Transducers Lecture: Outline

• Quick Review: history, basic acoustics
• Piezoelectric Effect
• Transducer modeling & matching
• Array construction & applications

What is sound?

• a propagating vibration in a medium

• Local particle motion:

• ultrasound means above range of audible frequencies! \( f > 20kHz \) (often 1.5-8MHz)
Acoustics

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk modulus</td>
<td>( B )</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho_0 )</td>
</tr>
<tr>
<td>Longitudinal phase velocity</td>
<td>( c_l = \sqrt{\frac{B}{\rho_0}} = \frac{\omega}{k} = \lambda f )</td>
</tr>
<tr>
<td>Acoustic impedance</td>
<td>( Z = \rho_0 c_l )</td>
</tr>
<tr>
<td>Local pressure</td>
<td>( p )</td>
</tr>
<tr>
<td>Local particle velocity</td>
<td>( v )</td>
</tr>
<tr>
<td>Ohm's Law of Acoustics</td>
<td>( p = vZ )</td>
</tr>
</tbody>
</table>

\[
\rightarrow Z = \frac{p}{v} = \rho_0 c_l = \sqrt{B \rho_0}
\]

Acoustic Interfaces

\[
R = \frac{p_r}{p_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \\
T = \frac{p_t}{p_i} = \frac{2Z_1Z_2}{Z_2 + Z_1}
\]

*Note: energy is conserved, not pressure amplitude (in general, \( R + T \neq 1 \))
Ultrasound TRANSDUCERS

“tranduce” = convert signal (energy) to another form

\[ \text{[Electrical]} \leftrightarrow \text{[Mechanical/Acoustic]} \]

\( \text{made possible by the Piezoelectric Effect!...} \)

First, recall:

\[ D = \varepsilon \cdot E \]

\[ p = B \cdot S \quad \text{(Hooke’s Law)} \]

\( S = \frac{L_0 - L_f}{L_0} \)
Piezoelectric Effect (P.E.)

‘perovskite’ ceramics
FCC crystal w/central atom
PZT: Pb[Zr\textsubscript{x}Ti\textsubscript{1-x}]O\textsubscript{3} most common
‘poling’: high $E$, $T \rightarrow$ ctr atom *displaces* $\rightarrow$ dipole!
...mat’l not one domain (polycrystalline), but basically:

*then, if applied $E$ is:

\[ (+ \text{ dir.}) \rightarrow \text{shortens, compresses} \]
\[ (- \text{ dir.}) \rightarrow \text{stretches, elongates} \]

*after poling, mat’l exhibits P.E., quantified by piezoelectric stress constant:
\[ e = \frac{p}{E} \]

Piezoelectric Effect (P.E.)

constitutive equations:
\[
D = \varepsilon \cdot E + eS_{\text{app}} \\
p = B \cdot S - eE_{\text{app}}
\]
\[ e = \frac{p}{E} \]
\[ s = \frac{L_0 - L_f}{L_0} \]

if applied $E$ is:
\[ (+ \text{ dir.}) \rightarrow \text{shortens, compresses} \]
\[ (- \text{ dir.}) \rightarrow \text{stretches, elongates} \]

*note that $P$ dipole: $- \rightarrow +$ $E$ field: $- \leftrightarrow +$
$P$ dipole vector will tend to align with applied $E$ field lines

+ applied $S$ (compress.), $\uparrow D$
+ applied $E$, $\downarrow p$

In practice, we commonly choose piezoceramic $\lambda/2$ thick (resonator)
Transducer models & metrics

Approx. equiv. 1D circuits:

C₀ = ‘clamped capacitance’

Need performance metric (piezoelectric media)...

→ Electromechanical coupling coefficient \( k_t \)

\[
k_t = \sqrt{\frac{e^2}{B^D \varepsilon^S}} = \frac{\text{stored energy converted}}{\text{total input energy stored}} = \frac{\frac{n f_s}{Z_{fp}}}{\tan\left(\frac{f_s}{Z_{fp}}\right)}\]

*efficiency apparent in separation btw ‘series’ resonant and ‘parallel’ anti-resonant freq’s

Quarter-wave matching: what/why?

\[
Z_{in}(l) = \frac{Z_2 + jZ_m \tan(kl)}{Z_m + jZ_2 \tan(kl)}
\]

want \( Z_{in} = Z_2 \rightarrow Z_m = \sqrt{Z_1 Z_2} \)
Activity: predict the beam pattern

In far-field ($z \geq \frac{D^2}{4\lambda}$ = Fraunhofer), the field amplitude ≈ 2D Fourier Transform of the aperture!

@ Aperture

Field @ observation plane (still space domain!)

(how to deconstruct this mathematically?...)

*2D* space!
**Focusing** (& steering... Huygens-Fresnel)

- what happens optically... we can do electronically!

\[ F/\# = \frac{z}{D} \]

\[ \text{Lat. Res.} = \frac{\lambda z}{D} \]

**Focusing brings far-field pattern into near-field!**

**Linear, Curvilinear, Phased Array**
3D Transesophageal Echo (TEE)

Ultrasound Trends

- Live 3D: clinical & consumer!
- Low-cost & portable:
- Handhelds: