Acoustic Tweezing: Modelling, Implementation and Applications

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Course Content

The acoustic radiation force
   (Charles Courtney, University of Bath)
Tweezing with planar resonators
   (Martyn Hill, University of Southampton)
Dexterous acoustic tweezing
   (Bruce Drinkwater, University of Bristol)
How to make an acoustic tweezer
   (Sandy Cochran, University of Dundee)
Applications of acoustics tweezers
   (Martyn Hill, University of Southampton)
Acknowledgements

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The acoustic radiation force
(Hand-out to follow)

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University of Bath, UK

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Dexterous Acoustic Tweezing

Professor Bruce Drinkwater
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Contents

• Introduction to array-based tweezing
• Effect of device boundaries
• Design and modelling of dexterous devices
• High frequency beam-based tweezing
• Current capabilities and future directions
Examples of array devices

- 4-transducer water-backed\(^1\)

- Heptagon\(^2\)

- Planar array\(^3\)

- Circular array\(^4\)

\(^1\)Courtney et al in APL 101 (23), 2012
\(^2\)Bernassau et al in IEEE UFFC 58(10), 2011
\(^3\)Glynne-Jones et al in IEEE UFFC 59(6), 2012
\(^4\)Courtney et al in APL 102 (12), 2013
Array-based manipulation

Element outputs

Device

Reflections

Tweezing task

Array elements
Questions

• How to arrange the array elements?
• What acoustic field is needed to complete the tweezing task?
• How can this required acoustic field be created?
• What is the influence of the device boundaries?
Current devices

- Surround the region with elements for in-plane tweezing
- Use a plane of elements to create a beam for out-of-plane tweezing

These concepts could be merged for 3D manipulation
Effect of boundaries

Reflective boundaries

$u(x) = 2A[\cos(kx) + e^{i\phi/2}\cos(kx)]$

Transparent boundaries

$u(x) = A[e^{ikx} + e^{-i(kx-\phi)}]$
Transparent boundaries

Matching layer

Water

PZT

Absorber

Water-backed

Water

PZT

Water

Absorber

Grinenko et al in APL 101(23), 2012
Transparent boundaries

- Matching layer design

Transducer resonances
Effect of partial reflection

\[ \Delta x = \frac{1}{k} \arctan \left( \frac{R-1}{R+1} \tan \left( \frac{\Delta \Phi}{2} \right) \right) \]
4-element array

- Rectangular grid pattern formed
- Grid can be translated in the plane of the device
- Applications in biology and materials

Courtney et al in Proc Roy Soc 468, 2012
Simulating the device

\[ P_1(x, y) = P_0 \exp[i(kx + \varphi_1)] \]
\[ P_2(x, y) = P_0 \exp[i(-kx + \varphi_2)] \]
\[ P_3(x, y) = P_0 \exp[i(ky + \varphi_3)] \]
\[ P_4(x, y) = P_0 \exp[i(-ky + \varphi_4)] \]

4 plane waves, no reflections
\[
\phi_y = \phi_x
\]

Where, \( \varphi_x = \frac{\varphi_1 + \varphi_2}{2} \), and \( \varphi_y = \frac{\varphi_3 + \varphi_4}{2} \)
Acoustic radiation force

- Using Gor’kov $U = 2\pi a^3 \rho \left\{ \frac{\overline{p^2}}{3\rho^2 c^2} f_1 - \frac{v^2}{2} f_2 \right\}$

- $f_1 = 1 - \frac{K}{K_0}$

- $f_2 = 2\frac{\rho_0 - \rho}{2\rho_0 + \rho}$

And then

- $F = -\nabla U$
Force Measurement

- Locate single particle in trap.
- Shift acoustic field by $\lambda / 2$.
- Track motion with 200 fps camera.
- Fit solution for particle in sinusoidal potential well in presence of Stoke’s drag

$F_0 = 30$ pN
10,000 trapping points

- Uniform grid of equal traps
- Translatable in X and Y

10μm diameter polystyrene spheres in water, 5MHz
Translation of the acoustic field

Video

Four 10 μm particles

Composite photo

Composite image of a single 6 μm fluorescent particle maneuvered to shape the letters ‘ST’
Alternative concepts

- Mode switching

\[ F_{Total} = qF_Q + (1 - q)F_H \]
Mode switching

Varying the fraction of the quarter wavelength mode
Circular Array Device

Piezoceramic material
(Ferroperm Pz27)

Backing layer
(Alumina loaded epoxy)

10.98 mm
Ideal acoustic pressure field?

- Arbitrary trap locations
- Arbitrary trap numbers
- Sharp spatial gradients
- Minimal interference between traps

Ideal

Real device
Helical* beam creates local minima

Instantaneous pressure ($\alpha=1$)

$\alpha =$ topological charge

*As used in optical tweezers, e.g. Grier, Nature 424, 2003
How to generate a Helical beam

\[ \phi_n = \left( \frac{\alpha 2\pi n - 1}{N} - kr \right) \]

\( \alpha 2\pi \) radians around the ring

Moves trap centre
Effect of the number of elements
Performance limits and aliasing

N=60

- If the boundary is discretized, then, according to sampling theorem an inevitable aliasing appears

\[ p(r) = p_0 J_\alpha (kR_T)e^{i\alpha \theta_T} + p'(r) \]

- Controllable area is defined by:

\[ R_{T(Max)} = \frac{1}{2} \left( \frac{N - \alpha}{\pi e} \right) \lambda \]

\[ \approx \frac{N \lambda}{17.08} \]

Grinenko et al in Proc. Roy Soc. 468, 2012
Particle positioning
Multiple traps

• \( n^{th} \) element and \( m^{th} \) trap

\[
\phi_{nm} = \left( \frac{2\pi(n-1)}{N} - kr_{nm} \right)
\]

\[
V_{nm} = V_0 \exp(i(\omega t + \phi_{nm}))
\]

• Linear superposition.

\[
V_n = \sum_{m=1}^{M} V_{nm} = V_n' \exp(i\phi_n')
\]
Full FE simulation of 32-element array device
2 traps moving and merging

Schlieren

Video

Courtney et al in IUS Prague, 2013
What does high and low frequency mean in practice?

- **Low frequency** (Rayleigh scattering)
- **High frequency** (Ray acoustics or Mie scattering)

Graph of particle size/wavelength:
- **Eukaryotic cells**
- **Prokaryotic cells**
- **Multi-cell**

Frequency (MHz)

Particle diameter (um)

- 75 µm
- 200 MHz
Propagating Bessel beams

\[ p = e^{ikz} \cos \beta J_\alpha(k\rho \sin \beta)e^{i\alpha \varphi} \]
High frequency force regime

- \(a \gg \lambda\) (ray acoustics)
- In 2010 Lee et al trapped a 125\(\mu\)m lipid drop using 30MHz ultrasound (\(\lambda=60\mu\)m)
- In 2011 Lee et al+ trapped a Leukaemia cell (10\(\mu\)m) using 200MHz ultrasound (\(\lambda=7.5\mu\)m)

*Lee et al (USC), IEEE UFFC, 57(10), 2010
+Lee et al (USC), Biotechnology and Bioengineering, 108(7), 2011
High frequency array

- 26MHz ($\lambda=58\mu m$), 64 element array*
- $\Ø 45\mu m$ PS
- Standard phased array focussing

Applications

- Biology (e.g. tissue engineering)
  - High precision, high dexterity
  - Scale fixed by cell/tissue size
  - Non-destructive to cells

- Medicine (e.g. drug delivery)
  - Moderate precision, moderate dexterity
  - Scale fixed by delivery agent
  - Single sided
  - Destructive?

- Materials (e.g. composites)
  - Moderate precision, moderate dexterity
  - Large area, multi-scale
  - Fast
  - Flexible in terms of materials
  - No living matter involved
Cell patterning

- Biocompatible acoustic manipulator printed with rapid prototyping system
- Fits within a petri dish
- 15x15mm active area
- Easy to sterilise
- Good optical access
Cell patterning

Uses include:

• Cell-cell and cell-chemical interaction studies

• Forming the building blocks of engineered tissue

• Various new migration and/or adherence assays

MDCK Cells (Photo courtesy of Anne Bernassau, University of Glasgow)
Co-culturing cells

- SVP cells
- SVP + CPC cells

90 mins
Shift traps

Fluorescent microscopy

- CPC
- SVP cells
Composite manufacture

- Low viscosity photo-cure epoxy resin
- 15\(\mu\)m diameter, 50 \(\mu\)m length glass fibres
- Operated at 2MHz, so line spacing equals 325\(\mu\)m
Composite manufacture

Photo

Glass fibres set in epoxy resin (Photo courtesy of Marc Scholz, University of Bristol)

X-ray CT
Concluding remarks

• Dexterous acoustic tweezing is a reality
• Various concepts are being explored and showing significant promise
• Typically devices use wavelengths $\sim 100 \mu m$ to manipulate cells $\sim 10 \mu m$ in water (i.e. complimentary to optical tweezers)
• Order of magnitude variation in these length scales is possible
• Applications includes tissue engineering and micro/nano fabrication
How to make an acoustic tweezer

Professor Sandy Cochran
University of Dundee, UK

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Course Outline

- This part of the course focuses on Sonotweezers as **arrays of individual devices**
  - Acoustic tweezing and sonotweezing may also refer to simpler devices
- The components of a **Sonotweezer**
  - The tweezer itself
    - Piezoelectric material
      - Micromachining
    - Other components
  - The **electronics**
    - Conventional multichannel excitation
    - Array controllers
    - Maximally simplified electronics
- **Ancillary components**
The Components of a Sonotweezer
Conventional Transducer Structure

- **Classic single element transducer**

![Diagram of a transducer structure](image)

- Casing
- Mechanical damping
- Matching layers
- Piezoelectric plate
- Ultrasonic coupling gel
- Test object
- Ultrasonic coupling gel
- Tx-Rx

Mathematical notation:
\[ V_{tx-rx} \]

Variables:
- \( t \)
- \( V_{tx-rx} \)
Ultrasonic Array Structure

- An array is a **set of miniature transducers** known as array elements.
- The array elements are in **fixed, known positions** relative to one another.

![Diagram of Ultrasonic Array Structure]

- Casing
- Elements 12-64
- Individual coaxial cables
- Matching layers
- Protective layer
- Test object
- Couplant
- Piezoelectric elements
- Mechanical damping
Medical Implementation

- Arrays are implemented with an **integrated manufacturing process**
  - The array is first made with all the elements joined together, using monolithic pieces of the active material and other layers
    - The elements are **separated in situ**
  - This approach is also ultimately the **only practical one** for Sonotweezers
Sonotweezer Arrays

- **Piezoelectric elements**
  - Still required as a set of miniature transducers
    - Individual electrical connections also a necessity
- **Mechanical damping**
  - Acoustic tweezers are narrowband ultrasound sources
    - Hence mechanical damping is not needed
- **Matching layers**
  - Needed for some acoustic tweezers but not all
    - Can be omitted for simple, exploratory devices
- **Casing etc**
  - Designed ad hoc according to application
  - Unlikely to require protective front face layer
Examples

Not to scale
## Related Design Framework

<table>
<thead>
<tr>
<th>Dimensionality</th>
<th>3D array manipulator with mode switching</th>
<th>Crossed electrode array manipulator</th>
<th>2D array manipulator</th>
<th>Dual pair matched transducers</th>
<th>64-element device</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5D</td>
<td></td>
<td>2D multi wave-(\lambda) resonator</td>
<td></td>
<td>SAW counter propagating device</td>
<td></td>
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<tr>
<td>2D</td>
<td></td>
<td></td>
<td>Heptagon-on-flex device</td>
<td>Octagon-on-flex device</td>
<td></td>
</tr>
<tr>
<td>1.5D</td>
<td>Linear array manipulator</td>
<td></td>
<td>Mode switched (\frac{1}{2}\ \lambda) resonator</td>
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<td></td>
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<tr>
<td>1D</td>
<td></td>
<td></td>
<td>Ring transducers</td>
<td>HF SAW multi-(\lambda) capillary resonator</td>
<td>HF multi-(\lambda) capillary resonator</td>
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<td></td>
<td></td>
<td>Multi-(\lambda) vertical resonator</td>
<td>HF multi-(\lambda) lateral resonator</td>
</tr>
<tr>
<td>0.5D</td>
<td>Transwell chamber</td>
<td>SAW microchannel lateral resonator</td>
<td></td>
<td>Acoustic Cytometer</td>
<td></td>
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<tr>
<td></td>
<td>Bead sorter</td>
<td>LNO (\frac{1}{2}\ \lambda) resonator with capillary</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Thin layer resonator</td>
<td>(\frac{1}{2}\ \lambda) resonator with capillary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\frac{1}{4}\ \lambda) resonator</td>
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- **Resonant Chamber Devices**
- **Counterpropagating Wave Devices**
- **Progressive Wave Devices**
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<td>Insightec Matrix Array</td>
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<td>Octagon-on-flex device</td>
<td>Single pair matched transducers</td>
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<tr>
<td><strong>1D</strong></td>
<td>Mode switched ½ λ resonator</td>
<td></td>
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</tr>
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<td><strong>0.5D</strong></td>
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<td>½ λ resonator with capillary</td>
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<tr>
<td><strong>0.5D</strong></td>
<td>½ λ resonator</td>
<td>¼ λ resonator</td>
<td></td>
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</table>
Electronics

• Three choices
  1. Based on commercial **multichannel signal generators**
     • May need additional output amplification
  2. A commercial ultrasound **array controller**
     • Typically supplied for nondestructive testing
       • May not have sufficient drive capability
     • Alternative is system for focused ultrasound surgery
       • Likely to be low frequency / high power
  3. Fully **custom electronics**
     • Field programmable gate array (FPGA) control likely to be essential
       • With additional simple analogue electronics
Ancillary Components

- Some Sonotweezers may contain the working fluid and cells within their structure
  - These devices will either have to be experimental or disposable
- As an alternative, detachable components can be used to contain the working fluid
  - A very wide range of glass capillaries is readily available
    - These are inexpensive, mass produced items suitable as disposables
    - Their dimensions can vary significantly relative to acoustic requirements
  - A Sonotweezer can be designed to fit in a petri dish
- Other specific plastic or glass components could be manufactured
The Tweezer Itself
**Piezoelectric Material**

- Tweezers need **pressure to be generated** in response to an applied voltage.

- **Converse** piezoelectric effect:
  
  When a voltage is applied to a piezoelectric material external pressure is generated.

- The relevant parameter is \( d \), the **piezoelectric charge coefficient** (units NC\(^{-1}\) or mV\(^{-1}\)).
  
  - Typical value \( d_{33} = 600 \text{ pmV}^{-1} \)
# Possible Piezomaterials

<table>
<thead>
<tr>
<th></th>
<th>PZT-4 “Hard” piezoelectric ceramic</th>
<th>PZT-5H “Soft” piezoelectric ceramic</th>
<th>PVDF Piezoelectric polymer</th>
<th>LiNb03 Traditional single crystal</th>
<th>PMN-PT New, high performance single crystal</th>
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</thead>
<tbody>
<tr>
<td>Stiffness</td>
<td>$c_{33}^D$ GNm$^{-2}$</td>
<td>155</td>
<td>159</td>
<td>8.52</td>
<td>251</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho$ kgm$^{-3}$</td>
<td>7500</td>
<td>7500</td>
<td>1760</td>
<td>4640</td>
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<tr>
<td>Velocity</td>
<td>$v$ ms$^{-1}$</td>
<td>4560</td>
<td>4600</td>
<td>2200</td>
<td>7360</td>
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<tr>
<td>Acoustic impedance</td>
<td>$Z = \rho v$ MRayl</td>
<td>34.1</td>
<td>34.5</td>
<td>3.92</td>
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<tr>
<td>Piezoelectric strain constant</td>
<td>$d_{33}$ pmV$^{-1}$</td>
<td>289</td>
<td>593</td>
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<td>Piezoelectric voltage constant</td>
<td>$g_{33}$ VmN$^{-1}$</td>
<td>26</td>
<td>20</td>
<td>230</td>
<td>22</td>
</tr>
<tr>
<td>Piezoelectric figure of merit</td>
<td>$FOM = \frac{d_{33} g_{33}}{\rho}$ pmN$^{-1}$</td>
<td>7.51</td>
<td>11.9</td>
<td>5.75</td>
<td>0.129</td>
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<tr>
<td>Thickness mode coupling coefficient</td>
<td>$k_t$</td>
<td>0.508</td>
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<td>638</td>
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<td>$Q$</td>
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<tr>
<th></th>
<th>PZT-4</th>
<th>PZT-5H</th>
<th>PVDF</th>
<th>LiNbO₃</th>
<th>PMN-PT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;Hard&quot; piezoelectric ceramic</td>
<td>&quot;Soft&quot; piezoelectric ceramic</td>
<td>Piezoelectric polymer</td>
<td>Traditional single crystal</td>
<td>New, high performance single crystal</td>
</tr>
<tr>
<td><strong>Stiffness</strong></td>
<td>$c_{33}^{D}$ GNm⁻²</td>
<td>155</td>
<td>159</td>
<td>8.52</td>
<td>251</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>$\rho$ kgm⁻³</td>
<td>7500</td>
<td>7500</td>
<td>1760</td>
<td>4640</td>
</tr>
<tr>
<td><strong>Velocity</strong></td>
<td>$v$ ms⁻¹</td>
<td>4560</td>
<td>4600</td>
<td>2200</td>
<td>7360</td>
</tr>
<tr>
<td>Acoustic impedance</td>
<td>$Z = \rho v$ MRayl</td>
<td>34.1</td>
<td>34.5</td>
<td>3.92</td>
<td>34.1</td>
</tr>
<tr>
<td><strong>Piezoelectric strain constant</strong></td>
<td>$d_{33}$ pmV⁻¹</td>
<td>289</td>
<td>593</td>
<td>25</td>
<td>5.88</td>
</tr>
<tr>
<td><strong>Piezoelectric voltage constant</strong></td>
<td>$g_{33}$ VmN⁻¹</td>
<td>26</td>
<td>20</td>
<td>230</td>
<td>22</td>
</tr>
<tr>
<td><strong>Piezoelectric figure of merit</strong></td>
<td>$\text{FOM} = \frac{d_{33} \cdot g_{33}}{\varepsilon_{33}}$ pmN⁻¹</td>
<td>7.51</td>
<td>11.9</td>
<td>5.75</td>
<td>0.129</td>
</tr>
<tr>
<td><strong>Thickness mode coupling coefficient</strong></td>
<td>$k_t$</td>
<td>0.508</td>
<td>0.512</td>
<td>0.190</td>
<td>0.162</td>
</tr>
<tr>
<td><strong>Length-extensional coupling coefficient</strong></td>
<td>$k_{33}$</td>
<td>0.691</td>
<td>0.746</td>
<td>0.130</td>
<td>0.162</td>
</tr>
<tr>
<td><strong>Relative permittivity at constant stress</strong></td>
<td>$\varepsilon_{33}^{T}$</td>
<td>1275</td>
<td>3430</td>
<td>8.4</td>
<td>29.8</td>
</tr>
<tr>
<td><strong>Relative permittivity at constant strain</strong></td>
<td>$\varepsilon_{33}^{S}$</td>
<td>638</td>
<td>1470</td>
<td>10-12</td>
<td>29.0</td>
</tr>
<tr>
<td><strong>Mechanical quality factor</strong></td>
<td>$Q$</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Very high</td>
</tr>
</tbody>
</table>

All values are indicative only
Internal and External Waves

• Excitation voltage, \( V_{HV} \), is applied, with desired spectral content, e.g. sine wave for burst output

• Four distinct mechanical waves are set up
  • Two propagating in the external media
  • Two propagating within the piezoelectric material

• The waves in the piezoelectric material are partially internally reflected, creating an oscillating condition and resonance, with a frequency inversely proportional to thickness
Mechanical Resonance

- **Mechanical resonance** is a fairly straightforward physical effect
  - Hence the frequency, \( f_m \), is easily determined

\[
\lambda = 2D \quad \quad \quad f_m = \frac{\nu}{\lambda}
\]

where

\( \lambda \) = acoustic wavelength

\( D \) = thickness of piezoelectric material

\( \nu \) = acoustic velocity in piezoelectric material

- This **ignores** issues such as piezoelectric stiffening and modification of wave propagation by component shape
Electrical Resonance

• As the piezoelectric material forms an electrical component (as well as mechanical i.e. it is electromechanical) it also has an electrical resonance

• There is no particularly straightforward way to calculate $f_e$, the electrical resonance frequency

• One way, for wide, thin plates, is to back $f_e$ out of the expression for thickness mode coupling coefficient

$$k_t = \sqrt{\frac{\pi f_e}{2fm}} \cdot \sqrt{\tan\left(\frac{\pi f_e}{2fm}\right)}$$

• Because the elements in Sonotweezers are small, they are likely to operate best at $f_e$
Matching Layers

- Matching layers are designed to have **anti-reflective** properties to enhance energy transfer from the piezoelectric material through the couplant into the ultrasonic medium.

- **Theoretically**, the thickness of a single matching layer, $T_{ml}$ and its acoustic impedance, $Z_{ml}$, are defined as

\[
T_{ml} = \frac{\lambda_{ml}}{4}, \quad Z_{ml} = \sqrt{Z_{pm}Z_{um}}
\]

where $\lambda_{ml}$ is the wavelength in the matching layer, and $Z_{pm}$ and $Z_{um}$ are the acoustic impedances of the piezoelectric material and the ultrasonic medium respectively.

- Although a matching layer works ideally at only a single frequency, corresponding to $\lambda_{ml}$, it often increases the operating bandwidth by reducing reverberation in the piezoelectric material.
Micromachining

- Micromachining is needed to generate the **precise shapes** required for the piezoelectric material and the matching layer

- Three possible routes

  - Accessing a **conventional machine shop**
    - Problems with size of tools and machine precision
    - Problems with machining piezoelectric materials

  - Assembling or accessing a **specialised workshop**
    - Key components are dicing saw and lapping / grinding machines
    - Polymer handling / machining also required

  - Utilising **semiconductor / MEMS industry fabrication** processes
    - Highly restricted availability
Example: 64-element Array

Basic design layout

Fabrication process diagram

- Fabrication process is an integrated one
- Matches medical ultrasound approach
Example: Thick Film Sonotweezer

Electrical interconnect
- PZT, Array electrodes and electrode tracks all screen printed on substrate
- Mask-based fabrication

Fluidic & optical interface
- Array forms base of chamber, or
- Capillary coupled to array
Example: pMUTs

- Thin film deposition for PZT, array electrodes and electrode fan-out
- Fully mask-based fabrication
- Conventional Si-based microfabrication techniques can be used
Electronics for Sonotweezers
Commercial Signal Generators

- **Advantages**
  - Straightforward solution for *small numbers of elements*
  - Likely to provide *enough drive capability* without additional amplification
  - Offers *easy flexibility*

- **Disadvantages**
  - **Costly** because of need for flexibility in design
  - Feasible *maximum number of elements limited*
  - **Not** space efficient
  - **Multiple cables** needed: awkward and unreliable
Commercial Array Controller

- Advantages
  - Should be able to support **enough channels**
  - Provides automatic channel **phasing / synchronisation**

- Disadvantages
  - **May be as costly as separate signal generators**
  - Typically not well matched to Sonotweezers application
    - Will usually include **unnecessary hardware** for reception
    - Will usually **not allow CW excitation**

Custom Electronics

- Advantages
  - Relatively **inexpensive hardware**
    - **FPGA** evaluation board
    - Custom analogue drive board
      - Possible to drive Sonotweezers with **rectangular waveforms**
  - **Minimal hardware cost** per channel
  - Automatic **channel phasing** / synchronisation

- Disadvantages
  - **Low level programming** required - VHDL, or LabVIEW option
  - **Custom electronics design** and fabrication required
  - Large channel counts may need **complicated solutions**
Ancillary Components
Ancillary Components

- Translation of Sonotweezers from electronics lab curiosity to useful system requires application-specific front end

- Must work with Sonotweezers
  - Likely also to have to provide additional access for observation / measurement
- Must provide access for target of manipulation
  - E.g. connection to syringe driver
- Likely to be disposable for work in life sciences
  - Capillary, cuvette or petri dish

Feedback e.g. optical measurements
Example: 1D Array System

- Optical (observation) interface
  - Clear glass capillary with open window for microscope observation
- **Fluidic** interface
  - Capillary *coupled* to array substrate
  - Filled / flow controlled from *syringe*
Example: pMUTs

- Optical (**observation**) from above
- **Fluidic** interface still to be engineered
  - Basis in microscale silicon substrate will require further development
- **Electronic interface** achieved with a chip carrier
Example: Thick Film Sonotweezer

2D array

Glass coverslip
Perspex gasket (with inlet and outlet)
PCB gasket
Spring pins
Slide switches
SMA connector
PCB
Summary
Summary

• Sonotweezers development is **bifurcated**
  • **Simple devices** subject to *ad hoc* development
    • **Not** covered here
  • **Multielement devices** requiring specialised fabrication
• Three main components
  • **Sonotweezer** itself
    • Based on micromachined piezoelectrics
  • **Electronics**
  • **Ancillary hardware**
    • Requires **application specific** development
• PC also required for **control** in most systems
• **Many** future possibilities
  • Ultimate target is ultrasound equivalent of **spatial light modulator in optical tweezing**