On the damping of room resonances with electroacoustic absorbers in the low frequency range

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Summary

In closed spaces, standing waves occur at low frequencies, thus creating annoying acoustic resonances. Such unwanted phenomena are likely to affect the annoyance of noise sources in the low frequency range. Up to date, low-frequency treatments are mainly based on bulky devices, such as heavy enclosures. To alleviate this problem, electroacoustic absorbers, namely loudspeakers with shunt synthetic electric loads, can be used to damp room modes and then meet noise reduction specifications. Electrodynamic loudspeakers are good candidates for this type of noise control applications. Their mechanical resonance, typically of the order of tens of Hertz, is within the frequency range where acoustic modes are to be controlled. The interactions between these dynamic systems are significant, and a consequent amount of the acoustic energy in the room can be passively dissipated through internal losses in the loudspeaker. This paper investigates the design techniques and experimental validation of electroacoustic absorbers with a view to damp the low-frequency acoustic resonances, in the context of low-frequency noise reduction in inhabitations.

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1. Introduction

About 80 million people in the European Union are exposed to noise levels that are considered as unacceptable. Health, worker productivity, or comfort at home, are directly impacted by noise. Though, despite the many types of noise annoyances with respect to spectral characteristics or unsteadiness, regulations are often based on indicators that obviously decrease the influence of low frequencies (roughly below 200 Hz) on the referenced level. This situation might explain that only few low-frequency soundproofing solutions exist on the market.

However, the response of a room to a sound source in the low frequency range may result in a high sound pressure level at certain frequencies which coincide with the room natural frequencies, even with small amount of sound energy [1, 2]. This leads to an uneven spatial distribution of acoustic energy in the room. When a noise stops, the natural resonances of the room may even sustain its energy, and by way of consequence, the annoyance of the noise.

In the low frequency range, a room acoustic response is mainly modal, which is characterized by high levels at eigenfrequencies that can be very annoying inside rooms [3, 4]. As an illustration of such phenomenon, several measurements have been performed in the vicinity of the Geneva Airport, as reported in [2]. Fig. 1 illustrates the sound pressure levels measured in an office, located under the pathway of airplanes at take-off.

The left illustration shows the variation of power spectrum of an aircraft flying over a building versus time, whereas the right chart shows the same measurement in an office located inside the building. The difference of spectra between outside and inside is characteristic of such situation where modal behavior of the reception room has a significant influence on the perceived sound pressure levels inside the room compared to outside. The straight horizontal lines on Fig 1 (right chart), corresponding to sustained low frequency resonances (here below 100 Hz), highlight such modal behavior.

The only way to get rid of such resonance phenomena in rooms is to employ sound absorbing materials inside the room, capable of handling such low-frequency sound waves. Even if soundproofing treatments can be readily found for the high and middle frequency ranges, there is no real counterpart
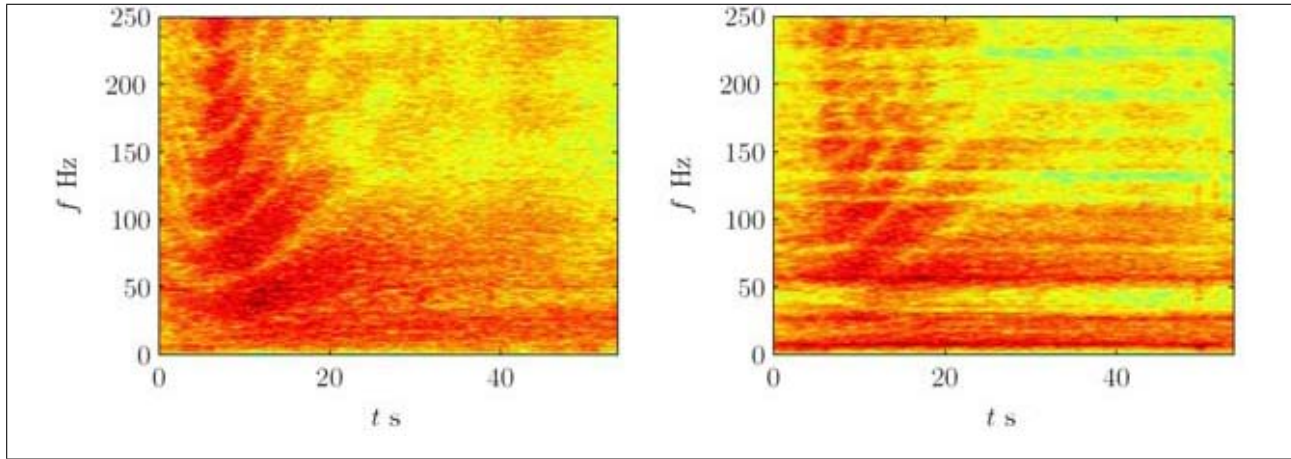
Figure 1. spectrograph measured during aircraft flyover outside a room (left chart) and inside (right chart).

for low frequencies sound absorption. Although some panel absorbers solutions exist, consisting of wide flat wooden panels, the dimensions they should present (especially the thickness), as well as their weight, reduce their interest for usual rooms. A solution could be the use of passive or active "electroacoustic absorbers" [5]. A preliminary study of passive electroacoustic absorbers for damping the low frequency modal behavior has been reported in [6]. This device developed for low frequency absorption, consists of a loudspeaker shunted with a passive electric resistance, thus achieving enhanced acoustic resistance at resonance, allowing frequency-selective sound absorption around the resonance frequency of the loudspeaker (over a range of lower than an octave). In [5], it has been shown how to employ active electric loads rather than passive ones, with a view to achieve broadband sound absorption in the low-frequency range, thus making possible the simultaneous damping of several resonance frequencies in the low-frequency range.

This paper aims at showing a novel active electroacoustic concept, where the passive electric load is substituted by an active electric network. It will especially show an application of such concept in an experimental setup in a room, for low frequency damping, with enhanced performances.

2. Electroacoustic absorbers

2.1. Governing equations

Let's consider an electrodynamic loudspeaker as depicted in Fig. 2. Here the loudspeaker is not used as a source of sound, but one should rather consider its diaphragm as an acoustic interface, capable of absorbing more or less energy from an exogenous sound field in its vicinity.

For small displacements and below the first modal frequency of the diaphragm, the governing equations of an electrodynamic loudspeaker can be derived after Newton's second law and the electrical meshes law .

With the use of Laplace transform, the characteristic equations of the transducer can be expressed as:

$$\begin{aligned} SP(s) &= \left(sM_{ms} + R_{ms} + \frac{1}{sC_{ms}} + \frac{\rho c^2 S^2}{sV_b}\right)V(s) \\ &\quad - Bl\,I(s) \\ E(s) &= (sL_e + R_e)\,I(s) + Bl\,V(s) \end{aligned} \quad (1)$$

where $s = j\omega$, is the Laplace variable, and

V is the normal velocity of the diaphragm, in $\mathrm{m\,s^{-1}}$

I is the electrical current, in A

P is the total exogenous sound pressure acting at the front of the diaphragm, in Pa

E is the electric voltage applied to the electrical terminals, in V

M_{ms} is the total moving mass of the diaphragm, in kg

C_{ms} is the mechanical compliance of the suspension, in $\mathrm{N\,m^{-1}}$

R_{ms} is the mechanical resistance, in $\mathrm{N\,s\,m^{-1}}$

R_e is the electrical resistance of the coil, in Ω

L_e is the electrical inductance of the coil in H

Bl is the force factor, in $\mathrm{N\,A^{-1}}$

S is the diaphragm area, in $\mathrm{m^2}$

V_b is the enclosure volume, in $\mathrm{m^3}$

ρ is the air density, in $\mathrm{kg\,m^{-1}}$

c is the sound celerity in the air, in $\mathrm{m\,s^{-1}}$

We denote in the following C_{mc} the total mechanical compliance of the closed-box loudspeaker, resulting from the combination of the cabinet mechanical compliance ($C_{mb} = \frac{V_b}{\rho c^2 S^2}$) and the loudspeaker suspension (C_{ms}). Eq. 1 becomes:

$$\begin{aligned} SP(s) &= \left(sM_{ms} + R_{ms} + \frac{1}{sC_{mc}}\right)V(s) - Bl\,I(s) \\ E(s) &= (sL_e + R_e)\,I(s) + Bl\,V(s) \end{aligned} \quad (2)$$

The coupling term $BlI(s)$ represents the Laplace force induced by the current circulating through the coil and $BlV(s)$ is the back electromotive force induced by the motion of the coil within the magnetic field.
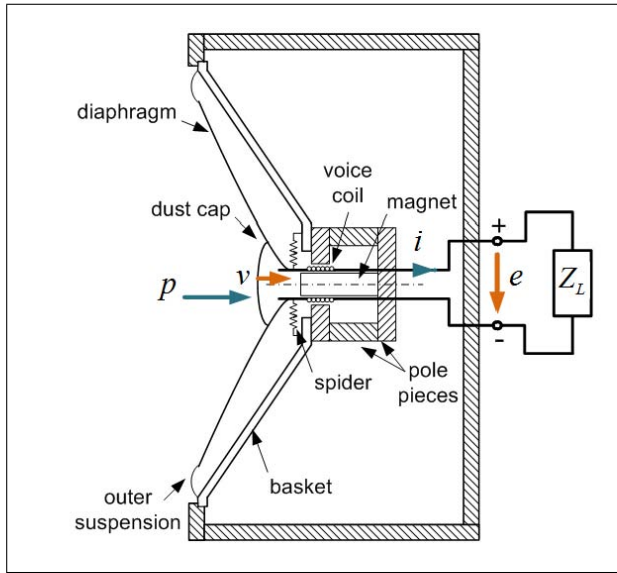
Figure 2. Electroacoustic absorber.

2.2. Coupling to an electrical load

By connecting an electric load Z_L as depicted in Fig. 2, the voltage applied across the transducer terminals becomes

$$E(s) = -Z_L(s)I(s) \tag{3}$$

and the electrical current flowing through the coil can be written as

$$I(s) = \frac{-Bl}{Z_e(s) + Z_L(s)}V(s) \tag{4}$$

where $Z_e(s) = R_e + sL_e$ is the blocked electrical impedance of the voice coil. When designed properly, the shunt electrical impedance Z_L can make a functional relationship between the induced voltage $BlV(s)$ and electrical current, thus taking precedence over the transducer dynamics.

2.3. Acoustic absorption capability

A closed form expression of the specific acoustic admittance at the transducer diaphragm can always be derived after Eq. 2 regardless of the load $Z_L(s)$ connected across its terminals. Normalizing relative to the characteristic impedance of the medium, the normalized specific acoustic admittance can be expressed as

$$y(s) = \rho c \frac{V(s)}{P(s)} \tag{5}$$

This dimensionless parameter reflects the velocity of the diaphragm that is caused by the driving acoustic pressure. By combining Eq. 2 and Eq. 4, this velocity response of the transducer diaphragm to an exogenous surrounding sound field can be expressed as

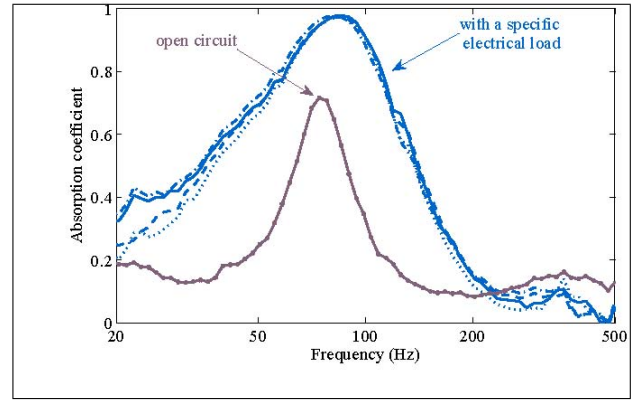$$y(s) = \frac{Z_e(s) + Z_L(s)}{(Z_e(s) + Z_L(s))Z_{mc}(s) + (Bl)^2} \tag{6}$$

Figure 3. Measured sound absorption coefficient of the four electroacoustic absorbers used in the experiments in open circuit and connected to a specific electrical load (in black: open circuit; in blue different lines: active electric load).

Table I. Small signal parameters of the Monacor SPH-300TC.

Parameter	Notation	Value	Unit
dc resistance	R_e	6.3	Ω
Voice coil inductance	L_e	1	mH
Force factor	Bl	10.3	$N.A^{-1}$
Moving mass	M_{ms}	68	g
Mechanical resistance	R_{ms}	3.24	$N.m^{-1}s$
Mechanical compliance	C_{ms}	0.85	$mm.N^{-1}$
Effective area	S	495	cm^2
Natural frequency	f_0	23	Hz

where $Z_{mc}(s) = sM_{ms} + R_{ms} + \frac{1}{sC_{mc}}$ is the mechanical impedance of the moving body of the closed-box loudspeaker. The corresponding absorption coefficient can be derived as:

$$\alpha = 1 - \left|\frac{1 - y(s)}{1 + y(s)}\right|^2 \tag{7}$$

Fig. 3 illustrates the measured sound absorption coefficient, assessed after ISO 10534-2 standard [7], when connecting a low-range Monacor SPH-300TC loudspeaker (see Tab. 2) mounted in sealed enclosure of volume $V_b = 23$ L, to a specific shunt electrical load designed to increase the control bandwidth, compared to the open circuitŠs case. As clearly shown in Fig. 2 an effective control of the acoustic impedance in the room is expected in the frequency range between 50 Hz and 150 Hz.

3. Modal equalization of the room

The present work considers a parallelepiped room. This basic geometry is a good example to understand the low-frequency distribution of acoustic energy in closed spaces. The corresponding experimental work is carried out in a technical room at EPFL (width L_x = 3 m by length L_y = 5.6 m by height L_z = 3:53

m) used to store containers of waste sorting. The total area is 94.3 m^2 and the volume is 59.3 m^3. Such a room is characterized by a strong sustain of sound energy due to rigid walls and is likely to have isolated modes, particularly at low frequencies.

3.1. Eigenfrequencies identification

The first stage is to identify the modes of the room to be damped. For ease of calculations, the room eigenfrequencies are identified with the help of Comsol Multiphysics.

Fig. 4 shows the computed sound pressure level distribution in the room for a selection of eigenfrequencies. This graphical representation clearly illustrates the nodes and antinodes of pressure. This result is essential for placement of sound absorbers: depending on the mode(s) to damp, an optimal position of the electroacoustic absorbers will be highlighted (namely antinode position, in red or blue in Fig. 4), which could potentially not correspond to the optimal placement for damping another mode. The next section presents the placement strategy of electroacoustic absorbers.

3.2. Placement of electroacoustics absorbers

The analysis of the acoustic energy distribution shows that the electroacoustic absorbers must be carefully placed in the room. At low frequencies, typically where the size of electroacoustic absorbers becomes small relative to the wavelength, the coupling with the room is inefficient when they are located on nodes of pressure [2]. For optimal performance, it is best to place them on pressure antinodes, while orientating the transducers diaphragm according to the modes structure to be damped.

Two configurations of electroacoustic absorbers placements will be discussed in this paper, denoted C_1 and C_2. In configuration C_1, the electroacoustic absorbers are placed in corners 3, 4, 7 and 8 of the room, as depicted in Fig. 5 (up). The orientation is such that the diaphragm of each loudspeaker is facing edges along the y-axis. In configuration C_2, the loudspeakers are located on the ground in the corners 1, 2, 3 and 4, and the orientation of the diaphragms is facing edges along the x-axis (Fig. 5 (down)).

4. Experimental assessment

4.1. Experimental setup

The sound source used for measuring the frequency response of the room is a low-midrange loudspeaker in sealed enclosure, designed to provide the necessary acoustic power in the frequency range of interest. It is placed on the floor in the corner 1 of the room. The signal excitation is a random pink noise the frequency span of which is between 20 Hz and 500 Hz. For the spectral analysis we used a frequency resolution of 0.1
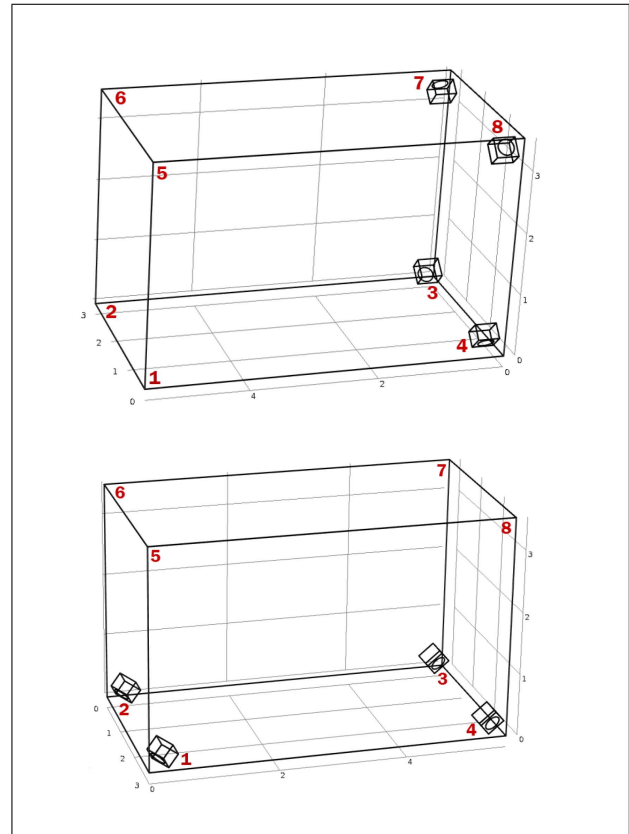

Figure 5. Location of electroacoustic absorbers in the room: configuration C_1 (up) and configuration C_2 (down).

Hz in order to examine the frequency response of the room in more detail. The measured response of the room is picked up by a 1/2" microphone (Norsonic Type 1225 cartridges mounted on Norsonic Type 1201 amplifier), the sensitivity of which is 50 mV Pa^{-1}, and processed through a 01dB-Metravib multichannel analyzer. In configuration C_1, the microphone is located in corner 8 and in corner 2 for the configuration C_2. Table I summarizes the small signal parameters of the low-range Monacor SPH-300TC loudspeaker used in the experiments.

4.2. Damping of the low-frequency modes

The sound pressure level measured in the room (in corner 8 with C_1 and in corner 2 with C_2) is shown in Fig. 6. The maximum gains in decibels for the frequency range between 70 Hz and 100 Hz are summarized in Tab. II.

One can observe very high noise reduction levels along the range 70-100 Hz with those two configurations, with locally about 14dB. However, globally, the configuration C_2 shows the best results in terms of broadband sound absorption, due to the setting of the electroacoustic absorber (resonance frequency is almost 100 Hz), and also due to the specificities of the modes (the quality factor of modes 121 could be a reason for such high attenuation). As expected, configuration C_2 present higher sound absorption than
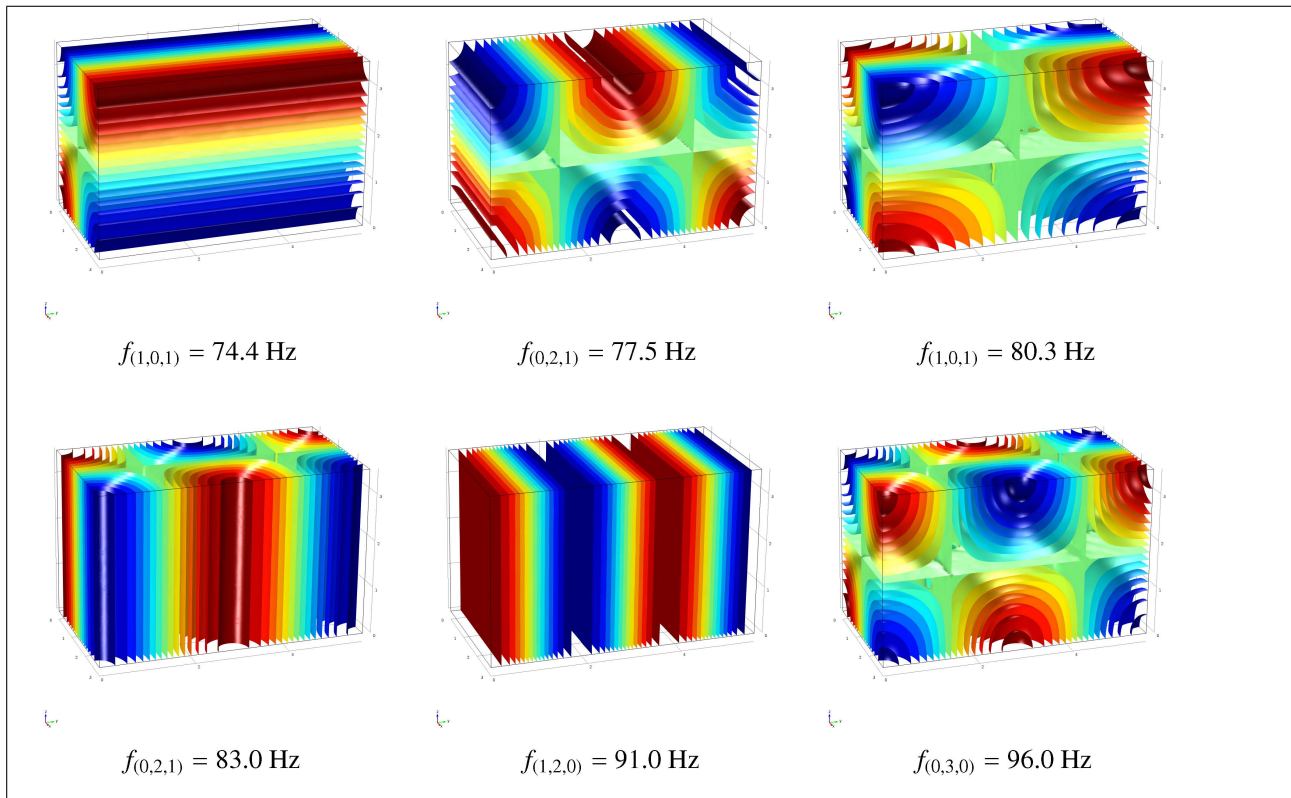
$f_{(1,0,1)} = 74.4$ Hz $f_{(0,2,1)} = 77.5$ Hz $f_{(1,0,1)} = 80.3$ Hz

$f_{(0,2,1)} = 83.0$ Hz $f_{(1,2,0)} = 91.0$ Hz $f_{(0,3,0)} = 96.0$ Hz

Figure 4. Selection of modes of the room between 70 Hz and 100 Hz.

Table II. Measured gains for the C_1 and C_2 configurations.

Mode	Eigen-frequency (Hz)	Attenuation C_1 (dB)	Attenuation C_2 (dB)
1 0 1	74.4	-11.7	-8.6
0 2 1	77.5	-4.0	-6.2
1 1 1	80.3	-6.8	-9.0
1 2 0	83.0	-7.9	-9.4
0 3 0	91.0	3.9	-4.7
1 2 1	96.0	-7.1	-13.6
Global		-2.4	-7.8

C_1 for the modes with non-null n_y (modes with a component along dimension y of the room), due to the orientation of electroacoustic absorber diaphragm that is likely to tackle such modes.

5.   Conclusions

In this paper we discussed a practical realization of electroacoustic absorbers in view of controlling the low-frequency sound field in closed spaces. A simple engineering approach employing an arrangement of electrodynamic loudspeakers the terminals of which are connected to a specific electrical load has been presented. Through judicious control of acoustic impedance in a test room a significant damping of the dominant natural resonances can be achieved. It is shown that the magnitude of the low-frequency res-onances of the room can be greatly reduced, even with a very small equivalent absorption area. The surface of acoustic treatment is only 0.2 m^2, while the total area of the room is 94.3 m^2. The measured gains are largely related to the location of the absorbers in the room as well as the orientation of the diaphragm relative to the modes structure.

The proposed methodology is a realistic solution for absorbing low frequency noise resulting from natural modes in rooms, far beyond what is attainable using a conventional soundproofing treatments. This study was mainly restricted to a frequency range between 70 Hz and 100 Hz. In order to address another frequency range, the transducers and the active electric loads should be modified in order to suit the corresponding requirements. But the methodology can remain unchanged.

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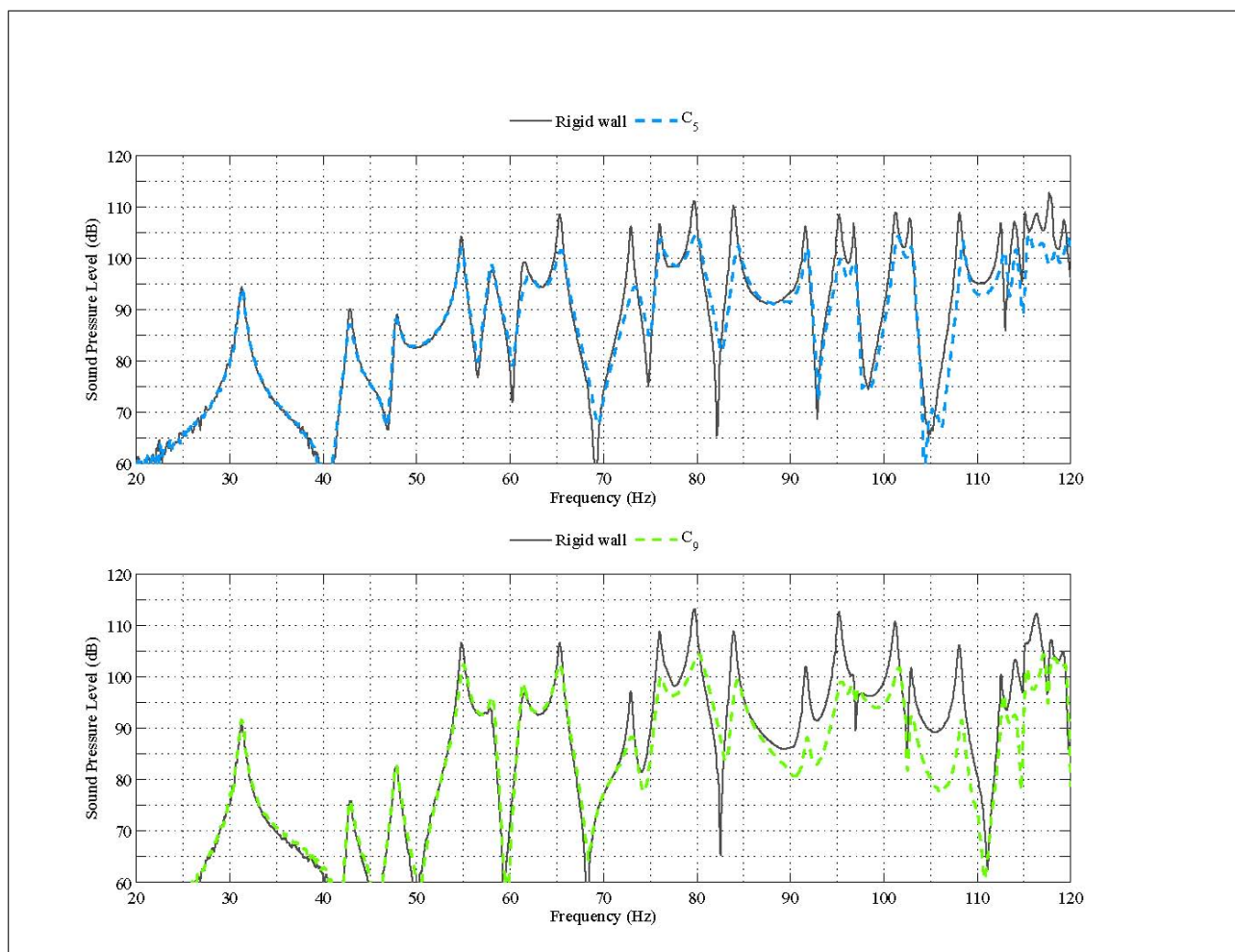
Figure 6. Location of electroacoustic absorbers in the room: configuration C_1 (up) and configuration C_2 (down).

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