Sound in Time and Frequency

Types of Sound Signals

- **Sound Signals**
  - Deterministic (predictable)
    - periodic
    - sine
    - sawtooth
    - rectangular
  - aperiodic
    - talking clock (date/time)
    - white noise
- Random (unpredictable)
  - stationary
    - white noise
  - non-stationary
    - speech

Characterization of Tones

- Sounds (digital and analog) are made up from combinations of tones, e.g.,
  - Pure Tone
  - Chord
  - Music
- Pure tones are also called sinusoids.
- A sinusoidal tone is characterized by its amplitude, frequency and phase.

Sinusoidal Tone

- Graph versus time for 10 ms:
- Formula: \( A \sin(2\pi f t + \phi) \)

Sinusoidal Tone: Parameters

- In \( A \sin(2\pi f t + \phi) \),
  - \( A \) is the **amplitude** of the sinewave. A loud tone has a high amplitude.
  - \( f \) is the **frequency**, i.e., the number of periodic repetitions per second. A low tone has low frequency, a high tone has high frequency. Note: \( \pi = 3.14159265359... \)
  - \( \phi \) is the **phase**, i.e., the time shift of the sinewave along the horizontal axis.
- The human ear is insensitive to the **phase** of individual tones. Modems use their own reference signal to transmit or receive data via phase changes.
- **Amplitude** or loudness is straightforward.
- **Frequency** is the most important parameter for us to characterize tones.
Sinusoidal Tone: Parameters

To understand more intuitively what amplitude and frequency mean, let's listen to an amplitude modulated (AM) signal and to a frequency modulated (FM) signal.

Example: Listen to this simple tune: We recognize the melody because of the specific changes in tone frequency.

The sine function is periodic, i.e., $\sin(x+2\pi) = \sin(x)$, $(2\pi$ is 360 degrees).

Frequency is defined as the number of periods per second or, equivalently, as "one over the period length in seconds."

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Frequency: Example

This graph shows 10 ms of a tone:

What is the frequency of this tone?

There are 5.25 periods. Thus, the frequency is: $f = 100 \times 5.25 = 525$ Hz.

Frequency of Tones

Note that frequency is usually measured in Hertz (in honor of Heinrich Hertz, 1857-1894, German physicist who discovered radio waves).

Note:

1,000 Hz = 1 kHz (kilo Hertz),
1,000,000 Hz = 1 MHz (mega Hertz),
1,000,000,000 Hz = 1 GHz (giga Hertz).

Frequencies

We can hear tones in the range from about 50 Hz to 16 kHz.

AM radio uses 540 kHz … 1.6 MHz.
FM radio uses 88 MHz … 108 MHz.
Microwave ovens use 2 … 3 GHz.
Frequency Domain
- When we look at a plot of sound intensity versus time, we say that we look at a waveform in the **time domain**.
- We can look at the same waveform through filters which pass only certain frequency bands, and plot intensity versus frequency. In this case we look at the waveform in the **frequency domain**.

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Frequency Domain: Example
- Spectrogram of 3 sequential tones:
- Spectrogram of chirp: 100 Hz … 20 kHz
- Spectrogram of musical tune:

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Harmonics
- Let $f_1$ be the fundamental frequency of a sound, e.g., from a music instrument.
- Then $f_2=2*f_1$, $f_3=3*f_1$, $f_4=4*f_1$, etc, are called the 2’nd, 3’rd, 4’th, etc, harmonics.
- The presence (or absence) of harmonics changes the “quality”, but not the “pitch” of the sound.

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Rectangular Waveform
- Has 1’st, 3’rd, 5’th, 7’th, etc, harmonics.
- 4 periods in 10 ms => $f_1 = 400$ Hz
Rectangular Waveform

- Has 1'st, 2'nd, 3'rd, 4'th, etc, harmonics.

Sawtooth Waveform

- Has 1'st, 2'nd, 3'rd, 4'th, etc, harmonics.

4 periods in 10 ms => f1 = 400 Hz

Human Voice

- Most energy is concentrated in the band from about 500 to 2000 Hz.
- The telephone transmits frequencies in the range from 300 to 3000 Hz.
- This is adequate for understanding speech, but not for Hi-Fi reproduction.

Hi-Fi

- Telephone (low pass)
- High pass

Human Voice: Time Domain

- The Hi-Fi version versus time:

Speech is easily identified by the pauses between words and sentences.

Human Voice: Frequency Domain

- Spectrogram of Hi-Fi version:

Note: Most energy is below 4000 Hz.
**Human Voice: Frequency Domain**
- Spectrogram of telephone version:
- Now frequencies above 2.5 kHz and below 250 Hz are cut off.

**Music**
- Music typically covers a larger frequency range than human voice.
- More energy at lower frequencies, but higher frequencies are needed to distinguish different instruments.
- For Hi-Fi quality, 50…16000 Hz range is needed.

**Music: Time Domain**
- The 50..20000 Hz version versus time:
- Intensity fluctuates in time, but pauses are much rarer than with speech.

**Music: Frequency Domain**
- Spectrogram of 50..20000 Hz version:
- High frequency content substantial.

**Music: Frequency Domain**
- Spectrogram of 50..5000 Hz version:
- Same tune, but “less Hi-Fi” sound.

**DTMF Signals**
- Dual Tone Multi-Frequency signals are used extensively in telephony.
- Example:

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>1209 Hz</th>
<th>1336 Hz</th>
<th>1477 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>697 Hz</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>770 Hz</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>852 Hz</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>941 Hz</td>
<td>*</td>
<td>0</td>
<td>#</td>
</tr>
</tbody>
</table>
DTMF Signal: Time Domain
- How do we know frequencies?
- Do we even know there are two?

DTMF Signal: Spectrogram
- Use filters (frequency domain).
- We see that there are 2 frequencies.

Different Types of Filters
- **LPF**: Lowpass filter, passes all frequencies below a cutoff frequency.
- **BPF**: Bandpass filter, passes all frequencies from a lower to an upper cutoff frequency.
- **HPF**: Highpass filter, passes all frequencies above a cutoff frequency.

DTMF Signal: After LPF
- After low-pass filter (LPF) at 1000 Hz:
  - 7.75 periods in 10 ms \( \Rightarrow \) \( f = 775 \) Hz

DTMF Signal: After HPF
- After high-pass filter (HPF) at 1000 Hz:
  - 14.75 periods in 10 ms \( \Rightarrow \) \( f = 1475 \) Hz

White Noise
- Contains all frequencies with equal power.
- Random signal, no visible regularity.
Spectrogram of White Noise

PSD of White Noise

Pink Noise

Equal power per octave.

Spectrogram of Pink Noise

PSD of Pink Noise