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Exam - Audio Engineering

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January 16, 2025 / 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, smarthones, tablets, etc.) should be kept switched off.
Please read carefully the entire exam prior to start answering.

In the following exercises, the numerical values of mass density ρ_{air}, speed of sound c_{air} and dynamic viscosity ν_{air} of the air are :
Numerical data : $\rho_{air} = 1.2$ kg.m^{-3}, $c_{air} = 343$ m.s^{-1}, $\nu_{air} = 1.810.10^{-5}$ kg.m^{-1}.s^{-1}.

Questions (2 points)

Q1 (0.2 pt)	The pan flute is a made of several wooden tubes that are open at one end (where the musician blows air) and closed at the other end. What is the theoretical length of the tube corresponding to the $A5$ note ($f_{A5} = 880$ Hz)? ☐ 9.75 cm ☐ 13.8 cm ☐ 19.5 cm
Q2 (0.2 pt)	The depicted microphone is more likely : ☐ omnidirectional ☐ bidirectional ☐ unidirectional 
Q3 (0.2 pt)	We measure the input electric impedance of a loudspeaker mounted on an IEC baffle. The measurements gives a dc resistance $R_e = 5.5\Omega$, a maximum value at resonance $\|Z_{HP}(f_s)\| = 22\Omega$. We read the two frequencies $f_- = 63,0$ Hz and $f_+ = 158.8$ Hz, for which $\|Z_{HP}(f_\pm)\| = 11\Omega$. A second measurement with an additional mass of 15 g gives $f'_- = 53.1$ Hz and $f'_+ = 107.7$ Hz. What is the value of the mechanical resistance of the loudspeaker? ☐ 2 N.s/m ☐ 6 N.s/m ☐ 8 N.s/m
Q4 (0.2 pt)	The noise level of a car passing by is measured at $L_1 = 80$ dB along a road. What would the total sound pressure level L_3 be if 3 identical cars were simultaneously passing at the same speed and the same distance to the sound pressure level meter? ☐ 83.5 dB ☐ 84.8 dB ☐ 89.5 dB
Q5 (0.2 pt)	What is the directivity factor of an infracardioid microphone of order n=1? ☐ 3,2 dB ☐ 4,8 dB ☐ 6,0 dB

Q6 (0.2 pt)

What is the location of the hair cells the most sensitive to pure tones at 50 Hz ?

☐ close to the base ?

☐ in the center of the cochlea ?

☐ close to the apex ?

Q7 (0.2 pt)

Let's consider a room of dimensions $l = 8$ m, $w = 6$ m and $h = 5$ m, all lateral walls and floor being made of concrete, while the ceiling is fully covered with a glasswool panel ("reference" room). If we install a carpet over the whole floor area ("modified" room), what is the average relative reverberation time reduction $< \frac{T_{\text{modified}} - T_{\text{reference}}}{T_{\text{reference}}} >$ (average over frequency bands) ?

	octave band (Hz)					
Absorption coefficient	125	250	500	1000	2000	4000
Concrete	0.01	0.01	0.02	0.02	0.03	0.04
Glasswool	0.10	0.45	0.80	0.90	0.95	0.95
Carpet	0.05	0.08	0.20	0.30	0.35	0.40

☐ -20%

☐ -25%

☐ -30%

Q8 (0.2 pt)

A person works 6 hours per day in a workshop with equivalent level $L_{eq1} = 90$ dB(A).
He has a lunch break of 2 hours in equivalent level $L_{eq2} = 80$ dB(A).
When he comes back home in the afternoon he spends 4 hours resting with equivalent level $L_{eq3} = 63$ dB(A).
Then 4 hours watching television with equivalent level $L_{eq4} = 70$ dB(A).
He then sleeps for the 8 remaining hours with an equivalent level $L_{eq5} = 55$ dB(A).
What noise dose does this person experience over one whole day ?

☐ $d = 5'800$ Pa^2.s

☐ $d = 9'000$ Pa^2.s

☐ $d = 11'600$ Pa^2.s

Q9 (0.2 pt)

What is the global A-weighted Sound Pressure Level of the following noise spectrum ?

	octave band (Hz)					
	125	250	500	1000	2000	4000
Noise spectrum (dB)	60.2	70.1	85.0	81.8	80.6	80.8
A-weighting (dB)	-16.1	-8.6	-3.2	0	1.2	1

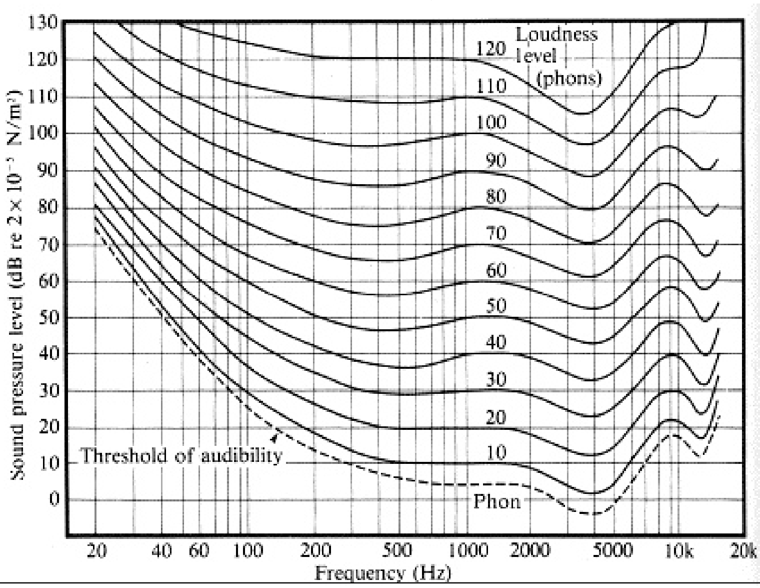
☐ 85.8 dB(A)

☐ 87.8 dB(A)

☐ 89.8 dB(A)

Q10 (0.2 pt)

What is the loudness of a pure tone of frequency 100 Hz and sound pressure level $L = 60$ dB ? (see equal-loudness contours below)



☐ 2 sones

☐ 4 sones

☐ 8 sones

☐ 16 sones

☐ 32 sones

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Exercise 1. Room modes (2 points)

Let's consider a shoebox room of unknown dimensions (l_x,l_y,l_z) (axes x,y,z are illustrated in Fig. 1). This room serves as a recording studio which is equipped with 4 subwoofers of same dimensions and acoustic rendering properties. The subwoofers are installed directly on the ground, two subwoofers (SW1 and SW2) being **centered** along the edge ($x = l_x$,$z = 0$) and distant by $l_y/2$ of each others, the two others (SW3 and SW4) being aligned along the edge ($x = 0$,$z = 0$), with a same arrangement. The sound engineer's listening position is exactly equidistant from the two front subwoofers (SW1 and SW2), at an height of 1.5m.

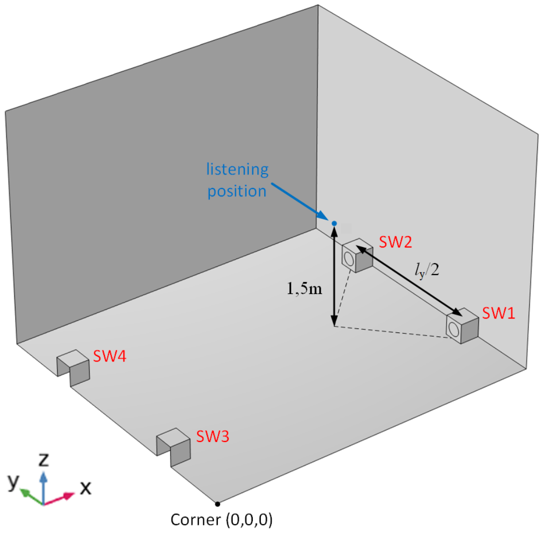
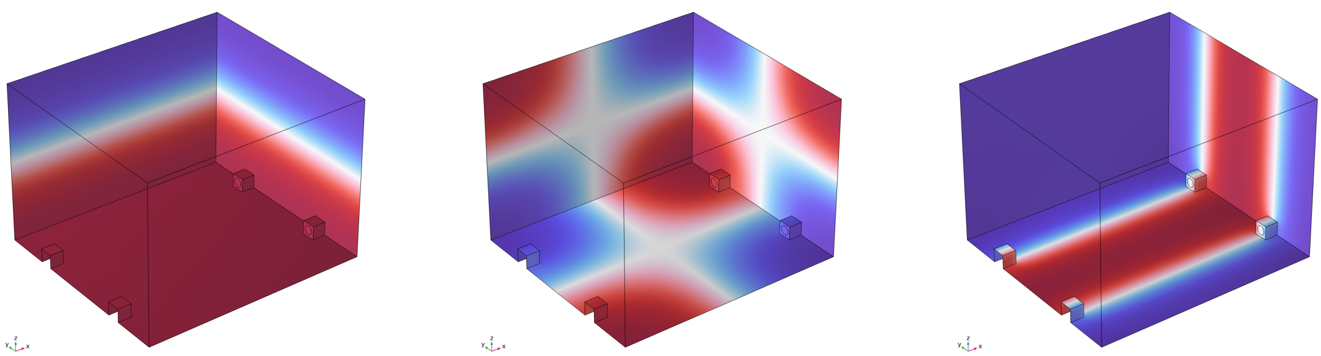


FIGURE 1 – Description of the listening room configuration

1. What is the expression of the eigenfrequencies of the room $f_{(m_x m_y m_z)}$ as a function of the room dimensions (l_x,l_y,l_z), the speed of sound c_{air} and the triplet of integers (m_x,m_y,m_z).

A numerical model of the room is processed to identify the room modes. We present in Fig. 2 the sound pressure distribution for three selected modes, corresponding to frequencies 49, 0 Hz, 71, 0 Hz, and 76, 2 Hz. The dark red and blue zones correspond to maxima and minima of pressure (antinodes) and the white zones corresponds to the nodes.



49,0 Hz 71,0 Hz 76,2 Hz

FIGURE 2 – Selection of 3 eigenmodes (left : 49,0 Hz ; center : 71,0 Hz ; right : 76,2 Hz)

2. Identify the modes indices (m_x,m_y,m_z) of the 3 selected modes.

Frequency	49,0 Hz	71,0 Hz	76,2 Hz
Mode indices	(, ,)	(, ,)	(, ,)

3. Deduce the dimensions (l_x,l_y,l_z) of the room (explain in a few lines your calculations).

l_x=	l_y=	l_z=

Explanations :

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The sound engineer would like to optimize the listening experience. In a first step, he measures the sound pressure levels at the listening position and at the corner (0,0,0), when only subwoofer SW1 is fed with a white noise signal ($s_1(t)$, t denoting time). The measurements are illustrated on Fig 3.

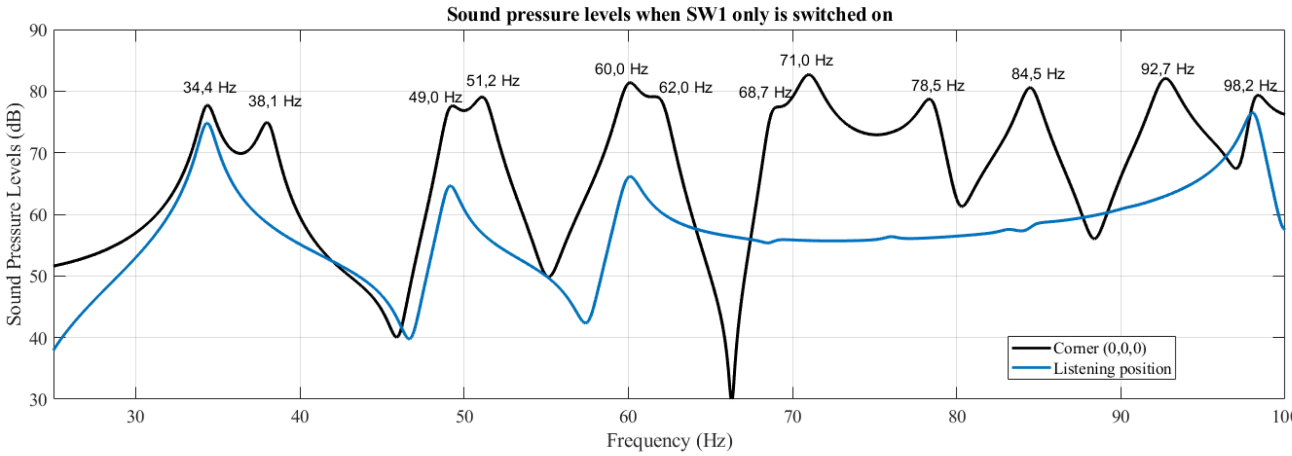

FIGURE 3 – Sound pressure levels measured with only subwoofer SW1 switched on (black : at corner (0,0,0) ; blue : at listening position)

4. Why are the modes at 49,0 Hz and 71,0 Hz visible on both measurements, but not the mode at 76,2 Hz ?

5. Why are the modes at 38,1 Hz, 51,2 Hz and 62,0 Hz visible on the measurement at corner (0,0,0) but not at the listening position ?

6. Do you think the loudspeaker response above 70 Hz is satisfactory at the listening position ?

Now the sound engineer makes several tests.

— He first feeds subwoofers SW1 and SW2 with the same signal $s_2(t) = s_1(t)$.

— Then, while SW1 and SW2 are still fed with the same signal $s_1(t) = s_2(t)$, he feeds subwoofers SW3 and SW4 with an out-of-phase version of the signal of SW1 and SW2, delayed by $\delta t = \frac{l_x}{c_{air}}$, such that :

$$s_3(t) = s_4(t) = -s_1(t - \frac{l_x}{c_{air}})$$

The measurements are illustrated on Fig. 4.

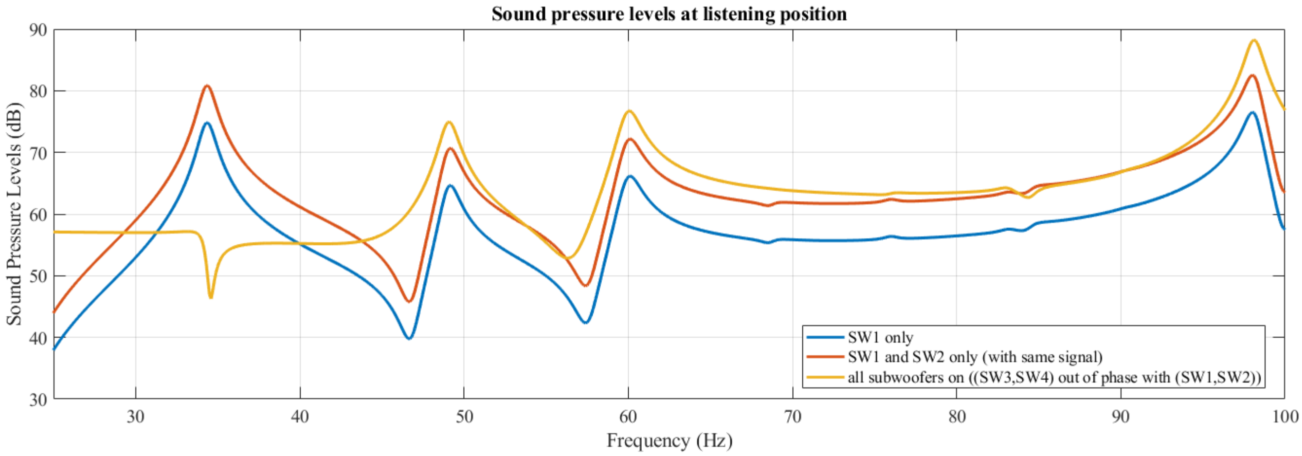

FIGURE 4 – Sound pressure levels measured at listening position for different subwoofers configurations (blue : only SW1 on ; red : only SW1 and SW2 on with same signal ; yellow : all subwoofers on, SW1 and SW2 with a same signal $s_1(t)$ while SW3 and SW4 are fed with modified signal $s_3(t) = s_4(t) - s_1(t - \frac{l_x}{c_{air}})$)

7. Can you explain why the first mode at 34,3 Hz is not visible anymore with the subwoofers pair at the rear are switched out of phase relative to the subwoofers pair in the front ?

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8. Could you propose a way to also flatten the two remaining modes at 49 Hz and 60 Hz ?

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Exercise 2. Band-pass loudspeaker (2 points)

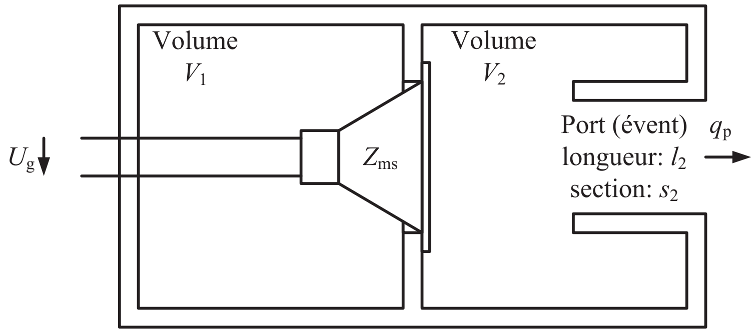

FIGURE 5 – Band-pass loudspeaker

We consider an electrodynamic loudspeaker with Thiele-Small parameters ($R_e, L_e, M_{ms}, R_{ms}, C_{ms}, B\ell, S_d$). The loudspeaker is mounted in a closed-box enclosure of volume V_1, and its front face radiates in a volume V_2 open on its front with a port of length l_2 and section s_2. We denote here $Z_{ms}(j\omega) = j\omega M_{ms} + R_{ms} + \frac{1}{j\omega C_{ms}}$ the mechanical impedance of the mobile parts of the loudspeaker.

1. Remind the expression, as a function of the above-mentioned parameters, of :
   - the acoustic counterparts R_{as}, M_{as}, C_{as} ($Z_{as} = R_{as} + j\omega M_{as} + \frac{1}{j\omega C_{as}} \equiv \frac{p}{q}$) of the mechanical elements R_{ms}, M_{ms}, C_{ms}
   - the acoustic resistance R_{ae} corresponding to the electrical losses in the coil R_e ;
   - the acoustic mass M_{ap} of a duct of length l_2 and section s_2 ;
   - the acoustic compliance C_{a2} of volume V_2 ;
   - the total acoustic compliance C_{ac} of the loudspeaker loaded by the rear volume V_1 (without the front volume V_2) ;
   - the acoustic pressure p_g equivalent to the source voltage U_g feeding the loudspeaker (we assume the amplifier presents a null source resistance $R_g = 0\ \Omega$).

$R_{as} =$	$M_{ap} =$
$M_{as} =$	$C_{a2} =$
$C_{as} =$	$C_{ac} =$
$R_{ae} =$	$p_g =$

2. Draw the equivalent acoustic scheme, **at low-frequencies**, of the loudspeaker system of figure 5, neglecting all acoustic resistances except in the loudspeakers as well as the electric inductance L_e. You will also consider that the acoustic mass M_{as} accounts for the discontinuity mass inside cavities V_1 and V_2.

We observe that the volume velocity radiated by the loudspeaker system is the one flowing out of the port, that we denote q_p.

3. Write the relationship between the radiated sound **power** and the volume velocity q_p (we assume here that the port behaves as a rigid piston of section s_2 on a box, and presents the same acoustic radiation resistance as a closed-box loudspeaker diaphragm).

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4. Neglecting the acoustic resistances in the volumes and in the port (but still considering the ones in the loudspeaker : R_{ae} and R_{as}), show that the acoustic power radiated by the loudspeaker system is of the form $P_a(\omega) = P_{as}|G(\omega)|^2$ with :

$$G(j\omega) = \frac{a_2(j\omega)^2}{b_4(j\omega)^4 + b_3(j\omega)^3 + b_2(j\omega)^2 + b_1(j\omega) + 1}$$

   Give the expression of P_{as}, a_2, b_4, b_3, b_2, and b_1 as functions of ρ_{air}, c_{air}, U_g, $B\ell$, S_d, R_{ae}, M_{as}, R_{as}, C_{ac}, C_{a2} and M_{ap}.

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5. Well aligned, the frequency response $G(j\omega)$ resembles a band-pass filter, the bandwidth of which being adjustable with acoustic resistances. What is your opinion on the practical use of such a system ? Can you propose an alternative solution to achieve such a behaviour ?