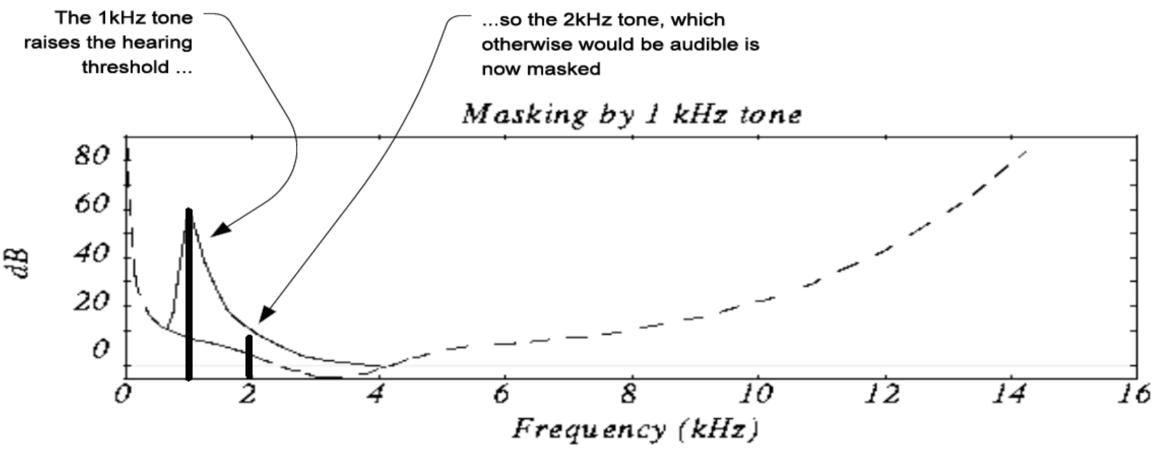
Audio Technology & Acoustics Exam 2021-10-26

Problem 1a)

Frequency masking means that a tone having a certain frequency (masker) raises the hearing threshold around the tone's frequency so another, weaker tone, having a frequency close to the masker's frequency, presented at the same time will not be heard. The threshold shift caused by the masker is greater above the masker's frequency than for frequencies below the masker's frequency as shown in the figure.



The reason for frequency masking arises from the functioning of our hearing. The inner ear performs some kind of spatial frequency analysis. Different parts of the basilar membrane are associated with different frequencies. As each tone sets into vibration a certain area of the basiliar membrane, a weaker tone with similar frequency may not be detected.

Problem 1b)

Read the threshold of hearing from the lower graph. If the levels of the harmonics are above the new masked threshold, they will be audible.

	800 Hz	4 kHz
Threshold	+5 dB	-4 dB
Shift	+40 dB	+28 dB
Masked threshold	45 dB	24 dB
level of the harmonic	30 dB	30 dB
Audible	No	Yes

Problem 2a)

$T_0 = 0.36$ s $\alpha_{\text{fiberglass}} = 0.8$ $\alpha_{\text{floor}} = \alpha_{\text{ceiling}}$

$T_{\text{des}} = 1.4$ s ("desired") $\alpha_{\text{table}} = 0.01$

$L = 10$ m, $W = 10$ m, $H = 3$ m, $S_{\text{table}} = 1\ \text{m}^2$

$V_0 = L \cdot W \cdot H = 10 \cdot 10 \cdot 3\ \text{m}^3 = 300\ \text{m}^3$

$S_{\text{wall}} = 2 \cdot (L \cdot H + W \cdot H) = 2 \cdot (10 \cdot 3 + 10 \cdot 3)\ \text{m}^2 = 120\ \text{m}^2$
$S_{\text{floor}} = S_{\text{ceiling}} = L \cdot W = 10 \cdot 10\ \text{m}^2 = 100\ \text{m}^2$
$S_{\text{tot}} = S_{\text{wall}} + S_{\text{floor}} + S_{\text{ceiling}} = (120 + 100 + 100)\ \text{m}^2 = 320\ \text{m}^2$

Diffuse field at 1 kHz?
$f_{S,0} = 2000\sqrt{\frac{T_0}{V_0}} = 2000\sqrt{\frac{0.36}{300}} = 69\ \text{Hz} < 1\ \text{kHz}$ ⇒ diffuse field at 1 kHz
$f_{S,\text{des}} = 2000\sqrt{\frac{T_{\text{des}}}{V_0}} = 2000\sqrt{\frac{1.4}{300}} = 137\ \text{Hz} < 1\ \text{kHz}$ ⇒ diffuse field at 1 kHz

Current situation:

$$T_0 = \frac{24 \ln 10\, V_0}{cA_0}$$

$$A_0 = \frac{24 \ln 10\, V_0}{cT_0} = \frac{24 \ln 10 \cdot 300}{343 \cdot 0.36}\ \text{m}^2 = 134.26\ \text{m}^2$$

First try Sabine's formula:

$$\alpha_0 = \frac{A_0}{S_{\text{tot}}} = \frac{134.26}{320} = 0.4196 > 0.3$$

$\Rightarrow$ must use Eyring's formula

$$A_0 = -S_{\text{tot}} \ln(1 - \alpha_0)$$

$$\alpha_0 = 1 - e^{-\frac{A_0}{S_{\text{tot}}}} = 1 - \mathrm{e}^{-\frac{134.26}{320}} = 0.3427$$

$\alpha_0 S_{\text{tot}} = \alpha_{\text{fiberglass}} S_{\text{wall}} + \alpha_{\text{floor}} S_{\text{floor}} + \alpha_{\text{ceiling}} S_{\text{ceiling}}$ (1)

Desired situation:

$$A_{des} = \frac{24 \ln 10\, V_0}{c\, T_{des}} = \frac{24 \ln 10 \cdot 300}{343 \cdot 1.4}\ \text{m}^2 = 34.52\ \text{m}^2$$

First try Sabine's formula:

$$\alpha_{des} = \frac{A_{des}}{S_{\text{tot}}} = \frac{34.52}{320} = 0.1079 < 0.3 \quad \Rightarrow \text{Sabine ok}$$

$\alpha_{\text{des}} S_{\text{tot}} = \alpha_{\text{fiberglass}}(S_{\text{wall}} - n\, S_{\text{table}}) + \alpha_{\text{table}}\, n\, S_{\text{table}} + \alpha_{\text{floor}} S_{\text{floor}} + \alpha_{\text{ceiling}} S_{\text{ceiling}}$ (2)

(1)-(2)

$$(\alpha_0 - \alpha_{\text{des}}) S_{\text{tot}} = \alpha_{\text{fiberglass}} n\, S_{\text{table}} - \alpha_{\text{table}}\, n\, S_{\text{table}}$$

$$n = \frac{(\alpha_0 - \alpha_{\text{des}}) S_{\text{tot}}}{(\alpha_{\text{fiberglass}} - \alpha_{\text{table}}) S_{\text{table}}} = \frac{(0.3427 - 0.1079) \cdot 320\ \text{m}^2}{(0.8 - 0.01) \cdot 1\ \text{m}^2} = 95.11 \approx 95$$

They need to install 95 table tops.

Problem 2b)

If we increase V (with no increase in A), T can be increased to reach T_{des} :

$$T_{\text{des}} = \frac{24 \ln 10\, V_{\text{des,b}}}{cA_0}$$

Now compare the sound pressure level in the desired room from a) (with $T_{\text{des}}, A_{\text{des,a}}, V_0$) to the sound pressure level in the desired room from b) (with $T_{\text{des}}, A_0, V_{\text{des,b}}$) for the same source power W:

$$L_{p,\text{a}} = L_W + 10\log\left(\frac{4}{A_{\text{des,a}}}\right) = L_W + 10\log\left(\frac{4\,cT_{\text{des}}}{24\ln 10\,V_0}\right)$$
$$L_{p,\text{b}} = L_W + 10\log\left(\frac{4}{A_0}\right) = L_W + 10\log\left(\frac{4\,cT_{\text{des}}}{24\ln 10\,V_{\text{des,b}}}\right)$$
$$L_{p,\text{b}} - L_{p,\text{a}} = 10\log\left(\frac{A_{\text{des,a}}}{A_0}\right) = 10\log\left(\frac{V_0}{V_{\text{des,b}}}\right) < 0$$

If we increase the volume to get the same T, the room would be "softer" (smaller Lp for the same source W).

Problem 3

a)

$$p_{\text{tot}} = A\mathrm{e}^{\mathrm{j}(\omega t - kx)} + rA\mathrm{e}^{\mathrm{j}(\omega t + kx)} = \{r = 1\} = A\mathrm{e}^{\mathrm{j}\omega t}\left(\mathrm{e}^{-\mathrm{j}kx} + \mathrm{e}^{\mathrm{j}kx}\right) = 2A\cos(kx)\mathrm{e}^{\mathrm{j}\omega t}$$

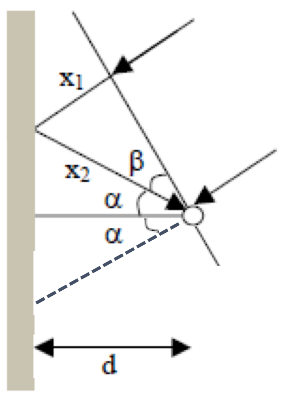
$$\left|\frac{p_{\text{tot}}}{p_{\text{inc}}}\right| = 2\cos(kd) = 10^{3/20} \rightarrow d = 2.9\text{ mm, (for } f = 15\text{ kHz)}$$

b) $|p_{\text{tot}}| = A\left|1 + r\mathrm{e}^{\mathrm{j}k2d}\right| = A\sqrt{1 + r^2 + r(\mathrm{e}^{\mathrm{j}k2d} + \mathrm{e}^{-\mathrm{j}k2d})} =$
$A\sqrt{1 + r^2 + 2r\cos(2kd)}$

The maximum increase will occur at $f = 0$.

$$|p_{\text{tot}}|_{max} = \begin{Bmatrix} f \rightarrow 0 \\ kd \rightarrow 0 \\ r \rightarrow 0.9 \end{Bmatrix} = A\sqrt{1 + 0.81 + 1.8} \rightarrow 20\log\frac{|p_{\text{tot}}|_{\text{max}}}{|p_{\text{inc}}|} = 5.6\text{ dB}$$

c)



Reflected wave travels a distance (x_1+x_2) longer than the direct path.

$$d/x_2 = \cos\alpha \rightarrow x_2 = d/\cos\alpha$$

$$\frac{x_1}{x_2} = \sin\beta \rightarrow \beta = 90° - 2\alpha$$

$$x_1 = x_2\sin(90 - 2\alpha) = x_2\sin 2\alpha = \frac{d}{\cos\alpha}(2\cos^2\alpha - 1) = d(2\cos\alpha - \frac{1}{\cos\alpha})$$

$$x_1 + x_2 = d\left(2\cos\alpha - \frac{1}{\cos\alpha}\right) + \frac{d}{\cos\alpha} = 2d\cos\alpha$$

For the reflected wave to cancel the impinging wave: $x_1 + x_2 = \lambda/2$

$$f = \frac{c}{\lambda} = \frac{c}{2(x_1 + x_2)} = \frac{c}{4d\cos\alpha} = \cdots = 35\text{ kHz}$$

Problem 4 a)

$$f_{q_x q_y q_z} = \frac{c}{2}\sqrt{\frac{q_x^2}{l_x^2} + \frac{q_y^2}{l_y^2} + \frac{q_z^2}{l_z^2}} \Rightarrow f_{110} = \frac{343}{2}\sqrt{\frac{1}{3.9^2} + \frac{1}{3.6^2}}\text{Hz} = 64.8\text{ Hz}$$

Problem 4 b)

Helmholtz absorber – eq. 7.17

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{S}{V\left(l_h + \frac{\pi}{2}b\right)}}$$

b: hole radius
l_h: hole length
x: distance between centre of the holes
d: distance between panel and the wall (this is the unknown variable)
$S = \pi b^2$(cross sectional area of each hole)
$V = x^2 d$ (volume behind each hole)

$$\left(\frac{2\pi f_0}{c}\right)^2 = \frac{\pi b^2}{x^2 d\left(l_h + \frac{\pi}{2}b\right)} \Rightarrow d = \frac{\pi b^2}{\left(\frac{2\pi f_0}{c}\right)^2 x^2\left(l_h + \frac{\pi}{2}b\right)}$$
$$= \frac{\pi(0.0025)^2}{\left(\frac{2\pi \cdot 64.8}{343}\right)^2 (0.12)^2\left(0.01 + \frac{\pi}{2}0.0025\right)}\ \frac{\text{m}^2}{\left(\frac{\text{s}}{\text{m s}}\right)^2 \text{m}^2\text{ m}}$$
$$= 0.0695\text{ m} \approx 70\text{ mm}$$

Problem 4 c)

Efficient absorption when thickness is $> \frac{\lambda}{4}$ (absorption ~ particle velocity)
f=65 Hz $\Rightarrow \lambda = \frac{c}{f} = \frac{343}{65}m = 5.3$ m, $\frac{\lambda}{4} = 1.3$ m thick absorber, too thick considering the size of the room

Problem 5a)

f= [500, 1000] Hz, $f_c=K_c/h= 32\,\frac{m}{s}$ / 0.013 m = 2460 Hz

=> $f<f_c$ => $R_d = 20\log m'' + 20\log f - 49dB$

$m'' = \rho \cdot h = 840\,\frac{\text{kg}}{\text{m}^3}\cdot 0.013\text{ m} \approx 10.9\,\frac{\text{kg}}{\text{m}^2}$

=> R_d= [25.7 31.8] dB

Including door ($R_{d,door}$= 20 dB): $S_{tot}=S_{wall}+S_{door}$= 10 m^2+2 m^2 = 12 m^2

$$R_{res} = 10\log\frac{S_{tot}}{S_{wall}\cdot 10^{-R_d/10} + S_{door}\cdot 10^{-R_{d,door}/10}} = [24.1\quad 26.5]\text{ dB} \approx [24\quad 27]\text{ dB}$$

Problem 5b)

$$L_{p1} = L_W + 10\log\frac{4}{A_1}\quad ,\qquad L_{p1} - L_{p2} = R_{\text{res}} + 10\log\frac{A_2}{S}$$

Sabine's formula gives (assuming negligible air absorption):

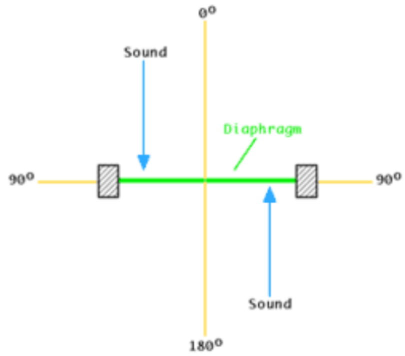
$$T = \frac{24\ln 10\, V}{cA} \Rightarrow A_1 = \frac{24\ln 10\, V_1}{c\cdot T_1} = \frac{24\ln 10\cdot 40}{343\cdot 0.4}\text{m}^2 = 16.11\text{ m}^2$$
$$A_2 = \frac{24\ln 10\cdot 60}{343\cdot 0.45}\text{m}^2 = 21.48\text{ m}^2$$
$$L_W = [84\quad 88]\text{ dB} \Rightarrow L_{p1} = L_W + 10\log\frac{4}{A_1} = [77.95\quad 81.95]\text{ dB}$$
$$L_{p2} = L_{p1} - R_{\text{res}} - 10\log\frac{A_2}{S} = [51.32\quad 52.92]$$
$$L_{p2,A} = 10\log\left(10^{(51.32-3)/10} + 10^{52.92/10}\right)\text{dB(A)} = 54.21\text{ dB(A)} \approx 54.2\text{ dB(A)}$$

Problem 5c)

$$L_{p1,\text{new}} = L_{p2,\text{new}} - R_{\text{res}} - 10\log\frac{A_1}{S}$$
$$L_{p2,\text{new}} = L_{p1,\text{old}} = [77.95\quad 81.95]\text{ dB}$$
$$L_{p1,\text{new}} = [52.57\quad 54.17]\text{ dB}$$
$$L_{p1,\text{new},A} = 55.46\text{ dB(A)} \approx 55.5\text{ dB(A)}$$

Problem 6)

a) The diaphragm sits in mid-air without any housing:

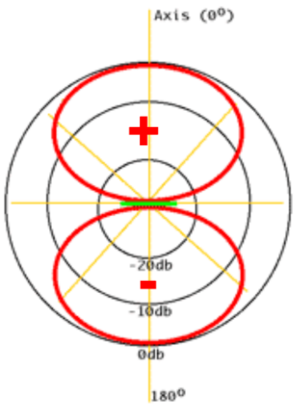


Sound that impinges from 0° or 180° has to travel an extra distance around the diaphragm to reach the rear side. This produces a pressure different between front and rear of the diaphragm that causes the diaphragm to experience a force. The algebraic sign differs for 0° and 180°.

Sound that impinges from +90° or 90° reaches the front and read of the diaphragm without any path length difference -> no pressure difference -> no force

Sound that impinges from other angles produces somewhat of a pressure difference -> small force -> low sensitivity for sound incidence from these directions.

Polar pattern:



b) 1: Place an omnidirectional microphone coincident with a figure-of-eight and add the output signals
2: Build a microphone capsule with a port on the back side