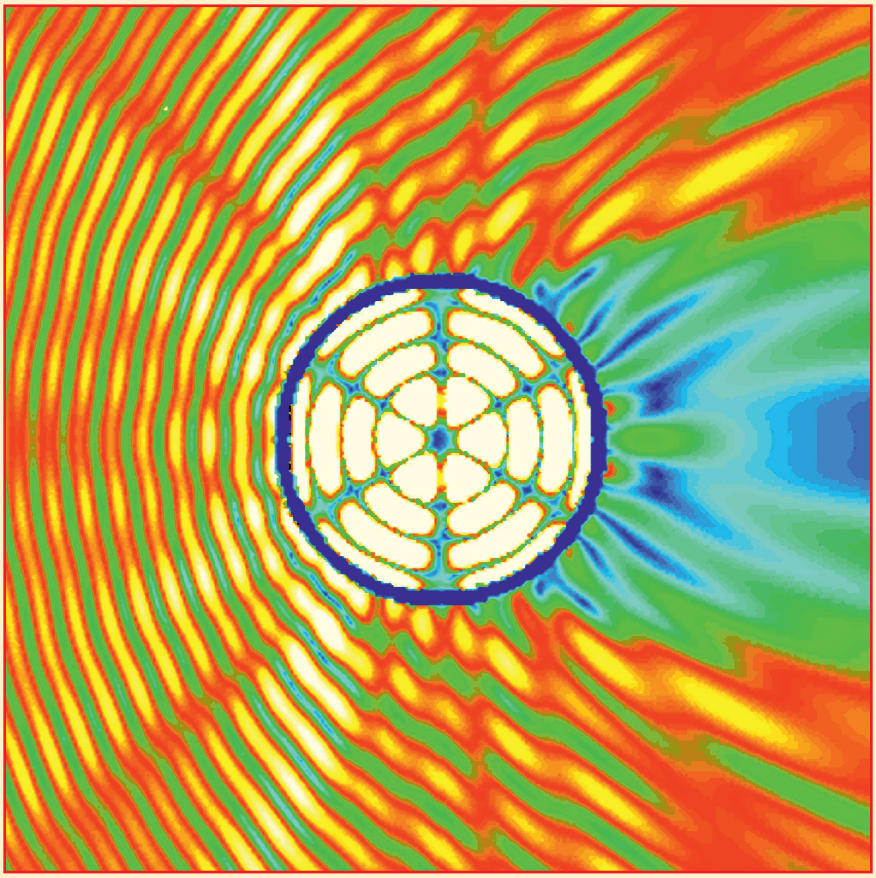
Abstracts



# Anglo-French Physical Acoustics 2018

**17–19 January 2018**
**Selsdon Park Hotel, Surrey, UK**

IOP Institute of Physics

# Anglo-French Physical Acoustics 2018

## Programme

### Wednesday 17th January

12:00 **Registration and lunch**
*Reception Foyer*

13:25 **Welcome address**
Nader Saffari, University College London, UK

13:30 **Acoustical vortices synthesis with flat microsystems for selective tweezing and manipulation of micro-particles**
Michaël Baudoin, University of Lille, France

13:50 **Acoustofluidics for enhanced delivery and screening of therapeutic agents**
Dario Carugo, University of Southampton, UK

14:10 **Flexible and wearable thin film acoustic wave sensing and fluidic devices**
Richard Fu, Northumbria University, UK

14:30 **Optimum acoustic lenses for micro-particle manipulation**
Amanda Franklin, University of Bristol, UK

14:50 **Trapping a single bubble with Acoustical Tweezers: Beyond Bjerknes forces**
Diego Baresch, Imperial College London, UK

15:10 Refreshment break
*Lobby area*

15:30 **(Invited) Bioacoustics - Investigation of hearing systems in insects to inspire the development of new acoustic and ultrasonic sensors and systems**
James Windmill, University of Strathclyde, UK

16:00 **Towards the democratisation of acoustic manipulation**
Asier Marzo, University of Bristol, UK

16:20 **Acoustic characterization of a viscoelastic medium**
Gautier Lefebvre, Institut D'Alembert - UPMC - CNRS, France

16:40 **The two dimensional fundamental resonant unit**
Jeremy Hawkes, Acoustic Machines, UK

17:00 Close

19:00 Dinner will served in the restaurant from 7pm

# Anglo-French Physical Acoustics 2018

## Thursday 18th January

08:30 **Registration**
*Lobby area*

09:00 **Modelling of the resonant interactions between two gas bubbles by using the spherical harmonics expansion**
Tony Valier-Brasier, Institut D'Alembert - UPMC - CNRS, France

09:20 **Evaluation of the resonance frequency shift of ultrasound-driven microbubbles embedded in tissue-mimicking phantoms**
Akaki Jamburidze, Imperial College London, UK

09:40 **Numerical and experimental study of rectified bubble growth in an optically transparent liver tissue phantom during boiling histotripsy exposure**
Ki Joo Pahk, Korea Institute of Science and Technology (KIST), South Korea

10:00 **Passive acoustic mapping of cavitation during shock wave lithotripsy**
Kya Shoar, University of Oxford, UK

10:20 **Metrics for bubble activity and tissue damage in histotripsy**
Matheus de Andrade, University College London, UK

10:40 **Coded excitation signals in micro-ultrasound**
Christina Lemke, University of Glasgow, UK

11:00 Refreshment break
*Lobby area*

11:30 **(Invited) Large arrays of microphones for inverse problems in acoustics: the MegaMicros project**
Régis Marchiano, Université Pierre et Marie Curie, Paris, France

12:00 **Comparison of finite element and analytical modelling of scattering of an acoustic wave by particles in a fluid**
Valerie Pinfield, Loughborough University, UK

12:20 **Demonstration of angular dependence of acoustic scattering of emulsions using acoustic diffractometer**
Mathew Francis, University of Leeds, UK

12:40 **Phase transition evaluation of a medium using acoustic reverberation time**
Hossep Achdjian, GREMAN, Université de Tours, France

13:00 Lunch
*Restaurant*

14:00 **(Invited) Use of ambient noise and ultrasound coda properties for SHM applications**
Emmanuel Moulin, Université de Valenciennes et du Hainaut-Cambrésis, France

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|---|---|
| 14:30 | **Simultaneous determination of wave celerity and thickness for overlapped echoes**<br>Julien Bustillo, GREMAN, Université de Tours, France |
| 14:50 | **Defect imaging in composite plates using sparse piezo-electric transducers network**<br>Andrii Kulakovskyi, Safran Tech, CEA LIST, France |
| 15:10 | **Interaction between SH0 guided waves and tilted surface-breaking cracks in steel plates**<br>Jérôme Combaniere, Imperial College London - Baker Hughes, UK |
| 15:30 | **The Half-Space Matching Method for guided wave scattering in anisotropic elastic plates**<br>Yohanes Tjandrawidjaja, CEA-LIST Digiteo, France |
| 15:50 | **NDT assessment of bonded assemblies using ultrasonic transducer arrays**<br>Yasen Polihronov, University of Bristol, UK |
| 16:10 | Refreshment break<br>*Lobby area* |
| 16:30 | **Effective rigidity of ribbed plates revealed by spatial spectra analysis**<br>Gautier Lefebvre, Institut D'Alembert - UPMC - CNRS, France |
| 16:50 | **Phase singularities and band gaps in a composite laminate – a phononic superlattice**<br>Robert Smith, University of Bristol, UK |
| 17:10 | **Finite element modelling of wave propagation in polycrystals**<br>Ming Huang, Imperial College London, UK |
| 17:30 | **Characterization of anisotropic plate properties using elastic guided waves**<br>Nicolas Bochud, Institut Langevin, ESPCI Paris, CNRS, France |
| 17:50 | **The spectral functions method for elastic plane wave diffraction by a soft wedge**<br>Samar Chehade, CEA LIST, France |
| 18:10 | **Close** |
| 19:00 | **Conference dinner and reception**<br>*Restaurant* |

# Anglo-French Physical Acoustics 2018

## Friday 19th January

08:30 **Registration**
*Reception lobby*

09:00 **(Invited) Seismic wave engineering with metamaterials**
Andrea Colombi, Imperial College London, UK

09:30 **Frequency domain (f-k) migration methods for 3D ultrasound imaging in non-destructive testing**
Lucas Merabet, CEA LIST, France

09:50 **Tea drinking in America and super-optical resolution acoustic imaging**
Matt Clark, University of Nottingham, UK

10:10 **Laser induced phased arrays for remote non destructive testing: the multi-frequency and multi-mode total focusing method**
Theodosia Stratoudaki, University of Strathclyde, UK

10:30 **Focusing ultrasound through the skull for neuromodulation**
Joseph Blackmore, University of Oxford, UK

10:50 Refreshment break
*Lobby area*

11:10 **A coupled boundary element formulation for trans-abdominal high-intensity focused ultrasound treatment planning**
Reza Haqshenas, University College London, UK

11:30 **Optimised high order compact difference schemes for internal acoustics problems on curvilinear domains**
Christopher Beckwith, University of Greenwich, UK

11:50 **Nondestructive evaluation of adhesive joints by using nonlinear ultrasonic**
Paul Zabbal, CEA LIST, France

12:10 **Surface reconstruction accuracy using ultrasonic arrays: application to non-destructive testing**
Robert Malkin, University of Bristol, UK

12:30 **Quantitative performance analysis of ultrasonic detection of corrosion rate changes**
Fangxin Zou, Imperial College London, UK

12:50 **Optimising resonance conditions for ultrasound cavitation treatment of liquid metals**
Georgi Djambazov, University of Greenwich, UK

13:10 **3D-Printed cellular electret sensor for acoustic applications**
Oluwaseun Omoniyi, University of Strathclyde, UK

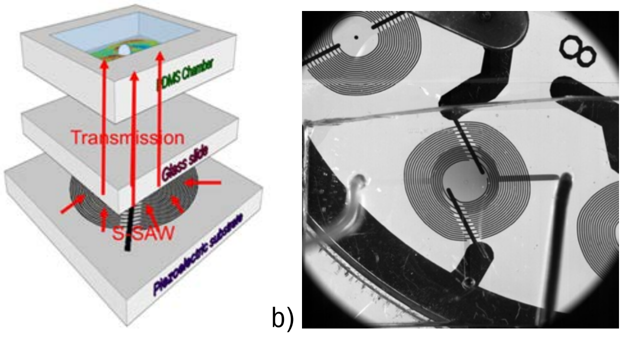
13:30 Lunch and close of conference

Anglo-French Physical Acoustics 2018

## Acoustical vortices synthesis with flat microsystems for selective tweezing and manipulation of micro-particles

M Baudoin[1], A Riaud[1,2], J C Gerbedoen[1], O Bou Matar[1] and J L Thomas[1]

[1]University of Lille, France, [2]Sorbonne Universités, France




a) b)

Figure 1: a) Principle of acoustic tweezers based on spiraling IDTs: Spiraling electrodes are deposited at the surface of a piezoelectric substrate. They generate a swirling surface acoustic wave (S-SAW) at the surface of the piezoelectric substrate, which creates an acoustic vortex in a microfluidic chamber after crossing a glass slide. Particles are trapped at the center of the acoustical vortex. b) Top view of an actual tweezer with a microfluidic channel at the top.

With the emergence of regenerative medicine, cell printers, labs on chips, and complex microsystems, the contactless *selective* manipulation of microscopic objects such as particles, cells or drops has become a key issue. A large span of methods using magnetic [1-2], optical [3-4] and acoustical forces [5-7] have been considered to achieve this task. Nevertheless, magnetic tweezers are limited to the manipulation of magnetic particles or require the attachment of magnetic microbeads to the manipulated object. Optical tweezers require intense light flux, which can cause detrimental local overheating. Acoustical waves appear as a tremendous alternative for particles trapping since (i) the acoustic wave momentum exceeds the one of light by several orders of magnitude at equivalent input power, limiting spurious heating and (ii) wave synthesis systems based on piezoelectric materials are available for frequency ranging from a few MHz to several GHz enabling the trapping of millimetric to nanometric particles.

In acoustics, particles denser and/or stiffer than the surrounding medium and significantly smaller than the wavelength are trapped at the nodes (i.e. at the minima of the wave intensity) of standing wave, and expelled from the antinodes. Thus, particles would be ejected from the center of a focused beam (corresponding to a maximum of the intensity). This problem (as first suggested in the mid 2000'th by Pr. Marston [8]) can be overcome by using a class of acoustic waves called acoustical vortices whose center is a minimum of the wave intensity surrounded by a ring of large intensity. The selective trapping of particles with acoustical vortices has been shown experimentally in 2D [5,6] and then in 3D [7] by using complex wave synthesis systems based on transducers arrays. The major drawback of these systems is that they require a transducer array and a high-end programmable electronics, not available for high frequency applications ($> 100$ MHz) and whose price skyrockets when approaching this critical frequency.

To overcome this difficulty, we developed alternative acoustic tweezers based on spiraling interdigitated transducers (IDTs) [9]. IDTs are electrodes sputtered at the surface of piezoelectric substrates and patterned by photolithography technics. They enable the synthesis of high frequency surface waves, that is to say waves propagating at the surface of the piezoelectric substrate. To synthesize acoustical vortices, we developed some specific IDTs [9] whose spiraling shape encodes the phase of the field like a hologram. The shape can be precisely computed to generate an acoustical vortex after crossing one or several layers of solid material, opening perspective for remote manipulation of particles without cross contamination. With these devices, we have shown that we were able to trap particles and displace them individually with forces up to several hundred pico-Newtons. For applications, tweezers based on spiraling IDTs have many attractive features: they are selective, flat, easily integrable and compatible with disposable substrates.


[1] I. De Vlaminck and C. Dekker, Annu. Rev. Biophys. 41, 453 (2012).
[2] F. Martinez-Pedrero and Pietro Tierno, Magnetic, Phys. Rev. Applied 3, 051003 (2015).
[3] A. Ashkin et al., Opt. Lett. 11, 288 (1986).
[4] J.R. Moffitt, Y.R. et al., Biochemistry 77, 205 (2008).
[5] C.R.Courtney, et al., App. Phys. Lett., 104(15):154103 (2014)
[6] A. Riaud, et al., Phys. Rev. Applied 4, 034004 (2015)
[7] D. Baresch, et al., Phys. Rev. Lett. 116, 024301 (2016)
[8] P. L. Marston, J. Acoust. Soc. Am., 120(6):3518–3524 (2006).
[9] A. Riaud, et al., Phys. Rev. Appl., 7, 024007 (2017)


### Acoustofluidics for enhanced delivery and screening of therapeutic agents


D Carugo, B Hammarstrom, U Jonnalagadda, F Plazonic, P Glynne-Jones and M Hill

University of Southampton, UK


Acoustofluidic devices have been widely employed to perform contactless manipulation of biological cells and microorganisms, for application in sample preparation and enrichment, detection of pathogens, and sorting of different cell types. More recently, they have been utilised to mechanically stimulate cells and induce therapeutically relevant responses. In this presentation, we demonstrate the development of acoustofluidic systems designed to impart different stress regimes on suspended cells, in order to enhance delivery and metabolism of bio-active compounds. By integration with advanced microscopy techniques, we are able to quantify the effect of these mechanical cues on sub-cellular physical properties. Finally, we demonstrate acoustically-driven assembly and stimulation of multicellular constructs, including neocartilage grafts and models of the mucosal airways, with potential for application in tissue engineering and pharmacological screening.

### Flexible and wearable thin film acoustic wave sensing and fluidic devices


R Fu, R Tao, H Wang and S Hasan

Northumbria University, UK


Thin film acoustic techniques have been used to fabricate Surface Acoustic Wave (SAW) and film bulk acoustic wave (FBAR) applications, which have been used for sample preparation (sorting, separating, mixing, nebulization and dispensing) as well as gas sensing and bio-sensing. This talk will focus on recent work on flexible thin film (mainly ZnO and AlN) for acoustic wave sensing and microfluidic applications. This paper presents the fabrication process and characterisation of an integrated acoustic wave based microfluidic devices using sputtered thin films on various substrates, but more focusing on polymer and metallic foils. The thin film based flexible SAW devices have the potential to be integrated with other microfluidic and sensing technology on a variety of substrates including CMOS integrated circuits to make novel lab-on-chip for bio-detection for wearable and flexible applications.

**Optimum acoustic lenses for micro-particle manipulation**

A Franklin, A Marzo and B W Drinkwater

University of Bristol, UK

Acoustic lenses are used to focus sound for applications including; sonar imaging[1], non- destructive evaluation and medical ultrasound therapy[2]. Recently, 3D-printed lenses have been employed to generate acoustic radiation force traps to manipulate micro-particles with a single-beam device[3]. Here we explore the challenge of optimising lens design to produce maximum trapping forces.

An acoustic trap is a field in which the radiation forces converge towards a point; they can be formed using a combination of a phase delay 'signature' and a focus[4], as shown in Fig.1(a). We establish that the acoustic radiation forces inside a trap are proportional to the maximum pressure at its focus and inversely proportional to the focal-spot width (FWHM). These properties allow us to explore the relevant parameter space and maximise the trapping forces.

The optimisation uses finite element simulations to explore different lens design methods across a range of focal lengths and lens radii. For holographic lenses[5], an f-number of 0.6 produced the smallest FWHM; the performance did not increase with larger lens radii, shown in Fig. 1(b). We manufactured these optimised lenses by 3D-printing and patterning the electrodes on a piezoelectric disk to embed signatures for the *twin-trap* and *bottle-trap* (Fig. 1(a)). The *twin-trap* results in the highest force in the lateral x-direction whilst the *bottle-trap* maximises the forces in the axial z-direction. These devices enable improved manipulation for various applications, e.g. positioning cell agglomerates for tissue-engineering or *in-vivo* movement of materials such as kidney stone debris.

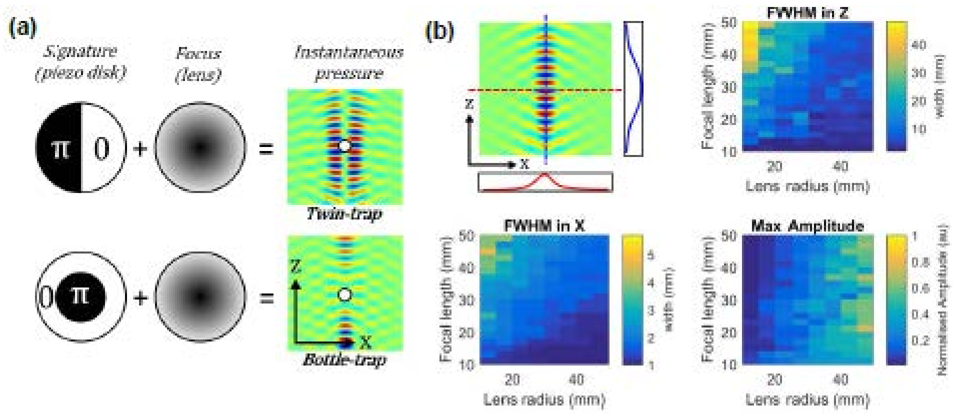



Figure 1. (a) Signature and focus required to create the *twin-trap* and *bottle-trap*. The trap position indicated by the white circle. (b) Holographic lens design performance for a range of focal lengths and lens radii. The first panel shows a schematic of the performance metrics FWHM in Z and X.

[1] K. Mori, A et al, Jpn. J. Appl. Phys. 46, 4990 (2007).
[2] J.E. Kennedy, G.R. ter Haar, and D. Cranston, Br. J. Radiol. 76, 590 (2003).
[3] A. Franklin et al, Applied Physics Letters, 111(9), 094101 2017.
[4] A. Marzo et al, Nat. Commun. 6, 8661 (2015).
[5] K. Melde et al, Nature 537, 518 (2016).

## Trapping a single bubble with acoustical tweezers: Beyond bjerknes forces

D Baresch and V Garbin

Imperial College London, UK

Micron-sized gas bubbles are notoriously difficult to isolate, handle and remotely control. Their large buoyancy in common liquids will usually force them to rise and burst at any gas/liquid interface or remain trapped against a solid boundary until dissolution. While bubble stability issues against dissolution have found numerous practical workarounds, the challenge remains at isolating and maneuvering a single bubble in free space to, for instance, perform precise single bubble dynamics experiments with applied ultrasound or to use them as active carriers for a specific payload deliverable on demand. Here we demonstrate that single-beam acoustical tweezers [1] can trap and manipulate in 3D a single bubble with the radiation pressure of helicoidal ultrasonic beams. Contrary to the situation where bubbles are trapped in the antinodes of a standing wave, the trapping vortex beam does not require oscillating volume changes of the bubble to generate a force, *i.e.*, the trapping mechanisms cannot be explained in terms of Bjerknes forces. Viscous boundary layer effects and large bubble stability will be discussed. Opportunities for our manipulation technique to probe the high speed dynamics and rheology of particle-laden armored bubbles will also be presented [2].

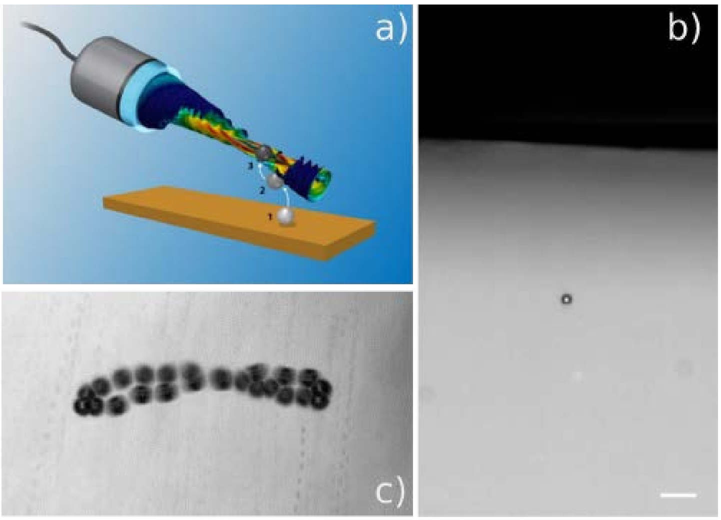



Figure 1: a) Acoustical tweezers can trap and manipulate particles in 3D. b) Bubble trapped through a layer of gel (top) against buoyant forces (Scale bar $100\mu m$). c) Large bubble (radius $a = 45\ \mu m$) in an orbital trajectory under action of torques applied by the acoustical tweezers.

[1[ D. Baresch *et al,* Phys. Rev. Lett., 116, (2016)

[2] V. Poulichet *et al,* PNAS, 112, (2015)].

## (Invited) Bioacoustics - Investigation of hearing systems in insects to inspire the development of new acoustic and ultrasonic sensors and systems

J Windmill

University of Strathclyde, UK

Taking inspiration from insect ears to develop acoustic devices is an idea that has been around for some time. Ongoing research to produce miniature directional microphones inspired by the extremely directional, sub-wavelength, *Ormia ochracea* fly's ear is a well-known example. Since the late 1990's researchers have been working to implement *Ormia* based micro-electro-mechanical systems (MEMS) acoustic devices, typically using standard silicon or similar microfabrication. Much of these past two decades has been spent trying to by-pass the important detail that the *Ormia* fly evolved to hear one very specific frequency, that of a calling cricket (~5 kHz). Therefore, it is not a broadband system as you might wish to have for a device such as an audio microphone. Further, taking inspiration from a system based on the mechanics of insect cuticle in order to build a silicon MEMS system also leads to various compromises.

This presentation will discuss ongoing research by the bioacoustics researchers at the Centre for Ultrasonic Engineering in Strathclyde on the design, modelling and microfabrication of acoustic devices inspired by the *Ormia* system, focusing on their solution to the single frequency mechanics problem (Figure 1). It will also describe some work by the Strathclyde team on other biological acoustic systems, in parallel with their ongoing development of further bio-inspired, and other, acoustic devices. This will include our work to produce wide bandwidth ultrasonic devices, passive mechanical frequency analysers, and very recent work on acoustic metamaterials.

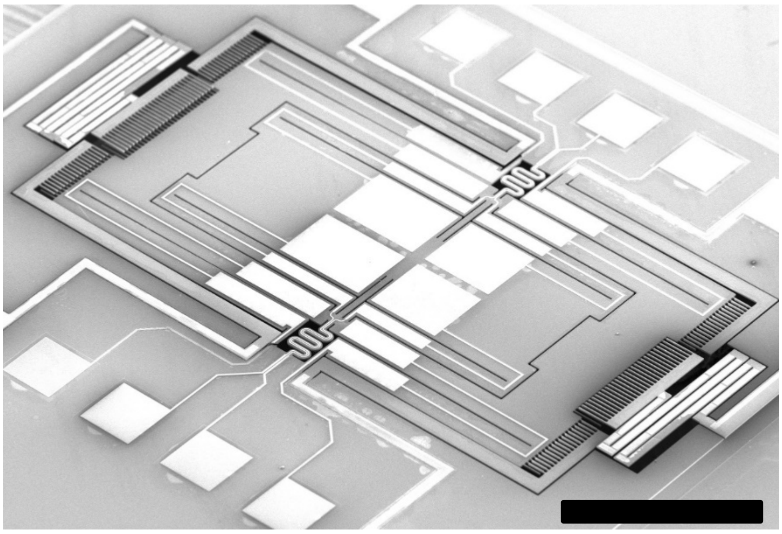


Figure 1 – *Ormia* Inspired MEMS Directional Microphone (Scale bar: 1mm)

# Anglo-French Physical Acoustics 2018

## Towards the democratisation of acoustic manipulation

A Marzo and Bruce W Drinkwater

University of Bristol, UK

The acoustic radiation force is a non-linear phenomenon that makes particles inside an acoustic field experience forces [1]. When these forces converge at a point, it is possible to trap samples without physical contact [2]. Acoustic manipulation has the advantage of applying remote forces and trapping objects of a wide variety of materials in different media such as air or water. Consequently, it has the potential to become a useful tool for contactless processing,e.g. chemical analysis, cell patterning for tissue engineering or lab-on-droplet applications.

To date, acoustic manipulation experiments have been limited to a few research labs due to the expertise that it is required to assemble the devices and operate them. This paper describes our attempts to simplify and refine acoustic manipulators to the point when even the non-expert can build them using affordable and readily available components. In doing this, our aim is to enable a wide range of research labs, across various disciplines, to discover new applications of acoustic manipulation as well as enabling educational uses both in schools and engineering/physics courses at university.

This paper will discuss the specifications and capabilities of the following devices: a standing- wave levitator capable of handling samples of up to 2.6g/$cm^3$ in air (TinyLev [3], Figure 1.a), an battery-powered airborne portable acoustic tractor beam designed to trap light millimetre- sized particles [4](Figure 1.b), and a 64-channel airborne phased array for applications in dynamic acoustic manipulations (Ultraino [5], Figure 1.c). In each case application examples will be presented. We will also highlight the success of other research labs or individuals in creating novel applications with these designs.

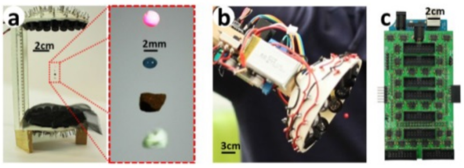



Figure 1: a) TinyLev levitating Styrofoam, coloured water, soluble coffee and paper. b) an acoustic tractor beam trapping a 2mm Styrofoam particle. c) driver board of Ultraino: a 64-channel airborne emitter phased-array.

[1] Bruus, H. (2012). Acoustofluidics 7: The acoustic radiation force on small particles. Lab on a Chip, 12(6), 1014-1021.
[2] Brandt, E. H. (2001). Acoustic physics: suspended by sound. Nature, 413(6855), 474-475.
[3] Marzo, A., Barnes, A., & Drinkwater, B. W. (2017). TinyLev: A multi-emitter single-axis acoustic levitator. Review of Scientific Instruments, 88(8), 085105.
[4] Marzo, A., Ghobrial, A., Cox, L., Caleap, M., Croxford, A., & Drinkwater, B. W. (2017). Realization of compact tractor beams using acoustic delay-lines. Applied Physics Letters, 110(1), 014102.
[5] Marzo, A., Corkett, T., & Drinkwater, B. W. (2017). Ultraino: an Open Phased-Array System for Narrowband Airborne Ultrasound Transmission. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control.

## Acoustic characterization of a viscoelastic medium

G Lefebvre, R Wunenburger and T Valier-Brasier

Institut D'Alembert - UPMC – CNRS, France

Although widely used for example in medical imaging, there are only few quantitative measurement methods exist for shear waves. The necessary addition of a highly viscous fluid coupling material to transmit shear waves from a source in a solid medium makes difficult to perform absolute measurements. This requires on one hand to perform a coupling in a reproducible manner, and on the other hand to characterize the rheological properties of the coupling material.

For this purpose, we set up an experiment to measure reflection and transmission coefficients of a coupling material layer. Reversible transducer devices associated with two delay lines enables the echoes of an incident pulse to be separated and analyzed in order to measure these coefficients. The thickness of the layer is controlled by multiple slip gauges in a reproducible manner.

The analysis of the signals and the reflection coefficient as a function of the frequency provides a very sensitive characterization of the properties of the medium. In particular, a large thickness gives rise to interference phenomena whose frequency signature reveals the attenuation of the medium. The commercial shear wave couplant (SWC-2) by Olympus has been characterized using this method. Zener's viscoelastic model allows to fit the experimental data and provides a measure of relaxation time for this fluid. We performed measurements with shear waves as well as longitudinal waves for a full characterization of the viscoelastic properties of the couplant.

## The two dimensional fundamental resonant unit

J Hawkes[1] and B Lipkens[2]

[1]Acoustic Machines, UK, [2]FloDesign Sonics, USA

Some methods for calculating one of the resonances of a square plate are described. These squares can be considered to be units with indivisible dimensions. By combining multiple squares it is possible to form many complex structures, all of which resonate at the square element's fundamental frequency. For example: resonant chambers for liquids and gases can be formed where the structure itself, not just the cavity and reflecting wall, is designed for a precise resonant frequency.

A violin string is half a wavelength long when resonating at its fundamental frequency. For structures with more dimensions the axis and the speed of sound governing each resonance are not always so obvious. Here we show that for a square plate an important fundamental frequency depends on the longest in-plane axis, the corner-to-corner distance (Figure 1).

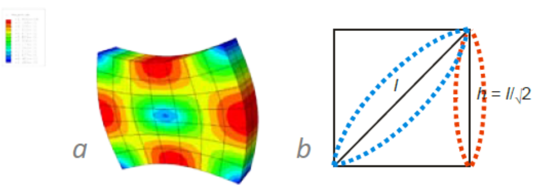



Figure 1 a. fundamental resonant unit. b. When Poisson's ratio= 0.33 the resonant frequency f can be calculated from the materials bulk velocity c and the fundamental length l $\mathrm{f} = {}^{\mathrm{c}}/_{\mathrm{l}} = {}^{\mathrm{c}}/_{2\mathrm{h}\sqrt{2}}$

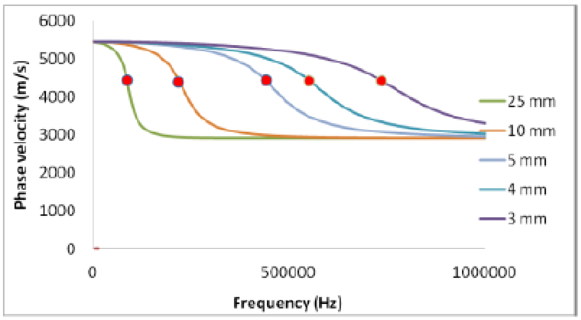



Figure 2.Mode S0 in aluminium plates. Red dots =point where plate thickness and half wavelength are equal.

If a materials Poisson's ratio is 0.33, its bulk velocity can be used to find the diagonal wave frequency. For a more general method, we use the symmetrical plate mode S0. The resonant square is formed when the mode's half wavelength is equal to the thickness of the plate. To find the frequency and phase velocity at this point we calculated the wavelength along the mode's frequency: phase-velocity curve. The points where the wavelengths are the same in two dimensions (the resonant frequency of the squares) are shown in figure 2.

Since the curvature of the wave is the same on all sides of the squares, when two squares are combined to produce a rectangle the curves will fit and vibrates at the same frequency as the single square but with an symmetric S0 mode on the short axis and an anti-symmetric A1 mode on the long axis. The rectangle can be extended by adding squares, additional squares do not change the resonant frequency but change the mode following the series S0, A1, S1, A2, S2 etc. shown in figure 3.

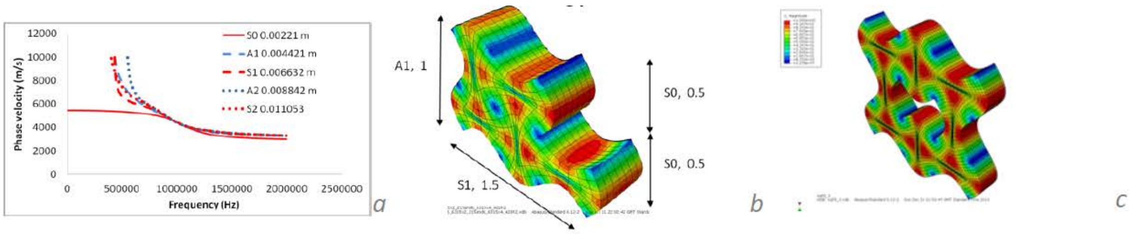



Figure 3. When the thickness of the plate is increased in increments of the fundamental resonant unit the resonance frequency and sound velocity do not change but the modes increase (S0, A1,S etc).shown a. graphically and b. pictorially. c. Shows a duct formed from fundamental resonant units.

Two analytical methods which do not require mode calculations are also given for calculating the speed of sound across the square in materials where the Poisson's ratio is not equal to 0.33.

### Modelling of the resonant interactions between two gas bubbles by using the spherical harmonics expansion

T Valier-Brasier

Institut D'Alembert - UPMC - CNRS, France

This work comes within the framework of the scattering of sound waves in suspensions of gas bubbles. The study of the interactions between two (very) close gas bubbles is of fundamental interest in the context of concentrated dispersions. In such case, it is well known that the Minnaert frequency splits into two resonance frequencies depending on whether bubbles oscillate in phase or not. This phenomenon is generally described by a model based on coupled Rayleigh-Plesset equations for which only the radial motion of bubbles is taken into account. The model used here is based on the spherical harmonics expansion of the incident and scattered waves and on the use of the addition theorem. In this case, the two resonance frequencies are calculated numerically and it appears that the number of modes to take into account depends on the distance between the two bubbles. It is shown that a large numbers of harmonics have to be taken into account when bubbles are very close together. The calculations of the scattering cross sections of the pair of bubbles show that the directivity associated to the higher resonance is much more complicated than that of a dipolar resonance due to the out of phase oscillations of the two bubbles.

### Evaluation of the resonance frequency shift of ultrasound-driven microbubbles embedded in tissue-mimicking phantoms

A Jamburidze[1], M De Corato[1], A Huerre[1], A Pommella[2] and V Garbin[1]

[1]Imperial College London, UK, [2]Laboratoire Charles Coulomb (L2C), France

With the advent of a new generation of contrast agents that can extravasate, namely perfluorocarbon nanodroplets that are transformed into microbubbles by acoustic vaporisation, it has become possible to deliver microbubbles to tissues and to effectively target tumours. It is therefore becoming increasingly important to understand the behaviour of bubbles embedded in tissues, both for imaging and therapeutic purposes. We studied the behaviour of bubbles embedded in agarose hydrogels mimicking the viscoelastic properties of different tissues. The hydrogels where characterized by rotational rheometry and the values of shear modulus and shear viscosity were measured. Bubbles of 100-200 µm excited at 30-50 kHz were used for this study, since this enabled time-resolved optical imaging using a high speed-camera at 300,000 frames per second. Importantly, the results translate directly to ultrasound contrast agent microbubbles excited in the MHz range. The experimental results show that the shear modulus of the material causes a significant shift in the resonance frequency of the bubbles. We fitted the data using the Rayleigh-Plesset equation combined with the Kelvin-Voigt model, which describes the linear deformation of viscoelastic solids, and obtained independent measurements of the viscoelastic properties of the hydrogels. Ultimately, this knowledge will help develop optimal insonation protocols as a function of tissue properties following extravasation of contrast agents.

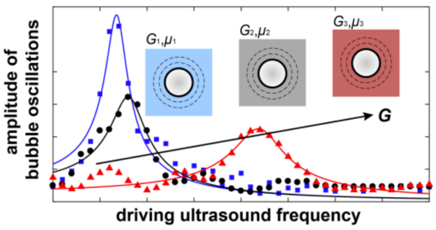



Figure 1. 180 µm sized bubbles driven acoustically inside three agarose gels with different concentrations (0.5%, 1% and 2%). The bubble resonance frequency increases with shear modulus and the amplitude of the oscillations decreases with increasing viscosity. The data points are fitted with the modified Rayleigh-Plesset equation to extract linear viscoelastic properties of the agarose gels.

# Anglo-French Physical Acoustics 2018

## Numerical and experimental study of rectified bubble growth in an optically transparent liver tissue phantom during boiling histotripsy exposure

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High Intensity Focused Ultrasound (HIFU) is a non-invasive ultrasonic technique that has been traditionally used to thermally ablate solid tumours. HIFU can now be used to mechanically fractionate soft tissue with a high degree of precision of the order of millimetre size. This technique is known as boiling histotripsy [1]. Our previous study has clearly shown that boiling bubbles were produced in a localised heated region within the HIFU focus and cavitation clouds were subsequently produced ahead of the expanding bubble, resulting in the production of a mechanically fractionated tadpole-shaped lesion [2]. The formation of a boiling vapour bubble at HIFU focus is essentially important to initiate the tissue fractionation process. The main objective of this present study is to investigate the formation and dynamic behaviour of a boiling vapour bubble during the course of boiling histotripsy. In this work, numerical and experimental studies on the bubble dynamics induced in optically transparent tissue-mimicking gel phantoms exposed to the field of a 2 MHz HIFU transducer were performed with a high speed camera. The *Gilmore-Zener* bubble model [3] coupled with the *Khokhlov-Zabolotskaya-Kuznetsov KZK* and the *Bio-heat Transfer BHT* equations was used to simulate the bubble dynamics driven by boiling histotripsy waveforms (nonlinear-shocked wave excitation) in a viscoelastic medium (*i.e.,* tissue phantom). *Figure 1* shows that the rectified bubble growth of a boiling vapour bubble can be observed, demonstrating good qualitative agreement with the experimental observations. To the best of our knowledge, this is the first study reporting the numerical and experimental evidence of the appearance of rectified bubble growth in tissue phantom. Our results suggest that the asymmetry in a shockwave and water vapour transport are the key parameters which lead the bubble to undergo rectified growth in a viscoelastic medium. Furthermore, accounting for tissue phantom elasticity $G$ adds a mechanical constraint to vapour bubble growth, which improves the agreement between the simulation and the experimental results.

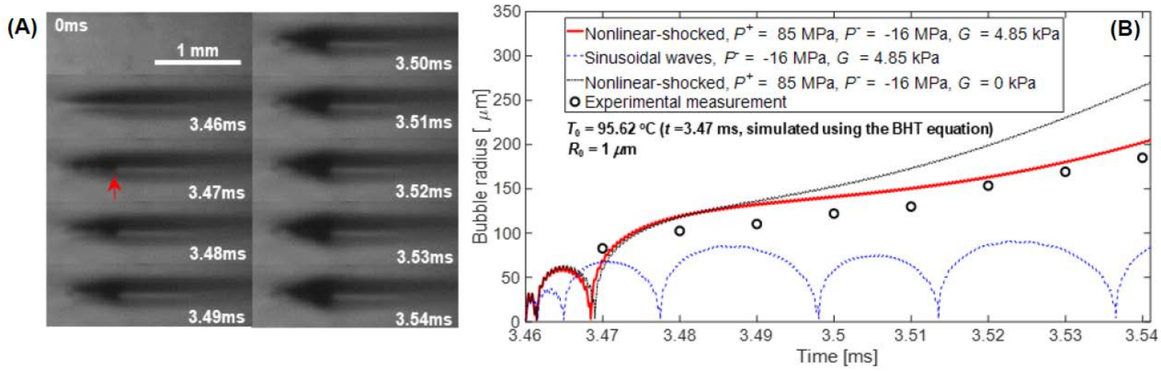


Figure 1. (A) A sequence of high-speed camera images obtained in an optically transparent tissue phantom during the single 10-ms HIFU insonation with peak positive $P^+$ and negative $P$ pressures of 85 MPa and -16 MPa at the HIFU focus. Images were captured at a 0.1 M frames per second. The formation of a boiling vapour bubble at $t$ = 3.47 ms (*red arrow*). The time at 0 ms corresponds to the start of the HIFU exposure. (B) A comparison between the experimentally measured bubble radius and the simulated radius vs time curve. $T_0$ = surrounding temperature, $R_0$ = Initial bubble radius, $G$ = Shear modulus of the tissue phantom used.

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## Passive acoustic mapping of cavitation during shock wave lithotripsy

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Passive acoustic mapping (PAM) has previously been used to localise inertial cavitation during high intensity focused ultrasound. Here, this technique has been applied to shock wave lithotripsy (SWL), a non-invasive procedure whereby kidney stones are fragmented. Conventional diagnostic ultrasound probes were used to detect acoustic emissions during SWL. Signals consisted of reverberation sound from the incident shock wave followed, several hundred microseconds later, by emissions from cavitation collapses. Time-gating was used to isolate the cavitation signals, which were then processed using PAM to create spatial maps of the cavitation activity. Experiments in water indicated the spatial resolution was an ellipsoidal volume 5mm long by 1mm wide. Experiments were carried out in ex vivo pig kidneys and it was observed that cavitation was initiated in the region of the focus but moved laterally by up to 10mm and during treatment exhibited a general migration towards the source. These results suggest that PAM can be used as a tool to map the location of cavitation during SWL and has the potential to differentiate cavitation in tissue (that could contribute to injury) from cavitation near the stone which affects comminution. [Work supported in part by NIH through P01-DK43881]

## Metrics for bubble activity and tissue damage in histotripsy

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Histotripsy is a non-invasive method for the mechanical disintegration of small volumes of soft tissue through ultrasound-induced nucleation of bubbles. Qualitative differences in tissue damage have been found upon histological analysis of histotripsy lesions between regions where boiling bubbles and cavitation clouds act[1]. We hypothesise that this distinction is related to the character of bubble nucleation in these two regions.

For this reason, developing appropriate metrics for analysing treatment outcomes with respect to the mechanisms controlling bubble nucleation becomes highly desirable. Proven their correlation, this would assist qualitative prediction of lesion formation. It would also help establish equivalence amongst protocols, serving as a parameter for comparison of bubble activity between experiments.

Hydrodynamic approaches to bubble nucleation were used in order to develop indices capable of distinguishing controlling mechanisms in the nucleation of boiling and cavitation bubbles. When plotted on a pressure-temperature plane alongside previously published histotripsy protocols[2], these non-dimensional quantities form clear boundaries indicating the regime of bubble activity and growth. This can be controlled by either the rates of vapour transfer into the bubble or the balance between viscous and inertial forces in the surrounding medium.

Results show the dominance of viscous forces over their inertial counterparts in cavitation histotripsy to be an order of magnitude higher than in boiling histotripsy. Boiling histotripsy also shows a heat transfer index at least two orders of magnitude greater than that of cavitation. Furthermore, histological analysis of cavities created in rat liver through boiling histotripsy shows qualitative differences in mechanical damage between the head and the tail of a histotripsy lesion.

Broken hepatocyte plates and pits with rough boundaries can be seen around the lesion head, where a cavitation cloud was formed and bubble nucleation is controlled by viscosity. Contrastingly, smooth boundaries that are sharply demarcated were observed at the tail of the lesion[1]. In this region, boiling bubbles with a high heat transfer index were observed, having viscous and inertial forces playing a similar role in bubble nucleation. Our results suggest these metrics as promising tools for linking bubble activity and the character of subsequent tissue disintegration in histotripsy.

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## Coded excitation signals in microultrasound


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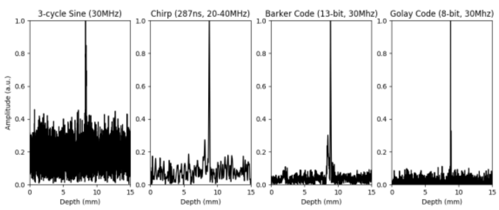
Coded excitation is an effective tool to overcome the trade-off between resolution and penetration depth in ultrasound. Known as pulse compression, it has been widely used in radar for decades. Its usability for medical ultrasound has been explored since the late 1970s [1] and has been reviewed more recently [2, 3]. In microultrasound (μUS) (i.e. f > 20 MHz), the high frequency in combination with tissue attenuation limits useful penetration to a few mm, making it a good candidate to benefit from coded excitation. A small number of studies have examined this combination but they have been limited to amplitude modulated chirps [4, 5].

The research reported here is motivated by the potential of ultrasound capsule endoscopy (USCE) to provide additional information about the wall of the gastrointestinal tract, particularly in the small bowel, in a minimally invasive manner, mimicking the now well-established use of video capsule endoscopy. In this region, the wall is a complex layered structure and it has been found in *ex vivo* and *in vivo* experiments that conventional pulse-echo ultrasound techniques may benefit from improved signal to noise ratio (SNR).

To explore the potential of coded excitation signals, we included amplitude tapered chirps and compared them to a Barker code, length 13, and Golay code pairs, lengths 8, 16 and 32. We used a physically scanned, single-element focused PVDF transducer operating at a centre frequency of 30 MHz and verified the effectiveness of the codes with a wire phantom and a layered tissue phantom. In our presentation, we show how the proposed codes enhance the SNR of μUS significantly and discuss their individual limitations.




Normalised pulse-echo amplitude of a single wire for pulses constructed by a standard 3-cycle sine and coded excitation (Chirp, Barker Code and Golay Code pair), showing the respective reduction of the noise floor in the coded excitation pulses.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[3] Misaridis, T., & Jensen, J. A. (2005). Use of modulated excitation signals in medical ultrasound. Part I: Basic Concepts and Expected Benefit. IEEE Trans. Ultrason. Ferroelec. Freq. Contr. 52 (2) 177 – 191

[4] Mamou, J. et al. (2008). Chirp-coded excitation imaging with a high-frequency ultrasound annular array. *Ibid.* 55 (2) 508 – 13

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### (Invited) Large arrays of microphones for inverse problems in acoustics: the MegaMicros project

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Université Pierre et Marie Curie, France

In this talk, we focus on solving inverse problems from microphone arrays. The signals measured by several sensors are used to find the characteristics of the sound sources that generated them (location, level, directivity or other). The best known method of resolution is beamforming. The results of this method are quite robust but very dependent on the characteristics of the antenna: its dimensions, its shape, its density of microphones. The recent advent of MEMS microphones has allowed an important miniaturization of the acquisition chain since a simple circuit allows to directly deliver a digital signal without the use of a heavy conditioning chain. We will show that these microphones are suitable for the realization of arrays with large numbers of channels (several hundreds) and a large scale (several tens of meters). We will illustrate the new possibilities offered for the resolution of inverse problems on several configurations: acoustic imaging of mobile sources and identification of aeroacoustic sources. These examples will also shed light on new issues brought about by this significant increase in the number of channels, such as the geometric calibration of the position of microphones or the management of data flows.

### Comparison of finite element and analytical modelling of scattering of an acoustic wave by particles in a fluid

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Loughborough University, UK

Particle interactions in an acoustic field are mediated not only by compressibility effects in the liquid suspending media, but also by thermal and shear mechanisms. These thermal and shear mechanisms are only significant within a very short (micron) inter-particle separation at MHz frequencies due to the short decay length (boundary layer) for these wave fields. In order to investigate such interactions, we have modelled, as a first step, the thermal and shear wave fields around a single spherical particle in a liquid with an applied acoustic field.

We report finite element modelling of the linearised thermo-visco-acoustic equations for this single particle case with an incident plane compressional wave. Since the length scale of the thermal and shear decay is orders of magnitude smaller than the propagational mode acoustic wavelength, fine meshing is necessary in the region of the particle/fluid boundary. We demonstrate the resolution of the thermal and shear wave modes within a few microns of the particle surface, by determination of the temperature field and the vorticity and evaluating its wave-like dependence. The finite element model is validated using the Rayleigh partial wave model, provided by Epstein and Carhart [JASA, 25, 533, (1953)] and Allegra and Hawley [(JASA, 51, 1546 (1972)] which is constructed using the three wave modes that are solutions of the linked Helmholtz equations.

## Demonstration of angular dependence of acoustic scattering of emulsions using acoustic diffractometer

M Francis[1], M Forrester[2], N Zucker[1], L Koh[1], Z Glover[3], M Holmes[1], M Povey[1] and V Pinfield[2]

[1]University of Leeds, UK, [2]Loughborough University, UK, [3]University of Southern Denmark, Denmark

The structure, stability and rheology of emulsions depend on the concentration and physical properties of the dispersed particles. To successfully predict the behaviour of emulsions these physical properties, specifically their particle size, need to be quantified. Many colloidal systems by nature can be difficult to characterise as they are opaque and the viscous, thermal and multi-scattering effects of the emulsions reduce the accuracy of the measurement. Light scattering methods such as laser diffraction and dynamic light scattering are currently viewed as the most reliable methods for the determination of the size of dispersed particles. These techniques measure the intensity of scattered light from different sized particles and interpret the result as a particle size distribution. To increase precision, these light-based techniques are generally performed at low concentrations to prevent photons from being scattered by multiple particles prior to detection. To be measured using light scattering, concentrated systems like emulsions require dilution which disrupts structural features.

Acoustic methods are more suited for determining the physical properties of concentrated systems. Measurements can be reliably performed on emulsions with concentrations between 1% and 80% by volume. Acoustic techniques are non-destructive and allow for concentrated systems to be characterised in situ. Acoustic-spectroscopy based particle sizing methods such as used by the Malvern Ultrasizer can measure the frequency dependent attenuation of a concentrated sample. This data can then be interpreted through mathematical models (e.g. ECAH) to yield an effective wave number of the emulsion system and hence estimate the particle size distribution and volume fraction of the dispersed phase. The model assumptions are based on low concentration systems where the effect of inter-particle visco-thermal scattering is negligible.

New mathematical and computational models are being developed which take into account inter-particulate scattering for the measurement of properties, including particle size, for concentrated systems and to determine angular dependence in the effective wavenumber which to-date has not been established. A new measurement technique, Acoustic Diffractometry, has been developed which can determine the angular dependence of acoustic scattering between multiple particles. The Acoustic Diffractometer can operate in flow and with a sample volume of a millilitre or less. This is a new instrument which is still under development. Results of recent work which demonstrate the utility of this system are presented here, along with supporting mathematical modelling developed using COMSOL Multiphysics.

## Phase transition evaluation of a medium using acoustic reverberation time

H Achdjian, J Bustillo, A Arciniegas, J Fortineau, N Doumit and L Blanc

GREMAN UMR 7374, France

Non-destructive monitoring of a material's state during its physicochemical transformations is of interest for several industrial fields including food processing, such as milk-derived products, and industrial manufactures, such as variation of mechanical properties of polymer and/or texture of creams in cosmetics. Recent research trends have indeed focused on the monitoring of elastic properties (Young's modulus, shear modulus) of these sol gel products. The use of ultrasound to provide reliable information about physicochemical properties is becoming increasingly popular. Indeed, ultrasonic techniques have the main advantage of being rapid and non-invasive methods that allow parameters such as product composition, structure and physical state to be obtained. Yet, classical techniques used in acoustic emission based on the study of the velocity and the attenuation of only the first received wave packets are commonly used to determine the phase change time of a local studied medium. Here, we propose an alternative technique based on the study of the reverberated waves, classically used in room acoustics. These complex signals contain useful quantitative and qualitative information about medium properties and are sensitive to structural changes. In previous works, this method has shown its capability to characterize materials as well, with the advantage over classical techniques to address a medium in its whole structure. In this context, the determination of sol-gel phase transition time of Salol using this method is presented. Measurements are performed in an aluminum mold using five piezoelectric (PZT) patches randomly distributed on rear face of the mold. One of them is used as the acoustic source and the others are connected to a four-channel oscilloscope and are used as receivers. The mean reverberation time over four receivers has been studied and its evolution is shown to lead to a good estimation of the phase transition time (figure 1).

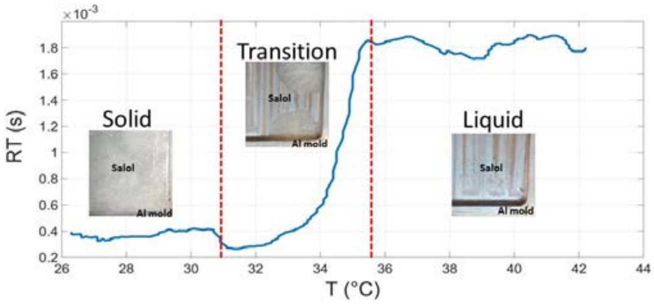


Figure 1 - Salol Phase Transition: Reverberation Time (RT) in function of temperature (°C). Phase transition between solid (Left) and liquid (Right) is characterized by a significant variation of RT.

### (Invited) Use of ambient noise and ultrasound coda properties for SHM applications

E Moulin

Université de Valenciennes et du Hainaut-Cambrésis, France

Useful information can be extracted from reverberation of acoustic signals in a closed medium. Room acoustics is a very common example. But as will be shown here, similar principles can be pertinent also in the context of E/NDT or SHM. In the work reported here, we have proposed a statistical model allowing to relate structural properties (material properties, dimensions, scattering, ... ) to the average features of reverberated acoustic signals in a solid plate. A simple procedure applied to signals recorded on a few ultrasound receivers then allows an experimental estimation of some of these properties. Another benefit of reverberation is the fact that it increases spatial diversity of effective sources, which allows efficient passive Green's function retrieval through noise correlation. This principle, associated to coherent array processing, has been successfully applied to passive defect detection, localization, and even quantitative tomography, in reverberant plates subject to friction or air-spray noise.

### Simultaneous determination of wave celerity and thickness for overlapped echoes

J Bustillo, H Aachdjian, A Arciniegas and L Blanc

GREMAN UMR 7347, France

Determination of the thickness and the wave celerity of a sample gives several information on its state. Indeed, the aging of the sample can cause a variation of the wave celerity due to appearance of cracks or elastic behaviour modifications. When thickness is unknown, simultaneous determination of thickness and wave celerity is mandatory to obtain reliable results.

The frequency domain analysis is often more robust. However, these methods often need modelling and inverse problem solving due to couplings with surrounding fluid or another layers which cause complex spectrum variations. Time-domain analysis is often faster but limited when an overlap is detected or when the signal is highly noisy.

For time-domain analysis, the determination of the time of arrival of two echoes is mandatory to simultaneously obtain the thickness and the wave celerity of the sample. These methods are usually limited to samples wherein the propagation path is long enough to allow an echo separation. For thin samples, overlapped echoes have to be separated to estimate the time of arrival. Several researchers have proposed reconstruction methods based on modelling of the echoes, on signal optimisation, on signal modelling or on signal shaping.

This work presents a deconvolution method based on the Forward-Backward algorithm in order to retrieve excitation signal. So, the time of arrival of each echo can be achieved even in case of overlap and simultaneous measurement of thickness and wave celerity is performed.

The method is validated using numerical simulation based on Ricker wavelets. It shows that the method is able to separate echoes having an overlap up to 80% with a discrepancy lower than 1%. The simultaneous retrieval of thickness and wave celerity have been performed on aluminium plates at different thickness in order to have an overlap up to 65%. The results show that this method is suitable to simultaneously retrieve thickness and wave celerity, even for overlapped signals up to 65 %, with a discrepancy as low as 1 %.

### Defect imaging in composite plates using sparse piezo-electric transducers network

A Kulakovskyi[1], B Chapuis[2], O Mesnil[2], O d'Almeida[1] and A Lhémery[2]

[1]Safran Tech, France, [2]CEA, LIST, France

Carbon fiber reinforced polymer (CFRP) plates and honeycomb composite (HC) structures (aluminum cores encapsulated by CFRP sheets) are widely used in the aerospace industry as they exhibit excellent strength-to-weight ratio, stiffness, toughness, corrosion resistance etc. Nevertheless, defects such as face sheet delamination or core-sheet debonding may appear due to impact forces or thermo-mechanical aging and may degrade these properties.

To reduce maintenance costs and to extende iservice time, a structural health monitoring (SHM) system, based on the use of Guided elastic Waves (GW) propagation phenomena, is considered as a promising solution. GW propagate over large distances while being sensitive to structural inhomogeneities. Our SHM system prototype relies on a sparse grid of piezo-electric transducers distributed over the structure, used for both actuating and sensing. Defect imaging is perfomed by means of a correlation based algorithm called Excitelet. It is based on the calculation of correlation coefficients between theoretical and experimental GW signals for each pixel of a grid that represents the structure of interest. Green's functions (GF) are required in order to reconstruct theoretical signal at each pixel at the region of interest of the inspected part. In CFRP plates, theoretical 3D excited wave field from a finite size transducer is computed here using the dispersion relationships and mode shapes obtained from 2D formulations thanks to semi-analytical finite element modeling. Analytical determination of Green's function for honeycomb panels is intractable. In this case, on pristine plates, experimental measurements of the Green's function are used. Defect imaging results on composite panels are illustrated with experimental measurements where the defect is simulated by magnets positioned on both faces of the plate.

### Interaction between SHO guided waves and tilted surface-breaking cracks in steel plates

J Combaniere, P Cawley, K McAughey and J Giese

Imperial College London, UK

The interaction between guided waves and vertical notches or cracks is already well understood and documented. However, many defects, in the Oil & Gas industry for example, cannot be modelled under such assumption that the defect is vertical. High pH stress corrosion cracking is known to produce cracks with complex geometries, which makes them harder to detect and characterise since many parameters are affecting the reflectivity of the defect. When so many parameters contribute to the reflectivity of a crack, it is virtually impossible to quantify their respective influence. To simplify the model, only the tilt of the defect is investigated in this paper. A Finite Element model is developed for simulating the ultrasonic response from a tilted surface-breaking crack. The effect of both the tilt and depth of the defect are investigated. Simulations are showing interesting results, in particular the effect of the sign of the tilt on the reflectivity of the crack and the existence of a tilt – at all depths – at which zero transmission is obtained. These results are then compared to experimental results, where defects were manufactured using an electrical discharge machining process, resulting in very thin – 0.35mm – tilted notches.

### The half-space matching method for guided wave scattering in elastic plates

V Baronian[1], A-S Bonnet-Ben Dhia[2], S Fliss[2] and Y Tjandrawidjaja[1, 2]

[1]CEA-LIST Digiteo, Saclay, France, [2]CNRS-INRIA-ENSTA ParisTech-Université Paris Saclay, France

In this work, we want to simulate the interaction of Lamb waves with a defect in an anisotropic elastic plate, in the framework of non-destructive testing. The strategy is to generalise the Half-Space Matching method that we have previously developed in the 2D case. In the present case, it consists in coupling a finite element representation of the solution around the defect with semi-analytic representations of the solution in at least 3 semi-infinite plates. The semi-analytic representations are obtained by combining a Fourier Transform with a modal decomposition on Lamb modes. Indeed, by knowing the displacement and the normal stress on the bands limiting the half-plates, using a Fourier transform in the direction parallel to the boundary of the half-plate and the bi-orthogonality of Lamb modes, the displacement field can be obtained in the semi-infinite plates. Ensuring that all the representations of the solution match yields to a system of equations which couples, via Fourier-integral operators, the FE representation in the bounded perturbed domain with the displacement and the normal stress of the solution on the infinite bands limiting the half-plates. Compared to integral methods, this method avoids the expensive calculation of the Green function of the anisotropic plate.

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### NDT assessment of bonded assemblies using ultrasonic transducer arrays

Y Polihronov, A Croxford and R Smith

University of Bristol, UK

Compromised interface bonds in high value components can lead to premature loss of structural integrity. These types of defects are very difficult to detect using traditional acoustic inspection techniques. Here we present results of novel inspection methodologies which allow for high confidence measurement of bond integrity. We assess the ability of linear ultrasonic non-destructive testing (NDT) methods to detect weak-kissing bonds and/or differentiate between weak, kissing, degraded or contaminated bonds from healthy ones. Ultrasonic transducer array(UTA) have been selected as the vehicle of choice, since they allow for increased informational content. Despite the considerable research that has been carried in the area of weak bonds detectability, this remains as a significant challenge for the industry and more studies are required for a better understanding and characterisation of bond quality. Our research addresses these issues in UTA measurement techniques, specifically FMC/TFM [1,2], Scattering Matrix(derived) [3,4] extraction in time domain, and other related or derived methods. We have developed an iterative testing methodology, in which the experimental variation in each of the following steps is significantly reduced;

Sample Preparation; Data Acquisition; Imaging [1,2] Feature Analysis [3,4] Characterization/Classification; Interpretation.

Using imaging optimisation routines, the coherence and quality of the image is increased up to 120% depending on imaging distance. This improves localisation of points of interest, allows automation of the process and increases separability of the classification data. The final quality metric can be compiled from both linear and non-linear data. The methodology is versatile, allows for metal and CFRP bonds to be tested, which is a particular interest of the automotive and aerospace industries.

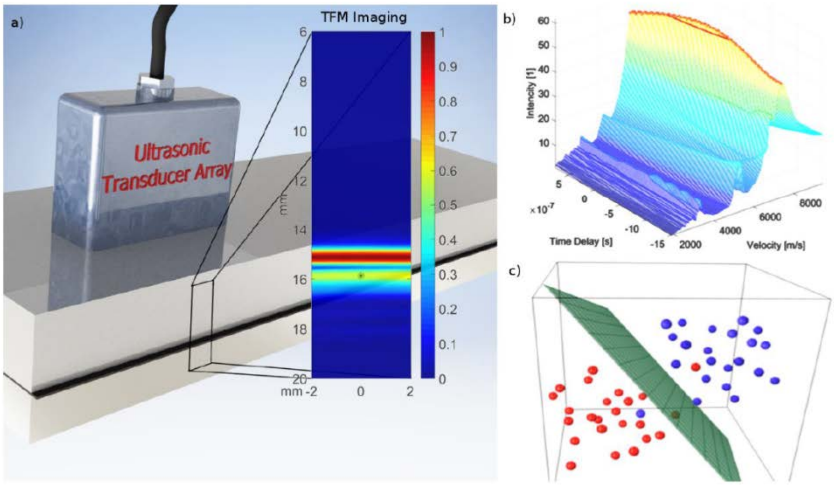


Fig. a) Schematic representation of the experimental simple 2 layered sandwich structure. Fig. b) Imaging parameter optimization. Fig. c) Schematic of classified extracted scattering matrix(derived) features.

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### Acoustic characterization of a viscoelastic medium

G Lefebvre, R Wunenburger and T Valier-Brasier

Institut D'Alembert - UPMC – CNRS, France

Although widely used for example in medical imaging, there are only few quantitative measurement methods exist for shear waves. The necessary addition of a highly viscous fluid coupling material to transmit shear waves from a source in a solid medium makes difficult to perform absolute measurements. This requires on one hand to perform a coupling in a reproducible manner, and on the other hand to characterize the rheological properties of the coupling material.

For this purpose, we set up an experiment to measure reflection and transmission coefficients of a coupling material layer. Reversible transducer devices associated with two delay lines enables the echoes of an incident pulse to be separated and analyzed in order to measure these coefficients. The thickness of the layer is controlled by multiple slip gauges in a reproducible manner.

The analysis of the signals and the reflection coefficient as a function of the frequency provides a very sensitive characterization of the properties of the medium. In particular, a large thickness gives rise to interference phenomena whose frequency signature reveals the attenuation of the medium. The commercial shear wave couplant (SWC-2) by Olympus has been characterized using this method. Zener's viscoelastic model allows to fit the experimental data and provides a measure of relaxation time for this fluid. We performed measurements with shear waves as well as longitudinal waves for a full characterization of the viscoelastic properties of the couplant.

## Phase singularities and band gaps in a composite laminate – a phononic superlattice.

R A Smith and L J Nelson

University of Bristol, UK

Designers and manufacturers are keen to be provided with detailed information about the internal microstructure of as-manufactured composites. Whilst X-ray Micro-CT is capable of high-resolution 3D imaging, there is a trade-off between resolution and component size which makes pulse-echo ultrasound the favored method for components larger than standard test coupons. The potential for ultrasonic 3D-characterisation of the internal structure of composites is being gradually revealed through modelling studies of the analytic-signal response of these regular one-dimensional layered materials. Using new ultrasonic parameters of instantaneous amplitude, instantaneous phase and instantaneous frequency, it has been possible to track plies in three dimensions and characterize and classify features such wrinkling, ply drops, tape gaps and tape overlaps [1]. The success of these methods is noticeably reduced in composites containing thick resin layers between plies due to thermoplastic-particle toughening. Recent modelling work has shown the cause to be the laminate behaving as a phononic superlattice with characteristic resonances and transmission band gaps [2]. This latest piece of the jigsaw puzzle explains why local zeros in amplitude (phase singularities) appear at certain times (depths) in the ultrasonic response and why these times are not consistent across a component. As a result, the complex response of these structures is at last being understood in a way that should make it possible to create a comprehensive inversion algorithm to convert the response into the full information about the microstructure. The modelling results will be used to explain experimentally observed phenomena in terms of the analytic-signal response of a phononic superlattice.

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[2] Robert A. Smith, Luke J. Nelson and Martin J. Mienczakowski, "Phononic Band Gaps and Phase Singularities in The Ultrasonic Response from Toughened Composites." 2017 Review of Progress in Quantitative NDE, in AIP Conference Proceedings, 2018.

## Finite element modelling of wave propagation in polycrystals

M Huang[1], G Sha[2], A Van Pamel[1], P Huthwaite[1], S I Rokhlin[2] and M J S Lowe[1]

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Wave propagation and scattering within inhomogeneous materials are important in the fields of non-destructive evaluation, medical imaging and seismology. The establishment of accurate models for these wave behaviours is a major concern for the development of methods to characterize material microstructure, as well as for the development of methods to suppress the attenuation and scattering thus discerning other material information.

Leading analytical models are based on low-order scattering assumptions; finite element modelling, however, presents no such limitations and has now enabled the accurate representation of wave behaviours [1]. This work exploits this approach to investigate the effect of grain elongation on the physical phenomena of the scattering-induced attenuation and dispersive wave speed. Inhomogeneous samples composed of statistically significant numbers of grains are used to represent polycrystalline materials, with the incorporation of grain elongation using different grain aspect ratios. The attenuation coefficient and wave velocity are measured from the mean field of longitudinal plane waves propagating within these polycrystals; and the wave behaviours are used to illustrate the influence of grain elongation, as well as to evaluate the analytical models.

[1] Van Pamel A, Sha G, Rokhlin SI, Lowe MJS. Finite-element modelling of elastic wave propagation and scattering within heterogeneous media. Proc R Soc A. 2017;473(2197):1–21.

## Characterization of anisotropic plate properties using elastic guided waves

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Elastic guided waves offer several advantages for the nondestructive evaluation and characterization of materials. Their dispersive and multimodal nature is particularly attractive when it is beneficial to use wavelengths of the order of the plate thickness or when it is necessary to measure in-plane elastic properties1, as the components of the elastic tensor affect each mode differently and with different sensitivities2. The identification of the stiffness tensor requires solving a model-based inverse problem, which often results complex due to the extraction of experimental data3 and their comparison with theoretical dispersion curves. To face these limitations, we propose a method that relies on the measurements of multimode guided waves, which are launched and detected in arbitrary directions along the plate using a linear transducer array driven by a programmable electronic device. The main contribution consists in defining an objective function built from the dispersion equation, which allows us to account for higher-order modes without the need to pair each experimental data point to a specific guided mode, thus avoiding the calculation of the dispersion curves and errors in the mode identification4. Compared to standard root-finding algorithms, the computational gain of our procedure is estimated to be greater than a hundred. This objective function is optimized using genetic algorithms, which allow identifying from a single out-of-symmetry axis measurement the full set of anisotropic elastic coefficients and either the plate thickness or the propagation direction (Fig.1). The efficiency of the method is evidenced using data measured on materials with different symmetry classes. Therefore, this method open promising perspectives for the real-time characterization of industrial materials with strongly anisotropic elasticity or compound of layered structures.

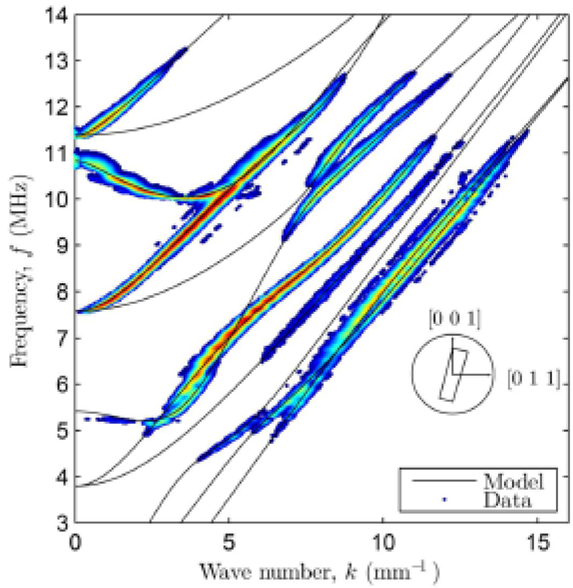


Fig. 1: Optimal matching between measured and modeled guided modes on a silicon wafer.

[1] W Rogers. Res Nondestr Eval 6(4):185-208, 1995.
[2] M Karim, A Mal, and Y Bar-Cohen. J Acoust Soc Am 88(1):482-491, 1990.
[3] L Claes, T Meyer, F Bause, J Rautenberg, and B Henning. J Sens Sens Syst 5(1):187-196, 2016.
[4] L Yan, H Cunfu, S Guorong, W Bin, C-H Chung, and Y-C Lee. J Nondestruct Eval 33(4):651-662, 2014.

### The spectral functions method for elastic plane wave diffraction by a soft wedge

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NDE examination of industrial structures requires the modelling of specimen geometry echoes generated by the surfaces (entry, backwall…) of inspected blocks. For that purpose, the study of plane elastic wave diffraction by a wedge is of great interest since surfaces of complex industrial specimen often include dihedral corners.

There exist various approaches for modelling the plane elastic wave diffraction by a wedge but for the moment, the theoretical and numerical aspects of these methods have only been developed for wedge angles lower than $\pi$.

Croisille and Lebeau (1) have introduced a resolution method called the Spectral Functions method in the different case of an immersed elastic wedge of angle less than $\pi$. Kamotski and Lebeau (2) have then proven existence and uniqueness of the solution derived from this method to the diffraction problem of stress-free wedges embedded in an elastic medium. The advantages of this method are its validity for wedge angles greater than $\pi$ and its adaptability to more complex cases.

The methodology of Croisille and Lebeau (1) has been first extended by the authors to the simpler case of an immersed soft wedge. It has then been developed here for the 2D scattering problem of an elastic wave incident on a stress-free wedge and a numerical validation of the method for all wedge angles is proposed.

[1] Croisille J-P, Lebeau G. Diffraction by an immersed elastic wedge. Berlin ; New York: Springer; 1999. 134 p. (Lecture notes in mathematics).

[2] Kamotski VV, Lebeau G. Diffraction by an elastic wedge with stress-free boundary: existence and uniqueness. Proc R Soc Math Phys Eng Sci. 8 janv 2006;462(2065):289‑317.

### (Invited) Seismic wave engineering with metamaterials

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The study of the interaction between waves propagating in a medium and its structure continues to be one of the most active research areas of wave physics. After the introduction of a new class of artificially engineered media called “metamaterials” in electromagnetism and acoustics, the idea that full control on wave propagation can be achieved through an appropriate design of the medium’s microstructure is now widely accepted. In elasticity for instance, several laboratory experiments have shown how waves can be stopped, converted or amplified using resonant inclusions or periodic arrangement of heterogeneities.

Also in seismology, metamaterials concepts and ideas are progressively gaining relevance with the first experiments addressing wave control capacities and feasibility. Major challenges remain in the upscaling of metamaterial designs and physics to both the long wavelength (up to hundreds of metres) and complexity (P, S, surface waves and other guided modes) characterizing the propagation of seismic waves in the ground.

In this talk, after reviewing the state of the art on the topic, I will present the results of the Metaforest experiment, a geophysical experiment where an array of 1000 seismometers have been installed for 10 days between a forest of pine trees and a canola field recording vibrations from active sources (ground shaker) and ambient noise. Several space-frequency analyses on the array data have revealed how the trees couple with the ground vibrations producing a metamaterial like effect. 3D elastodynamics simulations and tomographic surveys of the subsurface complement the interpretation of the experimental data.This unique experiment, offers the first reliable clue that seismic metamaterials can be practically realized and may find immediate application in groundborne vibrations mitigation.

## Frequency domain (f-k) migration methods for 3D ultrasound imaging in non-destructive testing

L Merabet[1], S Robert[1] and C Prada[2]

[1]CEA, LIST, France, [2]Institut Langevin, France

3D ultrasound imaging with matrix arrays is an attractive solution to characterize defects exhibiting complex geometries, or to image a large volume in the material at a fixed position. However, the formation of 3D images is often costly in computation times because of the large number of voxels (up to $10^7$) and array elements (up to 256) to deal with. In order to overcome this issue, we study here two frequency-domain methods inspired by Lu's method for medical imaging [1] and Stolt's $f$-$k$ migration for seismic imaging [2] and apply them to plane wave emissions. The former is based on a forward model of wave propagation in the physical medium and relies on Weyl's identity, which states that the Green's function of the Helmholtz equation can be written as a sum of plane waves. The latter is based on the Exploding Reflector Model (ERM), which states that the back-and-forth propagation of a plane wave from the array to the reflector distribution and back to the array is equivalent to the simultaneous explosion of all the reflectors at $t = 0$ in a virtual medium . The theories are expanded in the 2D case with contact or immersion linear arrays, and are then extended to 3D imaging with matrix arrays. Two examples of 3D images are given in steel specimens featuring either point-like (spherical inclusions) or extended defects (vertical cracks). The Fourier-domain imaging methods are then compared with the time-domain Plane Wave Imaging (PWI) in terms of computation times, lateral resolution and signal/noise ratio. It is shown that the $f$-$k$ methods provide 3D images of similar or even better quality according to these criteria, but also speed up computation times by a factor up to 30.

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[2] Garcia, L. Le Tarnec, S. Muth, E. Montagnon, J. Pore, and G. Cloutier, "Stolt's f-k migration for plane wave ultrasound imaging," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 60, 2013.

## Tea drinking in America and super-optical resolution acoustic imaging

M Clark, R Fuentes-Dominguez, S Naznin, F Perez-Cota and R Smith

University of Nottingham, UK

In conventional optical microscopy the resolution is limited by the Rayleigh criterion. This is where the size of the optical point spread function causes light from close-by objects to merge into one spot. By looking at the process of imaging in a slightly different way, and by finding a way to uniquely tag small objects, this limitation can be lifted and objects smaller than the Rayleigh criterion can be resolved.

In this talk, greater than optical microscopy resolution is demonstrated using nanobells resonating in the multi GHz frequency region.

## Laser induced phased arrays for remote non destructive testing: the multi-frequency and multi-mode total focusing method

T Stratoudaki[1, 2], M Clark[2] and P D Wilcox[3]

[1]University of Strathclyde, UK, [2]University of Nottingham, UK, [3]University of Bristol, UK

Laser Induced Phased Arrays (LIPAs) use post processing to focus and steer the generated ultrasonic beam, synthesising a phased array. Their principle is based in laser ultrasonics where lasers are used to generate and detect ultrasound. The technique is broadband, non-contact, and couplant free, making LIPAs suitable for large stand-off distances, inspection of components of complex geometries and hazardous environments. We present remote, non destructive testing with improved image quality, using this technique.

LIPAs will be presented that are synthesised by capturing the Full Matrix, a data acquisition method where all possible transmitter receiver combinations in the array are obtained, at the nondestructive, thermoelastic regime. The Total Focusing Method (TFM) is used as the imaging algorithm, where the captured signals are summed with the appropriate time delay, in order to synthesize a focus at every point in the imaging area. The TFM, which has been previously developed for conventional ultrasonic transducers, has been adapted to the needs of LIPAs in order to make more efficient use of the information in the data. Experimental results are presented from nondestructive, laser ultrasonic inspection of aluminium samples with side drilled holes and slots at depths varying between 5 and 20mm from the surface. The multi-mode and multi-frequency analysis of the data allows detection of defects in a wide range of angles.

## Focusing ultrasound through the skull for neuromodulation

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Focused ultrasound for neuromodulation is emerging as a non-invasive brain stimulation method; whereby low-intensity pulsed ultrasound is focused through the skull to locations within the brain. The ultrasound results in excitation of brain activity and response in the peripheral motor and visual centres has already been reported. One barrier is that the strongly heterogeneous skull bone distorts, aberrates and attenuates the ultrasound beam leading to disruption and shifting of the focus. Whilst transducer arrays can be used to correct for these aberrations, this equipment is expensive and complex. Here numerical modelling is used to determine the optimal placement of a single element focused transducer to achieve the required focusing. Numerical simulations, using a point source at the target locations in the visual cortex, are employed to determine the phase and amplitude on a spherical surface placed outside the head. The optimal placement of the transducer is determined by minimising the weighted phase error over the transduce surface. Appropriate focusing is then confirmed by simulating the pressure field in the brain tissue for the optimal transducer location. Both elastic and fluid-type models of the skull are considered to assess the impact of shear waves on the targeting.

**A coupled boundary element formulation for trans-abdominal high-intensity focused ultrasound treatment planning**

R Haqshenas, P Gelat, E van't Wout, T Betcke and N Saffari

University College London, UK

High-intensity focused ultrasound (HIFU) is a promising treatment modality for the non-invasive ablation of pathological tissue in many organs, including the liver. Since many patients are not suitable candidates for liver surgery, the possibility to locally deposit thermal energy in a non-invasive way would bear significant clinical impact. Optimal treatment planning strategies based on high-performance computing numerical methods are expected to form a vital component of a successful clinical outcome in which healthy tissue is preserved and accurate focusing achieved by compensating for soft tissue inhomogeneity and the presence of ribs. The boundary element method (BEM) is an effective approach for this purpose because only the boundaries of the ribs and soft tissue regions require discretization, as opposed to standard approaches which require the entire volume around the ribcage to be meshed.

The current state of the art coupled BEM formulations at high frequencies will be discussed. Subsequently, a coupled formulation for BEM-BEM implemented using the open source library Bempp [1] will be presented. This formulation was used to carry out simulations of Helmholtz through-transmission problems in spheroids. The speed, convergence and accuracy of the solution were investigated. These results manifest the challenges to overcome in order to develop a viable BEM formulation for trans-abdominal HIFU treatment planning.

[1] https://bempp.com/

# Anglo-French Physical Acoustics 2018

**Optimised high order compact difference schemes for internal acoustics problems on curvilinear domains**


<u>C Beckwith</u>, K Pericleous and V Bojarevics

University of Greenwich, UK



A numerical framework is presented for the solution of 2D and 3D internal acoustics problems using a high-order accurate fully staggered formulation on curvilinear domains. Optimised Compact Finite Difference schemes previously obtained in our previous paper [1] are used for spatial discretization, while a free parameter Linear Multistep method is used for temporal discretization. The resulting scheme does not require any numerical filtering, and several benchmark cases are provided which demonstrate the significantly reduced phase velocity errors, and greater resolving efficiency compared to existing methods.

Curvilinear domains are generated with the CRDT algorithm by Driscoll [3], with an 8th order accurate ODE Solver. The governing equations for the Curvilinear problem are based on a novel transformation of the decoupled velocity pressure wave equations, with simplifications made to reduce the need to interpolate derivatives at undefined locations which occur on staggered grids. The resulting transformed equations are valid only for orthogonal grids, but are computationally efficient and do not result in loss of accuracy or stability due to grid skewness.

Finally, a potential application is shown, demonstrating the solution of a generated acoustic field within a crucible of liquid aluminium by a top loaded electromagnetic induction coil. Generated pressure fields agree with results shown in previous work [2], and demonstrate the potential use as an alternative to the immersed sonotrode for the ultrasonic treatment of alloys.


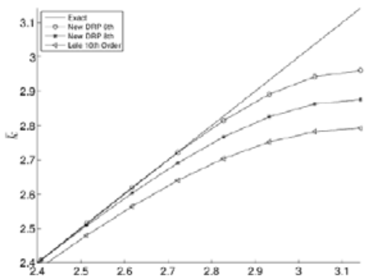

Figure 1, Obtained schemes optimized with a modified DRP approach show less dispersive behavior compared to maximum order scheme.

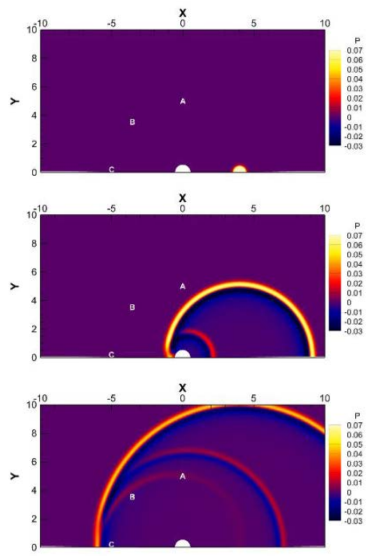

Figure 2, Time snapshots at t=0, t=5, and t=10 for Category 1, Problem 2, showing scattering from a cylinder. Solution agrees with analytic solution from Tam (1997)


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## Nondestructive evaluation of adhesive joints by using nonlinear ultrasonic


P Zabbal[1,2], G Ribay[1] and J Jumel[2]

[1]CEA, LIST, France, [2]University of Bordeaux, France


Adhesive bonding technology has now gained much attention in many industries as a very versatile assembling technique.. However, to be used for structural joining and critical application, high reliability is needed. Thus, efficient non-destructive control strategy should be proposed to evaluate the nominal bonding quality but also possible progressive in-service degradations.

Promising results have been presented in the literature using ultrasound-based methods. While linear ultrasound is efficient to detect decohesion or voids in a structure, it is barely sensitive to bond strength.

In this work, we present a method to generate high amplitude plane wave, which may produce nonlinear phenomenon which are able to reveal kissing bonds or other types of adhesion defects. In this purpose a new device has been designed, it acts as a two-dimensional virtual array and can be used to generate high energy plane wave. Numerical simulations and experimental measurements were made to optimize the device in order to obtain sufficient energy to solicit the structure. Then the method is applied and evaluated on metallic bonds with bonding defects. Combined with the pulse inversion technique, nonlinear phenomenon can be measured in the form of harmonic generation in the defect zone. We use this method to image a defect created by spraying PTFE on one adherent before bonding.

## Surface reconstruction accuracy using ultrasonic arrays: application to non-destructive testing

R E Malkin[1], A C Franklin[1], R L T Bevan[1] and H Kikura[2]

[1]University of Bristol, Bristol, UK, [2]Tokyo Institute of Technology, Japan

The accurate non-destructive inspection of an engineering structure using ultrasonic immersion imaging requires a precise representation of the surface. Here we investigate the relationship between surface geometry, surface measurement error using ultrasonic arrays and the total focusing method (TFM) and how this impacts on the ability to image a feature within a component. Surfaces shaped as sinusoids with surface wavelengths between 0.8-32$\lambda_{water}$ and amplitudes between 0.6-9$\lambda_{water}$ are studied, shown in Figure 1a,b. The surface reconstruction errors are shown to cause errors in imaging, such as reduced amplitude and blurring of the image of a side-drilled hole, shown in Figure 1c. These reconstruction errors are shown to increase rapidly with the maximum gradient of the sinusoid surface. Sinusoidal surfaces with maximum gradients <45° lead to average surface reconstruction errors <$\lambda_{water}$ and amplitude imaging errors within 6dB of a flat-surface case. It is also shown that very poor results are obtained if the surface gradient is excessively steep. The work suggests that the apparent severity of a defect (as determined by its size and prominence in an inspection image) is influenced by the component surface geometry, possibly resulting in misleading inspection results.

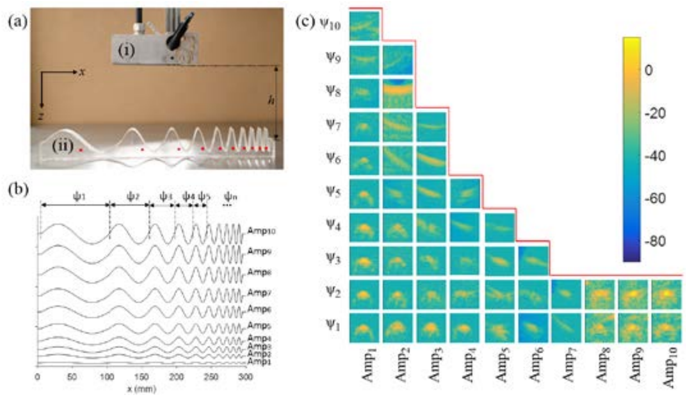


Figure 2 – Effect of surface geometry on TFM array imaging. (a) Experimental set-up showing (i) 128 element 5MHz array used in the study and (ii) one of the test specimens used with the locations of ⌀2mm side-drilled holes highlighted, (b) surface geometry of the 10 samples used in the study covering a range of feature lengths (ψ) and amplitudes (Amp), (c) TFM images of ⌀2mm side-drilled holes in the specimens tested. With increasing surface gradient there is a reduction in defect resolution and corresponding amplitude. Images where the side-drilled hole was not visually identifiable are excluded from the figure.

**Quantitative performance analysis of ultrasonic detection of corrosion rate changes**

F Zou and F B Cegla

Imperial College London, UK

The cost of corrosion has been estimated to be several billion dollars/year to the USA alone. Numerous corrosion induced component failures have occurred in the past and they have caused devastating consequences. Industry spends much money on corrosion monitoring to improve safety and sustainability of assets. Compared to conventional methods such as weight loss measurements [1] and electrochemical measurements [2], ultrasonic testing makes it possible to monitor corrosion online and in a non-intrusive way.

Corrosion rates are calculated from ultrasonic wall-thickness measurements by linear regression. The presence of measurement noise induces uncertainties in the rate estimates. In this paper the authors analyse data from a state-of-the-art ultrasonic corrosion monitoring setup (with a repeatability of thickness measurements between 20 and 40 nm [3]). From the measurement data it is determined how quickly statistically significant changes in corrosion rate can be detected. It is shown that acidic corrosion of carbon steel that results in corrosion rates of several mm/year can be detected over a timeframe of approximately 10mins. Based on the underlying thickness measurement capabilities of the ultrasonic system it can be predicted how long it will take to detect different changes in corrosion rates. For small rates that are commonly reported to be of interest in real plant processes (i.e. 0.1 – 0.2 mm/year), the current system will detect the corrosion within 1 – 2 hours (see figure below).

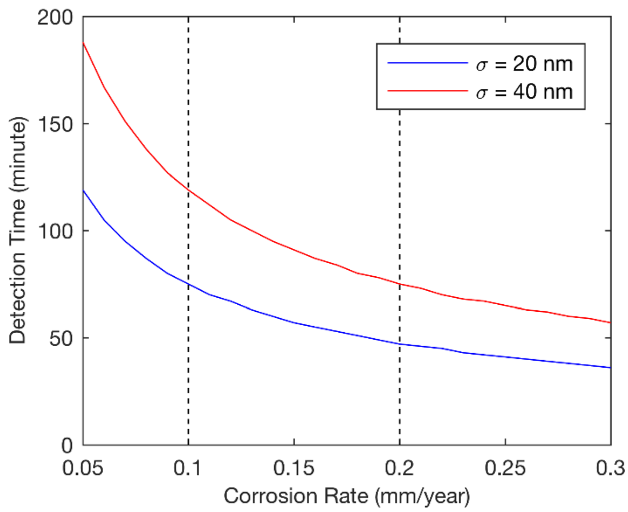


Figure 1. Detection times for different corrosion rates.

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## Optimising resonance conditions for ultrasound cavitation treatment of liquid metals

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University of Greenwich, UK

Ultrasonic melt treatment (UST) is a new advanced, economical, and pollution-free alternative to conventional melt-treatment processes like fluxing or gas lancing. UST involves the introduction of high-intensity ultrasonic waves into liquid metal to induce acoustic cavitation. UST offers beneficial effects, such as accelerated diffusion, activation of inclusions, improved wetting, dissolution, de-agglomeration and dispersion of particles leading to degassing, refined solidification microstructure and uniform distribution of constituent phases.

Traditionally UST is driven by a 'sonotrode' probe immersed in the melt. This technique is limited to light alloys and lower melting temperatures as liquid contact with the probe can be problematic at higher temperature, or with reactive metals leading to contamination of the melt with the sonotrode material.

An alternative contactless method of generating ultrasonic waves has been patented [1] which uses electromagnetic (EM) induction. As a bonus, the EM force induces vigorous stirring distributing the beneficial effects of the treatment into larger volumes of material.

The amplitude of the driving EM force at industrially viable magnetic field strengths is not sufficient by itself to produce and sustain cavitation of the tiny gas bubbles in the melt. This leads to the need of exploiting resonance to amplify the acoustic field inside the holding vessel.

Direct numerical modelling of the sound wave propagation in the liquid metal volume is used to investigate useful acoustic modes in sample geometries. The software solves acoustic travelling and standing wave motion with solid wall and free surface reflections based on first principles in time-dependent simulations. The computational scheme is comprised of optimised 4th-order spatial differentiation and 2nd-order temporal integration and is implemented in parallel on shared memory hardware.

Results show how suitable combinations of vessel dimensions and level of metal melt can be found to optimise the sound pressure amplitude for achieving desired cavitation conditions for a range of driving frequencies. In particular, double resonances can be achieved by adjusting the above parameters so that two acoustic modes (e.g. one axial and one spinning duct mode) have the same (or nearly the same) associated natural frequency. When the two resonant frequencies do not coincide but differ by only a small value, the driving frequency can be chosen in the middle of this interval so any fluctuation of the electrical parameters of the EM system power supply does not lead to substantial decrease of the sound pressure in the melt.

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### 3D-printed cellular electret sensor for acoustic applications

O A Omoniyi, B Tiller, R O'Leary and J F C Windmill

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The introduction of three-dimensional (3D) printing technology has opened up a world of rapid product development in different fields. Fast prototyping, high precision and low cost are some of its many advantages. 3D printing of piezoelectric materials has been growing in popularity in recent years showing increasing promise in the design of miniature sensors, diagnostics devices, and energy harvesters.

Piezoelectric materials play very important roles in the development of sensing and actuating devices. Many of these applications are used in the automotive field, medical field, military and even in day-to-day consumer products. Piezoelectric materials have the ability to couple mechanical and electrical energy, generating an electric charge when undergoing compressive stresses and conversely undergo a mechanical deformation when a voltage is applied [1]. Over the years, piezoelectric materials such as crystals and ceramics have been developed to meet the growing need for highly functional, miniature and cheap sensing and actuating devices. However, due to the inherent properties of these materials there is a limit to their use in achieving these aims [2].

The piezoelectric properties of certain polymers have been studied in depth and much work has been done to exploit this advantage. Polymers such as polytetrafluoroethylene (PTFE), polyvinylidenefluoride (PVDF), and Polypropylene (PP) have been shown to possess good piezoelectric properties and enhanced charge retention [3]. However, it has been shown that a new class of polymer electrets, the voided cellular polymer electrets, offers a number of advantages such as higher sensitivity constants and ease of production. Electrets are dielectric materials with quasi - permanent polarization. Voided polymer electrets are polymer materials consisting of internal voids, which are electrically charged. These materials have been reported to have higher piezoelectric constants due to their soft internal structure, when compared to other piezoelectric materials, and offer better acoustic impedance matching in water and air coupled ultrasonic applications [4].

In this study, we demonstrate that voided polymer electret material can be printed into 3D structures using Stereolithography (SL) printing technology and its use as a sensing and actuating device. A test sample was fabricated by printing a thin membrane of voided polymer electret sandwiched between two base structures. The polymer electret is formed by incorporating dry expanded Expancel microspheres into a photoactive polymer solution of polyethylene glycol diacrylate (PEGDA). The electromechanical properties of the material were determined. The results show the possibility of fabricating miniature 3D-printed sensors through a combination of 3D printing with cellular electret technology.

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