

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)



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The acoustic radiation force

(Hand-out to follow)

Dr Charles Courtney University of Bath, UK



Tweezing with planar resonators (Hand-out to follow)

Professor Martyn Hill University of Southampton, UK



Applications of acoustics tweezers

(Hand-out to follow)

Professor Martyn Hill University of Southampton, UK



Dexterous Acoustic Tweezing

Professor Bruce Drinkwater University of Bristol, UK

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-backed¹



• Planar array³



• Heptagon²



• Circular array⁴





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



Kerray-based manipulation







KQuestions

- 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 inplane tweezing

 Use a plane of elements to create a beam for out-ofplane 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







University of BRISTOL



K Transparent boundaries





Grinenko et al in APL 101(23), 2012



Kernet Kernet

Matching layer design







Effect of partial reflection







✓ 4-element array



Manipulation possible if boundary is transparent

Rectangular grid pattern formed

University of

- Grid can be translated in the plane of the device
- Applications in biology and materials





K 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 planewaves, no reflections







KAcoustic Pressure





Kernet Acoustic radiation force

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





KForce Measurement

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







10,000 trapping points



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



 $10\mu m$ diameter polystyrene spheres in water, 5MHz



Kernet Translation of the acoustic field

Video





Composite image of a single 6 µm fluorescent particle maneuvered to shape the letters 'ST'

Four 10 µm particles





Kernative concepts

Mode switching



•
$$F_{Total} = qF_Q + (1-q)F_H$$





Mode switching

Varying the fraction of the quarter wavelength mode







(c) 50%

(d) 99%





Circular Array Device





Courtney et al in APL 102(12), 2013



Ideal acoustic pressure field?

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







Kelical* beam creates local minima

Instantaneous pressure (α =1)



α =topological charge





*As used in optical tweezers, e.g. Grier, Nature 424, 2003

Ke How to generate a Helical beam







Effect of the number of elements









Verformance limits and aliasing



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

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

Controllable area is defined by:

$$R_{T(Max)} = \frac{1}{2} \frac{(N - \alpha)}{\pi e} \lambda$$
$$\approx \frac{N\lambda}{17.08}$$



N=60

Grinenko et al in Proc. Roy Soc. 468, 2012

K Particle positioning







K Multiple traps

• *n*th element and *m*th trap

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

$$V_{nm} = V_0 \exp\left(i(\omega t + \phi_{nm})\right)$$

• 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?






Kerne Propagating Bessel beams







Silva et al in IEEE UFFC 60(6), 2013

80

60

ົ 40 ຢ

20

0



Ke High frequency force regime



Gaussian intensity profile

- a>>λ (ray acoustics)
- In 2010 Lee et al trapped a125µm lipid drop using 30MHz ultrasound (λ=60µm)
- In 2011 Lee et al⁺ trapped a Leukaemia cell (10µm) using 200MHz ultrasound (λ=7.5µm)



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

Ke High frequency array

- 26MHz
 (λ=58μm), 64
 element array*
- Ø 45µm PS
- Standard phased array focussing





*Zheng et al (USC), APL 101, 2012



KApplications

- 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





MDCK Cells (Photo courtesy of Anne Bernassau, University of Glasgow)



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



Kell patterning



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





Kell patterning



Uses include;

- Cell-cell and cellchemical 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







KComposite manufacture



- Low viscosity photo-cure epoxy resin
- 15 μ m diameter, 50 μ m length glass fibres
- Operated at 2MHz, so line spacing equals 325 μm





KComposite manufacture

Photo

X-ray CT



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







Concluding remarks

- Dexterous acoustic tweezing is a reality
- Various concepts are being explored and showing significant promise
- Typically devices use wavelengths ~100µm to manipulate cells ~10 µm 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









IEEE ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL SOCIETY

How to make an acoustic tweezer

Professor Sandy Cochran University of Dundee, UK

IEEE International Ultrasonics Symposium Prague, Czech Republic 21 July 2013

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



Ultrasonic Array Structure

- An array is a set of miniature transducers known as array elements
- The array Casing Individual Elements elements 12 --- 64 coaxial are in **fixed**, Mechanical cables damping known positions Matching Piezoelectric relative to layers elements` one another Couplant Protective layer Test object

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



Related Design Framework



Resonant Chamber Devices

Counterpropagating Wave Devices

Progressive Wave Devices

9

Related Design Framework



Resonant Chamber Devices

Counterpropagating Wave Devices

Progressive Wave Devices

10

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

			PZT-4	PZT-5H	PVDF	LiNb0 ₃	PMN-PT
		-	"Hard" piezoelectric ceramic	"Soft" piezoelectric ceramic	Piezoelectric polymer	Traditional single crystal	New, high performance single crystal
Stiffness	C ₃₃ ^D	GNm ⁻²	155	159	8.52	251	135
Density	ρ	kgm ⁻³	7500	7500	1760	4640	8000
Velocity	v	ms⁻¹	4560	4600	2200	7360	4040
Acoustic impedance	Ζ = ρν	MRayl	34.1	34.5	3.92	34.1	32.3
Piezoelectric strain constant	d ₃₃	pmV ⁻¹	289	593	25	5.88	1430
Piezoelectric voltage constant	g ₃₃	VmN⁻¹	26	20	230	22	30
Piezoelectric figure of merit	FOM = d ₃₃ .g ₃₃	pmN ⁻¹	7.51	11.9	5.75	0.129	42.8
Thickness mode coupling coefficient	k t		0.508	0.512	0.190	0.162	0.566
Length-extensional coupling coefficient	k ₃₃		0.691	0.746	0.130	0.162	0.897
Relative permittivity at constant stress	ϵ_{33}^{T}		1275	3430	8.4	29.8	3950
Relative permittivity at constant strain	ε ₃₃ ^S		638	1470	10-12	29.0	818
Mechanical quality factor	Q		High	Medium	Low	Very high	Low

All values are *indicative only*

Possible Piezomaterials

			PZT-4	PZT-5H	PVDF	LiNb0 ₃	PMN-PT
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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

$$\lambda = 2D \qquad \qquad f_m = \frac{v}{\lambda}$$

where

 λ = acoustic wavelength

D = thickness of piezoelectric material

v = 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_{er} the electrical resonance frequency
 - One way, for wide, thin plates, is to back *f_e* out of the expression for **thickness mode coupling coefficient**

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

 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_{m} and its acoustic impedance, Z_{m} are defined as

$$T_{ml} = \lambda_{ml} / 4, \ Z_{ml} = \sqrt{(Z_{pm} Z_{um})}$$

where λ_{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 λ_{m/r} 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 piezoelecric 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



Crossedelectrode array

2D 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



www.diagnosticsonar.com







www.olympus-ims.com

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

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







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