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Sound Intensity Mapping to Synthesize and Rapidly Optimize the Reduction of Machinery Noise Emission

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ABSTRACT

Sound intensity scanning measurements were used to rapidly design an optimum package to reduce noise emission from a semi-trailer mounted refrigeration unit. The scans were taken with and without enclosures to identify the individual sources causing noise peaks in normal operation. Scanning gave us sound power level as the target metric to reduce emissions, independent of the test environment and microphone location, unlike standard sound pressure level measurements. This also allowed the synthesis of additional combination treatments, specifically, combinations not practical to measure, due to time constraints, using power difference. It gave us a quick and precise path to the optimized treatment package, with sound power nearly halved (a 2.5dB level reduction, which is a 44% reduction in radiated sound power).

1. INTRODUCTION

Sound intensity maps, with resulting sound power frequency spectra, can visually identify the loudest components in a machine.

The maps will also quantify how treatment to all these components can have cumulative benefits:

- From an acoustic perspective, this quantifies the value both in treating the entire enclosure, where feasible, and also evaluates alternative treatments (for example, the acoustic value in certain standard sizes, like 50mm or 25mm thick absorptive layers, with full or partial coverages);
- From a business perspective, sound power measurements can quickly give a menu to choose optimum packages addressing the dominant components identified, based on cost, benefit and profit.

Maps of the unit in production and treated conditions are therefore useful to compare the value of progressively optimized treatments. Comparing maps of certain repeated tests during this development also ensures a precise path of optimization to an eventual significant reduction in sound power level.

2. METHOD & RESULTS

The trailer mounted refrigeration unit consists of an upper condenser cabinet and lower engine and compressor bay, mounted on the outside front wall of the trailer, and an evaporator coil and fan inside the trailer. These components include various sub-components such as a cooling fan, drive belts and pulleys, and exhaust system, and are shown schematically in Figure 1. The measurement of sound power was made with a sound intensity probe measuring on a grid using a scanning robot. It could also be done manually by hand. The software for showing sound intensity over a surface is commercially available[1]. The measured intensity contours were displayed over this schematic in this publication but could also be displayed over exterior and interior photographs of the actual unit, to easily identify sound intensity and radiated power from all parts.

The refrigeration unit was operated consistently for all scans at full power in a climate controlled room, using heaters to preheat the trailer to a set temperature before each scan. With the unit operating at constant speed and power, it was measured uniformly with the sound intensity probe at 64 (8x8) locations, and for sufficient time in each location to produce an accurate map. This depends on test room and trailer temperatures, test room air conditioning, trailer cooling rate (trailer insulation and unit performance), engine stability and compressor cycle times. Each subsequent scan was then performed starting at the same temperatures, unit load setting and test room air conditioning (temperature, humidity and supply fan speed).

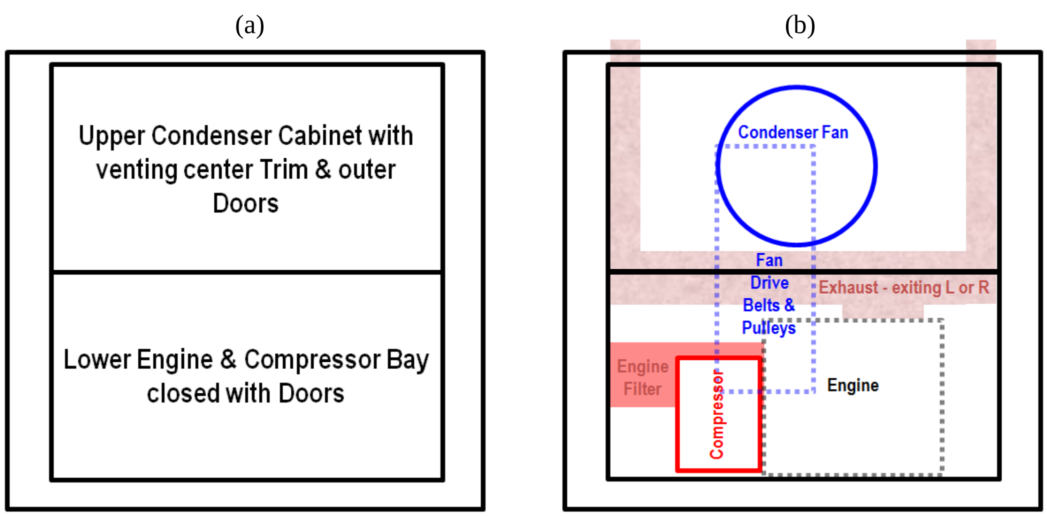


Figure 1: Typical layout of exterior (a) and interior (b) components in generic refrigeration unit.

The results for the unit in production form are shown in Figure 2, both with the doors mounted in their closed position, and then removed. The doors completely enclose the lower bay, unlike the upper cabinet, which has large openings for heat exchange. With doors removed, the compressor can be seen on the lower left, the engine on the lower right. For clarity in each door condition, the noise contours are of different amplitudes but have the same 10dB range in sound intensity level, between the color extremes from light yellow to light green.

- Operating normally, with the doors closed, the total Sound Power Level (SWL) was 92.2dB(A), relative to 1pW, with 90.9dB(A) flowing out through the upper cabinet, with its large openings, and 86.2dB(A) directly from the closed-off lower bay.

- Operating with doors removed, to identify individual contributors, the total was 96.8dB(A). Now the lower bay dominated - nearly an order of magnitude louder than before - with 95.5dB(A), and with noise through the upper cabinet almost unchanged, at 91.1dB(A).
- This shows that noise emanates from various components, mainly in the lower bay, which are all in a diffuse field, and treatment to the lower bay is necessary to reduce the dominant radiation coming from the upper cabinet. Noise sources are distributed throughout the unit, which is open at the top, therefore all significant sources must be addressed for significant noise reduction.

(a) (b)

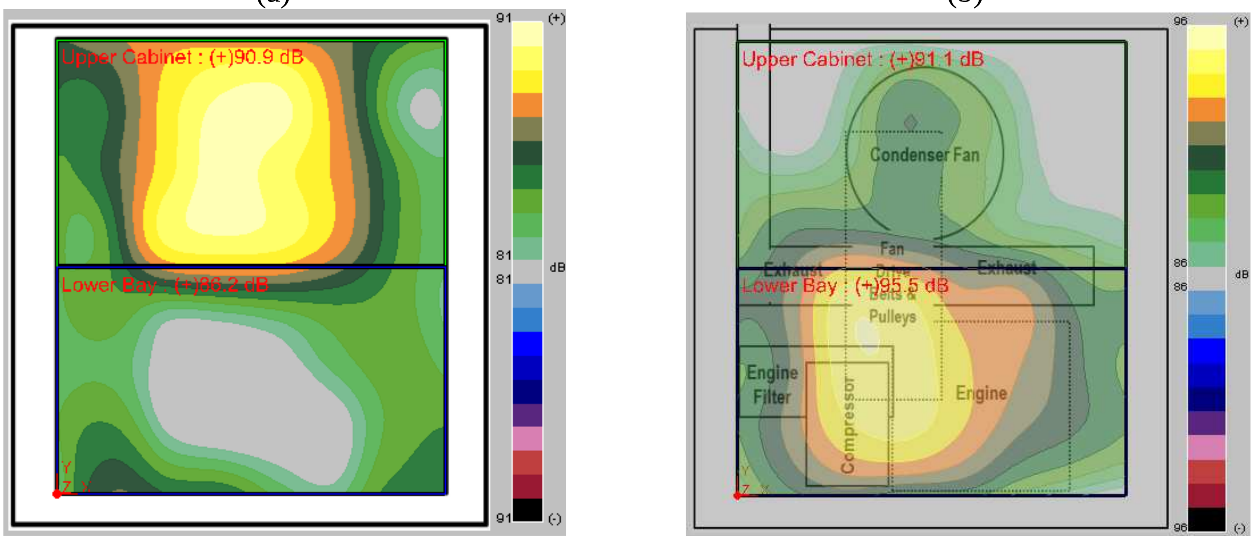


Figure 2: Sound intensity maps with doors closed (a) then removed (b).

A. Contribution of individual components

Figure 3 shows the noise spectrum of the production unit, which peaks in the 125 Hz band through the upper cabinet (as shown in the left map of Figure 2) together with dominant sources identified with the doors removed.

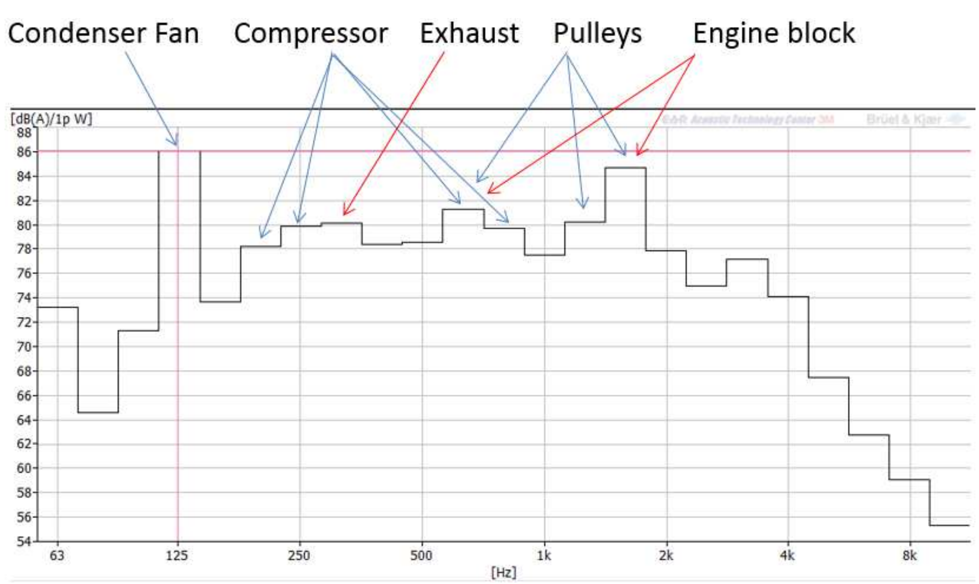


Figure 3: Sound power level spectrum and main noise sources with doors closed.

Figure 4 compares overall levels of the three loudest sources with the lower doors removed. The software gives SWL from each source, the sum of its average sound intensity level and decibel area, by simply tracing the visible shape of each source. It shows that not only the more exposed condenser cooling fan along with its drive belts and pulleys are important (90.9dB[A]), but also the compressor (87.6dB[A]) and diesel engine (91.2dB[A]) - though normally closed off. This only gives approximate estimates, given the schematic layout of sources used for this publication: estimating with an underlying photograph of the actual parts is usually done in confidential projects, and is more accurate.

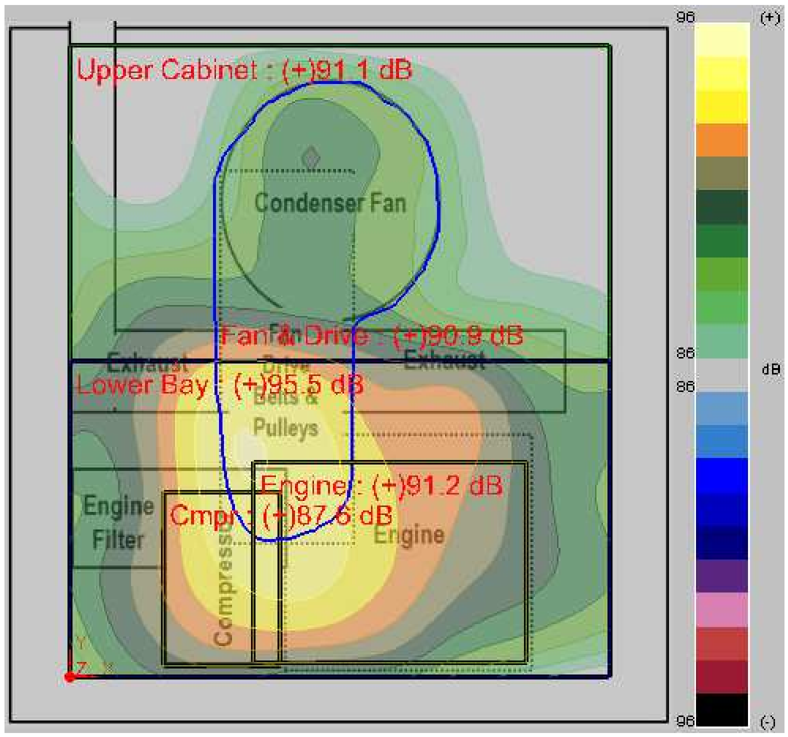
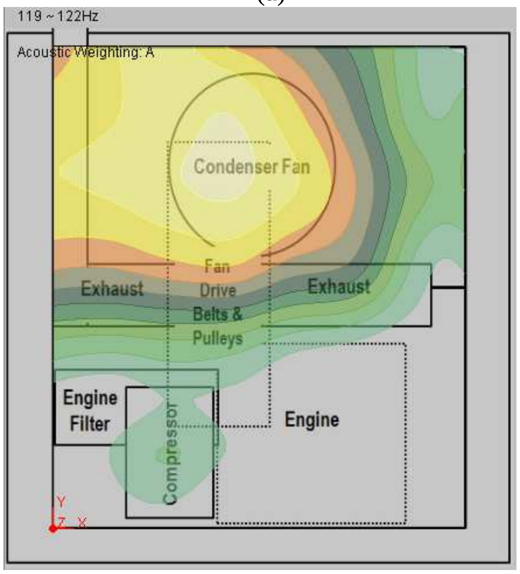


Figure 4: Overall sound power levels from each of the main noise sources.

While the graph in Figure 3 summarizes all sources with third octaves, the individual contributing sources shown were first identified, with doors removed, at the discrete frequencies that they peaked in noise, with the doors closed. For example, two sources contributing to the dominant 125 Hz and 1.6 kHz third octave levels are shown in Figure 5. With doors closed these levels were around 86 and 85 dB(A) respectively (see Figure 3). The peak frequency and sound power level with doors open was measured, to identify the most significant contributing sources and relative strength before treatments were applied. The resulting 83dB(A) SWL peak, measured from the condenser fan (a), thus has more significance than the 85dB(A) SWL from the lower fan pulley (b), doors removed, due to fan location in the vented, more open, upper cabinet.

(a)



(b)

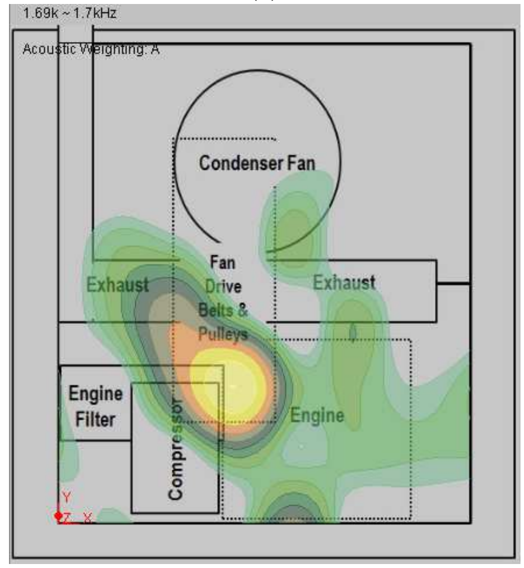


Figure 5: Doors removed to show individual sources, at narrow band frequencies, causing high one third octave band levels with doors closed – 125Hz band, condenser fan (a) and 1.6kHz band, lower fan pulley (b).

B. Treatment and evaluation

As our understanding grew, an accumulating plan of sound packages developed, summarized in Table 1. Pod and Trim refer to the upper cabinet around the condenser. Not only sound intensity but also sound pressure was recorded with several microphones, for customer tests and requirements, as well as binaural Sound Quality recordings. Additional information came from Beam Forming and vibration measurements, which also highlighted the noise from the fan drive pulleys. From the production conditions (#0x), with its doors and treatment on and off, we applied various combinations of absorption, based on our results, to reduce the diffuse field in the lower bay, and then continued into the upper cabinet. Adding mass and damping were also evaluated. Note that direct treatments to the main sources (engine and exhaust, compressor and fan drive) were not commercially feasible in this project.

Table 1: Specific treatments and tests.

Treatment Areas / *Package #*	Center doors	Outer Doors	Lower Engine & Compressor Bay	behind Engine	Upper Condenser Cabinet	Trim	Engine Support	Bottom Tray	*Tests Performed*	SI scan	SPL fixed Mics	SQ Recording	Sound Power Synthesis
0	As Received	As Received								x	x	x	
0A	Doors Removed	Doors Removed								x			
0B	Treatment Removed	Treatment removed								x	x	x	
1	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket								x	x	x	
2	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket						5kg/sq m mass barrier		x	x	x	
3	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket		51mm Sound Absorbing Blanket			32mm Constrained Layer Damping	5kg/sq m mass barrier		x	x	x	
4	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket				32mm Constrained Layer Damping	5kg/sq m mass barrier		x	x	x	
5	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket		51mm Sound Absorbing Blanket		32mm Constrained Layer Damping	5kg/sq m mass barrier		x	x	x	
6	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket		51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket	32mm Constrained Layer Damping	5kg/sq m mass barrier		x	x	x	
7	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket		51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket	32mm Constrained Layer Damping	5kg/sq m mass barrier & **51mm Sound Absorbing Blanket**		x	x	x	
8 is #7 with Doors Sealed	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket		51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket	32mm Constrained Layer Damping	5kg/sq m mass barrier/51mm Sound Absorbing Blanket		x	x	x	
9	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket			51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket							x
10	51mm Sound Absorbing Blanket	51mm Sound Absorbing Blanket			51mm Sound Absorbing Blanket								x
11	51mm Sound Absorbing Blanket									x	x	x	
12	25mm Sound Absorbing Blanket	25mm Sound Absorbing Blanket			25mm Sound Absorbing Blanket	25mm Sound Absorbing Blanket				x	x	x	
13	25mm Sound Absorbing & Heat Reflecting Foam	25mm Sound Absorbing & Heat Reflecting Foam								x	x	x	
14	25mm Sound Absorbing & Heat Reflecting Foam	25mm Sound Absorbing & Heat Reflecting Foam			25mm Sound Absorbing & Heat Reflecting Foam	25mm Sound Absorbing & Heat Reflecting Foam				x	x	x	

C. Sound power synthesis to estimate untested treatments

To minimize optimization time by reducing the number of packages tested, we also used sound power results to estimate additional package combinations. These were Packages 9 and 10, shown in red type in Table 1. Package 9 would be as if we had treated the inside of the lower bay doors and entire upper cabinet interior but without the further engine bay treatment that was also tested in Package 6. So the sound power in Package 9 would be that of Package 6 but increased by removing its engine bay treatments, other than those on the doors. These are quantified by the difference in sound power of Packages 1 and 4. The synthesis showed it would be 0.4dB louder than Package 6, and a further synthesis (Package 10) of removing absorption in the Trim (from the difference of Packages 5 and 6), would be 0.6dB louder than Package 6. The scans were taken in 1/24 octave bands and the synthesized data processed into 1/3 octave bands. Note that where 1/24 bands indicated a poorer performance with a treatment, these were not added to the 1/3 octave band results, since only radiated power was synthesized.

The best result in terms of objective sound power and subjective sound quality came with Package 7, with 2.5dB overall reduction in sound power level, which increased Package 6 with 51mm thick absorptive fiber material on the engine bay bottom tray. Figure 6 compares the spectra.

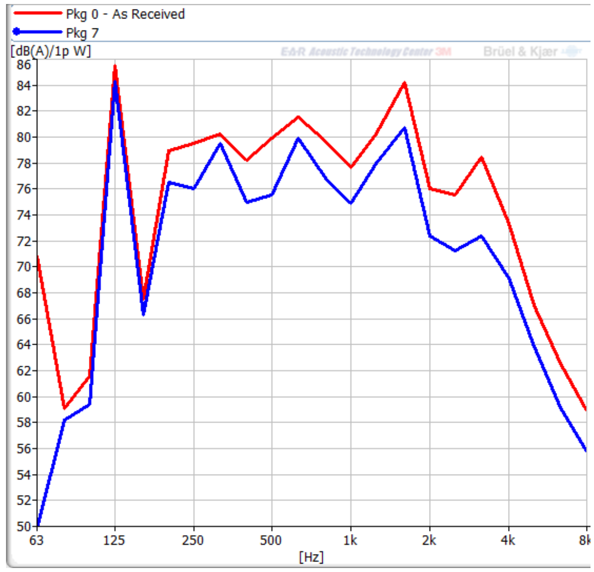


Figure 6: Spectra of production treatment and optimized package (#7).

Subsequent tests were the maximum potential of door redesign (#8), synthesized removal of some treatments with other treatments retained (#9 and #10 as discussed), and further reducing and then changing-out fiber-based absorptive material to foam (#11 through #14). The production intensity map is compared with Package 7 in Figure 7.

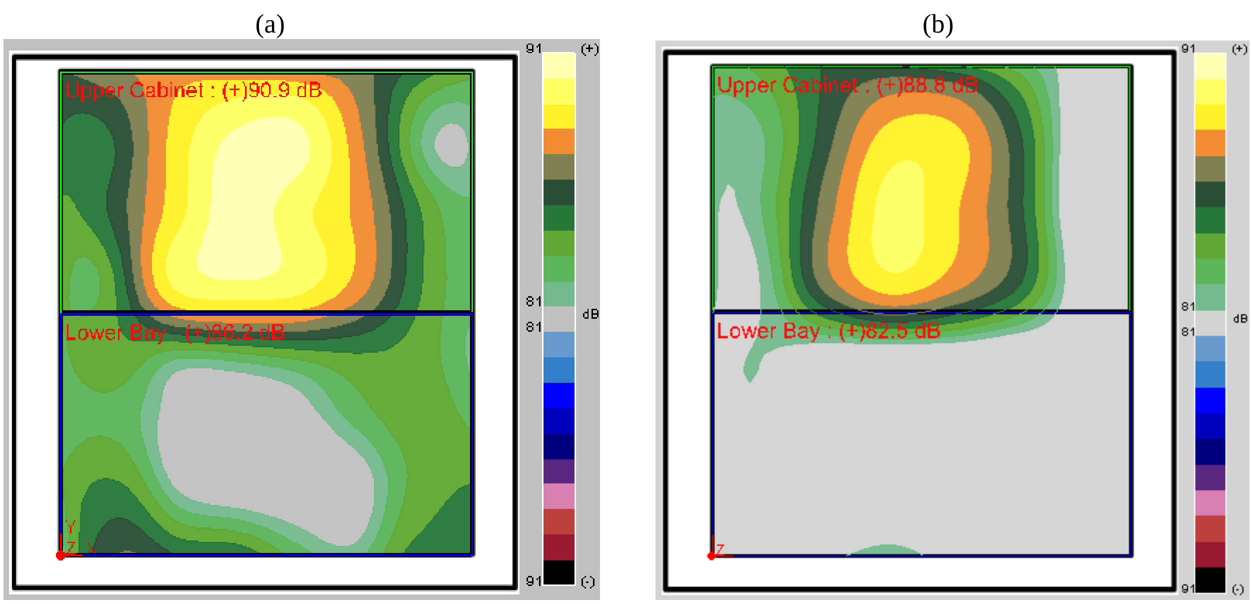


Figure 7: Sound intensity contours of production treatment (a) and optimized package (b).

Synthesis also gave us a ranking of the sound power absorption of different treatments, compared with the production radiated sound power spectrum, like the example shown in Figure 8, which helped us choose the best package, based on efficacy, cost and specific benefit at the most critical frequencies. Figures 7 and 8 show the effectiveness of treating the doors with 51mm blankets, helping to reduce overall engine bay power by 3.7dB in Package 7.

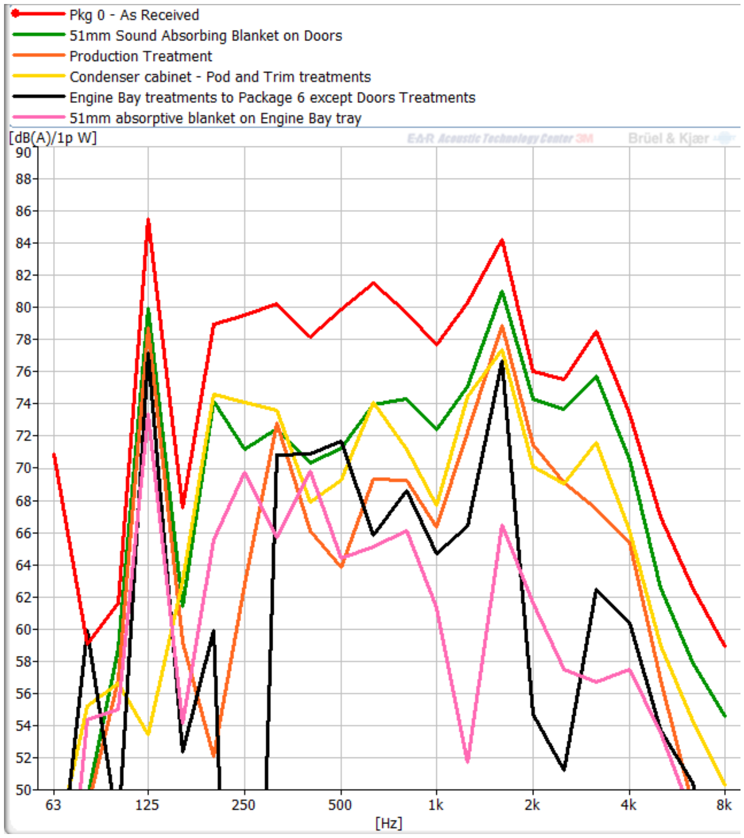


Figure 8: Spectra of radiated sound power as received and power removed by some treatment examples.

3. CONCLUDING COMMENTS

Sound intensity scanning provides an environment-independent means of rapidly identifying dominant sources. It also gives sound power allowing power difference synthesis to evaluate a number of treatment combinations without actually having to test every package combination.

ACKNOWLEDGEMENTS

Many thanks to Steve Sorenson for help with the tests.

REFERENCES

1. Brüel & Kjær software - Pulse Acoustic Test Consultant