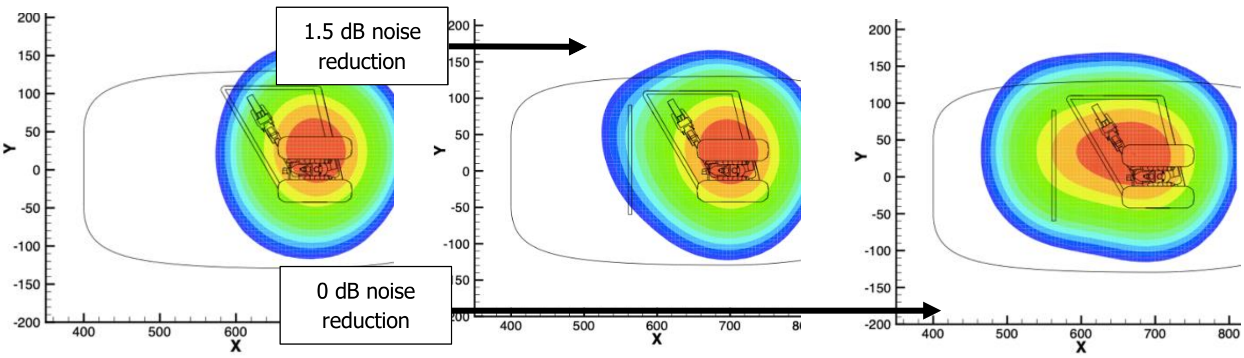
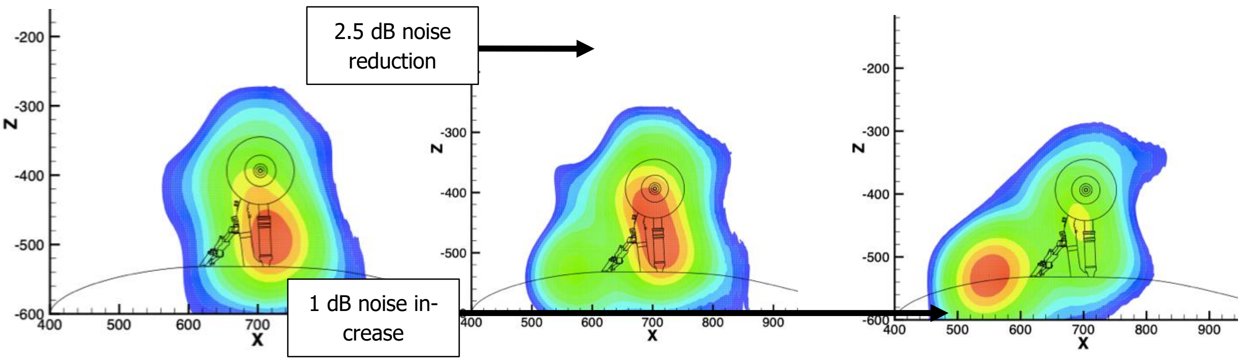


Figure 43. 1/3 octave bands for M6 microphone with bay cavity closed and a range of mass flow rates in the AB and 63 m/s cross flow velocity. With Side Stay.



(a) Reference (b) AB 11.3 g/s (c) AB 24.8 g/s

Figure 44. 5000Hz, top array, 63 m/s crossflow velocity, AB with no side stay and bay cavity open



(a) Reference (b) AB 11.3 g/s (c) AB 24.8 g/s

Figure 45. 8kHz, side array, 63 m/s crossflow velocity, AB with no side stay and bay cavity open

8 Conclusions

1. The Dassault Streamline shape with cavity closed, in isolation, adds little noise over the baseline of the flat plate as required. An example using a single microphone (M2) shows an increase of less than 0.5 dB on average over the full frequency range of up to 10 kHz. Of course, its presence when used with a landing gear installed will cause the air flow to accelerate over the gear and so it's contribution to the overall noise is not so straightforward.
2. The presence of the cavity adds between 2 dB to 6 dB in the frequency range of 500 Hz to 5 kHz and between 1 dB and 2 dB in the range 5 kHz to 10 kHz. Once again, this is an isolated measurement and the output could vary due to installation effects once the gear, door or nozzles, for example, are installed.
3. Preliminary flow visualization tests show that the air curtains are capable of redirecting the flow around the landing gear per the fundamental objective.
4. For a **closed** cavity, the Lagoon-*Like* gear creates between 10 dB and 15 dB in a frequency range of 2 kHz to 10 kHz. The Dassault gear, due to its added complexity, contributes approximately 3 dB more noise in the same frequency range with the exception of some frequency ranges where the noise output is the same as the Lagoon-*Like* gear. In addition, the Dassault gear appears to generate a tone at approximately 400 Hz.
5. For an **open** cavity, when compared to the open cavity baseline, both the Lagoon-Like and Dassault gear generate similar amounts of noise as each other viz. 5 dB – 8 dB in the 1 kHz to 10 kHz range. These results are similar to the closed cavity results once the cavity noise from Fig. 4(a) have been removed demonstrating an approximate linear superposition of cavity noise and gear noise. Unlike the closed cavity case, the noise outputs from both the Dassault and Lagoon-Like gear are now quite similar to each other in the presence of the open cavity. The exceptions to this are isolated frequency ranges where the noise output from the two gear differ by up to 3 dB. The low frequency tone in the Dassault gear is still present but appears to have increased in frequency in the presence of the open cavity.
6. By comparing Fig 4 (a) and Fig 5 (a), it appears that, above 1 kHz, the Dassault noise from the gear is louder than that from the Cavity, whereas below 1 kHz the cavity noise is of a similar magnitude or perhaps louder.
7. In Fig 5 (b) we see the effect of the side arm on far field noise as seen by one particular microphone (M6). It appears as if the side arm increases noise only above 10 kHz at this position. Interestingly, the removal of the side-arm results in an increase in noise at approximately 2 kHz. This might indicate that the presence of the side-arm causes a disruption in the shear layer and as a consequence a reduction in the cavity noise which is high in this frequency range, see Fig 4 (a). A reduction in wheel bay noise due to the presence of the gear has been reported previously in Neri et al. [4].
8. In Figs 6, 7, 8 and 9 we see that the main noise source from the Dassault Gear (above 2.5 kHz) is in the region between the main leg and the damper at this maximum velocity. According to point 6 above, if beamforming had been performed below 1 kHz it may have been seen that the cavity were the greater source of noise. However, resolution at such low frequencies would be poor. It should be noted however, that from the top array, the noise source does appear to be centered not fully on the leg region so perhaps the influence of the cavity noise is shifting the source towards the bay area.

9. Air Curtain Lagoon Analysis
    1. For a closed cavity (wheel bay) only the Air Tube air curtain nozzle reduced noise. At the maximum tunnel velocity (63 m/s) the noise reduction is significant, however, and spans a frequency range of 1.5 kHz to 8 kHz. Single far-field microphones measured up to 5 dB in noise reduction whereas beamforming identified reductions of up to 7.5 dB. Beamforming results showed that the noise source moved from the landing gear to the air tube itself. In the 1.5 kHz – 8 kHz range there was a net noise reduction whereas above 10 kHz with the noise source at the AT, its contribution was louder than the gear itself.
    2. For lower wind tunnel speeds, the air tube could still reduce noise as long as its flow rate, and therefore its self-noise, was also reduced.
    3. For an open cavity the Air Blade also was successful in reducing noise. However, the reductions were small and only of the order of magnitude of 1 dB for limited frequency ranges.
    4. From an analysis of flow rate versus nozzle self-noise output versus overall noise reduction it can be concluded that an optimum values exists. This conclusion was also discussed by Oerlemans and de Bruin, i.e. *unnecessarily* too much shielding results in too much self-noise.
10. Air Curtain Dassault GB-TA-MLG1 Analysis
    1. For an open cavity, once again the Air Tube successfully reduces noise by up to 5 dB this time in a slightly wider frequency range: 700 Hz – 8 kHz.
    2. In addition, the local nozzle LHD Wheel which was located just upstream of the leg also reduces noise by 3 dB albeit for just the frequency range around 1 kHz. As the Dassault gear produces a tone at 1 kHz in contrast to the Lagoon-Like gear, it is speculated that the main leg/damper leg configuration generates an acoustic source which is not found in the single cylinder Lagoon-Like gear. The LHD Wheel nozzle is well positioned to suppress this tone. Indeed, the AT also has a significant noise reduction of 5 dB at 1 kHz.
    3. Locally mounted air curtain nozzles successfully reduce low frequency velocity dependent which tonal noise but up to 3 dB. However, the nozzles do tend to increase noise above the baseline outside the tonal frequency range.
    4. Beamforming plots of the AT show noise reductions up to 6 dB with further reductions most likely possible for other octave bands. Interestingly, in contrast to the Lagoon-Like results, the noise source doesn't fully shift to the AT for the noise reduction cases but instead, it moves to the side-arm or between the side arm and the AT. This was predicted by the numerical analysis conducted by TCD some of which is documented in D2.11, i.e. that the jet from the AT would create a new source at the side arm.
    5. Figures 29-34 support this last point. By comparing beamforming plots with and without the side-arm, it can be seen that the noise source moves away from the side arm to the AT and also that greater noise reductions are possible, i.e. up to 7.2 dB at 3150 Hz.
    6. When the cavity is open, the AT is even more effective compared to the cavity closed case when examining <4 kHz as this is the frequency range where the cavity generates most noise. E.g. the AT can make a reduction of 5.7 dB cavity open versus 4.5 dB cavity closed at 3150 Hz.

7. The air blade was also shown to successfully reduce noise but only when the cavity is open and when the air flow rate is low. Reductions of up to 2.5 dB were measured in beamforming plots.

9 References

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[3] Bennett, G. J., and Zhao, K. Air Curtain Flow Control for Aerodynamic Noise Reduction. In *Fundamentals of High Lift for Future Civil Aircraft* (R. Radespiel and R. Semaan, eds.), Springer International Publishing, Cham, 2021, pp. 279–295.

[4] Eleonora Neri, John Kennedy, and Gareth J. Bennett. "Bay Cavity Noise for Full-Scale Nose Landing Gear: A Comparison between Experimental and Numerical Results." *Aerospace Science and Technology*, Vol. 72, 2018, pp. 278–291. https://doi.org/10.1016/j.ast.2017.11.016.