**UNIV 213 Science & Engineering of Music & Sound Spring 2020**

**Review Sheet for Exam #1**

Please review the "Exam Policies" section of the Exams page at the course web site. You should especially note the following:

1. You will be allowed to use a non-wireless enabled calculator, such as a TI-99.
2. You will be allowed to use two 8.5 × 11-inch two-sided handwritten help sheets and a set of graphs and formulas I will provide to you. No photocopied material or copied and pasted text or images are allowed on the self-prepared help sheets. If there is a table or image from the textbook or some other source that you feel would be helpful and that is not included on the sheet that I will provide to you, please notify me.
3. All help sheets will be collected at the end of the exam but will be returned to you later.
4. You may not leave the exam room without prior permission except for an emergency or for an urgent or documented medical condition. Please use the restroom before the exam. If you are allowed to leave the room, you must leave your cell phone behind. Only one student at a time may be absent from the room.

The following is a list of topics that could appear in one form or another on the exam. Not all of these topics will be covered, and it is possible that an exam problem could cover a detail not specifically listed here. However, this list has been made as comprehensive as possible.

Although significant effort has been made to ensure that there are no errors in this review sheet, some might nevertheless appear. The textbook is the final authority in all factual matters, unless errors have been specifically identified there either by the authors (in the form of published errata) or by me. You are ultimately responsible for obtaining accurate and authoritative information when preparing for your exam.

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What causes sounds?

Sound waves

- alternating compression & rarefaction of air molecules; transitions from compression to rarefaction are often periodic (i.e., pattern repeats over time)
- longitudinal waves (most sounds) vs. transverse waves
- In most cases, individual particles (usually molecules) oscillate back and forth over a tiny distance and eventually return to their original position after the wave passes (superposed on random Brownian motion).
- Wave energy and waveforms move at the speed of sound.
- energy transmission vs. motion of individual particles

Traveling waves vs. standing waves

Traveling sound waves

- almost always longitudinal (can be transverse on strings, solid surfaces, a few other cases)
- Pressure is in phase with particle velocity but out of phase with particle displacement
- speed of sound in air:
  $v = 20.1\sqrt{T}$ ,
  where $T$ = temperature in kelvins ($T$[K] = $T$[°C] + 273)

- mathematical representation:
  $$p(x,t) = A\cos(kx \pm \omega t) = A\cos(\omega t \pm kx),$$
  where $A$ = amplitude, $k$ = wave number, and $\omega$ = radian frequency
- definitions of frequency, radian frequency, wavelength, wave number, period, speed, and their relationships
  $$k = \frac{2\pi}{\lambda},\ \omega = 2\pi f,\ f = \frac{v}{\lambda},\ T = \frac{1}{f}$$
- $T$ can represent period or temperature; use context to determine which one applies

Vibration and resonance

- Vibrations are almost always standing sound waves.
- resonance of open pipe
  $$f_n = n\frac{v}{2L},$$
  where $n$ = index of harmonic frequency (fundamental corresponds to $n$ = 1), $v$ = speed of sound, $L$ = effective length; at $f_1$, length of pipe is $\lambda/2$
- resonance of closed pipe
  $$f_n = n\frac{v}{4L}$$; $n$ may only be odd
- effective length is the actual length plus the end correction:
  correction = 0.61$r$ for closed pipes;
  correction = 1.22$r$ for open pipes, where $r$ = radius of pipe
- resonance of string with both ends tied to stationary objects
  $$f_n = n\frac{v}{2L},$$
  where $n$ = index of harmonic frequency (fundamental corresponds to $n$ = 1), $v$ = speed of sound, $L$ = length of string; at $f_1$, length of string is $\lambda/2$

Structure of inner ear

- ear canal (closed pipe resonance around 3 kHz) and eardrum
- ossicles (inner bones), commonly called the hammer, the anvil, and the stirrup
- cochlea
  - oval window (pressure is 30 times that of eardrum)
  - long tube wound into a spiral
  - tube is split into multiple chambers or canals
  - large "upper" canal is the scala vestibuli; it is connected to the oval window; large "lower" canal is the scala tympani; s. vestibuli and s. tympani are connected together at the far end of the cochlea; both scala are filled with a fluid called perilymph
  - separating the canals is a complex structure that combines the basilar membrane, the cochlear duct, Reissner's membrane, and the organ of Corti
  - organ of Corti contains different types of hair cells that appear to be sensitive to different audio frequency ranges
- critical bands
  - each critical band is a range of frequencies over which the same section of the basilar membrane (with the hairs of the organ of Corti) is mostly active
  - about 24 critical bands span the audio spectrum (20–20,000 Hz)
  - roughly 100 Hz wide below around 500–1000 Hz; proportional to frequency above 1 kHz
  - play a significant role in the perception of pitch and other sound properties

Sound power (usually represented by *P*, although the textbook uses the symbol *W*) and sound power level ($L_W$)

- power unit is the watt, W
- change in power (increase or decrease) as a multiplying factor expressed in decibels

  $$\Delta L = 10\log\left(\frac{P_2}{P_1}\right)$$

- sound power level (always expressed in decibels)

  $$L_W = 10\log\left(\frac{P}{P_0}\right),$$

  where $P_0 = 10^{-12}$ W = 1 pW (reference power)

Sound intensity (*I*) and intensity level ($L_I$)

- intensity is the power per unit area (unit is watts per square meter, W/m$^2$)
- intensity level (always expressed in decibels)

  $$L_I = 10\log\left(\frac{I}{I_0}\right),$$

  where $I_0 = 10^{-12}$ W/m$^2$ = 1 pW/m$^2$ (reference intensity)
- intensity due to power source radiating in free space (no nearby obstacles, no ground)

  $$I = \frac{P}{4\pi R^2},$$

  where *P* = power of sound source (such as a loudspeaker or sonar transducer) and *R* = radius of spherical surface centered on sound source
- intensity due to power source radiating in hemispherical space with no nearby obstacles but over solid ground

  $$I = \frac{P}{2\pi R^2};$$

  intensity is twice as great for given applied power because the power is distributed over half the volume compared to completely open three-dimensional space
- both formulas for *I* ignore possible reflections and other interactions with nearby objects

Sound pressure (*p*) and sound pressure level ($L_p$ or SPL)

- pressure is force per unit area; unit is newton per square meter, N/m$^2$, or pascal, Pa
- sound pressure level (always expressed in decibels)

  $$L_p = 20\log\left(\frac{p}{p_0}\right),$$

  where $p_0 = 2 \times 10^{-5}$ Pa = 20 μPa (reference pressure; roughly equal to the threshold of hearing); note that 20, not 10, multiplies the logarithm for SPL
- relationship between sound intensity and sound pressure

  $$I = \frac{p^2}{\rho v},$$

  where *p* = pressure, $\rho$ = mass density of air (close to 1.2 kg/m$^3$ at room temperature and sea level), and *v* is the speed of sound; $\rho v \approx 400$ at room temperature and sea level

Calculation of sound power required to produce a specific SPL at a given distance

- use $I = \frac{P}{4\pi R^2}$ or $I = \frac{P}{2\pi R^2}$ to approximate relationship between radiated power from sound source to intensity at distance *R*; there could be considerable error using simple formulas, but they often provide accuracy to within a few dB

- account for efficiency of loudspeaker or other sound transducer being used (speaker efficiency can be very low; 2% to 5% is typical)
- use $I = \frac{p^2}{\rho v}$ (approximated using $I \approx \frac{p^2}{400}$ at room temperature and sea level) to relate intensity to pressure
- use $L_p = 20\log\left(\frac{p}{p_0}\right)$ for pressure to pressure level conversion

Fletcher-Munson curves

- original research by Fletcher and Munson completed in the early 1930s
- modern curves are actually the ISO 226:2003 standard, but are still often called Fletcher-Munson curves anyway
- curves express the perceived loudness of sounds at different frequencies relative to the loudness at 1000 Hz
- perceived loudness expressed in the phon unit; corresponds to loudness at 1000 Hz; for example, a 100-Hz tone with a perceived loudness level of 40 phons has an SPL of ~51 dB, but a 1000-Hz tone at the same perceived loudness level has an SPL of 40 dB
- loudness of composite sounds (made up of sounds over a range of frequencies) measured using sound level meter
    - A-weighting corresponds to sensitivity of human ear to audio range; low-frequencies and extremely high frequencies are weighted less than middle frequencies
    - Z-weighting applies even weighting (i.e., no filtering) to all frequencies across the audio spectrum

Pitch and virtual pitch

- For single tones, pitch is essentially determined by frequency, although pitch can be affected slightly by loudness, duration, and “attack” (how the sound wave evolves over time).
- Complex tones (i.e., sounds consisting of tones at different frequencies) have pitches that are affected by a wide range of factors.
- If a complex sound consists of a series of harmonically related frequencies, the pitch will correspond to the fundamental frequency, even if the tone at the fundamental frequency is missing (if the fundamental is a few hundred hertz).

Definitions of partial, harmonic, fundamental, periodic wave

Pitch standards

- seem to have been relatively stable during Renaissance (not much known about them before that) but rose considerably during 1700s and especially 1800s, probably because of widespread acceptance of brass instruments in orchestras
- standard frequency of $A_4$ (A above middle C):
    - ~424 Hz in early 1600s
    - ~422 Hz in time of Bach, Handel, Haydn, Mozart, and Beethoven
    - defined as 435 Hz by 1859 French commission
    - “scientific pitch” introduced in early 1900s; based C in consecutive octaves on powers of 2 (e.g., 128 Hz, 256 Hz, 512 Hz, etc.); $A_4$ is 427 Hz
    - defined as 440 Hz by 1939 international conference
    - time standard station WWV still transmits 440 Hz tone every hour at two minutes past the hour

Relevant course material:

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|---|---|
| HW: | #1 and #2 |
| Readings: | Assignments from Jan. 13 through Feb. 14 |
| Web Links: | Longitudinal and Transverse Wave Motion |
| | Wave Motion in Time and Space |
| | Standing Longitudinal Waves |
| | Overview of the Cochlea |
| | Anatomy of the Ear |
| | “Equal Loudness Contour” (Wikipedia) |
| | “Sound Level Meter” (Wikipedia) |