Tu. 3/12: Ch 6 *The Human Ear* **Th. 3/14:** Ch 17 *The Ear Revisited &* http://dx.doi.org/10.1063/1.3603917 http://phys.org/news/2013-02-human-fourier-uncertainty-principle.html	HW8: Ch6: 2,4[W]… Ch17: 1,3,4,16,20,23	**Mon. 3/11** or **Tues. 3/12:** Lab 9 *Electronic Amplification & Speakers*
Tu. 3/19: Review **Th. 3/21:** Exam 2 (*Ch 8,9,16,6,17*)		**Mon. 3/18** or **Tues. 3/19:** Lab 10 *The Ear 1: Limits of Hearing*

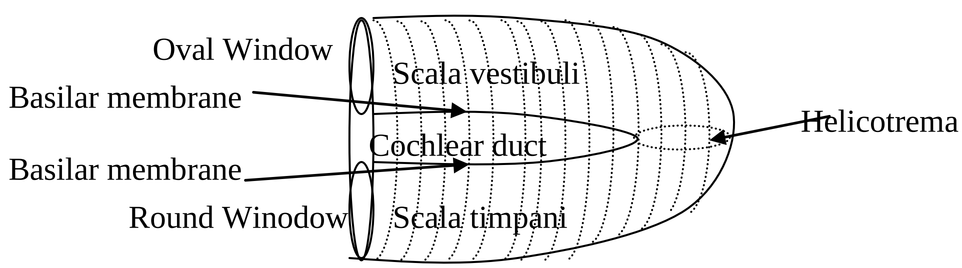
Equipment
Ppt with Ear
Alan's resonance demo
three function generators driving three speakers

Exam
I have already posted review notes for the 2nd exam on the course website.
For Tuesday, look over that and come in with questions

Last Time: Chapter 6 The Human Ear
We followed sound's path into the ear: through the protective and localizing outer ear, across the amplifying middle ear, and into the transducing inner ear.

This Time: Ch 16 The Ear Revisited
Now we think more carefully about exactly how the inner ear translates the mechanical motion into electrical signals that the brain interprets as sound. The book discusses three types of theories – telephone, place, and pattern-recognition. It's probably best not to look at these in their extremes and thus as competing, but take from each the best that it has to offer, thus as complementary theories, each telling a *part* of the whole story.

Telephone theory: In broad strokes, the ear serves as a transducer – in comes mechanical motion and that is translated into electrical signals. Now, even with a simple microphone, we could see that there was no such thing as a perfect transducer – its design invariably makes it better at some parts of the task and worse at others; so it is with the ear.

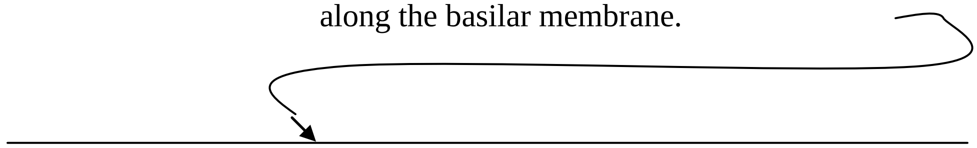


Place Theory: So, what *is* the design of this transducer? Acoustic nerves are attached to and sense the motion of hairs all along the length of the inner ear. The signals they produce are the 'electrical output' of the ear. The mechanical motion of the air triggers these as follows: Air pressure variations translate into pressure waves through a viscous fluid that flow around the outside of a membrane-walled & fluid filled cavity within a cavity (the Cochlear duct wrapped in the Scala vestibuil and Scala timpani), from the oval window to the round window. Along the way, the waves must make these membrane walls ripple to, however…

- The higher the frequency, the more rapidly the waves diminish as they propagate
- The lower membrane wall, the Basilar membrane, becomes thicker and looser further along

Both of these conspire to make high frequency waves strongly shake the cochlear duct near the windows while low frequency waves most strongly shake the duct at the far end. This tickles the hairs with the organ of corti, and so sends of the electrical signals – for high frequencies, from the hairs near the windows, and for low frequencies, from the hairs near the far end.

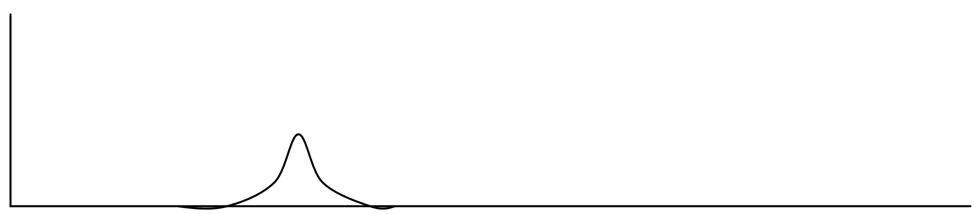
- Of course, just because a given frequency might excite one cross section of the basilar membrane the *most* doesn't mean that neighboring cross-sections don't respond a good deal too.
- **Example:**
    - Say you are listening to a particular tone, 500 Hz, and that is the resonance frequency of one spot along the basilar membrane.



Distance into cochlea from windows

- That results in displacement of the basilar membrane as illustrated.

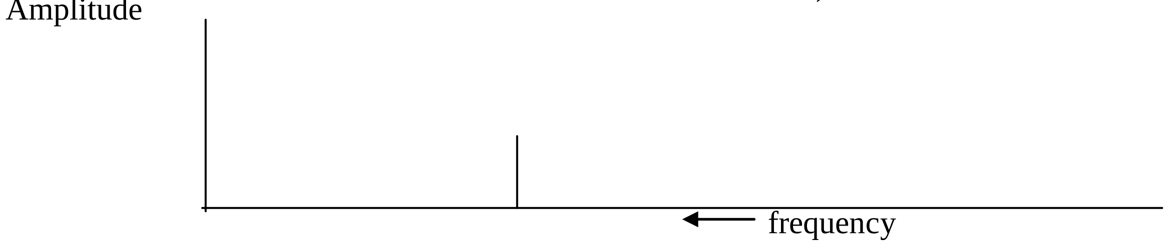
Displacement of Bassilar Membrane



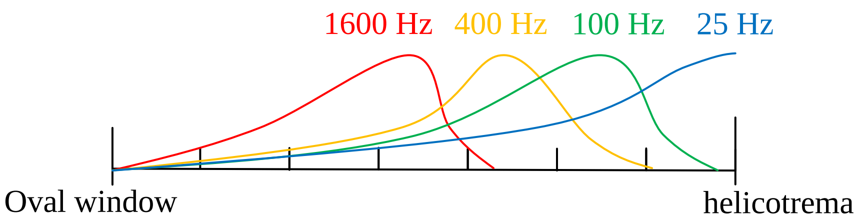
Distance into cochlea from windows

- The signals sent from the hairs to the brain look like this too. The hairs right in the middle of the displaced region sends the 'most' signal those further out send 'less' signals. (In what sense the signal is 'more' or 'less' is discussed in "Perodicity Theory" next).
- The brain, well aware of the limitations of the basilar membrane, interprets this combination of signals from the hairs in the displaced region as just 500 Hz, i.e., the *central*

hair's frequency (though we'll shortly see an additional mechanism to home in on this.)

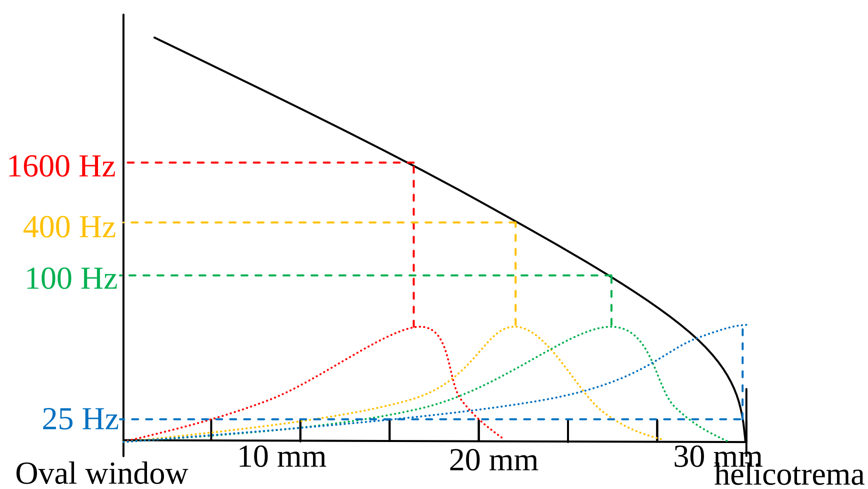


Measured along the Basilar membrane, from the Oval window toward the helicotrema (the whole at the far end) here are the response profiles for a few different frequencies:



(Fig 17.2 flipped)

Or, plotting out the locations of each frequency's peak

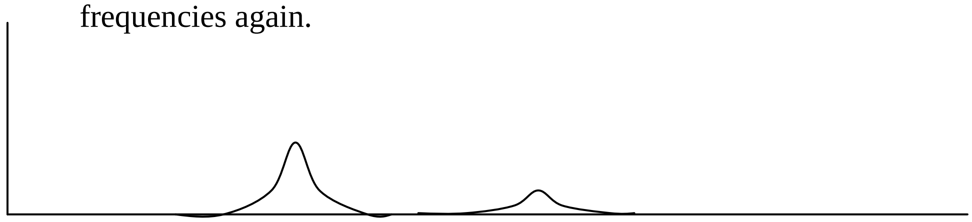


Near the oval window, the peak frequency response increases about an octave per 4mm.

Somehow (and "Periodicity theory" will help with this), the brain identifies this broad disturbance with the peak frequency.

- **Masking**. Now say you hear two tones at the same time. One a little lower in frequency and also amplitude. They simultaneously displace two distinct regions of the membrane and produce two peaks in frequency signals to the brain, and it intepets the signals it gets as just those two frequencies again.

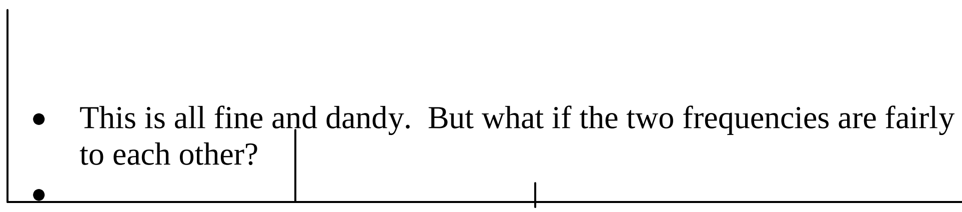
Displacement of Basilar Membrane



Distance into cochlea from windows

Amplitude

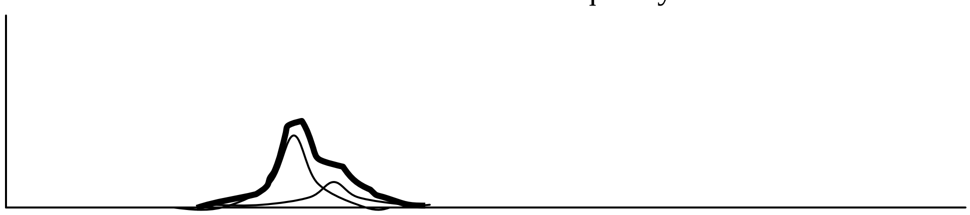
This is interpreted as



- This is all fine and dandy. But what if the two frequencies are fairly close to each other?
-

Displacement of Basilar Membrane

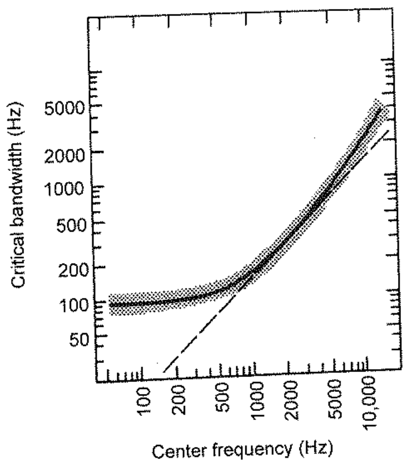
← frequency



Distance into cochlea from windows

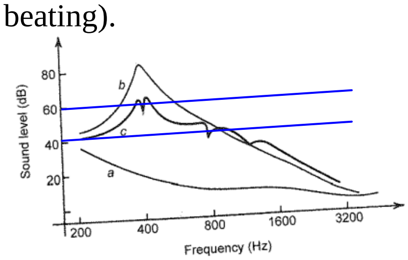
- The thick line is the composite motion of the membrane due to both frequencies driving motion of their respective locations on the membrane. The brain *might* still be able to figure out the signals it gets and resolve this into two individual pure tones, but maybe not. If one tone is *much* louder than another tone which is *quite* close in frequency, then the quiet tone gets completely lost & the brain can't hear it at all.
- At least for higher frequencies, above about 500 Hz, two peaks should be about 1 – 1.5 mm apart along the basilar membrane (corresponding to 2.5-3 semitones) for them to be registered as 'distinct'. This corresponds to the two frequency bands *not* significantly over lapping, and so *not* significantly firing the same nerves.
    - **Note**: this separation is not sufficient to completely separate the two bands, and so would not be enough if it weren't for our augmenting place theory with periodicity theory which helps to sharpen our resoltion.
- **Demo** – with one function generator playing one speaker and another playing another, slowly vary the frequencies from identical do significantly different.

- **Masking & Loudness**
  - Another phenomenon that's easy enough to understand in terms of these broad bands is how a loud noise masks a quieter one. If the two frequencies are within a band of each other, then the queiter one can be 'hidden' – it produces only a minor blip on the displacement curve and only a minor increase in activity.
  - **Fig 17.10** shows how the width of this 'critical band' varies with the frequency – frequencies up to about 500 Hz have ~100 Hz wide bands, so, for exmple, a loud 200 Hz tone can mask a quieter 250 Hz tone or 150 Hz tone (or much quieter 300 or 100 Hz tones).

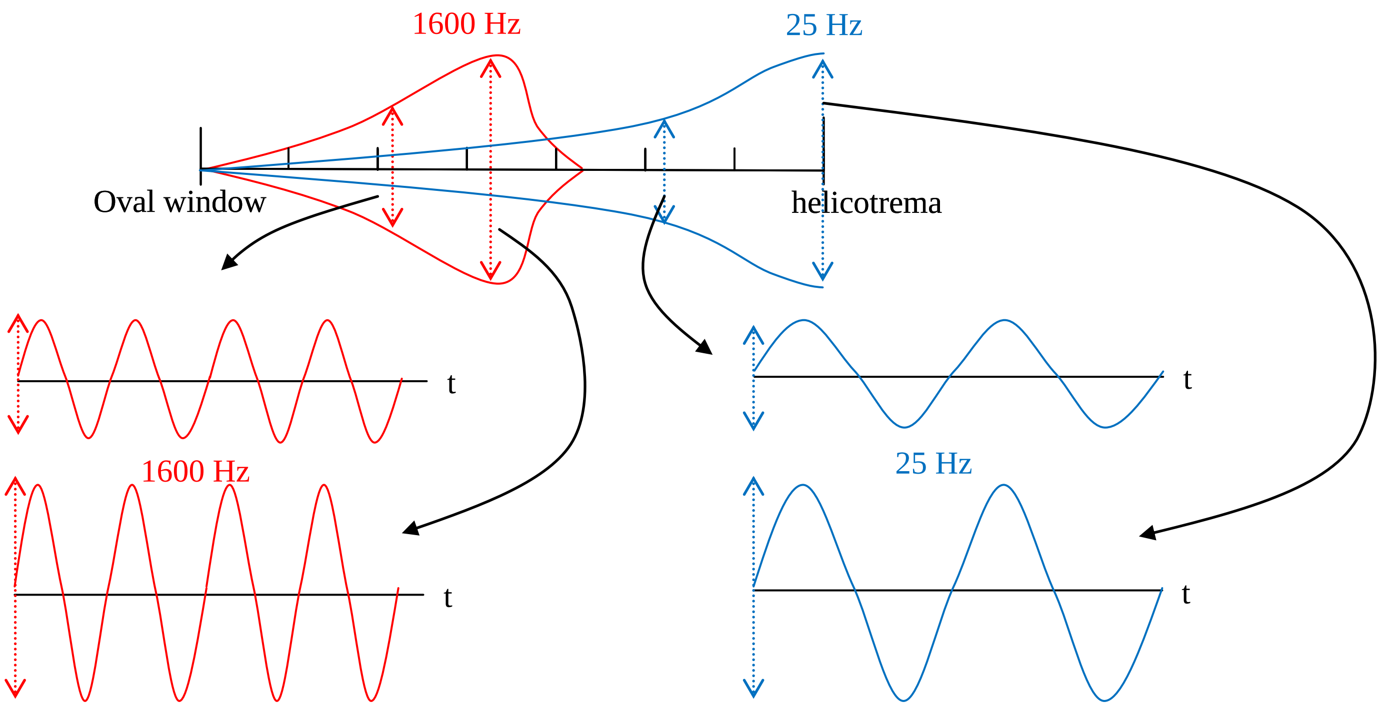


Problem 16 asks you about a loud trumpet playing mid-range (according to the back cover of the book, that's about 400Hz) masking other instrumetns above and below.

  - **Fig 17.17** Of course, it's not a hard limit; the relative loudnesses of the two tones effects how well one masks the other – Fig 17.17 gives a more detailed look. For example (*like problem 23*), if you're playing an 80dB 400 Hz tone and a 40 dB tone of *any* frequency up to about 800 Hz at which point you'd hear beating, then it disapears again until you reach about 1000Hz. But if the second tone is up at 60 dB, then it can be distinguished except for over the range of about 350 to 450 Hz (and even then, right near 400 Hz, while you won't hear the second tone, you *will* hear beating).

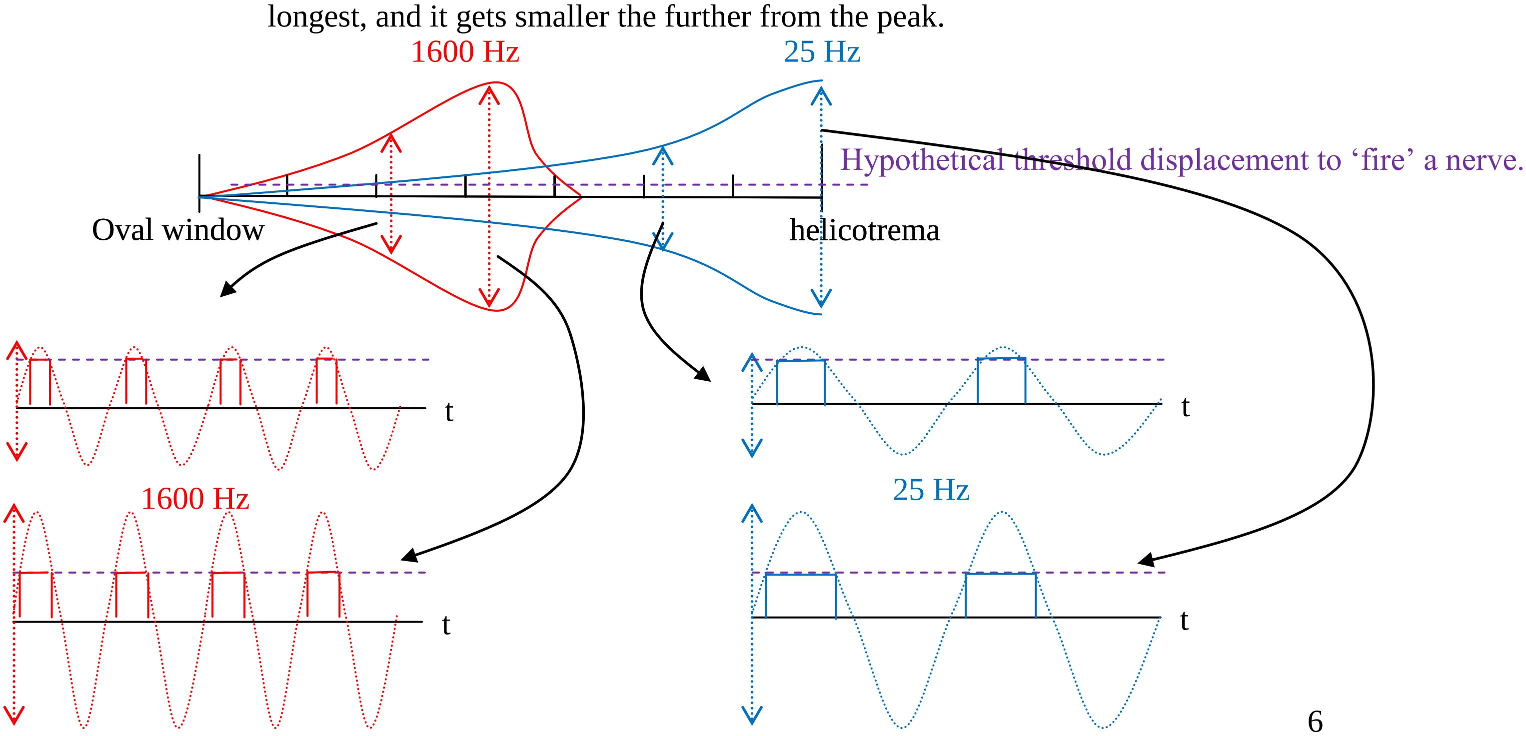


Transition to Periodicity Theory. It's important to remember though that the basilar membrane doesn't just bend and stay bent as long as the appropriate sound is present – with the undulating pressure waves, the membrane itself would undulate up and down, so think of those curves not as representing the static distortion, but as representing the amplitude of an oscillating distortion – tickling the hairs with the organ corti, and not tickling, tickling, and not tickling.



Periodicity Theory: If you imagine that a hair on the oscillating basilar membrane has to be moved yeah far / pressed yeah hard into the organ di corti for its nerve to fire, then two things must follow:

a) The nerves firing pattern is something like a square wave with the same periodicity as the driving frequency
b) and with a duty cycle (the ratio of 'firing' to 'not firing' time) that varies something like the curves in figure 17.2 – at the peak location, the firing time is longest, and it gets smaller the further from the peak.

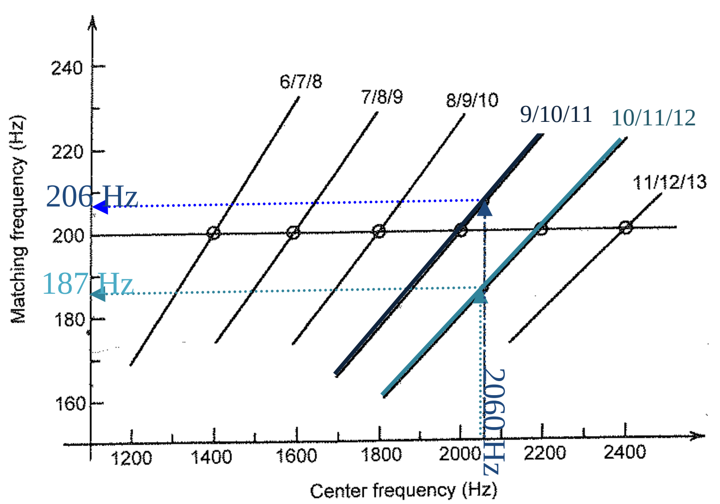


This gives the brain two different pieces of information to use in determining pitch – *where* the signals are coming from along the length of the cochlea, and the *frequency* of the signal.
You might think that the latter is all you need to determine the frequency, and it would be…if you only had to listen to one frequency at a time. Getting different frequencies from different regions helps to distinguish them.

Pattern Recognition. Still, the ear isn't the end of the story in processing and resolving sounds. The human brain is incredibly attuned to automatically recognizing and imposing patterns; indeed, many illusions exploit that fact. It seems that the brain analyzes the spectral information that ear sends it (region and frequency) and determines what information goes together to constitute a single sound with a single pitch, and what information goes together to constitute a separate sound. One piece of evidence that our brains play this role is that information presented at both ears goes into a final judgment; say, play 200 Hz for one ear and 300 Hz for the other and you're apt to 'hear' 100 Hz too, though these two sounds had no way of interacting with each other in one or the other ear.

Another example is finding a definite pitch when the source sounds are slightly anharmonic, like the modes of a bell.

Example/Demo: Listening to 1860, 2060, and 2260 Hz, our brain hunts around to find the harmonic pattern they'd fit into. In this case, they're quite nearly the 9th,10th, and 11th harmonic of 206 Hz or the 10th, 11th, and 12th harmonics of 187 Hz.



How'd I figure that out? Here's how to use the plot to help.

1. Along the horizontal axis, find the central of the three given frequencies (2060Hz).

2. Trace straight up the plot from there and mark anywhere you cross one of the diagonal lines. In this case, it crosses the "10/11/12" line down low and the "9/10/11" line up higher.
3. From those two points, look across at the vertical axis and read off the frequencies there: 187 Hz and 206 Hz.
4. Seriously, I could specify down to 1Hz by reading the plot? No, but if 1860, 2060, and 2260Hz are supposed to be approximately the 9^{th}, 10^{th}, and 11^{th} harmonic of something, then that something should be 1860Hz/9 = 206.7Hz; 2060Hz/10 = 206 Hz; 2260Hz/11 = 205.4Hz; those average to 206 Hz which is a rather flat A_3-flat. Similarly, if they're supposed to be the 10^{th}, 11^{th}, and 12^{th} harmonics, then dividing the three given frequencies by these integers gives 186Hz, 187Hz and 188Hz, so they average to 187Hz, which is a rather sharp F_3-sharp.