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Performance of Rectangular Duct Attenuators under Non-ideal Configurations with an Unlined 90° Bend

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SUMMARY

The acoustic performance of duct attenuators under non-ideal conditions is experimentally investigated. The experimental method, a modified variation of the standard ISO 7235:2003 – Laboratory measurement procedures for ducted silencers and air-terminal units, was used to design and test non-ideal configurations that reflect the realities of conditions present in modern building duct systems, comparing static insertion loss between each variant. Since the goal was not to obtain absolute figures, the test was not in strict accordance with the standard.

From the measurements, comparisons were made between test data obtained through testing that was done in accordance to the ISO 7235:2003 and data obtained using the modified variation of an ISO test rig. The key differences to a standard test rig were the omission of a cross modal filter and the use of MDF as the duct material. With the limitations of the timber rig understood, complete satisfaction of ISO 7235:2003 requirements was not critical in achieving the project outcome. Hence, the timber test rig was proven to be an appropriate substitute for this research.

From the investigation, the inclusion of a 90 degree bend in a duct configuration increases attenuator performance (Static insertion loss). However, it is inconclusive from the result as to whether situating the attenuator before or after the bend may result in the best performance due to the variability measured across the 5 measuring positions along the diagonal of the duct in the measuring station (MS), required by the ISO standard. Factors influencing the variability or Maximum Level Differences (MLD) may be mainly attributed to the anechoic termination (AT) performance, the lack of a modal filter, and cross modal excitation as a result of installing a bend.

INTRODUCTION

Duct attenuators are commonly used as noise control devices within building heating, ventilation and air conditioning systems. In many of these systems, they form the primary means of providing acoustic attenuation of the noise generated by mechanical equipment.

The design and installation of duct attenuators are especially critical for noise sensitive or special applications (e.g. healthcare) where a lower background noise level rating is

required. In most commercial projects, plant rooms and duct routes usually have space constraints due to limitations resulting from structural design, the need to accommodate other amenities and other coordination issues. The orientation and routing of duct systems do not necessarily meet the desired standards in such circumstances. This project studies the effects of non-ideal installation of the duct silencers on their noise attenuation.

GAP IN THE KNOWLEDGE

Poor inlet and outlet conditions (i.e. duct fittings within 3-5 duct dimensions of the attenuator) may cause a change in the acoustic performance of an attenuator – i.e. the insertion loss and an increase in the regenerated noise level. Industry guidance (e.g. ASHRAE Applications Handbook) includes guidelines for estimating the aerodynamic performance of an attenuator under poor flow conditions, but there is little or no data available to quantify the effect on the acoustic performance under non-ideal installations.

SCOPE OF THE PROJECT

To develop a set of broad evidence based principles and guides that can allow designers to predict with reasonable accuracy how an attenuator would perform in configurations that more accurately reflect the realities of modern building design.

OBJECTIVES

- Objective #1: Experimentally investigate the static insertion loss (SIL) of 597-702Wx500Hx1200L (33/43% open face area (OFA)) rectangular duct attenuators (2 modules of 100mm thick splitters), in a straight duct configuration.
- Objective #2: Experimentally investigate the SIL of 597-702Wx500Hx1200L (33/43% OFA) rectangular duct attenuators (2 modules of 100mm thick splitters), located 1 duct module (DM, 597-702Wx500Hx1200L) after a 90° bend with the sound source (SS) 1 duct module before the bend, in a duct configuration.
- Objective #3: Experimentally investigate the SIL of 597-702Wx500Hx1200L (33/43% OFA) rectangular duct attenuators (2 modules of 100mm thick splitters), located 1 DM after a 90°

bend with the SS located directly before the bend, in a duct configuration.

- Objective #4: Experimentally investigate the SIL of 597-702Wx500Hx1200L (33/43% OFA) rectangular duct attenuators (ATTR, 2 modules of 100mm thick splitters), located directly after a 90° bend with the SS 1 DM before the bend, in a duct configuration.
- Objective #5: Experimentally investigate the SIL of 597-702Wx500Hx1200L (33/43% OFA) rectangular duct attenuators (2 modules of 100mm thick splitters), located directly after a 90° bend with the SS 2 DMs before the bend, in a duct configuration.
- Objective #6: Experimentally investigate the SIL of 597-702Wx500Hx1200L (33/43% OFA) rectangular duct attenuators (2 modules of 100mm thick splitters), located before a 90° bend with the SS 2 DMs upstream, in a duct configuration.
- Objective #7: Experimentally investigate the SIL of 597-702Wx500Hx1200L (33/43% OFA) rectangular duct attenuators (2 modules of 100mm thick splitters), located before a 90° bend with the SS 1 DM upstream, in a duct configuration.

METHODS

The acoustic performance of an attenuator with changing inlet and outlet duct configurations (e.g. a straight duct configuration, a duct configuration with a bend before and after the attenuator etc.) was determined (see Figure 1). These acoustic measurements (i.e. static insertion loss) were used to investigate if there is any correlation between duct configuration and acoustic performance that may allow the development of an empirical prediction routine for estimating the “installation effects” on attenuator performance.

With proper experimental design, full acoustic test facilities were not expected to be a requirement for the project, because the aim is to investigate the relative change in acoustic performance resulting from changes in duct configuration. Two models/sizes of attenuator were investigated. Limiting insertion loss (LIL) measurements were used as stated in ISO 7235:2003(E) to investigate the influence of flanking noise on the measurements. A straight duct configuration was used initially to obtain the baseline performance of an ideal configuration for use as a referenced for the non-ideal configurations.

After the finalisation of a preliminary timber based modular design, a prototype was fabricated. Measurement series 1 performed with an initial straight duct test (SD1) allowed for the understanding of the optimisation needed. An iterative design process was then adopted throughout the prototyping stages to further optimise it, achieving the final test rig design. Hence thereafter, measurement series 2 and 3 established baselines SD2 and 3 for the testing of the 33% and 43% OFA configurations respectively.

Verification of the test rig and the extent to which the measurements are comparable to ISO 7235:2003 was done

by comparing data taken from measurement series 2 and 3 with existing Fantech test data for the attenuators.

Statistical analysis was performed to ascertain the significance of the results obtained.

RESULTS

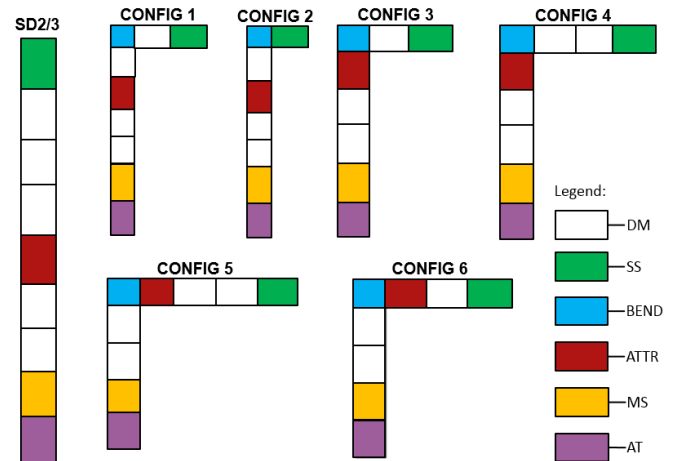


Figure 1. Schematic of test configurations

33% OFA LIL TEST

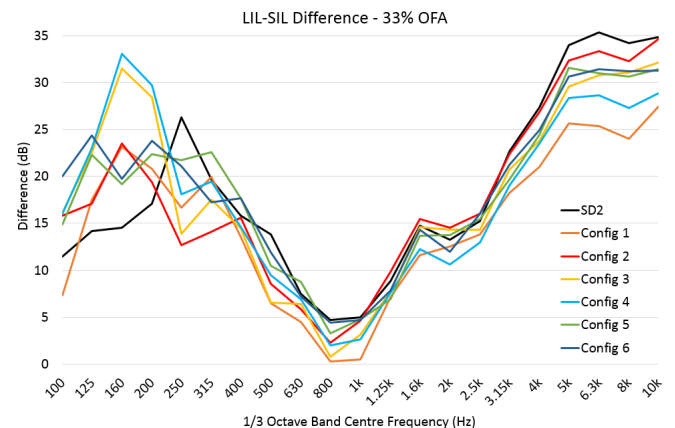


Figure 2. LIL- SIL for 33% OFA attenuator configurations

The graphs in Figure 2 of Configurations 1-4 show that, between the frequencies 500-1.25kHz, the differences were found to be less than the required 10dB as stated in C.2.2 of the ISO standard.

For SD2 and Configurations 5 and 6, the frequency range of 630-1.25kHz was also found to be under the required 10dB threshold. Hence, it cannot be concluded with certainty that the sound pressure levels measured by the microphone across all 5 positions were not influenced by break-in or background (BG) noise. It is likely that the sound pressure levels measured in-duct are affected by the various flanking transmission paths.

These frequency components should be dealt with cautiously when interpreting what the data means even after the above mentioned optimisation and rectification of the test rig was made. This problem was likely due to the use of a higher performing attenuator.

33% OFA SIL TEST

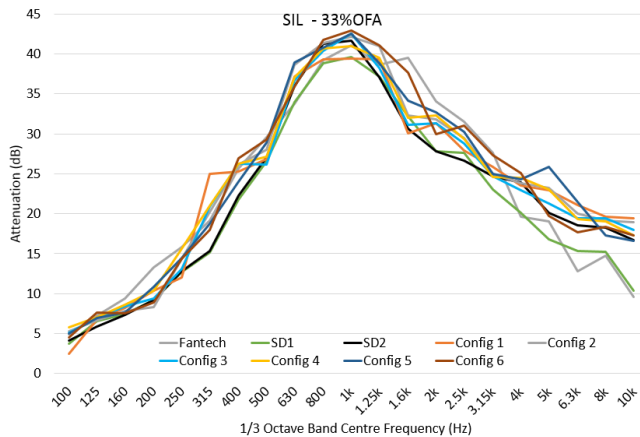


Figure 3. SIL comparison of 33% OFA attenuator configurations

The SIL graphs shown in Figure 3 are generally quite similar for the tested configurations. It was noticed that when contrasted against the ideal straight duct configurations, Fantech, SD1 and SD2, the non-standard configurations show an increase in attenuator performance outside the frequency range of 630-1.25 kHz highlighted in the LIL test. This may be due to cross modal excitation due to the presence of a square bend in the non-ideal configuration.

Comparing configurations 1-4 against configurations 5 and 6, it may be expected that locating the attenuator after the bend should result in greater attenuator performance compared to locating it before the bend due to a greater magnitude of transverse modes impinging on the attenuator.

However, it is important to note that the variability between the SILs of the ideal and non-standard configurations are relatively small. An uncertainty analysis will be performed to determine if the differences are statistically significant.

It is interesting to note that for SD2, the attenuator performance actually increased from 4 kHz and above as compared with SD1. This is likely due to the optimisation of the seals after the LIL verification done for SD1.

43% OFA LIL TEST

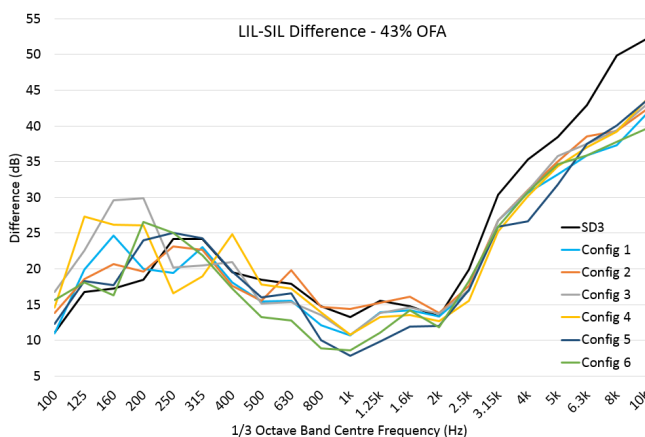


Figure 4. LIL-SIL for 43% OFA attenuator configurations

As observed in Figure 4, the graphs of SD3 and Configurations 1, 2, 3 and 4, in the frequency range of 500-1.25kHz, were found to be greater than the required 10dB stated in C.2.2 of the ISO standard. Hence, it can be concluded that the sound pressure levels measured by the microphone across all 5 positions were not influenced by break-in or BG noise. Hence, the results of these configurations were valid.

However, in the graphs of Configurations 5 and 6, in the 800-1.25kHz frequency range, the sound pressure level difference was found to be under the required 10dB. Hence, it cannot be concluded with certainty that the sound pressure levels measured by the microphone across all 5 positions were not influenced by break-in or BG noise.

For the range of frequencies 800-1.25kHz, it is inferred that the in-duct sound pressure levels measured for Configurations 5 and 6 are affected by the various flanking transmission paths and this range of frequency components should be regarded with caution when drawing conclusions.

43% OFA SIL TEST

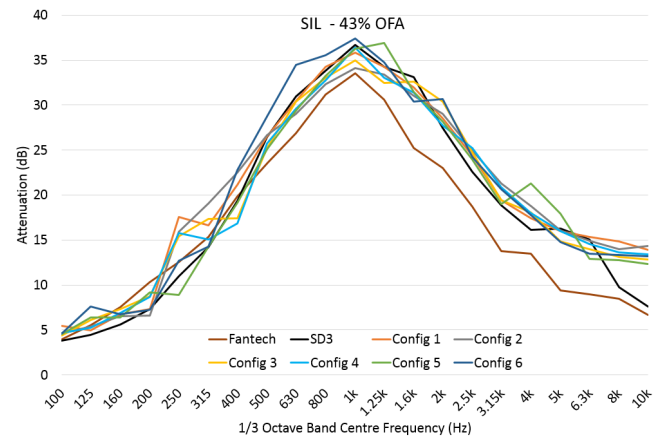


Figure 5. SIL comparison of 33% OFA attenuator configurations

The attenuation graphs in Figure 5 are generally quite similar to the attenuator performance SD3-SIL for the ideal straight configuration. There seems to be a visible improvement in attenuator performance when contrasted against the ideal straight duct configuration attenuator performance as observed in measurement series 2 as well. The extent of this improvement was noticed to be smaller in magnitude compared to that observed in measurement series 2. The extent of this improvement will be determined by an uncertainty analysis.

For some of the non-ideal configurations' SIL graphs, a peak was noticed at 250Hz and 315Hz for 43% and 33% OFA respectively. This is due to these frequencies being the cross mode cut on frequencies for a rectangular duct with cross sectional dimension 600-700mm.

As observed in 33% OFA case, comparing configurations 1-4 against configurations 5 and 6, it was expected that locating the attenuator after the bend should result in greater attenuator performance compared to locating it before the bend because of cross mode generation by the bend. However, due to the variability of the graphs it seems unclear that there is a conclusive difference in attenuator

performance between each non-ideal configuration and the ideal configuration.

MAXIMUM LEVEL DIFFERENCE (MLD) ANALYSIS – 33/43% OFA NON-IDEAL CONFIGURATIONS

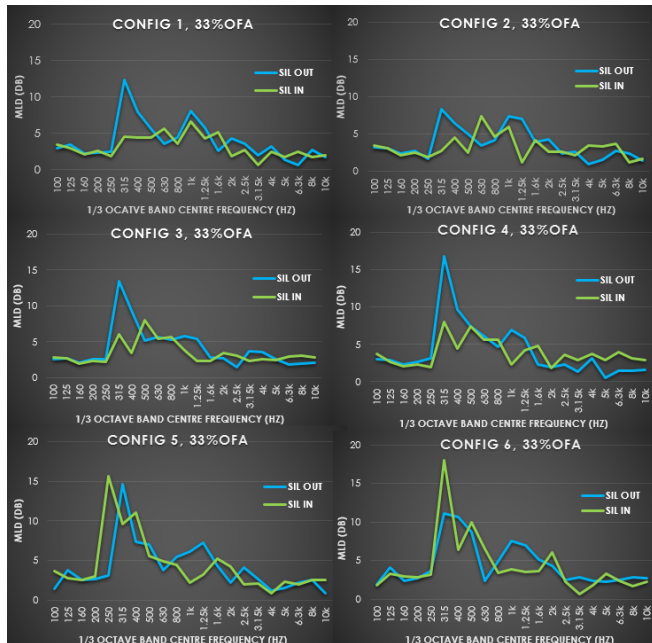


Figure 6. 33% OFA SIL IN/OUT MLD comparison

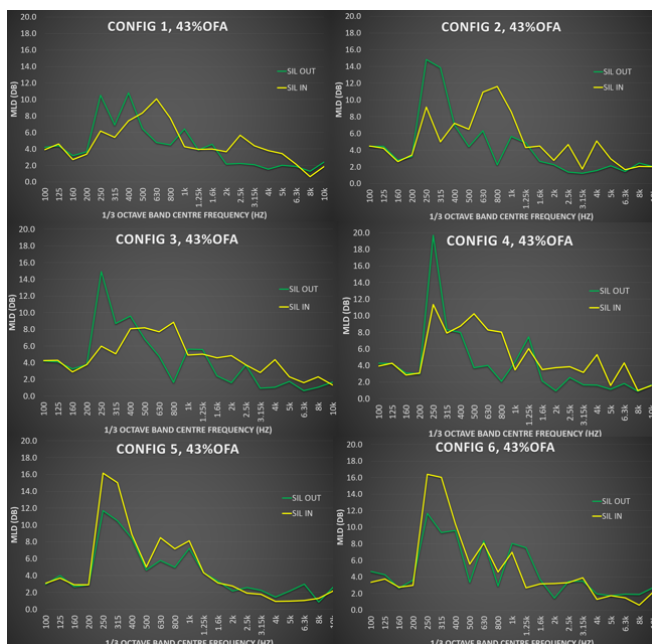


Figure 7. 43% OFA SIL IN/OUT MLD comparison

Comparing the SIL IN/OUT graphs in Figures 6 and 7 for both the 33% and 43% OFA non-ideal configurations before and after the bend, it is interesting to look at the results at 250 and 315Hz where the first cross mode cuts on as shown by the sharp peak. When the attenuator is situated after the bend, the attenuator in (SIL IN) MLDs are observed to be much lower than the attenuator out (SIL OUT) MLDs at these two frequencies for 43% and 33% OFA respectively. However, when the attenuator is situated before the bend, the opposite occurs.

This is consistent with the prediction that the attenuator acts as a cross modal filter. The attenuator is responsible for reducing the cross mode excitation while the bend does the opposite and increases the cross mode excitation. Below these frequencies, the cross modes are expected to be exponentially attenuated with distance and thus result in similar MLD graphs obtained with and without the attenuator. Above these frequencies, the reflections from the non-perfect stepped design anechoic termination will probably have as big an effect as the cross modes on the MLDs. At these higher frequencies there will be multiple cross modes excited and their individual effects on the MLDs will tend to cancel out. Hence, the MLDs decrease at these higher frequencies as shown in Figure 6 and 7.

The performance of the attenuator seems to increase slightly with the presence of a bend. However, the magnitude of this improvement and whether situating the bend before or after the attenuator results in better performance were uncertain.

UNCERTAINTY ANALYSIS

Therefore, to understand the variability of the results, a statistical analysis was performed to analyse the significance of the results and differences and whether they are random or not. As the sample size available was less than 30 samples, it could not be considered a population. Hence, the Student's t-distribution was used instead of a normal distribution.

For simple random samples, s is the standard deviation of the sample, x_i is the i th sample of the samples, and n is the sample size.

$$s = \sqrt{s^2} = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}, \quad (1.1)$$

The standard error is,

$$SE_{\bar{x}} = \frac{s}{\sqrt{n}}, \quad (1.2)$$

The results were tabulated in third octave bands from 100-10kHz, totalling 21 third octave bands. Hence, the 21 observations gave 20 degrees of freedom. From a Student's t-table, the 95% Confidence Interval for a two-tailed distribution is ± 2.086 .

For a Student's t-distribution,

$$t - \text{statistic} = \frac{\bar{x} - \mu_{\bar{x}}}{\frac{s}{\sqrt{n}}}, \quad (1.3)$$

From measurement series 1 and 2, SD2 was used as the reference configuration. Its SIL was subtracted from the SILs of the non-ideal configurations and the mean average differences across frequency were calculated. This was also done to determine if the differences were statistically significantly different from zero. It was assumed that the standard deviation did not vary with frequency and hence could be calculated across frequency.

From the statistical analysis of the differences from measurement series 1 and 2 with 33% OFA, Configurations 1-6 and SD1 were found to be statistically significantly different from the ideal straight SD2 configuration because zero is not included in any of the 95% confidence intervals.

Table 1. Statistical analysis – Configurations 1-6, 33% OFA

Average of Average Differences	Estimate of the standard deviation of the individual average differences	Estimate of the standard error of the average of the average differences	95% CL of the average of the average differences
1.541	0.414	0.169	± 0.334

The root mean square of the standard errors was taken to determine the standard deviation of the “average differences”. The average, the standard error and the 95% CL of the average of the “average differences” were then calculated (see Table 1).

The estimate of the mean with 95% CL was found to be 1.54 ± 0.33 dB. Directly calculating the standard deviation from the “average differences” results in lower standard deviation which is partially offset by the smaller number of degrees of freedom to give 95% confidence limits of ± 0.28 dB.

For measurement series 3, the straight configuration SD3 was taken as the reference configuration.

From the statistical analysis of the differences from measurement series 3 with 43% OFA, it was found that the mean average differences for Configurations 1, 2 and 6 were statistically significantly different from the ideal straight SD3 configuration because zero is not included in any of their 95% confidence intervals. Configurations 3, 4 and 5, however are not statistically significantly different from SD3.

Table 2. Statistical analysis – Configurations 1-6, 43% OFA

Average of Average Differences	Estimate of the standard deviation of the individual average differences	Estimate of the standard error of the average of the average differences	95% CL of the average of the average differences
1.065	0.478	0.195	± 0.386

The root mean square of the standard errors was taken to determine the standard deviation of the “average differences”. The average, the standard error and the 95% confidence limits of the average of the average differences were then calculated (see Table 2).

The 95% confidence limits and mean were determined to be 1.07 ± 0.39 dB. Directly calculating the standard deviation from the average differences results in a lower standard deviation which is partially offset by the smaller number of degrees of freedom to give 95% confidence limits of ± 0.33 dB.

To further determine if the data obtained from Measurement 2 is statistically significant from Measurement 3, the same statistical process was applied on the derived mean.

Table 2. Statistical Analysis of 33% and 43% OFA

	33%OFA	43%OFA	Difference	Mean
Mean	1.541	1.065	0.476	1.303
Std Dev	0.169	0.195	0.258	0.182
95% CL			0.511	0.359

From Table 5, the averages of the average differences were found to be not statistically significantly different since the 95% confidence limits of their difference included ± 0 dB. Since the average of the average level differences were not statistically significantly different at the 95% confidence level, they were averaged and the 95% confidence limits of this grand average were calculated.

Thus it was determined that in configurations with a bend, the performance of a rectangular attenuator increases by 1.30 ± 0.36 dB. This is a small but significant improvement compared to the performance of an ideal straight duct configuration.

DISCUSSION

The inclusion of a 90 degree bend in the configuration and the location of it relative to the attenuator in measurement series 2 and 3, which is the key area of research, has shown the effects of cross modes and their influence on attenuator performance.

SIL results showed that there was an improvement in attenuator performance when a bend was situated along the duct configuration. On average, it was found to have increased by 1.30 ± 0.36 dB across both the 33% and 43% OFA non-ideal configurations. This is likely due to an increase of cross modal excitation caused by the bend, resulting in an increase in transverse modes impinging on the attenuator.

However, although not discussed in the uncertainty analysis of this paper, the average differences associated with the non-ideal configurations were not statistically significantly different from one another. Thus, situating the attenuator before or after a bend makes no statistically significant difference in the attenuation.

The 3 main components contributing to the measurement variability as seen from the MLDs are likely to be the anechoic termination design, the 90° bend and the lack of a modal filter.

The anechoic termination was not as ideal as the cone shaped design given in the ISO standard. However, the design was selected due to the economical, logistical and time constraints associated with the research. Hence, the limitations of a non-perfect anechoic termination may have contributed some of the variability seen in the results.

As observed from the analysis of the non-ideal configurations' MLDs, it seems that the bend increases cross modal excitation at the frequency when the first cross mode cuts on. This is useful for understanding how situating the attenuator relative to bend in real world building design may result in a change in attenuator performance from that predicted.

In measurement series 2 and 3, from the analysis of the MLDs of the non-standard configurations, it can be seen that the splitters have behaved as a cross modal filter, attenuating some of the cross mode energy at the frequency at which the first cross mode cuts on when the attenuator is situated after the bend. Contrastingly, when the attenuator is situated before the bend, the bend is responsible for cross modal excitation at this frequency.

It maybe be worth performing further testing to better understand this phenomenon. This includes the use of a modal filter in the non-ideal configuration setups for future research to better understand the cross modal excitation and attenuation with and without the attenuator and its effect on variability and attenuation.

In relation to this research, the inclusion of a modal filter would eliminate some of the variability in the sound field due to cross modes. By eliminating one of the causes of measurement fluctuations, a more accurate measurement of attenuator performance may have been achieved.

The inclusion of a modal filter as required in the ISO 7235:2003, would be expected to decrease the performance of the attenuator as it reduces the amount of sound impinging on the splitters at an angle to the centre line of the duct.

It is also important to note that the withdrawn AS1277-1983 and the current ASTM E77-14 test standards do not specify the use of a modal filter. Hence, the ISO standard produces more conservative results than these other two standards.

However, with the introduction of bends, as observed in measurement series 2 and 3, it seems that the use of plain waves could be misleading when investigating real installations. On top of that, the inclusion of dynamic variables such as air flow and as a result the possibility of regenerated noise occurring would significantly influence the impact configurations may have on installed attenuator performance.

CONCLUSION

On the whole, the MDF-based modular design has proven to be a low cost and effective alternative method for testing and investigating the influence of duct configurations on attenuator performance under static conditions.

The inclusion of a 90 degree bend in a duct configuration slightly increases attenuator performance.

However, it is inconclusive from the results as to whether situating the attenuator before or after the bend results in the best performance due to the variability found. Factors influencing the variability or MLDs may be attributed to the lack of a modal filter, limitation in anechoic termination performance and cross modal excitation as a result of including a 90 degree bend.

However, the conditions which the tests were designed to be performed under were intended to mimic real world installations and hence were deemed to be relevant and useful for industry designers and practitioners in everyday design decisions.

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