Conception Optimale des Silencieux d’Ouvertures Internes de Ventilation Naturelle dans les Bâtiments Durables

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This paper discusses the optimal design of silencers for internal natural-ventilation openings in 'sustainable' buildings. Natural ventilation is considered to promote better indoor environmental quality and to reduce energy costs associated with mechanical ventilation equipment. However, these openings also reduce sound isolation and lead to poor speech privacy. Optimal design involves providing adequate sound attenuation, with minimal effect on ventilation airflows. A post-occupancy evaluation revealed this to be a major problem in six 'sustainable' buildings. A subsequent project in one naturally-ventilated building designed, installed and evaluated silencers for two types of opening. Subsequent research into the optimal design of such silencers characterized the acoustical and airflow performance using equivalent open areas for sound and for airflow, and characterized the combined performance by their ratio, the open area ratio. Optimal silencer design was investigated using theory, numerical prediction, and by experimentation, both in a laboratory facility and in the field (existing buildings). This work, and the lessons on optimal silencer design that were learned, are reviewed. Two case-study applications, applying the knowledge gained to the design, construction and evaluation of natural-ventilation silencers in the UBC Centre for Interactive Research on Sustainability (CIRS), are presented.

1 Introduction

This paper discusses an extensive program of research to investigate the acoustical and airflow performance of internal natural-ventilation openings and silencers ('ventilators') for natural-ventilation systems in 'sustainable' buildings, to develop best-practice guidelines for designers.

Natural ventilation uses wind- or buoyancy- (stack effect) induced pressure differentials to drive ventilation air through a building (see Figure 1). Typically, these pressures are small compared to those available in a mechanically-ventilated building, often not exceeding 10 Pa. In order for the low pressure to drive a sufficient volume of air, it is necessary to have low resistance to airflow throughout the building. To achieve this, large openings are created in partitions, allowing air to flow from one space to the adjacent space. Unfortunately, the openings are detrimental to the sound isolation between the spaces. Background studies to the research are described. Novel methods for characterizing and measuring acoustical and/or airflow performance are reviewed. Experimental (field and lab) and prediction work is described. Finally, two case-study applications of the knowledge gained are presented and key design guidelines summarized.

2 Background studies

2.1 Acoustical evaluation of six 'green' office buildings [1]

The objective of this 2006 work was to evaluate six 'green' office buildings acoustically, to learn design lessons. It involved performing an occupant-satisfaction survey (using a web-based survey tool developed by the Center for the Built Environment (CBE) at U. C. Berkeley), performing and analyzing the acoustical measurements and considering the design implications of the results.

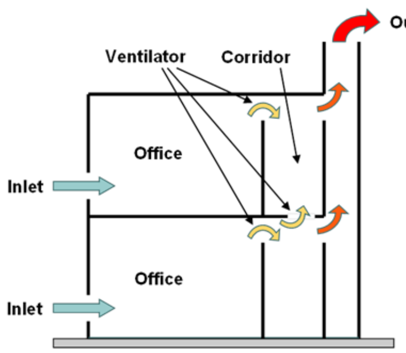

Figure 1 – Illustration in elevation of airflow in a naturally-ventilated office space.

The study involved six very different nominally-'green' office buildings, all designed to prevailing sustainable-development principles, evaluated 1-5 years after occupancy. All buildings had mainly glass façades for day-lighting, with sun shades and operable windows, and contained a mix of private and shared offices, and open-office cubicles. Two were naturally-ventilated.

The CBE survey asks occupants to rate their general satisfaction with the building and their workspace, with the office layout, with the office furnishings, with thermal comfort, air quality, lighting, acoustic quality and with the washrooms. Occupants rated quality on a scale of -3 (maximum dissatisfaction) to +3 (maximum satisfaction).

Figure 2 shows the results of the occupant-satisfaction surveys done in five of the buildings. Also shown (Ref) are the average scores from all buildings ('green' and non-'green') surveyed using the CBE survey. In general, satisfaction ratings were positive, indicating satisfaction. However, occupants were generally dissatisfied with the acoustical environment, which often received the lowest rating. Speech privacy was found to be the main acoustical issue. One of the main acoustical design implications of the results related to inadequate internal-wall sound isolation: a building designed to rely on a natural-ventilation system involves air-transfer openings and/or ducts in partitions, which significantly reduce sound isolation between areas, even when treated acoustically.

2.2 Evaluation and control of acoustical problems in UBC Liu Building [2, 3]

In 2007, a detailed study was made of the naturally-

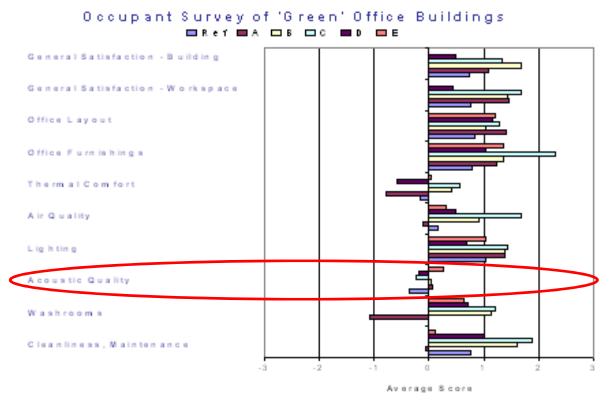

Figure 2 – Occupant-satisfaction-survey results for 'green' office buildings.

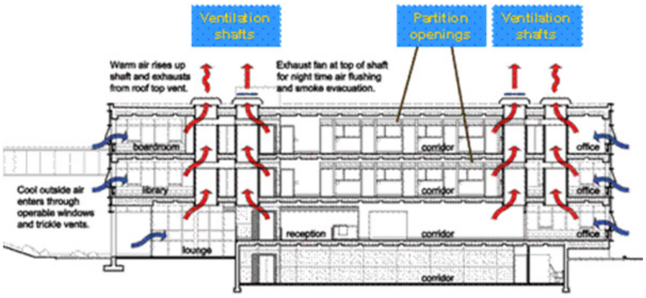

Figure 3 – Elevation of the Liu building, showing components of its natural-ventilation system.

ventilated, three-story office block of the Liu building on the UBC campus. Figure 3 shows components of its natural-ventilation system. Liu was evaluated by occupant survey and acoustical measurement.

Figure 4 shows the occupant-satisfaction results of Figure 2, with those for the Liu building, and for the adjacent, similarly naturally-ventilated Choi building, added. Of particular note is the extremely low satisfaction with acoustical quality in these two buildings.

The results of the occupant-satisfaction survey, and preliminary acoustical measurements, revealed two main sources of dissatisfaction with the acoustical quality:

- poor sound isolation between building floors due to sound transmission through ventilation shafts and natural-ventilation openings in the floor/ceiling slabs (Figure 5);
- poor sound isolation between offices and corridors on the 2nd and 3rd floors due to 45-cm-high natural-ventilation openings in the separating partitions (Figure 5).

Acoustical measurements were made of the sound isolation between floors in the vicinity of the north-end pair of ventilation shafts and floor/ceiling openings, and between a third-floor office and the adjacent corridor. The sound isolation between offices on the first and second floors was an inadequate Noise Isolation Class (NIC) 22-25; that between offices on the first and third floors was an adequate NIC 34-46. It was concluded, not surprisingly, that the ventilation shafts and floor/ceiling natural-ventilation openings have a significant effect on the transmission of sound between floors. The exact sound isolation obtained depends on the relative source and the receiver positions, and those relative to the ventilation shafts. Between the office and adjacent corridor, the sound isolation was an inadequate NIC 10.

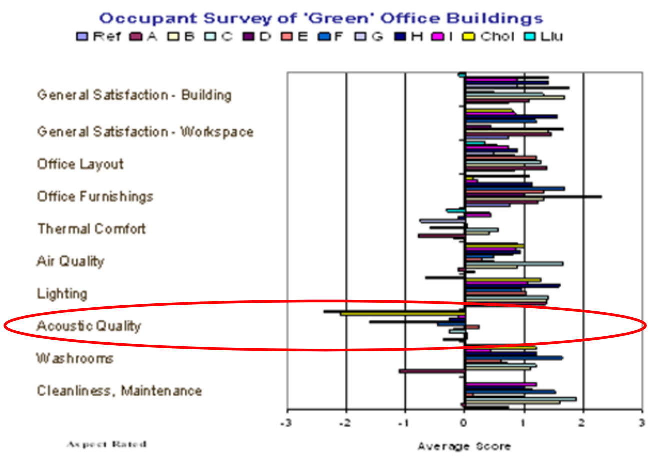

Figure 4 – Occupant-satisfaction-survey results for 'green' office buildings, including UBC Liu and Choi Buildings.

Figure 5 – Liu building natural-ventilation system: (left) shaft and floor openings; (right) office/corridor openings.

In summary, the measured values of NIC and speech privacy for offices at the north ends of the corridors were lower than desirable in important cases and acceptable in others; between the office and corridor they were unacceptable. Thus, a project was initiated to find engineered noise-control solutions to the identified problems. Given the NIC results, and the available budget, it was decided to target the pair of north-end ventilation shafts, and one office partition. The objective was to design and install noise-control devices with adequate acoustical performance, subject to ventilation constraints, and then evaluate the performance by acoustical measurement. The work was done on an informal consulting basis.

Preliminary meetings held to discuss feasible design concepts, the constraints on the design, and design evaluation criteria, came to the following conclusions:

- Ventilation shafts: feasible acoustical treatments could involve lining the internal surfaces of the ventilation shafts, and/or suspending sound-absorbing baffles in them; of course, these treatments are reminiscent of ventilation-duct linings and acoustical louvers;
- Office partition: the noise-control concept that was chosen was to create an acoustically-lined, Z-shaped crosstalk silencer in the natural-ventilation opening; this is similar to the concept of the transfer silencer, already used in naturally-ventilated 'green' buildings;
- Constraints: it was, of course, not acceptable in this 'green' building to excessively compromise natural-ventilation airflows through the silencers; preliminary airflow modelling imposed the design constraint that the treatment of the ventilation shafts could not reduce their cross-sectional area by more than 25%; as for the partition opening and lined Z-shaped silencer, a minimum airflow-path dimension of 125 mm had to be maintained. The sound-isolation design target was NIC 30-35 for general offices and 35-40 for private office.

An energy-based ray-tracing room-prediction tool was used to create a virtual model of the three floors of the north end of the Liu building with its ventilation shafts and floor/ceiling ventilation openings and to predict the sound isolation between floors. The building model was validated by comparing the predicted sound isolation with that measured in the untreated building. Ray tracing was then used to predict the sound isolation between floors for various engineered noise-control measures involving acoustical lining of the ventilation shafts, or a combination of lining and various configurations of absorbent baffles suspended in the shafts. Prediction modelling was also used to optimize the design lined Z-shaped silencer in the office-partition.

Considering the prediction results, the final design of the sound-isolation system for the ventilation shafts that

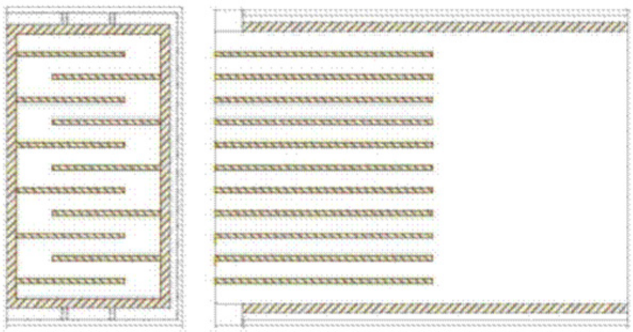

Figure 6 – Lining and baffle configurations installed in two pairs of ventilation shafts in the Liu building.

was implemented was as follows:

- Lining the inner surfaces of the lower boxes on the second and third floor shafts with 50-mm-thick acoustical liner;
- Lining the inner surface of the upper boxes on the first and second floor shafts with 25-mm-thick acoustical liner;
- Locating 11 baffles, each with dimensions of 25 x 400 x 800 mm, in the second- and third-floor ventilation shafts.

Figure 6 shows a drawing of the linings and baffles that were installed in the two pairs of north-end ventilation shafts on the second and third floors. Lining alone was installed in one of each pair, and lining and baffles in the other (to allow their independent evaluation). Figure 7 shows a drawing and photographs of the lined, Z-shaped silencer installed in the Liu office-partition opening.

The sound isolation was re-measured after treatment. The ventilation-shaft lining and baffles increased the sound isolation to NIC 39-56 (increase of NIC 15-23). The lined, Z-shaped silencer in the partition opening increased the sound isolation to ~NIC 25 (increase of NIC 15).

To investigate the effect of the office-partition silencer on airflows and air quality, indoor-air quality was measured (by Dr. Karen Bartlett, UBC) before and after treatment. The results were compared with flow rates recommended by ASHRAE: >10–15 air changes per hour (ACH) (depending on situation), > 17 ft^3/min (cfm) per person. It was concluded that no deterioration of air flows or air quality due to the acoustical treatment was measured. However, this may be explained, at least in part, by the fact that airflows in the untreated building were very low and could not be reduced much by treatment.

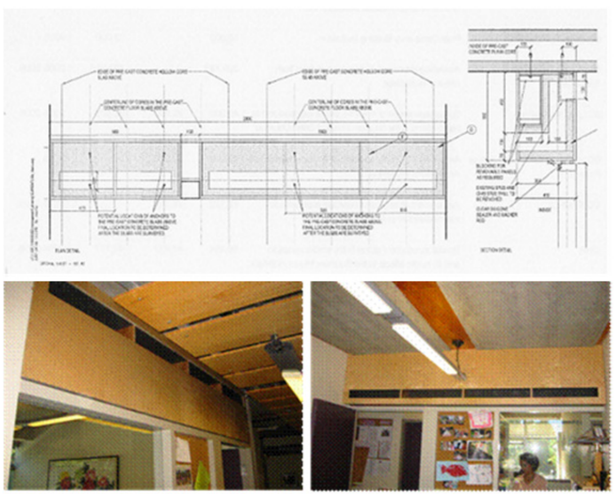

Figure 7 – Drawing, photographs of the lined, Z-shaped silencer installed in the Liu office-partition opening.

Figure 8 – UBC Choi Building absorbent treatment.

2.3 UBC Choi Building acoustical concerns

The UBC Choi Building is another early naturally-ventilated sustainable building whose occupants are concerned about the acoustical quality (see Figure 4). In 2008, an informal evaluation of the concerns again revealed that the main cause was poor sound isolation and speech privacy between offices and corridors, due to slot natural-ventilation openings between the tops of the partitions and the steel-deck ceilings. A professional acoustical consultant was retained to propose solutions to the problems. Of most interest here was the recommendation to install 25-mm-thick glass-fibre sound-absorbing material on the steel-deck surface adjacent and perpendicular to the slot openings. Figure 8 shows this treatment; its performance was later measured in the field and in a controlled laboratory environment (see Sections 5.1 and 5.2).

It had become increasingly clear that a more scientific investigation of the problem of natural-ventilation openings and its solution was needed.

3. Performance characterization [4]

This need was satisfied by the Masters research project of Bibby [5], which first identified three categories of opening, depending on whether the thickness of the partition is <5 cm, 5-20 cm or >20 cm, and mainly studied the first two. It considered how best to characterize the performance of ventilators. The combined acoustical and airflow performance was described by the open area ratio, OAR = EOA_f / EOA_s where EOA_f is the equivalent open area for airflow and EOA_s is the equivalent open area for sound. With reference to Figure 9, acoustical performance is measured following the ASTM E90-09 standard [6] in a two-room sound-transmission facility, the acoustical performance of the ventilator is defined by its frequency-varying transmission loss TL_v – the power-transmission coefficient τ_v expressed in decibels – and EOA_s. Assuming the sound fields in the two rooms are diffuse, diffuse-field theory is used to show that:

$$TL_v = L_1 - L_2 + 10\log\left(\frac{S_v}{A_2}\right) \qquad (1)$$

in which L_1 and L_2 are the reverberant sound-pressure levels in the source and receiver rooms, respectively S_v is the ventilator area and A_2 is the receiver-room sound-absorption area calculated from the measured reverberation time. Since transmission loss varies with frequency, to express TL_v as a single-number value the frequency components were weighted by a speech-source spectrum and that of the hearing sensitivity of a human listener (A-weighting) to obtain the transmitted speech spectrum ($-\mathrm{TL}_{\mathrm{A\_Speech}}$). The equivalent open area for sound (EOA_s) is then [4, 5]:

$$\mathrm{EOA}_s = S_v \tau_{A\_\mathrm{speech}} = S_v \bullet 10^{\frac{-\mathrm{TL}_{A\_\mathrm{speech}}}{10}} \quad (2)$$

Again referring to Figure 9, and following the ASTM E779-10 standard [7], the airflow performance of a ventilator is also measured in a two-room facility and is typically described by its discharge coefficient C_d, from which EOA_f is calculated. Assuming high-Reynolds number flow, and C_d independent of flow rate, it can be shown that [4, 5]:

$$\mathrm{EOA}_f = S_v \frac{C_d}{0.61} \quad (3)$$

The OAR optimization parameter for ventilators is simple to use and based on common, standardized measurement and analysis techniques. A simple aperture has a value of one; higher values indicate better performance, lower values worse performance.

It is useful to introduce 'specific' equivalent open areas for sound and flow as non-dimensional performance metrics that are normalized to, and therefore independent of, the ventilator area S_v:

$$\mathrm{SEOA}_s = \frac{\mathrm{EOA}_s}{S_v} \quad \text{and} \quad \mathrm{SEOA}_f = \frac{\mathrm{EOA}_f}{S_v} \quad (4)$$

It can be seen from Eqs. (2) and (4) that the specific equivalent open area for sound is equal to the A- and speech-weighted transmission coefficient and, from Eqs. (3) and (4), that the specific equivalent open area for flow is equal to the normalized discharge coefficient.

When using these performance metrics, it is important to remember the assumptions being made, the most significant of which are that the room sound fields are diffuse, and that the equivalent open area for flow is independent of flow rate. A detailed discussion of these limitations of the methods can be found elsewhere [4, 5].

4. Measurement methods

4.1 Acoustical performance

The measurement of acoustical performance, detailed below, took into account guidelines outlined in ASTM E90-09 [6], which involved a two-room sound-transmission facility, are based on diffuse-field source and receiver rooms separated by a partition containing the test ventilator and on measuring the sound-pressure-level difference between the rooms. Initially a full partition was constructed in the facility to determine the transmission loss and flanking limits, characterizing the maximum sound isolation obtainable between the two rooms. Average sound-pressure levels were obtained by energy-averaging sound-pressure levels measured at nine positions in the room. Each measurement was a ten-second average. Spot

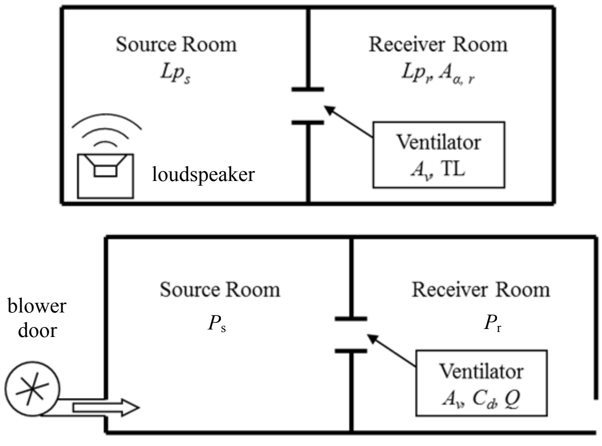

Figure 9 – (top) Acoustical and (bottom) airflow measurement of ventilation openings in a transmission facility.

measurements were made instead of scanning, because the operator cannot be in the room. Reverberation times were averaged over measurements made at the nine positions in the receiver room.

4.2 Airflow performance

Flow rate was measured using a blower door [Model 2000, Retrotec Inc., Everson, WA, USA; www.retrotec.com], a calibrated fan unit designed for testing the air-tightness of buildings, as per ASTM E779-10 [7]. It provides a method for calculating the flow rate based on the difference between the ambient pressure and the pressure at a tap in the fan, as well as the pressure differential across the fan. The flow rate (Q in m^3/s) is measured at a number of differential pressures ΔP; a log-linear regression is used to fit the flow rate as a function of pressure, and determine confidence intervals for the curve fit:

$$Q = C\Delta P^n \quad (5)$$

in which C and n are the flow coefficient and flow exponent, respectively. Letting $x=\ln(\Delta P)$ and $y=\ln(Q)$, linear regression can be used to determine C and n from the variance and covariance of x and y. The standard deviations of n and $\ln(C)$ can also be found [7].

To obtain accurate results, any obvious flow paths exiting the room, besides the ventilator, are blocked. The ventilator itself is completely blocked for the first set of measurements, to allow calculation of the flow rate exiting the room through paths other than the ventilator (the air 'leakage'). Measurements are then repeated with the ventilator open, to allow calculation of the airflow exiting all flow paths. If the flow rate with the ventilator blocked is not small compared to that with it open, elevated uncertainties exist.

Unfortunately, typical operating pressures for interior natural-ventilation openings are small compared to the pressures created during testing as described in ASTM E779-10 [4, 7]. Moreover, it is not possible to extrapolate below the measured data range accurately, because the data measured at high flow rates is not necessarily an accurate predictor of the ventilator's performance at low flow rates [4]. Thus the lowest test pressure (typically about 5 Pa) was used as the reference pressure for calculating EOA_f, introducing a source of error.

Table 1 – Field measurement-result summary, sorted by ventilator type (see text).

Building-Room	Opening type	Performance measure		
		$SEOA_s$	$SEOA_f$	OAR
R-1 (grille off)	O	0.83	1.18	1.41
L-2 (grille off)	O	0.88	1.22	1.38
L-3	R	1.04	0.74	0.71
C-4	R	0.92	0.98	1.06
C-5	A	0.22	0.83	3.82
C-6	A, D	0.51	1.46	3.42
G-7	D	-	1.61	-
K-8	X	0.046	0.11	2.48
L-9	X	0.030	0.10	3.42
G-10 (grille off)	X	-	0.48	-
G-11 (grille off)	X	0.02	0.72	9.89
R-1 (grille on)	G	0.89	0.64	0.73
L-2 (grille on)	G	0.85	0.65	0.76
G-10 (grille on)	G	-	0.25	-
G-11 (grille on)	G	0.02	0.32	4.47

5 Experimental investigations

5.1 Field testing in existing buildings [8]

Measurements were made of the acoustical and airflow performance of sixteen natural-ventilation openings in five existing naturally-ventilated buildings with rectangular and slot ventilation openings in thin and thick partitions with reflective and sound-absorptive adjacent surfaces, and of L-shaped crosstalk silencers. Some of the openings and silencers were equipped with non-acoustical grilles; in these cases, measurements were repeated with the grilles removed. The openings were classified into six types:

- Type O = rectangular opening in thin partitions;
- Type R = slot opening next to reflective surfaces;
- Type A = slot opening next to absorptive surfaces;
- Type D = duct-like, rectangular opening;
- Type X = crosstalk silencer;
- Type G = ventilator with grilles.

Table 1 shows the measured performance of all test ventilators, in terms of $SEOA_s$, $SEOA_f$ and OAR. From these, a number of best practices for successful ventilator design have been identified:

• The acoustical and airflow performance of rectangular ventilation openings in thin partitions is slightly better than the theoretical performance of a sharp-edged, rectangular opening;

• Adding sound-absorptive material to a surface next to a slot opening in a thin partition reduces $SEOA_s$ from about 1 to 0.5 or less, while causing insignificant reduction in $SEOA_f$. OAR increases to about 3;

• Duct-like ventilation openings have EOA_f approximately 50% greater than for a thin orifice of the same cross-section, and OAR ≈ 3. This suggests that pressure losses in ventilators can be reduced by creating a duct instead of a thin orifice;

• Z-shaped crosstalk silencers reduce sound transmission through the ventilation opening to the point that the opening was no longer a dominant transmission path across typical double-leaf, drywall partitions. Sound transmission was measured to be at least 16 dB less than that of a rectangular opening ($SEOA_s \leq$ 3-5%). These silencers are also associated with a small $SEOA_f$ of around 10%, resulting in an OAR of at least 2.5-3.5. The acoustical measurements for crosstalk silencers were generally limited by the performance of the partition; therefore, these results represent a lower-bound to the actual performance;

• Adding a grille to a ventilation opening results in negligible change in EOA_s; however, EOA_f approximately halves, so OAR halves. The practical implication is that, if an opening is covered with a grille, the opening will have to be twice as large not to induce additional pressure loss at the same airflow rate, resulting in an increase of transmitted sound power.

5.2 Laboratory testing [9]

A two-room transmission facility (the NVOS Lab) was created to allow controlled testing of the acoustical and airflow performance of natural-ventilation openings and silencers ('ventilators'). The facility consisted of a small office, divided into two rooms by a stud partition containing a variable test opening into which prototype silencers could be inserted. It was used to measure the acoustical and airflow performance of several configurations seen at field sites. Following are the configurations tested:

- non-acoustical grille (Figure 10);
- commercial acoustical louver (Figure 10);
- slot ventilators, with adjacent and perpendicular surfaces either sound reflective or absorptive (using 25- or 50-mm-thick glass-fibre panels of two sizes) (Figure 11);
- crosstalk silencers (Figure 12);
- novel door-vent silencer (see Figure 13).

Figure 10 – The non-acoustical grille and commercial acoustical louver tested in the NVOS Lab.

Figure 11 – Slot ventilation opening with 50-mm-thick glass-fibre panel on adjacent, perpendicular surface.

Table 2 – Performance results for the lab-test ventilators.

Configuration	$SEOA_s$	$SEOA_f$	OAR
Non-acoustical grille	0.89	0.59	0.67
Acoustical louvre	0.13	0.21	1.68
Slot ventilators			
No GF	2.38	1.09	0.46
1m x 1m x 2.5cm GF	1.43	1.09	0.76
1m x 1m x 5cm GF	0.94	1.09	1.15
1m x 0.5m x 5cm GF	1.03	1.09	1.06
Crosstalk silencers			
Straight	0.32	1.29	4.07
L-shaped	0.34	0.80	2.32
Z-shaped	0.28	0.68	2.44
Straight w/o GF	1.12	-	-
Door-vent silencer			
20-mm spacing	0.054	0.20	3.70
40-mm spacing	0.090	0.49	5.43

The results are shown in Table 2 in terms of $SEOA_s$, $SEOA_f$ and OAR. From these, a number of best practices for successful ventilator design have been identified:

• non-acoustical grilles should be avoided. Adding a grille to a ventilator halves the flow rate for a given pressure loss. Grilles have negligible effect on acoustical transmission;

• the addition of a glass-fiber absorptive liner to the surface adjacent to a slot ventilator increases the opening's acoustical performance by Sound Transmission Class (STC) 3-6, without affecting airflow;

• crosstalk silencers can have high combined acoustical and airflow performance compared to other types of silencer tested. Their acoustical performance can be improved by increasing the length of the acoustically-lined flow path; within reasonable limits, this increase in length does not further restrict, and can actually increase, air flow; the Straight crosstalk silencer has the best performance of the shapes tested;

• in order to be effective at attenuating speech frequencies, the acoustical liner in a silencer should be at least 50-mm thick;

• the novel door-vent silencer was found to have very promising performance (better than a commercial acoustical louvre), providing significant sound attenuation (STC 14-15) with only moderate restriction to airflow, and a strong combined performance (OAR > 3).

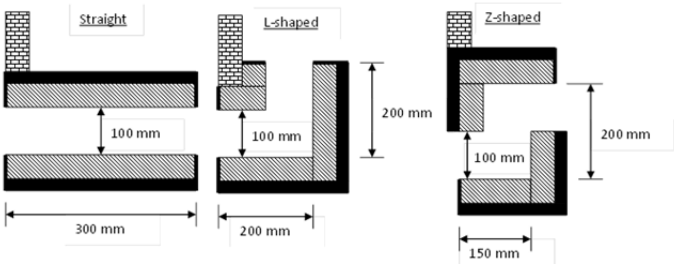

Figure 12 – Diagrams of 0.3-m Straight, L- and Z-shaped crosstalk silencers (50-mm-thick glass fiber shown as crosshatched; heavy black lines represent plywood panels).

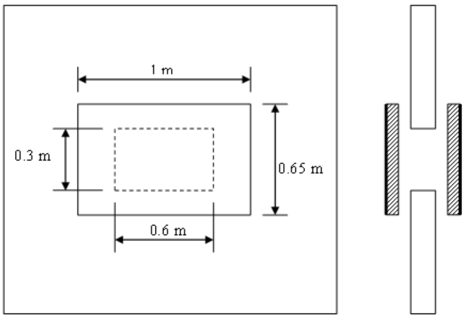

Figure 13 – Acoustical door-vent silencer – 25-mm glass fibre shown as crosshatched.

6 Prediction studies

6.1 Factors affecting speech privacy between rooms [10]

Using a simple diffuse-field model, factors affecting acoustical privacy (speech intelligibility index, SII) between two spaces separated by a partition were predicted. Factors considered were the room dimensions and surface materials, background noise, partition transmission loss, ventilation-opening transmission loss and opening size. The results showed the relationship between ventilation-opening acoustical performance and speech privacy. When a ventilation opening is included in a partition, its effect on privacy is dependent on the transmission loss of the original partition. Figure 14 shows, for four partition types, the predicted changes of SII, relative to that without the opening (SII_0), with the ratio of the sound-transmission performances of the opening (v) to the partition (w), EOA_v/EOA_w. To maintain the privacy provided by a partition, the sound energy transmitted through a ventilation opening should not exceed 10% of that transmitted through the partition.

6.2 Fundamental-mode attenuation [11]

In a theoretical study of the effect of cross-sectional dimensions and liner thickness in straight, unlined and lined ducts, an analytical solution was developed for the attenuation of the fundamental mode in such ducts. Figure 15 shows the variation with frequency of attenuation rate (in dB/m) of the first-order mode in a duct for different heights and absorber thicknesses.

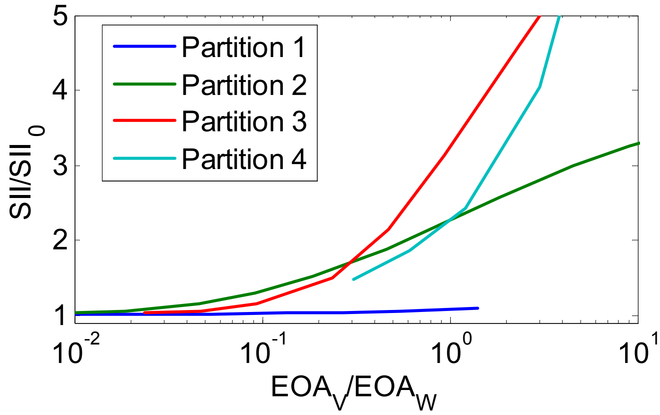

Figure 14 – Predicted change of speech privacy (SII) with EOA_v/EOA_w for four wall types.

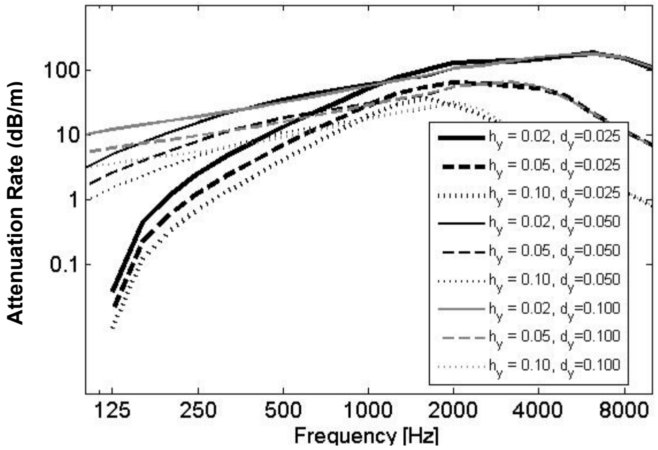

Figure 15 – Predicted variation with frequency of attenuation rate (in dB/m) for various duct heights (h_y) and liner thicknesses (d_y).

Duct-liner thickness does not significantly affect high-frequency performance; however, it limits low-frequency perform-ance. The performance of a 25-mm liner decreases below 1000 Hz; that of a 50-mm liner decreases below 250 Hz. If the objective is to attenuate A-weighted speech, a 25-mm liner is likely not thick enough to be effective; however, a 100-mm liner may be excessive.

6.3 Silencer acoustical performance [5]

Ventilation opening and silencer performance was predicted by the finite-element method – acoustical performance using COMSOL FEM and airflow performance using ANSYS Fluent. Model domains (see Figure 16) and boundary conditions were defined to be similar to those of the laboratory facility. The sound source is in the corner of the source volume. A diffuse sound field is generated, and transmits through the ventilation opening; the outlet is an anechoic termination. The airflow model has pressure inlet and outlet boundary conditions. The flow rate and the static pressures in the two volumes were determined to calculate the discharge coefficient.

Extensive work was done to ensure convergence of the acoustical models with respect to mesh size, frequency resolution, achievement of a diffuse sound field, and to validate the models with respect to sound-transmission prediction. While useful results were obtained from both of the modeling exercises, their validation is incomplete.

To prevent computational requirements from becoming prohibitive, a different source-volume size was defined for each third-octave band.

Predictions were made for the performance of crosstalk silencers, which had been identified as the best-performing silencer type in measurements and existing literature. Straight, L, U, and Z shapes were modelled (see Figure 17),

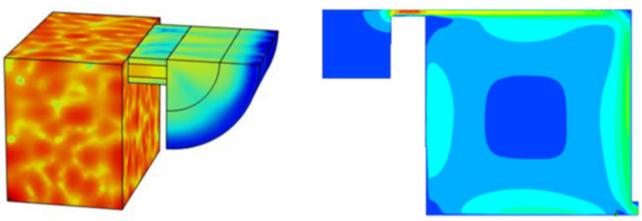

Figure 16 – Illustration of the acoustical (left) and airflow (right) prediction domains for finite-element prediction.

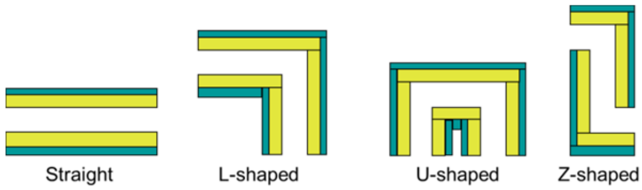

Figure 17 –Straight, L-, U-, and Z-shaped crosstalk silencers predicted by finite-element methods.

each with 0.3-, 0.5- and 1-m flow-path lengths.

Figure 18 shows the predicted effect of flow-path length on the acoustical performance ($SEOA_s$) of crosstalk silencers of various shapes. Figures 19 and 20 show the effect of flow-path length on $SEOA_f$ and OAR. The results allow a number of conclusions to be drawn about the factors affecting the acoustical and airflow performance of crosstalk silencers:

• Acoustical performance ($SEOA_s$) is independent of silencer shape. Elbows do not attenuate the frequencies that limit silencer performance (and if the wavelength exceeds the duct height). Figure 18 shows only slight differences between the different silencers, especially as the length increases. The U-shaped silencer has the highest performance and the straight silencer the worst, but the differences are small. The frequencies that limit silencer performance are the 250- and 500-Hz bands – at these frequencies all silencer shapes have similar performance. At higher frequencies the silencer shape has a large effect. The performance increases with silencer length;

• Airflow performance is dependent on silencer shape and length. Figure 19 shows this for $SOEA_f$. A plain opening has a value of one; the straight silencer approaches this. It is less restrictive to flow than the others, which indicates, not surprisingly, that elbows increase the flow loss. The effect is apparently complicated, because the U-shaped silencer, which has two elbows, is less restrictive than the L-shaped silencer, which has one. Surprisingly, except for the Z-shaped silencer, the flow restriction decreases with increasing silencer length. The 1-m straight crosstalk silencer allows 30% more airflow than a thin aperture with the same cross-sectional area. $SEOA_f$ increases with silencer length.

In summary, crosstalk silencers are very effective. Overall performance increases with increasing silencer length, which decreases $SEOA_s$, increases $SEOA_f$ and increases OAR strongly. The straight silencer was the most effective of the crosstalk silencers tested (see Figure 20).

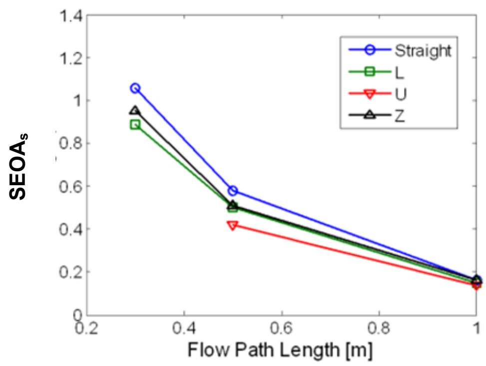

Figure 18 – Predicted effect of flow-path length on the acoustical performance ($SEOA_s$) of crosstalk silencers of various shapes.

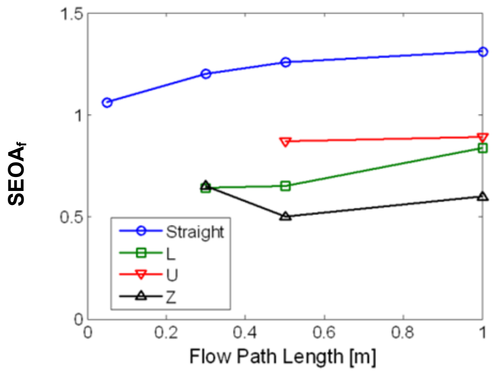

Figure 19 – Predicted variation of SEOA$_f$ with flow-path length for crosstalk silencers of various shapes.

7 Case-study applications

The knowledge gained in the optimal design of natural-ventilation-opening silencers was applied to two case studies in the UBC Centre for Interactive Research on Sustainability (CIRS). CIRS was designed to be the most sustainable building in North America. It involves natural ventilation, resulting in occupant concerns about the acoustical environment, some due to poor sound isolation and speech privacy associated with internal natural-ventilation openings. Two experimental projects were initiated to design optimal crosstalk silencers for openings in thin, glass partitions separating an office from a lab and a lunch room from an open-office area, to achieve acceptable acoustical and airflow performance. After an evaluation of the current performance, performance targets were set:

- natural ventilation (fresh air): 10 L/s per occupant;
- sound transmission: decrease by STC 10-15.

The pre-treatment evaluation revealed an important constraint: it is impossible for silencers to achieve high speech privacy because of the significant flanking sound transmission through the thin, glass partitions.

Since Z-shaped silencers had been used in previous applications, it was of interest to use Straight and U-shaped silencers here. Bibby's work [5] found that the former tend to have better airflow than acoustical performance whereas, for the latter, the acoustical performance tends to be best.

In both cases, the main parameters affecting acoustical, airflow and combined performance were expected to be the flow-path length and height, which had to be optimized. The third important factor, the absorbent lining thickness was 25 or 38 mm, given the material available, though it was known from previous work that 50 mm is optimal.

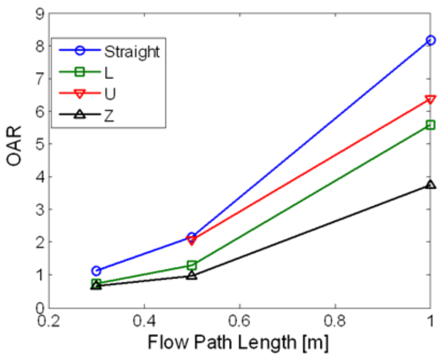

Figure 20 – Predicted variation of OAR with flow-path length for crosstalk silencers of various shapes.

Figure 21 – Natural-ventilation opening in the partition between the office and lab in the CIRS building.

7.1 Office / lab partition [12]

Figure 21 shows the opening in the partition between the CIRS office and lab. Since acoustical performance (high speech privacy) was considered to be more important than ventilation performance in the office occupied by one person, it was decided to use a U-shaped silencer. The length and height of the flow path were optimized by constructing various test silencer and measuring their acoustical and airflow performance.

Figure 22 shows five test configurations, their flow-path dimensions – length (in m) X height (in m) – and their measured EOA$_s$ and EOA$_f$. EOA$_s$ increased with height and decreased with length: acoustical performance increased with decreased height and increased length. They increased the sound attenuation by STC 6-12. EOA$_f$ increased with height (and, to some extent, length): airflow performance was mainly governed by silencer height. While even the best airflow performance corresponded to a decrease in EOA$_f$ of 70% relative to that of the untreated opening, tracer-gas measurements suggested that ventilation quality remained high (5.3-8.3 ACH) under typical natural-ventilation conditions.

Figure 23 shows the combined performance (OAR). Both height and length affected OAR but, in particular, OAR increased with length. The 1.8 X 0.26 and 1.5 X 0.26 configurations had very similar overall performance. However, since the 1.5 X 0.26 configuration was 30% more restrictive to flow, the 1.8 x 0.26 configuration, with its better acoustical performance, was considered the optimal U-silencer, since speech privacy is very important for the office application. Figure 24 shows the optimal silencer, as installed.

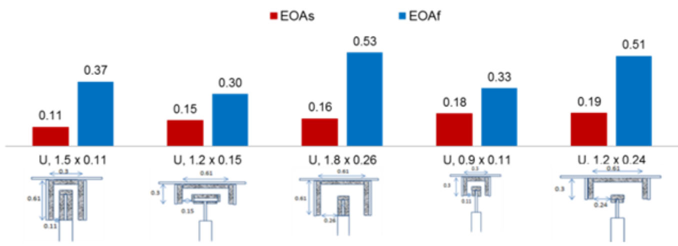

Figure 22 – Measured acoustical (EOA$_s$ in m^2) and airflow (EOA$_f$ in m^2) performance of five U-shaped silencers described by length (m) X width (m).

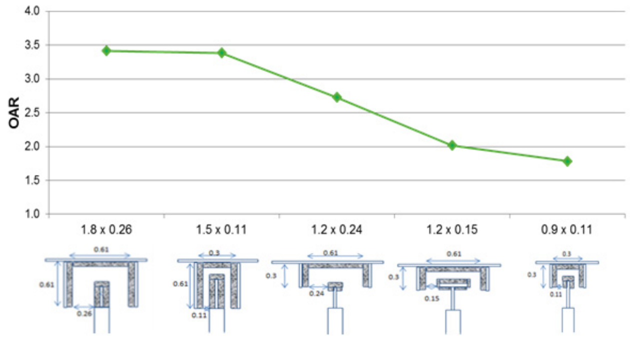

Figure 23 – Measured combined acoustical and airflow performance (OAR) of five U-shaped silencers.

7.2 Lunch-room / open-office partition [13]

Figure 25 shows the opening between the CIRS lunch room and open-office area. Since ventilation performance was considered to be more important than acoustical performance in the lunch room occupied by up to ten people at a time, a Straight silencer was used.

The length and height of the flow path were optimized by constructing various test silencers and measuring their acoustical and airflow performance.

Figure 26 shows four test configurations and their dimensions – height (in m) X length (in m). Table 3 shows their acoustical (EOA_s), airflow (EOA_f) and combined (OAR) performance. EOA_s increased with height and decreased with length: acoustical performance increased as height decreased and length increased. They increased the sound attenuation by STC 7-10. The straight silencer with small height and large length (0.14 m X 0.75 m) was nearly as effective at attenuating sound as the complete blockage of the opening. EOA_f increased with length (and decreased with height): airflow performance mainly increased with silencer length (and decreased with height). The silencer with the highest performance (0.50 m X 0.75 m) had 25% higher airflow performance than that of the untreated opening. With these silencers, tracer-gas measurements found that ventilation quality remained high (4.8-7.5 ACH) under typical natural-ventilation conditions.

As for the combined performance, both height and length affected OAR, but OAR mainly increased with length and decreased with height. Because of its high acoustical and overall performance, the 0.14 m X 0.75 m silencer was considered the optimal Straight silencer, since adequate ventilation was particularly important in this application. Figure 27 shows the optimal Straight silencer, as installed.

Figure 24 – The optimal U-shaped test silencer installed between the CIRS office and lab.

Figure 25 – Natural-ventilation opening in the partition between the lunch room and open-office area in the CIRS building.

8 Conclusion

The measurement and prediction results have provided a better understanding of the acoustical, airflow and combined performance of natural-ventilation openings and silencers designed to reduce sound transmission, but not airflow, at least in the case of non-thick partitions. They identify a number of key best practices for successful ventilation-opening and -silencer design:

• non-acoustical grilles covering ventilation openings are acoustically transparent, but reduce airflow by 50%. Non-acoustical grilles should be avoided;

• adding sound-absorptive material to a surface next to a slot opening reduces $SEOA_s$ from approximately 1 to 0.5 or less (increases acoustical performance by STC 3-6), with insignificant reduction in airflow ($SEOA_f$). Overall performance (OAR) increases to about 3;

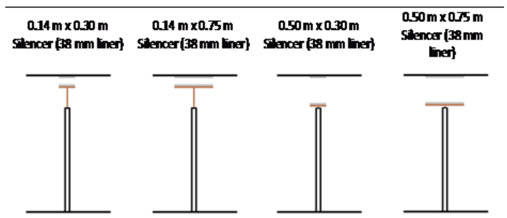

Figure 26 – Straight-silencer test configurations. open-office area.

Table 3 – Measured acoustical (EOA_s), airflow (EOA_f) and combined (OAR) performance of Straight silencers with different flow-path dimensions (in m): height X length.

Performance measure	0.50 x 0.30	0.14 x 0.30	0.50 x 0.75	0.14 x 0.75
EOA_s (m^2)	0.35	0.16	0.14	0.04
EOA_f (m^2)	1.01	0.42	1.35	0.53
OAR	**2.89**	**2.63**	**9.64**	**13.25**

Figure 27 – The optimal Straight test silencer installed between the CIRS lunch room and open-office area.

- crosstalk silencers with acoustical linings have high acoustical and airflow performance. The acoustical performance can be improved by increasing the length of the flow path which, within reasonable limits also increases airflow. The Straight silencer had the best performance of the shapes tested;
- a novel door-vent silencer was found to have very promising performance, providing significant sound attenuation (STC 14-15) with only moderate restriction to airflow, and a strong combined performance (OAR > 3), but the design must be optimized;
- to attenuate speech sounds, the acoustical liner in a silencer should be at about 50-mm thick;
- duct-like ventilation openings have EOA_f about 50% greater than for a thin orifice of the same cross-section, and OAR ≈ 3. This suggests pressure losses in ventilators can be reduced by creating a duct instead of a thin orifice.

The knowledge gained from the various experimental and prediction studies has been applied to two case studies in CIRS, involving openings in partitions separating an office from a lab and a lunch room from an open-office area. The users of these spaces report the silencers to be successful.

Two important assumptions were made in the work reported in this paper:

- that airflow through the ventilator has high Reynolds number; it is not known to what extent the results reported here apply to realistic, much lower natural-ventilation pressure differentials and airflows, or how to measure them accurately;
- that the sounds of concern in natural-ventilated buildings are mainly speech, so an A-weighted, speech spectral weighting was applied to frequency-varying acoustical results; this requires further experimental invest-igation – for example, by way of soundscape studies.

Current work is investigating the third category of opening – those in thick partitions, in which the opening is effectively a duct.

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