Experimental investigation of noise generation from the two stage expansion of a round air jet

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ABSTRACT

The flow induced noise from a two stage expansion of a round air jet has been investigated experimentally, with specific application to high velocity HVAC systems. The two stage expansion consists of an enclosed primary conical diffuser connected to a straight outlet duct section of arbitrary length followed by a secondary expansion of the jet into open space. The experimental analysis compares the effect of varying the angle of the primary conical diffuser and the length of the subsequent straight outlet duct length. A constant expansion area ratio of 9 was used. The optimum diffuser angle and duct length is determined for both minimum noise and minimum space constraints. The total sound power, octave sound power and 1/3 octave sound power levels are all consistent to within 2 to 3 dB. The acoustic effects of fitting HVAC air diffuser grills onto the outlets of each of the experimental cases presented is also documented to demonstrate the potential application of these results to HVAC installations.

INTRODUCTION

High Velocity HVAC ducts have been used in specific applications for more than 50 years with detailed design guidance provided in HVAC handbooks (Strock and Koral, 1965) as far back as 1959. For the purposes of this investigation high velocity is assumed to be an air distribution velocity above the limits stated in the ASHRAE standards (ASHRAE Fundamentals, 2005) established for a standard building based HVAC system. These standards are written to ensure adequate system operation and the delivery of minimum environmental conditions such as temperature, humidity, air movement and noise levels. Collectively these conditions determine the overall comfort level for occupants of the space served by the given HVAC system. The current accepted velocity limits are 7 ms^{-1} for rectangular ducts and 12 ms^{-1} for circular ducts.

High velocity HVAC duct systems are typically used in applications where space for building (or vessel) services is limited or otherwise comes at a premium capital cost. The significant increases in running costs associated with moving conditioned air at high velocity through small ducts is offset against the capital cost of the initial installation. The use of high velocity systems in buildings has largely been eliminated due to increased awareness of operational expenses and the general push for sustainable and energy efficient building designs. The distribution velocity inside HVAC ducts is generally kept in the low velocity region of 3 ms^{-1} to 7 ms^{-1} and this is reflected in the focus of published HVAC industry design guides

The recent shift in the global energy market and the increasing international pressures to reduce greenhouse gas emissions has generated renewed interest in the optimisation of the energy used in HVAC systems and other building services. The added power consumption required to operate a high velocity HVAC system in an every increasingly energy constrained environment has severely restricted their use. However these same energy cost constraints have opened niche applications where the added air handling costs can be offset against other operational costs. One such application is the fast ferry industry, where high velocity HVAC systems can be used to make considerable space savings with an overall net reduction in the vessel's running costs.

Initial experimental investigations by Neale et al (2004) and Neale (2006) have demonstrated the feasibility of using high velocity HVAC dusts on board ocean going fast ferries. The earlier work (2004) focused on the design and measurement of the acoustic performance of a primary diffuser used to expand and decelerate the high velocity distribution air upstream of the outlet grills supplying the treated air to the passenger cabin space. This two stage expansion process is shown schematically in Figure 1. A fixed primary diffuser angle (α) of 7 degrees was used initially, and the impact of the outlet diffuser grill was ignored. The effect of the length (L) of the outlet duct (calming length) was only explored to a limited extent in this earlier work.

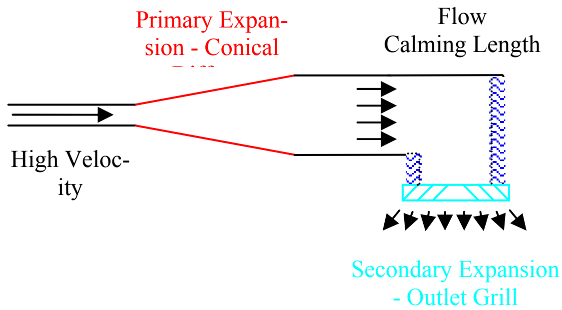

Figure 1. Two stage high velocity HVAC expansion outlet.

This paper documents the extension of this earlier work to investigate the effect of varying the primary diffuser angle, the outlet duct length and limited variations to the secondary outlet grill, as defined in Figure 2.

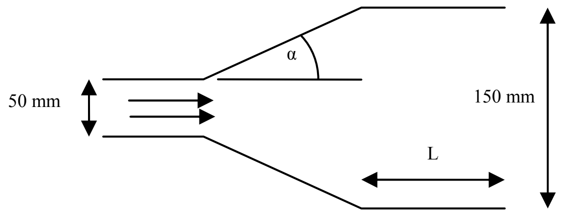

Figure 2. Two stage high velocity HVAC expansion outlet geometry definition.

EXPERIMENTAL INVESTIGATION

A parametric matrix was proposed to identify the most suitable outlet diffuser geometry that satisfied both airflow dispersion and minimised flow generated noise levels. With the limitation on ceiling space stipulated by the original project brief a conical diffuser design was selected with a range of primary diffuser angles of 7, 10 and 14˚ used. To allow for an interchangeable outlet pipe structure downstream from the diffuser a set exit diameter of 150 mm was selected. The nine fold increase in pipe cross-sectional area provided a useful drop in overall air velocity without overly extending the required ceiling height. Consequently the length of each conical diffuser varied in length according to the respective diffuser angle employed.

The second aspect of the diffuser section was the length of 150 mm diameter outlet duct used to allow the expanded flow to disperse and for any large scale turbulent eddies to be dissipated. Four outlet duct lengths of 0, 300, 600 and 900 mm were selected to provide a wide coverage of potential outlet diffuser configurations without overly extending the number of experimental tests to be conducted. Combining the three primary diffuser angles and the four outlet duct lengths outlined above provided 12 individual diffuser geometries to test for a range of jet velocities.

The parametric matrix covering the diffuser design was extended to include five different outlet grill options. The two dimensional 4x3 diffuser design matrix was extended into a third dimensional 4x3x5 matrix with a total of 60 individual design options for experimental evaluation across a range of centreline jet velocities. The five outlet options considered are listed below:

1. No outlet grill (Control)
2. Round conical grill
3. Standard square 4-way grill
4. Standard square 4-way grill fitted to a dampened cushion head
5. Standard square 4-way grill fitted to an upstream 90˚ elbow and cushion head

The round and square outlet grills are shown in Figure 3. The cushion head fitted to the square diffuser grill was lined with 12 mm acoustic lagging material. In the interest of containing the variables under consideration the thickness of the attenuation material was not varied. It is envisaged that the level of attenuation can be improved further by increasing the thickness of the lagging material used.

The experimental tests were conducted in the reverberation suite, located in the School of Mechanical and Manufacturing Engineering at the University of new South Wales. The high velocity airflow was generated from a centrifugal oil free compressor and is described in detail by Neale (2006). The reverberation suite was configured to minimise the impact of background and flanking noise on the measured sound pressure levels.

Figure 3. Outlet diffuser grills, with the square diffuser fitted to the cushion head box.

All sound pressure readings were taken using Bruel & Kjaer type 4189 (½ inch) Falcon microphones connected to Bruel & Kjaer type 2699 microphone preamplifiers. The raw acoustic signals were analyzed with a Bruel & Kjaer Type 2133 Dual Channel Digital Frequency Analyzer. Spatially averaged sound pressure levels were measured with the use of Bruel & Kjaer type 3923 Rotating Microphone Booms. The rotating booms were powered by a DC battery pack to eliminate any electrically generated harmonic noise and were rotated 360˚ every 64 seconds. The boom was moved to three asymmetric locations within the receiver room to increase the accuracy of the spatial averaging sound pressure measurements for each outlet diffuser configuration.

The acoustic properties of the reverberation suite are quite different from those encountered in a standard passenger cabin space on board ocean going fast ferries. Therefore any comparison needs to be made in terms of the sound power; an absolute reference to the total acoustic energy, rather than the sound pressure level which is also dependent on the acoustic properties of the space used.

By design the reverberation rooms are very reflective, which supports the establishment of a strong reverberant sound field in addition to the direct sound field created by the HVAC flows. In contrast to this arrangement a typical passenger cabin space is lined with materials that have a relatively high acoustic absorption (carpet, padding and ceiling tiles), which leads to a much weaker reverberant sound field. Therefore the total sound pressure level measured in a passenger space will be somewhat lower than the sound pressure level measured in the reverberation suite. By reporting the results in terms of absolute sound power levels a true understanding of the acoustic energy created by the HVAC flow field can be developed. This can then be used to predict the corresponding sound pressure field for a given set of known acoustic properties of a real passenger cabin application

To this end the reverberation time of the reverberation room containing the duct outlet was measured in ⅓ octave bands to facilitate the calculation of sound power levels, based on AS 1217.2-1985.

EXPERIMENTAL RESULTS

The independent influence of each of the primary diffuser angle, outlet duct length and the outlet grill configuration on the experimentally recorded total sound power level were investigated. By holding each of the two remaining variables constant the impact of the third variable is assessed. To limit the impact of any secondary effects each comparison is made across a number of outlet configurations. . The nature of a noise source can be identified by the relationship between the sound power level and the jet velocity, V, (in a log scale or logV). To aid in comparison between each result a consistent scale has been used throughout.

Variation with Conical Diffuser Angle

The effects of the conical diffuser angle on the sound power level for a selected range of outlet configurations was evaluated, firstly with no outlet termination grill and then with each of the four outlet grill configurations outlined previously. The three initial cases for an opened duct of 300, 600 and 900 mm length are shown in Figures 4, 5 and 6 respectively. For the short outlet duct of 300 mm the 7˚ and 10˚ cases follow a 50logV line with a minor increase in the slope at jet velocities above 35 ms^{-1}. As the outlet duct length is increased to 600 mm the point at which the slope of the sound power line increases occurs at a lower jet velocity of only 25 ms^{-1}, with the increase in slope more pronounced for the 10˚ diffuser. At an outlet duct length of 900 mm the slope of the line for the 10˚ diffuser is more in line with the 14˚ diffuser across the whole velocity range, while a minor inflection point remains for the 7˚ case. The 14˚ diffuser meanwhile follows a consistent 60logV slope across the entire jet velocity range considered for each outlet duct length.

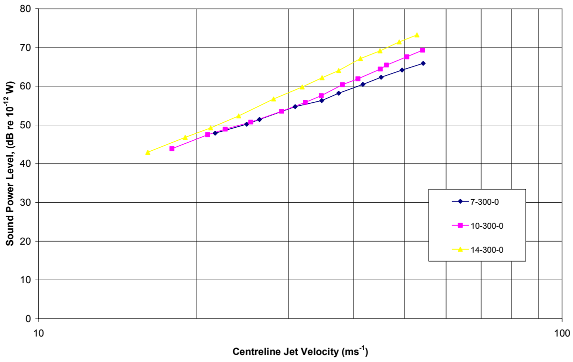

Figure 4. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – fitted with an open ended 300 mm long outlet duct.

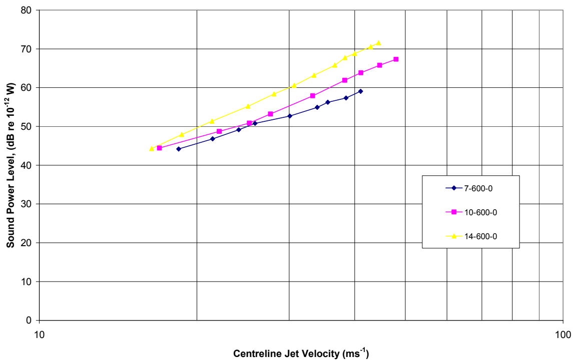

Figure 5. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – fitted with an open ended 600 mm long outlet duct

The increase in the slope of the sound power curve for each diffuser angle at higher jet velocities is a direct result of increased turbulence and the onset of flow separation. This indicates an increasing strength in the quadrupole acoustic sources in the shear layers inside the primary conical diffuser.

The impact of adding the four outlet termination grill configurations was investigated, focusing on the key outlet duct lengths of 300 and 600 mm. This decision was made given that the results for the 900 mm outlet duct showed it to be far less effective in reducing the level of flow induced noise. The results for the round jet termination grill (RJ) fitted o the 300 and 600 mm outlet ducts are shown in Figures 7 and 8 respectively. Figures 9 and 10 cover the square diffuser grill (SD), and the cushion head mounted SD grill (CH) cases are

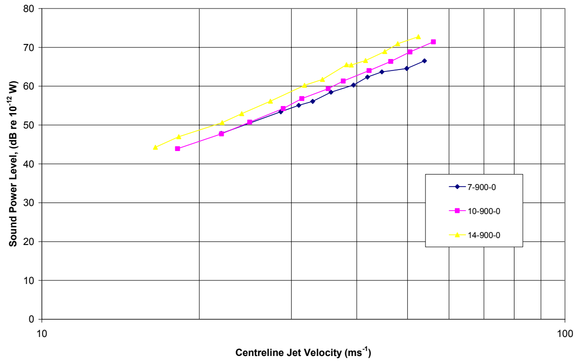

Figure 6. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – fitted with an open ended 900 mm long outlet duct

shown in Figures 11 and 12. The results for the two cases using the 90˚ elbow (ELCH) fitted into the CH configuration and then shown in Figures 13 and 14.

For all four outlet termination grill selections the 7˚ diffuser tended to follow a 50logV line while the 10˚ and 14˚ diffuser cases were more closely aligned with a 60logV line. The largest divergence between the two occurred with the RJ outlet fitted to the 600 mm long outlet duct at jet velocities over 40 ms^{-1}. The sound power level for each of the outlet configurations studied was very similar with a minor reduction observed when using a duct length of 600 mm over the shorter length of 300 mm.

The sound power produced by an ideal dipole acoustic source follows a 60logV line, while an ideal quadrupole source will follow an 80logV line. Based on this theory one could attribute the bulk of the 60logV cases being caused by strong dipole sources (surface generated flows) as opposed to quadrupole sources (shear flows). However experimental validation work has found that a true dipole source struggles to get much over the 50logV line due to losses in converting the flow energy into the radiated acoustic field. A similar result is also found with quadrupole sources, where an 80logV line is seldom measured experimentally.

The 50logV line found using the 7˚ diffuser suggest a strong presence of wall bounded flow generated noise (little or no flow separation) from dipole sources. The strong 60logV relationship found with the 10˚ and 14˚diffusers can be interpreted as having a significant quadrupole source component, which is therefore indicative of flow separation and shear flow based noise generation. The slight increase in slope as the diffuser angle is increased from 10˚ to 14˚ is also supportive of this conclusion. The upward shift seen in the slope of the sound power level curve above critical jet velocities further reinforces this view.

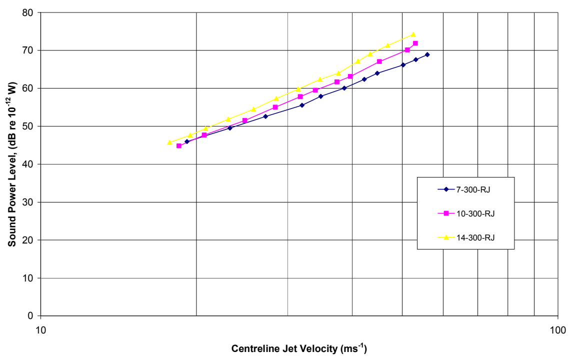

Figure 7. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – with a 300 mm long outlet duct fitted with the round jet outlet grill

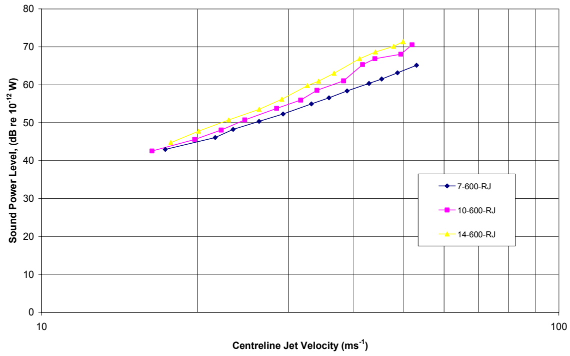

Figure 8. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – fitted with a 600 mm long outlet duct fitted with the round jet outlet grill

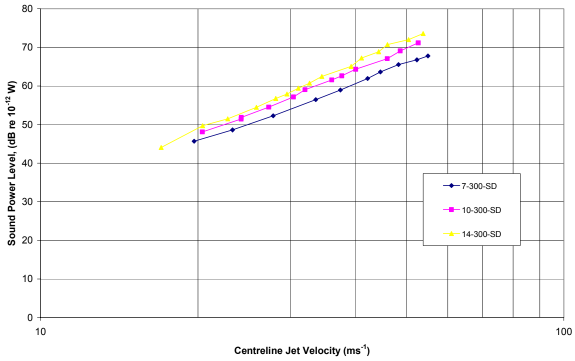

Figure 9. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – with a 300 mm long outlet duct fitted with the square diffuser outlet grill.

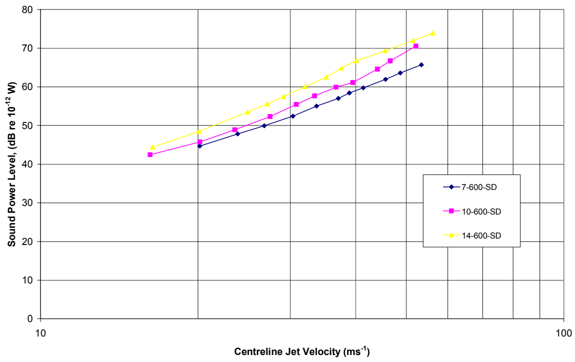

Figure 10. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – with a 600 mm long outlet duct fitted with the square diffuser outlet grill.

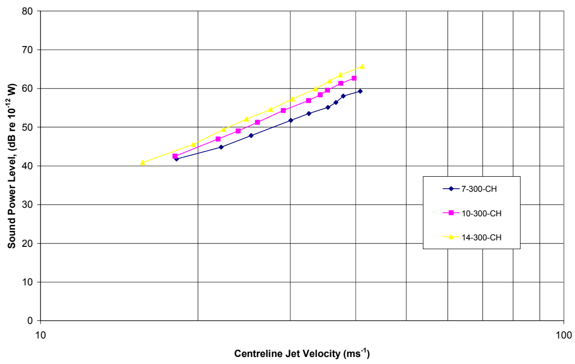

Figure 11. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – with a 300 mm long outlet duct fitted with the cushion head mounted SD outlet.

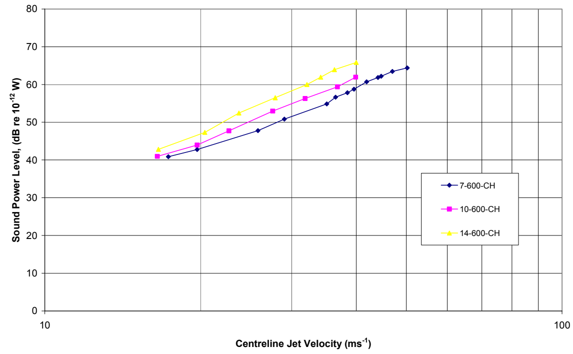

Figure 12. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – with a 600 mm long outlet duct fitted with the cushion head mounted SD outlet grill.

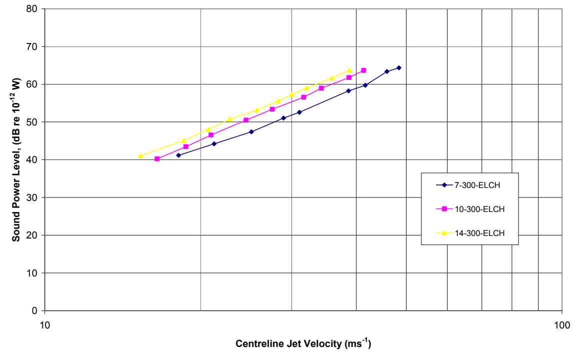

Figure 13. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – with a 600 mm long outlet duct fitted with the ELCH outlet grill.

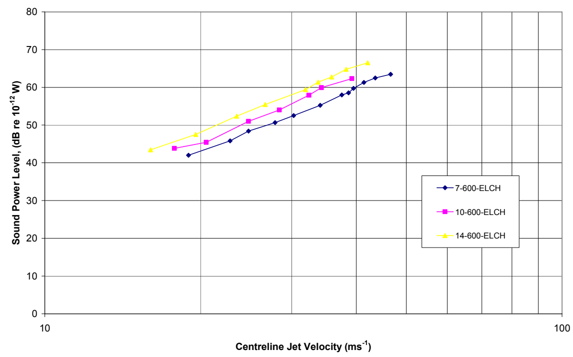

Figure 14. Sound power level comparison for conical diffuser angles of 7˚, 10˚ and 14˚ – with a 600 mm long outlet duct fitted with the ELCH outlet grill.

Variation with Outlet Termination Grill

The configuration of the outlet termination grill was found to significantly affect the perceived acoustic performance (in terms of the sound pressure level) of the outlet as a whole. Therefore it is important to complete a further analysis in terms of the absolute sound power generated by each outlet configuration. The first and simplest comparison is made with the round jet and square diffuser grills fitted directly onto each of the 7˚, 10˚ and 14˚ conical diffusers (an outlet duct length of 0 mm) as shown in Figures 15, 16 and 17 respectively. In all three cases the SD grill out performed the RJ grill, with the largest difference of 4 to 5 dB occurring with the 7˚ and 10˚ conical diffusers. The gap between the RJ and SD grill narrowed significantly to only 1 to 2 dB with the 14˚ conical diffuser.

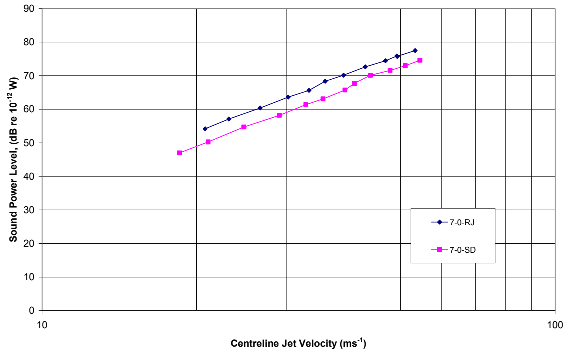

Figure 15. Sound power level comparison between the round jet (RJ) and square (SD) outlet termination grills fitted directly to the 7˚ conical diffuser.

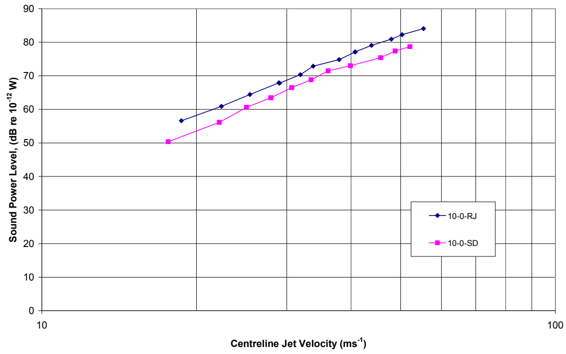

Figure 16. Sound power level comparison between the round jet (RJ) and square (SD) outlet termination grills fitted directly to the 10˚ conical diffuser.

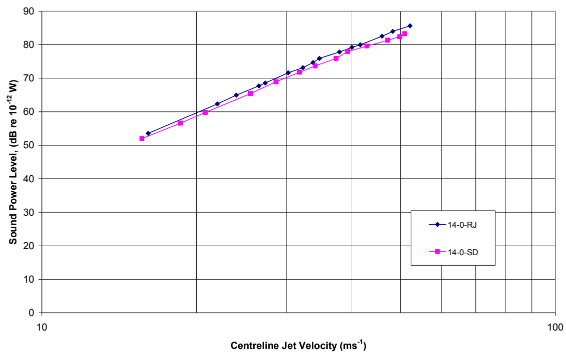

Figure 17. Sound power level comparison between the round jet (RJ) and square (SD) outlet termination grills fitted directly to the 14˚ conical diffuser.

The slope of the sound power level curve (against jet velocity) is also higher for the 14˚, at 55 (55logV), compared to only 50 (50logV) for both the 7˚ and 10˚conical diffusers. All three curves have a consistent slope across the velocity range considered of 20 to 50 ms^{-1}. The addition of the outlet grills has however reduced the slope of the curves from the 60logV levels seen in the models with no outlet grills fitted. Therefore it may be concluded that the grills do make some reduction in the level of flow separation and the subsequent generation of quadrupole noise sources.

The effect of each of the outlet grills on the total sound power level, when used in conjunction with an extended outlet duct was also investigated, beginning with the 300 mm long outlet duct fitted to each of the conical diffusers. The results for the 7˚, 10˚ and 14˚ conical diffusers are shown in Figures 18, 19 and 20 respectively. For the 7˚ diffuser the CH and ELCH outlet configurations both provided significant improvements in the sound power level, especially in the important 20 to 30 ms^{-1} jet velocity range. The SD and RJ outlet grills are both very similar to the baseline case of no outlet grill in the 20 to 30 ms^{-1} velocity range and worse by 1 to 2 dB at higher jet velocities. The slope of each curve is in the range of 40 to 50 (40logV to 50logV) for the lower jet velocity band of 20 to 30 ms^{-1}, and at jet velocities above this level there is a distinct increase in slope to the 55 to 60 (55logV to 60logV) level. This effect is particularly prominent in the case of the CH and ELCH outlets. The ability of these outlets to disperse the noise inducing turbulence is limited to a maximum jet velocity of the order of 30 ms^{-1}, with diminishing impact thereafter.

For the 10˚ conical diffuser each of the outlet grills perform worse than the baseline case of no outlet, with the exception of the CH and ELCH grills at jet velocities below 25 ms^{-1}. The improvement in the sound power level in this range is only in the order of 1 to 2 dB. The slope of each curve follows a very consistent 60logV line for each of the outlet grills considered.

The 14˚ conical diffuser results showed a similarly consistent slope of 60 (60logV) and the CH and ELCH grills were both 1 to 2 dB lower than both the baseline case and the remaining outlet grills (RJ and SD).

The same comparison was repeated for an outlet duct length of 600 mm, with the intent to further clarify the preferred outlet duct length and grill selection. The results for the 7˚, 10˚ and 14˚ conical diffusers are shown in Figures 21, 22 and 23 respectively. The results are very similar to the 300 mm outlet duct cases, with CH and ELCH outlets the best performed outlet when coupled with the 7˚ conical diffuser. Once again the slope of the curve for the 7˚ diffuser starts at 40 and increases to 50 above a jet velocity of 30 ms^{-1}.

Extending the outlet duct from 300 to 600 mm improved the performance of the 10˚ diffuser, with a reduction in the slope of the curve to only 45 to 50 for jet velocities below 30 ms^{-1}. The results for the 14˚ still show a consistent slope of 60 (60logV), but the extended duct length does improve the performance of each outlet over the baseline case of no outlet. A reduction in the overall sound power level of 2 to 3 dB was achieved for each of the four outlet grill configurations tested across the whole jet velocity range considered.

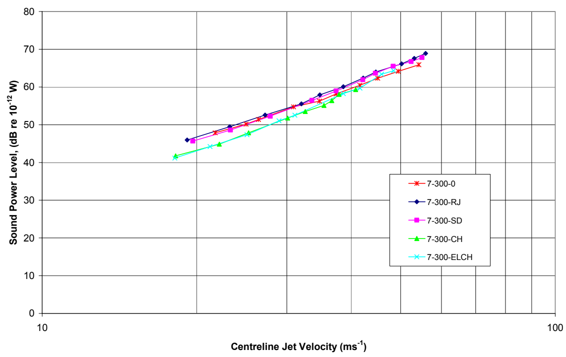

Figure 18. Sound power level comparison between each termination grill configuration fitted to the 7˚ conical diffuser with a 300 mm long outlet duct.

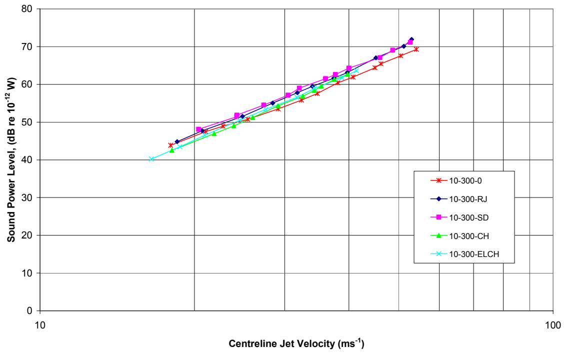

Figure 19. Sound power level comparison between each termination grill configuration fitted to the 10˚ conical diffuser with a 300 mm long outlet duct.

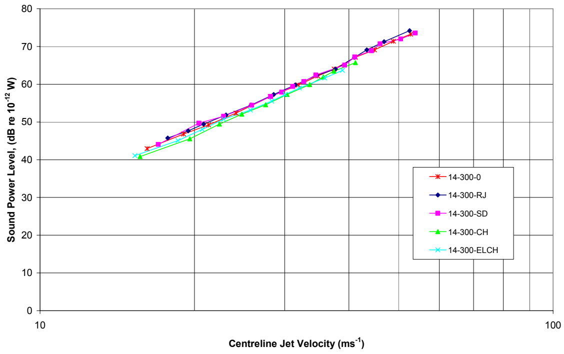

Figure 20. Sound power level comparison between each termination grill configuration fitted to the 14˚ conical diffuser with a 300 mm long outlet duct.

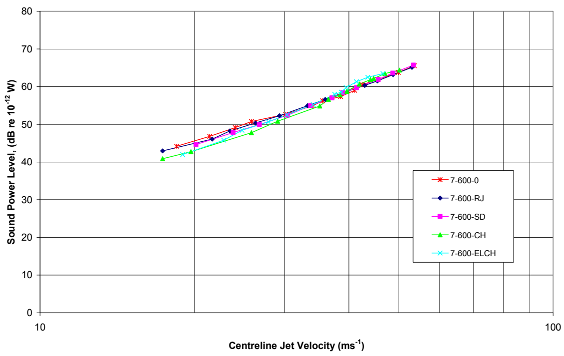

Figure 21. Sound power level comparison between each termination grill configuration fitted to the 7˚ conical diffuser with a 600 mm long outlet duct.

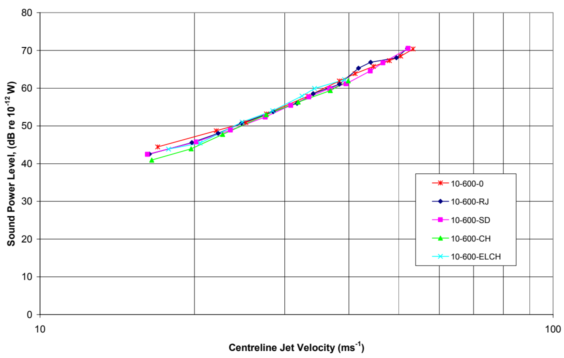

Figure 22. Sound power level comparison between each termination grill configuration fitted to the 10˚ conical diffuser with a 600 mm long outlet duct.

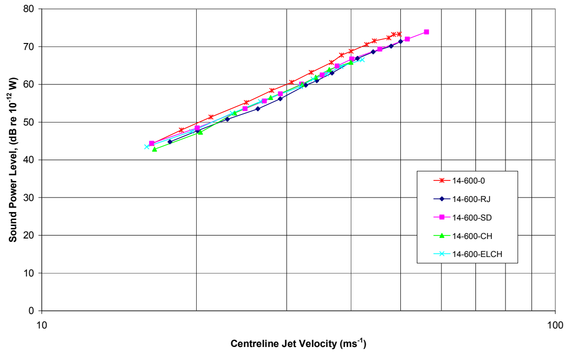

Figure 23. Sound power level comparison between each termination grill configuration fitted to the 14˚ conical diffuser with a 600 mm long outlet duct.

Variation with Outlet Duct Length

To initially isolate the effects of the outlet grill in this analysis the simplified case of fitting open ended outlet ducts to each of the conical diffusers was used. The sound power level generated by each of the three conical diffusers when fitted with an outlet duct length of 300, 600 and 900 mm is shown in Figures 24, 25 and 26 respectively. All three outlet duct lengths used with the 7˚ conical diffuser produced a very similar sound power level across the jet velocity range considered, with all three curves following a consistent slope of 50 (50logV). There are some minor variations at jet velocities above 30 ms^{-1}, with the 600 mm long duct the preferred selection. At jet velocities below 25 ms^{-1} there is virtually no difference between all three lengths trialled.

In the case of the 10˚ conical diffuser the 300 mm long duct performed marginally better by 1 to 2 dB than the 600 and 900 mm options. The slope of all three curves was around 50 (50logV) for jet velocities below 30 ms^{-1} and this increased to 60 (60logV) at jet velocities above this level. The increase in slope is best illustrated by comparing the sound power level at 50 ms^{-1}, which is 5 dB greater than for the same duct fitted to the 7˚ conical diffuser. The results for the 14˚ conical diffuser show a further 4 dB increase in the sound power level at the reference jet velocity of 50 ms^{-1}, when compared back to the results for the 10˚ conical diffuser. This increase is also reflected in the increase in the slope of the curves which is a consistent 65 (65logV) across the entire jet velocity range considered. This suggests the presence of quadrupole sound sources, and therefore evidence of flow separation within the primary conical diffuser section. Therefore the 14˚ primary diffuser angle is too large, unless some additional measures are taken to limit the onset of flow separation with the primary diffuser section.

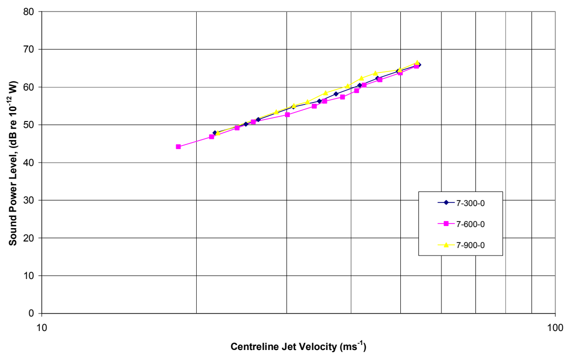

Figure 24. Sound power level comparison for the 7˚ conical diffuser fitted with an open ended 300, 600 and 900 mm long outlet duct.

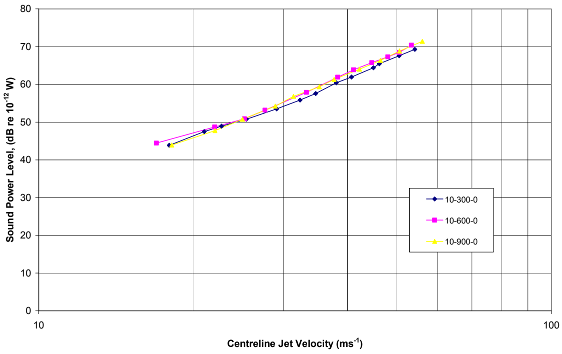

Figure 25. Sound power level comparison for the 10˚ conical diffuser fitted with an open ended 300, 600 and 900 mm long outlet duct.

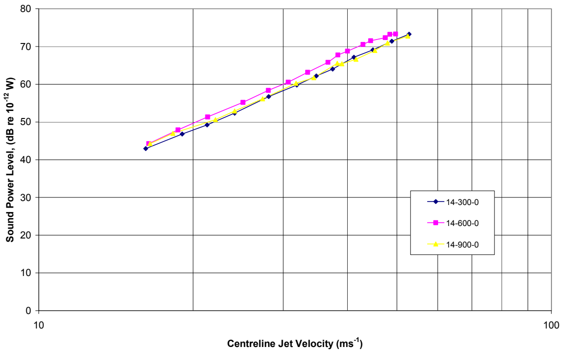

Figure 26. Sound power level comparison for the 14˚ conical diffuser fitted with an open ended 300, 600 and 900 mm long outlet duct.

The above cases where an open ended outlet duct is used provides a useful indication of the direct contribution of the outlet duct length to the overall sound power level, however it ignores the important secondary effects of coupling the outlet duct to the outlet termination grill. In a practical HVAC installation some form of outlet grill will be required for aesthetic reasons and to distribute the airflow evenly. Therefore it is important to assess the performance of a more realistic scenario of fitting an outlet termination grill to the same range of outlet duct lengths used above.

The above analysis was repeated for the square diffuser (SD) outlet grill fitted to the 300, 600 and 900 mm outlet ducts for each of the three conical diffusers used. The results for the 7˚, 10˚ and 14˚ diffusers are shown in Figures 27, 28 and 29 respectively. There is a significant reduction (up to 10 dB) in the total sound power level recorded for each outlet duct length, when compared back to the baseline of no outlet duct for each of the conical diffusers used.

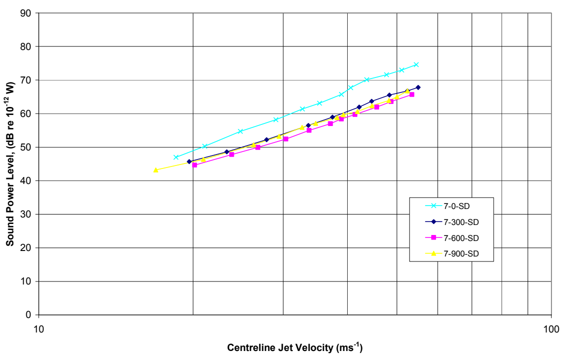

Figure 27. Sound power level comparison for the 7˚ conical diffuser fitted with the square (SD) outlet grill with an extended outlet duct of 0, 300, 600 and 900 mm.

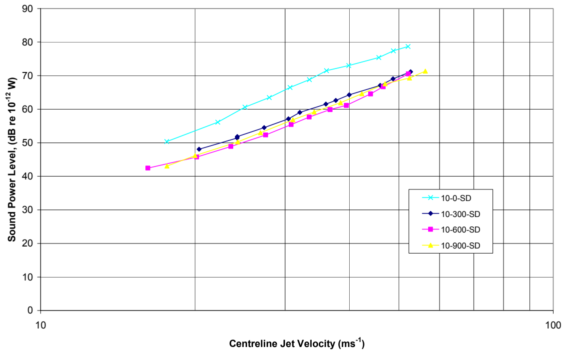

Figure 28. Sound power level comparison for the 10˚ conical diffuser fitted with the square (SD) outlet grill with an extended outlet duct of 0, 300, 600 and 900 mm.

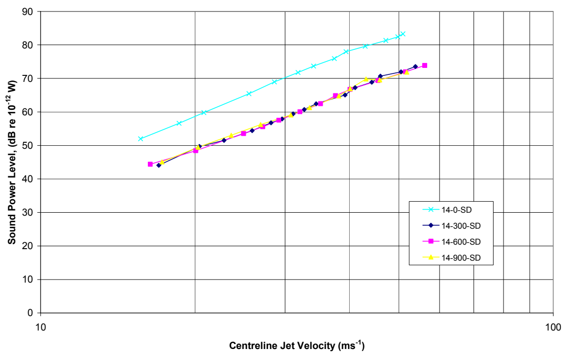

Figure 29. Sound power level comparison for the 14˚ conical diffuser fitted with the square (SD) outlet grill with an extended outlet duct of 0, 300, 600 and 900 mm.

The size of the reduction was also partially determined by the angle of the conical diffuser used. For the 7˚ conical diffuser the reduction was only 3 to 4 dB at a jet velocity of 20 ms^{-1}, increasing to a reduction of 8 to 10 dB at a jet velocity of 50 ms^{-1}. Meanwhile the 8 to 10 dB reduction achieved with the 10˚ conical diffuser was much more consistent across the entire velocity range that was tested. The size of this reduction increased further to 10 to 12 dB across the selected velocity range for the 14˚ conical diffuser.

The total sound power level at the reference jet velocity of 50 ms^{-1} is increased from 65 to 69 and then 72 dB as the conical diffuser angle is increased from 7˚ to 10˚ and then 14˚ respectively. This result is consistent with both the baseline case of no outlet grill and the corresponding results recorded for the RJ outlet grill (not pictured). It is therefore likely that this trend is strongly driven by an increase in the level of flow separation caused by the increases in conical diffuser angle.

At the lower jet velocities there is less flow separation with the 7˚ conical diffuser and therefore the need to have an extended outlet duct to allow some settling of the flow is not as critical to the acoustic performance of the outlet. A similar result was also observed with the 10˚ conical diffuser, but on a much smaller scale.

The influence of flow separation on these results is further reinforced by the variation in the slope of the sound power curves for each of the three conical diffuser angles used. The 7˚ conical diffuser models all had a slope of 40 to 50, with a slight increase seen as the jet velocity increased. The 10˚ conical diffuser models produced a slope of 50 to 60, with the flatter slope observed at jet velocities below 30 ms^{-1}. The 600 mm long outlet model however deviated from the previous results with a flatter slope at the lower jet velocities and a much steeper slope of 65 to 70 at jet velocities above 45 ms^{-1}. The 14˚ conical diffuser models once again had a consistent slope in the 60 to 65 range across the whole jet velocity range used.

FURTHER ANALYSIS

The sound power generated by each outlet duct configuration tested has also been analysed in ⅓ octave bands. This provides valuable information to the design of an optimum HVAC outlet that can be tuned to maximise the acoustic attenuation in the required frequency bands. Space limitations restrict the discussion of these analyses here and they will be reported in subsequent publications to come.

Numerical models have also been successfully developed to simulate the flow induced noise from a range of outlet duct configurations, with good agreement between the experimental results presented here on both an absolute and a ⅓ octave band sound power level basis. Space constraints once again prevent the presentation of these results at this time.

CONCLUSIONS

With the use of appropriately designed two stage outlet diffusers, a HVAC air distribution velocity of 20 to 30 ms^{-1} can be used without exceeding current passenger comfort thresholds of 65 dB(A). The experimental research presented herein demonstrates that the sound power levels radiating from these customised outlets can meet the current acoustic and airflow specifications dictated by the passenger comfort standards.

Under existing passenger cabin noise specifications applicable to ocean going fast ferries there is considerable scope to increase the HVAC air distribution velocity above the current levels of 5 to 7 ms^{-1} without excessive design work. Significant duct size reductions of over 50 to 75 percent can be achieved with careful design of the outlet diffusers employed.

In the event of more stringent passenger comfort specifications being implemented there is still room for significant increases in the distribution velocity and therefore reduction in the size of the installed HVAC ducts. However this would require a greater level of acoustic and flow analysis to ensure optimum system performance.

The optimum outlet diffuser geometry for any given application will depend on the specific constraints involved; however some general conclusions can be drawn from the results reported herein. A conical diffuser angle of 7˚ was preferred, with an outlet duct of 300 and 600 mm providing very similar results.

In the event that space limitations dictate the use of a larger diffuser angle a limit of 10˚ is recommended. In this instance an outlet duct length of 600 mm will provide a similar acoustic performance to a 7˚ conical diffuser. Extreme space constraints that dictate the use of an even greater diffuser angle (such as 14˚) will call for additional acoustic treatment in the header box connected to the outlet diffuser grill.

The onset of flow separation inside wider angle conical diffusers can however be at least partially mitigated with the installation of multiple guide vanes inside the diffuser. Careful alignment of the vanes can result in an effective diffuser angle of less than the preferred 7˚, and therefore a significant reduction in flow separation, whilst minimising the generation of flow induced noise.

The length of the outlet duct joining the primary and secondary diffusers should also be carefully tuned to ensure maximum low frequency attenuation of the higher levels of flow induced noise that will be produced. Standard square HVAC outlet grills were also found to perform marginally better

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