ASSESSMENT OF NOISE IN THE CAMPUS OF ÉCOLE DE TECHNOLOGIE SUPÉRIEURE IN MONTRÉAL AND PROPOSAL OF AN ACOUSTIC METAMATERIAL FOR THE REDUCTION OF ELECTRICAL TRANSFORMER NOISE

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Résumé

Les campus universitaires situés au cœur des villes peuvent être exposés à des niveaux de bruit importants qui peuvent nuire à l'apprentissage des étudiants et étudiantes, à la performance de la communauté enseignante et des membres du personnel mais aussi à la qualité de vie des résidents et résidentes du quartier. Cet article présente les résultats d'un projet d'étude réalisé par des étudiants du cours d'acoustique industrielle de l'École de technologie supérieure (ÉTS) et qui avait pour principal objectif de quantifier et évaluer le bruit extérieur et intérieur du campus universitaire de l'ÉTS. Les étudiants devaient aussi localiser les principales sources de bruit intérieures à l'aide d'une caméra acoustique et modéliser un métamatériau acoustique qui permettra de réduire le bruit tonal émis par les transformateurs en basses fréquences.

Mots clés : bruit environnemental, acoustique, université, campus, bruit intérieur, métamatériau acoustique

Abstract

University campuses located in the heart of cities can be exposed to significant noise levels that can hinder the learning of students, the performance of the teaching community and staff, as well as the quality of life for residents in the neighborhood. This article presents the results of a study project conducted by students of the "Industrial Acoustics" course at École de technologie supérieure (ÉTS), with the main objective of quantifying and assessing the outdoor and indoor noise levels on the university campus. The students were also tasked with identifying the main sources of indoor noise using an acoustic camera and modeling an acoustic metamaterial that would help reduce the tonal noise emitted by transformers at low frequencies.

Keywords: environmental noise, acoustics, university, campus, indoor noise, acoustic metamaterial

1 Introduction

Noise can have detrimental effects on individuals' health [1]: hearing loss, sleep disruption, difficulty in communication, cardiovascular and psychophysiological effects, reduced performance, discomfort, and impacts on social behavior. In educational settings, noise can also affect learning, particularly reading comprehension, memory, and speech intelligibility [2]. As a result, several studies have focused on noise in university campuses[3-5], generally concluding that noise levels are too high for an environment dedicated to learning. The campus of the École de technologie supérieure (ÉTS) is located in the heart of Montreal, Canada, and is, unsurprisingly, exposed to high noise levels as shown in the noise level mapping conducted in 2014 by Ragettli et al. [6, 7] and presented in Figure 1(a). According to this map, noise levels in this area exceed the maximum recommended level of 55 dB(A) by the World Health Organization (WHO) [1] (recommendation for outdoor spaces in schools). The noise pollution in this central area of Montreal is indeed a real issue, and the campus noise has been mentioned multiple times during a consultation on the campus urban development conducted in 2018 [8]. For example, some suggestions arising from these consultations include "*Creating relaxing soundscapes*," "*Designing green walls to counteract pollution and noise*," "*Building havens of peace (mitigate noise pollution) open to the public but intended for ÉTS employees and students, and maintaining a balance between the needs of the ÉTS community and the neighborhood residents*." However, the precise noise levels in different parts of the ÉTS campus are not known. A more detailed mapping would help identify (i) the quietest areas that would be most suitable for outdoor rest, as desired by the community, and (ii) the noisiest areas that would require acoustic improvements to enhance the comfort of the neighborhood residents and the ÉTS community.

The indoor acoustic environments of the different buildings are equally important. They need to be adapted to the learning context but also conducive to office work for all campus staff members. Just like outdoor noise, the indoor noise levels at the ÉTS campus are not known and need to be measured.

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As part of their semester project for the "Industrial Acoustics" course at ÉTS [10] (course code MEC636), a class had the mission to conduct a noise study on the ÉTS campus to contribute to improving the acoustic environments and thus the quality of life for the community. The first step of the project involved studying the outdoor noise on the ÉTS campus. The second step involved characterizing the sound environments of several rooms in different buildings at ÉTS (e.g., auditorium, classrooms, cafeteria, offices, library) and evaluating the acoustic quality of these environments. The noise sources of interest in this project were stationary sources associated with the operation of the buildings, such as ventilation, mechanical and electrical systems, and computer servers. Lastly, the students were required to locate the main sources of noise inside the buildings, including those from electrical and mechanical rooms. They also had to propose a concept for an acoustic metamaterial dedicated to enclosing electrical transformers to reduce their potential impact on adjacent rooms.

The purpose of this paper is to present the noise study of the ÉTS campus conducted by students of the Industrial Acoustics course at ÉTS as part of their semester project. The educational context of this student project is initially presented in Section 2. Section 3 then describes the measurement equipment used, the evaluated outdoor and indoor environments, and the indicators used to characterize their acoustic quality. Section 3 concludes with the presentation of the model used to simulate the acoustic behavior of the metamaterial intended for reducing transformer noise. Section 4 presents and discusses the results of the study. Section 5 summarizes the main conclusions and outlines the project's future prospects.

2 Pedagogical context of the project

The course "Industrial acoustics" (MEC636) is an advanced specialization course in the final year of the mechanical engineering bachelor's program at ÉTS. It aims to equip students with the skills to measure and reduce noise based on the theoretical foundations of industrial acoustics and associated experimental techniques. This course is primarily based on three unconventional pedagogical elements [11]: (i) an active pedagogical method based on cooperative learning, (ii) intensive use of computer tools through practical sessions and computer-based exams, and (iii) a team-based semester project.

The course spans 13 weeks of instruction. The semester project, which is the subject of this paper, consisted of three laboratory sessions and one practical session. The project started with the three laboratories in weeks 8, 9, and 10. The first laboratory aimed to conduct noise level mapping of the outdoor areas on the ÉTS campus. The following two laboratories focused on characterizing multiple indoor acoustic environments in the main buildings of the campus (Buildings A, B, D, and E, as shown on the map in Figure 1(b)). The semester project presented in this paper differs slightly from the projects of previous years, which focused on reducing the noise of small household equipment (e.g., kitchen blender, leaf blower, hairdryer) [11]. However, both types of projects allow students to apply the theoretical and experimental knowledge acquired during the course.

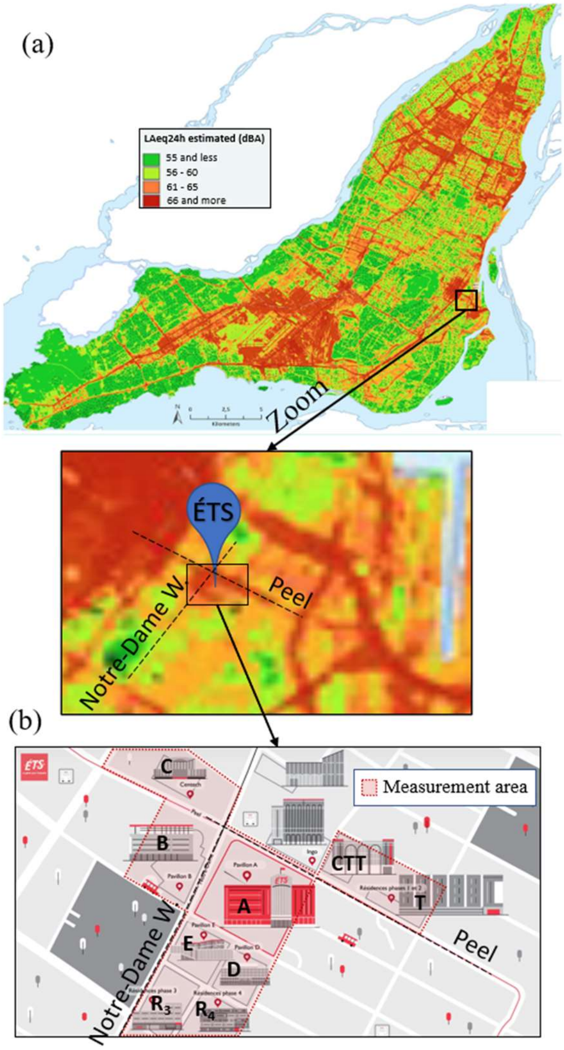

Figure 1: (a) Map of noise levels in the island of Montreal (adapted from [6, 7]); (b) ÉTS campus and outdoor noise measurement area.

Prior to the first project laboratory, students were trained in acoustic diagnostics of environments and noise sources, including the use of instruments to measure sound pressure levels (overall noise level) and the representation of signals in the frequency domain (e.g., octave bands, narrow bands). Students had already conducted noise measurements, analyzed and interpreted the results in order to assess noise complaints (primarily in the workplace). After the 7th week of the course, they were taught the theoretical foundations of wave propagation in dissipative and non-dissipative fluids, as well as the transfer matrix method [10, 12]. The transfer matrix method is used in the MEC636 course to simulate the acoustic behavior in absorption and transmission of various noise reduction systems, such as single and multiple walls, as well as reactive and dissipative mufflers. The practical session of the semester project (in week 13 of the semester) allowed students to apply this knowledge. The objective of the session was to design an acoustic material composed of a paving of quarter-wavelength and Helmholtz resonators, also known as metamaterial, to absorb acoustic energy at targeted and problematic frequencies from noise sources identified during the indoor measurement campaigns on the campus.

3 Material and method

3.1 Material

Outdoor noise

The outdoor measurements were conducted using the NoiseCapture application [13, 14] installed on the students' mobile phones (i.e., Galaxy A23 5G, A52 5G, S20 FE 5G by Samsung from Seoul, South Korea, and Pixel 3A by Google from Mountain View, CA, USA) (see Figure 2(a)). This application allows for noise level measurements to be taken and combined with GPS data to display them on an interactive map within the application. The devices were manually calibrated just before the measurement session using a manual calibration procedure guided by the lab instructor. This procedure involved correcting the noise level obtained by the application through comparison with a simultaneous measurement using a calibrated sound level meter.

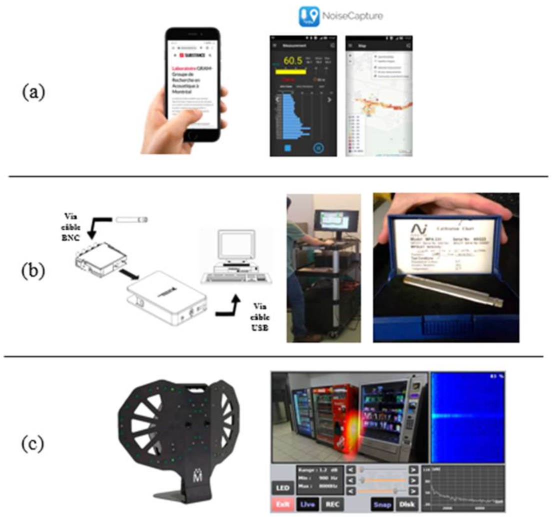

Figure 2 : (a) Mobile phone and "NoiseCapture" application [13, 14] for outdoor measurements; (b) instrumentation of the MEC636 course for indoor measurements; (c) LF-ANT acoustic camera (Mecanum, Sherbrooke QC, Canada) for acoustic imaging [15].

Indoor noise

The noise measurements in indoor environments were conducted using 1/2-inch free-field microphones (MPA231) of Class 1 from BSWA (Beijing, China), along with National Instruments (Austin, TX, USA) cDAQ-9171 data acquisition cards (see Figure 2(b)). The measurement chains were calibrated using a Larson Davis calibrator (Depew, NY, USA) CAL200. The "MEC636-V4" software, developed at ÉTS using LabVIEW (National Instruments, Austin, TX, USA), was used for data acquisition and post-processing. An LF-ANT acoustic camera (Mecanum, Sherbrooke, QC, Canada) [15, 16] (see Figure 2(c)) was also used to capture acoustic images of the environments and locate the main sources of noise. Similar to a thermal camera that shows hot spots of temperature, an acoustic camera reveals areas with the highest noise levels, allowing for visualizing sound. This equipment was purchased to complement the tools in the MEC636 course for the acoustic diagnosis of environments and noise sources. In the session project, this camera was used with the aim of improving the acoustic comfort of learning and working spaces on the campus by addressing the main noise sources in the buildings.

3.2 Environnements

Outdoor noise

The outdoor noise measurements were conducted in the designated area of the ÉTS campus highlighted in red on Figure 1(b). The main intersection of the campus is located at the corner of Notre-Dame West and Peel streets. The different zones within the campus indicated on the map are: (i) buildings A, B, D, and E, which include classrooms, offices, a library, auditoriums, conference rooms, cafeterias, a sports center, and a daycare center; (ii) Centech C, which is a technology incubator; (iii) student residences T, R_3 and R_4; and (iv) the thermal technology center (CTT).

Two measurement periods were conducted on the afternoon of February 22, 2023: (1) a first period from 2:30 PM to 3:30 PM, referred to as the "off-peak hour," and (2) a second period from 4:00 PM to 5:00 PM, referred to as the "peak hour." These two periods were chosen because the ÉTS campus is located near major roadways in Montreal, and significant differences in noise levels were expected between the two periods, with higher levels during peak hours.

Indoor noise

The indoor environmental measurements at ÉTS were conducted on February 23 and March 9, 2023. The measured locations were divided into three categories. The first two categories correspond to "**core learning spaces**" and "**ancillary learning spaces**" as defined in the ANSI/ASA S12.60 standard [17]. The first category includes open or enclosed teaching and learning spaces where oral communication is essential for students' academic achievement. This category partially encompasses classrooms, the library and auditoriums. The measurements were predominantly taken when the rooms were unoccupied and/or with quiet individuals present. The main sources of noise in these spaces were typically the ventilation and air conditioning systems. The second category comprises learning spaces where communication is crucial for the student but their primary function is not formal learning. Instead, they involve informal learning, social interactions, and similar activities. These spaces include common areas (e.g., atriums), cafeterias, sports facilities, and student life areas such as clubs. The third category corresponds to the "**electrical and mechanical rooms**" in various campus buildings, as well as adjacent rooms that may be impacted by the noise sources from these rooms.

3.3 Indicators and recommended maximum values

This section presents the different indicators used to characterize outdoor and indoor acoustic environments, as well as the recommended maximum values for the measured environments, taken from reference documents (e.g., WHO[1, 9], ANSI/ASA S.12.60 standard [17], ASHRAE handbook [18]).

Outdoor noise

The "NoiseCapture" application allows measuring the equivalent A-weighted sound level every second ($L_{Aeq,1s}$) while the recording is active and the student moves around the campus. The A-weighted sound pressure level approximates how the human ear perceives the different frequency components of sounds at typical speech listening levels. At the end of each measurement campaign ("off-peak hour" and "peak hour"), the application divides the space into hexagons with an equivalent radius of 15 meters. For each measurement campaign, the application combines all the measurements taken in each hexagon and provides an equivalent noise level L_{Aeq} per hexagon [13, 14]. The duration of the measurements taken during both campaigns ranged from 30 seconds to 5 minutes. The cumulative measurement time for all students was 1 hour and 57 minutes for the "off-peak hour" campaign and 1 hour and 55 minutes for the "peak hour" campaign.

Members of the ÉTS community who move outside the campus buildings are mostly exposed to road traffic noise. The maximum recommended exposure value (over 24 hours, $L_{Aeq,24h}$) by the WHO to prevent the effects of noise for sources related to road traffic (i.e., cardiovascular ischemic diseases; type 2 diabetes; annoyance, sleep disturbances, difficulty reading and oral comprehension) is 50 dB(A) [7, 9]. Although in practice, the measurements were taken for much shorter durations than 24 hours (for practical reasons), they can still be compared to a threshold value defined over 24 hours[6, 19]. Another more permissive limit value from the WHO of 55 dB(A) was recommended for outdoor environments of schools [1]. This maximum value is considered in this study as it has often been used in similar studies conducted on university campuses [3, 4].

Indoor noise

Two indicators are predominantly used to characterize the acoustic quality of learning spaces (core and ancillary) [17]: background noise level (A-weighted equivalent level, L_{Aeq}) and reverberation time (TR). Both indicators are measured when the rooms are unoccupied. Measuring the background noise level in a room allows assessing the magnitude of contributions from external noise sources (e.g., road traffic, air traffic, factories, activity in schoolyards) and internal noise sources (e.g., ventilation noise, noise from neighboring rooms). The reverberation time measures the extent of reverberation in a room and represents the time required for a continuous sound level to decay by 60 dB after being switched off. This time depends on the volume of the room, the absorption properties of the materials on the surfaces and the frequency. In this project, the reverberation time was measured in classrooms (category of core learning spaces), and noise level measurements were performed for durations of 10 to 15 seconds (due to time constraints associated with the limited duration of project-specific teaching laboratories).

Excessive background noise and/or reverberation in these spaces interfere with oral communication and constitute an "acoustic" barrier to learning [17]. Therefore, maximum recommended values are provided in reference works [17, 18] and are summarized in Table 1 below.

Table 1: Maximum recommended values for core and ancillary learning spaces.

Category	Type of space	L_{Aeq} max (dB(A))	TR (s) in octave bands 500, 1000 and 2000 Hz
Core learning spaces	Classrooms, library, private offices, conference rooms, music practice rooms.	35 (volume ≤ 566 m^3) [17] 40 (volume > 566 m^3) [17]	0,6 (volume < 283 m^3) [17] 0,7 (283 m^3 $<$volume $\le$ 566 m^3) [17]
	Classrooms (100 m^3 $<$ volume $\le$ 290 m^3)	40 for students aged 12 and older [20]	0,6$<TR<$0,7 [20]
Ancillary learning spaces	Cafeteria	40 [17]	
	Gymnasium	40 [17] 50 [18]	
	Open-plan offices	45 [18]	
	Large capacity spaces with speech amplification	55 [18]	

The maximum recommended values depend on the use of the rooms. The acoustic quality of a core learning space should be higher than that of an ancillary learning space, and therefore the recommended maximum values for the former are lower. There is a wealth of literature available specifically for classrooms, as this space is of utmost importance for oral communication and student learning. A literature review on this topic [20] concludes that, for small and medium-sized classrooms, a reverberation time (TR) between 0.6 and 0.7 is adequate for students of all ages, and the background noise level should not exceed 40 dB(A) for students aged 12 and older.

3.4 Acoustic metamaterial modeling

In order to reduce the low-frequency noise from electrical and mechanical rooms that can be perceived in neighboring spaces (see Section 4.2), an acoustic metamaterial has been proposed. This material will serve as an acoustic enclosure for the main noise source in the room, identified using the acoustic camera. The metamaterial consists of a tiling pattern of an absorptive unit cell composed of a two-degree-of-freedom Helmholtz Resonator (HR) and a quarter-wavelength resonator (QR), as shown in Figure 3(a). The absorption behavior of the material has been modeled using the transfer matrix method, considering normal incidence plane wave excitation at the material surface. In this case, a single cell is sufficient for modeling (see Figure 3(b)). The resonators are designed to absorb acoustic energy at four identified problem frequencies.

The absorption coefficient of the unit cell is determined based on the input acoustic impedance Z and the characteristic impedance of air Z_0:

$$\alpha = 1 - \left|\frac{Z - Z_0}{Z + Z_0}\right|^2 . \tag{1}$$

The input impedance of the surface of the metamaterial unit cell, Z, is calculated based on the input acoustic impedances of the quarter-wavelength resonator, Z_{QR}, and the Helmholtz resonator, Z_{HR}, using the admittance sum method [21, 22]:

$$Z = \left(\frac{S_{\mathrm{t}}}{S_{\mathrm{QR}}}\frac{1}{Z_{\mathrm{QR}}} + \frac{S_{\mathrm{t}}}{S_{\mathrm{HR}}}\frac{1}{Z_{\mathrm{HR}}}\right)^{-1}, \tag{2}$$

with S_{t} the total surface area of the unit cell, S_{QR} the input surface area of the quarter-wavelength resonator, and S_{HR} the input surface area of the Helmholtz resonator. The transfer matrix modeling of the acoustic impedances of the two resonators (Z_{QR} and Z_{HR}) is presented in the appendix.

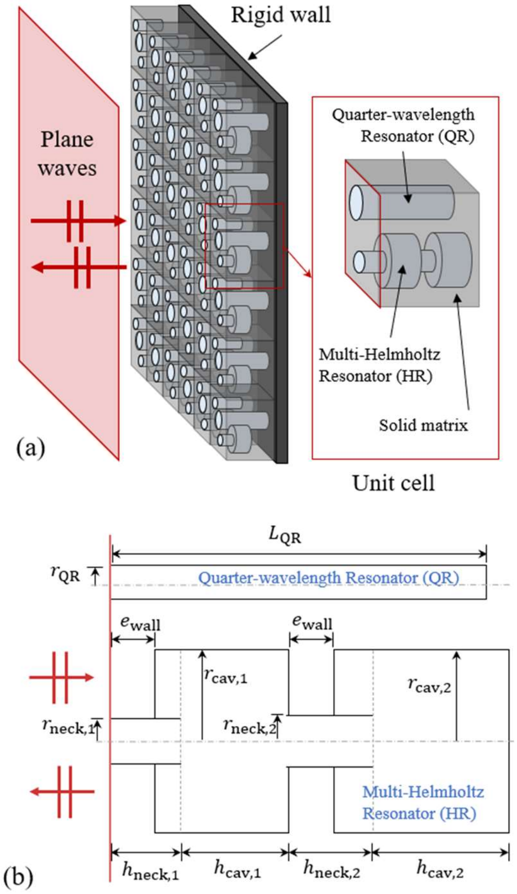

Figure 3: Acoustic metamaterial; (a) three-dimensional schematic, (b) cross-sectional view of a unit cell.

4 Results and discussion

4.1 Outdoor noise

The noise maps of the two outdoor measurement campaigns, "off-peak hour" and "peak hour," are presented in Figures 4(a) and 4(b), respectively. Overall, for both measurement periods, the trends shown on the noise level map in Figure 1(a) (see zoom) are observed: (i) the areas most exposed to noise are Notre-Dame West Street and Peel Street (as well as the area around Building C), and (ii) the noise levels in these areas are generally above 65 dB(A). A large part of the ÉTS campus is therefore exposed to levels well above those recommended by the WHO.

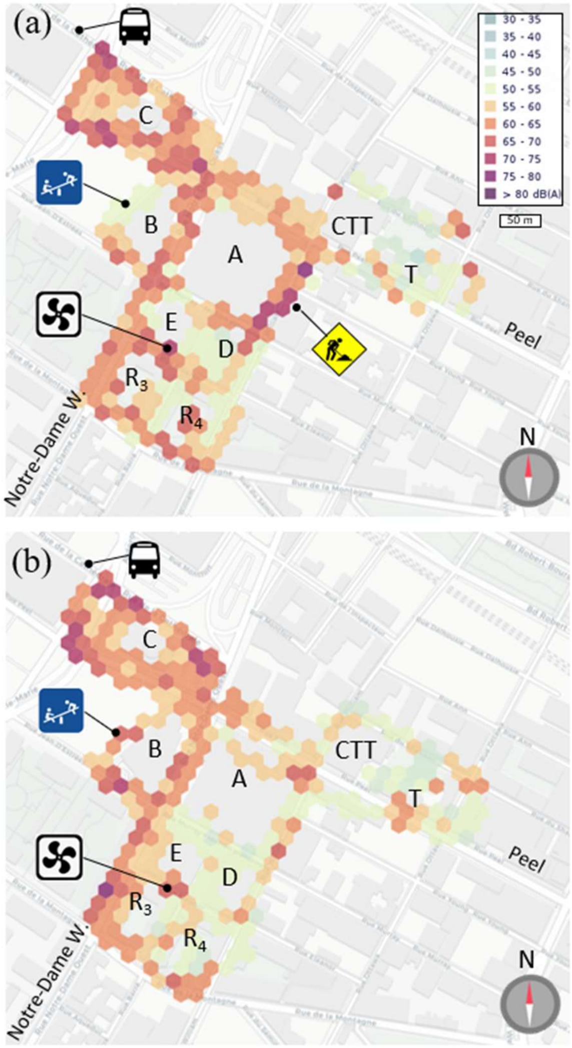

Figure 4: Noise mapping of the outdoor areas on the ÉTS campus during the following periods: (a) off-peak hour, and (b) peak hour.

The main source of noise on the ÉTS campus is road traffic. In the case of the area around Building C, the high noise levels could be attributed to the departure of buses from a station located slightly to the north (not visible in the figure), which use the street north of Zone C to access, among other things, a highway (see pictogram on Figure 4). However, Figure 4 shows that, counterintuitively, noise levels seem to be higher during off-peak hours than during peak hours. This can be explained by the significant number of constructions works in the area, generating both construction noise and road noise (dump trucks' noise being particularly high [23]), mainly before 4:00 PM. For example, a high noise level is observed only during off-peak hours on the street along the southeast side of Building A, caused by construction works for a new ÉTS building (see yellow pictogram on Figure 4(a)).

Four “quieter” areas (L_{Aeq} below 55 dB(A)) can be identified on both noise maps of the ÉTS campus, corresponding to outdoor courtyards: (i) between buildings E and D, (ii) between residences R_3 and R_4, (iii) between the CTT and residences T, and (iv) northwest of building B, which is a playground for the ÉTS daycare (indicated by a blue pictogram on Figure 4). For the latter zone, the noise level is higher during the "peak hour" measurement because children were playing in the courtyard. It is still interesting to note that this space is reasonably protected from traffic noise (see Figure 4(a)). The first three listed "quiet" zones would be prioritized for taking breaks (e.g., lunch) outdoors on the ÉTS campus. Unfortunately, this is not the case for the park surrounding building C, which is heavily impacted by traffic noise. This area could benefit from acoustic improvements (e.g., green screens) to enhance the acoustic comfort for users.

Lastly, a notable source of noise appears on both maps in Figure 4. It is a ventilation exhaust located south of building E, indicated by a pictogram on Figure 4. This noise can be perceived in the area between buildings E and D, reducing the "quiet" space between these two buildings.

4.2 Indoor noise

This section presents the results of the indoor noise studies for the three types of spaces mentioned in section 3.2.

Core learning spaces

A total of 15 rooms belonging to the category of core learning spaces were measured. Figure 5(a) presents the distribution of noise levels for the 15 rooms and shows that 80 % of the rooms have a noise level below 40 dB(A), and 40 % have a level below or equal to 35 dB(A). Among these 15 rooms, 5 are classrooms (with an average volume of approximately 290 m^3), and 80 % of these classrooms have a noise level below 40 dB(A) (see Figure 5(b)), which is considered suitable for learning according to [20]. Furthermore, the measured reverberation times (TR) at different octave bands (i.e., 500 Hz, 1000 Hz, and 2000 Hz) in these classrooms were all below 0.7 seconds, which again is considered adequate according to [20] (although slightly higher than the recommendations of the ANSI/ASA standard [17]). The only classroom measured that exceeds 40 dB(A) is located under the 6th floor of Building D, where the main mechanical room of the building is situated and is adjacent to a mechanical shaft. Despite this, the measured level is 41 dB(A), which is still very close to the proposed limit value in [20]. Figure 5(c) also shows that Building D has more rooms below the 40 dB(A) threshold compared to Building A, which is older.

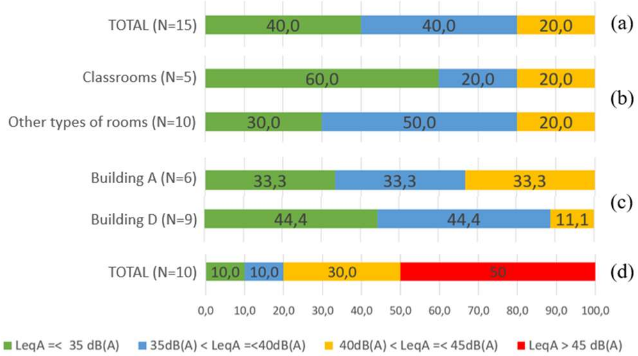

Figure 5: Distribution of noise levels, in dB(A), in core learning spaces: (a) all measured rooms, (b) classrooms vs other types of rooms, (c) rooms in Building A vs rooms in newer Building D. (d) Noise level, in dB(A), in ancillary learning spaces.

Ancillary learning spaces

Ten rooms belonging to the category of ancillary learning spaces were measured during indoor measurement sessions: the cafeteria, the gymnasium, student club rooms (twice), collaborative open spaces (three times), the atrium of Building E where amplified performances occasionally take place (twice), and a large capacity space (enclosed) with speech amplification. Figure 5(d) shows the distribution of sound pressure levels for these ancillary learning spaces, and Figure 6 presents acoustic images taken in some of these spaces. Half of the measured spaces have a noise level below or equal to 45 dB(A). The spaces that exceed this value are: (i) the cafeteria in Building A with 50 dB(A), presumably due to the numerous cooling equipment present (see Figure 6(a)), (ii) the gymnasium with 57 dB(A), due to ventilation (see Figure 6(b)), (iii) a collaborative space in Building D with 56 dB(A), which is located near a cafeteria, and (iv) the atrium of Building E with 48 dB(A), due to the escalator.

Electrical and mechanical rooms

Four electrical rooms, three mechanical rooms, and one server room were measured during the laboratory sessions of the project. The noise level in these rooms (see Table 2) is naturally higher than that in the learning spaces but is not very high according to the Quebec regulations on noise in the workplace [24], where the daily noise exposure limit ($L_{ex,8h}$) is set at 85 dB(A).

Table 2: Noise level in dB(A) in electrical, mechanical, and server rooms.

Type of room	**Number of rooms**	L_{Aeq} **(dB(A))**
Electrical room	4	$58 < L_{Aeq} < 73$
Mechanical room	3	$67 < L_{Aeq} < 69$
Server room	1	57

However, the noises generated in these rooms have a characteristic spectral signature with energy concentrated at certain frequencies, as shown in Figure 7 (see the blue curves in Figures 7(a), 7(b), and 7(c)). These noises are perceived in neighboring rooms (see the red and yellow curves in Figures 7(a), 7(b), and 7(c)), and although they have low amplitude, they can be bothersome to people working in these areas. These noises are primarily “electric hum” generated by transformer cores, characterized by significant acoustic energy at twice the power frequency (2×60 = 120 Hz) and its harmonics. One transformer has been identified as one of the main sources of noise in an electrical room, as shown in Figure 6(c) captured by the acoustic camera. The noise spectra in Figure 7 also exhibit a significant component at 60 Hz (and its harmonics, including 180 Hz), which can be perceived in neighboring rooms.

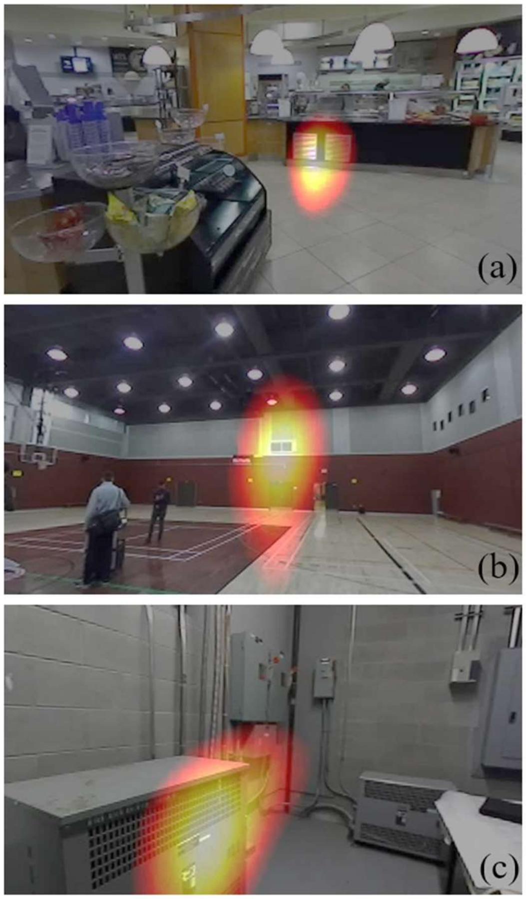

Figure 6: Acoustic images of three rooms: (a) cafeteria of Building A, (b) gymnasium of Building B, and (c) electrical room. The center of the colored spot indicates the position of the dominant acoustic source in the room.

One solution to reduce the noise from these equipments is the use of acoustic enclosures [25]. An enclosure isolates the noisy equipment from the external acoustic environment and should have internally lined absorbent walls to also reduce the acoustic energy within the internal cavity formed by the enclosure. The following section presents an acoustic metamaterial intended to be used as a constituent material for the transformer enclosure. A metamaterial-based solution is preferred because conventional acoustic materials are inefficient in absorbing energy at such low frequencies, here $f <$ 400 Hz.

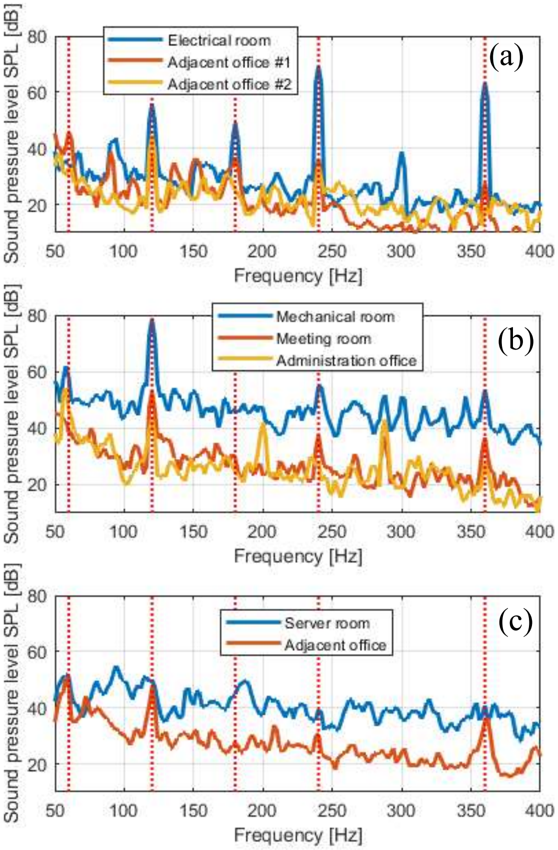

Figure 7: Spectrum of sound pressure levels in dB in (a) an electrical room and two adjacent offices, (b) a mechanical room and two adjacent spaces (a meeting room and an administration office), (c) a server room and an adjacent office. Vertical dashed red lines are placed at frequencies of 60 Hz, 120 Hz, 180 Hz, 240 Hz, and 360 Hz.

4.3 Acoustic metamaterial for noise reduction of electrical transformers

The previous section allowed to identify several frequencies for which the energy of the noise sources in the electrical and mechanical rooms is significant and requires treatment. In particular, the targeted frequencies in this project are: 60 Hz, 120 Hz, 180 Hz, and 360 Hz. The QR has been designed to absorb acoustic energy at a frequency of 120 Hz. For this purpose, its length is set to $L_{\mathrm{QR}} = 702{,}3$ mm (see Eqs. (A3) and (A4) in the appendix). Since the resonator is effective at its fundamental frequency and odd multiples of it, it allows for energy absorption at the frequency of 360 Hz (3×120 Hz). The diameter that provides the best absorption at these two frequencies was determined through a trial-and-error process to be $r_{QR} = 15$ mm.

The absorption of acoustic energy at the other frequencies of 60 Hz and 180 Hz is achieved by the HR. The dimensions of the HR were determined through an optimization process using a genetic algorithm, where the cost function is defined as follows:

$$\varepsilon = \left|f_{pic,1} - 60\right| - \left|f_{pic,i+1} - 180\right| , \qquad (3)$$

where $f_{\mathrm{peak},i}$ is the frequency of the i-th absorption peak. A constraint on the absorption coefficient values of the peaks was set to 0.8. The values of the geometric characteristics of the multi-resonator in Figure 3(b) are indicated in Table 3 below. The only imposed value was that of the wall thickness: $e_{\mathrm{wall}} = 5$ mm.

Table 3: Parameters of the geometry (in mm) of the Helmholtz multi-resonator.

$r_{\mathrm{neck},1}$	$r_{\mathrm{neck},2}$	$h_{\mathrm{neck},1}$	$h_{\mathrm{neck},2}$	$r_{\mathrm{cav},1}$	$r_{\mathrm{cav},2}$	$h_{\mathrm{cav},1}$	$h_{\mathrm{cav},2}$
6	7	7	45	83	72	40	40

A numerical model of the optimized unit cell geometry of the metamaterial is shown in Figure 8. The QR is spirally wrapped to minimize the overall thickness of the material [26]. The arrangement of the two resonators (i.e., QR wrapped around HR) was designed to be 3D printed. This design would help reduce material waste and machining complexity.

Figure 9 represents the absorption coefficient as a function of frequency for the proposed unit cell of the metamaterial. The four absorption peaks occur at the target frequencies, and their amplitudes are above 0.95.

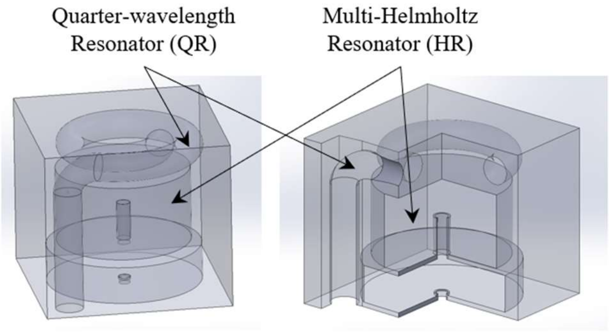

Figure 8: Unit cell of the metamaterial: (a) isometric view, (b) cross-sectional view.

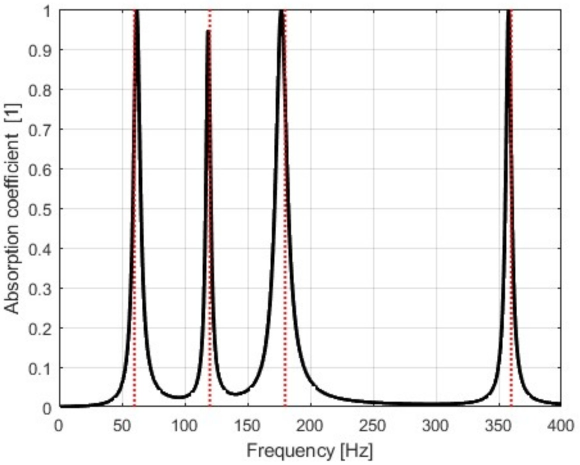

Figure 9: Absorption coefficient of the excited metamaterial under normal incident plane wave. Vertical dashed red lines are placed at frequencies 60, 120, 180, and 360 Hz.

Conclusion

This paper had the main objective of quantifying and assessing the outdoor and indoor noise on the campus of ÉTS in Montreal. All the work was carried out by students enrolled in the "Industrial Acoustics" course (MEC636) at ÉTS as part of their semester project. Their goal was twofold: (i) to apply the theoretical and experimental knowledge they acquired during the course, and (ii) to make their findings useful to the ÉTS community and the residents of the neighborhood.

The first stage of the project involved creating noise maps of the campus and identifying the quietest and noisiest areas. Unsurprisingly, this downtown campus experiences significant noise levels, exceeding the WHO's recommendations (above 55 dB(A)) across most of its surface. Noise levels are higher during the day (before 4:00 PM) due to ongoing construction work in the neighborhood. However, some quieter areas were identified, particularly in the outdoor pedestrian courtyards between buildings and university residences.

The second stage of the project focused on assessing the acoustic quality of various indoor spaces in different campus buildings, such as classrooms, offices, and the library. Generally, the measured classrooms were deemed suitable for learning, with background noise levels below 40 dB(A) and reverberation times below 0.7 s. However, 50 % of the ancillary learning spaces (e.g., gymnasium, cafeteria, atrium, collaborative spaces) exceeded 45 dB(A) and would benefit from acoustic improvements to enhance the acoustic comfort for the student community.

The third and final stage of the project concentrated on the noise from the electrical and mechanical rooms in the campus buildings. These rooms generate noise with characteristic tonal signatures, which can be perceived in adjacent rooms and disturb the personnel working there. One solution is to enclose the noise sources in these rooms. The students in the course used an acoustic camera to locate the main noise sources and designed an acoustic metamaterial specifically for encasing them. Simulation of the proposed metamaterial's acoustic behavior demonstrated its ability to absorb acoustic energy at four frequencies identified as problematic in the measured noise spectra of these rooms and neighboring offices.

This semester project work for the MEC636 course naturally has several limitations that will provide opportunities for future perspectives with other groups of students in the same course. Regarding outdoor measurements, they should be repeated for both studied periods and at various times of the year (only measurements in winter have been conducted so far) to obtain more representative average noise levels. The "NoiseCapture" application [13] is well-suited for this purpose as it is based on a collaborative approach to data production. Furthermore, this tool allows for integrating noise measurement with mobile phones within the course, emphasizing the different mechanisms required to obtain quality measurements with this type of device (e.g., calibration).

The number of measurements is also a limitation in the indoor noise measurement campaign presented in this paper. Longer duration measurements and measurements for more rooms should be conducted in the future. Other indicators could also be calculated and used to analyze the acoustic quality of indoor environments [20, 27]. Subjective measurements through questionnaires could complement the objective measurements taken with microphones, building on advances in research on soundscape characterization and analysis [28-30]. These measurements would help characterize how the campus environments (both outdoor and indoor) are perceived by people and provide better guidance for finding solutions to offer more comfortable acoustic environments. Regarding the metamaterial, it would be necessary to manufacture a cell to experimentally validate the concept and then design an enclosure using multiple cells' tiling to verify its effectiveness *in situ*.

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Appendix: Modeling of the metamaterial resonators using the transfer matrix method.

Wave propagation through air layers, considering visco-thermal dissipation and radiation at the openings.

The propagation of acoustic waves through an air layer of thickness L is considered using the following transfer matrix:

$$T_{air} = \begin{bmatrix} \cos(\tilde{k}_0 L) & j\tilde{Z}_0 \sin(\tilde{k}_0 L) \\ \dfrac{j\sin(\tilde{k}_0 L)}{\tilde{Z}_0} & \cos(\tilde{k}_0 L) \end{bmatrix}, \qquad \text{(A1)}$$

with $\tilde{Z}_0$ the specific impedance of air (Pa.s.m^{-1}), $\tilde{k}_0$ the wavenumber in air. $\tilde{Z}_0$ et $\tilde{k}_0$ are complex and frequency-dependent to account for visco-thermal dissipations in the necks and cavities. For this purpose, the Qunli model [31] is used by calculating the airflow resistivity of the different sections of the duct (e.g., neck, cavity) based on their radius r according to [12]:

$$\sigma_0 = \frac{8\eta}{r^2}, \qquad \text{(A2)}$$

with η, the dynamic viscosity of air (Pa.s).

The radiation at the openings (i.e., HR necks and QR inlet) was taken into account by applying a correction to the geometric length of the air layer that radiates into a larger air space. The length correction is given by:

$$L' = L + n \cdot 0{,}82 \cdot r\,, \qquad \text{(A3)}$$

with n=1 if the layer has only one of its two ends radiating (i.e., QR), or n =2 if both ends radiate (i.e., HR necks).

Quarter-wavelength resonator (QR)

The quarter-wavelength resonator was modeled using an air layer, $T_{\mathrm{QR}} = T_{\mathrm{air}}$, whose corrected length is determined by the target frequency f:

$$L'_{\mathrm{QR}} = \frac{c_0}{4f}, \qquad \text{(A4)}$$

with $f = 120$ Hz and c_0 is the speed of sound in air (m.s^{-1}).

From the transfer matrix T_{QR}, the input impedance of the QR is determined by:

$$Z_{\mathrm{QR}} = \frac{T_{\mathrm{QR},11}}{T_{\mathrm{QR},21}}. \qquad \text{(A5)}$$

Multi- Helmholtz resonator (HR)

Changes in section (CS) in the HR are taken into account using the following matrix:

$$T_{\mathrm{CS}} = \begin{bmatrix} 1 & 0 \\ 0 & \dfrac{S_{\mathrm{s}}}{S_{\mathrm{e}}} \end{bmatrix}, \qquad \text{(A6)}$$

with S_{e}, the surface area of the section upstream of the section change, and S_{s} the surface area of the section downstream of the section change.

Each neck of the HR extends into the cavity. Each cavity has been divided into two parts, delimited by the dashed gray line in Figure 3(b). The parts located before the neck can be considered as quarter-wavelength resonators of length $(h_{\mathrm{neck},i} - e_{\mathrm{wall}})$ (with i=1,2 for cavities 1 and 2). These resonators, located in parallel with respect to the propagation direction within the thickness of the HR, have been modeled using the following matrix:

$$T_{\mathrm{res},i} = \begin{bmatrix} 1 & 0 \\ \dfrac{1}{Z_{\mathrm{res},i}} & 1 \end{bmatrix}, \qquad \text{(A7)}$$

with $Z_{\mathrm{res},i}$ the acoustic input impedance of each quarter-wave resonator in cavities $i = 1{,}2$, and which is given by the following expression:

$$Z_{\mathrm{res},i} = \frac{Z_0}{j\tan\left(k_0\left(h_{\mathrm{col},i} - e_{\mathrm{paroi}}\right)\right)}. \qquad \text{(A8)}$$

The total transfer matrix of the HR is given by:

$$T_{\mathrm{multi}} = T_{\mathrm{air},1} \cdot T_{\mathrm{CS},1} \cdot T_{\mathrm{res},1} \cdot T_{\mathrm{CS},2} \cdot T_{\mathrm{air},2} \cdot T_{\mathrm{CS},3} \cdot T_{\mathrm{air},3} \cdot T_{\mathrm{CS},4} \cdot T_{\mathrm{res},2} \cdot T_{\mathrm{CS},5} \cdot T_{\mathrm{air},4}\,. \qquad \text{(A9)}$$

The calculation of the transfer matrix T_{multi} of the HR allows to find its input impedance from its components T_{11} and T_{21}, according to:

$$Z_{\mathrm{HR}} = \frac{T_{11-\mathrm{multi}}}{T_{21-\mathrm{multi}}}. \qquad \text{(A10)}$$

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