

Lecture 5: Frequency

Musicians describe sustained, musical tones in terms of three quantities:

- Pitch
- Loudness
- Timbre

These correspond to our perception of sound. I will assume you have an intuitive understanding of what each of these things “means.”

A physicist would describe the same tone in terms of three quantities:

- Frequency
- Intensity
- Overtone or Harmonic Structure

These correspond to a physical description of the sound. These three things are in close, but not exact correspondence to the musical descriptions:

- Pitch = Frequency (+ small loudness correction)
- Loudness = Intensity (+ substantial frequency and overtone corrections)
- Timbre = Overtone Structure (+ frequency, intensity corrections)

By far the simplest of these three to explain is pitch and frequency, so that is where we will start.

The first observation is that musical tones are generally (almost) **periodic**. This is an important concept so we should illustrate it.

Four sounds are played in the HTML version of this lecture. The sounds, in the order I made them, were

1. a finger being rubbed around the rim of a wine glass
2. a wooden whistle
3. the little siren I demonstrated in the second lecture
4. the human (my) voice, singing “aah”

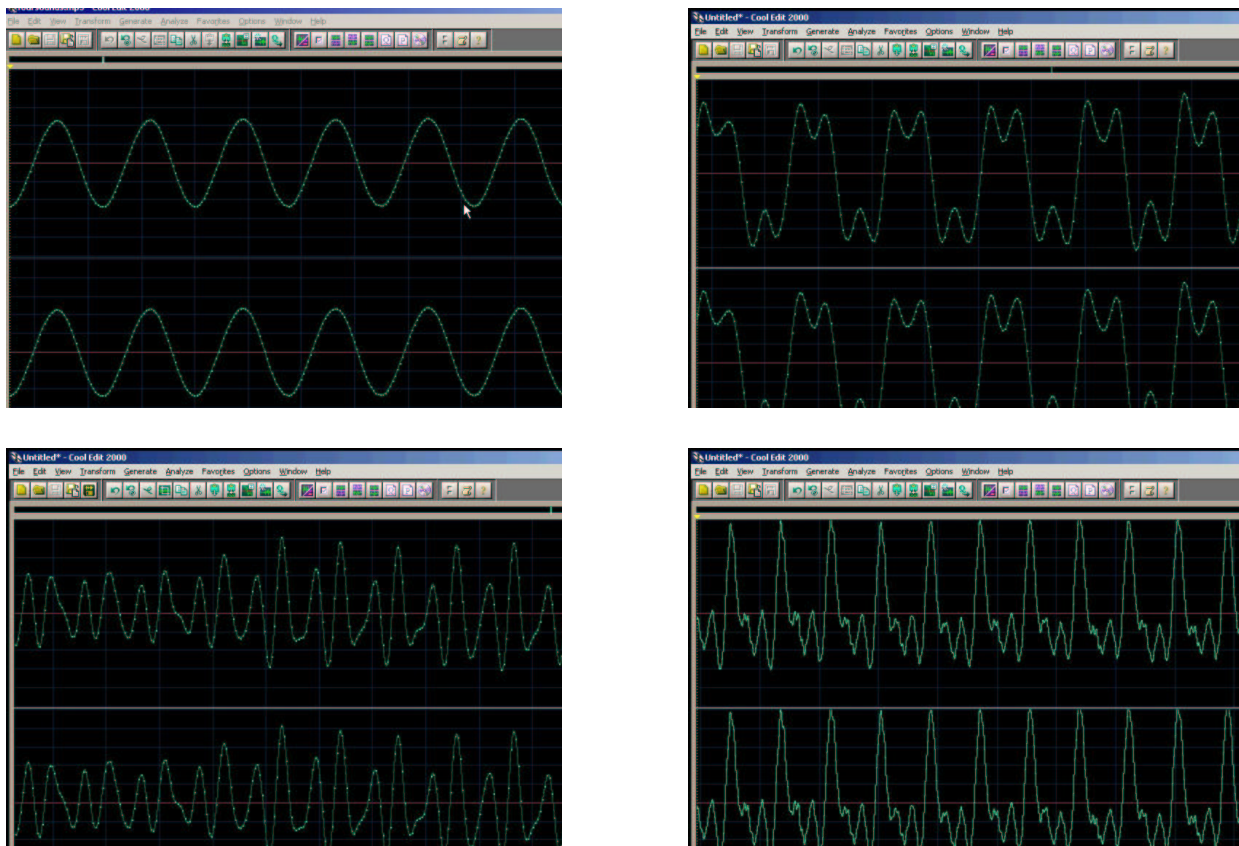


Figure 1: Pressure (vertical axis) against time (horizontal axis) for a finger on the rim of a wine glass (upper left), a wooden whistle (upper right), a toy siren (lower left), and the voice (lower right). Each plot appears twice because it was recorded in stereo but the microphones were next to each other.

Each of these sounds has a definite pitch, though the siren's pitch moves around during the sound.

Each of these sounds was sampled with a microphone. The pressure, as a function of time, is shown in Figure 1.

These recordings were made using software called Syntrillium Cool Edit; Syntrillium has been bought out by Adobe, which renamed it Adobe Audition.

The thing to notice about all four pictures is that the pressure pattern repeats over and over. In physics we call something which repeats like this **periodic**. The fact that these sounds are periodic, is the key to their having definite pitches. In fact, we can even say,

Sounds which are periodic have a definite pitch. Sounds with a definite pitch are periodic.

Of course nothing is perfectly periodic. However, musical sounds come surprisingly close.

Obviously we need language to describe periodic functions. The most basic property is

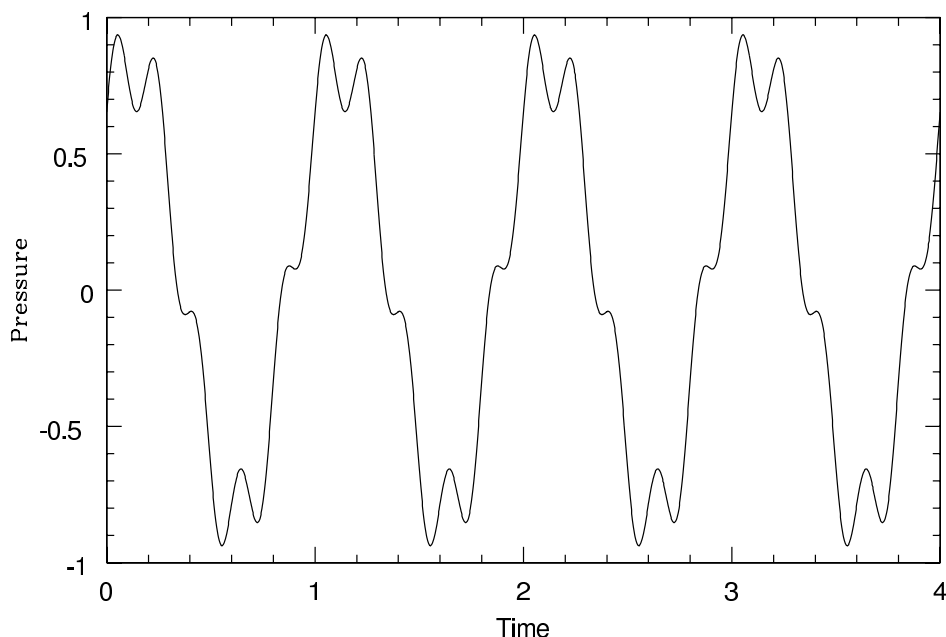


Figure 2: A periodic function, with period 1.

the **period**, which is just the time that it takes for the pattern to repeat. This is the same as the time difference between when some pattern appears, and when it appears again. For instance, for the plot in Figure 2, the period is 1 because every 1 on the horizontal axis, the pattern repeats.

Frequency is defined as the inverse of the period. Period is usually written as T , and is measured in seconds. Frequency is

$$f = \frac{1}{T}$$

and is measured in 1/seconds, which are called **Hertz**. Think of Hertz as “somethings per second,” specifically, how often something repeats per second. The more often something repeats, the shorter the period, but the larger the frequency.

The most familiar example to musicians is metronomic markings. At a *moderato* tempo of 100 beats per minute, the period is $(60 \text{ seconds}/100 \text{ beats}) = 0.6 \text{ seconds}$. The frequency is $1/\text{period} = 1/(0.6 \text{ seconds}) = 1.67 \text{ Hertz}$. Since there are 2 eighth notes in a quarter note, the frequency of 8'th notes is twice as high; sixteenth notes are twice as high again, so sixteenth notes in moderato tempo occur at a frequency of about $4/(0.6 \text{ seconds}) = 6.67 \text{ Hertz}$.

If something makes a series of sharp sounds, like staccato notes or like something bouncing in bicycle spokes, your ear can distinguish them as separate sounds if they are spaced less than about 12 or 15 per second. Beyond that, your perception tends to blur them together. [This is why musicians can get away with replacing a series of very fast notes with a slur

sometimes without anyone noticing.] At about 20 to 30 Hertz, you instead perceive them as forming a low, dull sound. As the frequency goes up, the interpretation as a sound of definite frequency becomes clearer.

You can test this by putting a bicycle in a high gear, flipping it upside down so you can spin the back wheel with the pedal, and sticking a pen or piece of cardboard into the spokes. Depending on the speed you spin the wheel, you can make the object strike the spokes anywhere from a few times to a few hundred times per second. When it goes above 40 or 50 times a second, it is easily recognizable as a pitch. The faster you spin the wheel, the higher the pitch, teaching us that

Pitch corresponds to the frequency of a sound. Higher frequency is higher pitch.

There are many ways to convince yourself of that.

The limits of the range of Human hearing are about 20 Hertz to about 17 000 Hertz. At the bottom end, your ear's sensitivity becomes very poor, and sound becomes more of a sensation than a hearing experience. It is hard to demonstrate because most things which make a low pitched sound are also making higher pitched sounds at the same time [overtones, the subject of future lectures], and what you hear is the higher pitched tones. For instance, for the deepest instruments, like the contrabassoon, the bottom range of the piano, or the E string on the string bass, your perception is based almost entirely on these higher frequencies [overtones] rather than the fundamental note itself.

(For the rest of this lesson, the HTML version of the notes will be more useful, since they include the sound files.)

That is not true of the top range of hearing. Again, you lose sensitivity above some frequency, but in a sharper way. Sounds outside your range of hearing are simply not perceived at all. To see this, listen (on headphones or speakers) to the sound file in the HTML version of these notes, which plays in succession, notes of

- 11 000 Hertz
- 12 000 Hertz
- 13 000 Hertz
- 14 000 Hertz
- 15 000 Hertz
- 16 000 Hertz
- 17 000 Hertz
- 18 000 Hertz

- 19 000 Hertz
- 20 000 Hertz

Chances are you hear clearly the first 5 or 6, and barely notice the next one, but cannot hear the ones past 18 kiloHertz (18 000 Hertz). This limit on your hearing will deteriorate with age. People in their 60's often cannot go past 11 000 Hertz, sometimes even less.

Higher frequency is higher pitch, but we also have a definite notion of how much higher pitched one note is than another. Is this determined in a simple way in terms of the periods or frequencies? The answer is yes, but not as simple as you were hoping.

The next sound file plays, in succession, notes of frequency

- 500 Hertz
- 1 500 Hertz
- 2 500 Hertz
- 3 500 Hertz
- 4 500 Hertz
- 5 500 Hertz
- 6 500 Hertz

which are **evenly spaced in frequency**. You will perceive them to be getting closer together in frequency instead. So even spacing in frequency is not the natural perception of even spacing in pitch.

Is it even spacings in period? The next sound file plays, in succession, notes of

- period $1/2000$ sec, or frequency 2000 Hertz
- period $3/2000$ sec, or frequency 667 Hertz
- period $5/2000$ sec, or frequency 400 Hertz
- period $7/2000$ sec, or frequency 285.7 Hertz
- period $9/2000$ sec, or frequency 222 Hertz
- period $11/2000$ sec, or frequency 181.2 Hertz
- period $13/2000$ sec, or frequency 153.8 Hertz

which are evenly spaced in period. You will perceive them as getting closer in spacing again. So the answer is something in between.

Let us try equal **ratios** of frequency, say, each note exactly twice the frequency of the note before. The next sound file plays notes of frequency

- 220 Hertz
- 440 Hertz
- 880 Hertz
- 1760 Hertz
- 3520 Hertz
- 7040 Hertz

which are of equal ratio, namely, the ratio of successive frequencies is 2. These **do** sound like they are evenly spaced. [Musicians will instantly recognize them as being spaced in octaves. Now you know what an octave is.]

To confirm this, we play notes spaced by factors of $3/2$: the next sound file plays notes spaced by this ratio, namely,

- 440 Hertz
- 660 Hertz
- 990 Hertz
- 1485 Hertz
- 2227 Hertz
- 3341 Hertz
- 5012 Hertz

These are also evenly spaced perceptually [and musicians will recognize them as being spaced by perfect fifths. Now you know what a perfect fifth is.]

This tells us that our perception of pitch is logarithmically related to frequency, and since the octave is the most important musical interval, we should study this using logarithms base 2. (More in the next lecture)