Sound of Music

How It Works

Session 2
Resonance: Building Musical Sounds

OLLI at Illinois
Spring 2020

Ocarina (Helmholtz Resonator)
Lena Leclaire 2012

Legend of Zelda Medley

D. H. Tracy
Course Outline

1. Building Blocks: Some basic concepts
2. Resonance: Building Musical Sounds
3. Hearing and the Ear
4. Musical Scales
5. Musical Instruments
6. Singing and Musical Notation
7. Harmony and Dissonance; Chords
8. Combining the Elements of Music
Visual Analyzer Demo

Whistle
Sound As Compression Waves

Frequency $f$

Wavelength $\lambda$

Speed of Sound $v_s$ (velocity)

$V_s = \lambda \times f$
Simple Harmonic Oscillator
Tuning Fork

Slo-Motion Video
Resonators can be excited by well-timed nudges
How can we make Sine Waves?

• Simple Harmonic Oscillators do it

  - Simple Pendulum
  - Mass on Spring
  - e.g. Tuning Fork
  - Circular Projection
  - e.g. Rotational Crank Mechanism

• Electronics can also do it
Helmholtz Resonators

Fig. 16a.

Herman von Helmholtz
1821-1894
Helmholtz Resonators

Air in neck

Air at atmospheric pressure

Inside Air compressed

Microphone

Simple Harmonic Oscillator

\[ f = \frac{v}{2\pi} \sqrt{\frac{A}{Vl}} \]

Demo
147 Hz Resonance
Ever experience a Whump-Whump in your car when a rear window is cracked open?
Ever experience a Whump-Whump in your car when a rear window is cracked open?

It's His Fault
Resonators Using Strings and Pipes
Resonators Using Strings and Pipes

Anne Sullivan playing Siciliana (Respighi)
Resonators Using Strings and Pipes

Prelude in C Major (Bach): Brian of the LDS [Liahona.net]
Resonators Using Strings and Pipes

Easiest way to understand these is via the concept of “Standing Waves”
2 Traveling Waves Combine…
To Form a **Standing** Wave

Freeze Waves at Some Instant

Node

Anti-node
Standing Waves in Air
Q: How Do We Make Standing Waves?

A: Reflections at a Boundary

Reflection is upside down!

Reflection is not inverted!
Q: How Do We Make Standing Waves?

A: Reflections at a Boundary

Reflection is upside down!

Reflection is not inverted!
Q: How Do We Make Standing Waves?

A: Reflections at a Boundary

Reflection is upside down!

Reflection is not inverted!

Air Pressure

Displacement

“Open”

“Hard”

“Closed”

Anti-Node

D Russell Penn State

2/4/2020

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Partial Reflection

Some Reflected...

... and some Transmitted

Fuzzy Wall or Discontinuity

D Russell Penn State
The Monochord

Fig. 148. Monochord
Mersenne’s Laws of Strings

Frequency $f$ depends on Length $L$, Tension Force $T$, and String Mass/length $\mu$:

- $f_0 \propto \frac{1}{L}$ inversely proportional to length
- $f_0 \propto \sqrt{T}$ proportional to square root of tension
- $f_0 \propto \frac{1}{\sqrt{\mu}}$ inversely proportional to square root of mass per unit length (‘fatness’)
Possible Pure String Modes

2 Nodes ; 1 Antinode

3 Nodes ; 2 Antinodes

4 Nodes ; 3 Antinodes

5 Nodes ; 4 Antinodes

6 Nodes ; 5 Antinodes

\[ f \]

\[ 2f \]

\[ 3f \]

\[ 4f \]

\[ 5f \]

Fundamental

Harmonics
Try to Launch the Fundamental Mode:

Sine shape

We could carefully pull the string into a half-sine wave and then suddenly let it go....

But we actually pluck a triangle ...
Try to Launch the Fundamental Mode:

Sine shape

But we actually pluck a triangle ...

We could carefully pull the string into a half-sine wave and then suddenly let it go....

Many modes superimposed!
Try to Launch the Fundamental Mode:

Plucked String in Slo-Mo

Dan Russell, Kettering/Penn State
(2011)

Many modes superimposed!
The First Electric Monochord?

Yuri Landman (YouTube 2011)

Tristan Andreas (YouTube 2012)
The Monochord

8 foot Electric Monochord Demo
Organ Pipe – One Closed End

Air Displacement

Fundamental Mode
\[ L = \frac{\lambda}{4} \]

Third Harmonic
\[ L = \left(\frac{3}{4}\right) \lambda \]

Fifth Harmonic
\[ L = \left(\frac{5}{4}\right) \lambda \]

Standing Sound Waves in the Pipe
Illustration of Wave Reflection at Open End of Pipe

(Animation)
Open Organ Pipe: 9th Harmonic

Particle Displacement ↔

Pressure ⇧
**Resonant Cavities: Augmenting Sounds**

- **Pipes**
  - $\lambda_1 = 4L$
  - $\lambda_1 = 2L$
  - Overtones are integer multiples of fundamental frequency

- **Helmholtz Resonators**
  - Mainly has fundamental resonance
  - Typically lower frequency than a pipe of similar length

- **Irregular Resonators**
  - Non-uniform Pipe
    - Overtones *not* integer multiples unless conical
    - Example: Saxophone

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Closed vs. Open Pipe (*Pressure Modes*)

**Closed One End**
Clarinet, e.g.

- $f_C$
- $3f_C$
- $5f_C$

**Odd Harmonics Only**

**Open Both Ends**
Flute, e.g.

- $f_0$
- $2f_0$
- $3f_0$

$f_0 = 2f_C$
Open Pipe

\[ \approx 5.6 \text{ ft} \]
Closed Pipe

$\approx 5.6$ ft
Demo: Not Carried Out

Open Pipe
(Bent 4.7ft)
This is as far as we got.....
Air Column Instrument Examples

Open Cylinder

Flute
Air Column Instrument Examples

- **Open Cylinder**
  - $\frac{1}{2}$ wave

- **Closed Cylinder**
  - $\frac{1}{4}$ wave

- **Conical**
  - $\frac{1}{2}$ wave

- **Flute**
  - $\lambda_0 \approx 4 \text{ ft}$

- **Clarinet**
  - $\lambda_0 \approx 8 \text{ ft}$

- **Oboe**
  - $\lambda_0 \approx 4 \text{ ft}$
What About Timbre?

- **Open Cylinder**: $\frac{1}{2}$ wave
- **Closed Cylinder**: $\frac{1}{4}$ wave
- **Conical**: $\frac{1}{2}$ wave
- **Flute**: All Harmonics, $\lambda_o \approx 4$ ft
- **Clarinet**: Odd Harmonics only, $\lambda_o \approx 8$ ft
- **Oboe**: All Harmonics, $\lambda_o \approx 4$ ft

2/4/2020
Comparison of Standing Wave Modes

Open Cylinder Pipe

Closed Pipe

Conical Pipe

Same Length, Fundamental Frequency, and Harmonics

J Wolfe, University of New South Wales
More Complex Resonators

Common Characteristic:
Modes are generally not harmonics of Fundamental
Singing Prayer Bowl
Resonant Vibrational Modes of a Wine Glass

High Speed Camera
Benjamin Franklin’s Glass Harmonica (1761)

Stick/Slip on rotating glass bowls

Thomas Bloch, Paris Music Museum 2007
Great Paul Bell
St. Paul’s Cathedral

1882, 17 tons

Apparent Frequency:
317 Hz

Great Paul - spectrum plotted against 153.6 Hz
Vibrating Bars

\[ f_0 \]
\[ 2.76 \, f_0 \]
\[ 5.40 \, f_0 \]
\[ 8.93 \, f_0 \]

Dan Russell
(Penn State)

Open University [GB]

Not anywhere near harmonic!
Drumheads:
Two Dimensional Membranes
Fundamental Mode of a Drumhead (0,1)
The (0,2) Drumhead Mode

Nodal Line

Outer Edge
Always a Nodal Line

\[ f = 2.295 f_0 \]

D Russell Penn State
The (1,1) Drumhead Mode

Symmetric:
No net air volume change under the drumhead

\[ f = 1.593 f_0 \]
More Drumhead Modes

0,1

1,1

2,1

3,1

0,2

1,2

2,2

3,2

0,3

3,600 \, f_0

3.652 \, f_0

4,1

3.156 \, f_0

5,1

4.060 \, f_0

2.653 \, f_0

3.501 \, f_0

2.918 \, f_0

2.296 \, f_0

1.593 \, f_0

2.135 \, f_0

f_0
What you’re hearing...
Measured Sound Spectrum of 12” Tom Drum

"Lug Tone"

Struck at Center
Struck Halfway Out

(0,1)
(1,1)
(2,1)
(0,2)
Room Modes

A Resonant Frequency:
74.88 Hz

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Resonant Modes for 25 x 10 x 8 foot Rectangular Room

- Longitudinal "Organ Pipe" modes
- Pressure Mode

- Resonant Frequency (Hz)
  - 22.5 Hz
  - 45 Hz
  - 67.5 Hz
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