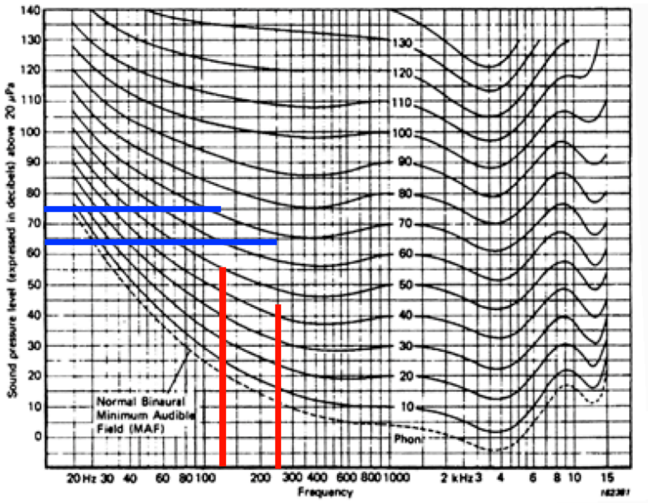
Audio Technology & Acoustics Exam 2019-10-19

Problem 1a)



The frequency dependency of human hearing is described by equal loudness level contours. These show that human hearing is most sensitive around 1-4 kHz. Phon is the unit of loudness level. Two sounds with the same loudness level are perceived as equally strong. The phonscale is defined so that it is coincident with the sound pressure level for a 1-kHz sine tone (at all levels). dBA-, dBB-, & dBC- weighting filters are used in measuring sound pressure level in order to adjust to fit our hearing's sensitivity. These filters are gross approximations of inverses of the equal loudness level curves at 3 different levels: dBA (~40 phon), dBB & dBC for stronger signals.

Problem 1b)

125 Hz – component: 50 phons → (check in equal loudness level graph) → 55 dB
250 Hz – component: 45 phons → (check in equal loudness level graph) → 44 dB

Increase 20 dB after removing the cover:
125 Hz –component: 75 dB → (check in equal loudness level graph) → 71 phon
250 Hz –component: 64 dB → (check in equal loudness level graph) → 68 phon

⇨125 Hz component increases 21 phon
⇨ 250 Hz component increases 23 phon

A-weighting:
125Hz: 75dB – 16dB = 59 dB
250Hz: 64dB – 9dB = 55 dB

Total A-weighted SPL: $L_{p,\mathrm{A}} = 10 \log(10^{59/10} + 10^{55/10})$ dB(A) = 61dB(A)

Problem 2a)

$$L_\mathrm{u} = 20 \log_{10} \frac{\tilde{s}}{\sqrt{0.6}\,\mathrm{Vrms}} \text{ dBu}$$

$$\tilde{s} = \sqrt{0.6}\,\mathrm{Vrms} \cdot 10^{\frac{L_\mathrm{U}}{20\,\mathrm{dBu}}}$$

$$\tilde{s} = \sqrt{0.6}\,\mathrm{Vrms} \cdot 10^{\frac{4\,\mathrm{dBu}}{20\,\mathrm{dBu}}} = 1.2\,\mathrm{Vrms}$$

Problem 2b)

$$\tilde{s} = 1\,\mathrm{Vrms} \cdot 10^{\frac{-10\,\mathrm{dBu}}{20\,\mathrm{dBu}}} = 0.32\,\mathrm{Vrms}$$

Problem 2c)

The microphone sensitivity expressed in dBu is:

$$L_\mathrm{mic} = 20 \log_{10} \frac{0.015\,\mathrm{Vrms}}{\sqrt{0.6}\,\mathrm{Vrms}} \text{ dBu} = -34 \text{ dBu (@ 94 dBSPL)}$$

A microphone signal of level L_MAX produces a signal of level L_OUT at the output of the pre-amplifier that has a gain of G:

$$L_\mathrm{OUT} = L_\mathrm{MAX} - 94\text{ dB} + L_\mathrm{mic} + G$$

So that

$$L_\mathrm{MAX} = L_\mathrm{OUT} - L_\mathrm{mic} - G + 94\text{ dB}$$

With $L_\mathrm{OUT} = 24$ dBu:

$$L_\mathrm{MAX} = 24 - (-34) - 30 + 94 = 122\text{ dBSPL}$$

Problem 3a

V = 7800 m^3, S = 2500 m^2, T_{old} = 2.45 s

=> $\alpha_{old} = \frac{0.16\,V}{T_{old} \cdot S} = 0.204$ (Sabine OK)

$$A_{panel} = \frac{0.16\,V}{T_{panel}} = \alpha_{old}(S - S_{abs}) + \alpha_{abs} S_{abs}$$

$$\alpha_{abs} S_{abs} = \frac{0.16\,V}{T_{panel}} - \alpha_{old}(S - S_{abs}) = \frac{0.16\,V}{T_{panel}} - \frac{0.16\,V}{T_{old} S}(S - S_{abs}) =$$

$$= 0.16\,V\left(\frac{1}{T_{panel}} - \frac{1}{T_{old}} \frac{(S - S_{abs})}{S}\right)$$

$$\rightarrow \alpha_{abs} = \frac{0.16\,V}{S_{abs}}\left(\frac{1}{T_{panel}} - \frac{1}{T_{old}} \frac{(S - S_{abs})}{S}\right) = 0.91$$

Problem 3 b

$T_{new} = \frac{0.16\,V}{A_{new}} = 1.9$ s $\qquad A_{new} = \alpha_{old}(S - S_{abs2}) + \alpha_{abs} S_{abs2}$

$$A_{new} = \frac{0.16\,V}{T_{new}} = \alpha_{old}(S - S_{abs2}) + \alpha_{abs} S_{abs2} = \alpha_{old} S + S_{abs2}(\alpha_{abs} - \alpha_{old})$$

$$S_{abs2} = \left(\frac{0.16\,V}{T_{new}} - \alpha_{old} S\right) \frac{1}{\alpha_{abs} - \alpha_{old}} = 221 \text{ m}^2$$

$\frac{A_{new}}{S} = 0.26$ => Sabine still OK.

Problem 4 a)

The acoustic element described is an example of a porous absorber. As a sound wave passes through the fabric, some of the wave's energy is transformed in to heat due to friction in the material. It is therefore important that the fabric has a certain flow resistance to create this friction. Also, the impedance cannot be too high because then too much of the sound is reflected. Furthermore, high damping is only achieved if the particle velocity is high. The particle velocity has its (first) maximum at $\lambda/4$ m from the wall, so one must hang the cloth relatively far from the wall to achieve low frequency absorption. Porous absorbers are therefore generally used as mid-high frequency broad band absorbers. Absorbers in general are used to lower the reverberation time, to damp single reflections or to lower the overall sound pressure level in a room.

Problem 4 b)

This is an example of a resonant absorber, more specifically a membrane absorber. The mass of the gypsum board and the enclosed air forms an acoustic mass-spring system which is set in motion by the impinging sound wave. Losses have to be inserted into the system to achieve absorption, e.g. by placing a porous absorber inside the membrane absorber. High absorption (resulting from a lot of motion) is achieved around the system's resonance frequency which can be calculated as: $f_0 \approx \frac{60}{\sqrt{m"d}}$, where m" is the mass per unit area of the membrane (the gypsum board). Membrane and other types of resonance absorbers are used for low frequency damping and they have a relatively narrow working range (around the resonance frequency).

Problem 4 c)

The panel depicted in the figure is, depending on its dimensions, a diffusing element. Diffusors are used in concert halls to break up (scatter) strong specular reflections, from e.g. rear walls, which otherwise create disturbing echoes, to get rid of flutter echoes and to make the sound field more diffuse and "enveloping". One needs large irregularities to scatter low frequencies and small irregularities to scatter high frequencies. (*To be more exact, but not required for full number of points: Impinging sound waves will not be affected by the diffusor unless the depths of the irregularities of the panel have sizes ~ λ/4*)

Problem 5

Case 1 (C1): Daniel is playing in room 1

$$L_{p1}^{C1} - L_{p2}^{C1} = R + 10\log\frac{A_2}{S}$$

$$L_{p1}^{C1} = L_W + 10\log\frac{4}{A_1}$$

$$\Rightarrow L_{p2}^{C1} = L_W - R + 10\log\frac{4S}{A_1 A_2}$$

Case 2 (C2): Daniel is playing in room 2

$$L_{p2}^{C2} - L_{p1}^{C2} = R + 10\log\frac{A_1}{S}$$

$$L_{p2}^{C2} = L_{p1}^{C1} = L_W + 10\log\frac{4}{A_1}$$

$$\Rightarrow L_{p1}^{C2} = L_W - R + 10\log\frac{4S}{{A_1}^2}$$

Comparing the cases

$$\Delta L = L_{p2}^{C1} - L_{p1}^{C2} = 10\log\frac{4S}{A_1 A_2} - 10\log\frac{4S}{{A_1}^2} = 10\log\frac{A_1}{A_2}$$

$$A_1 = \frac{55\,V_1}{c\,T_1} = 12.8\ \mathrm{m^2S}\,,\ A_2 = \frac{55\,V_2}{c\,T_2} = 7.3\ \mathrm{m^2S}$$

$$A_1 > A_2 \Rightarrow \Delta L > 0$$

This means, it is not true! The total A-weighted sound pressure level will be higher in room 2 if Daniel is playing in room 1 compared to the total A-weighted sound pressure level in room 1 if Daniel is playing in room 2. Daniel should move to room 2.

Alternatively, you can solve the task by calculating the numerical values of the A-weighted sound pressure levels:

Total area $S = S_{door} + S_{wall} = 2\ \mathrm{m}^2 + 10\ \mathrm{m}^2 = 12\ \mathrm{m}^2$

Reduction index $R = 10\log\left(\frac{S}{S_{door}\,10^{-R_{door}/10} + S_{wall}\,10^{-R_{wall}/10}}\right)$

	250 Hz	1 kHz
R_{door} , dB	20	31
R_{wall} , dB	32	44
R, dB	26.6	37.8

Case 1 (C1): Daniel is playing in room 1

	250 Hz	1 kHz
L_{p2}^{C1}, dB	55.5	44.3

$L_{p2,tot,A}^{C1} = 10\log\left(10^{(55.5-9)/10} + 10^{44.3/10}\right) = 48.5 \text{ dB(A)}$

Case 2 (C2): Daniel is playing in room 2

	250 Hz	1 kHz
L_{p1}^{C2}, dB	53.1	41.9

$L_{p1,tot,A}^{C2} = 10\log\left(10^{(53.1-9)/10} + 10^{41.9/10}\right) = 46.1 \text{ dB(A)}$

Same conclusion as above, Case 2 leads to a lower sound pressure level in Vincent's room.

Problem 6a

Height of loudspeaker and listener above ground: $h = 0.8\text{m}$
Length of direct path: $r_\text{d} = 2.5\text{m}$
Pressure reflection coefficient: $r = 1$

Length of reflected path:

$$r_\text{r} = 2 \cdot \sqrt{\left(\frac{r_\text{d}}{2}\right)^2 + h^2} = 2 \cdot \sqrt{\left(\frac{2.5\text{ m}}{2}\right)^2 + (0.8\text{ m})^2} \approx 2.97\text{ m}$$

Direct sound in listening position:

$$\underline{p}_\text{d} = \frac{A}{r_\text{d}} e^{-jkr_\text{d}}$$

Reflected sound in listening position:

$$\underline{p}_\text{r} = r\frac{A}{r_\text{r}} e^{-jkr_\text{r}}$$

Total sound in listening position:

$$\underline{p}_\text{tot} = \underline{p}_\text{d} + \underline{p}_\text{r} = \frac{A}{r_\text{d}} e^{-jkr_\text{d}} + r\frac{A}{r_\text{r}} e^{-jkr_\text{r}}$$

Deviation from free field response:

$$\Delta L_p = L_{p,\mathrm{tot}} - L_{p,\mathrm{d}} = 10\log\left(\frac{\tilde{p}_{\mathrm{tot}}}{\tilde{p}_{\mathrm{d}}}\right)^2 = 10\log\left(\frac{\left|\underline{p}_{\mathrm{tot}}\right|}{\left|\underline{p}_{\mathrm{d}}\right|}\right)^2$$

$$= 10\log\left(\frac{\left|\frac{A}{r_\mathrm{d}}e^{-jkr_\mathrm{d}} + r\frac{A}{r_\mathrm{r}}e^{-jkr_\mathrm{r}}\right|^2}{\left|\frac{A}{r_\mathrm{d}}e^{-jkr_\mathrm{d}}\right|^2}\right) = 10\log\left(\frac{\left|\frac{1}{r_\mathrm{d}}e^{-jkr_\mathrm{d}} + r\frac{1}{r_\mathrm{r}}e^{-jkr_\mathrm{r}}\right|^2}{\left|\frac{1}{r_\mathrm{d}}\right|^2}\right)$$

$$= 10\log\left(\left|e^{-jkr_\mathrm{d}} + r\frac{r_\mathrm{d}}{r_\mathrm{r}}e^{-jkr_\mathrm{r}}\right|^2\right)$$

$$= 10\log\left(\left(e^{-jkr_\mathrm{d}} + r\frac{r_\mathrm{d}}{r_\mathrm{r}}e^{-jkr_\mathrm{r}}\right)\left(e^{jkr_\mathrm{d}} + r\frac{r_\mathrm{d}}{r_\mathrm{r}}e^{jkr_\mathrm{r}}\right)\right)$$

$$= 10\log\left(1 + r\frac{r_\mathrm{d}}{r_\mathrm{r}}2\cdot\frac{1}{2}\left(e^{jk(r_\mathrm{r}-r_\mathrm{d})} + e^{-jk(r_\mathrm{r}-r_\mathrm{d})}\right) + r^2\frac{r_\mathrm{d}^2}{r_\mathrm{r}^2}\right)$$

$$= 10\log\left(1 + 2\,r\frac{r_\mathrm{d}}{r_\mathrm{r}}\cos\left(k(r_\mathrm{r}-r_\mathrm{d})\right) + r^2\frac{r_\mathrm{d}^2}{r_\mathrm{r}^2}\right)$$

$$\Delta L_{p,\max} = 10\log\left(1 + 2\,r\frac{r_\mathrm{d}}{r_\mathrm{r}} + r^2\frac{r_\mathrm{d}^2}{r_\mathrm{r}^2}\right) = 10\log\left(1 + r\frac{r_\mathrm{d}}{r_\mathrm{r}}\right)^2 = 20\log\left(1 + r\frac{r_\mathrm{d}}{r_\mathrm{r}}\right)$$

$$= 20\log\left(1 + 1\cdot\frac{2.5\ \mathrm{m}}{2.97\ \mathrm{m}}\right) \approx \underline{5.3\ \mathrm{dB}}$$

$$\Delta L_{p,\min} = 10\log\left(1 - 2\,r\frac{r_\mathrm{d}}{r_\mathrm{r}} + r^2\frac{r_\mathrm{d}^2}{r_\mathrm{r}^2}\right) = 10\log\left(1 - r\frac{r_\mathrm{d}}{r_\mathrm{r}}\right)^2 = 20\log\left(1 - r\frac{r_\mathrm{d}}{r_\mathrm{r}}\right)$$

$$= 20\log\left(1 - 1\cdot\frac{2.5\ \mathrm{m}}{2.97\ \mathrm{m}}\right) \approx \underline{-16\ \mathrm{dB}}$$

Problem 6b

Minimum when $\cos\left(k(r_\mathrm{r}-r_\mathrm{d})\right) = -1 \Longrightarrow |k(r_\mathrm{r}-r_\mathrm{d})| = (2n+1)\,\pi$ with $n = 0,1,2,\ldots$

$$\left|\frac{2\pi f_n}{c}(r_\mathrm{r}-r_\mathrm{d})\right| = (2n+1)\,\pi$$

$$f_n = \frac{(2n+1)\,\pi\,c}{2\pi|r_\mathrm{r}-r_\mathrm{d}|} = \frac{(2n+1)}{2}\frac{c}{|r_\mathrm{r}-r_\mathrm{d}|}$$

First minimum ($n = 0$):

$$f_0 = \frac{1}{2}\frac{c}{|r_\mathrm{r}-r_\mathrm{d}|} = \frac{1}{2}\frac{343\,\frac{\mathrm{m}}{\mathrm{s}}}{|2.97\ \mathrm{m} - 2.5\ \mathrm{m}|} \approx \underline{365\ \mathrm{Hz}}$$

Second minimum ($n = 1$):

$$f_1 = \frac{3}{2}\frac{c}{|r_\mathrm{r}-r_\mathrm{d}|} = \frac{3}{2}\frac{343\,\frac{\mathrm{m}}{\mathrm{s}}}{|2.97\ \mathrm{m} - 2.5\ \mathrm{m}|} \approx \underline{1095\ \mathrm{Hz}}$$

Problem 6c

The derivation in a) holds for any real-valued r.

$$\Delta L_{p,\max} = 20\log\left(1 + r\frac{r_\mathrm{d}}{r_\mathrm{r}}\right)$$

$$1 + r\frac{r_\mathrm{d}}{r_\mathrm{r}} = 10^{\frac{\Delta L_{p,\max}}{20}}$$

$$r = \frac{r_\mathrm{r}}{r_\mathrm{d}}\left(10^{\frac{\Delta L_{p,\max}}{20}} - 1\right)$$

$$\alpha = 1 - |r|^2 = 1 - \left|\frac{r_\mathrm{r}}{r_\mathrm{d}}\left(10^{\frac{\Delta L_{p,\max}}{20}} - 1\right)\right|^2 = 1 - \left|\frac{2.97\ \mathrm{m}}{2.5\ \mathrm{m}}\left(10^{\frac{2}{20}} - 1\right)\right|^2 \approx \underline{0.91}$$

$$L_{p,\min} = 20\log\left(1 - r\frac{r_\mathrm{d}}{r_\mathrm{r}}\right)$$

$$1 - r\frac{r_\mathrm{d}}{r_\mathrm{r}} = 10^{\frac{\Delta L_{p,\max}}{20}}$$

$$r = \frac{r_\mathrm{r}}{r_\mathrm{d}}\left(1 - 10^{\frac{\Delta L_{p,\max}}{20}}\right)$$

$$\alpha = 1 - |r|^2 = 1 - \left|\frac{r_\mathrm{r}}{r_\mathrm{d}}\left(1 - 10^{\frac{\Delta L_{p,\max}}{20}}\right)\right|^2 = 1 - \left|\frac{2.97\ \mathrm{m}}{2.5\ \mathrm{m}}\left(1 - 10^{\frac{-2}{20}}\right)\right|^2 \approx \underline{0.94}$$

If a maximum deviation of ± 2 dB from flat frequency response is required, the absorption coefficient α needs to be at least 0.94.