Outline

• Intro to Acoustics
• Overview of Acoustics Disciplines
  – SOFAR Channel
  – Theory + Experiment
• Applications of Acoustic Refraction
Continuum Mechanics

\[ \rho_{in} \quad v_{in} \quad P_{in} \]

\[ \rho \quad v \quad P \]

\[ \rho_{out} \quad v_{out} \quad P_{out} \]
Governing Equations

Mass Conservation
\[
\frac{\partial}{\partial t} (\rho) + \nabla \cdot (\rho \mathbf{v}) = 0
\]

Momentum Conservation
\[
\frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla P
\]

Linearize and Simplify
\[
P(\mathbf{r}, t) = P_0 + \delta P_1(\mathbf{r}, t)
\]
\[
\rho(\mathbf{r}, t) = \rho_0 + \delta \rho_1(\mathbf{r}, t)
\]
\[
\mathbf{v}(\mathbf{r}, t) = 0 + \delta \mathbf{v}_1(\mathbf{r}, t)
\]
Wave Equation

\[
\left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) P(\mathbf{r}, t) = 0
\]

\[
c^2 \equiv \left( \frac{dP}{d\rho} \right)_S
\]

\[c_{\text{Ideal Gas}}^2 = \frac{\gamma RT}{MW}\]

\[c_{\text{Liquid or Solid}}^2 = \frac{K}{\rho}\]

\[c_{\text{air}} = 343 \, \text{m/s}\]

\[c_{\text{Helium}} = 970 \, \text{m/s}\]

\[c_{\text{water}} \approx 1500 \, \text{m/s}\]

\[c_{\text{steel}} \approx 6000 \, \text{m/s}\]
Acoustics vs Optics

• Wave Equation
  – Linearized Compressible Navier-Stokes Equation
  – Maxwell’s Equations

• Human Hearing
  – 20Hz to 20kHz
  – 20Hz to 20kHz
  – 20Hz to 20kHz

• Amplitude + Phase
  – 13 orders of mag.
  – 13 orders of mag.

• Quiet to Loud
  – 13 orders of mag.
  – 13 orders of mag.

• Human Sight
  – 430THz to 790THz

• Intensity
  – 7 orders of mag.

• Polarization
  – Gas/Liquid: 1
  – Solid: 3
  – Usually: 2

  – Usually: 2
  – Usually: 2
ACOUSTICS DISCIPLINES
Cochlear Mechanics

2 kHz
Base

6 kHz
Base

2 kHz
Apex

Apex

http://bio1151b.nicerweb.net/Locked/media/ch49/49_10CochleaPitch.jpg

http://bio1151b.nicerweb.net/Locked/media/ch49/49_10CochleaPitch.jpg

https://coastline.files.wordpress.com/2011/01/outer-middle-inner-ear.jpg

http://web.tbgu.ac.jp/ait/wada/wadalab/vib-bm-e.html
Speech Communication

http://hyperphysics.phy-astr.gsu.edu/hbase/music/imgmus/fantvowred.gif

http://sail.usc.edu/~lgoldste/General_Phonetics/Source_Filter/Best_vowels.gif
Diagnostic Ultrasound

http://upload.wikimedia.org/wikipedia/commons/2/2f/CRL_Crown_rump_length_12_weeks_ecografia_Dr._Wolfgang_Moroder.jpg
http://bfiultrasound.com/images
Petroleum Exploration

S. Liu, “A Deaf Whale is a Dead Whale”, Oceana (2012)
http://www.geomore.com/seismic/
http://i.ytimg.com/vi/7f-0MKACtrc/maxresdefault.jpg
Solid Mechanics

Bulk Waves

Surface Waves

http://www.geo.mtu.edu/UPSeis/waves.html
Seismology

http://www.geogarific.com/2012/02/seismic-waves.html
http://seismology.geophysik.uni-muenchen.de/images/earth_big.jpg
At their brightest and most vibrant, coral reefs are among the...
Signal Processing


http://www.evaluate.in/lab2/pages/BPSK-mod/BPSK/BPSK_I.html
Structural Acoustics

http://en.wikipedia.org/wiki/Bending
Automotive Acoustics

THE BIKE STARTED UP

BETTER REV THE ENGINE A DOZEN TIMES TO MAKE SURE

http://www.mscsoftware.com/application/acoustics
Architectural Acoustics

https://acousticengineering.files.wordpress.com/2013/07/anechoic-6.jpg
http://www.creativeacousticsnw.com/Assets/images/IndexNivo/2.jpg
Ocean Acoustics

Optical Absorption in Seawater

**Distance Sunlight Travels in the Ocean**

- **Sunlight (euphotic) zone**
  - Sunlight rarely penetrates beyond this zone.

- **Twilight (dysphotic) zone**
  - Sunlight decreases rapidly with depth. Photosynthesis is not possible here.

- **Midnight (aphotic) zone**
  - Sunlight does not penetrate at all. This zone is bathed in darkness.

http://science.kennesaw.edu/~jdirnber/oceanography/LecuturesOceanogr/LecOceanStructure/0620B.jpg

http://oceanservice.noaa.gov/facts/light_travel.html
Ocean Sound Speed

- Warm: $\frac{K}{\rho}$
- Cool: $\frac{K}{\rho}$
- Cold: $\frac{K}{\rho}$

Very Low Pressure
Low Pressure
High Pressure
Ocean Sound Speed

\[ \sim c^2_{\text{medium}} \]

\[ \sim c^2_{\text{low}} \]

\[ \sim c^2_{\text{medium}} \]

\[ \frac{K_{\text{low}}}{\rho_{\text{low}}} \]

\[ \frac{K_{\text{low}}}{\rho_{\text{high}}} \]

\[ \frac{K_{\text{high}}}{\rho_{\text{high}}} \]
Ocean Sound Speed

- **Ocean Surface** (High T, Low P)
- **Twilight Zone** (Low T, Low P)
- **Ocean Bottom** (Low T, High P)

Increasing Depth

Increasing Sound Speed
Each line represents ~ 8 m/s
Ocean Sound Speed

- Well-mixed Ocean Surface
- Thermocline
- Deep Ocean

Temperature (°C)

Pressure (atm)
SO WHAT?
\( n = 1.00 \)

\( n = 1.75 \)
\[ n = 1.00 \]
\[ n = 1.11 \]
\[ n = 1.21 \]
\[ n = 1.32 \]
\[ n = 1.43 \]
\[ n = 1.54 \]
\[ n = 1.64 \]
\[ n = 1.75 \]
Bending Toward Slow Medium
\[ n = 1.75 \]
\[ n = 1.00 \]
\( n = 1.75 \)

\( n = 1.50 \)

\( n = 1.25 \)

\( n = 1.00 \)
Bending Toward Slow Medium
SOFAR Channel Propagation
Waveguiding Effect

Spherical
Pressure $\sim \frac{1}{r}$
Intensity $\sim \frac{1}{r^2}$

Cylindrical
Pressure $\sim \frac{1}{\sqrt{r}}$
Intensity $\sim \frac{1}{r}$

Heard Island

$\pi R = 20 \text{ Mm}$

16 Mm

4 Mm

18 Mm
Heard Island Feasibility Test
Heard Island Feasibility Test

http://www.davidcmartin.com/ships/cory-chouest.jpg
10 Beaufort scale

30 ft. seas
70 mph winds

Transducers

Sources decay with an e-folding time of 1.74 days, or, with a half-life of 1.21 days.

Whale Vocalizations

http://www.itravel-cabo.com/images/blue%20whale.jpg
Locating Downed Planes

S.O.F.A.R. (SOnund Fixing And Ranging)

http://upload.wikimedia.org/wikipedia/commons/b/ba/MH370_SIO_search.png
http://static2.lxdcdn.net/images/max/w/806/c25994dece9000c3a21358642dfef873.jpeg
Locating Russian Submarines (SOSUS)

http://www.dosits.org/people/history/SOSUShistory/
http://foxtrotalpha.jalopnik.com/the-massive-soviet-sub-that-inspired-hunt-for-red-octo-1552057821
Measuring the Temperature of the Ocean

Acoustical Ocean Thermometry
Summary

• Intro to Acoustics
• Overview of Acoustics Disciplines
  – Ray Approximation
  – SOFAR Channel
  – Heard Island Feasibility Test
• Acoustic Refraction
  – Project Mogul
  – Battle of Gettysburg
THE END

http://i.huffpost.com/gen/1438088/images/o-PACIFIC-OCEAN-WARMING-facebook.jpg