Noise Radiated by Circular Ventilation Ducts

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ABSTRACT

Noise remains a major concern for building occupants, both in their home and workplace. Ventilation system is one of the noise sources in buildings. Usually, the main issue is the resulting noise level in the room. It is generated by the fan and the ductwork components, travels inside ducts, and is then radiated into the room by air diffusers, air inlets, and air outlets. But ducts also go through other indoor spaces. Airborne noise will pass through the duct wall and radiate in the surrounding space. This can be an issue for occupants.
There is today no data available from manufacturers on noise radiated by ducts, no standard to determine the noise passing through duct wall and a lack of experience from acoustic consultants, despite results published in the 80's on breakout characterisation of rigid ducts.
CETIAT performed a wide experimental campaign to characterize ventilation ducts, most of them with a 160 mm diameter, with varying parameters such as material (metal, plastic, PU), shape (round, oval, rectangular, corrugated), stiffness (rigid, flexible), and presence of an acoustical or thermal insulation layer. The experimental approach consists in producing sound inside the duct, and measuring both injected sound power level and sound power level radiated by the portion of duct under test.
Test results show a wide variety of acoustical behaviour, from high insulation to high transmission, with in some cases ducts as transparent as if there were no duct.
Beyond these results, several issues should be considered: how to make the measurement more reliable, how to define a metric to express the sound insulation ("breakout" is well suited for high insulation duct, but not for low insulation ones), how to deal with duct performance in between high and low insulation?

KEYWORDS

Noise, ductwork, duct, sound insulation

1 INTRODUCTION

Ventilation ductworks convey air but also noise energy. When the ducts are situated in a living quiet space, the ducts are the only shield to the noise avoiding it to escape in the surrounding. According to the sound insulation level of the ducts wall, the noise will radiate more or less loudly in the quiet space.
This characteristic of sound insulation, also called "breakout", is often not known. It has been studied in literature for high insulation ducts.
The present study deals with ventilation ducts available on the market, of different natures – from rigid to soft ducts – and geometries – from circular to rectangular or specific shapes. All these ducts have been submitted to experiments.
A section is dedicated to describe their sound insulation, and the way to measure it. The choice of the best descriptor according to their insulation capacity is analysed.
Then the experimental results for insulation are presented and analysed.

2 DUCTS UNDER TEST

The list of tested ducts can be sorted according to several categories

Rigid ducts:
1. Galvanized steel round spiral Ø 160 mm
2. Galvanized steel double wall round spiral Ø 160 mm with 25 mm mineral wall
3. Expanded Polyethylene EPE Ø 160 mm
4. Polystyrene, internal circular Ø 100 mm, external square 140 mm

Figure 1: rigid ducts under test

Soft ducts:
1. PVC film round spiral Ø 160 mm and 125 mm
2. PVC film rectangular spiral, equivalent 125 mm
3. Aluminium film round spiral Ø 160 mm internal, thermally insulated with rockwool or glass wool
4. PVC film round spiral Ø 160 mm internal, for acoustic, with rockwool or glass wool

Figure 2: soft ducts under test

Flexible duct:
1. Plastic, externally corrugated

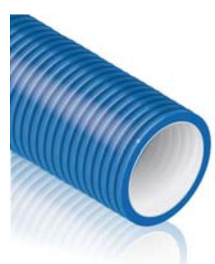

Figure 3: flexible duct

3 SOUND INSULATION METRIC AND MEASUREMENT METHOD

3.1 Breakout measurement

The breakout or TL of a duct is related to the sound power level travelling inside the duct, the sound power level radiated by the duct, and the areas: it can be written as the ratio of sound intensities:

$$TL = 10\,log\left(\frac{Wi/Ai}{Wr/Ar}\right) \quad (1)$$

where W_i is the incoming sound power and A_i the section in the upstream duct, W_r is the radiated sound power and A_r the radiating area of the duct under test (perimeter multiplied by length).
This breakout is an intrinsic data of sound insulation, associated to the duct construction. Equation 1 can be arranged to give:

$$TL = L_{wi} - L_{wr} + 10log\left(\frac{A_r}{A_i}\right) \quad (2)$$

where L_{wi} is the sound power level in the upstream duct and L_{wr} the sound power level radiated by the duct.

Only one standard is related to this topic, ISO 15665 (2003) "*Acoustic insulation for pipes, valves and flanges*" but its scope is far away from ventilation ducts as "*It is valid for pipes up to 1 m in diameter and a minimum wall thickness of 4.2 mm for diameters below 300 mm, and 6.3 mm for diameters from 300 mm and above. It is not applicable to the acoustic insulation of rectangular ducting and vessels or machinery*". Another test set-up than the one described in this standard must be imagined.

A perfect test set-up would require a reverberant room placed between two other adjacent rooms and face to face apertures between the reverberant room and each of the two adjacent rooms to install the duct through the reverberant room. As this does not exist at CETIAT, the test set-up shown in Figure 4 was used, in which the duct under test (pink) is installed in the reverberant room (blue). A loudspeaker is positioned upstream of the duct with 3 microphones to measure the incoming sound power level, based on ISO 5136 approach. The downstream end of the tested duct goes into an insulated plenum to minimize the noise escaping from its end to the measurement room. A 300 mm plug of absorbing material (yellow) at the end of the duct inside this plenum reduces this noise and plays the role of a simplified anechoic termination. As the duct under test can be shorter than the reverberant room length, the upstream part of the test set-up is a double layer insulated duct, in order to reduce the unwanted noise radiations.

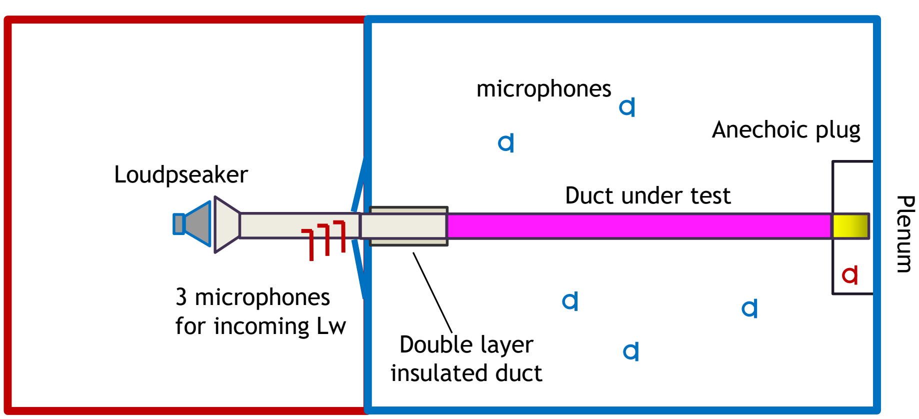

Figure 4: test set-up to characterize the sound insulation of a duct

The sound power levels are measured in the upstream duct L_{wi} (incoming sound) and in the reverberant room L_{wr} (radiated sound). Knowing the section of the incoming duct and the radiating area, the sound insulation or breakout can be calculated according to (2), provided certain assumptions are fulfilled, as described in §3.2.

Several difficulties can be met using this set-up:

1. The measurement of injected sound power level is complex when the section of the duct is small. The ISO 5136 is applied but for sections lower than Ø 160 mm, it is difficult to insert 3 microphones in such a small diameter duct. Moreover, standing waves are harder to eliminate for small diameter ducts especially when using an absorbing plug as a simplified anechoic termination.
2. A longer sample of the duct under test would be better to increase the radiated noise level, but it is common that ducts longer than 3 m are obtained by assembling several elements. The quality of assembly can affect the result.
3. Upstream incoming sound power level must be measured in a circular duct, according to ISO 5136 method. For rectangular ducts, adaptation pieces have to be inserted after the measurement section, pieces which are usually not of the same construction as the ducts, and may modify the measured radiated sound level. In general, the results are very sensitive to connections and adaptations elements.

3.2 Limits of the sound insulation concept

If the incoming sound power is constant throughout the length of the considered duct (which means that the sound energy losses along the duct should be small on that length), it is possible to calculate the radiated power of another length duct L_{wr}, knowing the incoming sound power level L_{wi}, and areas A_i and A_r:

$$L_{wr} = L_{wi} + 10log\left(\frac{A_r}{A_i}\right) - TL \tag{3}$$

Note: this assumption of constant sound power level in the duct is also required when the breakout of a duct is experimentally determined according to equation (2).

If the duct has a low sound insulation, the equation (3) cannot be used, as the sound level inside the segment of duct under test is no longer constant. This means that the sound escapes from the duct under test just downstream of the junction with the upcoming duct, with a low influence of the length of the sample (ducts of 2 or 4 meters can even produce the same result). To illustrate this issue, a couple of simple calculations are presented below as examples for a 4 m duct with two values of breakout (high and low sound insulation), subdivided for the calculation in 8 segments of 50 cm. Equation (3) allows to calculate the sound radiated by each segment. With the conservation of energy law (neglecting the losses due to the wave traveling in the air), the available sound power level at the end of each segment can be calculated, considering the sound radiated through duct walls and the incoming sound level (e.g. $L_{w\ incoming}$ = 90 dB, $L_{w\ radiated}$ = 89 dB, $L_{w\ leaving}$ = 83 dB as logarithmic sum leads to 83+89 = 90). The sum of the noise radiated by the 8 segments is then calculated.

Example 1: Incoming noise 90 dB, high duct breakout (35 dB), 8 segments of 0.5 m.

Table 1: example of a 4 m duct with breakout of 35 dB and incoming noise of 90 dB

Segment #	1	2	3	4	5	6	7	8	
Distance from duct entrance (m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	
Incoming Lw of the segment (dB)	90.0	90.0	90.0	89.9	89.9	89.9	89.9	89.9	overall
Lw radiated by the segment (dB)	66.0	66.0	65.9	65.9	65.9	65.9	65.9	65.8	**74.9**
Proportion of overall radiated noise	13%	13%	13%	13%	12%	12%	12%	12%	

Table 1 shows that that the incoming L_{wi} of each segment remains almost constant throughout the length. Then, each segment radiates more or less the same sound power level around 66 dB. The overall noise radiated by the 8 segments L_{wr} is 74.9 dB. The calculation of the characteristic sound insulation of this duct according to the areas (Ø 160 mm and length 4 m) using (3) leads to a sound insulation of 35.1 dB which is consistent with the breakout of 35 dB taken as a characteristic of the duct.

Example 2: same data than example 1 except low duct breakout (15 dB)

Table 2: example of a 4 m duct with breakout of 15 dB and incoming noise of 90 dB

Segment #	1	2	3	4	5	6	7	8	
Distance from duct entrance (m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	
Incoming Lw of the segment (dB)	90.0	87.8	85.6	83.4	81.3	79.1	76.9	74.7	overall
Lw radiated by the segment (dB)	86.0	83.8	81.6	79.4	77.2	75.0	72.9	70.7	**89.9**
Proportion of overall radiated noise	40%	24%	15%	9%	5%	3%	2%	1%	

In this case, a significant part of energy is lost in each segment, which leads to the decreasing of the incoming L_{wi} along the duct: more than 2 dB are lost after the first segment (90 ⇨ 87.8) and more than 15 dB for the whole duct (90 ⇨ 74.7). Consequently, the noise radiated by the different segments decreases along the duct. The overall noise radiated by the 8 segments L_{wr} is 89.9 dB. After calculation using the areas, this means that the apparent sound insulation of this duct would be 20.6 dB, instead of 15 dB taken as characteristic of the duct. The calculation is then wrong. This shows that for low sound insulation ducts, equation (3) cannot be used.

The last line of Table 1 and 2 shows the contribution of each segment to the overall radiated noise. In example 1, the first segment contributes for 13 % (as the 7 others) to the overall sound level whereas in example 2 the first segment weights for 40 % (and less and less for the next segments). This case of low sound insulation ducts shows that the sound mainly escapes from the duct in the first decimetres. Taking into account the total length of the duct becomes meaningless as the sound radiated by the whole duct is driven by the upstream part of the duct under test.

Finally, for low sound insulation ducts, as the duct length is no longer a parameter, a meaningful result could be the *raw sound insulation*:

$$RSI = L_{wi} - L_{wr} \tag{4}$$

The use of RSI means that for a constant incoming L_{wi} value, a smaller radiated L_{wr} leads to higher RSI. In the case of low insulation duct, results of 2 m or 4 m length duct should give the same results.

4 RESULTS

4.1 Introduction

The goal of this section is not to give an exhaustive view of products characteristics, nor to rank them, but to understand that ducts can have highly various acoustic behaviours.

4.2 Ducts with high sound insulation

For ducts with high sound insulation, the intrinsic characteristic breakout (TL) is naturally the right characteristic to observe.

Results are given for the common galvanised steel spiral duct, single and double wall (Figure 5). The breakout is high, with the same values at low frequency. The double wall configuration brings an improvement of sound insulation in the medium and high frequency range, where the uncoupling between the inside and outside ducts is the most efficient.

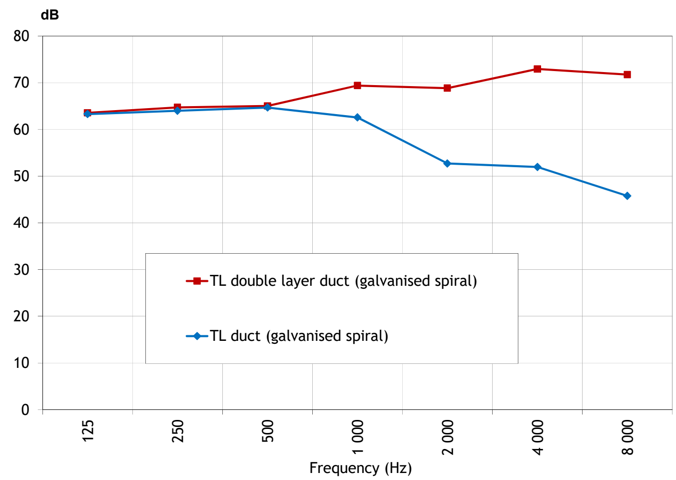

Figure 5: breakout of rigid round spiral duct, single and double layer

4.3 Ducts with low sound insulation

Section 3.2 showed why the breakout is not the right quantity to describe low sound insulation ducts. Values of RSI for PVC film round spiral ducts are presented in Fig. 6 for 3 lengths. From 125 to 1000 Hz, the 3 curves are merged, with around 15 dB of raw sound insulation at 250 Hz. This means that for L_{wi} = 90 dB, the radiated noise is L_{wr} = 75 dB in the room. No influence can be observed due to the length.

For high frequencies, a light difference occurs between results for the 3 lengths, with a higher insulation for 1 m length. The length of radiating duct being smaller, the radiated noise is then smaller.
The very low value of RSI around 1000 and 2000 Hz has to be noticed: only 5 dB. The major part of noise conveyed by the duct is then radiated in the surrounding, even for a 1 m length duct.
For the low frequency range, the higher sound insulation is due to end reflection of the duct and not to the duct material itself.

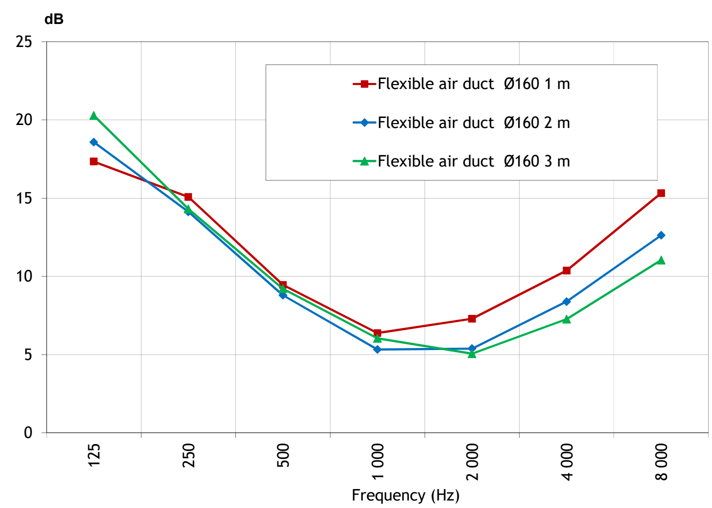

Figure 6: breakout of rigid round spiral duct, single and double layer

Generally, this phenomenon of end reflection occurs at the open end of a duct, where the sudden change between the inside part of the duct and the surrounding open space leads to an acoustic impedance change, then, reflection inside the duct. Less sound energy is transmitted to the surrounding. The end reflection loss (ERL) for free termination in free space is described, according to ISO 5135, by:

$$ERL = 10lg\left[1 + \left(\frac{c}{4\pi f}\right)^2 \frac{4\pi}{S}\right] \quad (5)$$

with c the sound celerity (m/s), f the frequency (Hz) and S the open duct area (m²). The smaller is the diameter, the bigger is the reflection loss.

In the present case, even if the duct is continuous (incoming duct + duct under test), the low sound insulation of the duct acts as if the incoming duct was open, and the end reflection loss occurs at the junction between incoming duct and duct under test.

Fig. 7 shows the experimental and calculated end reflexion loss for a duct Ø 160 mm, terminating in free space. It is obvious that the negative slope at low frequency is consistent between calculation and measurement but there is presently no explanation for the 3 dB off-set between experimental and calculated results for Ø 160 mm.

The experimental curve goes up at high frequency, which is still unexplained; as the impedance change would theoretically tend to zero when the frequency increases. The dotted curve reminds the result of Fig. 8 for flexible PVC film duct. The shape of the curve is consistent with the experimental duct end reflexion loss.
These first results can be interpreted according two points of view.

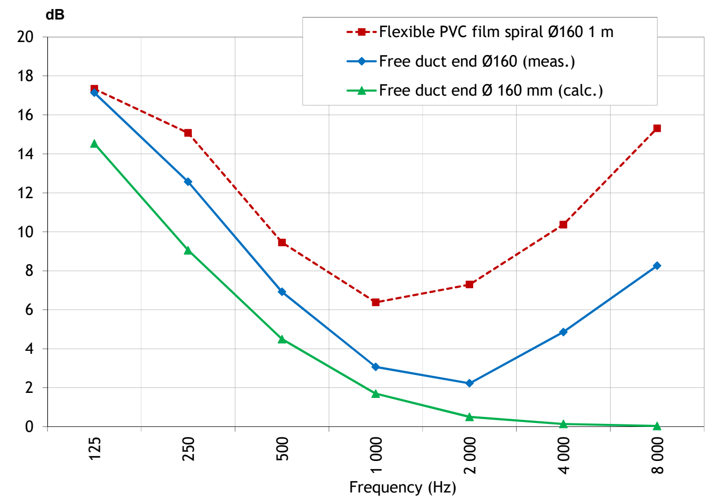

Figure 7: experimental and calculated duct end reflexion

The first one will only consider the *raw sound insulation* of the duct: using the incoming sound power level, it gives the radiated sound power level by the duct, without consideration of its length (minimum of 1 m). Another approach would be to calculate an *insertion gain*, i.e. the difference between the RSI of the duct under test and the one of the open free duct (considered as the reference). This insertion gain will give the sound level attenuation of the considered duct compared to the case where there would be no duct.

Fig. 9 shows the RSI of 6 ducts (Ø 125 and 160 mm), with low insulation performances, expressed as *insertion gain*. There are mainly PVC film spiral ducts, in Ø 125 and 160 mm. The rectangular duct is built in the same way, and its section is equivalent to a circular Ø 125 mm (Figure 8).
For two products (circular 125 and rectangular), the external PVC film is tested in standard thickness and reinforced thickness.

Figure 8: rectangular PVC film spiral duct

PVC film round spiral ducts (160 and 125 mm) have the same poor performance, around + 2 to +4 dB better than the open duct. The rectangular standard version is in the same range of performance, and less than 0 dB at 125 Hz. The reinforced thickness circular version brings much improvement especially for low frequencies while the rectangular version is even less efficient.
Finally, the rigid and light EPE duct is some how efficient in high frequency, but of the same range of soft ducts otherwise. At 1000 Hz, its insertion gain is around 1 dB, which means that it is almost as transparent as if there were no duct.

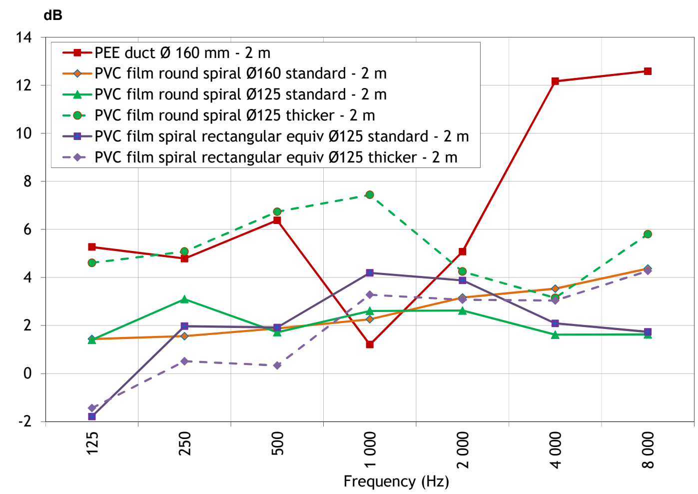

Figure 9: experimental "insertion gain" for the 6 products

The ducts with thermal or acoustical insulation are made with two soft layers (PVC or aluminium) and an insulating material such as glass-wool in between. For the acoustic duct, the inner layer is perforated, whereas it is not for the thermal insulated duct. Fig. 10 shows the *insertion gain* results for 2 ducts from 2 manufacturers, for each kind of duct. It can be seen that the thermal insulated duct has surprisingly the best sound insulation, for the whole frequency range and especially at low and medium frequency. Without inner perforation, the sound remains inside the duct.

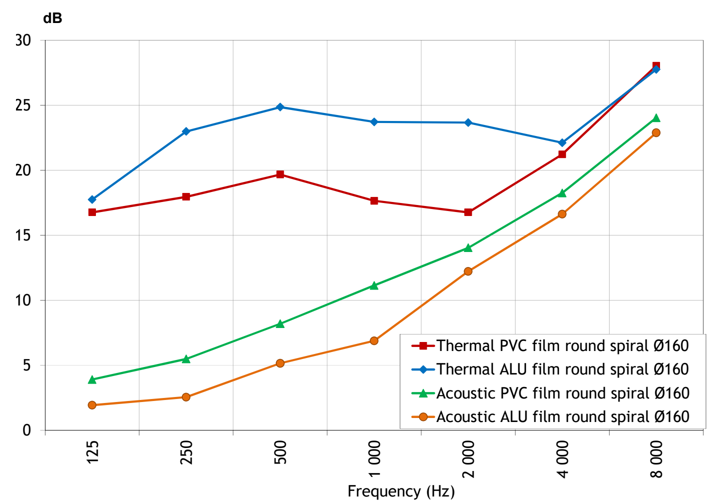

Figure 10: experimental "insertion gain" for 2 thermally insulated ducts and 2 acoustic insulated ducts

The longitudinal insertion loss of such ducts (i.e. the reduction of the sound level along the duct) has been measured and is, as expected, better for acoustic duct than for thermal duct.

The plastic corrugated ducts are commonly used in ventilation. They have been tested for 3 lengths and Ø 75 mm. Their insertion gain in Fig. 11.
These ducts bring rather high insulation, due to the rigid external wall provided by the corrugation. For the low frequency range, the length of the tested duct is not significant, at the contrary of the high frequency range, where longer duct leads to lower insulation due to the bigger radiative area.

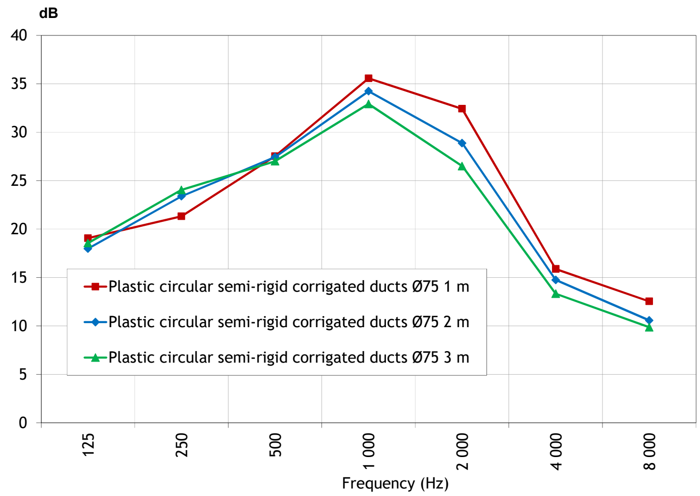

Figure 11: experimental "insertion gain" for corrugated ducts

Finally, rigid EPS ducts, external 140x140 mm, Ø 100 mm internal are tested, and compared to open free duct of Ø 100 mm for insertion gain result (Figure 12).
The acoustic behaviour is totally different from previous ducts with high performance at low frequencies, probably driven by the radial stiffness of the duct, and low attenuation at high frequency, because the EPS is very light.
Of course, measurement of shortest duct 1 m gives better results than for for 2 m and 3 m, for which the junctions can explain the identical results.

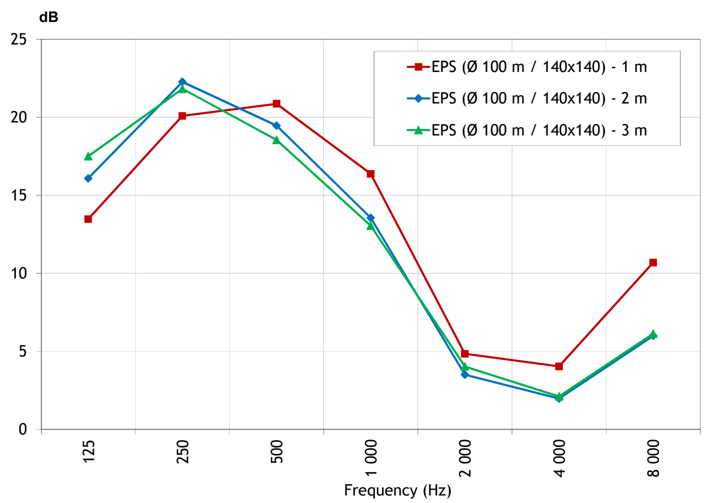

Figure 12: experimental "insertion gain" for expanded polystyrene

This last case finally raises the sensitive question about the description of ducts with insulation performances in between "low insulation" and "high insulation" ducts, or with both "low" and "high", even though the limit between "low" and "high" insulation can not be clearly defined.

5 CONCLUSIONS

Ventilation ducts conduct the air from high pressure to low pressure areas. In the same way, the noise always goes from high sound pressure to low sound pressure areas, this means from louder to quieter. But acoustics is not aerodynamics. The airtight ducts can be very transparent for acoustics, from inside to outside.

The metric for sound insulation of galvanized steel ducts is breakout, but most ventilation ducts are soft with thin walls so that their sound insulation is small and not suitable for using breakout as a metric. In this case the sound escapes from inside to outside on the upstream parts of the tested duct, quickly reaching an asymptote along its length. The new issue is to define a metric applicable to low insulation ducts. Two options are considered:

- The "raw sound insertion" is the difference between inside incoming and radiated sound power levels, regardless the duct length. For very thin soft ducts, the raw insertion loss can only be a little higher than for the same duct with an open end. The low frequency range appears to be driven by the end reflexion loss, as if the duct was open.
- The "insertion gain" is calculated by comparing the raw sound insertion of the duct to the one of the open duct, considered as the reference. This gives a quick view of the effect of the duct insertion compared to the same free open duct

All soft ducts based on PVC film spiral ducts present low raw sound insulation values. The sound escapes from the duct in its upstream section. It can really be an issue for the surrounding where most of the sound level is radiated, even though it could be an advantage as the remaining sound energy at the other tip of the duct is greatly reduced.

Other ducts such as polystyrene or flexible corrugated ducts have variable results, with isolation levels that can be high at certain frequency ranges and low at others. Describing their behaviour is an issue as both breakout and raw sound insulation could be used.

This study highlights the wide variety of acoustic insulation results of ducts used in ventilation. An effort should be made to ensure that these characteristics are provided by duct manufacturers. But this requires the definition of a metric to describe sound insulation in all cases, regardless of the isolation value. Finally, the drafting of a test code should also be considered by standardization bodies.

6 ACKNOWLEDGEMENTS

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