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Exam - Audio Engineering

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January 31, 2024 / 15h15 - 18h15 / ELD 020

Forewords : Please answer directly on the exam sheets with an **ink pen** (no carbon pen), in the spaces devoted to your answers. Don't forget to write down your name and surname on each sheet.

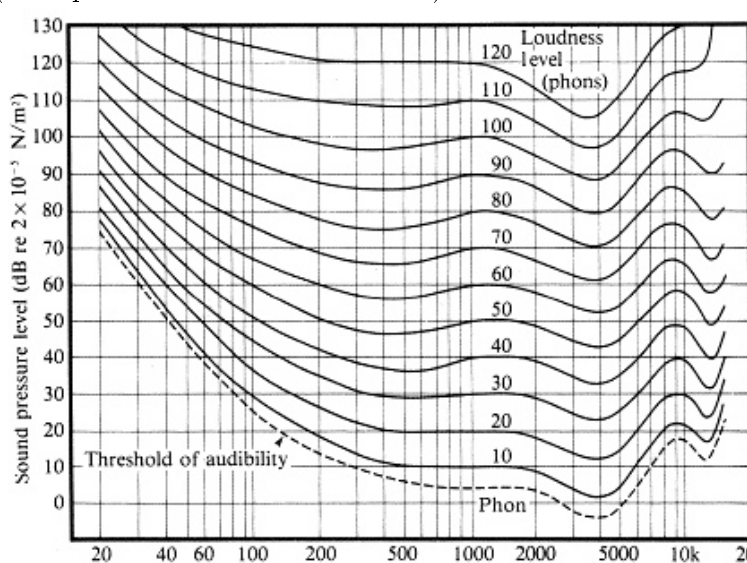
You are allowed to consult any written document (books, lecture notes, exercises and corrections, etc.). Calculators are also allowed. However, computers and other communication devices (cell phones, smartphones, tablets, etc.) should be kept switched off.

In the following exercises, the numerical values of mass density ρ_{air} , sound celerity c_{air} and dynamic viscosity ν_{air} of the air are :

Numerical data : $\rho_{air} = 1.2 \text{ kg.m}^{-3}$, $c_{air} = 340 \text{ m.s}^{-1}$, $\nu_{air} = 1.810.10^{-5} \text{ kg.m}^{-1}.\text{s}^{-1}$.

Questions (2 points)

Q1 (0.2 pt)	The tonotopy designates ☐ the simultaneous masking effect of a pure tone of frequency f_0 towards sounds of nearby frequencies (f close to f_0) ☐ the spatial arrangement of hair cells along the basilar membrane allowing sounds of different frequencies to be processed by the brain ☐ a hearing disability caused by impulsive sounds of high sound pressure level
Q2 (0.2 pt)	We remind that, legally, the maximal equivalent level for a weekly working time of 40 hours is 87 dB(A). How many hours can a DJ work with an average level of 93 dB(A) ? ☐ 10 hours ☐ 15 hours ☐ 20 hours
Q3 (0.2 pt)	The depicted microphone is :  ☐ omnidirectional ☐ bidirectional ☐ unidirectional
Q4 (0.2 pt)	A clarinet can be assimilated as a hollow cylinder of length $L \approx 60 \text{ cm}$, with one extremity closed and the other open. What is approximately its fundamental frequency ? ☐ 140 Hz ☐ 280 Hz ☐ 560 Hz
Q5 (0.2 pt)	What is the directivity factor of a sound source with directivity $D(\theta) = \frac{(1 + 3 \cos \theta)}{4}$? ☐ 4.8 dB ☐ 5.7 dB ☐ 6.0 dB

Q6 (0.2 pt)	We consider a room of width $l = 8\text{m}$, width $w = 5\text{m}$ and height $h = 3\text{m}$. What is the mode number corresponding to the resonance frequency at 102 Hz ? ☐ [1 2 1] ☐ [2 2 1] ☐ [0 3 0]																					
Q7 (0.2 pt)	We measure the following linear (unweighted) sound pressure level of a noise source, split by octave-bands. What is the corresponding total A-weighted sound pressure level $L_{A,\text{total}}$? <table><tr><td>f (Hz)</td><td>125</td><td>250</td><td>500</td><td>1000</td><td>2000</td><td>4000</td></tr><tr><td>L (dB)</td><td>90</td><td>95</td><td>95</td><td>97</td><td>93</td><td>93</td></tr><tr><td>A-weighting (dB)</td><td>-16</td><td>-9</td><td>-3</td><td>0</td><td>+1</td><td>+1</td></tr></table> ☐ $L_{A,\text{total}} = 96 \text{ dB(A)}$ ☐ $L_{A,\text{total}} = 98 \text{ dB(A)}$ ☐ $L_{A,\text{total}} = 100 \text{ dB(A)}$	f (Hz)	125	250	500	1000	2000	4000	L (dB)	90	95	95	97	93	93	A-weighting (dB)	-16	-9	-3	0	+1	+1
f (Hz)	125	250	500	1000	2000	4000																
L (dB)	90	95	95	97	93	93																
A-weighting (dB)	-16	-9	-3	0	+1	+1																
Q8 (0.2 pt)	During a typical day, a person is subject to an average $L_{\text{work}} = 70 \text{ dB(A)}$ during his 8h work time at the office, to an average $L_{\text{transport}} = 65 \text{ dB(A)}$ for his 1 h (total back and forth) commute from home to work, and to $L_{\text{home}} = 60 \text{ dB(A)}$ at home during the remaining day time. It is assumed that the average level at home in the evening and night is 10 dB(A) lower than during the day. What is the value of the day-evening-night indicator L_{den} for this person ? ☐ $L_{\text{den}} = 60 \text{ dB(A)}$ ☐ $L_{\text{den}} = 63 \text{ dB(A)}$ ☐ $L_{\text{den}} = 66 \text{ dB(A)}$																					
Q9 (0.2 pt)	What is roughly the resonance frequency of a Helmholtz resonator composed of a cavity of volume $V = 0.7 \text{ L}$ and a neck of radius $r = 0.85 \text{ cm}$ and length $l = 3.3 \text{ cm}$? ☐ $f_r = 17 \text{ Hz}$ ☐ $f_r = 170 \text{ Hz}$ ☐ $f_r = 1\text{'700 Hz}$																					
Q10 (0.2 pt)	What is the loudness of a pure tone of frequency 4'000 Hz and sound pressure level $L = 80 \text{ dB}$? (see equal-loudness contours below)  ☐ 2 sones ☐ 4 sones ☐ 8 sones ☐ 16 sones ☐ 32 sones																					

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Exercise 1 : Wooden panel prototypes (2 points)

A designer has proposed a new concept of wooden panels for sound absorption. It consists in inserting wooden fibers rows along a wooden panel, as illustrated on Figure 1. Each wooden panel sample (without or with wood fiber rows) has dimensions $1,5 \text{ m} \times 1,2 \text{ m} \times 8 \text{ cm}$

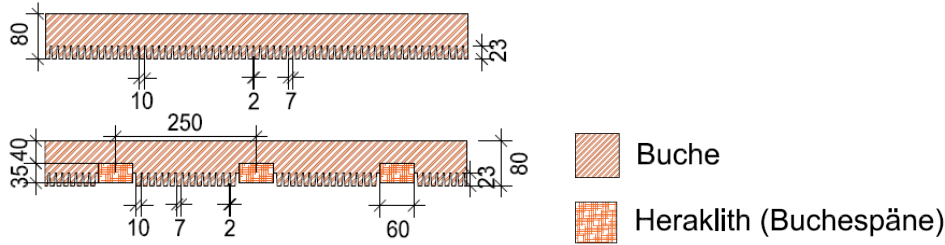


FIGURE 1 – Sketch of the proposed samples (top : **Sample 1** (only wood, without wood fiber) ; bottom : **Sample 2**(wood with inserts of wood fibers))

1. Absorption coefficient measurements

The designer asked us to measure the absorption coefficient of the 2 categories of samples in the reverberation chamber of the laboratory (Figure 2). The measurement, based on the ISO 354 standard, consists in first estimating the reverberation time (per octave), in the empty room (without samples) and then estimating the reverberation times in the room equipped with a surface, **that should be higher than 10 m^2 and lower than 12 m^2** , of each sample, assembled on the ground. For each case (empty room, room with $10\text{-}12 \text{ m}^2$ of sample 1, and room with $10\text{-}12 \text{ m}^2$ of sample 2), the measurements should be repeated 12 times, and the averages of all measurements, for each octave, are reported on Table 2 for estimating the sound absorption coefficient of each sample.

- 1.1. How many samples do we need to match the requirement of the measurement in terms of absorbing material area ?
- 1.2. Remind the Sabine's law on reverberation time T_{60} , in a room of volume V_0 , total surface S_0 in the presence of a sample of surface S_{sample} and absorption coefficient α_{sample} .

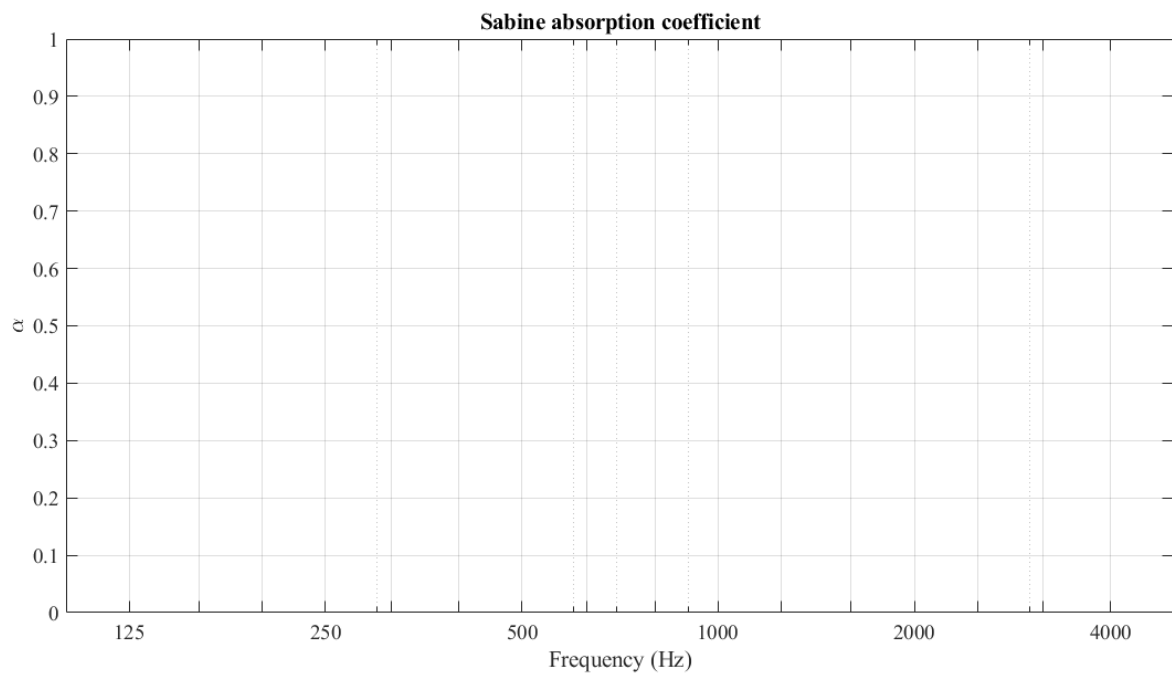
- 1.3. The measurements of the average reverberation times give the values of Table 2.
What is the formula to derive $\alpha_{\text{sample } i}$ for each sample i ?

Fill in Table 2 with the values of α for the 2 samples.

Frequency (Hz)	125	250	500	1000	2000	4000
$T_{60, \text{Empty room}}$ (s)	23,4	18,0	13,7	11,1	6,5	2,8
$T_{60, \text{Sample 1}}$ (s)	19,3	11,8	9,2	7,6	4,6	2,2
$T_{60, \text{Sample 2}}$ (s)	18,0	8,3	6,5	5,0	2,5	1,7
$\alpha_{\text{Sample 1}}$						
$\alpha_{\text{Sample 2}}$						

TABLE 2 – Measured reverberation times (in s)

- 1.4. Draw the absorption coefficients of the two samples on the graph below (draw 'o' markers for sample 1, and '+' markers for sample 2, with different colors if you can). What is the best sample in terms of sound absorption?



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2. Application to room correction

It has been decided to use the "best" sample (in terms of sound absorption) to acoustically treat a small music recording room, of size $6\text{ m} \times 5\text{ m} \times 2.3\text{ m}$, made of concrete. The floor of this room is fully covered by a carpet, and the ceiling is fully covered by Helmholtz resonators perforated panels (the absorption coefficients of which are given in Table 3).

Frequency (Hz)	125	250	500	1000	2000	4000
Concrete	0.01	0.01	0.02	0.02	0.03	0.04
Carpet	0.05	0.08	0.20	0.30	0.35	0.40
Perforated panel	0.30	0.60	0.90	0.45	0.10	0.01

TABLE 3 – Absorption coefficients of floor and ceiling

2.1. Calculate the reverberation times of the room with only the floor and the ceiling treated.

Frequency (Hz)	125	250	500	1000	2000	4000
$T_{\text{baseline recording room}} (s)$						

TABLE 4 – Reverberation times (in s) in the baseline room (without treatment)

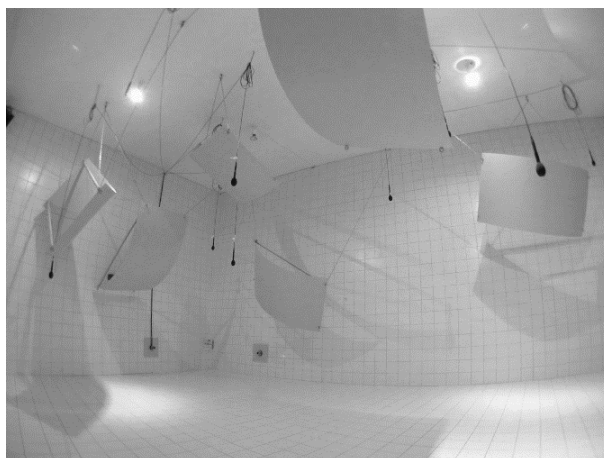
The standard for music recording studios requires that the reverberation time remains between 200 ms and 500 ms for all octave bands above 200 Hz.

2.2. How many full panel(s) of the best wooden sample should you apply on the walls to satisfy this requirement?

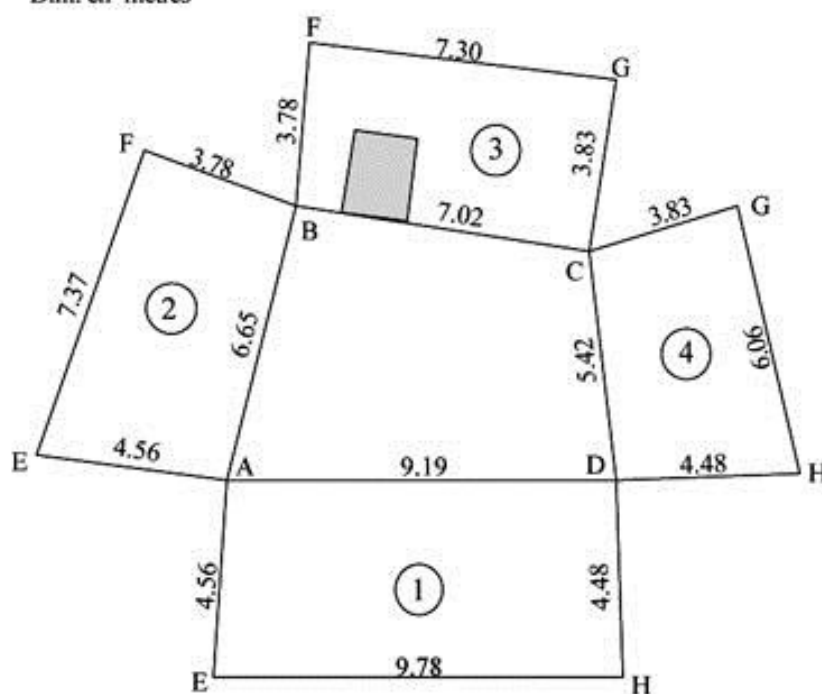
Frequency (Hz)	125	250	500	1000	2000	4000
$T_{\text{treated recording room}} (s)$						

TABLE 5 – Reverberation times (in s) in the room with N wooden panels

2.3. What could you propose to treat the remaining problem in the 125 Hz band?



Echelle: 1:150
Dim. en mètres



plus petite dimension: 3.78 m
plus grande diagonale: 11.52 m

Volume: 215.6 m³
Surface totale: 226.9 m²

Sol: 48.0 m²
Plafond: 56.2 m²
Paroi1: 42.8 m²
Paroi2: 29.0 m²
Paroi3: 27.2 m²
Paroi4: 23.7 m²

FIGURE 2 – Reverberation chamber (top : picture ; bottom : sketch of the room)

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Exercise 2. Rectangular sound source (2 points)

Let's consider a rectangular sound source of width a and height b within an infinite screen (of null velocity). We define the cartesian coordinates $Oxyz$, where O is the center of the rectangular sound source, Ox and Oy are the axes over the plane, respectively along width a and along height b , and the z axis is normal to the plane. This sound source is assumed to vibrate as a rigid piston, so that the vibrating velocity of every point $M_0(x_0, y_0)$ over its area is $\vec{v}(x_0, y_0) = \vec{v}_0 = v_0 \cdot \vec{e}_z$, $\vec{e}_z$ being the unitary vector along axis z .

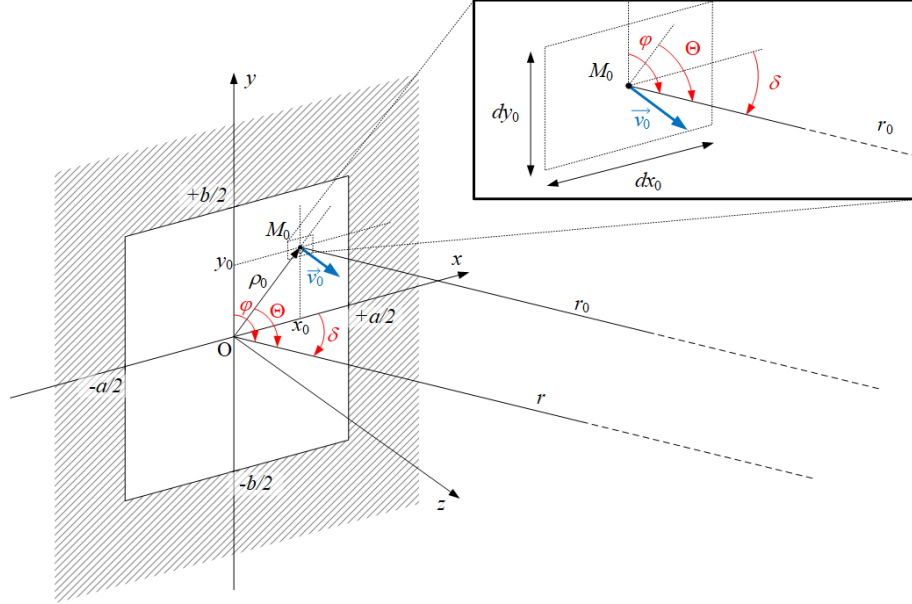


FIGURE 3 – Rectangular source with a zoom of element $dx_0 dy_0$ around M_0

We now consider a point $M(x, y, z)$ in the far field, so that $r = \sqrt{x^2 + y^2 + z^2} \gg \max(a, b)$. In the following, we will use an alternative "spherical" coordinates system (r, δ, φ) , where r is the distance of point M to O , while δ [respectively φ] is the angle between $\vec{OM}$ and $\vec{Ox}$ [$\vec{Oy}$ respectively].

Last, we define the angle Θ as the angle between $\vec{OM} = \vec{r}$ and $\vec{OM}_0 = \vec{\rho}_0$, as defined on Figure 3.

M being in the far field, we will assume in the following that the vectors $\vec{OM} = \vec{r}$ and $\vec{M_0M} = \vec{r}_0'$ are colinear, so that the same angles δ, φ and Θ are seen from points O and M_0 .

2.1. Express the infinitesimal flow velocity dq_0 of the semi-monopole of surface area $dx_0 dy_0$ around M_0 .

2.2. Express the relationship between r_0 and r as a function of ρ_0 and Θ under the assumption that the two "rays" are parallel.

2.3. Rewrite the relationship between r_0 and r as a function of x_0 , y_0 , δ and φ .

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- 2.4. Derive the sound pressure radiated by the whole rectangular membrane at any point $M(r, \delta, \varphi)$ in the far field $r \gg \max(a, b)$ as the following form : $p(r, \delta, \varphi) = p_{sm0}(r) \cdot D_\delta(a) \cdot D_\varphi(b)$, where $p_{sm0}(r)$ is the sound pressure generated at M by an ideal sound source centered at O and $D_\delta(a)$ [resp $D_\varphi(b)$] are directivity functions of a and δ [resp of b and φ]. Give the expressions of p_{sm0} , $D_\delta(a)$ and $D_\varphi(b)$.