# Anglo-French Physical Acoustics Conference 2024

**17–19 January 2024**
Lodge on Loch Lomond, Loch Lomond, Scotland

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# Conference Programme

## Wednesday 17 January 2024

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| | 12pm – 1pm | **Lunch** |
| | 1pm – 1:20pm | **Registration and Tea/Coffee** |
| | 1:20pm – 1:30pm | **Welcome** |
| P | 1:30pm – 2pm | **Invited Speaker**<br>Ultrasound: a therapeutic swiss army knife?<br>**Gail ter Haar,** Institute of Cancer Research, UK |
| 1 | 2pm – 2:12pm | Exploring the limits to quantitative elastography: supersonic shear imaging in stretched soft strips<br>**Fabrice Lemoult,** Institut Langevin, France |
| 2 | 2:12pm–2:24pm | Evaluating the physical limits of acoustic holograms for transcranial brain applications<br>**Rachel Burstow,** King's College London, United Kingdom |
| 3 | 2:24pm– 2:36pm | OptimUS: a Python library for therapeutic ultrasound<br>**Pierre Gélat,** University College London, United Kingdom |
| 4 | 2:36pm–2:48pm | Comparison of shear wave speed measurements using two shear wave elastography approaches<br>**Andre Alvarenga,** National Physical Laboratory, United Kingdom |
| 5 | 2:48pm – 3pm | All- optical laser ultrasound tomography for biomedical imaging using deep neural networks for image reconstruction<br>**Ahmed Al Fuwaires,** University Of Strathclyde, United Kingdom |
| 6 | 3pm – 3:12pm | Mechanisms of Therapeutic Ultrasound on Biomimetic Models of Cancer<br>**Daniel Silva,** University College London, United Kingdom |
| 7 | 3:12pm – 3:24pm | A non-linear delayed resonator for mimicking the hearing haircells<br>**Jana Reda,** Institut Langevin, France |
| 8 | 3:24pm – 3:36pm | Towards a 3D-printed acoustic sensor inspired by hair-like structures of arachnids and insects<br>**Samuele Martinelli,** University of Strathclyde, United Kingdom |
| | 3:36pm – 4pm | **Afternoon Break** |
| | 4pm – 4:12pm | Materials with elastic membranes : negative acoustic density<br>**Juliette Pierre,** D'Alembert Institute - CNRS, France |
| 9 | 4:12pm – 4:24pm | The spin angular momentum of sound waves and its conversion in a simple scattering experiment<br>**Diego Baresch,** CNRS - Université de Bordeaux, France |
| 10 | 4:24pm–4:36pm | Multimodal approach of the guided wave propagation from a spatially extended source<br>**Charlotte Comte,** Le Mans Université, France) |
| 11 | 4:36pm–4:48pm | Efficient finite element simulation of elastodynamic scatterer responses in arbitrarily complex materials and geometries<br>**Paul Wilcox,** University of Bristol, United Kingdom) |
| 12 | 4:48pm – 5pm | Multimodal radiation and directivity of open-ended waveguides<br>**Simon Félix,** Le Mans Université, France |
| 13 | 5pm – 5:12pm | Friction-driven directed movement with surface acoustics waves<br>**Marina Terzi,** Le Mans University, France |
| 14 | 5:12pm– 5:24pm | Multi-modal characterization of ultrasonic bulk wave properties in heterogeneous textured media through finite element computations<br>**Vincent Dorval,** Université Paris-Saclay, France |
| 15 | 5:24pm– 5:36pm | Analysis of defects in symmetrical parts by non-contact modal analysis<br>**Chloë Palerm,** Safran, France |

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| | 5:36pm | **Day 1 Closes** |
| | 7pm | **Dinner** |

## Thursday 18 January 2024

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| P | 9am – 9:30am | **Invited Speaker**<br>Probing mechanical phenotype with optoacoustics: from characterization to control<br>**Thomas Dehoux,** Institut Lumière Matière, France |
| 16 | 9:30am – 9:42am | 3D phononic endo-microscopy of sub-micron biology<br>**Salvatore La Cavera,** University Of Nottingham, United Kingdom |
| 17 | 9:42am – 9:54am | Numerical study of a Fabry-Perot based elastic EAT system at MHz regime<br>**Jiacheng Chen,** Université de Tours, France |
| 18 | 9:54am – 10:06am | Super-resolution imaging using nanobells<br>**Rafael Fuentes-Dominguez,** University of Nottingham, United Kingdom |
| 19 | 10:06am – 10:18am | Through-aberration accurate ultrasound focusing with SelF-EASE method<br>**Samuel Rodriguez,** University of Bordeaux, France |
| 20 | 10:18am – 10:30am | Development of GHz optoacoustic lenses for sub-optical resolution imaging<br>**Rafael Fuentes-Dominguez,** University Of Nottingham, United Kingdom |
| | 10:30am – 10:50am | **Morning Break** |
| P | 10:50am – 11:20am | **Invited Speaker**<br>3D Variational Bayesian Full Waveform Inversion<br>**Andrew Curtis,** University of Edinburgh, United Kingdom |
| 21 | 11:20am – 11:32am | Recent Developments in Multimode Multiple Scattering in Soft Media<br>**Valerie Pinfield,** Loughborough University, United Kingdom |
| 22 | 11:32am – 11:44am | Ultrasonic Characterization of Solid Suspensions in a Viscous Fluid<br>**Moustafa Eid,** University Le Havre, France |
| 23 | 11:44am – 11:56am | Simultaneous ultrasonic and rheological monitoring of medium density polyethylene with temperature in a rheometer<br>**Nesrine Houhat,** Université de Tours, France |
| 24 | 11:56am – 12:08pm | Digital twin of a MIMO sonar for real-time underwater imaging<br>**Oleksandr Malyuskin,** Queen's University Belfast, United Kingdom |
| 25 | 12:08pm – 12:20pm | Ultrasonic characterization of post-mortem interval (PMI) of human bones<br>**Andres Arciniegas,** CY Cergy Paris Université, France |
| 26 | 12:20pm–12:32pm | Exploring ultrasonic coherent wave characteristics in Cast Austenitic-Ferritic Stainless Steels through virtual microstructure modelling and different analyses using numerical simulations<br>**Zakaria Aghenzour,** EDF Lab les Renadières, France |
| 27 | 12:32pm – 12:44pm | Machine learning for real-time inversion of locally anisotropic weld properties using in-process ultrasonic array measurements<br>**Richard Pyle,** University of Strathclyde, United Kingdom |
| 28 | 12:44pm – 12:56pm | Microstructural Characterisation of Nickel-based Superalloys using Ultrasound<br>**Jennifer Jobling,** Imperial College London, UK |
| | 1pm – 2pm | **Lunch** |

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| P | 2pm – 2:30pm | **Invited Speaker**<br>Modal approach for the development of tools to simulate nondestructive evaluation techniques based on elastic guided waves<br>**Alain Lhémery,** Université Paris-Saclay, France |
| 29 | 2:30pm – 2:42pm | Determination of ageing indicators on glass-fibre polyester composite skins using Lamb guided waves<br>**Khalid Aoujdad,** Le Havre Normandy University, France |
| 30 | 2:42pm – 2:54pm | Integrated Analysis of Materials for Offshore Wind Turbine Blades: Mechanical and Acoustical Coupling<br>**Khalid Aoujdad,** Le Havre Normandy University, France |
| 31 | 2:54pm – 3:06pm | High-resolution ultrasonic characterization of an adhesive film in an aeronautical assembly<br>**Youness Ezziani,** University of Le Havre Normandy, France |
| 32 | 3:06pm – 3:18pm | Inverse problem identification of thickness and viscoelastic properties of a film deposit by scanning acoustic microscopy<br>**Pooyan Manoochehrnia,** University of Le Havre Normandy, France |
| 33 | 3:18pm – 3:30pm | Reconstruction of layer structure of composite materials by reverse time migration<br>**Lily Tu,** University of Bristol, United Kingdom |
| | 3:30pm – 3:50pm | **Afternoon Break** |
| 34 | 3:50pm – 4:02pm | Detection and imaging of BVIDs in composite plates<br>**Pierre Goislot,** CEA/LIST/DIN/LSPM, France |
| 35 | 4:02pm – 4:14pm | Impact of resynchronization errors on the quality of defects localization in reverberant plates<br>**Omar Bouchakour,** (Univ. Polytechnique Hauts-de-France, France) |
| 36 | 4:14pm – 4:26pm | Towards monitoring the state of charge of Li-Ion batteries using ultrasonic methods<br>**Yassine Moradi,** (GREMAN UMR 7347 Laboratory, INSA - Centre Val De Loire, France) |
| 37 | 4:26pm – 4:38pm | Golay-Based Total Focusing Method Using a High-Frequency, Lead-Free, Flexible Ultrasonic Array to Improve Industrial Inspections<br>**Elmergue Germano,** University of Strathclyde, United Kingdom |
| 38 | 4:38pm – 4:50pm | Strategies for robotic structural inspection<br>**Anthony Croxford,** University of Bristol, United Kingdom |
| 39 | 4:50pm – 5:02pm | Ultrasonic inspection of pipes using mobile robotics<br>**Bruce Drinkwater,** University of Bristol, United Kingdom |
| 40 | 5:02pm – 5:14pm | Reconstruction of smooth shape defects in additive manufactured waveguides by laser-ultrasound<br>**Alexandre Charau,** (Université Paris-Saclay, France |
| 41 | 5:14pm – 5:26pm | A methodology for large area inspection using reconfigurable Laser Induced Phased Arrays<br>**Don Pieris,** University of Strathclyde, United Kingdom |
| | 5:26pm | **Day 2 Closes** |
| | 7pm | **Conference Dinner**<br>**Whisky Tasting Follows Dinner** |

## Friday 19 January 2024

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| P | 9am – 9:30am | **Invited Speaker**<br>Nonthermal Effects of Ultrasound: A Force for Good in the Body<br>**Nader Saffari,** University College London, UK |
| 42 | 9:30am – 9:42am | Quantitative characterisation of cavitation signals using wavelet packet transform and k-means clustering<br>**Reza Haqshenas,** University College London, United Kingdom |
| 43 | 9:42am – 9:54am | Unlocking Acoustic Chaos: Characterising the cavitation in a tube transducer with increasing drive amplitude<br>**Hilde Metzger,** University Of Glasgow, United Kingdom |
| 44 | 9:54am – 10:06am | Active microrheology of soft materials with acoustical tweezers<br>**Antoine Penneron,** Institut D'Ingénierie et de Mécanique, France |
| 45 | 10:06am – 10:18am | Acoustic amplitude of resonating bubbles<br>**Vincent Gourmandie,** Université Paris Cité, France |
| 46 | 10:18am – 10:30am | Imaging of crystal degradation upon non-hydrostatic compression via time-domain Brillouin scattering<br>**Samuel Raetz,** Le Mans Université, France |
| 47 | 10:30am – 10:42am | Elasticity and grain morphological characterization in polycrystalline materials using spatially resolved acoustic spectroscopy (SRAS++)<br>**Carolina Guerra,** University of Nottingham, United Kingdom |
| 48 | 10:42am – 10:54am | Anisotropic Orientation Inversion using Stein Variational Gradient Descent<br>**James Ludlam,** University of Strathclyde, United Kingdom |
| | 10:54am – 11:30am | **Morning Break** |
| 49 | 11:30am – 11:42am | Coherent Multi-Transducer Ultrasound (CoMTUS) imaging: Towards large field-of-view imaging with three probes<br>**Paul Dryburgh,** King's College London, United Kingdom |
| 50 | 11:42am – 11:54am | Can Mn:PIN-PMN-PT piezocrystal replace hard piezoceramic in power ultrasonic devices?<br>**Xuan Li,** University of Glasgow, United Kingdom |
| 51 | 11:54am – 12:06pm | Characterisation of a Lead-free Piezoceramic using a Hybrid of Techniques<br>**Olubunmi Onanuga,** University of Glasgow, United Kingdom |
| 52 | 12:06pm – 12:18pm | Development and simulation of high-temperature ultrasonic transducers with porous metal backing<br>**Guy Feuillard,** GREMAN INSA Centre Val De Loire, France |
| 53 | 12:18pm – 12:30pm | The influence of phase microstructure transformations on the dynamic response of Nitinol Langevin ultrasonic transducers<br>**Mahshid Hafezi,** University of Glasgow, United Kingdom |
| 54 | 12:30pm – 12:42pm | Design of a bespoke, additively manufactured HIFU transducer characterised at high power<br>**Jack Stevenson,** University of Glasgow, United Kingdom |
| 55 | 12:42pm – 12:54pm | Zinc Oxide Thin Film as a candidate for Lead-Free Ultrasound Transducers<br>**Claire Thring,** Novosound, United Kingdom |
| | 12:54pm – 1:30pm | **Lunch (grab and go) and Depart** |

# Invited Speaker Presentations

## Modal approach for the development of tools to simulate nondestructive evaluation techniques based on elastic guided waves

**Alain Lhémery**[1], Vahan Baronian[1], Jordan Barras[1], Karim Jezzine[1]
[1]*Université Paris-Saclay, CEA-LIST, France*

Invited Talk: January 18, 2024, 14:00 - 14:30

This presentation aims to show a set of models and associated simulation tools that have been developed at CEA-LIST over the last 20 years for simulating nondestructive evaluation techniques based on elastic guided waves and providing modal solutions. A significant part of the models discussed in this presentation was presented over the years at AFPAC and published in its proceedings. The presentation will show the overall long-term consistency of the modal approach.

We will focus on models developed under several formal constraints. i) For the various problems to be treated, these models deal with modal bases of guided waves wherever possible so that final results are given as modal solutions. ii) They are designed to be easily chained together. iii) When modal bases do not exist, local finite element (FE) computations are involved, that include specific artificial boundary conditions to ensure both their transparency and to decompose FE results at these boundaries onto modal solutions available in regions connected to the FE zone (hybrid modelling).

Models for a set of connected unidirectional guides and for plate-like structures will be discussed and exemplified (tube, rail inspections, radiation by arbitrary sources in a composite plate of finite size, scattering by a stiffener).

All these works were initiated by doctoral theses and then, were the subject of numerical implementation within the very constrained framework of development of the commercial NDE simulation platform CIVA.

Special thanks to Laura Taupin, Marouane El Bakkali, Mathilde Stévenin, Amond Allouko who carried out their doctoral thesis (co-)supervised by Alain Lhémery (as did the co-authors of this paper who are now his colleagues) on works which were discussed in this presentation.

# 3D Variational Bayesian Full Waveform Inversion

**Andrew Curtis**[1], Xin Zhang[1]
[1] *University of Edinburgh, United Kingdom*

Invited Talk: January 18, 2024, 10:50 - 11:20

Seismic Tomography is a method to image the Earth's subsurface using acoustic and elastic waves. In order to better interpret the resulting images it is important to assess imaging uncertainties, but this is hard to achieve. Monte Carlo random sampling methods are often applied for this purpose but the 'curse of dimensionality' makes them computationally intractable for high-dimensional parameter spaces. To extend uncertainty analysis to larger systems, variational inference methods developed in the machine learning community are introduced to seismic tomography. In contrast to random sampling, variational methods solve an optimization problem yet still provide probabilistic results. Variational inference is applied to solve two types of tomographic problems: full waveform inversion (FWI), and time-dependent (known as 4D) FWI. Three different variational methods are tested: automatic differential variational inference (ADVI) and both deterministic and stochastic versions of Stein variational gradient descent (SVGD). ADVI provides a robust mean velocity model but biased uncertainties, whereas deterministic SVGD produces an accurate match to the results of Monte Carlo analysis, but at fraction of the computational cost. SVGD is significantly easier to parallelize, and for very large problems can be run in minibatch mode which is impossible using Monte Carlo methods without incurring probabilistic errors. Stochastic SVGD is shown to be the only method that may be capable of providing useable results for 3D FWI problems. This method is therefore extended to time-dependent monitoring problems of the type expected to be encountered in CO2 of Hydrogen storage applications. Variational methods thus have the potential to extend probabilistic analysis to other Geophysical inverse problems and to higher dimensional tomographic systems than is currently thought possible.

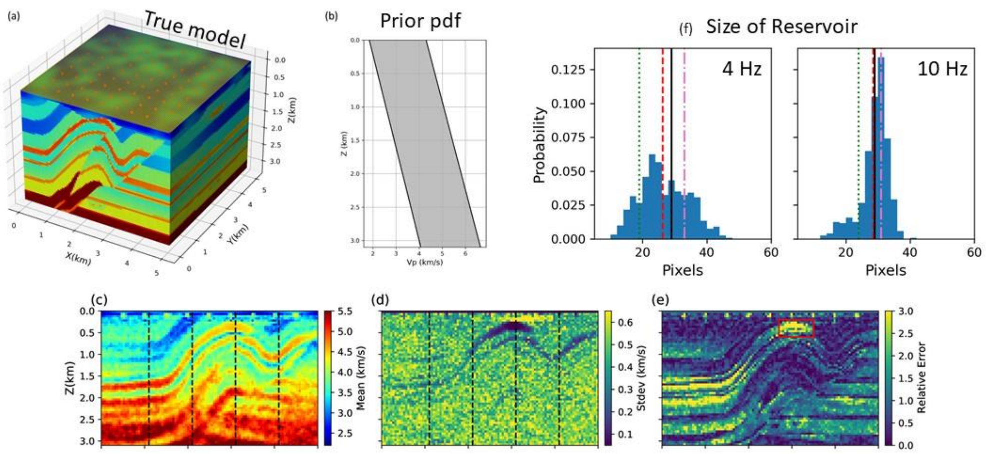



Figure: (a) 3D synthetic model. (b) Uniform prior probability density function. (c),(d),(e): Respectively the mean, standard deviation and relative error (difference between true and mean models, divided by the standard deviation) across central vertical slice in x-z plane. (f) Results of an interrogation problem to answer the question, "How large is this storage reservoir?" given probabilistic FWI results, using two different wavelet central frequencies: black line indicates the correct value.

# Probing mechanical phenotype with optoacoustics: from characterization to control

**Thomas Dehoux**[1]
[1] *Institut Lumière Matière, France*

Invited Talk: January 18, 2024, 09:00 - 09:30

The phenotype is the composite of the organism's observable characteristics or traits. When it comes to mechanical phenotype, it includes adhesiveness, permeability, and stiffness. Since the advent of mechanobiology in the 2000's, many techniques have been developped to probe such quantities, mostly relying on a contacting probes or tracking fluorescent markers. Thanks to improvements in spectrometer technology, acquisition times have been reduced significantly in recent years, opening new applications in biology and medicine. In recent years, a new quantitative microscopy based on Brillouin light scattering (BLS) has been proposed that uses the interaction of a laser light with picosecond timescale density fluctuations in the sample.

Since 2015, BLS has been successfully used for mechanical phenotyping and imaging with a contrast based on the stiffness in single cells using spectroscopic and time-resolved implementations, live organisms, plant tissues and teeth. Because it is label-free, all-optical and non-destructive, BLS has gained interest in the pharmaceutical and biomedical fields as a promising tool to investigate the mechanobiology of different pathologies. However, its relevance from a physiological standpoint remains debated due to the ultrashort timescales involved. Since the probing mechanism involves coupling of photons to longitudinal phonons, variations in the scattering spectra can be interpreted as the response of the sample to an infinitesimal uniaxial compression. With a few examples and some fundamental concepts, I will give some insights on how to interpret such data in biological samples, and offer new perspectives in the first part of this presentation.

Such developments demonstrate that phonons can be used to characterize cells and tissues, with applications in medicine and biology. But one can also envisage doing the opposite : controlling phonon propagation with engineered tissues. At the end of my talk, I will discuss our latest investigations of cell monolayers with sub-GHz phonons, and discuss the design of new biologically-derived hypersonic materials controlled by the phononic phenotype of the cells.

# Nonthermal Effects of Ultrasound: A Force for Good in the Body

**Nader Nader Saffari**[1]
*[1] University College London, United Kingdom*

Invited Talk: January 19, 2024, 09:00 - 09:30

Over the last 20 years, investment in therapeutic ultrasound has grown from under $100M to over $3.0 billion in the US alone. The applications of ultrasound based on thermal ablation are now almost routinely used in the UK for treatment of prostate cancer, pain palliation for bone metastases and essential tremor. But the nonthermal effects of ultrasound in the body are now generating a huge amount of interest for a plethora of applications. These nonthermal effects include acoustic streaming, bubble formation and cavitation, and application of mechanical force through radiation pressure.

This talk reviews some of the recent studies that have involved ultrasound's mechanical mechanisms for therapeutic effect. These range from cavitation and radiation pressure-based effects which are being used in clinical trials such as for blood brain barrier (BBB) opening and drug delivery, to those which show great promise in the laboratory, such as histotripsy for cell transplantation and immunotherapy. Lastly, the role of ultrasound in mechanobiology will be discussed where the influence of stress and strain on biological processes at a cellular level is being investigated for neuromodulation and the treatment of neurological diseases, amongst others.

# Ultrasound: a therapeutic swiss army knife?

**Gail Ter Haar**[1]
*[1]Institute of Cancer Research, United Kingdom*

Invited Talk: January 17, 2024, 13:30 - 14:00

Most people are aware of the use of ultrasound for imaging, especially for examination of the fetus in the pregnant uterus. The assumption here is that this is a 'safe' examination, producing no biological effects in mother or babe. This appears to be valid, so long as the scan is conducted properly, following professional guidelines.

However, it is well accepted that ultrasound can produce changes in biological tissues. These can be harnessed for beneficial effect in a wide range of therapeutic applications. Absorption of ultrasonic energy leads to thermal effects, with the induction of temperatures sufficient to produce instantaneous cell death being possible, thus allowing thermally ablative procedures involving temperatures in excess of 43oC, Negative acoustic pressures that are sufficiently high to be able to draw gas out of solution can be propagated in tissue, thus leading to the possibility of effects due to cavitation such as tissue emulsification and changes in cell permeability.

One area in which ultrasound therapies have the most promise, and the widest variety of action is in cancer therapy, Here, thermal ablation of tumours has been investigated, as has mechanical destruction of tumours, enhanced drug delivery and stimulation of the immune response, both of these last two usually involving the infusion of microbubbles.

Some of the applications under consideration will be discussed, including ultrasound's potential to enhance the effect of oncolytic (cancer attacking) viruses in the treatment of pancreatic cancer, and our efforts to improve immunotherapy treatment of neuroblastoma. Finally, and away from the cancer arena, an exciting opportunity to use ultrasound induced haemostasis in fetal medicine will be described.

# Oral Presentations

## Determination of ageing indicators on glass-fibre polyester composite skins using Lamb guided waves

**Khalid Aoujdad**[1], Pierre Marechal[1], Damien Leduc[1], Mounsif Ech-Cherif El-Kettani[1]
[1] *Lomc Umr Cnrs 6294, France*

Afternoon Session III, January 18, 2024, 14:30 - 15:30

Structural adhesive bonding based on GFRP (glass-fibre reinforced polyester) composite is used in industries such as aeronautics, automotive, renewable energy (tidal turbines blades, offshore wind turbines blades…). These structures, and especially their skins, are exposed to severe environmental conditions (high variations in temperature, humidity, pressure, wind turbulence…) that induce structural ageing. Industrials are interested in non-destructive evaluation methods to control the structural health status during the life cycle. This work focuses on GFRP composite skins representative of offshore wind or tidal turbine blades. Samples of two different thicknesses (4-plies and 6-plies) were subjected to accelerated ageing in a thermostated tank (40°C or 60°C) of seawater, while the others (the reference samples) had not undergone any particular ageing. The aim is to evaluate the properties changing using ultrasonic Lamb waves and to identify indicators of ageing [1].An experimental setup consisting of a contact transducer for emission and a laser velocimeter for reception is used to generate guided Lamb waves. The normal displacement of the propagating waves is measured for several positions in the propagation direction. Time and space double FFT is performed to obtain the experimental dispersion curves. The study is conducted on unaged 4 and 6 plies samples of GFRP and aged ones for 15 and 28 weeks respectively. Results shows that for a given frequency the wavenumber in the aged sample is increasing compared to the unaged. This induces a decreasing of the phase velocity in accordance with previous results showing the decreasing of the mechanical properties of the material with ageing [2]. The difference between wavenumbers in aged and unaged is more significant on the 6 plies samples compared to 4 plies ones, which can be explained by the difference ageing period.

References

[1] Y. Gélébart, H. Duflo, J. Duclos, « Air coupled Lamb waves evaluation of the long-term thermo-oxidative ageing of carbon-epoxy plates », NDT & E Int., vol. 40, n°1, p. 29-34, 2007 (DOI: 10.1016/j.ndteint.2006.07.010).
[2] P. Davies, F. Pomiès, et L. A. Carlsson, « Influence of water and accelerated aging on the shear fracture properties of glass/epoxy composite », Appl Compos Mater, vol. 3, n°2, p. 71 87, 1996, (DOI: 10.1007/BF00158994).

# Integrated Analysis of Materials for Offshore Wind Turbine Blades: Mechanical and Acoustical Coupling

**Khalid Aoujdad**[1], Elhadji-Amadou Ba[2], Pierre Marechal[1], Damien Leduc[1], Alexandre Vivet[2], Florian Gehring[2], Mounsif Ech-Cherif El-Kettani[1]
*[1]LOMC UMR 6294 CNRS, Le Havre Normandy University, France, [2]CIMAP, Normandie University ENSICAEN, UNICAEN, CEA, CNRS, CIMAP, France*

Afternoon Session III, January 18, 2024, 14:30 - 15:30

Offshore wind turbine blades, which are critical components of renewable energy systems, require materials that have been engineered to withstand harsh marine environments and dynamic operational conditions to generate sustainable electricity.
Our project centres around a comprehensive integrated analysis that combines the study of acoustic and mechanical indicators of structural degradation caused by continuous exposure to the marine environment of representative offshore wind turbine blade materials. The combination of the two approaches, acoustic and mechanical, is carried out by comparing the results obtained by these two methods on similar samples under different conditions and configurations.
Two laboratories are involved in this project: the LOMC UMR 6294 is managing the accelerated hydric ageing and the ultrasonic characterisation of its consequences on the material. CIMAP UMR 6252 is carrying out sample fabrication and mechanical testing.
Samples comprise a unidirectional glass-fibre and polyester resin composite laminate, integrated with a SAN (Styrene Acrylo-Nitrile) foam core. Our ongoing research involves assessing the aging impact on both the laminate composite and sandwich plate, with a specific focus on the exterior skin, which bears the brunt of the most severe environmental factors. The specimens are immersed in seawater at temperatures of 40°C and 60°C to comprehensively investigate temperature aging effects, hypothesized to be non-linear.
Various ultrasonic non-destructive characterization methods for structural health monitoring have been employed at LOMC laboratory, including experimental setups for water-coupled wave transmission through materials, air-coupled wave transmission, acoustical microscopy, and laser velocimetry, aimed at enhancing precision and results. Conversely, at the CIMAP laboratory, mechanical testing is conducted through 3- and 4-point bending tests. This testing methodology yields properties such as Young's modulus, flexural strength, flexural modulus, flexural strain, modulus of rupture, load-deflection behaviour, and energy absorption.
On the one hand, first works on UD Glass-polyester Composite of 4 and 6 ply in both aged and unaged states (28 weeks for 6 plies and 15 weeks for 4 plies), have shown a small loss in the compression velocity through the thickness direction. Indeed, ultrasound velocities (compression and transverse) are supposed to undergo a degradation due to the ageing process. This is similar to the results provided by our mechanical partners who measured a loss in Young modulus.
On another hand, C-scans performed on the same samples have shown that the attenuation through the thickness [1] is increasing with the ageing process.
Those first results are showing a matched conclusion between the mechanical and acoustical analysis. The next step will be the study of more aged samples, in the aim to carry out acoustical indicators corroborated by destructive mechanical tests.

N. T. Duong, J. Duclos, L. Bizet, et P. Pareige, « Relation between the Ultrasonic Attenuation and the Porosity of a RTM Composite Plate », Physics Procedia, vol. 70, p. 554 557, janv. 2015, doi: 10.1016/j.phpro.2015.08.015.

# High-resolution ultrasonic characterization of an adhesive film in an aeronautical assembly ( Oral Presentation )

**<u>Youness Ezziani</u>**[1], Pierre Maréchal[1], Mounsif  Ech-cherif El-kettani[1], Damien Leduc[1], Mathieu Ducousso[2], Nicolas Cuvillier[2]
*[1]LOMC, UMR 6294 CNRS, University of Le Havre Normandy, France, [2]Safran Tech, France*

Afternoon Session III, January 18, 2024, 14:30 - 15:30

The reduction of weight in aeronautical structures is a significant challenge in decreasing aircraft fuel consumption and reducing polluting emissions. Adhesive bonding addresses this need for weight reduction and offers numerous advantages compared to more conventional techniques like welding or riveting. Hence, there is a necessity to perform non-destructive evaluation (NDE) to assess the quality of the adhesion. Several non-destructive methods are currently employed for this purpose [1, 2], including the identification of imperfections such as porosities, cohesive delamination within the adhesive bond, as well as adhesive delamination between the adhesive and the substrate [3]. In this study, the sample under investigation is representative of the Leap engine fan blade and is provided by Safran. It is composed of three materials: a 994 µm titanium alloy TA6V (Ti) bonded to a 13.5 mm thick 3D woven composite (Comp) using an epoxy resin AF191K (Epo) with an estimated thickness of 135 µm. As a result, the studied structure is a trilayer stack made referenced as (Ti/Epo/Comp), and the epoxy adhesive film requires the use of transducers with a centre frequency of a few tens of MHz. The aim of this work is to develop an acoustic method to assess the viscoelastic properties of the adhesive film. Up to now, it is still a challenge to bring a robust information on the level of adhesion, which is strongly dependent on the adhesive thickness and the acoustical impedances ratios. The difficulty in obtaining an ultrasound evaluation with a favourable signal-to-noise ratio arises from the acoustical impedance contrast. This contrast is high between TA6V and epoxy resin, and low between epoxy resin and the composite, making the detection of the epoxy/composite interface particularly challenging. Additionally, the material's inherent attenuation contributes to the loss of ultrasonic wave energy during its propagation.

This assessment is carried out using a non-destructive evaluation with an ultrasonic method with high frequency and high resolution, utilizing the scanning acoustic microscope (SAM) PVA TEPLA 301 (pulse-echo method). Preferably, a focusing transducer is used for imaging and a planar transducer for characterization (amplitude). Another method for modelling signals reflected at different interfaces is the Debye series method developed by J.M. Conoir and implemented by P. Marechal [4], which allows expressing the reflection and transmission coefficients at various interfaces. Subsequently, the expression of the overall reflection coefficient enables the reconstruction of the signal with echoes associated with each layer of the assembly. The model also provides the possibility to introduce viscosity and change interface conditions, allowing the simulation of defects of cohesive or adhesive nature. Numerical and experimental results are in good agreement and presented to assess adhesive film thickness and impedance, aiming to provide an estimation of the adhesion quality in an aeronautical assembly of TA6V/Composite.

References:
[1] R. Hodé et al., Appl. Phys. Lett., 2020 (DOI : 10.1063/1.5143215).
[2] M. Ducousso et al., Appl. Phys. Lett., 2018 (DOI : 10.1063/1.5020352).
[3] L. Attar et al., NDT&E Int., 2023 (DOI : 10.1016/j.ndteint.2023.102841).
[4] A. Khaled et al., Ultras., 2012 (DOI : 10.1016/j.ultras.2012.11.011).

# Ultrasonic Characterization of Solid Suspensions in a Viscous Fluid

**Moustafa Eid**[1], Pierre Maréchal[1], Ahmed Benamar[1]
*[1]LOMC, UMR 6294 CNRS, University Le Havre Normandy, France*

Morning Session II, January 18, 2024, 11:20 - 13:00

This research focuses on the characterization of a random distribution of solid particles suspended in a viscous fluid. As an investigation tool, the ultrasonic waves in the MHz frequency range and their propagation through such suspensions and bringing some information on the effective properties of the suspensions. In this context, the objective of this work is to establish the relationship between ultrasonic signals and suspended particles properties, considering their geometry, dimensions, concentration and distribution.

Currently, ultrasonic methods are yet omnipresent in several fields of applications:

- Sedimentation: Evaluation of characteristics such as concentration, average particle size, particle size distribution (PSD)…
- Polluted fluids: Treatment of wastewater and regulation.
- Food products: Characterization of lipids, proteins, and other components…

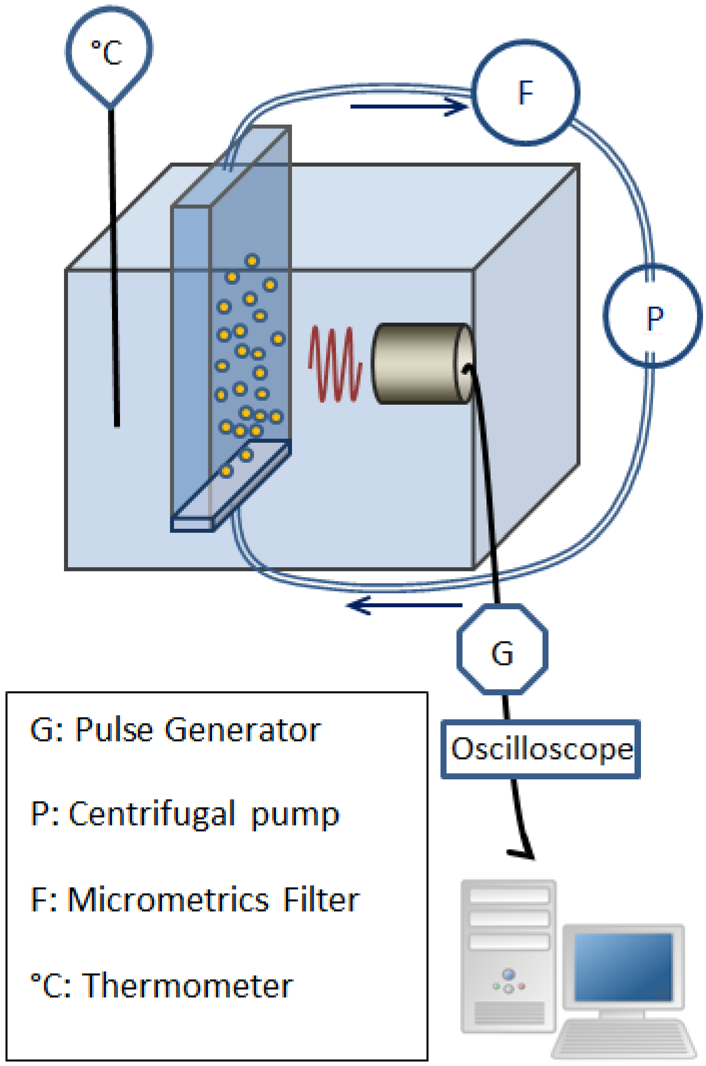
Within this framework, in order to achieve those objectives, the objectives are divided in two parts: Numerical and experimental.

The objective of the numerical study is to consolidate previous numerical results with new configurations and develop a numerical model dedicated to our case of study involving ultrasonic, suspended micro-particles, and viscous fluid. The usually considered models are involving strong assumptions such as spherical particles, low concentrations, small average wavenumber-radius product ka, constant temperature, suspensions without fluid flow. In the developed approach, such models are implemented, involving known spherical particles with a very narrow distribution density, low concentration c, viscosity , and regulated temperature T. Using Matlab, the numerical implementation of those models and their limits are compared and discussed: ECAH, Waterman and Truell, Forester and Pinfield.

In a complementary approach, the experimental work consists in designing and constructing a practical experimental setup for ultrasonic measurements for the characterization of suspensions in a dynamic flow. In this aim, a specific instrumentation was developed to measure the effective ultrasonic properties (attenuation and velocity). The emission and reception of ultrasonic waves in the MHz frequency range was investigated for the characterization of suspended particles using a circulating pump in a temperature-regulated aquarium. Using Python, the acquisition of temporal signals was realized. A post-processing of the acquired signals was carried out using FFT, in order to determine attenuation and phase velocity as well as their frequency dependence.

As a summarize, the obtained results include:

- Numerical validation (Matlab) of a model adapted for the studied solid suspensions in a given viscous fluid.
- Development of an experimental setup and measurement protocol, outlining signal acquisition procedures (Python), FFT processing, and determination of attenuation and velocity curves as a function of frequency.
- Quantification of the influence of the flow rate, temperature, concentration and frequency.


°C
F
P
G
Oscilloscope
G: Pulse Generator
P: Centrifugal pump
F: Micrometrics Filter
°C: Thermometer

# Inverse problem identification of thickness and viscoelastic properties of a film deposit by scanning acoustic microscopy

**Pooyan Manoochehrnia**[1], Pierre Marechal[1], Damien Leduc[1], Mounsif Ech-Cherif El-Kettani[1]
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Afternoon Session III, January 18, 2024, 14:30 - 15:30

Solving an inverse problem has been always a matter of importance. In this study, the question focuses on finding acoustic parameters of the structure and the transducer thanks to a numerical implementation of a physical model matching with the experimental ultrasonic response. In this paper, it has been tried to apply a step-by-step matching methodology, that isolates important characteristics of the ultrasonic signal and matches the model parameters (individually or as linked coefficients) with experimental signal.

A 85 µm thick layer of epoxy resin has been deposited on a glass plate of 1.66 mm thick to form a two-layered structure. The structure is characterized using scanning acoustic microscope (SAM) equipped with a plane wave transducer with a central frequency of 50 MHz. The Debye series model (DSM) has been chosen for its efficiency to calculate the reflection coefficient of the structure as a function of the frequency. This reflection spectrum is then multiplied by the Gaussian envelope of the transducer's response. Therefore, the DSM is run with 11 different parameters and its result is then compared to experimental signal.

A step-by-step, reproducible and physically consistent method has been carried out to match parameters of DSM model with experimental signal. The first set of parameters includes the central frequency (f0), the relative bandwidth, as well as the phase-shift of the Transducer Gaussian envelope. The second set of parameters includes material acoustic parameters notably thickness (Th), longitudinal velocity (CL), density and attenuation, both for deposit layer and substrate layer. Varying these 11 parameters, results in a quantifiable mismatch between the model and the experiment. The visual form of the resulting signal, as well as the physical consistency of parameters and the value of mismatch error, are indicators of the way ahead.

The identification consists in isolating the first reflection echo on the substrate, then identifying each surrounding echoes and fitting each of those methodically. The first step of the inverse problem concerns the transducer's response, which is modelled by the central frequency (f0) and relative bandwidth ( ), corresponding (in a first approach in the time domain) to the pseudo-period and echo duration. In addition, the phase shift ( ) of the transducer's response is updated to match to the local minima and maxima. The second step consists in the syncing of Time of Flight (ToF) inside the deposit layer, using the (Th/C)d ratio. The third step focuses on the amplitude mismatch adjustment through the mismatch between the acoustic impedance of the deposit (.C)d and that of the substrate (.C)s layers. The amplitudes of the subsequent echoes are related to attenuation of deposit layer (Alpha)d.

Varying the model parameters as described earlier, results in a very good match between the model and experimental signal. Notably, a very good agreement between form of signals is achieved, since the time shift between echoes has been corrected, and the amplitudes have been matched.

# Impact of resynchronization errors on the quality of defects localization in reverberant plates

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Afternoon Session IV, January 18, 2024, 15:50 - 17:26

In the context of structural health monitoring (SHM), recent research has been carried out to take advantage of the correlation of ambient noise to locate and characterize defects in reverberant plates. The back-propagation-based imaging algorithms developed in this way require that the signals recorded by the sensors of the control network be perfectly synchronized. This implies that these sensors must be linked to a common clock to ensure their synchronization, which generates significant complexity of the monitoring system in the case of embedded applications. Post-processing resynchronization is a promising solution to deal with this problem. However, in less favorable cases and especially in the presence of additive noise this resynchronization could be made with some errors. In this work, we are interested in quantifying statistically the degradation of the contrast of localization images as a function of the resynchronization error. The obtained results are promising and can be of great interest for embedded applications.

# Microstructural Characterisation of Nickel-based Superalloys using Ultrasound

**Jennifer Jobling**[1], Michael Lowe[1], Bo Lan[1]
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Morning Session II, January 18, 2024, 11:20 - 13:00

Nickel-based superalloys are widely across the engineering industry, due to their superior mechanical properties at elevated temperatures, and excellent resistance to creep and fatigue under harsh working conditions. The microstructure of the material, including influences of phase composition and grain size, greatly affects these characteristics. A notable superalloy is Inconel 718, where the amount of the gamma double prime phase precipitated within the main gamma phase matrix is most important for material performance – though others phases are also present, including gamma prime and delta. Existing methods for material characterisation are destructive, expensive and time-consuming (such as SEM and EBSD), as are techniques for determination of fatigue life of components (which require surface preparation for hardness testing); hence it would be highly beneficial to develop a non-destructive, rapid and reliable method enabling quick inspections for characterising a material's microstructure, to assess its suitability for a particular application.

This project aims to develop a non-destructive inspection method using ultrasound for phase characterisation of nickel-based superalloys. A new technique, involving ultrasonic wave speed measurements with a spherical convolution theoretical framework, has been assessed in terms of its feasibility in being able to detect microstructural changes. In contrast to existing characterisation techniques, this method gives a statistical average over a volume, as opposed to surface or near-surface measurements only. Four samples of Inconel 718 were used for this investigation, two of which were retained in the as-received condition with the others undergoing a heat treatment simulating heat damage. Experiments have shown conclusive evidence that this spherical convolution technique is capable of detecting phase changes within the material; the uncertainty of the ultrasonic water tank system has also been quantified. The test setup has also been used to acquire attenuation measurements, with the aim of combining these two streams of information as a useful tool for fatigue life analysis. Subsequent tests on a further set of Inconel 718 samples which have undergone different heat treatment processing have been used to predict the amount of delta phase present, and thus laid the foundations for the development of this method for rapid phase characterisation of nickel-based superalloys.

# Can Mn:PIN-PMN-PT piezocrystal replace hard piezoceramic in power ultrasonic devices?

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Morning Session IV, January 19, 2024, 11:30 - 13:00

Mn:PIN-PMN-PT (Pb(In1/2Nb1/2)O3 - Pb(Mg1/3Nb2/3)O3 - PbTiO3) piezocrystal is investigated to determine whether the material's enhanced energy density makes it a candidate transducer material for power ultrasonics applications. To this end, the electromechanical and vibrational characteristics of a simple configuration of a bolted Langevin transducer (BLT) and then an ultrasonic surgical device, both incorporating Mn:PIN-PMN-PT piezocrystal, are compared with the same configurations of BLT and ultrasonic surgical device but incorporating a conventional hard PZT piezoceramic, as commonly used in high-power ultrasonic transducers.

The material properties of Mn:PIN-PMN-PT are determined using a single sample characterisation technique and these are used in a finite element analysis (FEA) to design and then fabricate the BLT and ultrasonic surgical device, tuned to the first and second longitudinal modes at 20 kHz respectively. FEA is similarly used for the hard PZT versions. It is observed that the superior elastic compliance of the Mn:PIN-PMN-PT material results in a higher radial piezo-stack deformation than the hard PZT under ultrasonic excitation of the BLT. However, the resulting longitudinal displacement amplitude of the two BLTs and two ultrasonic surgical devices is found to be equal, despite the higher figure of merit (Qk_eff^2) of those incorporating Mn:PIN-PMN-PT. The electrical impedance is measured at increasing excitation levels to evaluate the effect on quality factor, Q. It is found that damping in the BLT with hard PZT is negligibly affected by excitation level, however, the BLT incorporating Mn:PIN-PMN-PT exhibits a large reduction in Q. These initial findings indicate that, for measurements in air, the advantages of the higher figure of merit of the piezocrystal material are not realised in a high-power transducer due to the significant increased damping at high excitation levels.

To compare the vibrational response of the two ultrasonic surgical devices, an L-C configuration electrical impedance matching circuit was implemented to maximise the efficiency of energy transfer from the driving source to the transducer under load. Results suggest that similar responses occurred for the two ultrasonic surgical devices in cutting tests using a low strength bone mimic material. However, the Mn:PIN-PMN-PT device exhibited more outstanding performance in cutting through the higher strength ex-vivo chicken femur.

# Active microrheology of soft materials with acoustical tweezers

**Antoine Penneron**[1]
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Morning Session III, January 19, 2024, 09:30 - 10:54

Probing the local and internal elastic properties of soft materials is important to characterise the mechanics of biological tissues. Therefore, this work focuses on the development of an active microrheological method based on the use of acoustical tweezers, a recently developed technique to exert contactless forces on microscopic objects. Here, a focused acoustic vortex beam pulls on a microbubble (100 µm in size) embedded in a soft hydrogel with the radiation force. This force can be modelled using precise pressure measurements of the incident beam, and the net displacement of the microbubble centre can be optically obtained. Combined with a simple elastic model for the medium, the local elastic properties of the hydrogel can finally be deduced. By using carbopol hydrogels with typical shear moduli ranging from a few tens to a few hundreds of pascals, microbubble displacements of 1 to 10 micrometers were observed, consistent with forces in the micronewton range. Overall, this novel approach presents real benefits compared to conventional
rheology methods, as it can be considered minimally intrusive, local, and well-adapted to probe thick and opaque-to-light materials in bulk such as cellular tissues.

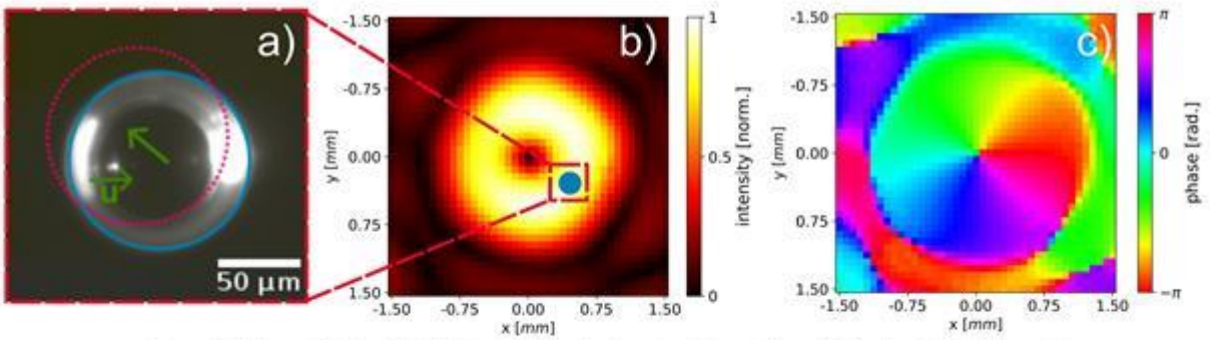


**Figure :** **a)** Displacement of a microbubble (100 µm in size) by a few micrometers in the vortex beam, **b)** Normalized intensity of the vortex beam, **c)** Phase of the vortex beam.

# Friction-driven directed movement with surface acoustics waves

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Afternoon Session II, January 17, 2024, 16:00 - 17:36

Small objects on a substrate can be moved by a friction force generated via surface acoustic waves. The effect is referred to as vibrational transport and is used, in particular, in food and pharmaceutical industries. Future applications can also include dust removal or manipulating components of micromachines.

The behavior of a particle is affected by two forces, normal and tangential/frictional, created by surface vibrations. Depending on inertia, normal and tangential force oscillations can have variable phase lag. This phase lag can be such that the normal reaction is considerably higher than average when the friction force is directed to the right, while during the left excursion of the friction force the normal one is considerably lower than usual. In that case, the particle will have a tendency to slide to the right, since its opposite movement is impeded by higher compression. In other words, during the advancing phase the compression is lower than during the receding phase. The resulting steady motion of the particle depends on a number of system parameters, and a theoretical parametric study can be more efficient in comparison to blind variation of parameters in experiment. In addition, the particle can detach and start bouncing that produces a poorly predictable behavior since each jump will highly depend on local properties of the surface etc.

Our analysis differs from a traditional one in which the particle is considered as a material point. A more realistic approach accounts for a finite size of the particle and for its shape. For an axisymmetric body, the contact zone is a circle that can contain a smaller circle of stick surrounded by an annulus of slip. This type of behavior in described by the Hertz-Mindlin mechanics that has been recently upgraded into a contact model applicable to input signals (here contact displacements) arbitrarily changing in time. The model called the Method of Memory Diagrams produces the corresponding hysteretic contact forces that makes is possible to solve dynamic equations of motion.

Despite a large number of system’s characteristics, the dimensionless form of the equation of motion contains only two parameters, the normalized mass and the normalized vertical wave displacement amplitude. We present a detailed analysis of various regimes depending on their values and show, in particular, that a deformable body can move both with the wave and against the wave, whereas the material point can only move against the wave propagation direction. This possibility offers an opportunity of more elaborate object positioning. The developed numerical tool is capable of modeling for various systems and scenarios.

# Exploring ultrasonic coherent wave characteristics in Cast Austenitic-Ferritic Stainless Steels through virtual microstructure modelling and different analyses using numerical simulations

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Morning Session II, January 18, 2024, 11:20 - 13:00

Cast austenitic-ferritic stainless steel, also known as cast duplex stainless steel (CDSS), constitutes many components in the primary circuit of pressurised water reactors. Due to their manufacturing process, these steels have metallurgical structures characterised by very coarse grains and significant microstructural complexity. Their dual-phase microstructure consists of grains with various morphological scales (ranging from 100µm to 2cm) and substantial complexity. Ultrasonic testing (UT) of these materials is thus a challenging issue. Indeed, in these coarse-grained structures, ultrasonic waves undergo scattering at grain boundaries, resulting in significant attenuations and structural noise that disrupt the inspection. Using 3D numerical simulation tools and providing a detailed description of the microstructure, it is possible to understand the multiple interactions between ultrasonic waves and microstructure and quantify the impact of microstructural features on NDT performance. This communication details the approach used to simulate the effect of the multi-scale microstructure of CDSS on ultrasonic wave propagation. To achieve this, a specific method was established to generate representative elementary volumes (REVs) from Electron Back-Scattered Diffraction (EBSD) acquisition data (phases, grain size distribution, orientation relationships). These REVs are then used as an input of two different 3D finite element solvers developed by EDF R&D (A3D-CND [1]) and CEA LIST (Microstruct plugin set in the platform CIVA [2]). For each simulation tool, a technique for characterising the effective medium is proposed to estimate the behaviour of the coherent wave (velocities and attenuations). A benchmark study of the results obtained using these two techniques is then carried out between the two approaches over the frequency ranges commonly used in UT methods for these components.

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# Ultrasonic characterization of post-mortem interval (PMI) of human bones

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Morning Session II, January 18, 2024, 11:20 - 13:00

In order to improve the evaluation of the post-mortem interval (PMI) of human bone, experts in forensic anthropology from the french national gendarmerie are interested in new characterization methods and in particular non-destructive testing (NDT). If Nile Blue colorimetry methods currently allow dating up to a hundred years, these techniques alter the bone which is evidence in a criminal investigation. In order to avoid this degradation, the work presented hereby proposes a method for characterizing PMI using ultrasonic methods that have proven successful for the NDT of complex materials, including bones in medical applications. The objective is to identify relevant ultrasonic parameters representative of PMI.

The propagation velocities of compression and shear waves are measured through parallelepiped samples of cortical bone taken from human femurs while respecting the anatomical orientation of the bone. These measurements carried out in the 3 directions of space make it possible to calculate the diagonal coefficients of the stiffness matrix Cijkl. Measurements of the propagation velocity of compression waves are carried out in transmission, using PinducersTM transmitter/receiver immersed in water. The measurement of shear wave velocities is made via a second non-immersed device using contact transducers. The results presented come from ultrasonic signals measured on bones, coming from individuals with similar pre-mortem parameters, whose PMI varies between 1 and 50 years. The six diagonal coefficients of the stiffness matrix are represented and discussed in terms of the PMI. A first classification of bones is possible according to their PMI. In order to assist the analysis and interpretation of the results, a single parameter is proposed, the Trace of the stiffness matrix (Tr(Cijkl)), confirming the possible contribution of the ultrasonic techniques to be used for the dating of human bones.

# Detection and imaging of BVIDs in composite plates.

**Pierre Goislot**[1], Guillemette Ribay[1], Emmanuel Moulin[2], Lynda Chehami[2]
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Afternoon Session IV, January 18, 2024, 15:50 - 17:26

Detection and imaging of BVIDs in composite plates.

Composite materials are increasingly used in the aerospace industry. However, they may be subjected to Barely Visible Impact Damages (BVIDs). BVIDs can occur during maintenance phases or during flight and are almost impossible to detect with the naked eye. Although very small, these defects greatly weaken the structure and present a significant safety risk if they are not detected early enough. Currently, very high frequency non-destructive testing methods can be used for BVIDs localization but involve immobilizing the aircraft. In addition, some parts are difficult to access. This explains the growing interest for Structural Health Monitoring or SHM in the industry. Indeed, the objective is to integrate the sensors throughout the life of the aircraft and to carry out control in near real time. This makes possible to increase the frequency of inspections while reducing costs.

Most aeronautical parts have plate-like geometries, and are therefore commonly inspected using ultrasound guided waves. Guided waves have the advantage of propagating over long distances, but are rapidly attenuated at high frequencies in composite materials. Linear methods require a sufficiently small wavelength relative to the defect size and are sensitive to high-frequency heterogeneities. Furthermore, the microcracks created by BVIDs are partially closed and therefore difficult to detect with linear methods, even at high frequencies. Hence, we propose to use low frequency guided waves non-linear methods. In order to precisely locate defects, it is necessary to take the dispersive nature of guided waves into account. A Beam Forming algorithm with dispersion compensation in very anisotropic media is presented. In a first step, the algorithm has  been validated numerically and experimentally in a linear imaging version for both A0 and S0, respectively from data simulated with the CIVA software and with measurements on a CFRP composite plate, in the frequency range 10kHz-90kHz. Then this algorithm will be adapted to the non-linear case with a pump-probe type setup, and evaluated on impact defects (BVID created by compressed air impactor).

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# Reconstruction of layer structure of composite materials by reverse time migration

**Lily Tu**[1], Jie Zhang[1], Alberto Gambaruto[1], Paul Wilcox[1]
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Afternoon Session III, January 18, 2024, 14:30 - 15:30

Laminated composites such as carbon fibre reinforced polymers (CFRP) have seen increased usage as structural materials, especially in the aerospace industry. Non-destructive evaluation (NDE) of the material post manufacturing or in-service is important for ensuring the safe operation. Defects such as wrinkles arise in the manufacturing processes greatly reduce the mechanical properties of the affected region. Therefore, it is motivated to accurately reconstruct the internal structure of composite laminates to characterise the severity of wrinkles if present.

Ultrasonic phased arrays are considered to be one of the most widely used and robust NDE methods for composites. However, imaging of CFRP has always been challenging due to the complexity of the material, which includes wave propagation in anisotropic layered media, and high structural noise due to multiple ply reflections. Conventional delay-and-sum imaging algorithms such as the total focusing method (TFM) calculates the image intensity from the travel time of the ultrasonic waves, based on the assumption that rays go in straight lines. However, this assumption is only valid in special cases where the anisotropy is homogeneous and translationally invariant. Therefore, it can be difficult for TFM to accurately resolve the internal structure in any scenario with ply curvature or ply drops causing curvature and/or refraction; this includes curved composites, thick-section composites with ply drops and tapers, as well as defects such as wrinkles.

This work proposes the use of reverse time migration (RTM), a technique widely used in seismology, for the reconstruction of internal structure in CFRP. Ray-based imaging such as TFM requires a forward model that predicts ray-paths and travel times, which is challenging to implement if the paths aren't straight; RTM on the other hand does not require explicit ray-tracing and can instead use any numerical model of wavefield propagation, such as finite element (FE). The RTM process involves correlating a forward wavefield, which is a FE model propagating a toneburst as the excitation signal, and a reverse wavefield, which backpropagates the time-reversed measured signal in the same FE model. A computationally efficient way of implementing RTM was developed, so that the reverse model can be obtained from the forward model, without running the same FE simulations again. RTM was demonstrated to have similar imaging ability to TFM by using a simulated point scatterer in an isotropic media, and the difference is that RTM inherently incorporates the transducer directivity, but the default unweighted TFM does not. This means RTM produces images equivalent to TFM multiplied by transducer directivity. RTM was also applied to FE simulated CFRP data with wrinkles.

# A non-linear delayed resonator for mimicking the hearing haircells

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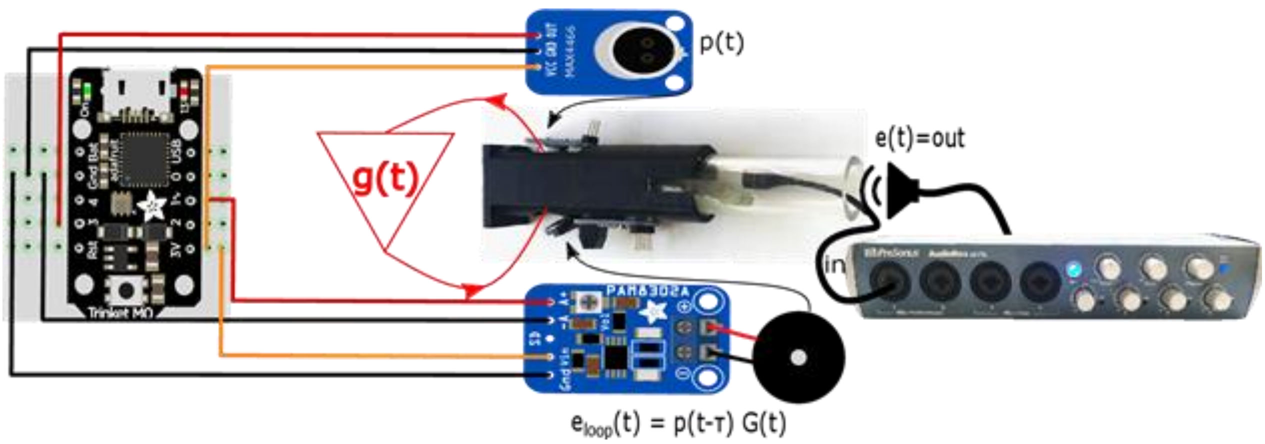
Afternoon Session I, January 17, 2024, 14:00 - 15:36

The hearing system is remarkable, possessing super sensitivity and the ability to discern specific frequencies. However, these characteristics can sometimes lead to imprecise responses due to nonlinear effects that we do have in our ears. The active behavior observed may be attributed to the hair cells as suggested by studies and real-life observations. These hair-cells seem to function like critical oscillators near a critical point known as Hopf bifurcation. To comprehend this better, we designed a delayed Hopf resonator. Upon studying its behavior, we noted striking similarities to the functioning of our ears. We identified two effects resembling those present in hearing: the masking effect and the emergence of phantom tones. After a careful characterization of our single non-linear resonator, we have performed experiments where the resonator is stimulated with two tones excitation in order to reproduce these two effects. These findings will bolster our confidence in hearing theories associated with the Hopf bifurcation (Jana Reda, 2023).



# Exploring the limits to quantitative elastography: supersonic shear imaging in stretched soft strips

Alexandre Delory, Daniel Kiefer, Claire Prada, **Fabrice Lemoult**[1]
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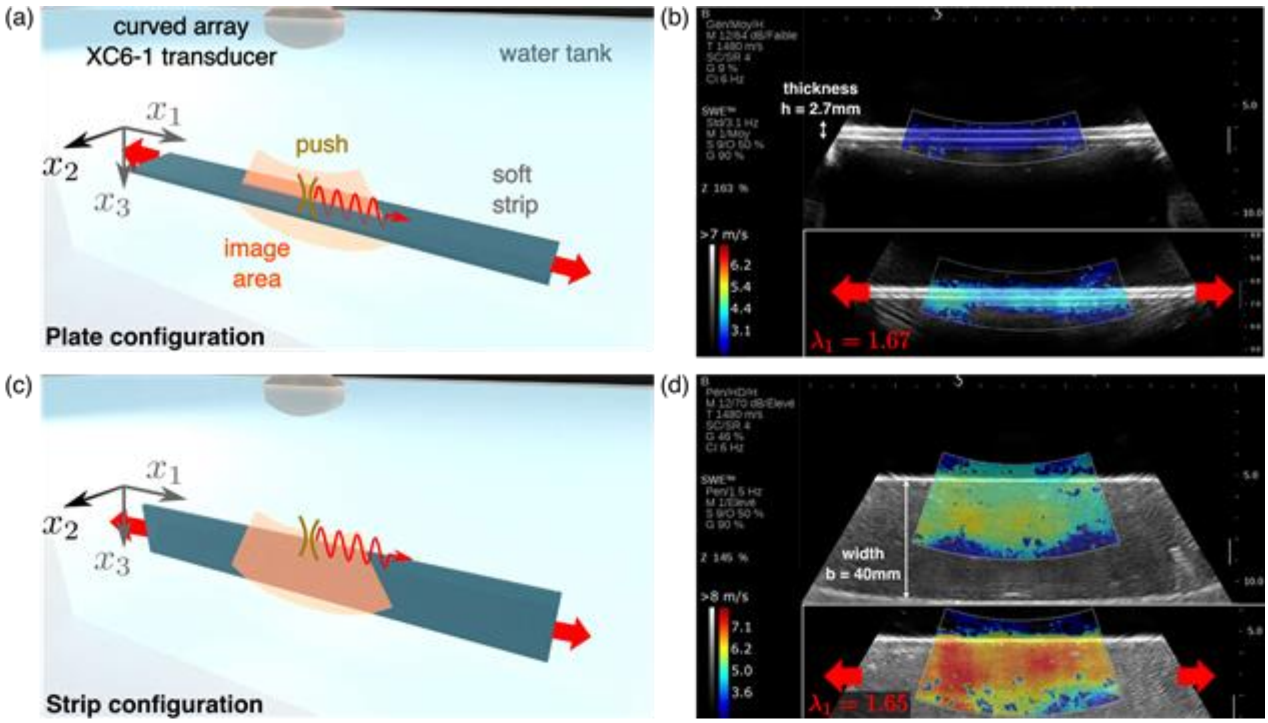
Afternoon Session I, January 17, 2024, 14:00 - 15:36

Shear wave elastography has permitted to bring quantitaveness in ultrasound medical imaging by measuring tissues' stiffness. Nevertheless, this method still suffers from some limitations due to viscoelasticity, guiding geometry or static deformations. To explore these limits, a nearly-incompressible soft elastomer strip is chosen to mimic the mechanical behaviour of an elongated tissue. A commercial supersonic shear wave scanner measures the propagation of shear waves within the strip. Repeating the experiment on the same sample for different orientations and applying a static deformation, the scanner cannot find a single shear wave velocity but provides a wide range of values from 2 to 6 m/s. After evidencing the waveguiding effect, the spatio-temporal Fourier transforms on the raw data allow to extract their dispersion diagrams. We provide a theoretical model which accounts for the static deformation and permits to retrieve the sample's mechanical parameters, including its rheology and hyperelastic behaviour. To overcome some limitations of current elastography, we propose a method which allows to characterize jointly the viscoelastic and hyperelastic properties of soft tissue, paving the way for robust quantitative elastography of elongated tissues.



# Through-aberration accurate ultrasound focusing with SelF-EASE method

**Samuel Rodriguez**[1], Garance Sauderais[1], Adrien Arnaud[1], Alexandre Duboué[1]
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Morning Session I, January 18, 2024, 09:30 - 10:30

In 2016, the Selective Focusing through identification and Experimental Acoustic Signature Extraction (SelF-EASE) method [S. Rodriguez et al., Ultrasonics 68, pp. 8–16] was presented and its strong potential for accurate ultrasound focusing possibilities assessed with numerical experiments. It consists in: (i) using a transducer array for building a sonographic image following the topological imaging procedure; (ii) modifying the image to keep the identified target alone; (iii) applying an image inversion procedure to retrieve the acoustic signature and (iv) emitting the time-reversed acoustic signature to achieve focusing. The main advantage of the method is that the extraction procedure of the experimental signature is efficient even if the original image is distorted due to inaccurate medium properties or to the presence of heterogeneities not taken into account in the image construction. Thus, time reversing the signature is expected to lead to accurate focusing even with a poor knowledge of the medium. In the present work, real experiments are performed on an aluminum test sample for demonstrating the improved SelF-EASE signal extraction procedure. The improvements made in comparison to [S. Rodriguez et al., Ultrasonics 68, pp. 8–16] allow a more robust and quicker inversion procedure for retrieving the acoustic signature of the target. The method is also experimentally performed through an aberrating medium composed of a 3D-printed human skull model immersed in water. The 2D focusing patterns are measured with a hydrophone and compared. The results show that SelF-EASE method allows much better accuracy comparing to time of flight methods without any further knowledge on the surrounding medium. In particular, the aberrating medium geometry and properties do not need to be taken into account.

# Zinc Oxide Thin Film as a candidate for Lead-Free Ultrasound Transducers

**Claire Thring**[1], Manuel Pelayo Garcia[2], Blair Rocks[1], Kevin McAughey[1], Daniel Irving[1], Dave Hughes[1]
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Morning Session IV, January 19, 2024, 11:30 - 13:00

Research into lead-free piezoelectric materials has been driven by regulatory pressures and environmental concerns due to the toxicity of lead used their manufacture. The challenges in this field revolve around finding materials that not only match the piezoelectric performance of lead-based counterparts but also ensure stability, scalability, and cost-effectiveness for their intended applications.

A number of materials, based on adding dopants to existing piezoelectrics such as potassium sodium niobate (KNN), bismuth titanate (BiTO) and barium titanate (BTO), have shown promising piezoelectric properties (d33 ~ 500-600 pC/N) while being biocompatible for medical applications. However, commercially available options are closer to 100 pC/N. This is because these materials suffer from poor temperature stability and complex, low consistency manufacturability due to phase impurities, grain boundaries, and sintering difficulties.

Thin film ultrasound materials present an alternative lead-free option. This research demonstrates a proprietary zinc oxide technology as a promising candidate for multiple applications. It is created using magnetron sputtering, and so does not require poling as it is manufactured in the desired Wurtzite structure. As such, it exhibits exceptional stability and temperature resilience. A multilayer resonator composition of the thin film is utilised to get usable frequencies in the 10 – 50 MHz range, giving both exceptional bandwidth and high resolution for detailed imaging. The full stack is still <0.1 mm in thickness and so has high flexibility for applications with complex geometries, while still being durable to repeat flexing.

This thin film is then further demonstrated built into sensors with capability in both biomedical and industrial applications. Rapid fabrication for scalable, cost-effective production of 260um – 1mm pitch array transducers is presented, and the performance tested with both metals and tissue mimics.

Conventional thin films such as AlN, ZnO and PVDF are often dismissed as a potential lead-free alternative, especially for low contrast tissue imaging in medical applications, due to their low d33 (~30 pC/N). Recent work has demonstrated the potential to drastically improve this, closing the gap between ZnO and competitor materials such as KNN, without sacrificing the associated scalable manufacturing and flexibility. This research demonstrates a ZnO thin film with controlled porosity and a glancing angle deposition creating a d33 three times that of standard ZnO.

In conclusion, the study demonstrates the potential of ZnO thin films as a viable alternative for lead-free ultrasound transducers, offering promising prospects for the advancement of environmentally friendly and biocompatible imaging technologies.

# Materials with elastic membranes : negative acoustic density

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Afternoon Session II, January 17, 2024, 16:00 - 17:36

Metamaterials are structured materials that exhibit unique wave propagation behaviours arising from their microstructure. Among the frequently discussed exotic properties of metamaterials are negative constitutive parameters, such as negative permeability and/or permittivity in electromagnetism, as well as negative density and/or compressibility in acoustics.
It seems that the concept of « negative density » is generally the most difficult to accept at first sight, because it is hard to imagine a negative gravitational density. However, in acoustics, this refers to an inertial density, which can be negative without any conceptual difficulty. In a recent theoretical study, we introduce a straightforward system to better understand the emergence of negative density, representing an elastic response interpreted as an inertial response [1]. This system yields analytical equations and can serve as a simplified model capable of qualitatively reproducing the acoustic behaviour observed in various existing membrane metamaterials [2, 3, 4].

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# Towards a 3D-printed acoustic sensor inspired by hair-like structures of arachnids and insects

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Afternoon Session I, January 17, 2024, 14:00 - 15:36

Biological studies of the different sensing methodologies in insects in the past century gave an understanding of the plethora of different sensory methodologies present in insects that react to acoustic stimuli [1]. Among these, the trichoid sensilla is of particular interest because by a change of the hair structure, or stiffness of the basal area, the sensilla can be tuned to a specific low frequency, near field sound, and are present in different insects and arachnids [2]. Additionally, it is believed that from this sensilla other sensing capabilities are derived, such as airflow, acceleration [2, 3] and, maybe, even odour [3, 4] and infrared sensing [5].
This research aims to replicate a similar approach to develop 3D-printed sensors that would allow filtering of different frequencies at the acquisition phase, i.e., cancelling the need for computational processes like the Fast Fourier Transform (FFT) to determine the frequency content of a sound after acquisition. This has been proved possible in previous research [6], where, by changes in the structure (shown in Figure 1), the hair could react to different narrow frequency-bands when stimulated by a periodic chirp. Study with an X-ray microCT scanner found that the 3D-printer hair sensors have very fine dimensional tolerances. Following this, improvements to the manufactured sensors have been made. This work presents results (Figure 2) obtained by the same testing conducted in [6], with new, more accurate, 3D-printed sensor structures. Moreover, COMSOL simulations showed an absolute mean error in the peak frequency of 5.1%, with a maximum of 14.2% and a minimum of 0.3%.

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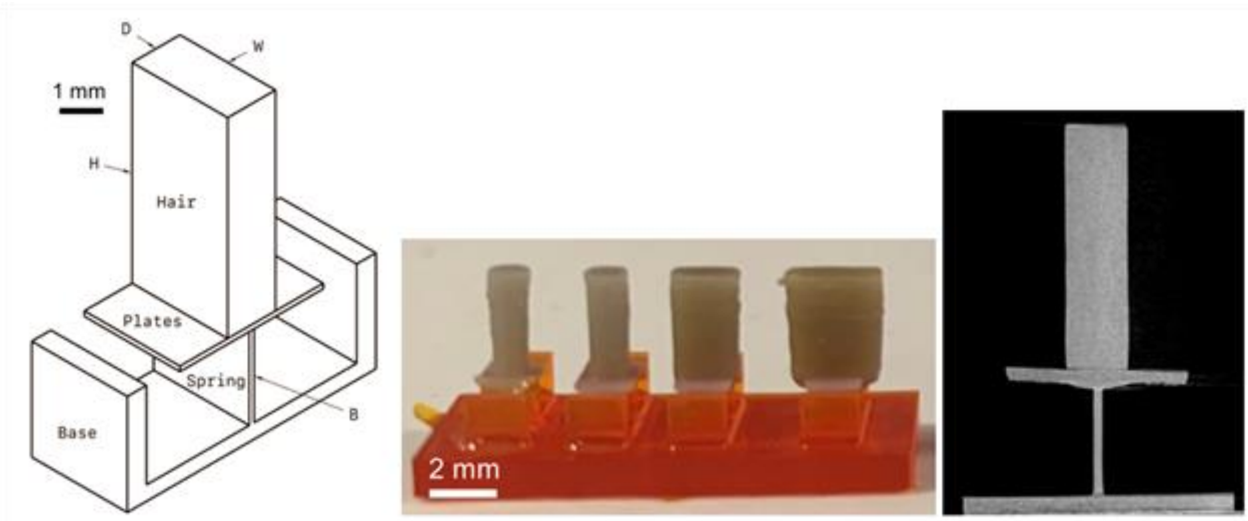


*Figure 1: Design of the proposed sensor structure (left), structure printed for hair shape testing (centre), X-ray microCT scan of an accurately printed hair (right).*

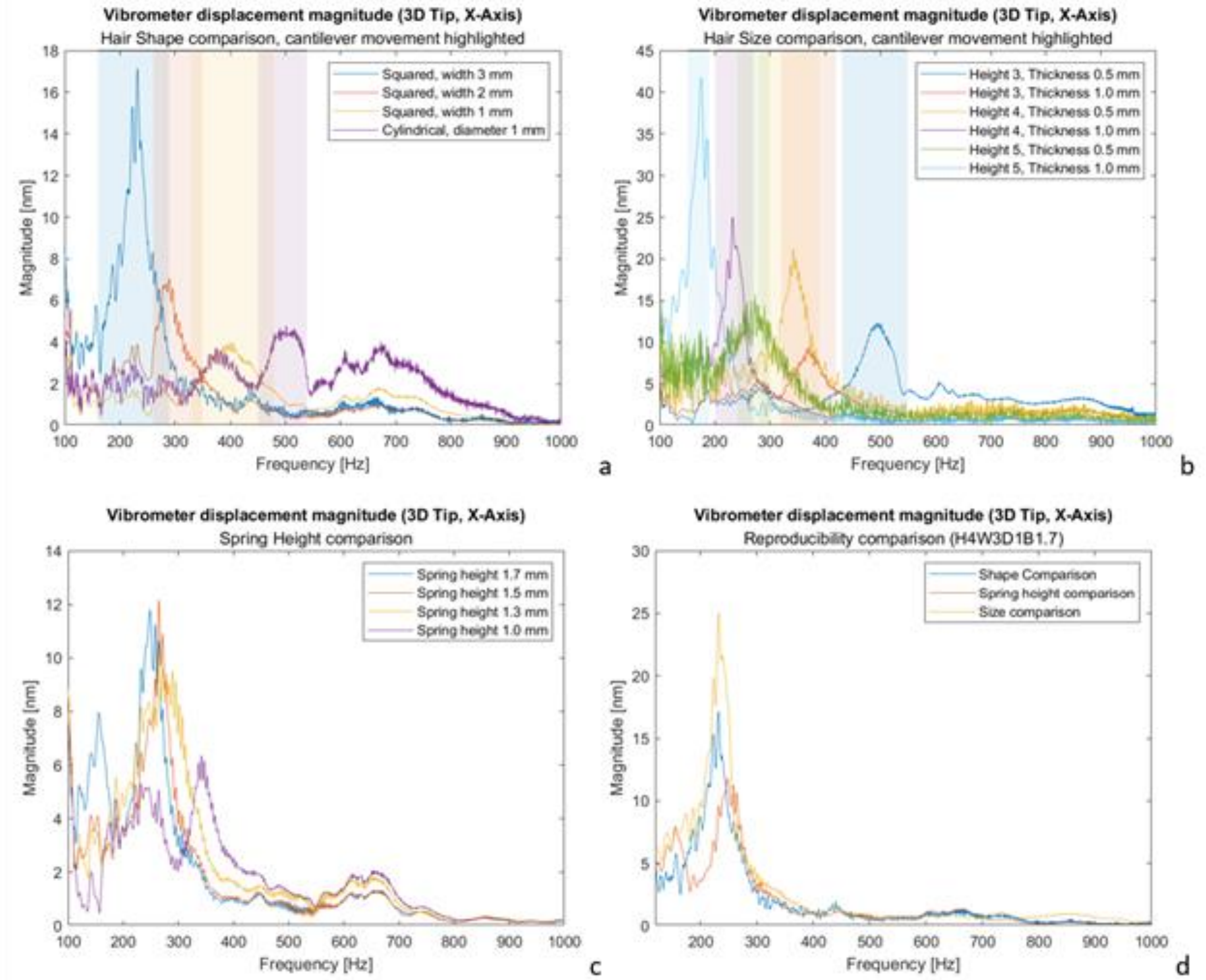


*Figure 2: Displacement of the tip of the hair sensor in the X-axis recorded with a Laser Doppler Vibrometer (LDV). Hair shape comparison (a), hair size comparison (b), spring height comparison (c), and reproducibility comparison (d) experiments.*

# Evaluating the physical limits of acoustic holograms for transcranial brain applications

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Afternoon Session I, January 17, 2024, 14:00 - 15:36

## Introduction

Acoustic holography is the process of recording a sound wave interference pattern and reconstructing it through a 3D-printed lens attached to a single-element ultrasound transducer. This process reconstructs the desired pressure field on an image plane [1]–[3], overcoming phase aberrations and defocusing effects caused by refraction in heterogenous media, such as the skull [4]. Acoustic holography is currently being evaluated as an affordable and personalized way to improve targeting in ultrasound-mediated brain therapies. The first in vivo demonstration of acoustic holograms established that blood-brain barrier (BBB) opening can be achieved in two foci simultaneously [5]. However, the physics limits of bifocal targeting have not been yet evaluated.

## Methods

K-wave was used to simulate an isotropic grid with 5 points per wavelength for a curved transducer (H-204, 1.68 MHZ; Sonic Concepts) and a flat transducer (0.5 MHz, 44 mm aperture size; Precision Acoustics). A time reversal method was used to design a phase-only holographic lens [5], which was manufactured using a FormLabs 3B+ resin printer. A convergence test was used to prove the simulation robustness and stability. The simulations were then used to investigate the computational and physical limits of the holograms.

## Results

For a bifocal flat lens, the optimal distance between two foci was roughly half the lens aperture (15-25 mm). However, larger distances of up to 100 mm can be achieved with an error <10.5%, shown in the figure part (c). The flat transducer gave an error of 3.2% for two foci 10 mm apart, whereas the higher frequency curved transducer gave an error of 1.4%. Focus diameters (2–28 mm) were also investigated for the flat transducer; an increased focal diameter resulted in an exponential loss of precision, as shown in part (d) of the figure. A larger focus size is useful for medical applications since this increases the size of the treatment area, reducing the number of procedures needed to treat large volumes. We estimated that the focal size can be enlarged by up to 2.8 times, without considerable loss of focusing quality.

## Discussion

This work evaluated the physical limits of bifocal targeting using transducers relevant to preclinical BBB opening. Flat transducers could be used for faster lens design and more complex fields; however, the focused transducer is well-suited to in vivo experiments requiring high-precision focusing. Future work includes designing holograms to target different structures in the mouse brain, and consequent in vivo testing. Holograms are expected to target complex brain structures more precisely and improve control over brain therapies, such as BBB opening and targeted drug release.

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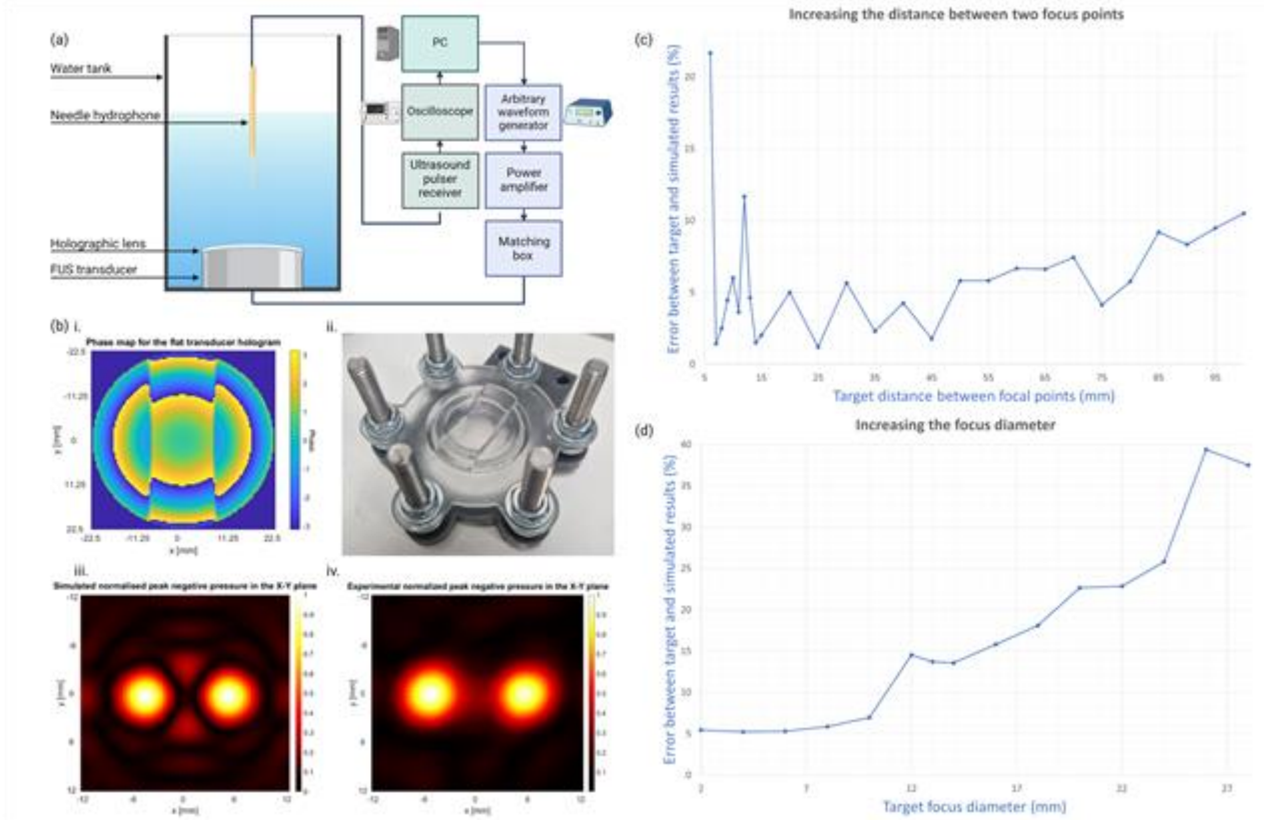
(a)
Water tank
Needle hydrophone
Holographic lens
FUS transducer
PC
Oscilloscope
Arbitrary waveform generator
Ultrasound pulser receiver
Power amplifier
Matching box
(b) i.
Phase map for the flat transducer hologram
ii.
iii.
Simulated normalised peak negative pressure in the X-Y plane
iv.
Experimental normalized peak negative pressure in the X-Y plane
(c)
Increasing the distance between two focus points
Error between target and simulated results (%)
Target distance between focal points (mm)
(d)
Increasing the focus diameter
Error between target and simulated results (%)
Target focus diameter (mm)

# Characterisation of a Lead-free Piezoceramic using a Hybrid of Techniques

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Morning Session IV, January 19, 2024, 11:30 - 13:00

The piezoelectric material is the driving component of a power ultrasonic transducer. To design an ultrasonic transducer using finite element analysis (FEA), the elastic-piezoelectric-dielectric (EPD) properties of the piezoelectric material are required inputs and therefore must be determined. Lead-based piezoceramic is the piezoelectric material predominantly used in power ultrasonic devices due to its high piezoelectric constants [1]. Nonetheless, the adverse effect of lead on human and environmental health, and legislation relating to its use, has led to an increase in research to provide lead-free piezoelectric materials [2] as an alternative driver material. Therefore, the characterisation of emerging lead-free piezoceramics to determine their EPD properties is essential. In this study, the EPD matrix of a lead-free piezoceramic (Na0.5Bi0.5)TiO3-BaTiO3 (also known as NBT-BT) (Pz12, CTS Ferroperm, Denmark) was fully populated by characterisation using a combination of the IEEE technique and the Levenberg–Marquardt (LM) optimisation algorithm.

Only samples with three of the four resonant mode geometries were available for characterisation using the IEEE technique because of poling challenges. The three resonant mode samples and dimensions, shown in Fig. 1 and Table 1 respectively, were characterised using an Impedance Analyser (Agilent 4395A, Keysight Technologies, USA) to obtain their impedance magnitude and phase data. Then, using the Piezoelectric Resonance Analysis Program (PRAP), a commercial curve fitting software, corresponding EPD constants were obtained from this experimental data. These results from the IEEE technique were then used as input to the LM optimisation algorithm. Thereafter, the miniature sample shown in Fig.1 with dimensions estimated from FEA, was diced from the LTE mode sample. By combining the miniature sample's impedance magnitude measurement, EPD constants estimated from the IEEE technique, and an optimisation algorithm based on the Levenberg-Marquardt method, characterisation of the NBT-BT piezoceramic was carried out. The NBT-BT is a piezoceramic with C∞/6mm symmetry, therefore, the EPD matrix contains ten components namely, five elastic, three piezoelectric and two dielectric constants. Using the hybrid characterisation technique, the EPD matrix was fully populated.

The EPD properties determined from both techniques align with those of similar piezoceramics available in the literature. The piezoelectric and dielectric constants in particular are very closely matched, whereas the elastic constants had differences ranging from 1–6%.

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Figure 1: Piezoceramic Samples for Experimental Characterisation

| Name | Dimension [mm] |
|---|---|
| Radial/TE (disc) | d = 20; t = 0.5 |
| TS | l = 10; w = 10; t = 0.94 |
| LTE | l = 10; w = 3; t =1 |
| Miniature | l = 1; w = 1; t = 1 |

TE=thickness extensional; TS=thickness shear; LTE=length thickness extensional

Table 1: Pz12 dimensions; poling direction in red

# Machine learning for real-time inversion of locally anisotropic weld properties using in-process ultrasonic array measurements

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Morning Session II, January 18, 2024, 11:20 - 13:00

Many welds exhibit significant local anisotropy due to their elongated grain structure. Ultrasonic inspection of these anisotropic materials is challenging as the variations in sound speed alter the direction of acoustic propagation within the component. This is detrimental to the quality of ultrasonic array imaging, as without accurate knowledge of the local anisotropic properties precise focusing cannot be achieved. A common approach to remedy this issue is to use lower frequencies (<3MHz) and/or techniques that do not require focusing in reception such as sectorial scanning and time-of-flight diffraction. However, to leverage the high spatial resolution ultrasonic array imaging can provide, knowledge of the weld's local anisotropy is required.

This paper aims to improve ultrasonic array based inspection of anisotropic welds by mapping local variations in anisotropy. This has been achieved previously with iterative solvers such as Markov Chain Monte Carlo methods (Tant et al., 2020) (Zhang et al., 2012) and genetic algorithms (Fan et al., 2015) but these involve repeated running of forward simulations, making them computationally intensive, precluding their use for in-process inspection. Building on the work of (Singh et al., 2022) real-time inversion is achieved in this paper by training a neural network to invert for the grain orientations in the weld using time-of-flight (TOF) measurements. The 32x32 TOF matrices are measured after each layer of weld deposition using two arrays, in tandem, positioned either side of the weld. The neural network is trained on data simulated using the anisotropic locally interpolated fast marching method (ALI-FMM) (Ludlam et al., 2023). Performance is measured in two ways. Firstly, by comparing the predicted and true grain orientations where ground truth is available, and secondly, by using the predicted orientations to calculate anisotropic travel time maps and observing the improvement in image quality compared to imaging with an assumption of isotropy.

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# Development and simulation of high-temperature ultrasonic transducers with porous metal backing

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Morning Session IV, January 19, 2024, 11:30 - 13:00

Most of the standard ultrasonic transducers are based on the use of lead zirconate titanate piezoceramic that converts the electrical signal into an ultrasonic signal and conversely. Very often, this piezoelectric element is bonded on a backing material the role of which is to absorb the ultrasonic wave generated on the rear face of the active element and to damp the vibration. Both backing material and active element are limited in temperature. Indeed, the first one is generally based on a polymer powder composite, and the second one is limited by the Curie temperature. In order to face these limitations, high-temperature ultrasonic transducers are based on high Curie temperature piezoelectric crystals, such as Lithium Niobate (LiNbO3). Nevertheless, due to the lack of passive elements that can withstand high temperatures, the electro-acoustic performances of these transducers are still constrained and therefore lead to a limitation of their applications to telemetry. The goal of this research is to develop a high attenuating backing made of porous metal that can absorb a part of the energy generated by the piezoelectric element, hence broadening the bandwidth and raising the axial resolution of these transducers.

First, the acoustic properties (velocity attenuation and acoustic impedance) of porous stainless steel backing ranging from 25% to 50% of porosity were determined at an ambient temperature and a high temperature up to 400°C by ultrasonic measurement methods. Results reported show that stainless steel materials are good candidates for backing in a high-temperature transducer.

Based on these results, the electroacoustic response of several high-temperature ultrasonic transducers was simulated with the equivalent one-dimensional KLM model. The transducers are made of a Z-cut lithium niobate single crystal mounted on porous backing, with respectively 25%, 35% and 45 % of porosity with a 1.2 mm thick protective front face.

Based on these simulations three prototypes of transducers with various porous backing were fabricated and characterized. Experimental pulse-echo responses were compared to the simulations and were found in relatively good agreement. Both theoretical and experimental results show a strong increase of the axial resolution. While the conventional transducer -6dB axial resolution in water was close to 50 mm, it now ranges from 2 mm to 5 mm depending on the selection of the porous backing.

As a conclusion, this new design allows these transducers to be used for imaging and/ or Non-Destructive Testing and Evaluation at high temperatures.

The authors wish to thank Mathieu Jean for the manufacturing and characterization of transducers and Louis-Pascal Tran-Huu-Hue for providing KLM software.

# Simultaneous ultrasonic and rheological monitoring of medium density polyethylene with temperature in a rheometer

**Nesrine Houhat**[1], Laksana Saengdee[1], Thibaut Devaux[1], Samuel Callé[1], Séverine Boucaud Gauchet[1], François Vander Meulen[1]

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Morning Session II, January 18, 2024, 11:20 - 13:00

This work is part of a project dedicated to the optimization of the rotomolding process of medium density polyethylene (MDPE) hydrogen tank liners. In this study, simultaneous ultrasonic and rheological measurements have been performed to correlate ultrasonic velocity with rheological properties of MDPE as a function of temperature. A specific acoustic instrumentation adapted to a parallel plate Anton-Paar dynamical rheometer (MCR302) has been developed.

It is composed of a high temperature 5MHz that is in contact, under a 4mm thick quartz plate supporting the tested material (Fig 1.a). The electrical impulse is generated by the pulser/receiver, then, transmitted to the transducer. The signal is received by the same transducer in echo mode and digitized by an oscilloscope. Simultaneously with ultrasound measurements, the rheological properties are measured at a controlled temperature and a controlled gap. The chamber is equipped with a parallel plate geometry of 25 mm diameter. The experiments were conducted during a temperature sweep with 5°C/min. Tests were performed in a temperature range from 160-200°C for heating step and from 200-115°C for cooling step. The gap between the quartz plate and the upper metallic plate was set initially to 1.2 mm. A preliminary preparation procedure of the MDPE has been achieved during the melting process to eliminate air bubbles.

To measure the MDPE echo time of flight (TOF) in the rheometer, two configurations have been considered; the first without the MDPE which gives the reference signal and the second with the MDPE layer. Given the low layer thickness, MDPE echo is overlapped with the quartz echoes making its detection difficult. A method based on the scaled subtraction of the reference signal propagating in the quartz plate alone is used to determine accurately the echo TOF is the MDPE. The temperature variations induce signals time shifts, amplitude and frequency variations which have been considered by shifting and scaling the reference signal.

Simultaneous measurements of ultrasonic velocity and complex viscosity $\eta^*$ have been achieved during heating and cooling step (Fig 1.b). During the heating (from 160°C to 200°C), a slow decrease has been observed for both parameters . During the cooling (from 200°C to 130°C), both velocity and complex viscosity show a slow increase. A fast increase can be noted from de 130°C to 115°C and 120 °C to 115°C for respectively an ultrasonic velocity and the complex viscosity. The ultrasonic velocity is an ultrasonic parameter that can be used to monitor the evolution of polymer viscosity with temperature. Ultrasonic parameters appear to be more sensitive to changes in polymer state, and would enable more accurate detection of the onset of polymer solidification. The study paves the way of ultrasonic real-time monitoring of the rotomolding process.

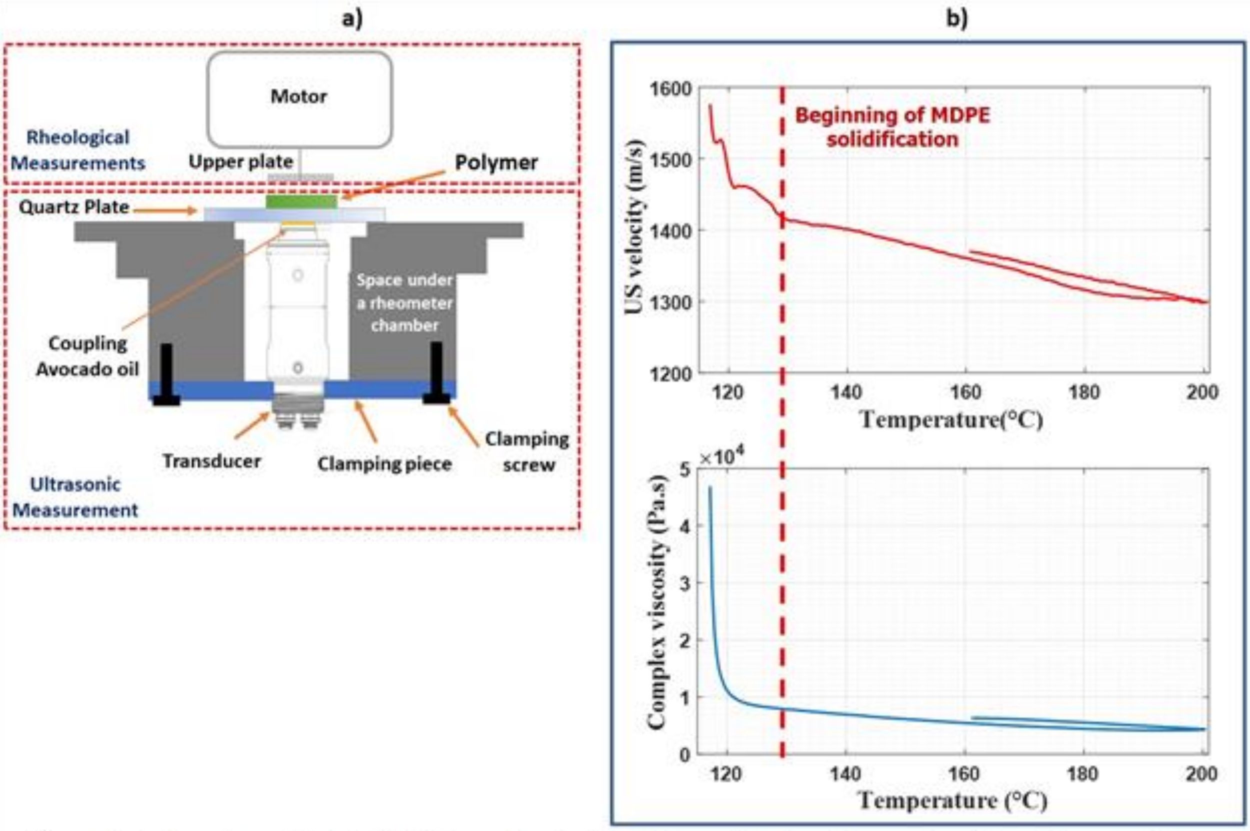


**Figure 1. a) Experimental setup b) Ultrasonic velocity and complex viscosity as a function of temperature**

# Acoustic amplitude of resonating bubbles

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Morning Session III, January 19, 2024, 09:30 - 10:54

Bubbles are well-known to be strong sources of sound, from the murmur of the brook [1] to the sound of rain on water [2]. While the frequency of the emitted signal has been extensively studied [3], there is less research on its amplitude. An interesting result is that bubbles injected from a nozzle make more noise the larger they are, while bubbles entrained by a droplet falling on a bath are noiser when they are smaller. An other difference is that the signal generated by the former starts with a depression, while that of the latter with an overpressure.

We did experiments on these two ways of producing bubbles, recording the acoustic signal with an hydrophone, and filming the birth of the bubbles with a high-speed camera. We found that the acoustic amplitudes could be well explained by considering that the bubbles behave as harmonic oscillators with initial velocities that could be measured on the videos.

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# Imaging of crystal degradation upon non-hydrostatic compression via time-domain Brillouin scattering

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Morning Session III, January 19, 2024, 09:30 - 10:54

Laser ultrasonics proves to be an invaluable technique for characterizing, evaluating, and imaging materials in extreme conditions, such as high pressures. Time-domain Brillouin scattering (TDBS) utilizes ultrafast laser pulses to generate and detect coherent acoustic pulses (CAPs) propagating through a transparent material at the probe laser wavelength [1-2]. In TDBS, the probe light scattered by the CAPs interferes with the probe light reflected on a stationary interface, resulting in a signal with Brillouin oscillations (BOs). The TDBS signal can also exhibit an echo if a CAP is reflected and transmitted through a material interface. Both BOs and echo features are employed for profilometry of (buried) interfaces [3-5], utilizing information from measurements at different lateral positions while scanning co-focused pump and probe beams.

A recent theoretical development in non-collinear sound-light interaction [6] offers the opportunity for interface profilometry without lateral averaging, providing a local estimation of the angle using a single measurement. This technique was applied to monitor the degradation of a lithium niobate (LiNbO3 – LN) single crystal under non-hydrostatic compression in a diamond anvil cell (DAC) [7]. The LN crystal, prepared from a nominally 20 µm-thick single-crystal disk (x-cut), showed modifications in its thickness profile and face profiles due to non-hydrostatic compression. The 3D TDBS imaging in the DAC revealed changes in the crystal inclination angles, estimated to increase by at least two orders of magnitude.

The developed analytical theory [6] allowed estimation of the inclination angle of the Ti-coated surface of the LN relative to the diamond anvil surface by fitting the experimental signals. This local assessment of inclination, revealed through modifications of BOs or detection of CAP echoes, complements the traditional use of BOs amplitude and frequency variation. The diverse TDBS signals gathered in this sample require further theoretical investigations to fully explain all waveforms, considering the optical and elastic anisotropy of LN and water ice. Performing TDBS experiments by analysing probe polarization would also complement our current analysis.

This research is supported by the Agence Nationale de la Recherche [project ANR-18-CE42-I2T2M].

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# The spin angular momentum of sound waves and its conversion in a simple scattering experiment

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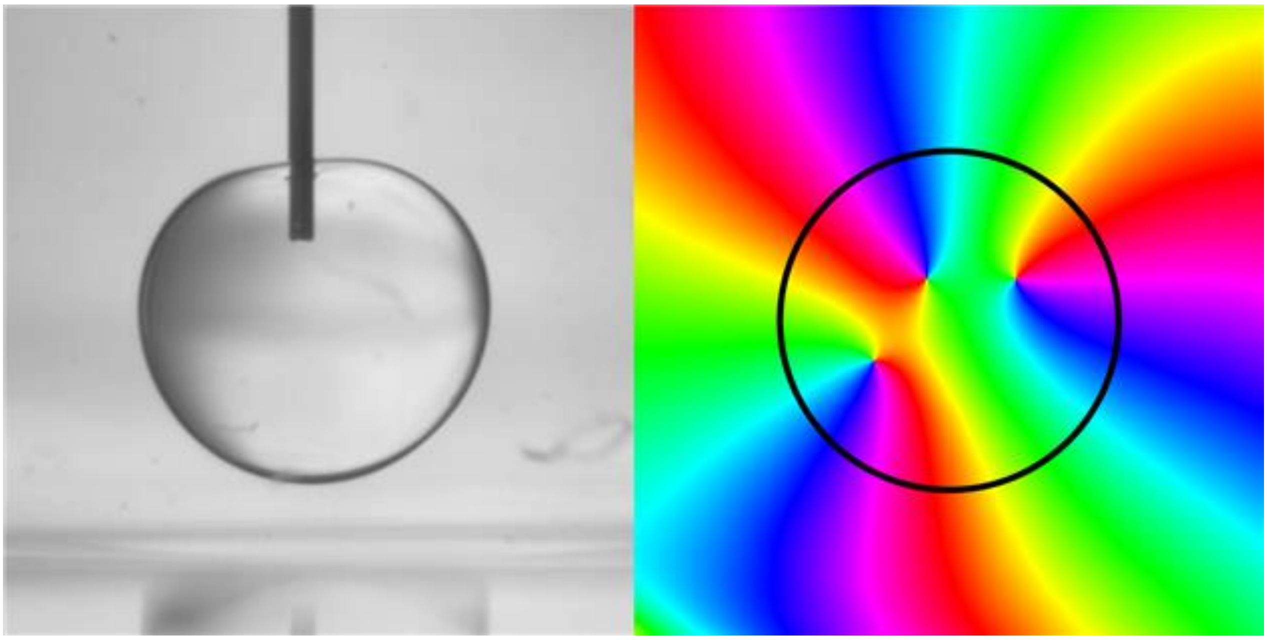
Afternoon Session II, January 17, 2024, 16:00 - 17:36

Sound and light waves are characterized by polarization properties that describe the direction of oscillations of the propagating physical field. Polarization properties also importantly set the amplitude and direction of the wave momentum - or pseudo-momentum in a material continuum - whose manifestation becomes clear when the wave interacts with an interface and exerts an average radiation force or torque. It is known for instance that transverse electromagnetic waves can be circularly polarized, carry spin angular momentum and exert a radiation torque on particles. Sound waves in contrast are purely longitudinal in a fluid, and are commonly thought to have trivial polarization properties and lack the kind of rotational degrees of freedom that give rise to angular momentum. While this holds true for homogeneous plane waves in which the medium particles oscillate back and forth in the direction of propagation, it has recently been realized that the polarization properties in any inhomogeneous wavefront are non-trivial and lead to the existence of acoustic spin angular momentum. Because inhomogeneous waves include many practical implementations of sound propagation such as focused beams, evanescent waves, interferences or vortex beams, the thorough investigation of their polarization properties and of the way their angular momentum is conserved and exchanged remains necessary.

We have observed and studied an acoustic process in which angular momentum is converted between its two forms: spin angular momentum and orbital angular momentum. The interaction between an evanescent wave propagating at the interface of two immiscible fluids and an isolated droplet was considered. The elliptical motion of the fluid supporting the incident wave is associated with a simple state of spin angular momentum. The evanescent wave predominantly forces an internal directional wave circling the droplet's circumference, revealing the existence of confined phase singularities. The circulation of the phase, around a singular point, is characteristic of angular momentum in its orbital form, thereby demonstrating the conversion mechanism. We will discuss the implications of this work for our fundamental understanding of the angular momentum of sound waves, and for applications such as particle manipulation with radiation forces or torques, acoustic sensing and imaging.



# Numerical study of a Fabry-Perot based elastic EAT system at MHz regime

**Jiacheng Chen**[1], Lionel Haumesser[1], Remi Rouffaud[1], Eun Bok[2], Marc Lethiecq[1], Oliver B. Wright[3], Thibaut Devaux[1]

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Morning Session I, January 18, 2024, 09:30 - 10:30

Keywords: EAT, energy focusing, metamaterial, simulations.

Since its first discovery in 1998 by T.W. Ebbesen[1], Extraordinary Transmission (ET) has aroused the interest of acousticians and opticians, as it offers the potential to concentrate more wave energy than geometric considerations[2], in sub-wavelength regions. The objective of this study is to develop an ET system for elastic waves operating in the MHz range. It provides a new feasible solution for sub-wavelength acoustic imaging applications. A three-dimensional EAT architecture is studied through a numerical model using the finite element method (FEM).

The EAT structure is based on the Fabry-Pérot resonance, complemented by a groove pattern[3]. Two blocks serving as the propagation medium, are connected by a cylinder functioning as a resonator, as shown by Fig1.a). The theoretical fundamental frequency, determined by the resonator's length and extensional velocity, is set at 667 kHz. Concentric grooves on the input side ensure wave conversion. The incoming longitudinal wave at the groove interface is converted into surface acoustic waves which are converging towards the pillar input.

To quantify the acoustic energy transmission T, the mechanical displacement is measured. The transmission efficiency, denoted as $\eta (f) = T^2(f)\alpha^2$, where $\alpha$ is the geometrical factor, is defined to indicate the level of the EAT phenomenon in the current setup.

As shown by Fig1.b), FEM results demonstrate, at f = 667kHz, $\eta = 0.75 < 1$ for no groove case, and $\eta = 5$ with input side grooves, i.e. more energy than geometrical consideration ($\eta > 1$). Adding a grooved structure at the input side has a significant impact on η, depending on the spatial distribution. Applications of this energy transmission enhancement include ultrasonic subwavelength microscopy.

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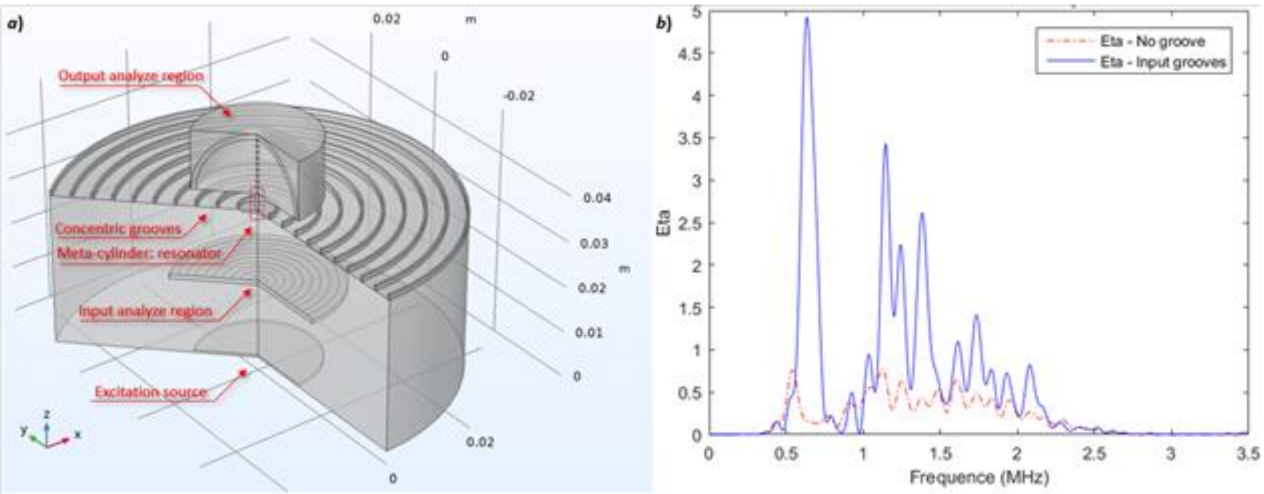


*Fig1. a) COMSOL 3D-model; b) Transmission Efficiency: no groove vs. input grooves*

# Unlocking Acoustic Chaos: Characterising the cavitation in a tube transducer with increasing drive amplitude

**Hilde Metzger**[1], Yikai Zhang[1], Paul Daly[1], Andrew Hurrell[2], Andrew Feeney[1], Andrea Cammarano[1], Paul Prentice[1]

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Morning Session III, January 19, 2024, 09:30 - 10:54

Lauterborn and Cramer's subharmonic route to chaos [1] was published over 40 years ago and yet the cavitation activity responsible for the spectral features reported, fig. 1 (a), are still not fully understood. Here, we revisit Lauterborn's experiment with enhanced acoustic detection and a high-speed camera to gain a better understanding of bubble dynamics. An in-house built tube transducer, with a radial resonance frequency at 15.5 kHz, is submerged in de-ionised water and excited with a linearly increasing input voltage to generate a bubble field within the bore. High-speed shadowgraphic imaging is undertaken at 80,000 frames per second, fig. 2, and data from a 4 mm needle hydrophone used to generate a spectrogram of the cavitation emissions, fig 1. (b).

Fig. 1 shows that spectral features in the acoustic data of this study, (b), are comparable to that shown in Lauterborn's paper, (a). Subharmonics at $f_0/2$, $f_0/3$ and $f_0/4$ are mediated by periodic shockwaves from the periodic collapse of the bubble clouds, as described by Song et al. [2]. The increasing broadband noise from 110-154 ms is attributable to a gradual dephasing in shock wave emissions from the bubble population, as the voltage is increased. The sudden reduction in broadband noise at 154 ms is due to phase-locking of the period-doubled oscillations.

Mathematical modelling with initial parameters informed by the experimentally observed cavitating system provides additional insights and validates the experimental results. A multi-bubble system including migration and coalescence is developed and programmed in MATLAB. Using the high performance computer cluster at the University of Glasgow with an allocation of 48 CPU-cores/96 threads supported by 512 GB of RAM, a minimum sampling time step of ~$1 \times 10^{-22}$ s is achieved. This means a higher resolution of spectral features than experiment can be reached. The post-processing of the results generates spectrograms with the same resolution as those presenting the experimental result permitting a direct comparison. However, higher resolution spectrograms can provide further spectral analysis without artificial issues such as aliasing.

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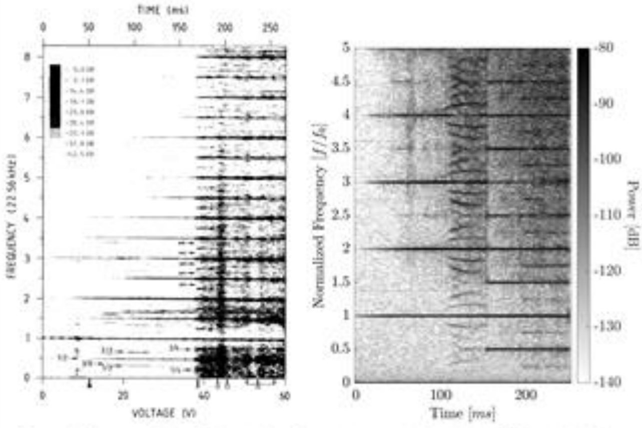


Figure 1: A comparison of Lauterborn's spectrogram a) and that of this study (b) which can be correlated to bubble activity captured by the high-speed imaging.

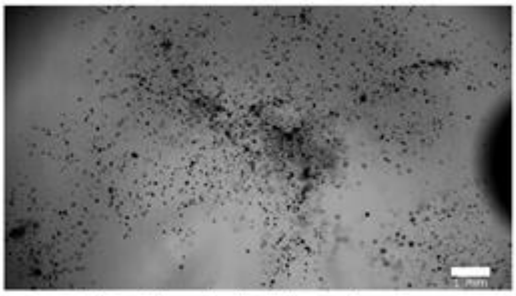

Figure 2: A single frame from the high-speed imaging sequence used to characterise the cavitation

# Elasticity and grain morphological characterization in polycrystalline materials using spatially resolved acoustic spectroscopy (SRAS++)

**Carolina Guerra**[1], Wenqi Li, Paul Dryburgh, Rafael Fuentes-Domínguez, Rikesh Patel, Richard Smith, Matt Clark
*[1]The University of Nottingham, United Kingdom*

Morning Session III, January 19, 2024, 09:30 - 10:54

Abstract
The elastic modulus provides vital insights into material behaviours, allowing the prediction of various critical mechanical properties for engineering components. Often elasticity measurements are done through destructive methods such as tensile strength, which provides a materials bulk behaviour without information relating to the crystallographic texture and grain orientation. To interpret the mechanical properties, it is necessary to complement the characterization using various techniques such as optical and scanning electron microscopy (OM and SEM) and electron backscatter diffraction (EBSD), among others. In essence, researchers need to employ multiple techniques to gain a comprehensive understanding, which is costly in terms of both time and equipment.
Spatially resolved acoustic spectroscopy (SRAS) is an acoustic microscopy technique that can image the microstructure, measure the crystallographic orientation of grains and estimate the elastic modulus of the material in one instrument. This non-destructive technique based on surface acoustic waves (SAW), works by measuring the surface velocity via the acoustic spectrum. Figure 1 shows its usual configuration where the SAWs are generated by laser using a pattern of lines and detected by laser at a point close to this grating-like source [1]. The use of the acoustic spectrum to measure velocity has several practical advantages, which make the technique robust and fast and give excellent spatial resolution. This makes the measurement suitable for imaging large areas and gives it advantages over traditional laser UT and microstructural measurement techniques.

Figure 1. A schematic of the SRAS operation - a surface acoustic wave is generated and detected using separate lasers, with the perturbation due to the wave picked up using a detector [2].

This provides a viable method to measure the elastic constants in real components, which are polycrystalline, large, and of different shapes. The main aim of the presentation is to review the experimental instrument, the inversion procedure (for calculating both crystallographic orientation and elastic constants) of a Ti alloy, and present recent experimental results with an outlook for future applications.

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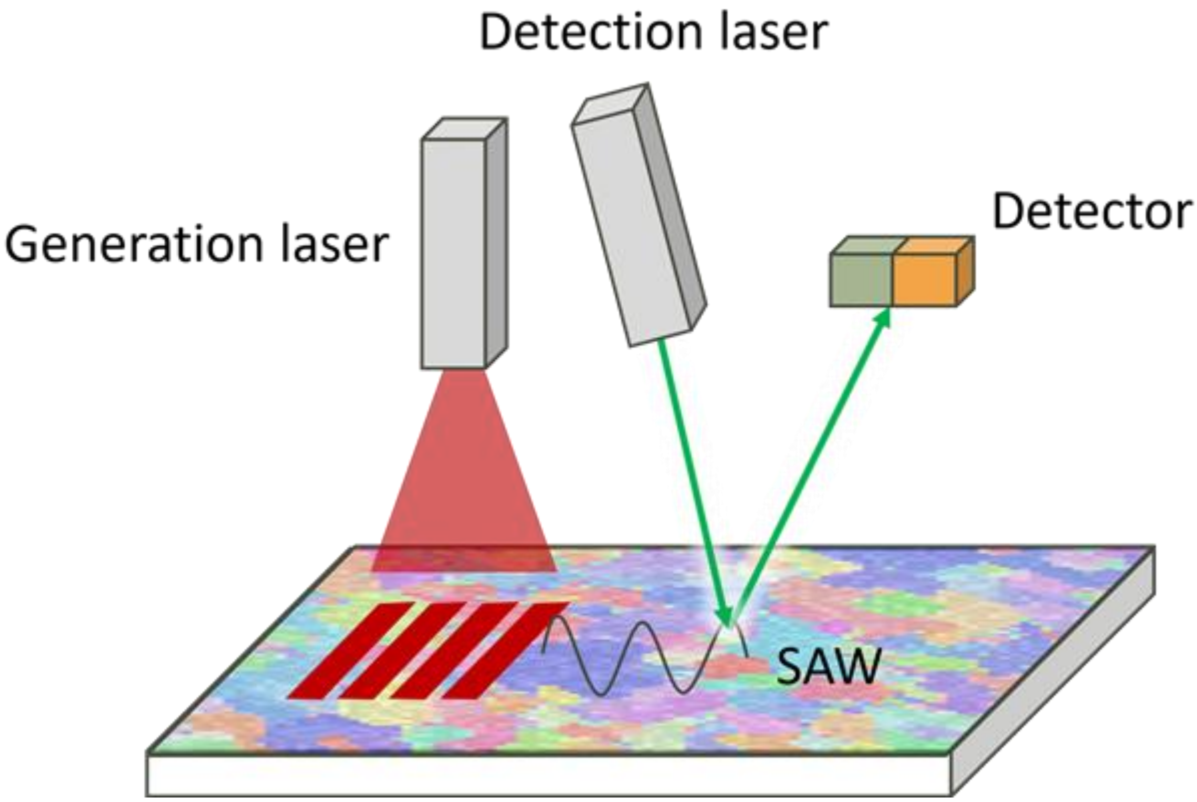
Detection laser
Detector
Generation laser
SAW

# OptimUS: a Python library for therapeutic ultrasound

**Pierre Gélat**[1], Elwin van 't Wout[2], Seyyed Reza Haqshenas[1], Nader Saffari[1]
*[1]University College London, United Kingdom, [2]Pontificia Universidad Católica de Chile, Chile*

Afternoon Session I, January 17, 2024, 14:00 - 15:36

Ultrasound has a growing number of therapeutic applications. These include the treatment of cancers of the prostate and of the liver, as well as uterine fibroids. Transcranial ultrasound neurostimulation is an emerging modality which may one day treat mental health conditions such as depression. Despite this, a set of standardised guidelines and recommendations for researchers using therapeutic ultrasound in humans has yet to be agreed upon. Key to this standardisation lies the validation of computational models simulating the propagation of ultrasound in heterogeneous media. Such models are expected to be crucial for treatment planning of therapeutic ultrasound and are expected to be vital to wider clinical adoption of this treatment modality. The numerical modelling of the propagation of ultrasonic waves in heterogeneous media presents several challenges, such as dense computational meshes leading to a high computational footprint. Furthermore, commonly used volumetric computational methods such as the finite element method, finite difference time domain methods and k-space pseudospectral methods, can suffer from numerical pollution and dispersion effects.

The boundary element method (BEM) employs the Green's function of the Helmholtz equation to reformulate the volumetric wave problem into a boundary integral equation at the interfaces of piecewise homogeneous domains embedded in free space. The numerical discretisation leads to a dense system of linear equations, whose computational footprint is reduced through hierarchical matrix compression. The convergence of the iterative linear solver is improved with a novel on-surface radiation condition preconditioner.

OptimUS is a Python library developed at University College London and Pontificia Universidad Católica de Chile. It incorporates the above developments in a user-friendly interface enabling the prediction of ultrasonic waves in piecewise homogeneous media in the frequency domain, with minimal numerical pollution and dispersion effects. OptimUS can significantly reduce run times relative to traditionally used volumetric solvers.

An overview of the OptimUS interface will be provided. Transabdominal and transcranial ultrasound focusing applications will be reviewed. Prospective solutions to address nonlinear wave propagation using boundary integral methods will be presented, as well as the implementation of detailed bone heterogeneity.

# Towards monitoring the state of charge of Li-Ion batteries using ultrasonic methods

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*[1]GREMAN UMR 7347 Laboratory, INSA - Centre Val De Loire, France, [2]GREMAN UMR 7347 Laboratory, Tours university, France, [3]LaSTI Laboratory, ENSA-Khouribga, Sultan Moulay Slimane University, Morocco*

Afternoon Session IV, January 18, 2024, 15:50 - 17:26

Due to global climate change, the use of fossil fuel must be reduced in the energy and transport sector, leading to an increasing need in battery storage. Different battery technologies exist but the Li-Ion ones have the highest specific energy density. Yet, this technology can lead to fire hazard if their use is not well controlled (mostly overcharging and thermal abuses), so a battery management system (BMS) is necessary.
Currently, most BMS rely on electrical parameters to estimate the state of charge (SoC) and state of health (SoH). In 2010, Redko [1] introduced an innovative approach utilizing ultrasonic wave propagation through the battery. This method estimates SoC by monitoring the variation in mechanical parameters across each layer during charge and discharge cycles, providing an absolute SoC measurement, in contrast to the relative measurements obtained through electrical methods.
In this work, we present the ultrasonic propagation wave modelling through the battery, including the porous layers and their variations, to calculate the theoretical reflection and transmission coefficients for an incident longitudinal wave. This model will be used in further works to estimate the SoC and the SoH of an unknown battery by solving an inverse problem.
A Li-Ion battery consists of cells containing cathode and anode materials, current material, electrolyte, and separator. The cathode utilizes aluminium foil, the anode employs copper foil, and the separator facilitates lithium-ion mobility. This model, utilizing Cervenka's formalism [2], computes theoretical reflection and transmission coefficients. It is expanded to porous materials by incorporating Biot's theory [3], adapting Allard's formalism [4].
By using the mechanical parameters of each layer taken from literature [5] in the simulation, the variation of these coefficients for the whole range of SoC can be calculated. The result shows that these parameters are sensitive to the SoC, mostly for low levels, whereas the use of the battery can lead to its premature ageing. Nevertheless, it can be observed that the transmission coefficient seems to be less sensitive at high levels of SoC, where the hazards appear, even if it can be retrieved by solving an inverse problem.

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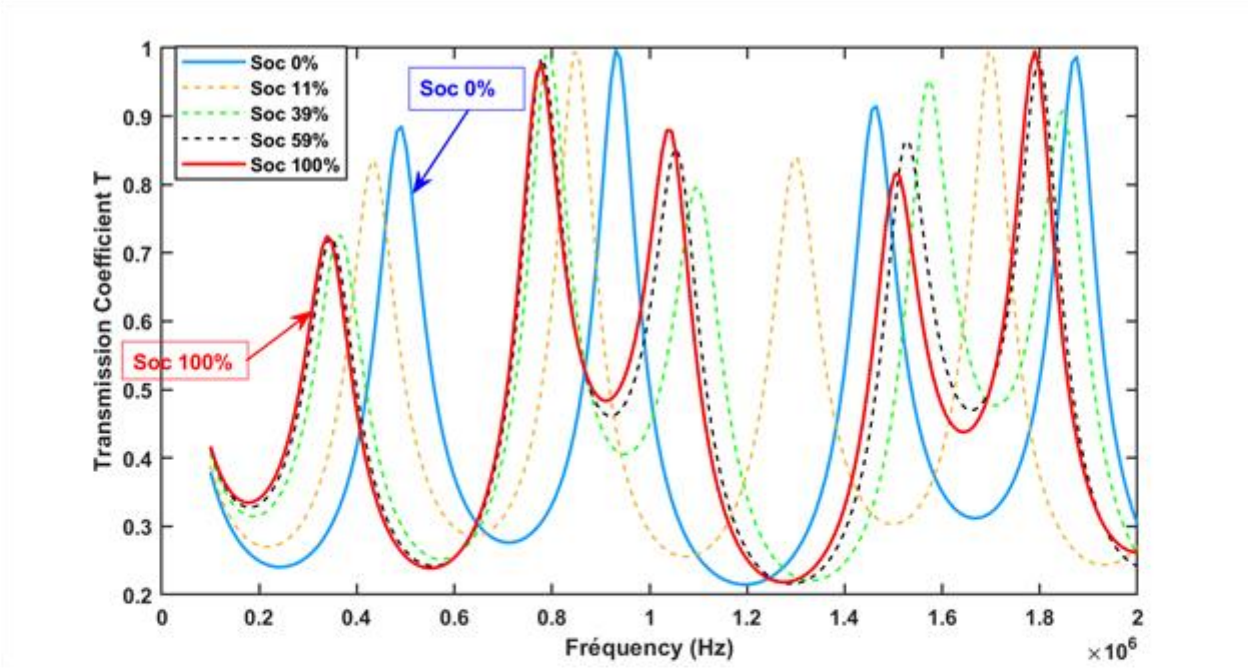

Soc 0%
Soc 11%
Soc 39%
Soc 59%
Soc 100%
Soc 0%
Soc 100%
Transmission Coefficient T
Fréquency (Hz)
×10^6

# The influence of phase microstructure transformations on the dynamic response of Nitinol Langevin ultrasonic transducers

**Mahshid Hafezi**[1], Yuchen Liu, Andrew Feeney
*[1]Centre for medical and Industrial Ultrasonics, University of Glasgow, United Kingdom*

Morning Session IV, January 19, 2024, 11:30 - 13:00

The Langevin transducer is arguably the most widely known and commercially exploited ultrasonic transducer configuration, utilised across medicine and industry. For example, it has been successful for dental and bone surgeries, but also for generating cavitation for cleaning or sonoprocessing of materials. In power ultrasonics, the Langevin transducer is typically tuned to a resonant mode at a low ultrasonic frequency, in the region of 20-100 kHz. However, a new generation of ultrasonic transducer is emerging, capable of exhibiting adaptive dynamic behaviours, for example in the tuneability of resonance frequency. A principal mechanism to enable such adaptive behaviours is through the incorporation of materials into the transducer configuration whose physical properties can be controlled. A candidate emerging in recent years is the shape memory alloy nickel-titanium, or Nitinol. This material can switch from a relatively compliant martensitic microstructure, around 30-40 GPa, towards a stiffer cubic austenite, around 70-90 GPa, principally via temperature triggers. The incorporation of Nitinol into the cymbal-type flextensional transducer as endcaps has shown the capacity of the material to enable frequency tuneability in the region of several kHz at low ultrasonic frequencies. The challenge for the Langevin transducer is that the manufacture of Nitinol masses for the configuration is extremely challenging, with material properties which are difficult to control. Furthermore, there is currently little understanding of how the material properties of Nitinol influence the dynamic properties of a Langevin ultrasonic transducer incorporating Nitinol.

In this study, shape memory Nitinol has been integrated into a Langevin ultrasonic transducer, to assess the tuneability of its operational frequency, and its resonance stability over a range of suitable temperatures. This information is vital to demonstrate its suitability for practical industrial and medical applications. To these ends, Nitinol end-masses have been fabricated with a transition temperature to austenite of 45°C, where threads have been introduced via electrical discharge machining (EDM), and where the end-masses sandwich hard lead zirconate titanate (PZT26). The assembly of a Langevin transducer typically requires a preloading process, and material analysis has revealed that Nitinol's hardening behaviour is nonlinear, decreasing relative to the depth of displacement in the material lattice. Therefore, there are implications of the transducer fabrication and assembly process on the material properties of Nitinol and its characteristic transformational response in practice.

A fabricated Langevin transducer incorporating Nitinol is shown in Fig. 1 alongside characteristic response data, where it exhibits its first longitudinal mode at 44.14 kHz for an 8 V excitation. Electrical impedance measurements are used to show the tuneability of this resonant mode, approaching 1 kHz, in the region of 20-50 °C. Experimental data relating to resonance stability at elevated temperatures is also presented, showing the capacity of Nitinol to stabilise the frequency response of a Langevin transducer, useful for temperature-dependent industrial and medical applications, and where material characteristics are linked to dynamic response. This research demonstrates a step forward in the application of advanced materials in ultrasonic devices.

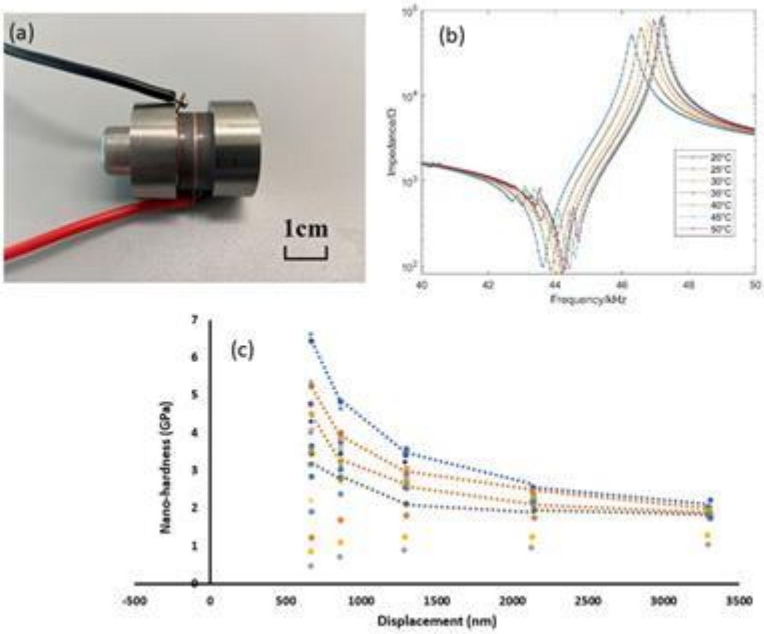


Fig 1. (a) The Nitinol Langevin transducer; (b) Impedance-frequency response; and (c) Nitinol hardness.

# Anisotropic Orientation Inversion using Stein Variational Gradient Descent

**James Ludlam**[1], Katherine Tant[1], Andrew Curtis[2], Victorita Dolean[1]
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Morning Session III, January 19, 2024, 09:30 - 10:54

In ultrasonic non destructive testing, imaging defects in anisotropic welds presents a significant challenge due to the presence of anisotropic grain structures, which cause scattering and refraction. Basic imaging techniques often assume a constant wave speed throughout the medium, which leads to unreliable defect detection. However if information on the anisotropic orientation of the crystal structure is available, it can be used to correctly focus the phased array in a region of interest [1] and a significant improvement in flaw detection and accuracy can be obtained. Orientation mapping using travel time tomography has been achieved using Markov Chain Monte Carlo (MCMC) Methods [2], however due to the high dimensional parameter space, often consisting of thousands of parameters, these methods take many iterations to form an estimate of the probability distribution and are thus computationally expensive. Variational Bayesian Inversion approaches can offer more efficient methods of inversion for these high dimensional parameter spaces as they are posed as an optimisation problem instead of relying on random sampling. Stein Variational Gradient Descent (SVGD)[3] is one such method which uses the gradient of the probability density function to pick a set of particles to sample the probability density function. Unlike MCMC methods this sample is chosen using optimisation and so can represent the probability density function using a much smaller sample size. We perform orientation mapping with SVGD using gradients calculated from the fastest ray path between transducers which are obtained using a novel approach to ray tracing through travel time fields [4]. Using these methods we have been able to reconstruct the grain structure in some toy examples consisting of multiple regions with different anisotropic orientations. Since we obtain an estimate of the probability density function, a measure of uncertainty is obtained for all model parameters. High standard deviation often corresponds to boundary's between different materials and locations which are poorly imaged.

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# Multi-modal characterization of ultrasonic bulk wave properties in heterogeneous textured media through finite element computations

**Vincent Dorval**[1], Nicolas Leymarie, Alexandre Imperiale, Edouard Demaldent
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Afternoon Session II, January 17, 2024, 16:00 - 17:36

Ultrasonic Non Destructive Testing can be heavily affected by heterogeneous materials, such as some coarse-grained metals, concretes or composites materials. Understanding and predicting the behaviour of ultrasonic waves in such complex media has been a longstanding focus of research. Originally, theoretical analytical models have been developed. Their utility tend to be constrained by their inherent approximations and by the difficulties associated with verifying them. In recent years, transient Finite Element computations have been used to overcome these limitations. By simulating the propagation of ultrasonic waves through representative volumes of the material, it is possible to determine the properties of the coherent wave. However, this approach has been mainly applied to longitudinal waves only, and the analysis methods used are not necessarily applicable to shear waves.

This communications shows how, with a dedicated simulation setup, it is possible to characterize the behaviour of both longitudinal and shear waves. Both waves can be characterized using a single computation, saving on computation times. The presented methodology is also applicable to statistically anisotropic medias, such as textured metallic microstructures, in which three distinct modes can be observed in the coherent field: one quasi-longitudinal and two quasi-shear modes. These three modes can be characterized in a single simulation.

One of the objectives of this technique  is to provide material input data for ray-based macroscale simulations using ray-based or high order Finite Element models in application to the control of various metallic parts, including welded components with textured regions.

# Multimodal approach of the guided wave propagation from a spatially extended source

**Charlotte Comte**[1], Simon Felix[1], Gwenaël Gabard[1]
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Afternoon Session II, January 17, 2024, 16:00 - 17:36

The computation of the propagation of guided waves is a classical problem in various fields of wave physics, such as acoustics, elastodynamics, electromagnetism or matter waves. Usual numerical methods such as finite elements can be used to solve the wave propagation in complex waveguides, but at a computational cost that can be prohibitively high for wave propagation over long distances, at high frequency, or when the problem displays various scales. Multimodal methods are well suited for solving this issue and have been, over the years, developed and adapted to a wide variety of problems in waveguides with complex geometries, disorder, flow, etc.

The basic idea behind these methods is to project the solution on a basis of local transverse modes. The initial wave field, which is a function of the three dimensions of space, is then represented by a vector of modal amplitudes whose variations along the waveguide axis remain to be computed. In the absence of a source inside the domain of interest, the homogeneous wave equation and its boundary conditions (the source condition from a given incident wave and a radiation condition) are reformulated as a pair of two initial value problems by introducing an admittance matrix operator. The use of a Magnus-Möbius scheme then allows for an efficient and stable numerical integration of the two initial value problems.

When a source term in the wave equation accounts for the presence of a spatially extended source in the computational domain, solving this inhomogeneous problem requires redefining the transformation from the original boundary value problem to a sequence of initial value problems. The proposed approach consists in first splitting the wavefield into two components (that reduce, in the trivial problem, to the right and left-propagating waves in an infinite cylindrical waveguide), and two associated admittance matrices. Then two pairs of initial value problems can be formulated and numerically integrated in parallel, to compute the wavefield. Various examples will be given to validate and illustrate the method.

# Efficient finite element simulation of elastodynamic scatterer responses in arbitrarily complex materials and geometries

**Paul Wilcox**[1]
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Afternoon Session II, January 17, 2024, 16:00 - 17:36

In NDE applications, there is increasing demand for ultra-realistic 3D simulations from large populations of scatterers to provide training data for machine learning and test data for inspection qualification. However, despite massive advances in computational power, direct numerical simulation of elastodynamics using finite elements remains extremely computationally expensive. This paper proposes a methodology for significantly reducing this computational burden, which can be implemented in a standard, explicit time-marching finite element code.

The general steps for a pulse-echo configuration are as follows. First the incident wavefield from a transducer is simulated in a domain covering the complete geometry in the absence of the scatterers of interest. This is the only model that must be executed on the full domain. A region enclosing the potential scatterers is defined, and time histories of the transmitted displacement field are recorded at nodes in the immediate vicinity of this boundary. A smaller modelling domain surrounded with a suitable absorbing layer is defined which encloses this region and includes the scatterer of interest. The displacement histories from the boundary nodes in the larger domain are converted to time-domain forcing functions and applied to the equivalent nodes in the smaller domain; this is a numerical implementation of the Kirchhoff–Helmholtz integral which recreates the incident field on the scatterer. If the absence of a scatterer, it follows from the definition of the Kirchhoff–Helmholtz integral that the displacement field will be completely contained within the boundary nodes. However, if a scatterer is present, the scattered wavefield passes through the boundary nodes to be eventually dissipated in the absorbing layer. A complete description of the scattered displacement wavefield is therefore provided by the displacement on the boundary nodes, which can again be converted into equivalent time-domain forcing functions. These could be applied as forces in the larger domain, but this would obviously not provide any reduction in computational cost since the larger model could have simply been executed with the scatterer of interest included in the first place. Instead, reciprocity between the forcing function and the boundary node responses in the original model is exploited. Convolution with these responses allows the scattered field to be converted back to the displacement that would be measured at the original transducer location.

Therefore, the method allows the response from any scatterer to be simulated using only the smaller domain. Because the large simulation domain includes the complete geometry, the effects of reflections from structural features on both the incident and scattered fields are implicitly included. First-order scattering effects are captured with identical accuracy to that of a numerical model of the same scatterer in the larger domain. Higher-order scattering effects (i.e. multiple interactions with the scatterer region) are not captured because the coupling between domains is one-way; although the scheme can be iterated to include these if desired. In contrast to previous approaches, the method does not require knowledge of analytical Green's functions, which means that both domains can include arbitrarily complex geometrical features, anisotropy, and inhomogeneities.

# Golay-Based Total Focusing Method Using a High-Frequency, Lead-Free, Flexible Ultrasonic Array to Improve Industrial Inspections

**Elmergue Germano**[1], Morteza Tabatabaeipour, Ehsan Mohseni, David Lines, Anthony Gachagan, Dave Hughes, Heather Trodden
[1] *University of Strathclyde, United Kingdom*

Afternoon Session IV, January 18, 2024, 15:50 - 17:26

High frequency (>15 MHz) ultrasound arrays have attracted considerable interest in recent years due to their ability to provide images with enhanced spatial resolution, offering higher sensitivity to smaller defects in materials and structures. Defects can be detected at earlier growth stages as compared to lower frequency counterparts. Conversely, high-frequency sound waves have limited penetration depth that can hinder the inspection of thicker components. Moreover, research into lead-free alternatives to lead zirconate titanate (PZT) is prominent due to the European Union's Restriction of Hazardous Substances (RoHS) regulation. Achieving optimal ultrasound imaging with lead-free materials remains a persistent challenge, given the importance of transducer sensitivity. Here, an advanced approach combining a high-frequency, lead-free, flexible ultrasonic array and Golay-coded excitation to address the limitation in penetration depth in ultrasound imaging, particularly of samples with non-planar surface geometries, is presented.

This study employed a commercial 20 MHz 64 element 1 mm pitch lead-free flexible linear ultrasonic array, developed by Novosound Ltd, using Golay-coded excitation to improve the penetration depth and exploit the flexibility for operation on both planar and non-planar components. Golay complementary sequences were designed and employed to excite the array. Pulse compression was realised through the application of a matched filter.

A signal-to-noise ratio (SNR) improvement verification study was conducted with the array deployed on a 20 mm thick planar aluminium sample. As anticipated, an increase in SNR was observed as the length of the Golay codes increased, matching the theoretical 3 dB improvement between successive length doubling. Furthermore, the appropriate Golay code length is contingent on the specific demands of the application with respect to acceptable SNR and minimisation of the dead zone to improve near surface inspection capability. The array offers the versatility to adapt to complex surface profiles. A curved test specimen with known defects was next explored. Total focusing method (TFM) images of the sample for both pulse and Golay excitations were obtained and compared. The Golay-based TFM outperformed the standard pulse-based TFM, resulting in an improved imaging penetration depth.

The proposed approach, which integrates a RoHS-compliant, flexible array with Golay-coded excitation, has the potential to improve the quality of industrial inspections in terms of efficiency, accuracy, and reliability.

# Multimodal radiation and directivity of open-ended waveguides

Hao Dong[1], Jean-Baptiste Doc[2], **Simon Félix**[1]
*[1] LAUM, CNRS, Le Mans Université, France, [2] LMSSC, CNAM, France*

Afternoon Session II, January 17, 2024, 16:00 - 17:36

In a wide variety of practical situations, wave guiding systems also behave, through one or more open ends, as sources, whether this sound radiation is desired or not. Exhaust and engine systems, heating, ventilation and air conditioning networks, horn loudspeakers, musical wind instruments, or the vocal tract can be cited as examples, and many others could be listed in other fields of wave physics whether optical, mechanical, etc. As radiating systems, they therefore raise the question of how to predict, control and possibly optimize their directivity. This paper investigates the directivity properties of open-ended waveguides using a multimodal method. The method is fully algebraic, accurate, and much faster than, e.g., the finite element method when dealing with a large number of frequencies, and allows for an arbitrary velocity distribution on the opening of the horn.

We will first show how such a method allows for a rigorous derivation of the maximum directivity factor of a flanged aperture with arbitrary shape by projecting its surface velocity on the waveguide modes, enabling the creation of a directional beam in any desired direction. The theoretical beam that is obtained in a subspace spanned by all the propagating modes can then be synthesized by a group of incident modes or a point-source array within the waveguide.

We will also investigate the beamwidth behaviour of a waveguide mounted in a finite enclosure, with respect to frequency, dimensions and shape of the waveguide. At low frequencies, a fitted model is proposed to precisely depict the intrinsic beam narrowing governed by the enclosure diffraction. Above this range, the asymptotic behaviour of the beamwidth is explored as the flange width increases. At mid- to high-frequencies, where the shape of the waveguide plays an important role, we report on the possibility of exploiting enclosure diffraction to extend the bandwidth of a constant directivity horn.

# Reconstruction of smooth shape defects in additive manufactured waveguides by laser-ultrasound

**Alexandre Charau**[1], Jérôme Laurent[1], Tony Valier-Brasier[2]
*[1]Université Paris-Saclay, CEA, List, France, [2]Sorbonne Université, Institut Jean Le Rond D'Alembert, France*
Afternoon Session IV, January 18, 2024, 15:50 - 17:26

The use of additive manufacturing (AM) processes, to produce components with complex geometries has grown significantly over the last decade. Complex 3D-printed structures can take the form of thin shells, plates of varying thicknesses, or having functional graded materials. Improving NDT methods using guided waves is a challenge in particular by local contactless all-optical methods. Elastic waveguides allow waves to propagate with complex dispersion, even if the waveguides have graded elasticity or non-uniform geometrical properties. This can lead to anomalous wave propagation. Several theoretical, numerical, or experimental studies [1] have investigated the guided waves in free elastic plate with different cross-sections, or elastic graded materials (adiabatic modes, Maxwell's fish-eye, trapped modes, phase conjugation effect, backward propagation modes, etc.) [2]. However, the study of ultrasound propagation in these peculiar waveguides remains original. In this presented work, numerical experiments were carried out using SFE simulation code developed in the laboratory [3], which was adjusted to account for laser generation (thermal and optical effects have been neglected). The LPBF process has been used to print multiple aluminium plates with linear thickness losses along the plate h(x, y, z) or locally non-uniform cross-sections (h can increase or decrease in a Gaussian annular shape). Dispersion curves and ultrasonic wavefield were measured by laser ultrasonic technique (LUT) on millimetre inhomogeneous plates. Either with sub-millimetre local Gaussian shape cross-section or with slow linearly thickness variations in one or two directions, waves can propagate in this area due to their width relative to the acoustic wavelengths used. Absolute normal displacements were measured at different points using a broadband laser interferometer and then processed in the spatial and temporal Fourier domain, by filtering the 3D-dispersion curves (kx, ky, ω) of Lamb modes, to determine the thickness variations. Comparatively to thickness measurements using ZGV resonances, we then became interested in the limits and robustness of methods using propagative modes for reconstructing the smooth shape defects along such waveguides. To accomplish this, we used the instantaneous wave number (IWN) method using the A0 mode [4] or we exploited the A1-mode cut-off frequency [5]. By tracking the cut-off frequency of this mode, or local thickness-shear resonance and the associated Airy functions, we reconstructed the profile of the waveguides. The experimental and numerical results are in good agreement.
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# Digital twin of a MIMO sonar for real-time underwater imaging

Oleksandr Malyuskin[1]
*[1]Queen's University Belfast, United Kingdom*

Morning Session II, January 18, 2024, 11:20 - 13:00

This presentation outlines the development principles, model elements, computational algorithms and codes of a digital twin of a sparse multiple-input multiple-output (MIMO) sonar with application in fast (almost real-time) underwater imaging.

Of specific interest is the imaging scenario arising in the collision avoidance of fast-foiling hydrofoil vessels when underwater imaging is required in a low submergence depth layer (typically, 30-50cm below the water surface).

In this scenario, environmental parameters, such as wind, precipitation and bathymetry (for shallow water navigation) define the state of the water surface and underwater acoustic propagation channel which in addition to the fast foiling vessel kinematic parameters (velocity, acceleration and vessel orientation) define the key performance characteristics of sonar image acquisition and target classification.

In this presentation, the operational principles and key imaging characteristics of a sparse, pulsed MIMO sonar are discussed first with an emphasis on beamforming and spatial diversity in both transmit and receive modes with a specific application to imaging in a low underwater submergence layer. The effect of the sea surface state on the received signal quality, target(s) recognition and target(s) classification is discussed using full-wave analytical and computational acoustic models.

Next, the mathematical model and effect of vessel motion dynamics on the underwater scene acquisition are discussed to understand the key limitations of a MIMO sonar arising as a result of fast foiling vessel motion. Finally, an attempt is made to demonstrate how the use of a digital twin and specifically, predictive modelling can improve underwater imaging in this extremely complex acoustic imaging scenario.

The results of this study can be useful for other applications, particularly biomedical imaging and ultrasonic-assisted surgery and biomedical interventions where acoustic imaging and beamforming are performed in complex inhomogeneous and non-stationary media.

# Quantitative characterisation of cavitation signals using wavelet packet transform and k-means clustering

Max Au-Yeung[1], Reza Haqshenas[1]
*[1] University College London, United Kingdom*

Morning Session III, January 19, 2024, 09:30 - 10:54

Acoustic cavitation refers to the formation, expansion, and pulsation of bubbles (i.e., cavities filled with gas and vapour) in a liquid subjected to acoustic waves. These bubbles may periodically oscillate whilst exposed to acoustic waves (known as stable cavitation) or grow and implode violently within one or a few cycles of excitation (known as transient cavitation). There are several physical effects associated with acoustic cavitation, including creation of free radicals, shock waves, shear stresses, micro-jets, and micro-streaming in the insonated liquid.

Ultrasound waves are commonly used to produce acoustic cavitation for diverse applications such as imaging ultrasound, therapeutic ultrasound, sono-chemistry, and sono-crystallization. To effectively harness these effects and conduct in-depth studies, it is crucial to quantitatively measure and evaluate acoustic cavitation. A commonly used approach involves the use of passive cavitation detectors (PCD) to measure acoustic emissions from cavitating bubbles. Analysing these emissions is challenging due to complex information present in both time and frequency domains. The signal from a PCD contains multiple features: (i) a range of harmonics with frequency of nf0 where f0 is the fundamental frequency and n=1,2,3,… is an integer, (ii) sub-harmonics with frequency of f0/n, (iii) ultra-harmonics with frequency of m f0/n where m is an integer and not equal to n. These components can be formed by both stable and inertial cavitation. (iv) broadband frequency component which is usually considered as an indicator of transient cavitation. The shock wave produced by an inertial collapse manifests as broadband noise in the spectrum. In the case of a cloud of bubbles, the interaction between bubbles can produce harmonics and sub- and ultra-harmonics as well, further increasing the difficulty in analysing the PCD data. To address this challenge, we have developed a novel method that combines discrete wavelet packet transform, statistical signal processing, and k-means clustering for the quantitative analysis of acoustic emissions. PCD data is decomposed into narrow-band packets, characterised by statistical metrics. The k-means method is applied to these metrics to classify packets based on cavitation features explained above, allowing quantitative differentiation between different signatures in the signal, such as sub-harmonics, ultra-harmonics, and broadband signals. Its multi-resolution nature not only distinguishes these signatures in the frequency domain but also extracts the corresponding time-domain components of the signal.

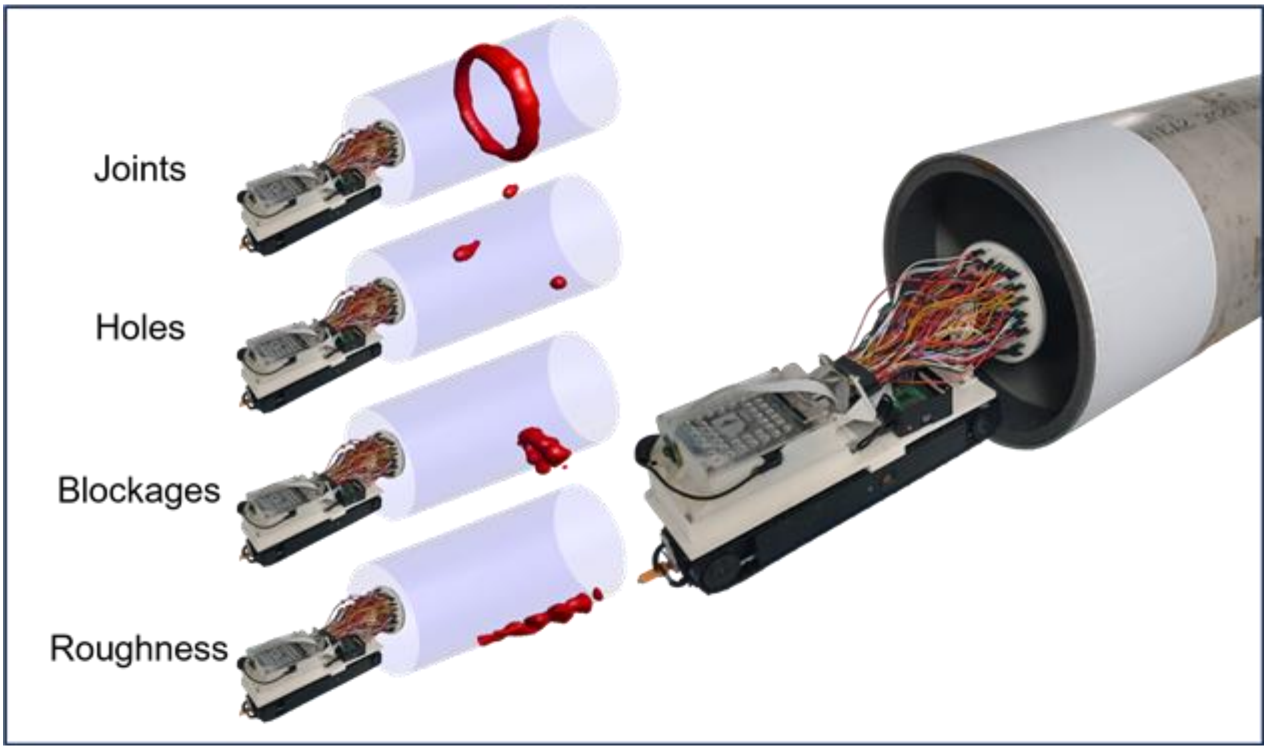
The method's effectiveness for identification and classification of features of cavitation was validated through processing numerical and experimental data. We numerically solved the Gilmore-Akulichev equation to simulate acoustic emissions from a bubble subjected to ultrasonic waves with different amplitudes and frequencies, replicating diverse stable and transient cavitation scenarios. Experimental validation involved the use of a High Intensity Focused Ultrasound transducer and a broadband PCD to produce and monitor cavitation in a water tank. Our method could successfully extract, classify and characterise (sub- and ultra-) harmonics and transient components of the signals and reconstruct time-domain signals corresponding to those components. The method has been implemented into a Python library, accessible through a GitHub repository.

# Ultrasonic inspection of pipes using mobile robotics

**Bruce Drinkwater**[1], Xiaoyu Sun, Xudong Niu, Alex Towlson, Jie Zhang, Anthony Croxford[1]
[1] *University of Bristol, United Kingdom*

Afternoon Session IV, January 18, 2024, 15:50 - 17:26

As the cost of mobile robotic solutions decreases, so the opportunities for their widespread use in NDT applications grows. However, this opportunity comes with challenges as the complexity of the NDT processes, quantity of data, rate of data flow and processing must be matched to the capabilities of the robots. This talk discusses these emerging possibilities and presents examples of low-cost acoustic and ultrasonic sensing strategies that are suitable for the inspection of underground water and sewerage pipe networks. Detailed information on the interior of the pipe is obtained using an ultrasonic array mounted on a robotic platform with bespoke electronics for signal generation/reception. The array developed has a pseudo random element layout and is optimised for a given pipe geometry. Fewer elements can be used to achieve a given detection performance, but this is at the expense of the ability to image and characterise the features. Multiple reflections from within the pipe are present as noise and their effect is discussed and the minimised in the array optimisation process. These systems are demonstrated on a realistic test pipe network and the array is shown to be capable of measuring defects, surfaces roughness as well and imaging blockages and internal pipe geometry.



# Coherent Multi-Transducer Ultrasound (CoMTUS) imaging: Towards large field-of-view imaging with three probes

**Paul Dryburgh**[1], Daniele Mazierli[2], Joseph V Hajnal[1], Alessandro Ramalli[2], Laura Peralta[1]
*[1]King's College London, United Kingdom, [2]University of Florence, Italy*

Morning Session IV, January 19, 2024, 11:30 - 13:00

Abstract
Ultrasound is a widely used clinical imaging tool, and its advantages in terms of portability, safety, and low cost over other medical imaging modalities are well known. However, the field of view (FoV) and resolution of ultrasound scanners are typically limited by the probe aperture and view-dependent artifacts. These limitations are most prominent when attempting to image at greater depths, such as those required in abdominal imaging.

The Coherent Multi-Transducer Ultrasound (CoMTUS) framework presents an innovative approach to overcome these challenges in medical imaging. CoMTUS enables the use of multiple arrays as one large effective aperture by combining the received RF datasets [1]. By maximizing the coherence between backscattered echoes from targeted point-like scatterers in the common field of view, the transducer localizations, along with the average speed of sound in the medium, are deduced, allowing the signals to be coherently combined. This framework allows for imaging with enhanced resolution, extended field-of-view, and higher sensitivity, compared to the currently typical one-probe operation and can be applied to acquisitions in both 2- and 3-D [2]. Figure 1 provides an overview of the CoMTUS methodology (a) and an example of the improvement in the resolution of the imaging system, even when working at extended depths.

CoMTUS relies on creating an overlapping FoV between the probes; the use of more than two probes and diverging rather than plane waves have provided an avenue to greatly extend the field-of-view while maintaining high contrast and high-resolution images, and make the practical alignment of the probes easier. To combine the received signals from the three probes and access the higher spatial resolutions promised, a harmonious coordinate system between the probes is obtained through the inversion.

This talk will review the CoMTUS framework, including the inversion procedure, noting the recent modifications to the inversion to allow for three (or more) probes to be used on a unified coordinate system. This will be followed by the presentation of recent results, including the first demonstration of coherent imaging using three probes in both 2D and 3D, comparing both experimental and simulated results. The talk will conclude by discussing future challenges, including coping with aberration, the place for advanced beamformers in the CoMTUS framework, and the current perspective on real-time in-vivo applications."

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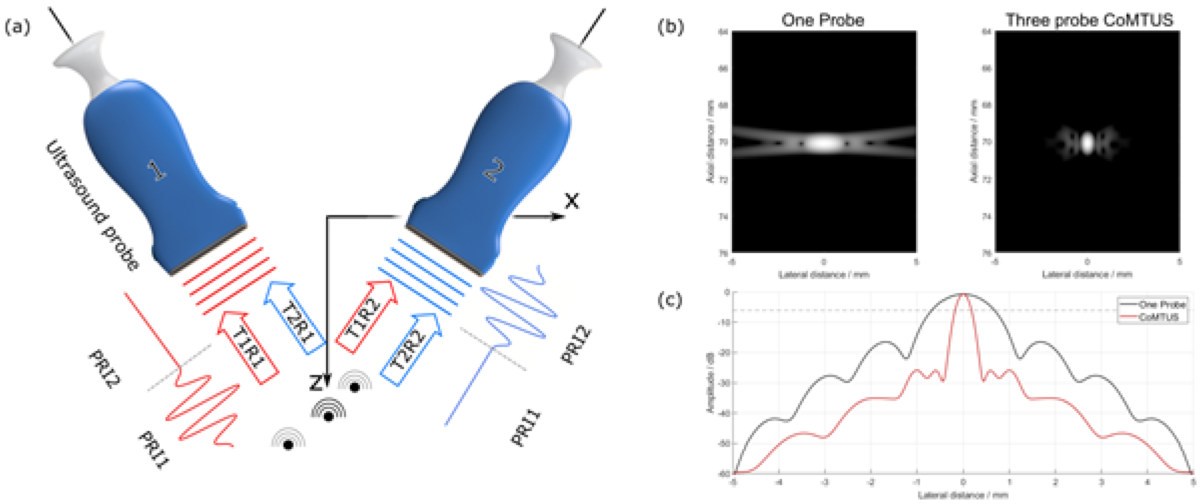


**Figure 1:** (a) Working principle of CoMTUS. At each pulse repetition interval (PRI) one of the ultrasound probes transmits. The corresponding backscatter signal is then recived on all of the probes. The sequence continues until each probe has transmitted (two probes shown but can be three or more). The final CoMTUS image is generated by coherently summing the each of the datasets (e.g. T1R1+T1R2+T2R1+T2R2). (b) The point spread function obtained with three probe CoMTUS (top row), compared to one probe. (c) Point spread functions of the two configurations for a target 70mm deep. The lateral resolution improves from 1.3mm to 0.4mm, thanks to CoMTUS.

# Design of a bespoke, additively manufactured HIFU transducer characterised at high power

**Jack Stevenson**[1], Sandy Cochran[1], Margaret Lucas
[1]*University Of Glasgow, United Kingdom*

Morning Session IV, January 19, 2024, 11:30 - 13:00

High Intensity Focussed Ultrasound (HIFU) transducers come in three main categories – bowl, acoustic lens and array – the latter being preferred for miniaturisation. While arrays excel at beam steering via phase delay between elements, they are complex to manufacture, requiring an electrical channel for each element [1]. This limits the capability of a bespoke miniaturized transducer for soft tissue ablation. This research proposes a single element transducer with an additively manufactured lens and housing, enabling bespoke devices and removing the requirement for complex wiring and driving solutions, hence allowing the device to be robotically delivered with ultrasonic b-mode imaging of the focal zone as feedback for control.

By using additive manufacturing techniques, it is possible to rapidly produce bespoke, miniature HIFU devices. The Fresnel lens design allows the lens to be tailored to produce a more effective acoustic field.

12 devices where manufactured using four different piezoelectric driving materials (PZ12, PZ54, PZ37 and PZ29 from CTS Ferroperm). After a selection process, the lens material was chosen to be StrongX (Liqcreate). The focal zone of each transducer was measured in a 3D acoustic scanning tank and compared to a finite element analysis (FEA) model. At the -6dB point in the focal zone the transverse dimension was found to be (1 ± 0.2) mm, as seen in Fig. 2.

The maximum acoustic power was then measured in a radiation force. The results in Fig. 3 show that the porous piezoelectric ceramic material (PZ37) performed well in the device, suggesting that the better acoustic impedance match plays a significant role. The lead-free piezoceramic (PZ12) could be driven at higher amplitudes without failure, to achieve a large acoustic power output. However, this also shows that PZ12 results in a less efficient device than PZ37, requiring up to 100 V higher driving signal to achieve the same acoustic power output.

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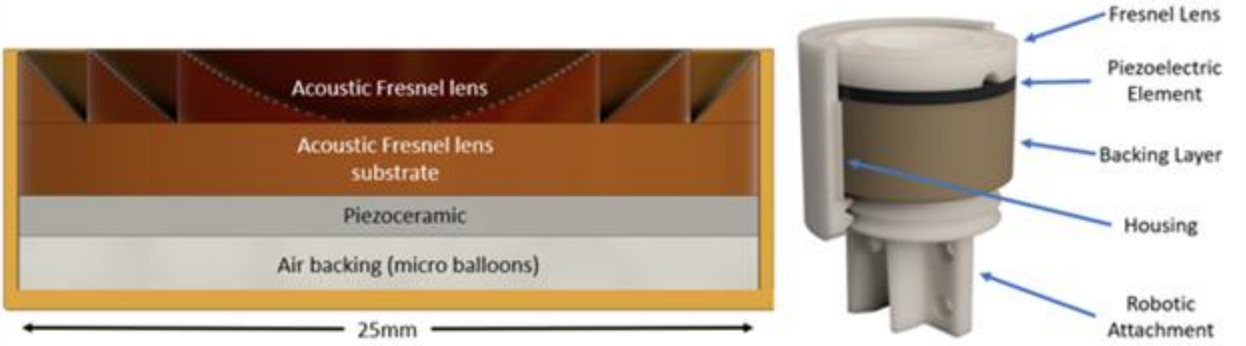


Fig. 1 left, a cross section schematic of the transducer design and right, a render of the design within the 3D printed housing and robotic pick up, showing scale.

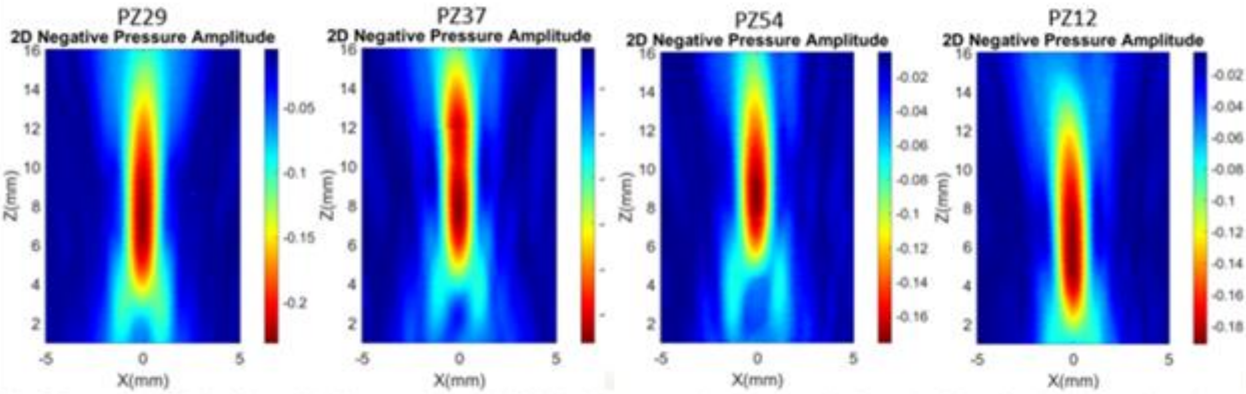


Fig. 2 The acoustic fields of the additively manufactured HIFU devices grouped by the piezoelectric material used as the active element. The position of the transducer is -22mm in Z and centred with respect to the X axis.

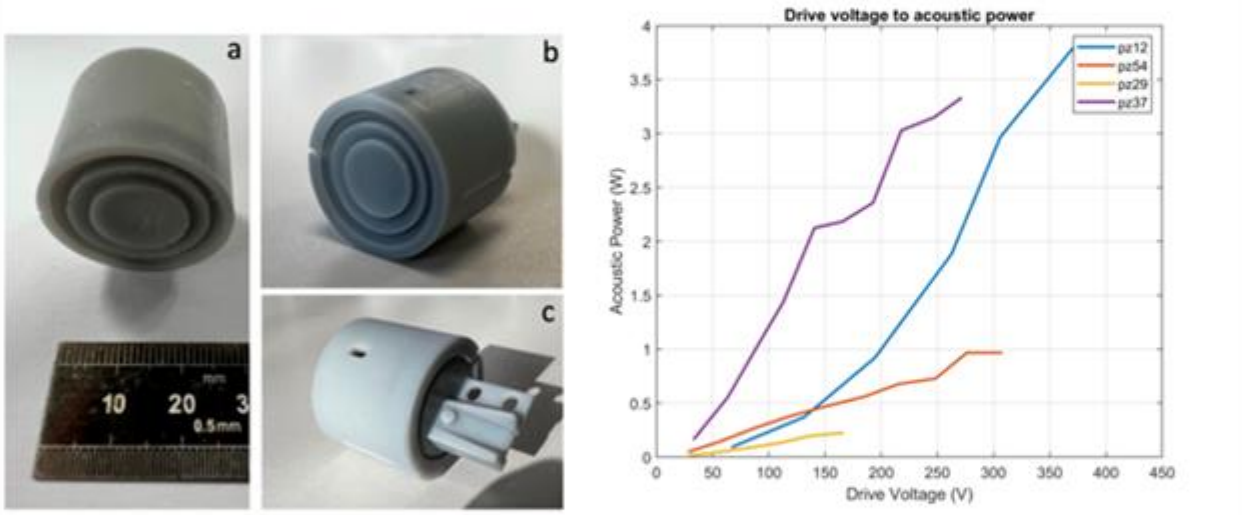


Fig. 3 a)-c) a Fresnel lens based HIFU device additively manufactured from photopolymer Strong-X. The graph showing the acoustic power output from each type of device in a radiation force balance.

# Analysis of defects in symmetrical parts by non-contact modal analysis

**Chloë Palerm**[1], Julien De Rosny, Claire Prada, Benoît Gérardin
*[1]Safran, France*

Afternoon Session II, January 17, 2024, 16:00 - 17:36

The modal properties of a part depend on its geometry, its material and its boundary conditions. A change in any of these characteristics leads to changes in the resonant frequencies and their associated Q-Factor, and/or in the modal shapes. Therefore, modal analysis is a useful tool to check and monitor the conformity of a part.
In symmetrical components, some modes are degenerate: they share the same natural frequency and some geometrical aspects of their modal shapes. The presence of a flaw generally breaks the symmetry and leads to a splitting of the degeneracies. The way in which the various degenerate modes split provides information about the type and location of the defect. However, for light parts, the measuring equipment can also be a cause of peak splitting. Here, we then propose an analysis of different types of damaged symmetrical structures by analyzing their acousto-elastic transmission matrix. This matrix enables a completely non-contact measurement, which has no influence on the modes of the examined parts. Both the case of continuous and discrete rotational symmetry is shown.

# 3D phononic endo-microscopy of sub-micron biology

**Salvatore La Cavera**[1], Fernando Perez-Cota[1], William Hardiman[1], Mengting Yao[1], Rafael Fuentes-Dominguez[1], Richard Smith[1], Matt Clark[1]
*[1]University Of Nottingham, United Kingdom*

Morning Session I, January 18, 2024, 09:30 - 10:30

We present the first implementation of picosecond ultrasonics and time-resolved Brillouin scattering via fibre optics toward wider spread adoption of the technology particularly in endoscopic applications. Our phonon endoscope is capable of 3D resolving variations in tissue stiffness with optical lateral resolution and sub-optical axial resolution provided by GHz-acoustics. Simultaneous topographic mapping is also made possible through time frequency analysis and can be delivered with nanoscale precision. In this talk we show that this new technology is highly applicable to the 3D elasticity imaging of biological tissue from the single-cell scale to multi-cellular organisms and provides a future pathway for the clinical application of in-vivo Brillouin spectroscopy of tissue.

# Comparison of shear wave speed measurements using two shear wave elastography approaches

**Andre Alvarenga**[1], John Civale[2], Emma Harris[2], Srinath Rajagopal[1]
*[1]National Physical Laboratory - NPL, United Kingdom, [2]Institute of Cancer Research - ICR, United Kingdon*

Afternoon Session I, January 17, 2024, 14:00 - 15:36

Shear wave elastography (SWE) evaluates the mechanical properties of soft tissue by analysing shear wave (SW) induced by external excitation or acoustic radiation force (ARF). SWE has significant diagnostic potential as tissue mechanical properties are associated with the tissue physical state. In a joint effort to improve SW speed (SWS) measurements, the National Physical Laboratory (NPL) and the Institute of Cancer Research (ICR) carried out measurements to estimate the SWS on 4 commercial phantoms of varying elastic moduli using different techniques.

NPL used ARF push to generate SW using a Verasonics system running a code adapted from [1]. The system was operated using a L7-4 linear array, with a push and track transmit frequency set to 5.2 MHz. The push was focused at 25 mm. IQ data was recorded and the displacement was calculated using [2]. SWV was calculated over an ROI (20 mm × 2 mm) around the push focus. After low-pass filtering (2 kHz), interpolation (n=5) and zero-padding, the 2D FFT was computed. The SWS was calculated multiplying the frequency by the lateral displacement. See [1,3] for details.

ICR also used a Verasonics and L7-4. Continuous monochromatic vibrations (100 - 800 Hz) were applied to the phantoms to induce SW. Vibrations were generated by signal generator and audio amplifier used to drive a mini-shaker coupled to a cylindrical contactor (1 cm × 5 mm diameter). The contactor was on the phantom's surface, 1 cm from the probe, with coplanar alignment to the imaging plane. Ultrafast wave imaging sequence captured SW vibrations; axial oscillations were detected using a phase-sensitive algorithm [4] applied to IQ data. SW field data was processed using directional filters (n=8), and a 1 mm-kernel size was used to determine localised spatial autocorrelations for each filtered data set. SW wavelength (λ) was determined enabling SWS estimation ($c=f\times\lambda$). SWS maps were computed by applying a weighted average of the filtered SW fields. Mean and standard deviation of the SWS were derived. See [5] for details.

Typically, there is agreement between SWS values derived by ICR and NPL and nominal values provided by manufacturer, within the measurement repeatability (Fig. 1). Differences may be explained by effects of noise, relatively small kernel and autocorrelation lag used to estimate wavelength. Future work will involve assessment of systematic effects on both measurement infrastructure with uncertainty budgets.

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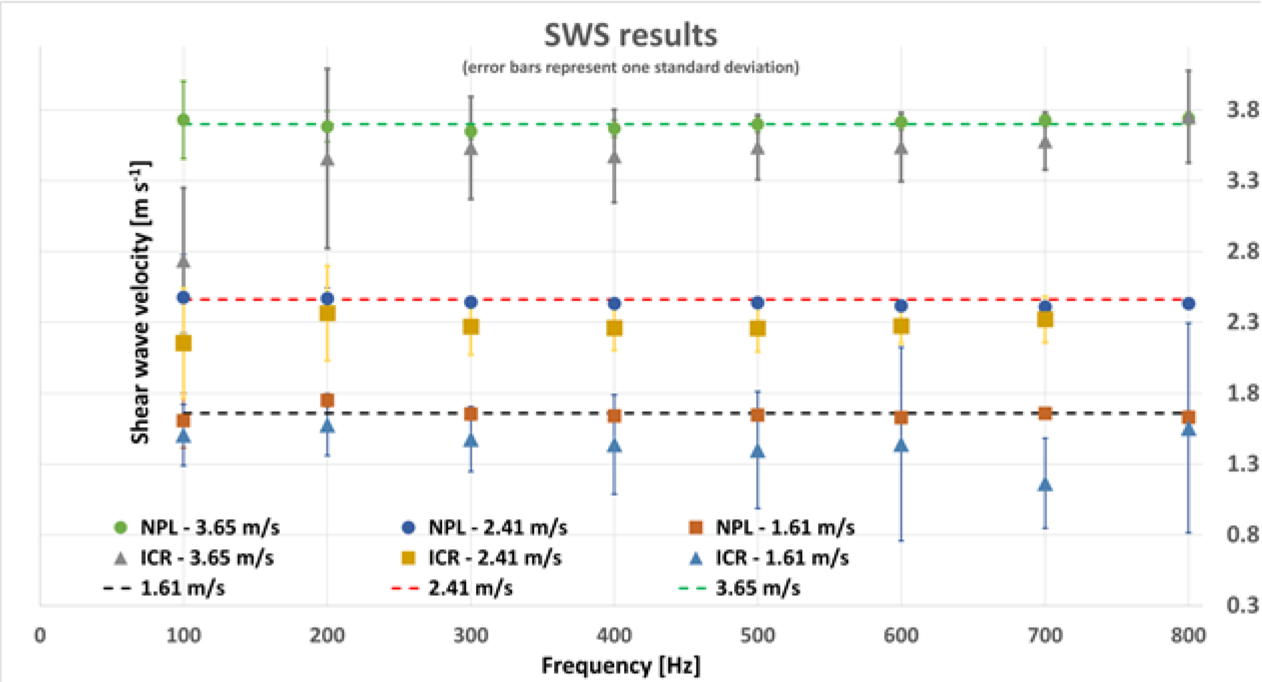

SWS results
(error bars represent one standard deviation)
Shear wave velocity [m s-1]
3.8
3.3
2.8
2.3
1.8
1.3
0.8
0.3
0
100
200
300
400
500
600
700
800
Frequency [Hz]
NPL - 3.65 m/s
NPL - 2.41 m/s
NPL - 1.61 m/s
ICR - 3.65 m/s
ICR - 2.41 m/s
ICR - 1.61 m/s
1.61 m/s
2.41 m/s
3.65 m/s

# Development of GHz optoacoustic lenses for sub-optical resolution imaging

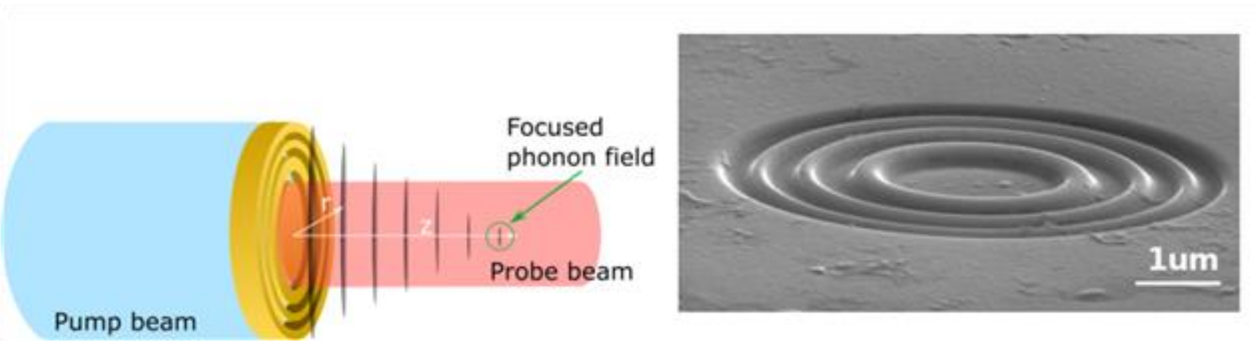
Mengting Yao[1], **Rafael Fuentes-Dominguez**[1], Fernando Perez-Cota[1], Salvatore La Cavera III[1], Richard Smith, Matt Clark
[1] *University Of Nottingham, United Kingdom*

Morning Session I, January 18, 2024, 09:30 - 10:30

The utilisation of Phonon microscopy has allowed for the imaging of elasticity in living biological cells in 3D by utilising coherent phonon fields to measure the Brillouin frequency (i.e. time-resolved Brillouin scattering). By producing phonons within the GHz frequency range, this technique provides an opportunity for obtaining images with sub-optical axial resolution ($\lambda$acoustic ~280nm). However, the lateral resolution is still limited by the optical system used to generate coherent phonon fields.

To overcome the limitations of lateral resolution and obtain true acoustic resolution in both axial and lateral dimensions, we suggest using novel optoacoustic lenses with GHz frequencies to focus coherent phonon fields (see Figure). For example, the flat lens Fresnel zone plate and the common acoustic focusing transducer design of concave lenses can be utilised for this purpose. These lenses can be fabricated at the nanoscale and can also be compatible with ultrasonic endoscopic imaging systems by attaching them to the tip of hair-thin optical fibres.

In this talk, we will explain multiple designs of these GHz optoacoustic lenses and demonstrate their capabilities for focusing coherent phonon fields, and also talk about future experiment plans to obtain sub-optical resolution images.



# Super-resolution imaging using nanobells

**Rafael Fuentes-Dominguez**[1], Mengting Yao[1], Kerry Setchfield[1], Salvatore La Cavera III[1], Richard Cousins[1], Fernando Perez-Cota[1], Richard Smith[1], Matt Clark[1]
*[1]University Of Nottingham, United Kingdom*

Morning Session I, January 18, 2024, 09:30 - 10:30

Super-resolution optical microscopy has a tremendous impact in life sciences over the last decade for its ability to reveal the insights of biological processes at the nanoscale dimensions [1,2]. These methods usually rely on the optical properties of either fluorophores or nanostructures to provide super-resolution.

An alternative to light (photons) is sound (phonons) which offers sub-optical resolution as well as enabling the elasticity quantification on biological cells [3]. This is key to understand changes at sub-cellular level due to diseases (e.g. cancer).

In this talk, a new scheme of super-resolution acoustic imaging [4] will be shown by characterising nanostructures (including size, shape, position and orientation) with a precision of 3 nm (see Figure) and the latest developments towards elasticity measurements at the nanoscale.

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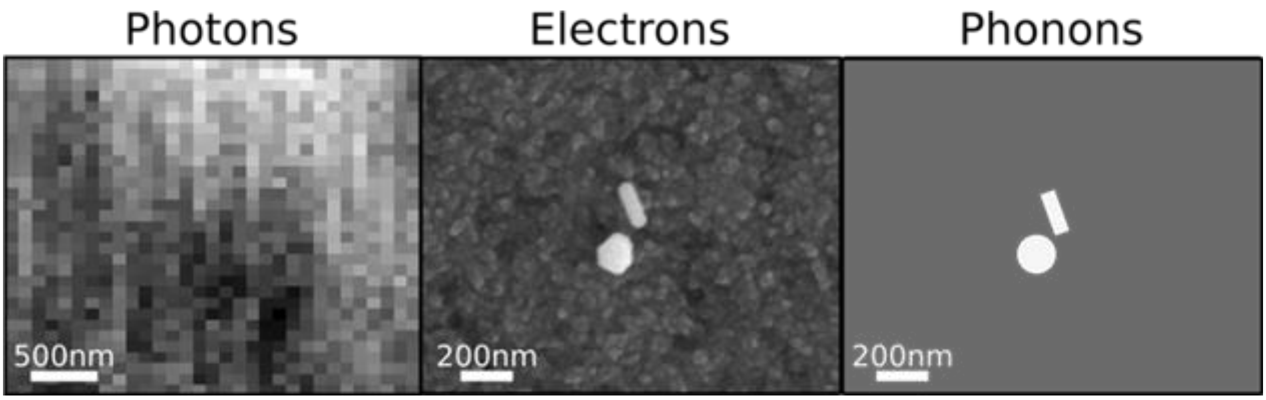

# Mechanisms of Therapeutic Ultrasound on Biomimetic Models of Cancer

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Afternoon Session I, January 17, 2024, 14:00 - 15:36

Therapeutic ultrasound has shown promise in treating various cancer types, overcoming the invasive and systemic side effects observed in conventional cancer therapies that impact patient quality of life. Low-intensity ultrasound (LIUS) has been proposed to selectively eradicate cancer cells without inducing cell death in healthy counterparts, but the underlying mechanism remains unknown. This project aims to characterise this phenomenon and address potential issues encountered in ultrasound based in vitro experiments that can lead to misleading results.

To help understand the influence LIUS has on cancer cells, 2D monocultures of MCF-7 and MDA-MB-231 breast cancer cells were initially set up, sonicated at varying acoustic intensities (0.1-0.5 W.cm-2) and excitation time parameters (1-10 minutes). To begin recapitulating relevant in vivo conditions, cancer cells were also seeded into 3D collagen hydrogels. To determine any distinguishing biological responses, 2D monocultures of healthy Human Dermal Fibroblast and MCF-10A breast cells were also sonicated at varying acoustic intensities (0.1-0.5 W.cm-2). To establish the influence culturing plates have on ultrasound propagation, the acoustic wave propagation software OptimUS was used to solve this through six-well plate models at a frequency of 500 kHz. At 1 MHz frequency, 20% duty cycle, 100 Hz pulse repetition frequency, a significant drop in cancer cell viability was observed at an intensity of 0.5 W.cm-2 and over a 10-minute excitation time. Healthy cells sonicated under the same ultrasound parameters demonstrated no distinguishing effects when compared to cancer cells. Interestingly, sonication of breast cancer cells seeded in 3D collagen hydrogels revealed no effect in cell viability compared to unsonicated controls. OptimUS confirmed and identified that the culturing plate materials for our culturing vessels significantly alters the acoustic field and is likely to influence our results.

Under specific ultrasound parameters, LIUS sonication of 2D monocultures induced identical biological responses in both breast cancer and healthy cells lines, with the underlying mechanism still unidentified. However, studies have shown that LIUS is able to induce cellular proliferation in healthy cells. Interestingly, breast cancer cells seeded in collagen hydrogels resulted in no biological response when compared to 2D monocultures. This observation could suggest that when translating towards in vivo representations it provides a protective environment from the physical effects of ultrasound. In these orientations, it is likely that thresholds required to induce cellular bioeffects are stabilised and are subsequently increased, thus not reached under these parameters. OptimUS was able to highlight the issues of using near-field sonication methods and multi-well culturing plates. Future investigations will focus on using a platform that aims to reduce the influence of conventional culturing vessels, opting for a platform that utilises mylar film windows and underwater placement to achieve homogenous cell sonication. Future investigations will focus on a wider scope of ultrasound parameters with the aid of ultrasonic wave modelling software’s. Parameters will be applied to progressively developing 3D breast cancer models and exploring the complex mechanotransduction pathways responsible for cellular responses to mechanical stimuli with the hope to characterise and identity LIUS treatment of healthy and breast cancer cell lines.

# Strategies for robotic structural inspection

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Afternoon Session IV, January 18, 2024, 15:50 - 17:26

The move to autonomous robotic inspections of structures, raises new challenges as to how such robots should be placed on structures to ensure uniform coverage at a certain level. This paper explores an optimisation approach to guarantee a certain level of performance. Firstly a model to characterise probability of detection (POD) for a given false call rate (FCR) is derived and its performance demonstrated on an example real inspection. This model is then used to determine the detection capability of different inspection configurations that can be used to provide global coverage, exploring different grid shapes and how much information is available. Finally conclusions for how to use inspections for detecting different defects in a large structure are discussed.

# All- optical laser ultrasound tomography for biomedical imaging using deep neural networks for image reconstruction

**Ahmed Al Fuwaires**[1], Don Pieris[1], Geo Davis[1], Peter Lukacs[1], Richard Pyle[1], Helen Mulvana[1], Katherine Tant[1], Theodosia Stratoudaki[1]

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Afternoon Session I, January 17, 2024, 14:00 - 15:36

Laser ultrasound (LU) is a non-contact, couplant-free imaging technique that uses non-ionizing radiation. These are advantages over other imaging modalities such as X-rays and conventional, transducer ultrasonic imaging. The absence of a couplant allows for the imaging of regions on the body where contact with a transducer not permitted such as burnt skin or locations on the eye. Also, by being absent of non-ionizing radiation, the ability to have longitudinal studies conducted is increased as multiple images can be taken without the fear of harmful radiation. In addition, LU assures repeatability and lends itself well to automation, compared to manually delivered ultrasound examination, making the technique a prime candidate for tomography applications. This allows for measurements over time to be compared with accuracy of size and location. We propose an all-optical system capable of tomographic imaging of biomedical related samples. Such a system could be used for breast tomography in order to detect tumorous or cancerous regions. The aim of the presented study is to demonstrate laser ultrasound imaging of a phantom, tissue mimicking material, situated in water, and recreate a speed of sound (SOS) map of the tested material by way of a Deep Neural Network (DNN) trained with simulated data. The experimental setup includes a water tank and a phantom with areas of varying speeds of sound located at the centre of the tank. Ultrasonic wave generation is done by a laser incident on a glass plate coated with a light absorbent material, while ultrasonic detection is achieved via a laser incident on a glass plate coated with aluminum to assure reflectivity. Signals are acquired in a through transmission setup. A time-of-flight (TOF) matrix is created based on the experimentally acquired signals. Prior to the experiment, a DNN is trained using simulated data, generated from physics-based models. The trained DNN is then used to reconstruct an SOS map of the experimentally investigated region using the experimental TOF matrix as input. The method shows the potential for a trained network to be used in real-time (<1 second), on unseen datasets, without the need for high-performance computing during data acquisition.

# Recent Developments in Multimode Multiple Scattering in Soft Media

**Valerie Pinfield**[1]
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Morning Session II, January 18, 2024, 11:20 - 13:00

We will consider the propagation of ultrasound in nano/microparticle suspensions consisting of randomly distributed solid particles in a viscous liquid which is a system relevant to industrial process monitoring and to the characterisation of soft materials e.g. biological media, and potentially offers opportunities for interesting metamaterials. An important and interesting characteristic of these systems is the existence of two wavenumbers of very different magnitudes in the continuous phase – the compressional and shear modes. For typical liquids at MHz frequencies, and with colloidal particles, the dimensionless compressional wavenumber (based on particle size) may be small whereas the dimensionless shear wavenumber can range from small to large and is always much larger than the dimensionless compressional wavenumber. In addition, we have another length scale that affects the multiple scattering, i.e. the interparticle separation; its effects are usually accounted for through the concentration or number density but it may be helpful to consider these effects in terms of additional dimensionless wavenumbers relating to the interparticle distance.

Recently, a new formulation for the effective wavenumber arising from multiple scattering in a multi-mode media was published (Luppe, Conoir & Valier-Brasier, Wave Motion 115 (2022) 103082). In this presentation, we will show analytical asymptotic results obtained from the model at long compressional wavelength (low frequency), but arbitrary shear wavelength for these soft media, highlighting the dominant wave-conversion and correlation contributions. We will show numerical results to validate the approximations made for this system and compare with experimental data.

# A methodology for large area inspection using reconfigurable Laser Induced Phased Arrays

**Don Pieris**[1], Peter Lukacs[1], Panagiotis Kamintzis[1], Theodosia Stratoudaki[1], Geo Davis[1]
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Afternoon Session IV, January 18, 2024, 15:50 - 17:26

Laser Induced Phased Arrays (LIPAs) combine the principles of laser ultrasonics and use lasers to generate and detect ultrasound. The lasers are scanned across a sample surface to acquire the data from varying element positions, and an array is synthesized in post-processing by applying a variety of ultrasonic imaging algorithms. Transducer-based phased arrays have a fixed geometry, number of elements, pitch and operational ultrasonic frequency. Whereas LIPAs present flexibility in array design and introduce the element of reconfigurability, where the array can be tailored to the requirements of the specific inspection scenario [1]. We have already demonstrated the potential of LIPAs for Non-Destructive Evaluation (NDE) [2]. This paper demonstrates how LIPAs can be used for large-area NDE inspections.

A two-stage data acquisition methodology, known as selective matrix capture (SMC), has been presented previously [3]. This methodology was developed to provide a step change in the LIPA inspection time to keep up with advanced manufacturing processes such as additive manufacturing [2]. The presentation will explore optimisations made to the first stage of the SMC methodology. In this first stage, a sparse array is synthesised to identify a Region of Interest (ROI) which may contain a defect. The sparsity of the array is iteratively decreased based on the information received during the scan. This paper explores how the first stage of the SMC process can be optimised by calculating the Probability of Detection (POD) of a ~1 mm defect in a metal sample. The POD is used to optimise the number of array elements required for reliable defect detection. This information is presented in a Receiver Operating Characteristic (ROC) curve by varying the acoustic threshold used to detect a region of interest.

This entire process is automated and used to demonstrate the improvement achieved in the current generation of LIPA inspections compared to the previous. This includes experimental results from a large area inspection using both the first stage (identification of ROI) and the second stage of the SMC process. The latter utilises the reconfigurable nature of the LIPA to create an array with a maximum sensitivity targeted at the ROI identified in the first stage. Finally, the above methodologies are demonstrated on the surface of an as-deposited wire-arc additive manufacturing (WAAM) component and used to detect a 1.2mm side drilled hole.

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