Proceedings of ACOUSTICS 2017
19-22 November 2017,
Perth, Australia

Tackling the Whining Noise of a 4WD Bus – A Case Study

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ABSTRACT
Very high levels of tonal noise were causing great discomfort to passengers, resulting in the whole fleet of 4WD tourist buses being taken out of service while attempts were made to address the noise issue. A comprehensive investigation and testing program was carried out to address a highly unpleasant, tonal whining noise. The effectiveness of each soundproofing treatments, such as vibration isolation materials, vibration damping treatments and air-borne noise reduction applications were investigated. Once each of acoustic treatments were applied, a corresponding on-road noise test was undertaken to determine the effectiveness of the treatment stage. The final results found that the overall noise level had been reduced from an uncomfortable 88 dB(A) to a much more tolerable 74 dB(A). The annoying whining noise was no longer a problem and all buses returned to service. This paper discusses the effectiveness of each treatment with real-life measurements and results.

1. INTRODUCTION
APT Australia's (ATP's) brand new fleet of 4WD off-road tourist buses were designed and built for outback exploration. A typical vehicle is illustrated in Figure 1.

Figure 1: One of the 4WD buses from ATP's outback exploration fleet

To meet with stringent safety requirements for off-road vehicles, each bus's body had been rigidly connected to the chassis using U bolts. During bus operation, a high-pitch whining noise was generated by the differential gear box, and via the rigid chassis connection, this noise became amplified inside the bus and throughout its structure. The whining noise that was heard inside the bus was so high that it caused headaches and extreme discomfort for the passengers, particularly on long trips. On one occasion, a passenger refused to re-board the bus after stopping only a few hours into a tour, demanding that APT send them a 'quieter' vehicle.

After many complaints about the whining noise were received, APT had no choice but to take the whole fleet out of service and find a noise solution.

2. ATTEMPTS MADE TO SOLVE THE ISSUE
In the ensuing 12 to 18 months, both the bus builder and chassis manufacturer investigated many sound insulation materials and soundproofing methods to solve the noise issue, as detailed in Section 2.1 to Section 2.7.

2.1 Differential gearbox specification analysis
The source of the noise was the differential gearbox (as shown in Figure 2). The chassis manufacturer, Mercedes Benz, conducted a full investigation into the differential gearbox. Its laboratory in Germany confirmed that all was compliant with design requirements[1] and that the whining noise being emitted was a standard gearbox noise. As a result, no further investigation into the differential gearbox was undertaken.

Figure 2: The noise source: the differential gearbox

2.2 Treatment applied to the gear shafts

Possible options for treating the gear shafts were investigated, including 1.) Soft coupling, 2.) Telescopic shaft to shift the resonant frequency of the drive shafts, 3.) Torsional shaft vibration damper, and 4.) Damping treatment on the drive shaft – such as tuned dampers, and so on.

Options 1, 2 and 3 proved not to be practical due to the high cost to implement, and current design constraints[2]. Option 4 seemed promising and so two types of damping treatment were considered. However, the chassis manufacturer advised that any attachment or modifications to the drive shafts would make void the manufacturer's warranty. ATP decided that treating the gear shafts was not an option[3].

2.3 Damping treatment of the differential gearbox housing

A proposal was put forward to apply damping material to the housing of the differential gearbox that was designed to reduce the housing resonance, and thus, reduce the whining noise.
Again, the chassis manufacturer had also advised that any treatment or attachment to the differential gearbox, or its housing, would void the manufacturer's warranty[3].

2.4 Treatment applied between cabin and chassis

The bus body builder[3] then undertook various trials, starting by inserting a rubber pad between the U bolts and chassis, as shown in Figure 3. There was no improvement.

Figure 3: Rubber pad inserted between U bolts and chassis

Then, they used a much softer polyurethane (PU) pad, as shown in Figure 4. Again, there was very little difference in noise reduction before and after installing the PU pads.

Figure 4: U bolts with polyurethane (PU) pads (in red) and fitted in-situ

2.5 Soft mounting of the whole cabin

A proposal was put forward to completely insulate the cabin from the chassis by soft mounting the cabin. However, these mounts were rejected by the safety engineer due to the stringent safety requirements for the off-road vehicles[3].

2.6 Treatment applied to the transfer case

A 'cocoon'-like effect was suggested to be built around the transfer case itself. This design would form a semi-enclosure that hung around the transfer case[3]. Yet further study indicated that the 'cocoon' would be extremely difficult to secure above the gearbox, and ATP had concerns that this cocoon would not last due to likely impact from rocks and water underneath the vehicle[2]. ATP therefore rejected this proposal.

2.7 Insulation under the cabin floor

Another supplier recommended a total of four layers of noise insulation materials to be installed under the cabin floor[1]. The photos in Figure 5 show a bus with all the multiple layers of these noise control materials installed.

Figure 5: Multiple layers of noise control materials applied under the cabin floor

It was estimated that the costly insulation materials added an extra total weight of about 500 kg. Despite these layers and insulation, the extremely uncomfortable whining noise still persisted and the devastated owner then approached Megasorber for a solution.

3. MEGASORBER'S APPROACH TO SOLVING THE ISSUE

ATP had set-out the project requirements and design limits as follows: 1.) No modification can be applied to the chassis, differential gearbox or cabin by using mounting methods, 2.) Must be suitable for extremely tough conditions, as such outback conditions, and 3.) Each treatment must show an improvement. ATP provided a bus and an installation crew to assist Megasorber in undertaking the work. The details are as follows.

3.1 Noise treatment preparations

3.1.1 Initial activities

The first actions undertaken in assessing the noise problem were to remove all the insulation materials previously installed underneath the bus floor. Then baseline noise tests were carried out on the noise emissions during bus operations. Once baseline test results were determined, we then established a noise reduction treatment plan in response.

3.1.2 Noise testing conditions and equipment

Noise testing was selected for two conditions: 1.) Acceleration from 65 km/hr to 100 km/hr, and 2.) Deceleration from 100 km/hr to 65 km/hr. All noise testing was conducted on the Eastern Freeway in Melbourne, Australia. Measurements were taken using a Center 320 sound pressure level meter and SpectraLAB software, from Sound Technology Inc.

The sound pressure level meter was affixed to the aisle seat's headrest approximately 1m above the cabin floor, and it remained there for the duration while all measurements were taken.

3.2 Baseline noise testing results

3.2.1 Baseline frequency spectrum measurements results

During acceleration

The test results of accelerating from 65 km/hr to 100 km/hr are shown in Figure 6.

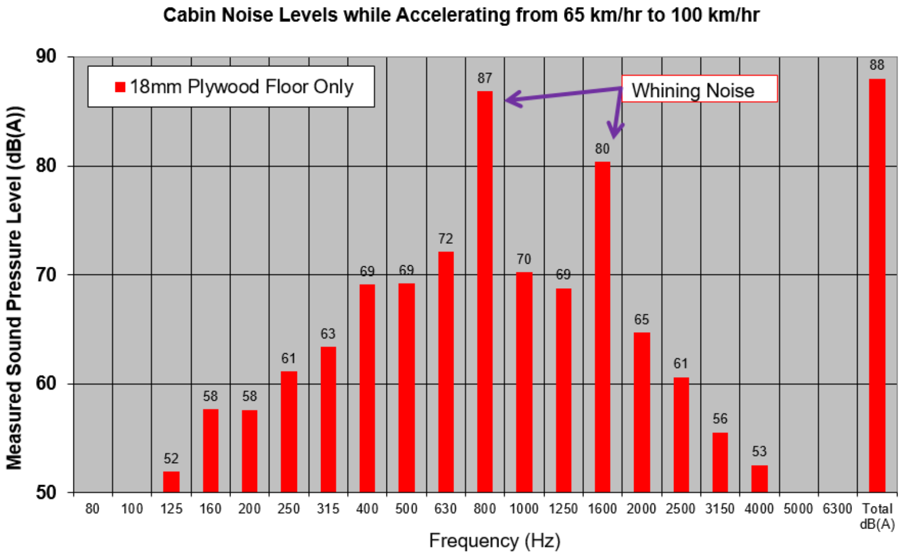

Figure 6: Primary and secondary whining noises (shown by purple arrows) identified during baseline acceleration testing

The key findings were: 1.) A primary whining noise was determined at 800 Hz, with a noise level of 87 dB(A), and 2.) A secondary harmonic whining noise was determined at 1,250 Hz, with a noise level of 80 dB(A).

During deceleration

The test results of decelerating from 100 km/hr to 65 km/hr are shown in Figure 7.

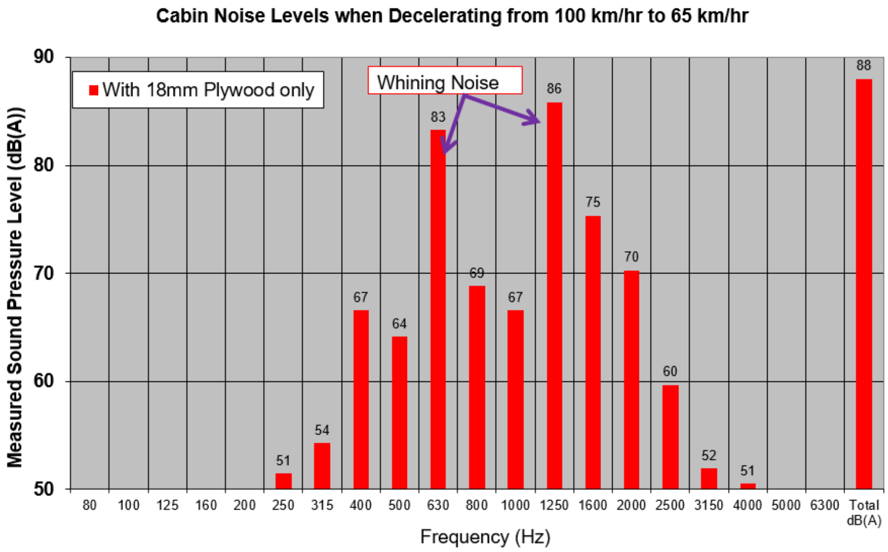

Figure 7: Primary and secondary whining noises (shown by purple arrows) identified during baseline deceleration testing

The key findings were: 1.) A primary whining noise was determined at 630 Hz, with a noise level at 83 dB(A), and 2.) A secondary harmonic whining noise was determined at 1,250 Hz, with a noise level at 86 dB(A).

3.3 Treatment response

Megasorber applied a staged approach for addressing the primary and secondary whining noises identified in the test results.

3.4 Stage 1: Floor system treatment with vibration isolation and damping material

Based on the test results obtained and our calculation of sound transmission loss for the floor system, it was concluded that the 18-millimetre plywood did not provide sufficient noise insulation. As the plywood has a low internal loss factor and is relatively rigid, it was actually amplifying the whining noise. Additionally, the rigid plywood structure has a critical frequency of about 1,600 Hz, which decreased the sound transmission loss of the plywood floorboard around 1,600 Hz, as per Mass Law. Please refer to the dotted line for 'low damping' in Region 3 that is provided in Figure 8.

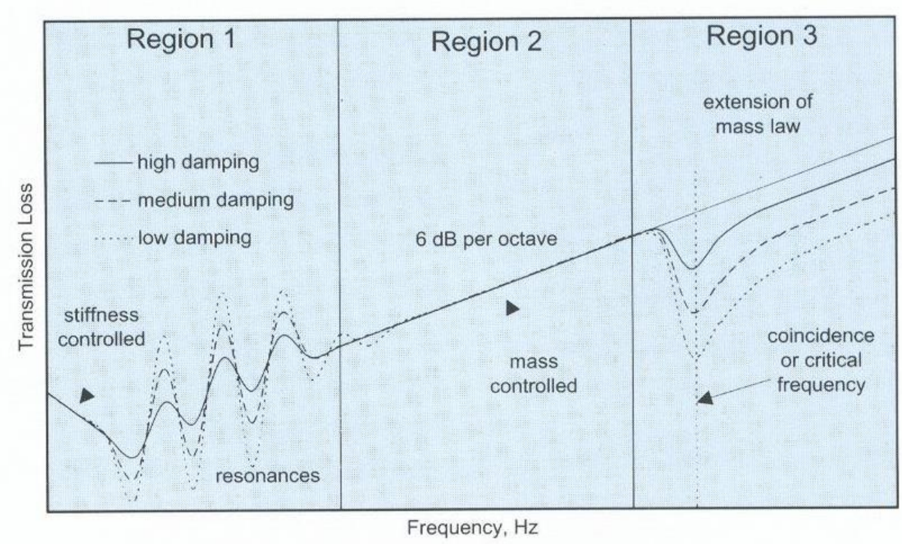

Figure 8: Mass Law shown with high, medium and low damping affects, with the dotted line for 'low damping' in Region 3 being applicable to typical sound transmission loss characteristic of a partition

Our first task was to increase the Rw (Weighted Sound Transmission Loss or STC rating) of the floor system by providing a vibration isolation and damping solution. The criteria for applying suitable materials was: 1.) Be self-adhesive for easy installation, 2.) Have a high vibration damping coefficient over wide range of temperatures, preferable from -20°C to 80°C, 3.) Be soft to provide vibration isolation, and 4.) Have temperature resistance up to 180°C.

Megasorber DIS8 was the product selected. This material is a 2-millimetre-thick vibration damping and insulation sheet with self-adhesive on both sides. It is a viscoelastic polymer alloy with built-in adhesive technology, and can withstand temperatures up to 180°C.

DIS8 was applied onto the substrate first. Then a top layer of 3-millimetre-thick steel plate was adhered to the top of the DIS8 to form a constrained layer damping system. The calculated system loss factor was 0.10.

Floor areas treated with DIS8 were: 1.) The whole floor board, 2.) The side walls, from the floor up and to 280 mm in height, 3.) The front wall, and 4.) The back steps' areas.

Figure 9 presents a schematic drawing of the Megasorber DIS8 floor system treatment applied.

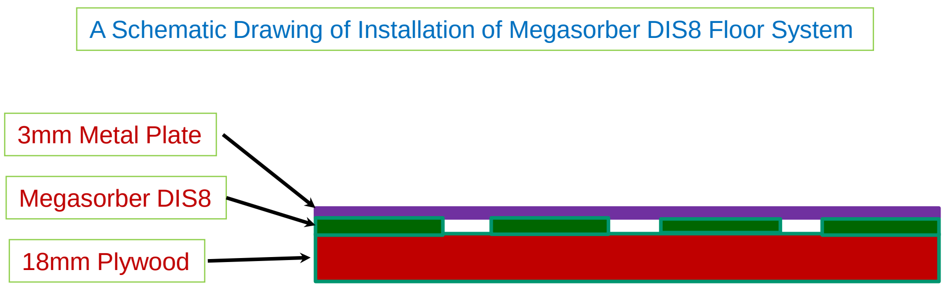

Figure 9: Schematic drawing of the Megasorber DIS8 floor system solution

3.4.1 Stage 1 test results

During acceleration

Test results that compare before (in red) and after (in blue) installation of Megasorber DIS8 while accelerating are provided in Figure 10.

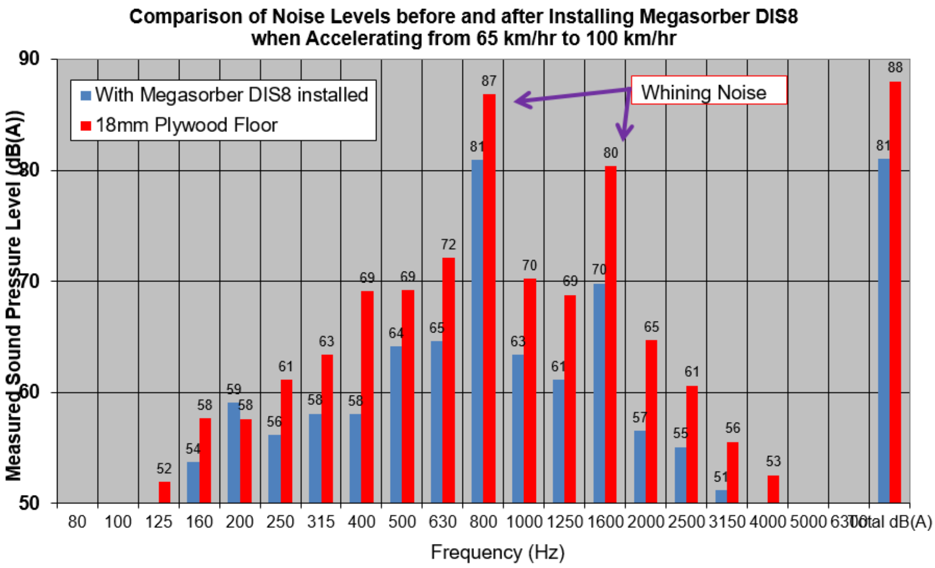

Figure 10: Noise measurement results before (in red) and after (in blue) installation of Megasorber DIS8 during acceleration

It is evident from the graph in Figure 10 that the DIS8 floor system reduced the primary whining noise during acceleration by 6 dB(A) to 81 dB(A), and the secondary harmonic whining noise by 10 dB(A) to 70 dB(A). The DIS8 floor system therefore reduced the overall noise levels during acceleration by 7 dB(A), from 88 dB(A) to 81 dB(A).

During deceleration

Test results that compare before (in red) and after (in blue) installation of Megasorber DIS8 while decelerating are provided in Figure 11.

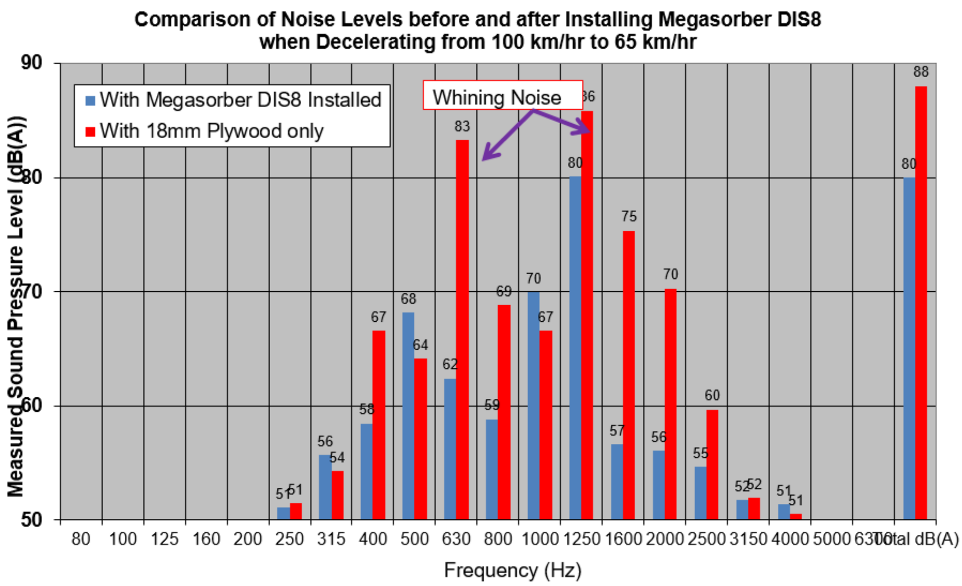

Figure 11: Noise measurement results before (in red) and after (in blue) installation of Megasorber DIS8 during deceleration

It is evident from the graph in Figure 11 that the DIS8 floor system reduced the primary whining noise during deceleration by 21 dB(A). Although it reduced the secondary harmonic whining noise, it was only by 6 dB(A). Overall, the application of DIS8 has reduced the overall noise levels during deceleration by 8 dB(A), from 88 dB(A)

to 80 dB(A).
While the application of DIS8 damping and isolation system achieved significant noise reduction, an irritating whamming noise remained audible.

3.5 Stage 2: Other noise pathway treatments then applied

The persistent whining noise after the DIS8 floor treatment indicated that there were other noise pathways that needed addressing to further reduce the high tonal noise emissions. These pathways are described in the following.

3.5.1 Sound absorption treatment near the differential gearbox

To prevent noise energy build-up near differential gearbox, a high sound-absorbing product was now needed around the gearbox. Based on the frequency spectrum, the material needed a high sound-absorption coefficient at about 500 Hz to 1,600 Hz, and ideally a peak sound absorption coefficient at about 630 Hz, 800 Hz and 1,600 Hz. Additionally, the sound absorption material MUST be fireproof, water-repellent, tough and durable.
Water-repellent ‘WR’ Megasorber FG50WR was the product selected, due to its matching properties to the above criteria. This material has a fluid-repellent, fireproof and sound-absorbing Soundmesh G8 facing, with a peak sound absorption coefficient around 500 Hz to 630 Hz, as shown in Figure 12.

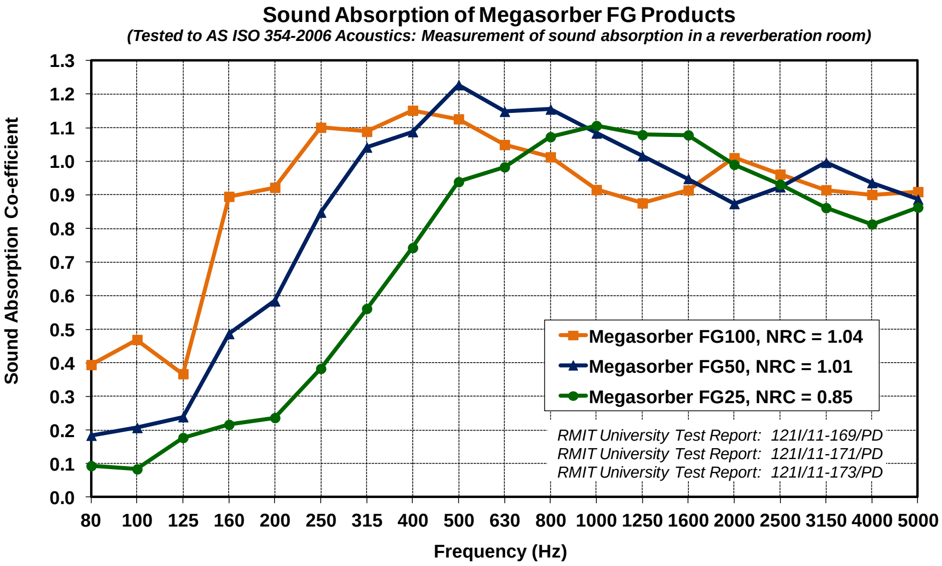

Figure 12: Reverberation sound absorption coefficient test results for Megasorber FG50 (as shown in blue)

Figure 13 presents a schematic drawing of the Megasorber FG50WR differential gearbox cavity treatment applied, and the installed product and mesh in-situ under the floor boards. Expanded metal mesh was also applied to the FG50WR to protect and prolong its life.

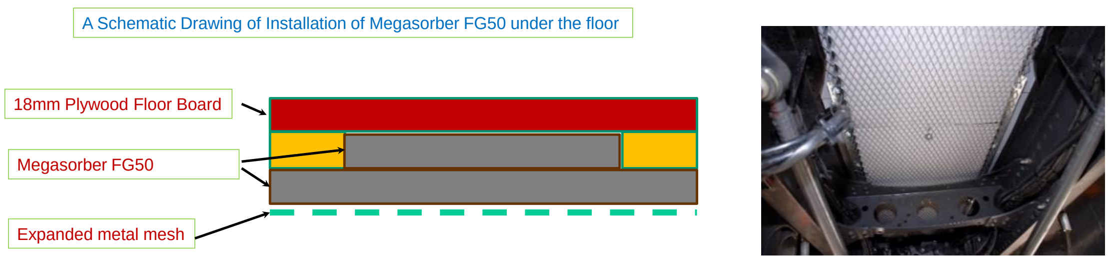

Figure 13: Schematic drawing of the Megasorber FG50WR
solution for the differential gearbox cavity

3.5.2 Above the transfer case

Three-millimetre steel plate was then added across the chassis right above the transfer case. The underside of the steel plate was lined with Megasorber FG50WR. Figure 14 presents a schematic drawing of the Megasorber FG50WR treatment applied above the transfer case, with expanded metal mesh applied and shown in-situ.

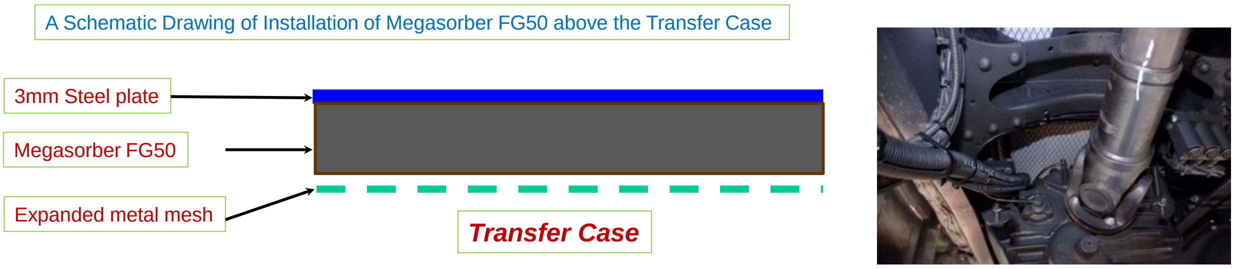

Figure 14: Schematic drawing of the Megasorber FG50WR solution
above the transfer case, with expanded metal mesh applied and shown in-situ

3.5.3 Body panel damping and step casing treatments

The body panel was made of 2-millimetre aluminium plate while the step casing was made of 3-millimetre steel plate. Hence, a damping material was needed to provide sufficient damping for the aluminium and steel plates. The key requirements of the damping materials were as follows: 1.) It must be self-adhesive for easy application, 2.) It must provide sufficient damping effect on 3-millimetre-thick metal plate, with a system loss factor greater than 0.10, 3.) It must provide high damping performance over a wide range of temperatures, typically from -20°C to 80°C, and 4.) It must have high temperature resistance up to 180°C.

Megasorber D14 was the product selected because it met the above criteria very well. The damping treatment applied to the body panels and back wall is shown in Figure 15.

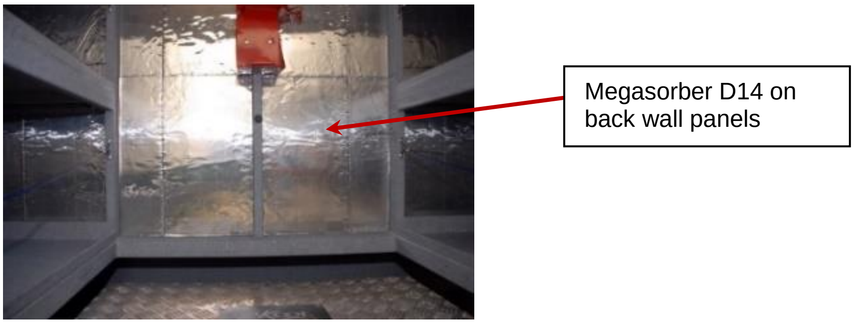

Figure 15: Installed Megasorber D14 on back wall panels

Megasorber D14 was applied onto the metal plate; then Megasorber FG50WR was installed, with 3-millimetre-thick steel plate placed on top, as shown by the schematic drawing in Figure 16. All edges were sealed.

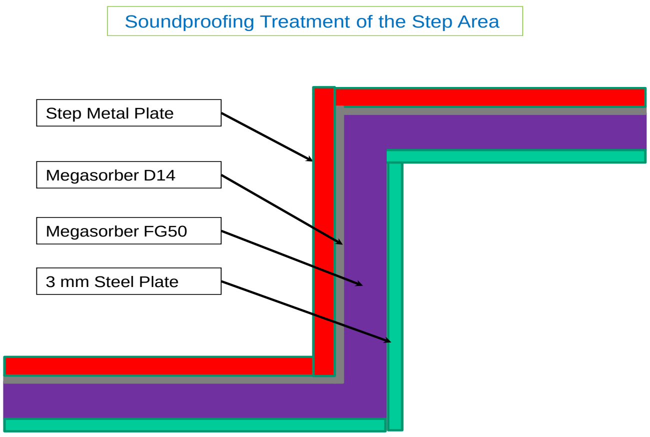

Figure 16: Schematic drawing of the treatments applied to the step area

3.5.4 Stage 2 test results

During acceleration

Test results that compare baseline results (in red) with installation of Megasorber's treatment solutions of DIS8 and D14 (in blue) and DIS8, D14 and FG50 (in green) while accelerating, are provided in Figure 17.

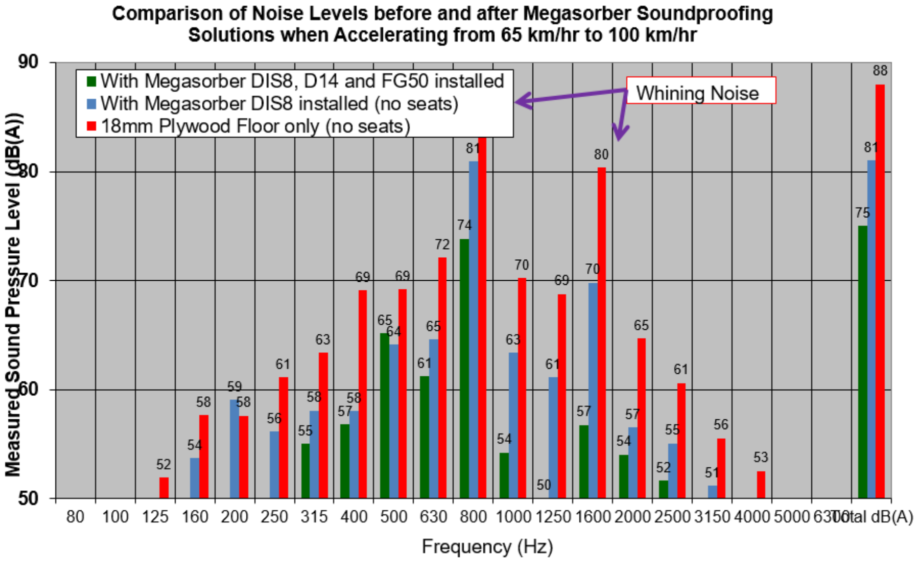

Figure 17: Noise measurement results compared to baseline test results (in red) and both treatments (in blue and green) during acceleration

It is evident from the graph in Figure 17 that both treatments have reduced both the primary and secondary whining noises during acceleration. When the Megasorber DIS8, D14 and FG50 treatment was applied during acceleration, the primary whining noise was reduced by a further 7 dB(A), from 81 dB(A) to 74 dB(A). The secondary harmonic whining noise was reduced by a further 13 dB(A), from 70 dB(A) to 57 dB(A). Thus, the overall noise level was reduced further by the Megasorber DIS8, D14 and FG50 treatment during acceleration, by another 6 dB(A), from 81 dB(A) to 75 dB(A).

During deceleration

Test results that compare baseline results (in red) with installation of treatment solutions of DIS8 and D14 (in blue) and DIS8, D14 and FG50 (in green) while accelerating, are provided in Figure 18.

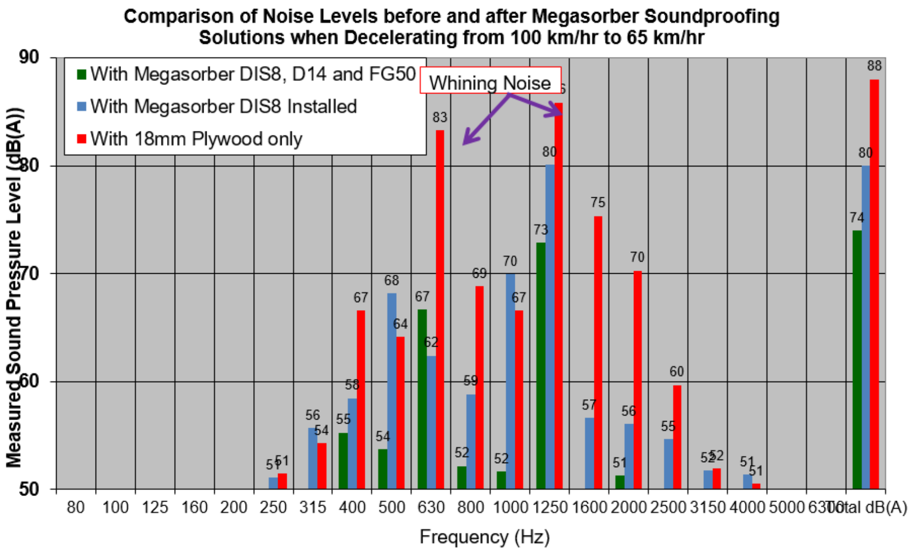

Figure 18: Noise measurement results compared to baseline test results (in red) and both treatments (in blue and green) during deceleration

It is evident from the graph in Figure 18 that the above treatments have reduced overall both the primary and secondary whining noises during deceleration. When the Megasorber DIS8, D14 and FG50 treatment was applied during deceleration, the primary whining noise was somehow increased by 5 dB(A), but still reduced overall from originally 83 dB(A) to 62 dB(A), to 67 dB(A). The secondary harmonic whining noise was reduced by a further 7 dB(A), from 80 dB(A) to 73 dB(A). Thus, the overall noise level was reduced further by the Megasorber DIS8, D14 and FG50 treatment during acceleration, by another 6 dB(A), from 80 dB(A) to 74 dB(A).

4. CONCLUSION

The biggest improvement was achieved by firstly installing the Megasorber DIS8 system in Stage 1, which reduced the whining noise and overall noise levels significantly.

The implementation of Megasorber FG50 and D14 products further reduced the whining noise levels, as well as the overall noise levels during acceleration and deceleration.

The implementation of the above treatments effectively reduced the overall noise levels of distressing primary and secondary harmonic whining noise, both during acceleration and deceleration. As a result, ATP was able to resume normal bus operations for all its fleet again.

ACKNOWLEDGEMENTS

We would like to thank APT Australia for the opportunity to carry out this full study on their bus fleet, as well as their permission to publish the test results obtained. We would also like to thank Able Bus & Coach Australia and Mercedes Benzes Australia for providing valuable assistance and the detailed test results.

REFERENCE

Case study details were provided by the following companies, as footnoted in this paper:

[1]ATP Australia Pty Ltd
[2]Mercedes Benz Australia Pty Ltd
[3]Able Bus & Coach Australia.