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Control of low frequency noise from an environmental test facility

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ABSTRACT

Environmental test chambers are used in the automotive industry to verify the resilience of vehicles. In just a few hours it is possible to take a car from mid-winter in the artic, via a high mountain range, to mid-summer in a desert. Powerful ventilation systems are used to change the temperature, pressure and humidity of the air in the chamber, and the variable speed blowers are a major source of low frequency noise, which can cause significant disturbance at neighbouring properties if there are gaps in silencer performance.

This paper details a study to assess the attenuation requirements for silencers to meet a standard criterion for low frequency far-field noise levels, and to select a reactive silencer system to achieve that specification under all circumstances. The system used standard silencer components where possible, but needed to take account of long pipe runs through the facility, with tail-pipe resonances being a particular issue, and was further constrained by space and loading limits for the building. Design layouts were verified using the Actran FE code, taking account of interactions with existing silencers and transfer functions to the far-field, to give very high confidence of a successful outcome. A good final result was achieved, with measured insertion losses agreeing well with predictions and the noise complaint being resolved.

1. INTRODUCTION

Environmental test chambers are used in the automotive industry to verify the resilience of vehicles to varying climatic conditions. Variable speed Roots blowers are used to change the air in the chambers, and these are a major source of low frequency noise which can cause disturbance at neighbouring properties if there are gaps in silencer performance.

In the case described here there had been complaints for a significant period of time, and noise from the test chambers had been measured on a number of occasions, but the highly variable nature of the source meant that it was difficult to determine a clear specification for the required improvement in silencer performance. The variability also complicated the issue of identifying the root cause

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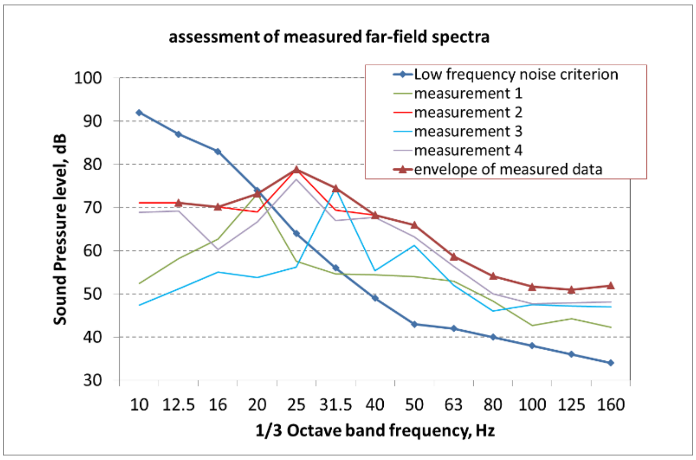
of the problem since it was difficult to correlate complaints with specific operations of the chambers.

An assessment method for low frequency noise is provided in reference [1], which provides a criterion for determining whether a certain level of low frequency noise is likely to lead to complaints. The criterion is normally applied to levels measured inside buildings, whereas only external data at the site boundary were available here. In some circumstances, for example where structural resonances of lightweight buildings are excited, it is possible that noise levels inside a building could be higher than levels outside. There may also be other adverse effects for occupants of buildings, such as rattling windows and bouncing floors. These factors are not directly considered here, but the possibility that they may be contributing to the problem was taken into account by including a safety margin relative to the standard criterion.

The variability of noise levels at the boundary of the neighbouring property is illustrated in Figure 1a, which shows spectra recorded on four separate occasions compared with the low frequency noise criterion from [1]. The levels exceed the criterion by 10-20 dB at various frequencies in the 20-100 Hz range.

Since the aim of the investigation was to completely avoid future complaints, the cautious approach of considering the envelope of all measured data was taken. The difference between the criterion and the envelope was taken as the minimum attenuation required, shown in Figure 1b, but an additional margin of 5dB was added to give the target for the minimum insertion loss of new silencers.



a)

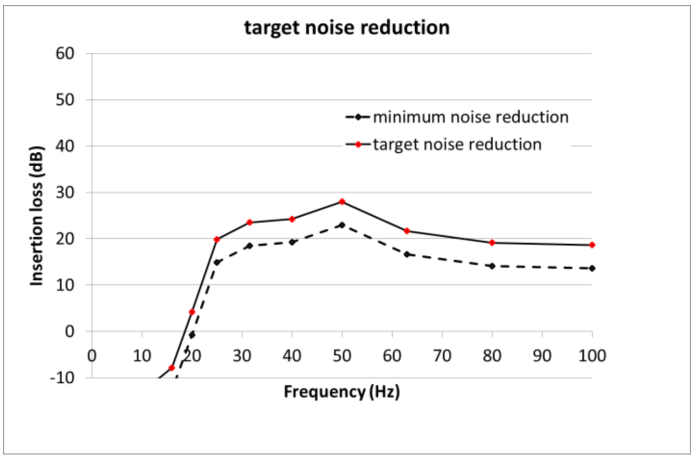


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Figure 1: a) Far-field noise spectra compared with the low frequency noise criterion. b) Target noise reduction for additional silencers.

2. ASSESSMENT OF THE NOISE SOURCE

The chamber ventilation system is shown schematically in Figure 2. The system uses two Roots blowers, each of which has two ducts leading to roof level, the discharge duct and the jet intake. The two blowers operate independently, but there were a number of circumstances where they run at close speeds which can result in low frequency beating at 1-10 Hz and complex far-field radiation patterns. Spatial interference effects between jet intake and discharge ducts on the same blower system also occur, so that the far-field noise levels can vary widely with the speeds of the two blowers and the temperature of the air in the various ducts.

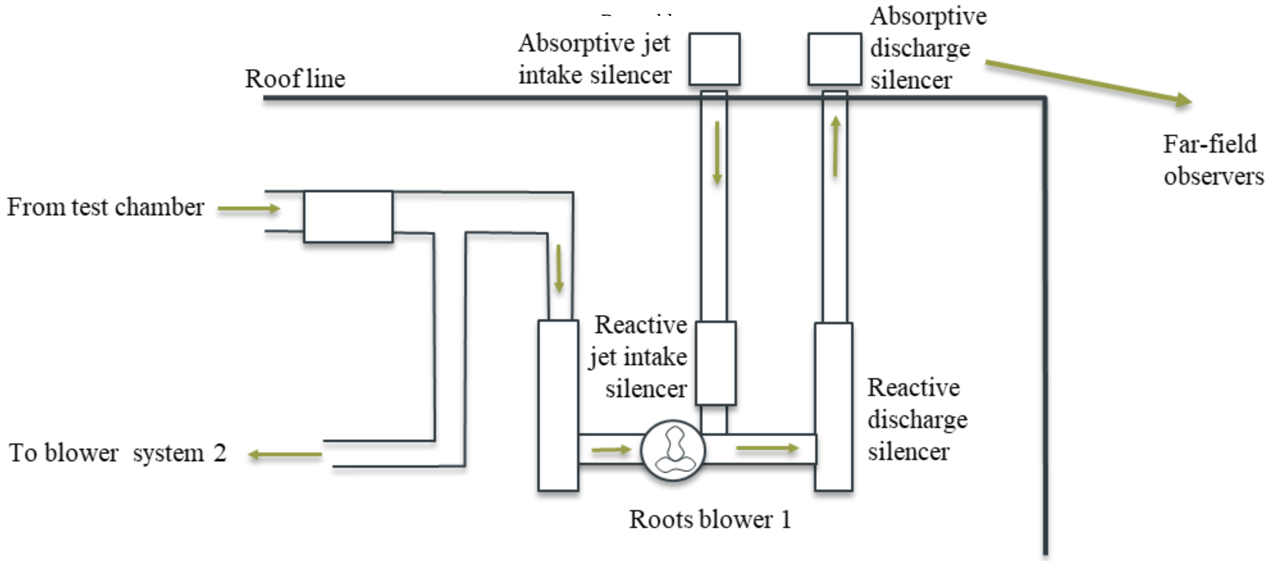

Figure 2: Schematic layout for the ductwork and silencers of each blower system.

The noise levels adjacent to the two duct outlets were monitored during a run-up and run-down of the blowers, and Figure 3 shows the transient spectrum for a typical measurement. The green curve shows the narrow band spectrum for one short time period, the analysis bandwidth was 0.39 Hz corresponding to an analysis time window of 2.56 sec, and the grey ghost spectra show the narrow band spectra for the remainder of the event.

The harmonic content of the pulsations from the blower are clear, with the 30 Hz fundamental frequency indicating a pump speed of about 450 RPM, i.e. 4 pulsations per rotation for two lobed blowers. It is also useful to consider the envelope of the ghost spectra which, although not covering the entire frequency window, does show clear peaks at 25, 58 and 88 Hz, which are an indication of gaps in the performance of the silencer system.

A problem with this external measurement is that it was not possible to determine the relative contributions of the jet intake and discharge ducts. This was achieved by lowering a microphone a short distance into each duct and repeating the transient operating cycle for the blower.

Taking the max-hold envelope of the instantaneous 1/3 octave band spectra for the two in-duct measurements during a complete transient run-up and run-down gave the result presented in Figure 4. This data indicates that although the discharge duct has generally higher levels at most frequencies, the jet intake had the highest levels below 31.5 Hz. This is likely to be a function of the performance of the different reactive silencers in the two ducts.

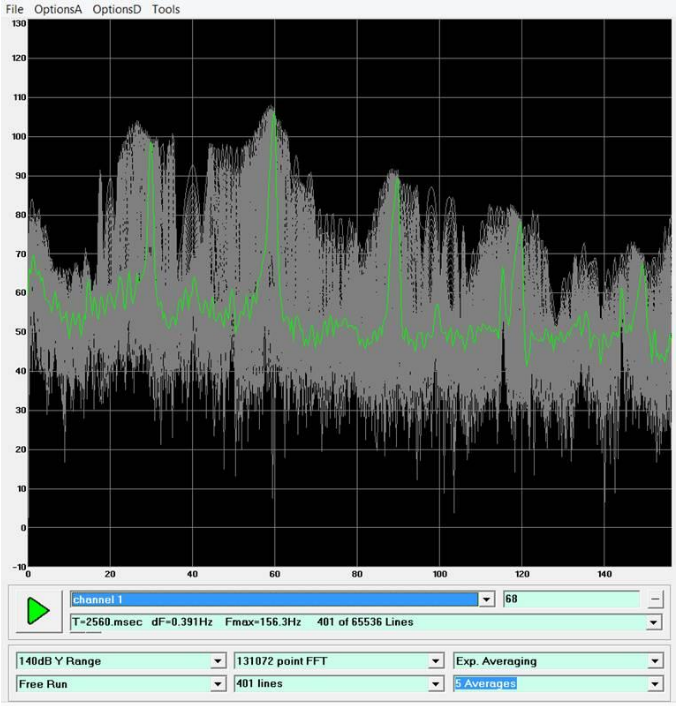

Figure 3: Spectrum envelope of low frequency noise levels on the roof-top during a transient event.

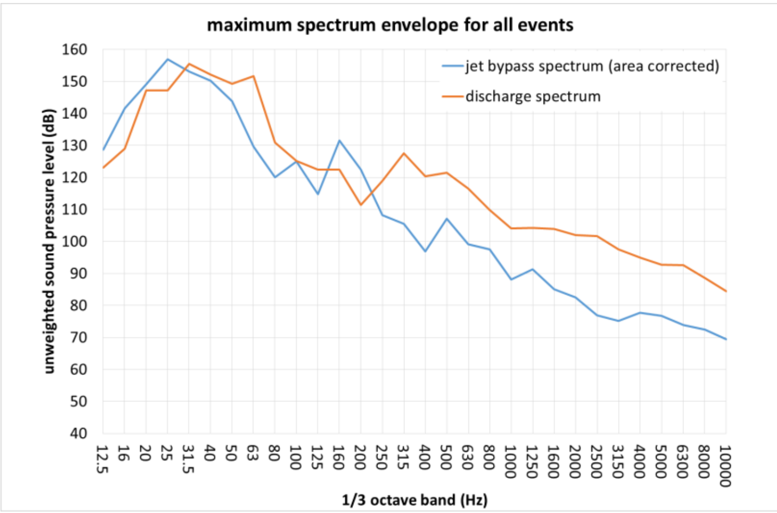

Figure 4: In-duct noise data for the jet bypass and discharge ducts, showing the maximum envelope of all recorded 1/3 octave band spectra.

2.1. Evaluation of Current Duct and Silencer System using FE modelling

The design layout of the existing system shows how there is a relatively long tailpipe on each of the reactive silencers. Although there were absorptive silencers at roof level, these were relatively small components which would have little effect at the low frequencies of interest here.

It is well known that tailpipe resonances can reduce the effectiveness of reactive silencers. These occur when the length of the tailpipe is nominally a multiple of a half wavelength, i.e. the resonant frequencies of an open-open pipe. In this case there is some uncertainty in the calculation, depending on the effect of the absorptive silencers, the temperature and speed of sound, and standard theoretical ‘end corrections’ that make pipes appear acoustically longer than their physical length. Using nominal values, the tailpipe length was about 6.5 m, so that with a speed of sound of 350 m/s the resonances might occur at 27, 54 and 81 Hz, from which it seems likely that this is the origin of the peaks noted in Figure 3.

A prediction of the performance of the current silencers including the tailpipe can be obtained by modelling the system using the Finite Element method (FE). The existing discharge duct silencer shown in Figure 5a comprised two chambers with internal ‘side-branch’ tubes to improve performance at higher frequencies. The FE model of the system was developed using the ACTRAN code, [2], and an example of the simulated pressure map for an incident plane wave of unitary amplitude is shown in Figure 5b.

Depending on the specified in-duct boundary conditions, the ACTRAN model can predict both the transmission loss (TL) and the insertion loss (IL) of a silencer. The TL is the theoretical attenuation of the silencer in an infinite duct system, with an incident plane wave at the inlet and no downstream discontinuities. The IL is the performance provided when the silencer is placed into a finite duct system, taking into account the impedance of any upstream components and reflections from downstream discontinuities such as the duct termination.

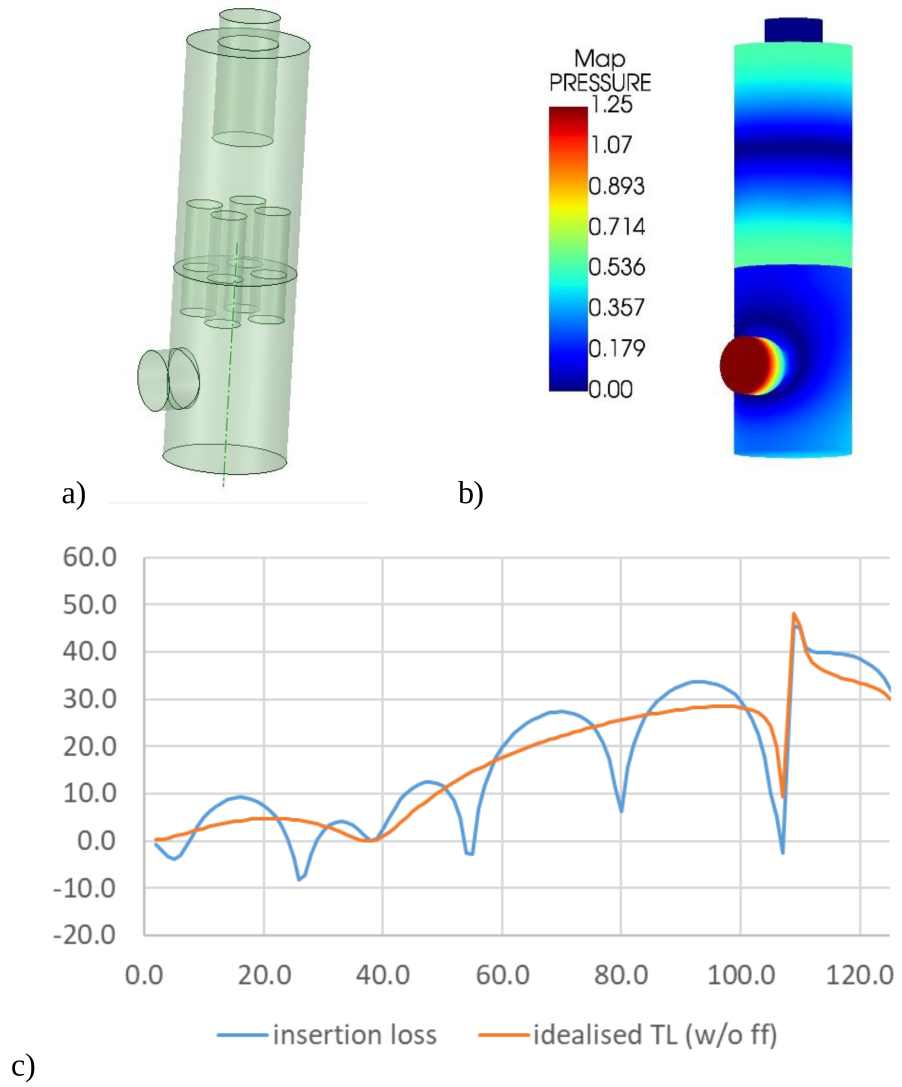

Figure 5: a) CAD schematic of the existing silencer. b) FE pressure (Pa) map at 110 Hz of existing silencer for a unitary incident plane mode, c) Predicted transmission loss and insertion loss of the existing silencer system.

Each silencer must be modelled in detail, but the process of evaluating the various duct layouts that were considered during the design optimization of the system was greatly accelerated by use of the Transfer Matrix method (TMM) in ACTRAN. Using TMM the transfer function between particle velocity and pressure at the input and output of each component are predicted using FE, but the matrices for wave propagation in long pipes are modelled analytically. The performance at each frequency for the complete system is then predicted by multiplying together the complete set of transfer matrices.

The predicted TL and IL for the existing discharge silencer are shown in Figure 5c. These results indicate two reasons why there was a noise problem: the TL shows that the silencer provides very little attenuation below 50 Hz, and the IL confirms that tailpipe resonances create significant gaps in silencer performance.

It should be noted here that this prediction is for a nominal speed of sound of 340 m/s, whereas because the air temperature on the discharge line can vary from -20°C to + 40°C the speed of sound may vary in the range 318 m/s – 355 m/s, which will alter the resonant frequencies. The jet intake sees less temperature variation, but significant differences do occur between summer and winter.

Besides modelling the induct silencer performance, ACTRAN can also be used to predict the transfer function from induct sound pressure levels at the duct termination to sound pressure level in the far-field. This model, which includes the use of infinite elements, provides a prediction of the directivity of the sound radiation. In this case the observer was at approximately 200 m lateral distance, at an angle of about 100° relative to the duct axis. The scattering effect of the edge of the building was neglected.

Applying this transfer function to the measured in-duct levels gave the predicted far-field levels presented in Figure 6, showing remarkably good agreement in the key frequency range of 25-63 Hz. The trend at lower and higher frequencies is probably indicative of background noise from other sources.

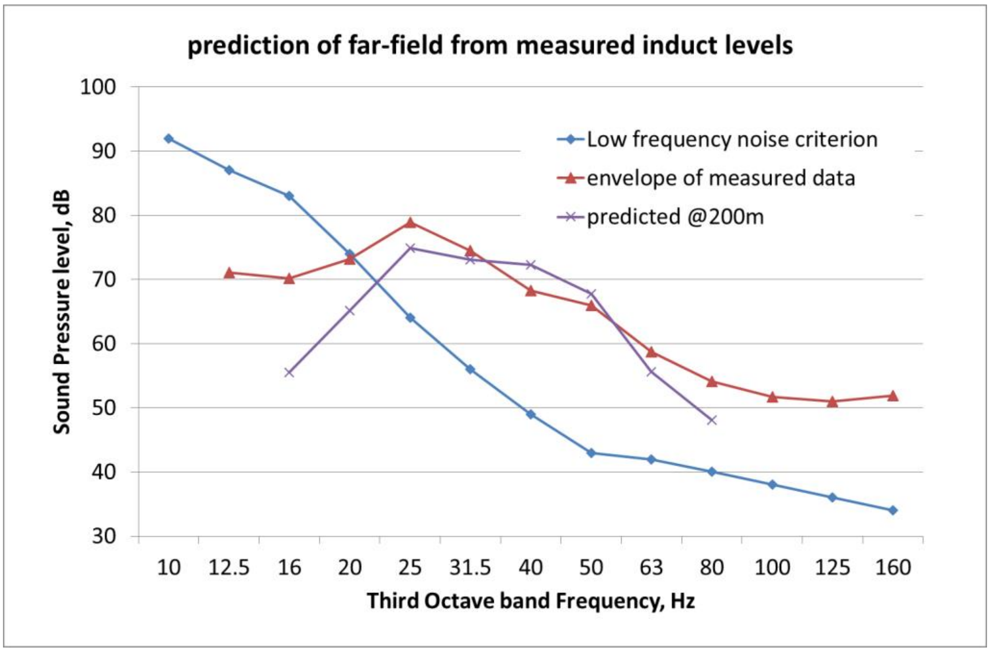

Figure 6: Far-field levels predicted from induct levels using the ACTRAN radiation model.

3. LAYOUTS FOR ADDITIONAL SILENCERS

The target attenuation spectrum in Figure 2b indicates a requirement for reductions of 20-30 dB in the 25-50 Hz range. This is a substantial level of attenuation that requires either a single silencer with a large expansion ratio or two smaller silencers. In either case, and considering that both jet intake and discharge ducts for the two blowers needed to be treated, it was apparent that a significant weight problem was expected. Space was also an issue, although this could be resolved by installing some silencers on the roof. Potentially also the discharge ducts for the two blowers could be combined to reduce the number of silencers, but this would then need to be increased in size to provide the required flow duct area and expansion ratio. Some weight saving was also possible by removing the existing silencers, but the attenuation from these at higher frequencies was potentially useful.

Given these difficulties with application of reactive silencers some alternatives were considered. One possibility was using a very long absorptive silencers below the roof-line, but it was quickly apparent that the diameter required to achieve the low frequency performance would be substantial. The possibilities for active control was also reviewed, but the very high induct levels shown in Figure 4 were considered an insurmountable issue.

In the final analysis four options for the discharge ducts were considered, as listed below, with options 2 and 3 being presented in Figure 7. These two designs are quite similar acoustically, but with very different duct lengths and weight implications for the building.

All designs were based on use of one or two additional components: silencer A was suitable for a single blower line, and silencer B was a larger component to be used where the ductwork of blowers 1 and 2 were combined into a single duct. FE predictions for each case were carried out, and as noted previously the TMM option was useful since the matrices for A and B only needed to be predicted once and all the ducting was simulated analytically.

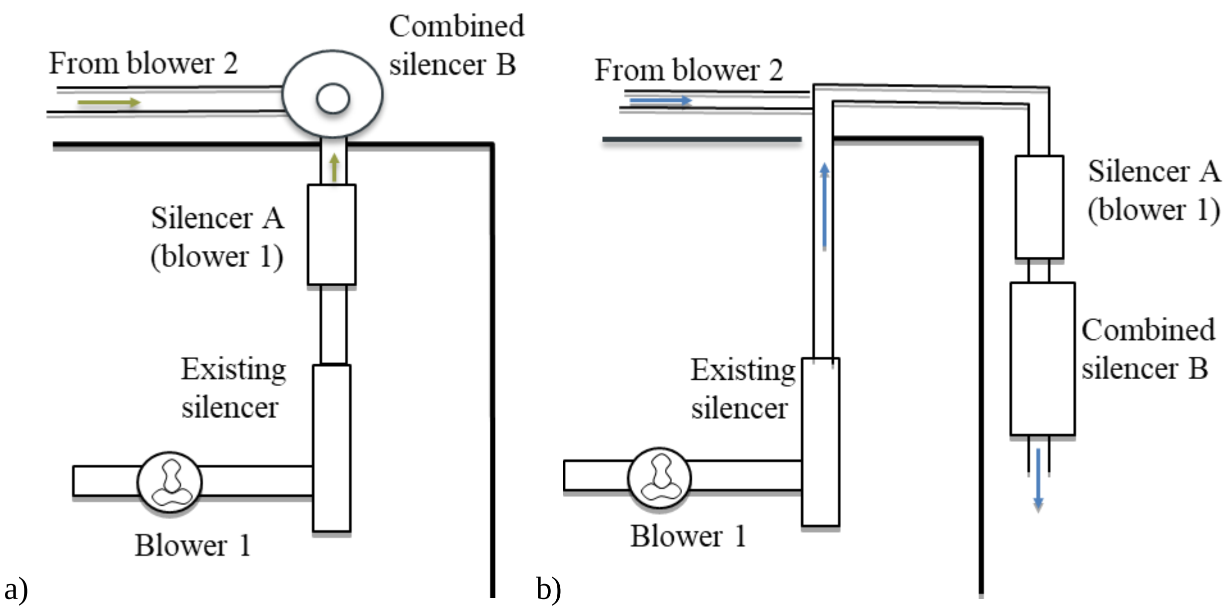

Figure 7: Design options for the discharge duct: a) option 2; b) option 3.

The predicted performance of each option is presented in Figure 8. It is important to bear in mind that a key driver for the design was the level of any dips in predicted attenuation, whereas peaks had no importance. The specification and evaluation of each option for the discharge ducts were as follows:

1. Silencer A fitted inside the plant room on each blower, leaving the existing silencer in situ. This solution could be acceptable, but it was marginal in the 31.5 Hz band.

2. Silencer A fitted in the plant room for each blower and combined silencer B fitted on the roof (Figure 7a). This would definitely reduce the discharge noise to below the criterion, and it may be possible to dispense with the existing silencers to save weight if necessary.
3. Both silencer A and silencer B fitted outside the building and supported from the ground (Figure 7b). This was also predicted to resolve the discharge noise problem. The predicted dips in performance due to the long pipe run between the existing and new silencers were not an issue, and removing the existing silencers to simplify the pipe run was a possibility, but was not necessary for weight reasons. The outlet duct could point down as the exhaust gas was only air close to normal temperatures. Reflections from the facade was considered as an issue since that might add up to 6 dB to far-field levels, but the high level of attenuation meant that this was not a problem.
4. A single combined discharge silencer B fitted on the roof to attenuate both blowers. This relatively low cost option was not a satisfactory solution because the duct length between the existing silencer and the new roof level silencer caused significant dips in performance.

A similar range of design options for the jet intake were also analyzed. Bearing in mind the weight and space constraints applied to the complete system, the final designs selected were:

- For the jet intake, an additional silencer A installed inside the building, similar to option 1
- For the discharge duct option 3 was selected, Figure 7b. A photograph of the final installation is shown in Figure 9c.

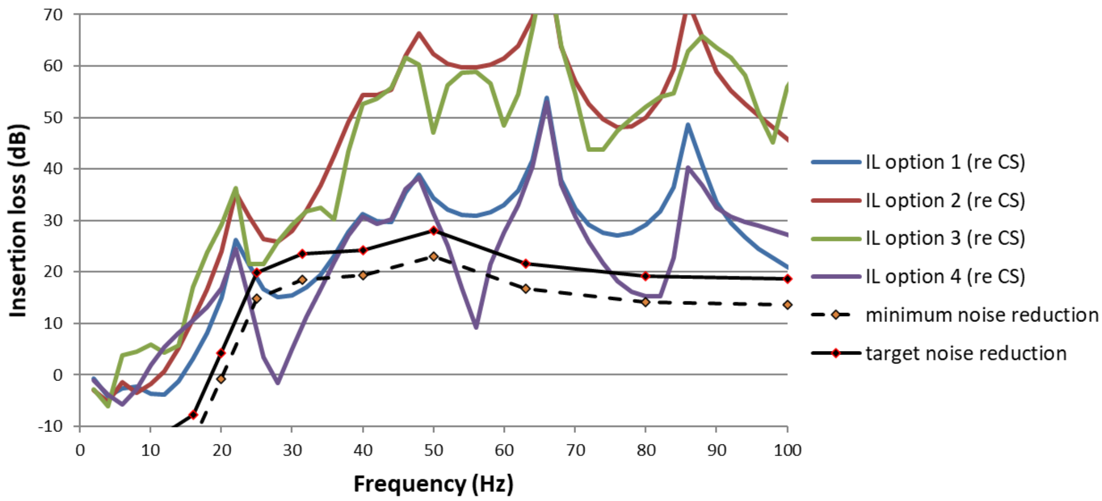

Figure 8: Predicted insertion losses for the proposed discharge silencer options assuming the existing silencer remains in-situ.

4. FINAL TESTING

A site visit to assess the performance of the installed silencers was made. Far-field levels were too low to be measured against daytime background noise. Instead, induct measurements for the discharge and jet intake ducts were carried out using the same spectrum envelope method over a complete transient cycle as before. An area correction needed to be applied to account for the larger outlet duct diameter of silencer B, and the resulting levels were then as shown in Figure 9a. The insertion loss is for the single silencer in the jet intake and the two silencers in the discharge duct are presented in Figure 9b.

Since the spectrum envelope method captures the maximum at each frequency, the inferred insertion loss shown is actually the minimum attenuation that was achieved at each frequency, bearing in mind the effect of changing speed of sound during the transient. The predicted minimum attenuation for option 3 shown in Figure 7 was 40-50 dB, which is in reasonable agreement with the measured insertion loss.

Although the design options for the jet intake are not presented in detail, the predicted attenuation for the selected single silencer A option was similar to that of the discharge duct option 1 plotted in Figure 8. The minima shown are in reasonable agreement with the measured minimum insertion loss of 20-30dB shown Figure 9b.

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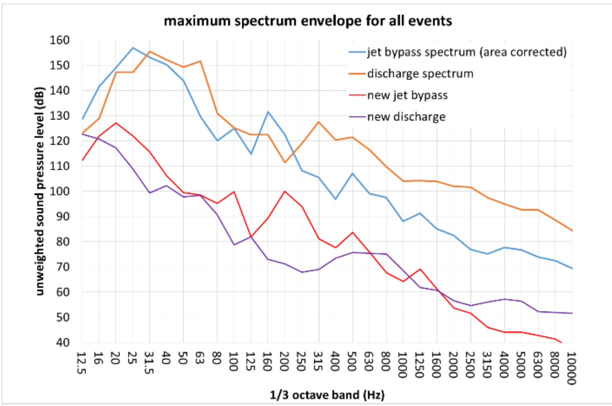

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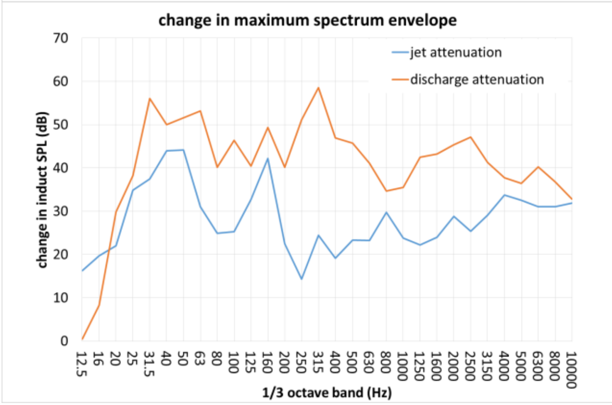

c)

Figure 9: In duct sound pressure levels for jet intake and discharge ducts before and after treatment: a) absolute levels, b) area corrected insertion loss. c) Photo of the discharge duct silencers.

5. CONCLUSIONS

This case study highlights the difficulty of determining silencer performance requirements when the sound source is highly variable. The spectrum enveloping method provided a surprisingly easy way of assessing both the level of far-field noise, and hence the target attenuation, and the relative source levels for the jet intake and discharge ducts. The fact that there was good agreement between predicted and measured far-field levels helped to confirm that these were the dominant sources, and that contributions from other paths, such as sound transmission through the building facade, could be neglected in the first instance.

The low frequency noise criterion is normally applied to levels recorded indoors, whereas that information was not available here. Making an allowance for the fact that in some circumstances levels indoors could be higher than outdoors helped boost confidence that the proposed design solution would resolve the complaints.

Most important in the methodology however, was the use of FE to accurately assess the minimum insertion loss that would be achieved by each design option. The good correlation between predicted and measured minimum insertion losses for the final design confirms the efficacy of the approach used, which was the key to the completely successful outcome of the project.

6. REFERENCES

1. Moorhouse, A. T. & Waddington, D. C. & Adams, M. D. A procedure for the assessment of low frequency noise complaints. *Journal of the Acoustical Society of America*, **126**, 1131 (2009).
2. *Actran User's Guide*, Free Field Technology, Belgium.