Design Considerations for HIFU Transducers

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Introduction

Intent of this workshop is to outline some design considerations and guidelines for various types of transducers intended to be used for HIFU applications:

Medical: Ablation, drug delivery, etc
Industrial: droplet jets, descaling, etc
Consumer: drug delivery, atomization, etc
“Invention is 10% inspiration and 90% perspiration” Thomas Edison
Bio

- 1982: BSE - Purdue University
- 1982 – 1999: Etalon, Inc
- 1999 – 2007: Piezotech, LLC
- 2007 to present: Better UltraSonic Technologies
- 26 years of piezo and ultrasound transducer design, manufacture and marketing
- 17 years of medical HIFU
Outline

- Define Your Application
- Select best transducer configuration
- Determine Frequency and Sound Field
- Determine Power Requirements
- Select Piezo Material
- Determine Best Matching Layers
- Select Adequate Interconnects
- Tune Electrical Impedance
Outline

• Consider Thermal Management
• Model, Model, Model
• Consider MRI Compatibility
• Test and Characterize Performance, Life and Safety

• Consider Other Uses
• References
• Questions / Discussion
Define Your Application

- Assuming Medical
- Extracorporeal – Laparoscopic – Endocavity
  - Low F, long FL; High F, short FL; Mid, FL
- Durable – Disposable
- Biocompatibility of contact materials needs to be Class VI
- Imaging Modality
  - Integral to HIFU F
  - Integrated with HIFU
  - Other Modality: MRI, PET, CT, etc
  - Compatibility issues?
Define Your Application

• Identify Target Tissue(s) and Properties
• Identify Target Depth
• Identify any Intervening Materials and Properties
• Determine Treatment Volume Estimate
• Minimum Site Intensity ($I_s$)
Define Your Application

• Determine Treatment Time
  – (ref’s: 10,11,12,51,52)
  – +70 C = 1 S, +56 C = 3 S, +43 C = 7200 S
  – After L. Crum, Therapeutic Workshop, 2007 US Symposium

• Consider Best Packaging
Select Best Transducer Configuration

• Single Element
  – Flat piezo element with Lens: low cost, less eff.
  – Cylindrical segment: medium cost, line focus
  – Spherical section: high cost, point focus, requires controlled scanning

• Multi-Element
  – Annular Array: medium to high cost, point focus, allows movement of focus along beam axis
  – Linear Array: expensive, can be concave, convex, phased, allows focusing along beam axis and transducer length, requires controlled scanning on transducer width for 3D
Select Best Transducer Configuration

• 2D Array: very expensive, phasing allows focusing in 3D

• CAUTION: Arrays create grating lobes – points of focus other than those intended-that can create hot spots/ lesions outside of the intended treatment area

• References: 13 – 22, 37
Determine Frequency and Sound Field

• Application is defined – how (ex, lap, endo), depth, intervening matl’s, vol., \( I_s \), Thermal

• Can calculate Frequency, \( F \); Aperture, \( D \); Focal Depth, \( FL \); and Power, \( Po \)

• Frequency
  – Mainly dependent on depth to target due to intervening tissue attenuation
  – Typical is \( \alpha = 0.5 \) to 1.5 dB/cm-MHz, 1 dB/cm-MHz is used
Determine Frequency and Sound Field

Example
Let \( z = 6 \text{ cm}, F = 1 \text{ MHz} \)
Loss to target = -1 dB/cm-MHz * 1 MHz * 6 cm
= -6 dB = 10 \log (P/P_0)

Based on assumptions and estimates made, the Site Intensity, \( I_s \), needs to be estimated

\( I_s \) typically between 1 kW/cm\(^2\) and 10 kW/cm\(^2\)
For simplicity, let \( I_s = 1 \text{ kW/cm}^2 \)
Determine Frequency and Sound Field

Need to set an Aperture, D, as well; may be affected by packaging or anatomy, etc.

Typically, F number = 1 = D/FL but can be from about .7 to 2 effectively.

Since FL = 6cm, then D = 6 cm as well.

Assume element geometry is the concave section of a sphere.

From \( I_s \), calculate \( P_o \)

\[ I = P/\text{area} \quad \text{where} \quad \text{ba} = \text{area} \]
Determine Frequency and Sound Field

Calculate Focal beam Dia., Dt, Beam Area, ba, and Focal Zone Length, FZL (Da)

\[ Dt = \frac{FL \cdot c}{(F \cdot D)}, \text{ cm} \]
\[ ba = \pi \cdot d^2/4, \text{ cm}^2 \]
\[ Da = FZL \sim 10 \cdot d, \text{ cm} \]
\[ \text{Vol} = ba \cdot FZL, \text{ cm}^3 \]
Determine Frequency and Sound Field

\[ Dt = \frac{6 \times 0.15}{1 \times 6} = 0.15 \text{ cm} \]

\[ ba = \pi \times \frac{0.15^2}{4} = 0.018 \text{ cm}^2 \]

\[ Da = 10 \times 0.15 = 1.5 \text{ cm} \]

This is an iterative process based on requirements of the application.
Determine Power Requirements

Calculate Site Power, $P_s$, from $I_s$ and $ba$

$$P_s = I \times ba = 1000 \times 0.018 = 18 \text{ W}$$

Calculate Power, $Po$, from loss and $P_s$

Loss = -6 dB = 10 log ($P_s/Po$)

$$Po = P_s/10^{-0.6} = 18 / 0.25 = 72 \text{ W}$$
Determine Power Requirements

Calculate Surface Intensity, $I_a$, on piezoelement

$\text{surface area, } sa = \pi \frac{D^2}{4} = 29 \text{ cm}^2$

$I_a = \frac{P_o}{sa} = \frac{72}{29} = 2.55 \text{ W/cm}^2$

this is well within limits of piezo materials
$P_{max} = sa \times I_s = 29 \times 10 = 290 \text{ W}$

The power and intensity limits need to be balanced against the possibility of damaging tissue between the transducer and target site.
Select Piezo Material

Limit to “high drive” types
Assume 50 ohm source and desired load
Calculate capacitance
\[ C = \frac{1}{\omega \times Z} \]
Where \( C \) is Farads, \( Z \) is impedance, \( \omega = 2\pi F \)
\[ C = 3200 \text{ pF} \]
Select Piezo Material

Calculate dielectric constant, $K$

$$K = \frac{C \times t}{(sa \times \varepsilon_o)}$$

where $t =$ thickness $= .21 \text{ cm}$;
and $\varepsilon_o = 8.85 \times 10^{-14} \text{ F/cm}$

$$K = 260$$
## Select Piezo Material

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Select Piezo Material

Calculate Power and Voltage Limits

\[ P_o = 2 \pi F E^2 k^2 \varepsilon_{33} T Q_m, \quad \text{W/cm}^3 \]
where \( E \) is V/cm, \( \varepsilon \) is F/cm

\[ P_d = 2 \pi F E^2 \varepsilon I_f \]

(ref. 2)
Select Piezo Material

Need to balance Surface Intensity with applied Voltage using

\[ P_o = \frac{V^2}{R} \]

where \( V \) = drive volts, rms

\[ V = (P_o \cdot R)^{1/2} = (72 \cdot 50)^{1/2} = 60 \text{ Vrms} \]
\[ V_{\text{max}} = t \cdot E = 0.21 \cdot 8000 = 1680 \text{ Vrms} \]
\[ P_{\text{max}} = V_{\text{max}}^2/R = 56 \text{ kW} \]
\[ V_{\text{max real}} = (290 \cdot 50)^{1/2} = 120 \text{ Vrms} \]
Select Piezo Material

Composites (36)
Can be made from any PZT, no gain for PbT
Pros: increase $k$, vary volume % ceramic $\rightarrow$ $K, Za, Ze$
minimal lateral modes,
minimal side lobes
Base for 2D array
30 W/cm$^2$ reported

Fig. 1: 1-3 Piezocomposite after W. A. Smith
Select Piezo Material

Cons

More expensive
Less solid ceramic $\rightarrow$ less real power
$\sim 1/3$ thinner for same F $\rightarrow$ less Voltage
Have to manage heat effectively
Select Piezo Material

Single Crystals
  Large $k = .7$ to $.9+$
  Low loss, $< 1\%$ typically

But
  High $K \rightarrow$ low $Ze$, ok for array elements
  Low $Tc$ w/ phase change near $25\,C$
  can they be focused?
  very expensive: $1/mm^3 = 1000/cm^3$
Determine Best Matching Layer(s) (3, 17)

1. None
   a. Ok if therapy only
   b. Still needs coating to protect electrode, leads, seal, etc
   c. Can get > 50 % eff. If properly designed
   d. Very narrow BW
   e. Use PLL to stay on Fo
   f. Ex - CV
Determine Best Matching Layer(s)

2. Single $\lambda/4$
   2 Main Equations

   a. Geometric Mean
      $Z_{ml} = (Z_I \times Z_x)^{1/2}$
      = 7.2 MR
Determine Best Matching Layer(s)

b. After DeSilet, et al

\[ Z_{ml} = Z_l^{2/3} \times Z_x^{1/3} \]

\[ = 4.3 \text{ MR} \]

used KLM, sets
Qm = Qe to max.
BW, min. PL
Not always best for max Po
Determine Best Matching Layer(s)

3. Single $\lambda/2$
   same eq’s.

   a. Geometric Mean
   $Z_{ml} = 7.2$ MR
   narrowband
Determine Best Matching Layer(s)

b. DeSilet

$Z_{ml} = 4.3 \text{ MR}$
Determine Best Matching Layer(s)

c. Example from physiotherapy

\[ Z_{ml} = 17.1 \text{ MR} \]

Aluminum
Determine Best Matching Layer(s)

4. Double $\lambda/4$

3 Main Derivations
Max. BW

a. Geometric Mean
$Z_{ml1} = Zx^{2/3} \cdot Zl^{1/3}$
$= 12 \text{ MR}$

$Z_{ml2} = Zx^{1/3} \cdot Zl^{2/3}$
$= 4.2 \text{ MR}$
Determine Best Matching Layer(s)

b. DeSilet

\[ Z_{ml1} = Z_x^{4/7} \times Z_l^{3/7} \]
\[ = 9 \text{ MR} \]
\[ Z_{ml2} = Z_x^{1/7} \times Z_l^{6/7} \]
\[ = 2.4 \text{ MR} \]
Determine Best Matching Layer(s)

c. After Goll

\[ Z_{m1} = Zx^{3/4} \times Zl^{1/4} \]
\[ = 15.5 \text{ MR} \]

\[ Z_{m2} = Zx^{1/4} \times Zl^{3/4} \]
\[ = 3.5 \text{ MR} \]
Determine Best Matching Layer(s)

5. Materials (4)
   a. $Z = 1$ to $10$ MR:
      polymers, carbon, magnesium
      fillers: AlO, AlN, SiC, W, Others
   b. $Z = 10$ to $15$ MR:
      glass, glass ceramic, fused silica
   c. $Z = 15$ to $20$ MR:
      x-cut quartz, aluminum, silicon, indium
Determine Best Matching Layer(s)

6. Precautions

High Power, i.e. Surface Intensity →

High surface deformation & heat

a. electrode: high adhesion to piezo

b. ML: void free, high Tg, low α, some plasticity – Shore D 70 to 90

c. May require use of chemical primers

d. Mid to high thermal conductivity
Select Adequate Interconnects

1. Electrodes on element
   a. Fired silver frit
   b. Sputtered or electroless copper, gold, nickel, platinum, palladium, indium, tin, etc
   c. Needs to be solderable, preferably nonmagnetic

2. Wires and Cables
   a. Foils: copper, tin, brass, nickel, silver
   b. Small gauge wires, solid or stranded, copper with tin, silver or gold plate, etc
   c. Cables: typ. Coax but can be twinax, triax, etc
Select Adequate Interconnects

3. Solders
   a. Pb/Sn, Sn/Ag, Pb/Sn/Ag, Sn/Ag/Cu, Au/In, etc.
   b. Conductive polymers
   c. Need to be somewhat pliable due to high mechanical stress
   d. Need to have high Ts / Tl due to high thermal stress
   e. Must be compatible with electrode and wire materials to prevent scavenging / leaching
Tune Electrical Impedance

Transducer can be modeled as a simple Lumped-element Circuit

(ref’s 5, 6, 7, 8, 9)

Figure 1: Lumped element representation of a piezoelectric transducer (near resonance)
Tune Electrical Impedance

1. Parallel eq. Circuit
   a. Parallel Inductor

   \[ R_p = Z / \cos \theta \]
   \[ X_p = Z / \sin \theta \]
   \[ L_p = X_p / \omega \]

   Requires high saturation core & large wire gauge

Figure 2: Thevenin’s equivalent circuit representation for the impedance and phase angle
Tune Electrical Impedance

b. Transformer

\[
\frac{Z_{\text{sec}}}{Z_{\text{pr}}} = N^2
\]

set \( Z_{\text{sec}} = \omega \times X_p \)

or \( L_p = L_{\text{sec}} = \frac{X_p}{\omega} \)

\( Z_{\text{pr}} = R_s \)

and \( N = \frac{t_s}{t_p} \)

\[
= (\frac{\omega \times L_p}{Z_{\text{pr}}})^{\frac{1}{2}}
\]
Tune Electrical Impedance

b. Transformer

can be toroid, C-core, E-core, balun, etc
be cautious with wire gauge and core material
typically high Q but can control with additional capacitance

\[ Q = \frac{R_p}{X_p} \]
Tune Electrical Impedance

2. Series Eq. Circuit

\[ R_{ser} = Z \times \cos \theta \]
\[ X_{ser} = Z \times \sin \theta \]
\[ L_{ser} = \frac{X_{ser}}{\omega} \]

cancels reactance

\[ Z = R_{ser} \]

\[ Z \neq R_s \text{ unless design is right} \]
Tune Electrical Impedance

3. The L Network
   Near lossless, max. power transfer, esp. if true conjugate of $Z_s$; high or low pass choose by:
   $RL > Rs$, $RL < Rs$
Tune Electrical Impedance

3. L Network

High pass preferred for harmonic content. Nonlinear component increases rate of tissue necrosis due to increased absorption at focus (ref. 9); components should be rated for power and values are at F, technique can be written as a program and can be extended to more complex $T$ and $\pi$ networks can easily adjust for stray cap. and ind.
Tune Electrical Impedance

3. L Network

\[ Q_s = Q_p = \left(\frac{R_p}{R_s} - 1\right)^{\frac{1}{2}} \]
\[ X_s = Q_s \times R_s \]
\[ X_p = \frac{R_p}{Q_p} \]

\[ L = \frac{X}{\omega} \]
\[ C = \frac{1}{(X \times \omega)} \]
Tune Electrical Impedance

Tuning Example
Double $\lambda/4$, Geo. Mean
Use simple series $L$
$L_s = \frac{X_s}{\omega} = \frac{43.64}{6.28 \times 10^6} = 6.95 \mu H$
Tune Electrical Impedance

Results from implementing into model

\[ Z <\theta = 47.1 \ \Omega < +2^\circ \]

\[ R + jX = 47 + j \ 1.6 \]
Consider Thermal Management

At high power, duty cycles – things will get hot!

To do:
1. Heat sink to thermal absorber
2. Thermal sensor
3. Coolant
Consider Thermal Management

Results:
Matching Layer and electrode delaminating, blistering, cracking
Piezo cracking, depole arcing, breakdown
Tuning Circuit and Wires burnout

FIGURE 1. Cracked transducer front face due to an excessive applied power (about twice the maximal acceptable excitation level)
1. Equivalent Circuits
   a. Mason’s Model – Lumped element – not used except for simple devices
   b. Redwood – modified Mason’s Model
   c. KLM – implemented in most software today
   d. Fs vs. Fp Operation

(ref. 1, 23 – 27)
2. Implementation
   a. Commercial SW Packages
      1. PiezoCAD – 1-D, Sonic Concepts
      2. ANSYS – FEA, Swanson
      3. COMSOL – FEA,
      4. PZFLEX – FEA, Weidlinger
   b. Write own in C, MatLab, MatCad, Spice
3. What can be done
   a. Predictive: Po, BW, IL, Imp, Field, Thermal
   b. Parametric: include active & passive components, load losses
   c. FEA: 2 & 3D, defects, mode coupling, etc

Figure 5. Axisymmetric model of an ocular tumor, showing focused ultrasound beam (above) and temperature distribution at 3 sec below. Note focal temperature in excess of 100 °C. The transducer as a 4 cm aperture and 9 cm focal length.
4. An Example Using PiezoCAD

Single $\lambda/4$, $Z = 4.3$

No electrical tuning

$Z/\theta = 49/ -37 \ @ \ 1M$

$P_o/P_i = .938 \ W/W \ @ \ .94$

$R_{max} = 49 \ @ 1.116 \ M$

$\Gamma_p \ @ \ .868 \ M$

$V_{RC} = .317 \ V/V \ @ \ .95 \ M$
MODEL, MODEL, MODEL
Adjust Matching Layer Thickness to affect F, R

Po/Pi = 0.944 W/W @ 0.97
Z / θ = 69.5 / -30 @ 1 M
Gp @ 0.876 M
AND
R max = 60 @ 1 M
VRC = 0.121 V/V @ 0.94
MODEL, MODEL, MODEL
Add Tuning to cancel reactance
Series $L = 5.6 \, \mu H \ @ \ 1 \, M$

Results
- $P_o/P_i = 0.944 \, W/W \ @ \ 0.97$
- $Z/\theta = 60 / 0 \ @ \ 1 \, M$
- $R_{max} = 60 \ @ \ 1 \, M$
- $V_{RC} = 0.09 \, V/V \ @ \ 1 \, M$
- $G$ shows typical split peaks
Consider MRI Compatibility

1. Material Selection
   b. Safe: Aluminum, Titanium, Gold, Platinum, Palladium, Silver, some Stainless Steels, most piezo materials – some contain iron, nickel, gadolinium – be sure of trace additives
   c. Dangerous: magnetic / para-magnetic materials – iron and compounds, nickel, gadolinium, some piezo’s

(ref’s: 28, 29)
Consider MRI Compatibility

2. Design Issues
   a. long cable runs from source, typ 7 to 10 M, signal losses
   b. can not electrically tune @ the transducer with coils, chokes, transformers
   c. avoid internal wire loops – can cause stray inductances
   d. exercise caution with fillers in polymers – know purity
Consider MRI Compatibility

3. Verification of Product
   ASTM, ANSI, ISO, IEC, NEC, FDA and others all publish standards for Testing Methods, Labeling Requirements, Definitions, etc.

www.mrisafety.org
Test and Characterize Performance, Life and Safety ref (4, 30 – 35, 57)

1. Attended the preceding workshop “Acoustic Output Measurements”, Mark Hodnett, NPL
2. Standards Bodies: IEC, FDA, AIUM, ANSI, NEC, NEMA, etc.
3. Testing – parameters, output, linearity, repeatability, life expectancy, safety
   a. Output Power – TAP Meter, RF Amp, FG, PC, O’scope
Test and Characterize Performance, Life and Safety

3. Testing
   b. Sound Field
      1. Scanning Tank with Hydrophone: 5 – 6 axis of freedom, can map in 3D, low power BUT new high power hydrophones being developed
Test and Characterize Performance, Life and Safety

3. Testing
   b. Sound Field

2. Schlieren Optical

High resolution,

...can identify flaws or non-uniformities at low & high power,

Software can do 3D

![Highly focused beam showing anomalous sidelobe caused by a crack in the radiating surface.](image)
Test and Characterize Performance, Life and Safety

3. Testing
   b. Sound Field
      3. Acoustic Streaming (57)
         similar to Schlieren but uses suspended particles to map velocity profiles

4. Phantoms
   several sources for HIFU phantoms, reasonably clear and closely mimic tissue, can visualize treatment
Test and Characterize Performance, Life and Safety

3. Testing
   c. Environmental
      1. Thermal Conditions: storage, shipping, operating
      2. Hermiticity: IP rating, splash, immersion, etc., gas sterilization
      3. ESS/ Burn-in: validate to full spec
      4. Accelerated Life
      5. FMEA
   d. Electrical Safety
      1. HiPot
      2. Insulation Resistance
      3. Current Leakage
      4. EMI/ EMS
Test and Characterize Performance, Life and Safety

4. Safety
   a. use common sense
   b. always operate loaded
   c. Always make sure source is off when connecting or disconnecting
   d. always use degassed water
   e. know limits
   f. always have path to ground
   g. NO BODY PARTS!

FIGURE 1. Cracked transducer front face due to an excessive applied power (about twice the maximal acceptable excitation level)
Consider Other Uses  

ref (38 – 41)

1. Industrial
   a. Droplet Jetting: basically same as HIFU, must know material properties; ex. Ink jets, coating
   b. Nebulize / Atomize: chemical analyzers, FUSION

\[ d = 0.34 \times \left( \frac{\pi^3 \cdot T}{\rho \cdot F^2} \right)^{1/3} \]
Consider Other Uses

1. Industrial
   c. Megasonic Cleaning – uses streaming
   d. Descaling – think Lithotripsy
   e. Pumps – streaming

2. Pharma / Consumer
   a. Cosmetic – skin / wrinkle enhancement
   b. nebulizers – inhalable drugs – asthma, diabetes
   c. needleless injection – drugs that are too large
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47. US Patent 6716184, “Ultrasound Therapy Head Configured to Couple to an Ultrasound Imaging Probe…” \, Roy W. Martin, et al, assigned to University of Washington