



# A mobile reverberation cabin for acoustic measurements in an existing anechoic room

Elsa Piollet, Simon Laroche, Marc-Antoine Bianki, Annie Ross

## ► To cite this version:

Elsa Piollet, Simon Laroche, Marc-Antoine Bianki, Annie Ross. A mobile reverberation cabin for acoustic measurements in an existing anechoic room. Inter-Noise 2016, Aug 2016, Hambourg, Germany. hal-01391681

**HAL Id: hal-01391681**

**<https://hal.science/hal-01391681>**

Submitted on 3 Nov 2016

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## A mobile reverberation cabin for acoustic measurements in an existing anechoic room

Elsa PIOLLET<sup>1</sup>; Simon LAROCHE<sup>2</sup>; Marc-Antoine BIANKI<sup>3</sup>; Annie ROSS<sup>4</sup>

<sup>1,2,3,4</sup> Ecole Polytechnique de Montreal, Canada

### ABSTRACT

Large reverberation rooms are generally prescribed for the acoustic characterization of materials. Diffuse-field absorption properties are measured in a reverberation room, while transmission loss properties can be measured between a reverberation source room and an anechoic receiving room. The large volumes needed (ASTM standards require 80 m<sup>3</sup>) make the building of such rooms impractical, and transforming existing anechoic rooms in transmission suites is generally impossible.

In the present work, a mobile reverberation cabin is developed and placed inside an existing anechoic room for acoustic material characterization. Light materials (plywood and wood) are chosen to enable easy assembly, disassembly and transportation of the cabin. An external thick layer of open-cell foam is used in order to maintain the anechoic properties of the surrounding room. The interior dimensions of the cabin are taken from a similar design in the existing literature: no walls are parallel, and the interior volume of the cabin is less than 1 m<sup>3</sup>. The sound field measured inside the lightweight mobile cabin is presented, and a lower frequency limit is determined for its diffuse field behavior. A procedure for the characterization of acoustic samples in absorption and transmission loss is defined, and validated with known materials.

Keywords: Sound, Experimental, Transmission I-INCE Classification of Subjects Number(s): 73.6 (See <http://www.inceusa.org/links/Subj%20Class%20-%20Formatted.pdf>.)

### 1. INTRODUCTION

Acoustic materials are used mainly for their absorption or transmission loss properties. Absorption relates to the capacity of the material to dissipate acoustical energy, and thus to reduce sound levels inside a room or a cavity. Transmission loss relates to the ability to prevent the transmission of sound between two rooms or cavities.

Two main types of laboratory set-ups are generally used to determine absorption and transmission properties of materials. On one hand, impedance tubes can be used to determine these properties under a normal incident sound field (1, 2). On the other hand, large reverberation rooms can be used to determine these properties under a diffuse incident sound field (3-5). The advantage of the diffuse-field measurements is the fact that diffuse field is more representative of usual real-life sound fields. Moreover, structural effects can be observed with a reverberation room set-up, whereas impedance measurements are limited to small samples which do not allow structural vibrations. However, to obtain diffuse fields, large facilities must be used. ASTM E90 and ASTM E2249 recommend a room volume of 80 m<sup>3</sup> (4, 5), while ASTM C423 recommends a minimal volume of 125 m<sup>3</sup> (3).

In the present work, transmission loss measurements have to be made in a laboratory which possesses an anechoic room, but no reverberation room. Building a full-scale reverberation room is impossible both for space and cost considerations. Thus, the objective of the present work is to develop a set-up for transmission loss measurements by installing a small-scale mobile reverberation chamber inside the existing anechoic room. The internal dimensions are taken from the literature (6). Materials

---

<sup>1</sup> elsa.piollet@polymtl.ca

<sup>2</sup> simon.laroche@polymtl.ca

<sup>3</sup> marc-antoine.bianki@polymtl.ca

<sup>4</sup> annie.ross@polymtl.ca

are chosen to ensure the mobility of the chamber. Characterization of the reverberation chamber and anechoic room are presented, and transmission loss properties of aluminium plates are measured.

The paper is organized as follows. Section 2 describes the design of the mobile chamber, based on the existing literature and the present constraints. Section 3 presents the characterization of the mobile chamber. Section 4 presents the analysis of the sound field in the anechoic room with the mobile chamber. Finally, section 5 shows the first transmission loss measurements made with the set-up for aluminum plates.

## 2. DESIGN OF THE MOBILE CHAMBER

### 2.1 Set-up principle

The proposed set-up is based on the measurement of sound transmission loss using sound intensity, as described in standards ASTM E2249 (4) among others. Figure 1(a) illustrates the principle of the full scale set-up. The test specimen is placed between a reverberation source room and an anechoic receiver room. In the reverberation room, the sound field is diffuse: the sound pressure level is uniform across the room. In the anechoic room, the sound field is free: for a point source, the sound pressure level theoretically decreases by 6 dB each time the distance from the source is doubled.

In the present paper, an alternative set-up is proposed. The laboratory already possesses an anechoic room. A mobile reverberation chamber is placed inside the anechoic room, as described on Figure 1(b). The mobile chamber acts as the reverberation source room. Thus, it must be designed to achieve a diffuse sound field, and the frequency range of validity must be analyzed, as will be described in the following sections.

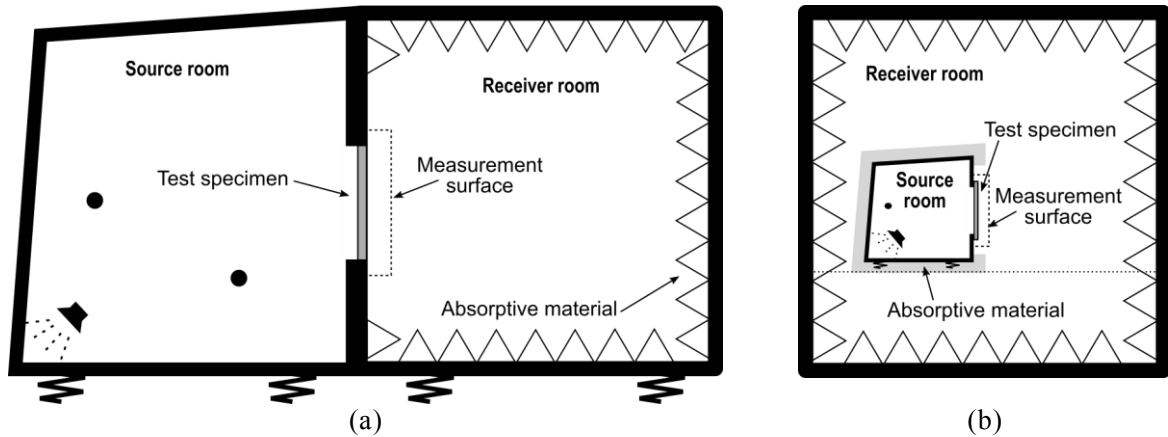


Figure 1 –Transmission loss set-ups with five-sided box measurement surface: (a) ASTM E2249, and (b) proposed configuration

The sound transmission loss ( $TL$ ) through a panel is defined as the ratio between the incident sound power  $W_i$  and the transmitted sound power  $W_t$ :

$$TL = 10 \log_{10} \frac{W_i}{W_t} \quad (1)$$

With a reverberation source room, the incident sound power is obtained by measuring the average sound level in the source room at several locations with fixed or moving microphones, and by writing:

$$W_i = S_s I_i = S_s \left( \frac{\langle p^2 \rangle}{4\rho_0 c} \right) \quad (2)$$

where  $S_s$  is the surface area of the sample,  $I_i$  is the incident sound intensity on the sample,  $\langle p^2 \rangle$  is the spatial and time average of the pressure in the reverberation room,  $\rho_0$  is the air density and  $c$  the speed of sound in the air.

The receiver room being anechoic, a measurement surface is defined to enclose the tested sample (see dotted lines in Fig. 1(a) and (b)). The transmitted power is obtained from the average normal intensity measured on this surface:

$$W_t = S_m \bar{I}_n \quad (3)$$

where  $S_m$  is the measurement surface area and  $\bar{I}_n$  is the measured normal intensity.

## 2.2 Design constraints for the mobile chamber

### 2.2.1 Acoustic field inside the chamber

In order to use the set-up as a transmission suite with a reverberation source side and an anechoic receiver side, the source acoustic field should be diffuse to ensure the validity of Equation (2). In a diffuse field, the sound level is constant with respect to the position, and measurements made at different locations are representative of the pressure incident on the sample. Achieving a diffuse field, however, depends on the characteristics of the room.

Indeed, the response of a room to acoustic excitation is a superposition of its acoustic modes. When one mode only is excited, the pressure follows strong spatial variations across the room.

In order to obtain a more homogeneous pressure distribution in the room, several modes have to be excited simultaneously. The modal density in rooms increases with frequency, causing modes to overlap: hence, a diffuse sound field can be obtained. Different definitions of the cut-off frequency between modal and diffuse behaviors can be found in the literature (7). However, the most widely used is the so-called Schroeder frequency given by:

$$f_{sch} = 2000 \sqrt{\frac{T_{60}}{V}} = 2000 \sqrt{\frac{0.163}{S\bar{\alpha}}} \quad (4)$$

where  $V$  is the volume of the room,  $T_{60}$  is the reverberation time, or the time taken for a sound in the room to decrease by 60 dB,  $S$  is the total area of the walls, and  $\bar{\alpha}$  is the average absorption coefficient of the walls (8). The second expression is obtained using Sabine's theory, which implies that a low value of  $\bar{\alpha}$  is assumed.

As illustrated by this equation, room dimensions are an important factor in the cut-off frequency. For small rooms, the modal behaviour is dominant up to frequencies higher than for large rooms.

For small-scale room, the frequency range below the Schroeder frequency is large and optimizing the spectrum in this range is crucial. The modal frequencies should be as uniformly spaced as possible, preventing gaps and overlaps of modes (6).

To achieve a diffuse field, absorption at the walls should also be as low as possible, to minimize energy loss (7). However, this will actually increase the Schroeder frequency of the room.

### 2.2.2 Use inside an anechoic room

The chamber has to be placed inside the anechoic room. This limits the chamber dimensions in two ways. First, the chamber has to be smaller than the anechoic room so that it can be placed inside it. Secondly, and more importantly, the acoustic field in the anechoic room should not deviate significantly from a free field after inserting the mobile chamber. This limits further the size of the reverberation chamber. The dimensions of the present anechoic room, from the tips of the anechoic wedges, are 4,3 x 4,6 x 3,5 m, and the chamber external dimensions must be considerably smaller than these dimensions. Acoustical reflections on the chamber should also be minimized, which constrains the materials used outside of the chamber.

Moreover, as other experimental measurements are regularly performed in the anechoic room, the chamber has to be easily installed and removed. This means that the chamber should either be very small and light, or should be composed of independent small and light parts, easily assembled and disassembled. A mass limit of 30 kg is set so that one or two people can manage the parts without external help.

Finally, when testing the transmission properties of samples, sound power should be transmitted mainly through the tested sample and not through the chamber walls, which should therefore exhibit high transmission loss.

### 2.2.3 Compromises

It can be observed that the constraints on the size of the chamber are in contradiction with the constraints on its acoustical field. First, the chamber should be as small as possible to reduce its impact on the anechoic room, while it should also be as large as possible to ensure a diffuse field for frequencies as low as possible. Secondly, designing a lightweight chamber for mobility reduces the maximum achievable transmission loss through the walls, and implementing removable parts assembly instead of a single consolidated body increases the risk of acoustic leaks.

These opposing design constraints have led to compromises in the final design, and careful testing

of the chamber must be performed to ensure acoustical constraints are met.

## 2.3 Final design of the mobile chamber

### 2.3.1 Dimensions

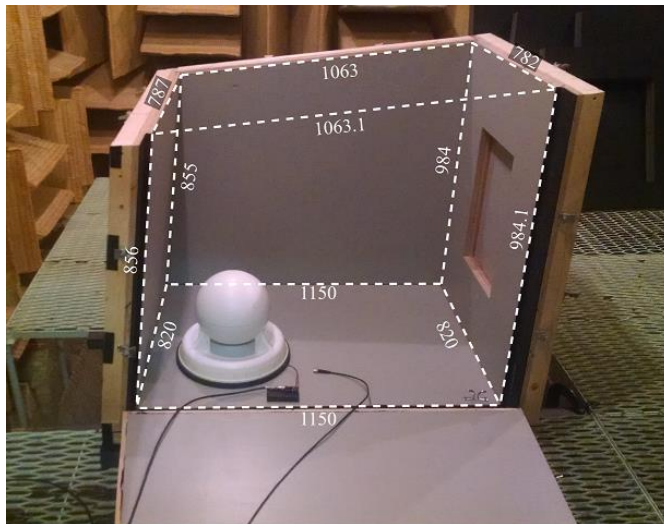
Several small-scale reverberation chamber designs were found in the literature (6, 9, 10). Unfortunately, in most publications, either the dimensions are not stated or sufficient background on the choice of the dimensions is not provided.

A detailed study of a small scale cabin has been made recently by Vivolo (6), providing strong theoretical and experimental justifications for the cabin dimensions:

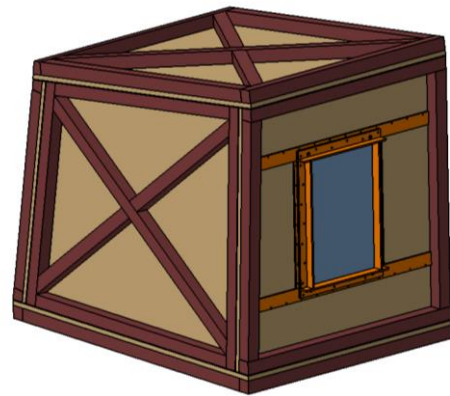
- First, dimension ratios leading to the most uniform modal frequency distribution are chosen: 1 x 1.2 x 1.4, selected from the work of Blaszak (11) and from numerical simulations.
- Secondly, no two walls are parallel, in order to increase the uniformity of the distribution.

The present set-up uses the exact same internal dimensions, shown in Figure 2(a) on a photograph of the set-up during assembly. All dimensions are comprised between 780 mm and 1170 mm. The final internal volume is 0.8 m<sup>3</sup>.

There is one major difference between the two set-ups: the initial cabin was placed in an ordinary laboratory room with no special acoustic treatment, whereas here the surrounding room is anechoic. This leads to differences in the choice of materials, and in the measurement methods as described in the following sections.



(a)



(b)

Figure 2 – Design of the reverberation chamber: (a) actual chamber during assembly with internal dimensions in millimeters, and (b) computer model showing plywood walls (beige), wood reinforcements (brown), sample (grey) and steel frame (orange).

### 2.3.2 Choice of materials

In order to comply with the weight constraint described in section 2.2, plywood and wood are chosen as the main materials. The walls are made with two layers of plywood of 19.1 mm (3/4 in.) each, and are stiffened with wood. The same type of materials was used by Tsui (9) for a similar small scale reverberation chamber. The mass of each wall is comprised between 24 kg and 30 kg. The inner face the walls are painted with epoxy paint in order to limit surface porosity and acoustic absorption. The chamber materials are presented on Figure 2(b).

For easy assembly and disassembly, hinges are used to fasten the side walls with the chamber floor. Clamps are used to secure the side walls together and with the ceiling. All these links can be easily removed by hands. Rubber seals are bonded on the side of the walls to ensure that the chamber is airtight, and to limit coupling between the walls.

Figure 3 presents the final chamber placed inside the anechoic room. The chamber is covered with a rubber coated fabric layer topped with a 76.2 mm (3 in.) polyurethane foam to limit reflections. Velcro patches are sewn to the absorptive treatment to allow easy installation and removal. The exterior dimensions of the chamber are 1.1 x 1.4 x 1.3 m<sup>3</sup>. The volume occupied by the chamber is therefore 3% of the free volume in the anechoic room.

Apart from ergonomic considerations, the use of common materials also simplifies the manufacturing of the chamber.

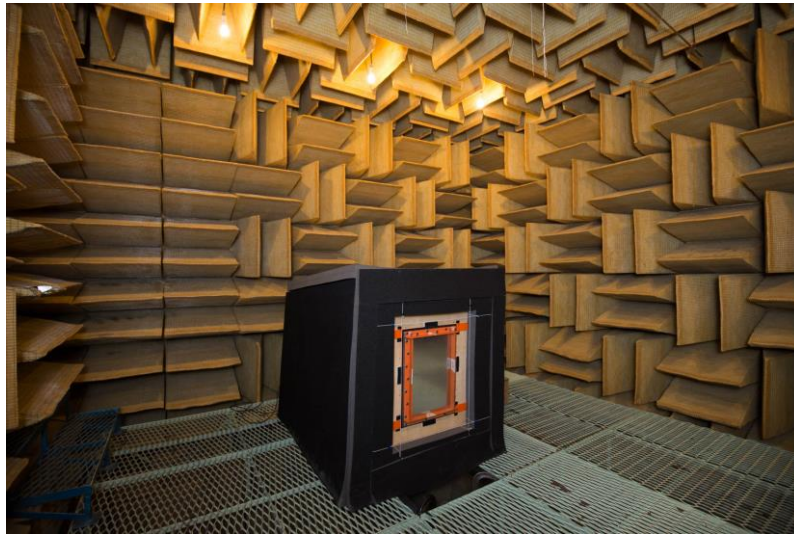


Figure 3 – Final reverberation chamber inside the anechoic room.

### 2.3.3 Sample dimensions and boundary conditions

The dimensions of the aperture for the samples is 330.2 mm x 495.3 mm (13 in. x 19.5 in.). A 6.35 mm (1/4 in.) thick steel frame is screwed to the front wall to serve as a rigid support for clamping. The samples are clamped with 26 screws with a 6.8 N·m (60 lb·in) torque, the clamping force being spread on the whole periphery of the samples using steel angles. A thin 1.59 mm (1/16 in.) rubber seal is inserted to prevent sound leaks between the steel frame and the sample. Both frame and angles can be seen on Figure 2(b) and Figure 3, in orange. To ensure the durability of the threads and the repeatability of the clamping process, steel inserts are placed inside the wood front wall.

## 3. CHARACTERIZATION OF THE CHAMBER

### 3.1 Excitation and measurement methods

The characterization aims at determining two main properties of the chamber:

- The spatial variation of the sound field in the chamber, and the frequency at which a diffuse field is obtained.
- The average absorption coefficients of the walls.

A commercial loudspeaker is used as the acoustical source for the following tests. The source can be seen on Figure 2(a) and Figure 4. A loudspeaker is directed towards the floor and a diffuser redirects the sound. The directivity of the source is analyzed in section 4.2. The commercial specifications give a useful frequency range of 100 Hz to 20 kHz with a tolerance of  $\pm 10$  dB.

A third-octave band white noise signal with a given root-mean-square voltage is sent to the source, starting from the 160 Hz third octave frequency band up to the 8000 Hz frequency band. Thus, the tests span over a frequency range of 140.3 Hz to 8979.4 Hz. Since the first resonant frequency of the chamber is 154 Hz (6) (predicted numerically for infinitely rigid walls), measurements below 140 Hz are of little interest for the characterization.

Measurements are performed at 27 locations inside the chamber. A horizontal grid with 9 microphone positions is translated vertically to achieve the 27 locations, as illustrated on Figure 4.

The chamber is closed by using a 19.1 mm (3/4 in.) plywood sample.

Prior to the characterization, verification is made that the chamber is airtight, and all local leaks are sealed.



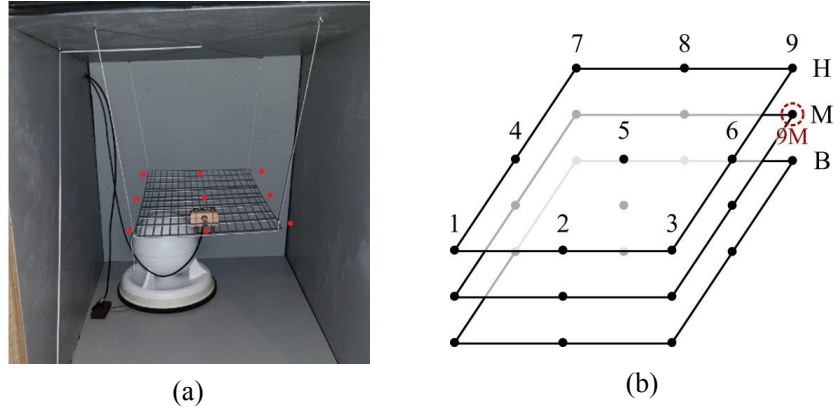


Figure 4 – Microphone positions in the reverberation chamber: (a) grid at the lower position and (b) grid high (H), medium (M) and low (B) positions, with position used for transmission loss testing highlighted (microphone 9M)

### 3.2 Spatial variations of the sound field

Five 6-second measurements are made at each microphone location, and the levels are averaged. Figure 5 shows the results for the 18 third octave bands measured. Large variations in the levels measured at the 27 positions can be observed at low frequencies; however, the variations decrease with increasing frequency, as the modal density in each third octave band increases.

Variations of the space averaged level throughout the spectrum can also be observed in Figure 5 (thick blue line), which can be explained by acoustic coupling between the sound source and the cavity.

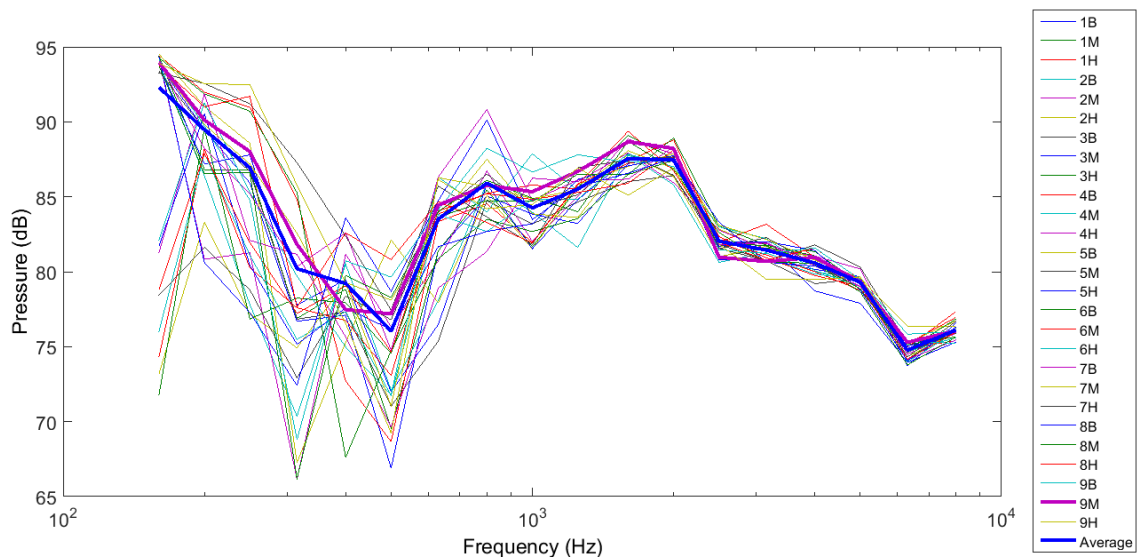


Figure 5 – Third octave sound pressure level measured at each of the 27 microphone locations. Thick blue line: average sound pressure level. Thick purple line: selected representative microphone.

Figure 6 shows the standard deviation of the levels measured by the 27 microphones. The black line shows the limits prescribed by ISO-3471 (6), and the dotted line shows a 1 dB limit. The standard deviation is below 1 dB from the 1600 Hz third octave frequency band and higher, and below the ISO limits from the 3150 Hz third octave frequency band. This is fully consistent with the results found by Vivolo (6) for similar dimensions and different materials.

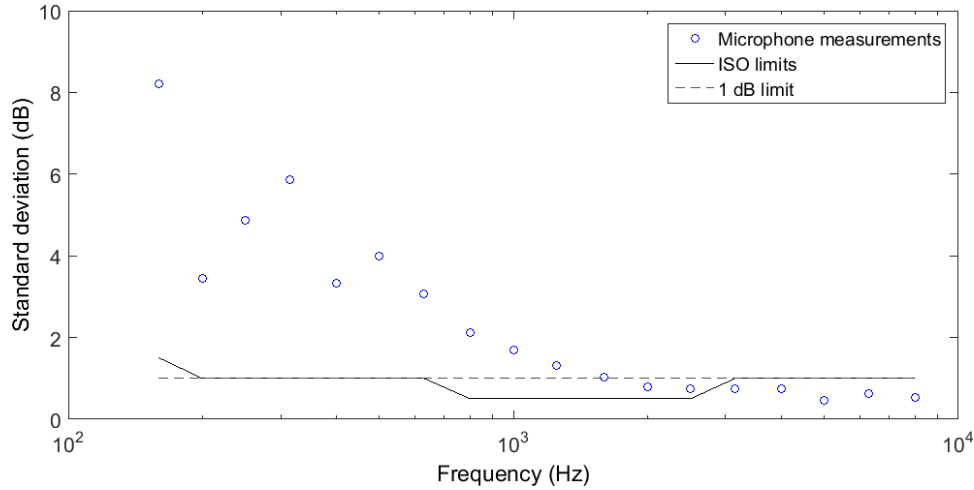


Figure 6 – Standard deviation of the sound pressure levels measured at the 27 microphone positions

Because measurements at 27 locations either require a large number of microphones or are very time-consuming, a limited number of locations have to be selected for material testing. In the present paper, one location is selected, where the measured sound pressure level is very close to the average in the chamber. The sound pressure level at the selected location is represented as a thick purple line on Figure 5. The corresponding position (9M) is highlighted on Fig 5. In the preliminary transmission loss testing presented in section 5, this microphone location will be used to determine the sound power incident on the sample. Future work will determine other locations that could give a view of the modes in the lower frequency range.

### 3.3 Wall absorption

The reverberation time method is used to determine the average absorption coefficient of the walls. A white noise is emitted and stopped for each third octave band, and the decay rate for a 25 dB drop is used to obtain the absorption, as described by standard ASTM C423 (3).

Figure 7 shows the absorption obtained from measurements made at the 27 microphone locations. Again, the results vary slightly (less than 0.05) with the locations at low frequency, and increasing homogeneity in the results is found with increasing frequency (variations within 0.01 above 1600 Hz). The average absorption coefficient (thick blue line on Figure 7) ranges between 0.04 and 0.07 for the entire frequency range. Microphone 9M selected for sound pressure level (thick purple line on Figure 7) also gives an absorption coefficient close to the average value.

The average over all third octave frequencies is 0.05, and is the same when averaging from the 1600 Hz third octave frequency band up to the 8000 Hz frequency band.

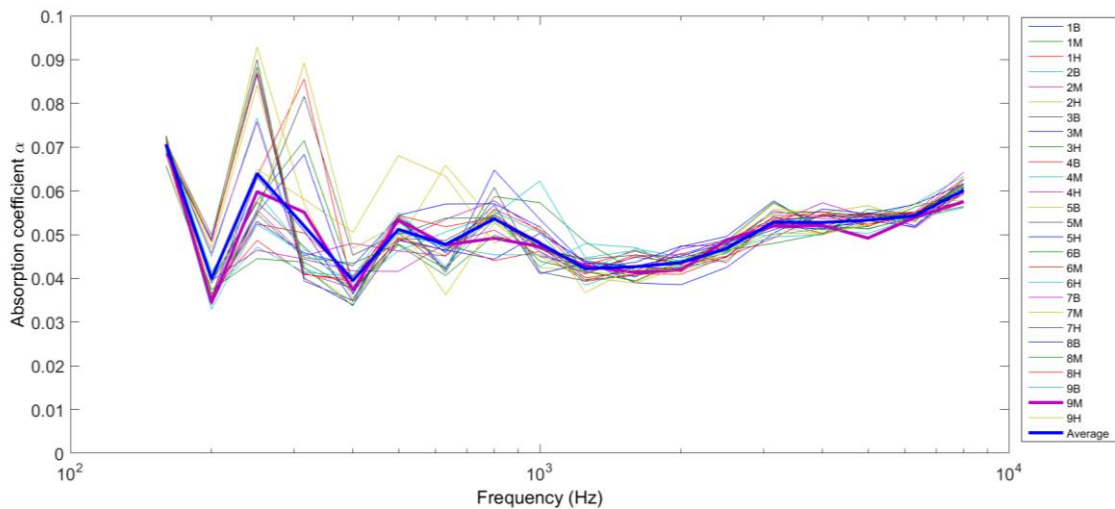


Figure 7 – Third octave absorptions coefficients obtained from measured decay rates at the 27 microphone locations. Thick blue line: average absorption. Thick purple line: selected representative microphone.



### 3.4 Discussion

The sound pressure level homogeneity is totally consistent with results obtained by Vivolo (6). The absorption of the walls (0.05) is greater than what was obtained by Vivolo with reinforced concrete walls (0.01), as could be expected, but it is consistent with results obtained by Tsui for similar wall materials (9). Standard ASTM C423 requires that the average absorption coefficient of the room surfaces be less than or equal to 0.05 for third octave bands from 25 Hz to 2500 Hz, and less than or equal to 0.1 below 250 Hz and above 2500 Hz bands (3).

Using Schroeder's formula, the theoretical cut-off frequency of the reverberation chamber is 1553 Hz, compared to 3200 Hz for concrete walls in the case of Vivolo (6). Nevertheless, the observed standard deviation between microphones is totally consistent in the two cases. This can be interpreted as a difference between the behavior of small cavities and large rooms.

Based on both the Schroeder formula and the standard deviation analysis, the acoustic field is considered to be diffuse starting from the 1600 Hz third octave band for this chamber.

## 4. CHARACTERIZATION OF THE SOUND SOURCE AND ANECHOIC ROOM

### 4.1 Objectives

This part presents a preliminary analysis of the acoustic field in the anechoic room after the reverberation chamber has been put inside it. The procedure is based on Annex A of standard ISO 3745 (12). The standard requires the use of an omnidirectional source (equal sound intensity in all directions). However, for the preliminary testing presented here, a commercial source is used. The source is the one that is used inside the reverberation chamber for all other measurements presented in this paper.

This test is divided in two sections: the evaluation of the directivity of the source and the characterization of the anechoic room.

### 4.2 Sound source directivity

Sound pressure level was measured at 1.0 m from the source for the following angles: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° parallel to the ground for all of the following angles perpendicular to the ground: 20°, 40°, 60°, 80°, 100°, 120°, 140° and 160°. This gives 64 positions all around the source. The standard specifies a measurement distance of 1.5 m, but this was reduced to 1 m in the present test for space considerations. The levels are obtained on 3-second measurement for each third octave frequency band of interest. Figure 8 shows the sound pressure level on a vertical plane around the source for 160 Hz, 1000 Hz and 8000 Hz third octave bands. As can be observed, the source is omnidirectional at low frequencies, and becomes more directional at higher frequencies in a vertical plane. Horizontally, the source is found to be omnidirectional.

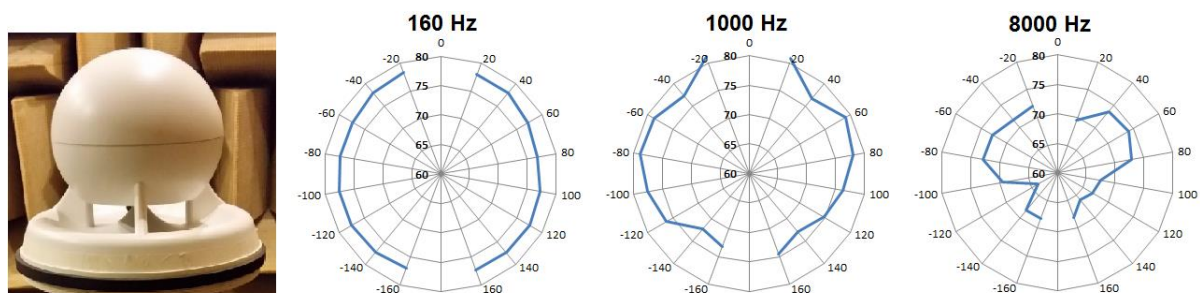


Figure 8 – The commercial source and its vertical directivity for three third octave bands

As the source is not omnidirectional for all frequencies, the results of the measurements in the anechoic room will have to be considered carefully. However, with the diffuser placed in front of the loudspeaker, the source does emit in all direction (although not equally). Therefore, for its use in the reverberation chamber, the source will be placed in a corner to increase reflections.

### 4.3 Anechoic room characterization

Assessment of the anechoic room requires taking pressure level measurements along 5 axes starting from the source with a minimum of 10 measurement points per axis and a maximum of 0.1 m between

the positions along the axis (12). Therefore, microphone distance from the source ranges from 0.5 m to 1.4 m. In addition, the standard specifies that 4 of the 5 axes be directed toward the upper corners of the room. Since the aim is to assess the impact of the reverberation chamber on the sound field, the fifth axis is directed towards the chamber. Figure 9 illustrates the 5 axes.

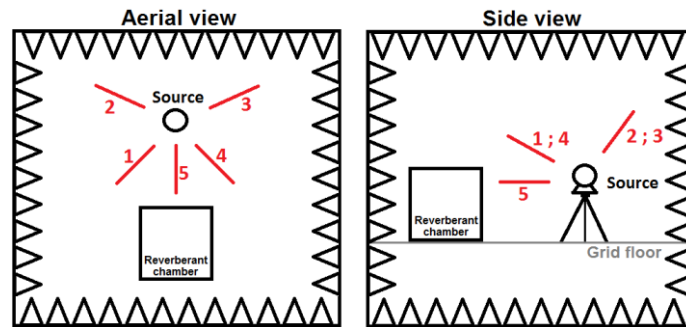


Figure 9 – Axes positions for anechoic room qualification.

The inverse square law stipulates that in a free field, sound pressure level decreases by 6 dB at each doubling of the distance from the source. The pressure levels calculated with the inverse square law and the experimental measurements are compared for each third octave band between 160 Hz and 8000 Hz. The allowable deviations are presented in Table 1. Figure 10 shows percentage of values that comply with the standard for each measured axis. The column numbers refer to the axes numbers identified in Figure 9.

Table 1 – Allowable deviations for room qualification from ISO 3745 (12)

Third octave band (Hz)	Allowable deviations for room qualification (dB)
$\leq 630$	$\pm 1,5$
800 to 5000	$\pm 1,0$
$\geq 6300$	$\pm 1,5$

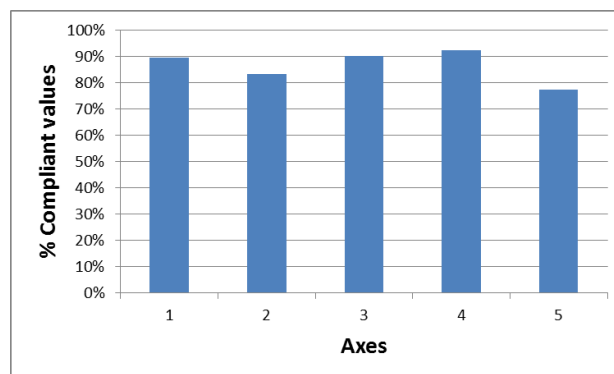


Figure 10 - Percentage of measured sound pressure levels that comply with the inverse square law according to allowable deviations in Table 1. Axes as described on Figure 9.

As can be observed for axes 1, 3 and 4, 90% of the measurements for all third octave bands are compliant to the standard. Axis 2 shows a result of 83%, slightly below the other top corners of the room. This can be explained by a ventilation hatch placed in this corner which could cause reflections of the sound field.

The result obtained on the fifth axis, towards the reverberation chamber, is lower than for the other axes, with 77% of the measurements in agreement with the inverse square law. This shows that the enclosure does indeed have an impact on the anechoic room acoustic field. While foam was added around the enclosure, its thickness is only 76.2 mm (3 in.), making it inefficient to absorb low

frequencies. Indeed, foam is not effective for wavelengths larger than four times its thickness (8). Therefore, low frequency waves reflect on the reverberation chamber walls and come back to disrupt the free field, without being completely absorbed by the foam.

As this was a preliminary characterization, one 3-second measurement was made for each frequency band and each position. Averaging over more measurements may reduce some of the observed discrepancies and help identify the cause for some other discrepancies. On the other hand, measurements in the anechoic room without the enclosure could also allow identifying intrinsic limitations, and correcting them. Ways to reduce the impact of the chamber on the acoustic field will also have to be identified.

## 5. TRANSMISSION LOSS MEASUREMENTS

### 5.1 Method and materials

The measurement method in ASTM E2249 standard (4), as described in section 2.1, was adapted to the present set-up. For each third octave frequency band of interest, white noise is emitted in the reverberation chamber. Sound pressure level is measured with one microphone only for these preliminary testing. The microphone position is 9M, as highlighted on Figure 4.

On the receiver side, sound intensity is measured over a five faced measurement surface enclosing the sample, as described on Figure 11. Intensity is measured with a p-p intensity probe (two facing microphones). One scanning path is used for the sides, and two perpendicular scanning paths are used for the front face, as proposed in the standard (4). Scanning is done by hand. The difference between the average levels obtained for the two scanning paths is below 1 dB as requested by the standard, which confirms the validity of the measurement.

Two sample configurations are tested. First, one aluminum plate of 3.1 mm (1/8 in.) thickness is tested. Then, two separate aluminum plates of 3.1 mm (1/8 in.) thickness each are tested together.

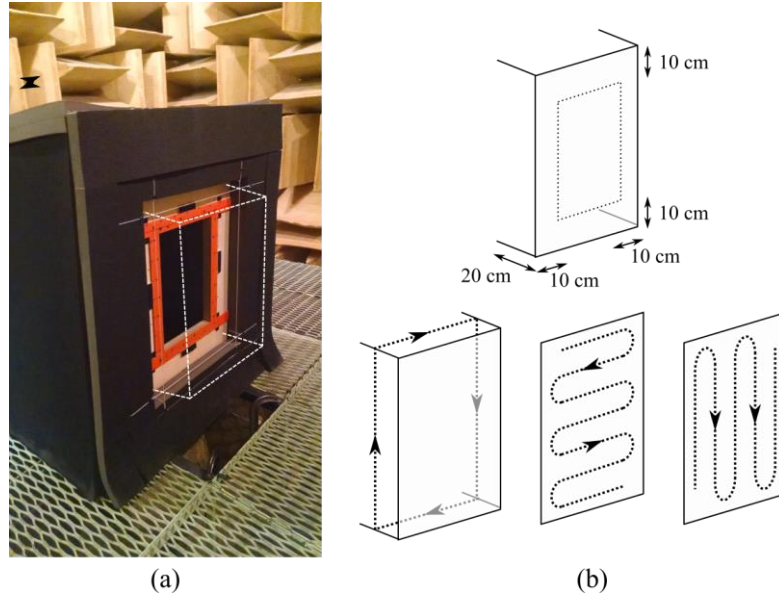


Figure 11 – Five faced measurement surface enclosing the sample aperture: (a) Position relative to the chamber. (b) Dimensions and scanning paths (dotted line).

### 5.2 Results

Figure 12 shows the measured transmission loss for the two tested configurations. The results are compared with a model for plate transmission loss under diffuse field proposed by Fahy (13):

$$\begin{aligned}
 TL &= 10 \log_{10} \frac{1}{\tau_d} & \tau_d &= \int_0^{\frac{\pi}{2}} \tau(\phi) \sin 2\phi \, d\phi \\
 \tau(\phi) &= \frac{1}{\left[ \left( 1 + \frac{\omega m''}{2\rho_0 c} \cos \phi \left( \frac{k}{k_b} \right)^4 \eta \sin^4 \phi \right)^2 + \left( \frac{\omega m''}{2\rho_0 c} \cos \phi \left( 1 - \frac{k}{k_b} \sin^4 \phi \right) \right)^2 \right]} & (5)
 \end{aligned}$$

where  $\tau_d$  is the transmission coefficient for a diffuse field,  $\tau(\phi)$  is the transmission coefficient for a given incidence angle  $\phi$ ,  $\omega = 2\pi f$  is the circular frequency,  $m''$  is the plate surface mass,  $\rho_0$  is the air density,  $c$  is the speed of sound in air,  $k = \omega/c$  is the wavenumber in air,  $k_b$  is the wavenumber in the plate,  $\eta$  is the structural loss factor of the plate.

In the present simulation,  $\eta = 0$ . In further work, fitting the curves will allow identifying the actual value of  $\eta$ .

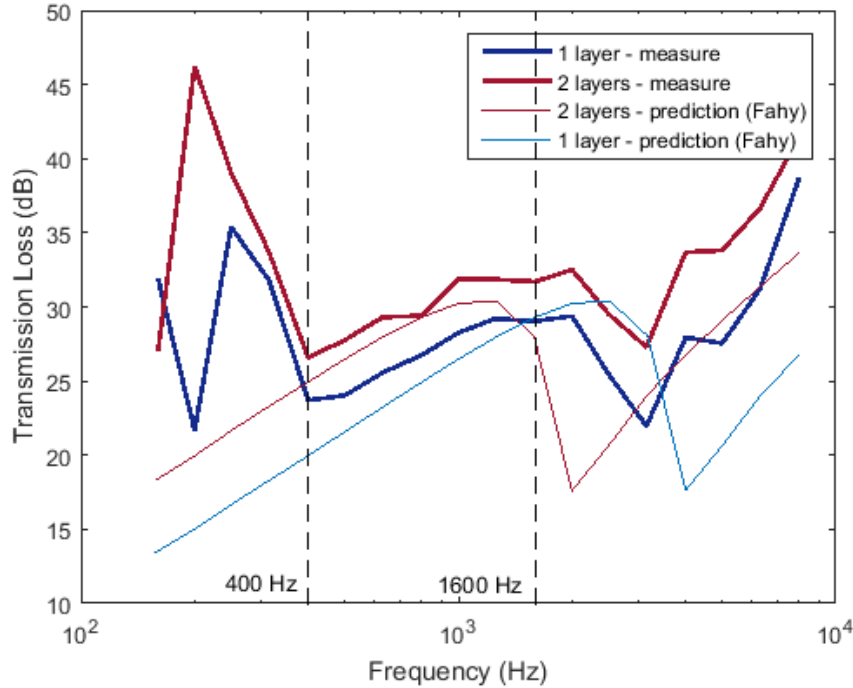


Figure 12 – Transmission loss of one and two aluminum plates of thickness 3.1 mm each

Good agreement of the levels and slope is obtained for third octave frequency bands as low as 400 Hz, even though a diffuse field in the chamber occurs only from the 1600 Hz frequency band. This good result will be confirmed by further testing.

The fact that the two configurations lead to the same coincident frequency (dip in transmission loss observed around 3000 Hz) is easily explained by the fact that two non-laminated plates are tested, while the model predicts the response for a thicker 6.2 mm plate. However, the discrepancy between the theoretical and measured coincidence frequencies of the one-layer plate has yet to be explained.

## 6. CONCLUSIONS

A new set-up consisting of a small-scale reverberation chamber in an existing anechoic chamber was developed. The set-up allows measurement of the sound transmission loss properties of plates with the sound intensity method. The internal dimensions were taken from the literature. The chamber was built from six independent plywood and wood panels to ensure an easy assembly and disassembly. The characterization of the chamber showed excellent agreement with the literature. A diffuse field starting from the 1600 Hz third octave frequency band was obtained. The acoustic field in the anechoic room with the reverberation chamber was analyzed, and a non-negligible deviation from free field was observed. Future work is needed to identify the causes and reduce the discrepancies.

Transmission loss measurements made with one and two aluminum plates showed that the set-up can be used for third octave bands as low as 400 Hz.

## ACKNOWLEDGEMENTS

This work is funded by a NSERC Collaborative Research and Development Grant and Elasto Proxy. The authors wish to thank Elasto Proxy for their collaboration, and more specifically Philippe Grenier for building the reverberation chamber.

## REFERENCES

1. ASTM International. ASTM Standard E1050 - 12 "Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones and a Digital Frequency Analysis System". 2012.
2. ASTM International. ASTM Standard E2611-09 "Standard Test Method for Measurement of Normal Incidence Sound Transmission of Acoustical Materials Based on the Transfer Matrix Method". 2009.
3. ASTM International. ASTM Standard C423 - 09a "Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method". 2009.
4. ASTM International. ASTM Standard E2249 - 02 "Standard Test Method for Laboratory Measurement of Airborne Transmission Loss of Building Partitions and Elements Using Sound Intensity". 2002.
5. ASTM International. ASTM Standard E90-09 "Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Standard". 2009.
6. Vivolo M. Vibro-acoustic characterization of lightweight panels by using a small cabin. Ph.D. dissertation. 2013.
7. Hasan MM. Diffuse Sound Fields, Reverberation-Room Methods and the Effectiveness of Reverberation-Room Designs. Master's thesis. 2015.
8. Müller G, Möser M. Handbook of Engineering Acoustics: Springer; 2013.
9. Tsui CY, Voorhees CR, Yang JCS. The design of small reverberation chambers for transmission loss measurement. *Applied Acoustics*. 1976;9(3):165-75.
10. Carlisle EJ, Hooker RJ, editors. Small Chamber Reverberant Absorption Measurement. *Proceedings of ACOUSTICS*; 2004.
11. Blaszk MA. Acoustic design of small rectangular rooms: Normal frequency statistics. *Applied Acoustics*. 2008;69(12):1356-60.
12. International Organization for Standardization. ISO 3745:2012 - Acoustics -- Determination of sound power levels and sound energy levels of noise sources using sound pressure -- Precision methods for anechoic rooms and hemi-anechoic rooms. 2012.
13. Fahy FJ, Gardonio P. Sound and structural vibration: radiation, transmission and response: Academic press; 2007.