INDIANA UNIVERSITY, DEPT. OF PHYSICS
P105, Basic Physics of Sound, Spring 2010

Midterm Exam #2
Thursday, 25 March 2010, 7:30 – 9:30 p.m.
Closed book. You are allowed a calculator.

There is a Formula Sheet and Equal Loudness Curves at the back of the exam
Fill in the answers on the exam sheets themselves. If you run out of room, use the back of
the sheets. You must show your work and give answers with units for full credit! In many
cases I give partial credit – try not to leave blank answers. Show your work for fill in the
blank and multiple-choice questions as well.

Please keep your work covered and your eyes on your own paper during the exam.
The penalty for cheating is an automatic zero!

1. Messing with clarinets:

(a) (3 pts) A clarinet can be modeled by a tube of a certain length $L$, closed at one end (reed
d end), and open at the other. Sketch below what the standing wave pattern would look like
for the third harmonic, $f_3$, in this tube, clearly labeling nodes and anti-nodes with "N" and
"A".

\[ f_n = \frac{nv}{4L} \]
\[ L = \frac{nv}{4f_n} \]
\[ L = \frac{3(343 \text{ m/s})}{4(400 \text{ Hz})} = 0.643 \text{ m} \]
\[ = 64.3 \text{ cm} \]

(b) (3 pts) This third harmonic, $f_3$, has a frequency of 400 Hz at a temperature of 20° C where
the speed of sound is 343 m/s.
Estimate the length of this tube modeling the clarinet: 64.3 cm.

(c) (3 pts) A musician picks up the clarinet and starts playing so that the air in the clarinet
warms up to a higher temperature. If the resulting new frequency of the third harmonic $f_3$ is
404 Hz, what is the temperature inside the tube (assuming that the length does not change)?

\[ f_n = \frac{nv}{4L} \]
\[ v = 4Lf_n \]
\[ n = 3 \]
\[ v = \frac{(4)(0.643 \text{ m})}{3}(404 \text{ Hz}) = 346.3 \text{ m/s} \]

\[ v_{air} = \left( \frac{331.3 + 0.6T}{m/s} \right) \]
\[ T = \left( \frac{346.3 \text{ m/s}}{0.6} \right) - 331.3 \text{ m/s} = 25.0° \text{ C} \]
(d) (2 pts) What is the fundamental frequency of the clarinet at this new temperature?

\[ f_n = n f_1, \quad f_1 = \frac{409 Hz}{3} = 134.7 \text{ Hz} \]

(e) (3 pts) How would the fundamental frequency change if the reed of the clarinet became messed up and the clarinet was acting as a tube open at both ends?

If open at both ends, \( f_n = \frac{nu}{2L} \) instead of \( f_n = \frac{nu}{4L} \).

This is a difference of exactly 2.

\[ f_1^\text{new} = 2(134.7 \text{ Hz}) \]

\[ f_1^\text{new} = 269.4 \text{ Hz} \]

2. Helping out with the Little 5 concert:

You are at a sound check for preparations for the Little 5 Snoop Dogg concert (outside at a fraternity). A speaker on stage playing a tone of 8000 Hz produces a sound intensity level of \( L_1 = 85 \text{ dB} \) at a distance of 10 m.

(a) (3 pts) What is the intensity of this sound (at the distance of 10 m)? \( 3.2 \times 10^4 \text{ W/m}^2 \)

\[ L_I = 10 \log \left( \frac{I}{I_o} \right); \quad 85 \text{ dB} = 10 \log \left( \frac{I}{I_o} \right) \]

\[ 8.5 = \log \left( \frac{I}{I_o} \right), \quad I = (10^{8.5})(10^{-12} \text{ W/m}^2) = 3.16 \times 10^{-4} \text{ W/m}^2 \]

(b) (3 pts) You are standing at this distance of 10 m with a microphone with a active element of area, \( A = 7.8 \times 10^{-5} \text{ m}^2 \). What is the force on this element? (assume spherical spreading of waves).

\[ L_I = L_P = 20 \log \left( \frac{P}{P_o} \right) \quad P = F/A; \quad F = PA \]

\[ 85 \text{ dB} = 20 \log \left( \frac{P}{P_o} \right) \]

\[ 4.25 = \log \left( \frac{P}{P_o} \right), \quad P = (10^{4.25})(2 \times 10^{-5} \text{ N/m}^2) = 0.356 \text{ N/m}^2 \]

\[ F = 2.77 \times 10^{-5} \text{ N} \]

(c) (3 pts) What is the sound power, \( W \), \( 0.40 \text{ dB} \) W and sound power level, \( L_W = \frac{116}{10} \text{ dB} \) of the speaker up on stage?

\[ W = 4 \pi r^2 I \]

\[ W = 4 \pi (10 \text{ m})^2 (3.16 \times 10^{-4} \text{ W/m}^2) \]

\[ W = 0.40 \text{ W} \]

(d) (2 pts) At the distance of 10 m, what is the sound loudness level, \( L_t \)? 73 phons. (use the attached equal loudness curves and draw on it how you found this loudness level).

(e) (2 pts) A roadie walks over to the speaker and adjusts the frequency to 1000 Hz, but leaves the sound power (and hence the sound intensity level) the same.

Will the sound be: (i) softer or (ii) louder? (Circle one).
What is the new loudness level $L_i$? \(85\) phons.
(use the attached equal loudness curves and draw on it how you found this loudness level).

(e) (2 pts) You find this uncomfortably loud and you move away from the speaker. To what distance do you have to move so that the sound intensity level is now $L_i = 75$ dB?

\[
75 \text{ dB} = 10 \log \left( \frac{I}{I_0} \right) \\
7.5 = \log \left( \frac{I}{I_0} \right) \\
I = (10^{7.5})(10^{-12} \text{ W/m}^2) \\
I = 3.16 \times 10^{-5} \text{ W/m}^2
\]

\[
I = \frac{W}{4\pi r^2}, \quad r = \sqrt{\frac{W}{4\pi I}} = \sqrt{\frac{0.4 \text{ W}}{4\pi \times (3.16 \times 10^{-5} \text{ W/m}^2)}} \\
= 31.7 \text{ m}
\]

(f) (3 pts) The roadie now plays white noise through the speaker producing a sound intensity level where you stand of $L_i = 75$ dB. He then switches on a number of identical speakers each producing a sound intensity level of 75 dB. You measure a total sound intensity level of $L_i = 86.7$ dB. How many speakers are playing on stage? \(15\) speakers (assume that they add incoherently, i.e., without interference).

\[
L_i = 10 \log \left( \frac{I}{I_0} \right) \\
86.7 = 10 \log \left( \frac{I}{I_0} \right) \\
L_i = 10 \log \left( \frac{I}{I_0} \right) \\
I = 3.16 \times 10^{-5} \text{ W/m}^2
\]

\[
\frac{I}{I_0} = \frac{\text{final intensity}}{\text{initial intensity}} = \frac{4.67 \times 10^{-4} \text{ W/m}^2}{3.16 \times 10^{-5} \text{ W/m}^2} = 14.8 \approx 15
\]

(g) (3 pts) What is white noise? Describe the difference between white noise and pink noise.

White noise is sound that has equal amplitudes at all frequencies: \[\text{Amp} \uparrow \quad f(f_2)\]

Pink noise has equal energy in each octave: \[\text{Amp} \uparrow \quad f(f_2)\]

(h) (2 pts) After the sound check, your ears are ringing. This is called \emph{tinnitus}.

3. Your amazing ear

(a) (2 pts) Two pure tones are close enough in frequency to overlap in their response on the basilar membrane are said to lie within the same \emph{critical} band.

(b) (3 pts) \emph{Low} frequency sounds are localized by their difference in timing between the ears since there is less intensity difference between the ears due to \emph{diffraction} of waves around one’s head.
(c) (4 pts) The function of the middle ear is to \underline{amplify} the pressure delivered to the oval window and to protect the inner ear through the \underline{acoustic reflex} (two words).

Give two ways how the middle ear accomplishes the first blank.

(i) \textbf{Artefact} > \textbf{Oval Window}, \textbf{Oval window} = \frac{\text{Artefact}}{\text{Oval Window}}

(ii) \textbf{Lever action of the ossicles of the middle ear}

(d) (4 pts) Where is the basilar membrane and describe how it operates in the detection of (i) pitch; (ii) intensity, and (iii) timbre.

The basilar membrane is in the cochlea where pressure waves in the fluid of the cochlea are excited by pressure variations on oval window.

(i) pitch: close to oval window, the membrane is fast and thin and corresponds to high freq; far from the oval window, it is loose and thick, responding to low freq. This is the Place Theory of Hearing.

(ii) intensity: larger vibrations of membrane, more neural signals from hair cells

(iii) timbre: pattern of which frequencies excited along length.

4. Details of Pitch

(a) (2 pt) What frequency is 3 octaves above a frequency of \( f = 1200 \text{ Hz} \)? \( 9600 \text{ Hz} \)

3 octaves; 3 doublings: \( 1200 \text{ Hz} \times 2 = 2400 \text{ Hz} \times 2 = 4800 \text{ Hz} \times 2 = 9600 \text{ Hz} \)

(b) (1 pt) Is this new frequency beyond the normal frequency response of a typical adult?

\( \text{Yes} \) (circle one)

(c) (2 pts) What frequency is three semitones below a frequency of \( f = 1200 \text{ Hz} \)? \( \frac{1200 \text{ Hz}}{(1.0536)^{3}} \)

\( 1008.3 \text{ Hz} \)

(d) (2 pts) At this frequency of 1200 Hz, the just noticeable difference, jnd, of frequency is \( 6 \text{ Hz} \).

\( 0.5\% \times (1200 \text{ Hz}) = 0.005 \times (1200 \text{ Hz}) = 6 \text{ Hz} \)

(e) (2 pts) Perceived pitch is quite closely proportional to frequency. Give two variables that result in small differences between perceived pitch and frequency.

\( \text{i) duration } \quad \text{ii) intensity } \quad \text{[iii) envelope]} \)

(f) (2 pts) If three sinusoidal sounds, each with a frequency of 1200, 2400, and 3000 Hz are played together, the pitch of the sound heard would be \( 600 \text{ Hz} \).

\( \text{Greatest common factor: } 600 \text{ Hz} \)

(g) (3 pts) A piano tuner with a middle A tuning fork giving a tone of frequency 440 Hz strikes it while hitting the middle A piano key and hears a beat frequency of 4 Hz.

(i) What are the possible frequencies of the piano key? \( f_{\text{beat}} = | f_{\text{A}} - f_{8} | \)

\( f_{8} = 444 \text{ Hz or } 436 \text{ Hz} \)

\( 4 \text{ Hz} = | 1440 \text{ Hz} - f_{8} | \)

(ii) What is actually changing at the beat frequency of 4 Hz?

\( \text{The amplitude of the fixed tone} \)

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5. (4 pts) For the given frequency spectrum input to a filter resulting in the output frequency spectrum shown, draw the filter function and name the type of filter.

![Filter Function Diagram]

Name of filter: **High-pass filter**
(or band-pass filter)

6. Getting more complex

(a) (2 pts) A complex tone consisting of a sawtooth (ramp) wave repeats itself every 6.0 ms and can be reconstructed by adding a series of pure sinusoidal tones with different frequencies and amplitudes. The frequencies of the first three Fourier sinusoidal frequencies are \(167\) Hz, \(333\) Hz, and \(500\) Hz.

\[ T = 6.0 \text{ ms} = 6.0 \times 10^{-3} \text{ sec} \]

\[ f = \frac{1}{T} = \frac{1}{6.0 \times 10^{-3}} \text{ sec} \]

\[ f = 167 \text{ Hz} \]

(b) (2 pts) If the amplitude of the first (fundamental) Fourier component is \(A_1 = 2.0\) Volts, then the amplitudes of the second and third Fourier components are \(A_2 = 1.0\) Volts and \(A_3 = 0.66\) Volts.

\[ A_n = A_1/n, \quad A_2 = \frac{A_1}{2} = \frac{2.0\text{V}}{2} = 1.0\text{V} \]

\[ A_3 = \frac{A_1}{3} = \frac{2.0\text{V}}{3} = 0.66\text{V} \]

(c) (3 pts) Sketch the waves (amplitude versus time) corresponding to the fundamental and second harmonic overlaid on the same plot (but don’t need to add together!) below. Make sure to fill in the time values on the horizontal axis!
7. Getting glottal

The frequency spectrum for a particular vowel sound spoken by Prof. Van Kooten is shown in the plot below along with an envelope function that represents the response of the vocal tract as a function of frequency.

(a) (2 pts) What frequency corresponds to the pitch that is heard? \(200\) Hz.

(b) (2 pts) What is the time between puffs of air coming through the vocal folds? \(5 \times 10^{-3}\) s.

(c) (3 pts) Estimate the frequencies of the first three formants:
\[ F_1 = 1200 \text{ Hz}; \quad F_2 = 2050 \text{ Hz}; \quad F_3 = 2800 \text{ Hz}. \]

(d) (3 pts) Prof. Van Kooten (foolishly?) sucks down a lung full of sulphur hexaflouride (SF₆) where the speed of sound is \(v_{SF_6} = 150\) m/s compared to the speed of sound in air of \(v_{air} = 343\) m/s.

(i) How does the nature of the sound from his vocal tract change?

Timbre gets lower in pitch.

(ii) Estimate the value of the new formant \(F_1 = \frac{525}{2744} \text{ Hz}. \)

{\text{Formants are resonances, } f = \frac{nu}{4L}. \}

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(e) (2 pts) To analyze speech, it is desirable to display sound level as a function of **frequency** and **time**, and this is called a **Spectrogram**.

(f) (2 pts) Although a terrible singer, Prof. Van Kooten starts to sing the vowel. Sung vowels and their formants differ from spoken vowels in the appearance of a "singer's formant" in the frequency range between 2500 Hz and 3000 Hz.

*Remember that the lecture on Friday (tomorrow) is cancelled. Have a good weekend!*

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**Equal loudness curves:**

![Equal loudness curves](image.png)

*Fig. 2 Estimated new equal-loudness contours*