22nd International Symposium on Nonlinear Acoustics

4th – 8th July 2022

St Catherine's College
University of Oxford
Oxford, UK

https://isna22.web.ox.ac.uk

Programme

2022nd ISNA

Chair:
Robin Cleveland

Co-Chair:
Jason Raymond

Organising Committee:
Mark Hamilton, Philippe Blanc-Benon, Oleg Sapozhnikov

Sponsors:

ASA Acoustical Society of America

Department of Engineering Science

University of Oxford

Practical Information

Conference Venue
St Catherine's College, Manor Road, Oxford, OX1 3UJ

Contact the Lodge for general enquiries about the College. The Lodge is staffed 24 hours a day, seven days a week.

Tel: +44 (0)1865 271 700
Email: lodge@stcatz.ox.ac.uk

Accommodation
Check-in time: 14:00
Check-out time: 10:00

Breakfast
For those attendees staying at the College, a complimentary hot breakfast is served daily from 8:00-9:00 in the College Hall.

Lunch
Lunch is served in hall at 12:45 each day for all attendees (resident and day attendees).

Dinner

Monday: Welcome Reception and Dinner. The welcome reception will take place on the evening of Monday 4th of July at 17:30 in the Middle Common Room at the College, followed by dinner in the College Hall starting at 19:00.

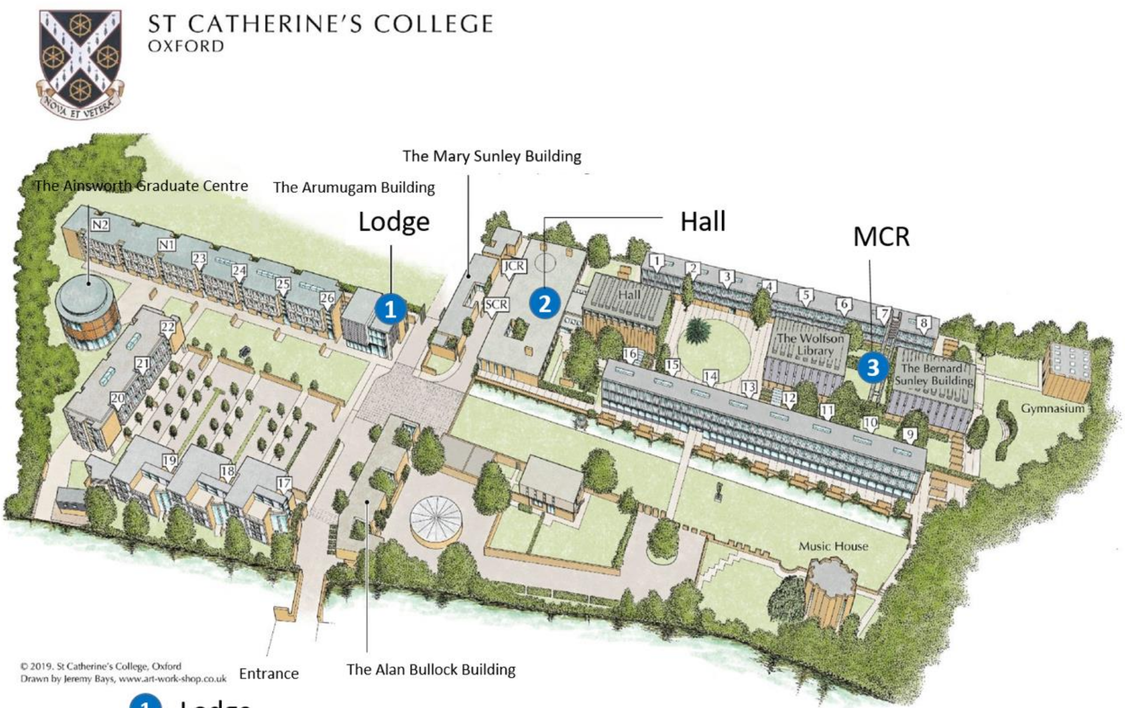
Tuesday: Free Evening/Pub Night. This is a free evening with no meal planned. One option would be to enjoy one of the many pubs in Oxford. A map with pubs is included is provided on page iv and a few highlighted pubs are listed. Note that table service is NOT standard procedure at a British pub; food is normally order and paid for at the bar. A typical procedure:

1. Find a table and note the number of the table and use items of clothing or a friend to hold the table.
2. Go to the bar and order your meal and drink. The bar tender will want your table number so that they know where the food is to be delivered. You pay at the bar and you can pay individually. You do not normally tip in a pub.
3. Get your drink from the bar-tender and then go back to your table and your food will be brought to you.

Wednesday Banquet Dinner The banquet dinner will take place on the evening of Wednesday 6th of July at 20:00 in the College Hall. Tickets for this should have been purchased separately.

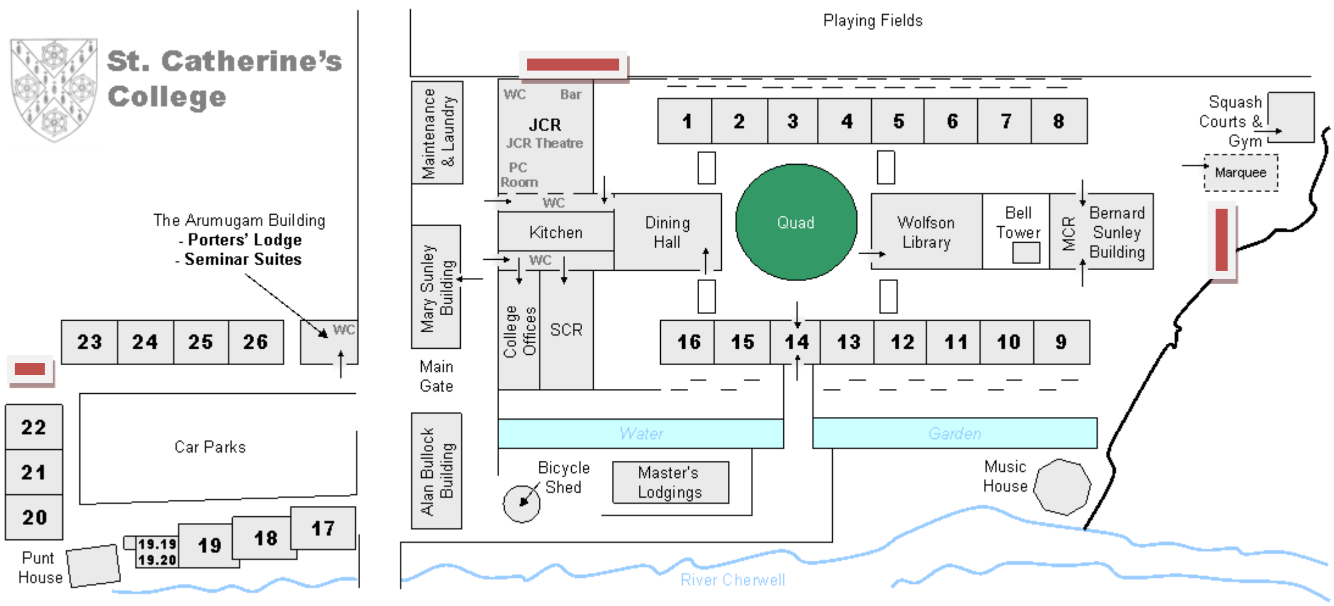
Thursday Dinner Attendees staying at the College are invited to attend dinner in the College Hall from 19:00 on Thursday 7th of July.

Site Map

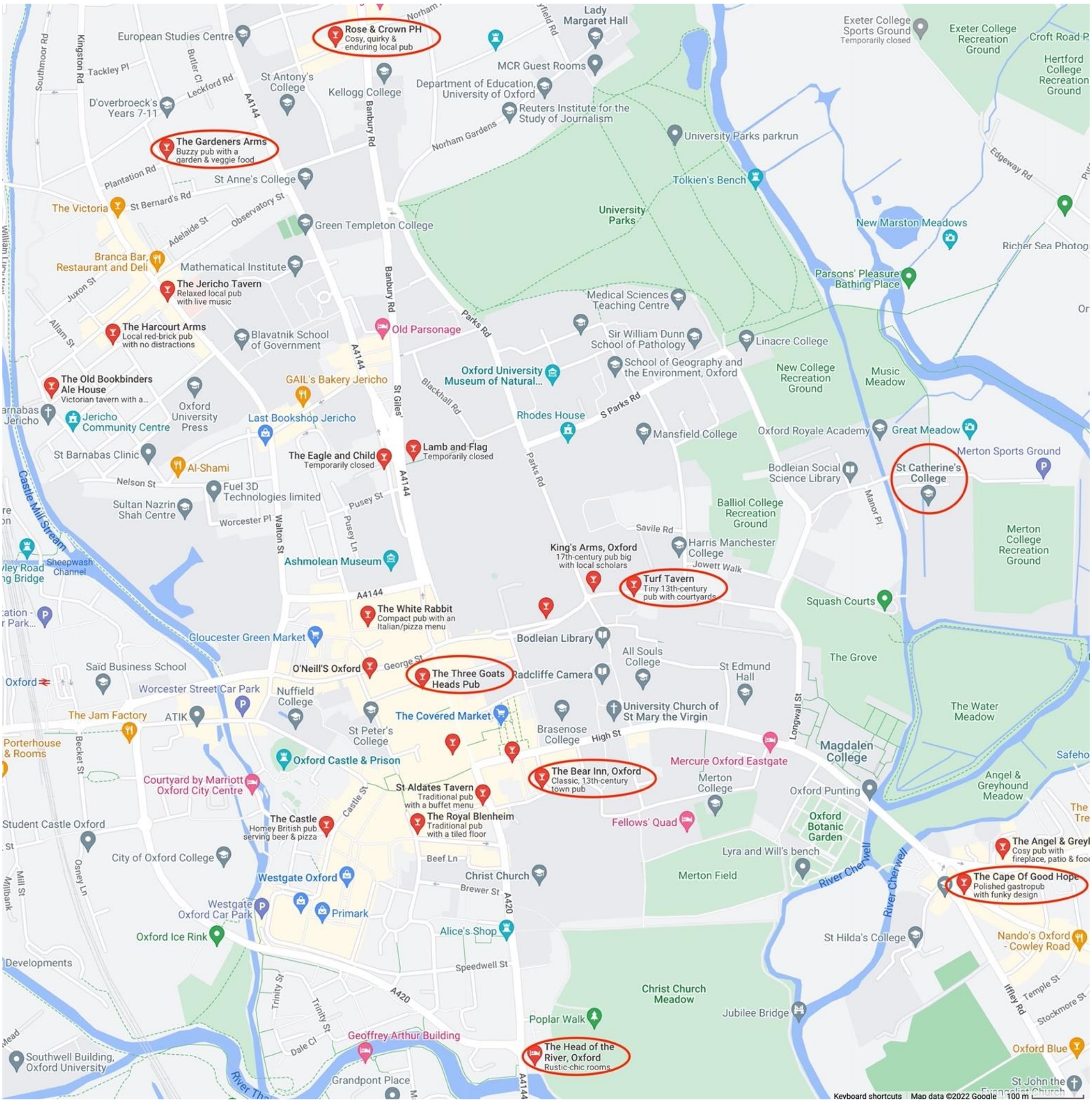


1. Lodge
2. Hall
3. MCR – Middle Common Room

College Accommodation Staircase Plan



Pub Map



Circled Pubs listed in order of increasing distance from St Catherine's College

- Turf Tavern (8 min), 4 Holywell St, Oxford OX1 3SU
- The Bear Inn (15 min), 6 Alfred St, Oxford OX1 4EH
- The Three Goats Head Pub (15 min), 3 St Michael's St, Oxford OX1 2DR
- The Cape of Good Hope (15 min), Iffley Rd, The Plain, Oxford OX4 1EA
- The Head of the River (23 min), Folly Bridge, St Aldgate's, Oxford OX1 4LB
- Rose & Crown Public House (23 mins), 14 N Parade Ave, Oxford OX2 6LX
- The Gardeners Arms (25 mins), 39 Plantation Rd, Oxford OX2 6JE

Note both The Lamb and Flag pub and The Eagle and Child pub are closed.

Committees

Symposium Organising Committee

R. O. Cleveland (UK), Symposium Chair
J. L. Raymond (UK), co-Chair
M. F. Hamilton (USA)
Ph. Blanc-Benon (France)
O. A. Sapozhnikov (Russia)

International Advisory Committee

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Ph. Blanc-Benon (France)
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L. A. Ostrovsky (USA/Russia)
O. A. Sapozhnikov (Russia)
I. Yu. Solodov (Germany/Russia)
T. Yano (Japan)
D. Zhang (China)

List of Participants

D. Andrés	Technical University of Valencia
A. Athanassiadis	Heidelberg University
A. Argüelles	Pennsylvania State University
R. Beltrán	TU Dresden
B. Carles	Sorbonne University
A. Casacchia	University of Texas at Austin
X. Cheng	University of Oxford
R. Cleveland	University of Oxford
J. Cormack	University of Pittsburgh Medical Center
F. Coulouvrat	Sorbonne University
C. Coussios	University of Oxford
B. Cox	University College London
L. Crum	University of Washington
V. Daru	Arts et Métiers ParisTech
W. Domanski	Military University of Technology, Poland
D. Dragna	University of Lyon
B. Drinkwater	University of Bristol
M. Foster	University College London
P. Ghodake	Indian Institute of Technology Bombay
C. Gokani	University of Texas at Austin
M. Haberman	University of Texas at Austin
M. Hamilton	University of Texas at Austin
T. Heimburg	University of Copenhagen
D. Hughes	Naval Undersea Warfare Center, USA
C. Inserra	University of Lyon
T. Jerome	University of Texas at Austin
N. Jiménez	Technical University of Valencia
P. Johnson	Los Alamos National Laboratory
D. Kartofelev	Tallinn University of Technology
K. Kaufmann	Apoha Limited
V. Khokhlova	University of Washington/Moscow State University
J. Kober	Czech Academy of Sciences
M. Koch	University of Göttingen
M. Korman	United States Naval Academy
M. Kreutzbruck	University of Stuttgart
T. Krit	Moscow State University
C. Kube	Pennsylvania State University
J. Kwan	University of Oxford
J. Lonzaga	NASA Langley Research Center
G. Marcucci	Apoha Limited
A. Matalliotakis	Delft University of Technology
R. Mettin	Georg August University Göttingen
M. Mussel	University of Haifa
E. Niri	New Mexico State University
Y. Ohara	Tohoku University
A. Pavlic	ETH Zurich
A. Perrin	Aix-Marseille University
J. Qu	Stevens Institute of Technology
J. Raney	University of Pennsylvania

J. Raymond	University of Oxford
M. Régis	Sorbonne University
P. Rendon	National Autonomous University of Mexico
J. Rivière	Pennsylvania State University
R. Roy	University of Oxford
Z.E. Saib	University of Bristol
É. Salze	University of Lyon
O. Sapozhnikov	University of Washington/Moscow State University
M. Scalerandi	Polytechnic University of Turin
D. Shimizu	Fukui University of Technology
S. Shrivastava	Apoha Limited
B. Simon	University of Texas at Austin
K. Suslick	University of Illinois at Urbana-Champaign
T. Szabo	Boston University
M. Tafkirte	Ibn Zohr University
T. Ulrich	Los Alamos National Laboratory
L. Usadi	University of Oxford
M. Verweij	Delft University of Technology
M. Vilipuu	Tallinn University of Technology
S. Vincent	Sorbonne University
G. Wahyulaksana	Erasmus Medical Center
W. Willis	University of Texas at Austin
C. Wong	University of Oxford
R. Zeman	Czech Academy of Sciences
S. Zendehroud	Free University of Berlin

Programme Schedule

Monday, 4th July	
09:00 10:30	Short Course: Nonlinear Acoustics
10:30 11:00	Break
11:00 12:30	Short Course: Nonlinear Acoustics
12:45 14:00	Lunch
14:00 15:30	Short Course: Computational Acoustics
15:30 16:00	Break
16:00 17:30	Short Course: Computational Acoustics
17:30	Welcome Reception

Tuesday, 5th July	
09:00 09:30	Opening Ceremony
09:30 10:15	Session 1: Physics
10:15 10:45	Break
10:45 11:45	Session 2: Metamaterials
11:45 12:30	Plenary Session
12:45 14:00	Lunch
14:00 15:45	Session 3: Physics/Streaming
15:45 16:15	Break
16:15 17:45	Session 4: Radiation Force
	Free (Pub Night)

Wednesday, 6th July	
09:00 10:15	Session 5: Cavitation
10:15 10:45	Break
10:45 11:45	Session 6: Cavitation
11:45 12:15	Plenary Session
12:45 14:00	Lunch
14:00 15:30	Session 7: Computation
15:30 16:00	Break
16:00 17:30	Session 8: General
20:00	Banquet

Thursday, 7th July	
09:00 10:00	Session 9: Biomedical
10:00 10:30	Break
10:30 11:45	Session 10: Membranes
11:45 12:30	Plenary Session
12:45 14:00	Lunch
14:00 15:45	Session 11: NDE
15:45 16:15	Break
16:15 17:30	Session 12: NDE/Rocks
19:00	Dinner

Friday, 8th July	
09:00 10:30	Session 13: Solids
10:15 10:45	Break
10:45 11:45	Session 14: Atmospheric Acoustics
12:45 14:00	Lunch

11:45 Departure for Tour of First Light Fusion

MONDAY, 4th July

Short Courses

09:00 – 10:30	**Short Course on Nonlinear Acoustics** Robin Cleveland, Mark Hamilton, and Oleg Sapozhnikov
10:30 – 11:00	**Break**
11:00 – 12:30	**Short Course on Nonlinear Acoustics** Robin Cleveland, Mark Hamilton, and Oleg Sapozhnikov
12:45 – 14:00	**Lunch**
14:00 – 15:30	**Short Course on Computational Acoustics** Bradley Treeby and Ben Cox
15:30 – 16:00	**Break**
16:00 – 17:30	**Short Course on Computational Acoustics** Bradley Treeby and Ben Cox

TUESDAY, 5th July

09:15 – 09:30 **Opening Ceremony**

Session 1: Physics
Chairperson: R. Cleveland

10:15 – 10:45 **Break**

Session 2: Metamaterials
Chairperson: M. Haberman

Plenary Session
Chairperson: TBA

11:45 – 12:30 **Nicholas Hawker, First Light Fusion**

12:45 – 14:00 **Lunch**

Session 3: Physics/Streaming
Chairperson: O. Sapozhnikov

WEDNESDAY, 6th July

Session 5: Cavitation
Chairperson: J. Raymond

Session 6: Cavitation
Chairperson: L. Crum

Plenary Session
Chairperson: TBA

Session 7: Computation
Chairperson: B. Cox

THURSDAY, 7th July

Session 9: Biomedical
Chairperson: M. Grey

Session 10: Membranes
Chairperson: S. Shrivastava

Plenary Session
Chairperson: TBA

Session 11: NDE
Chairperson: TBA

Session 12: NDE/Rocks
Chairperson: P. Johnson

FRIDAY, 8th July

Session 13: Solids
Chairperson: TBA

Session 14: Atmospheric Acoustics
Chairperson: R. Cleveland

A helicoidal parametric antenna for subwavelength vortex generation

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[2] School of Mechanical Engineering, Universidad del Valle, Cali, Colombia.
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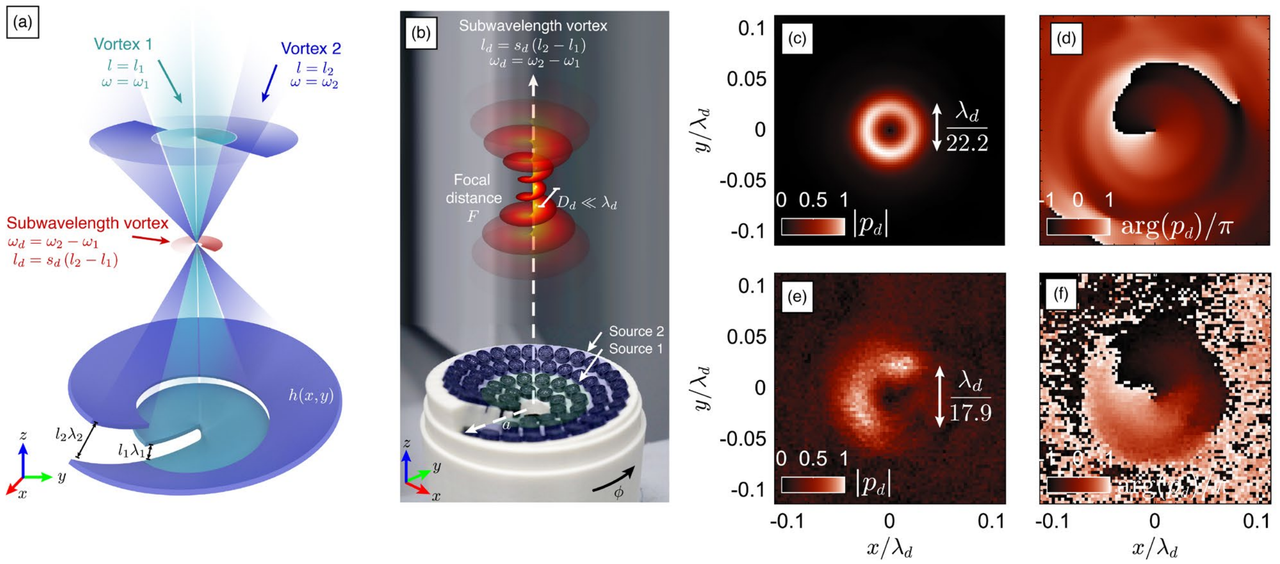
ABSTRACT
The natural diffraction of acoustic vortex beams results in vortices whose bright core is larger than the wavelength, limiting their use for practical applications such as long-range underwater communications. In this work, we synthesize a vortex beam of sub-wavelength size at a distance beyond Rayleigh diffraction length using the nonlinear mixing of two confocal, high-frequency and detuned vortex beams of different topological charges. A helicoidal focused acoustic source with two different curvatures is used to generate a pair of finite-amplitude vortex beams. A difference-frequency component emerges due to nonlinearity. By tuning the primary beams a low-frequency beam of integer topological charge is observed, whose distance between magnitude maxima is about 18 times smaller than its wavelength at a distance about 3 times the Rayleigh diffraction length. Subwavelength vortices of arbitrary topological charge emerge due to the spatiotemporal interference of two primary vortex beams and due to the conservation of angular momentum during nonlinear wave-mixing. This mechanism opens new venues to design directive parametric antennas for vortex transceivers or particle manipulation systems at scales well below the diffraction limit.



CAPTION: (a-b) Scheme and photograph of the experiment of the helical surface to focus two confocal vortex beams. (c-f) Transverse field cross-section at the focal spot showing the normalized magnitude and the normalized phase obtained numerically and experimentally, showing the subwavelength vortex at the difference-frequency component, respectively.

Manipulation of macro-scale objects using amplified secondary Bjerknes forces

Athanasios G. Athanassiadis[1], Rahul Goyal[1], Zhichao Ma[1], Peer Fischer[1,2]
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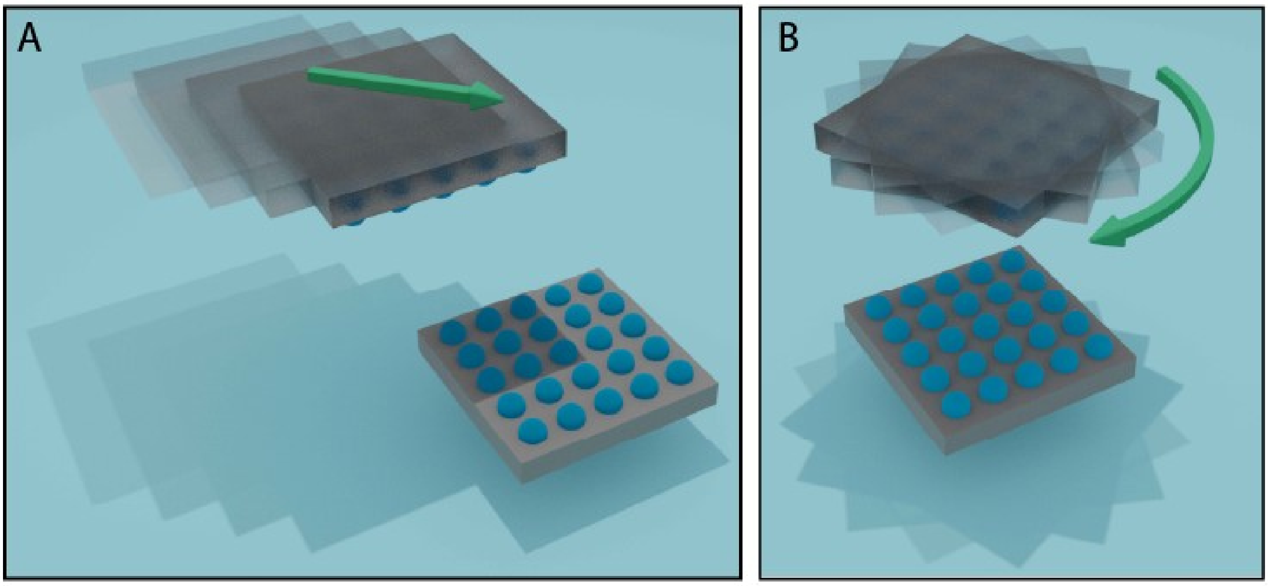
ABSTRACT

Gas bubbles can demonstrate unique and interesting behaviors in a sound field that range from strong scattering, to jetting, to mutual attraction. The mutual attraction of bubbles is a nonlinear phenomenon – driven by the secondary Bjerknes force – that can lead to the formation of intricate and complex 3D patterns in bubbly media. However, the Bjerknes force between two bubbles is extremely weak – typically in the nanonewton range – and thus has been largely ignored outside of the context of bubble clouds. Here, we demonstrate that patterning microbubbles into arrays can geometrically amplify the secondary Bjerknes forces, producing surprisingly high forces. These forces can be increased enough to enable precise, subwavelength assembly and manipulation of centimeter-scale objects in a fluid. We experimentally demonstrate the ability of a Bjerknes actuator to precisely position a 1 cm object with 15 µm accuracy, using sound with a 50 cm wavelength. We further show that, by modifying the bubble patterns, the Bjerknes actuator can act as a non-contact rotational motor, driving unidirectional motion of a freely-floating structure. We describe the amplification and manipulation behavior using a theoretical model, and show that a manipulator using amplified Bjerknes forces would outperform comparable magnetic actuators.



A Bjerknes actuator consisting of two arrays of microbubbles can be used for non-contact ultrasonic (A) alignment and (B) rotation of a freely-floating structure in a liquid. The secondary Bjerknes forces between bubbles are amplified by patterning the bubbles into arrays, making it possible to manipulate centimeter-scale objects using 100 micron-scale bubbles.

String collision and sliding against a smooth obstacle in a non-planar vibration setting

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ABSTRACT

This paper proposes a model of a plucked ideal string free to vibrate in two mutually perpendicular planes in the presence of a curved obstacle. We consider an obstacle which spans both in the direction of the string at its rest and perpendicular to it. The obstacle, mainly spanning perpendicularly to the string, is essentially a rod with a curved cross-section. The string collisions against the obstacle are modelled using a kinematic model that constrains the string displacement unilaterally. The string sliding against the obstacle surface is modelled using a dry sliding friction model proposed by Jim Woodhouse. The sliding friction model is coupled with the collision model. The *virtual* reaction force of a collision is used as an input into the dry sliding model. A *virtual* compression of the obstacle material is used to find the collision force. For simplicity, the material is assumed to be linearly elastic, capable of accepting forces in a single direction only, and lacking internal bulk or shear forces. Numerical simulation results show that the model can generate a rich variety of dynamics all strongly dependent on the selection of initial conditions and system parameters. This nonlinear model is numerically robust due to the used simplifying assumptions. Interactions of a vibrating string with spatially distributed barriers, such as fretboards, play a significant role in the physics of many stringed musical instruments. It is believed that the proposed model can be applied to sound synthesis and physics-based modelling of these musical instruments.

ACKNOWLEDGEMENTS

This work was supported by the Estonian Ministry of Education and Research (PRG1227), EU through the European Regional Development Fund.

Collisions of vector solitons in flexible mechanical metamaterials

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ABSTRACT
Flexible mechanical metamaterials are compliant structures designed to achieve desired mechanical properties via large deformation or rotation of their components. While their static properties (such as Poisson's ratio) have been studied extensively, much less work has been done on their dynamic properties, especially nonlinear dynamic properties induced by large movement of internal components. Here, we examine the nonlinear dynamic response arising from impact loading of mechanical materials that consist of 1D and 2D arrangements of rotating squares, which leads to formation of vector solitons. Permanent magnets are added to the squares, which causes the metamaterial to become multistable. Rotations of the squares can thereby lead to sudden rearrangements of squares into new phases. We experimentally and numerically characterize the collisions of vector solitons in these flexible mechanical metamaterials. Depending on their amplitude and chirality, these collisions can induce phase transitions that propagate outward from the nucleation site.

ACKNOWLEDGEMENTS
This work is supported by the U.S. National Science Foundation award number 2041410.

Do Periodic arrangement of Nonlinear Local Damages act as Nonlinear Metamaterials?

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ABSTRACT

Interaction of longitudinal wave with nonlinear circular inclusion shows a harmonic scattering of longitudinal and transverse waves around the inclusion. Amplitudes of higher harmonics of harmonically scattered waves are sensitive to the angle of scattering from the inclusion as seen from the theoretical solutions obtained by Kube (2018). The interaction of such multiple harmonically scattered waves from multiple nonlinear inclusions is complex and challenging to study through theoretical and experimental perspectives. In this paper, finite elements studies are carried out to understand the effect of periodically arranged circular (Figure 1) and square inclusions in different configurations. Figure 2 demonstrates that particular values of inclusion radius and intermediate spacing configuration 3 (C_3) don't show the generation of higher harmonics despite having more number of inclusions. The only reason behind such response is the cancellation of 2nd harmonics due to interference of multiple harmonically scattered waves, whereas though the harmonics of transverse modes near the inclusions are present they don't propagate up to the edge 2 (E_2) for all three configurations (C_1, C_2, & C_3). Configuration 4 is designed such that along with the longitudinal modes (Figure 3) the transverse modes (Figure 4) of the harmonically scattered waves are also dominant. Static terms in harmonical responses show their high sensitivity towards all the configurations.

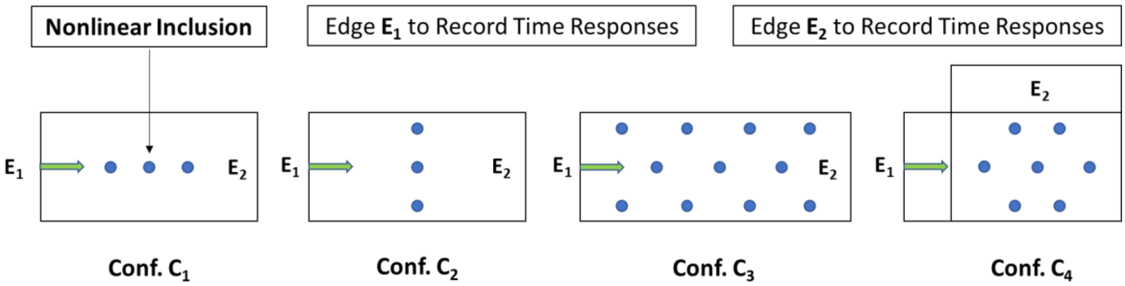

Figure 1. Different configurations of local circular damages modeled as nonlinear elastic material having the same linear impedance as linear steel considered for finite element studies to demonstrate interesting responses similar to metamaterials such as enhancing nonlinear effects

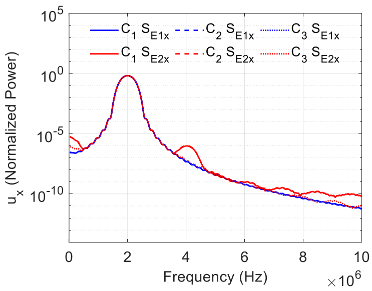

Figure 2. Comparing frequency responses of longitudinal waves noted at E_1 and E_2 of three configurations (C_1, C_2, & C_3). (**transverse waves are absent**)

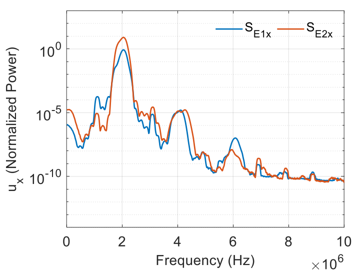

Figure 3. Frequency responses of longitudinal waves were noted at E_1 and E_2 of configuration C_4. (**transverse waves are present** (Figure 4))

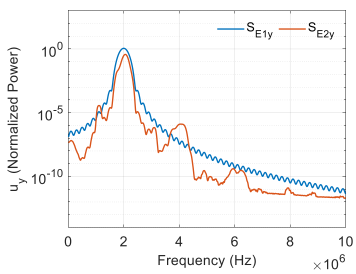

Figure 4. Frequency responses of transverse waves were noted at E_1 and E_2 of configuration C_4 due to multiple harmonic scatterings from nonlinear circular inclusions.

ACKNOWLEDGEMENTS

I would like to thank the Acoustical Society of America (ASA) for support through the student grant and the Indian Institute of Technology Bombay for the support through institute scholarship.

Pulse attenuation from acoustic resonances in nonlinear metamaterials with rough contacts

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ABSTRACT

Solitary waves are nonlinear pulses that are formed in strongly nonlinear periodic media from a delicate balance between dispersion and nonlinearity. While these waves are extensively studied in nonlinear metamaterials at low excitation frequencies, the understanding of their propagation characteristics at high-frequency excitations is still emerging. In this talk, we discuss the propagation of solitary waves in layered metamaterial with rough interfaces, importantly, at excitations of the orders of layer resonances. We present insights into how the energy distribution and propagation through this metamaterial depend on excitation frequency. Specifically, we show that solitary waves in this metamaterial are strongly attenuated for frequencies associated with the acoustic resonances of layers. Such unconventional nonlinear response is attributed to the unique architecture of the metamaterial, which is elastic continua (layers) coupled through nonlinear features (rough contacts) locally. These observations reveal that despite being strongly nonlinear, such metamaterials show regions of frequencies of attenuation equivalent to bandgaps of linear metamaterials. In fact, our study shows that the wave dynamics of the metamaterial drastically change at high excitation frequencies. Such understanding is crucial for these metamaterials to be used for controlling the propagation of mechanical wave energy.

ACKNOWLEDGEMENTS

This work was supported by the Army Research Office (U.S.) and was accomplished under Grant No. W911NF-20-1-0250. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for U.S. Government purposes notwithstanding any copyright notation herein.

Numerical analysis of the limits of effective medium theory for nonlinearly propagating waves

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ABSTRACT
The use of acoustic metameterials is an increasingly popular approach to controlling both linear and nonlinear sound propagation. In this approach, heterogeneous structures are engineered to behave as predetermined, and often exotic, continuous medium. A key requirement for a system to be accurately approximated as a homogeneous material for wave motion is that the smallest length scale of the waveform be much larger than any length scale associated with the microscale structure of the system. However, the fact that the characteristic length scales of a finite-amplitude waveform can change due to nonlinear effects (e.g., waveform distortion and shock formation) means that care must be taken when analyzing such signals in an acoustic metamaterial. This talk presents recent work toward understanding the breakdown of effective medium theory as finite-amplitude waves propagate in a heterogeneous system and weak shocks begin to form. A finite-element analysis software package was used to model the propagation of a pulse of sound in a one-dimensional heterogeneous domain using both a full description of the system and an effective-medium description. The difference between the solutions of the two models throughout propagation and shock formation provides a method by which one can estimate the error associated with using effective properties as a function of propagation distance as well as identify how those errors manifest themselves.

Influence of grain size on slow dynamics in hysteretic elastic media

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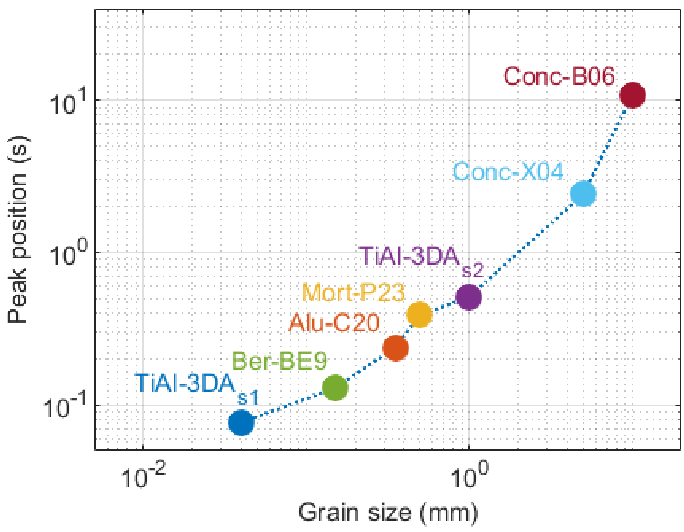
ABSTRACT
Slow dynamics in hysteretic elastic media (rocks, concrete, damaged composites and metals) consists in the dependence of elastic material properties on the stress history. When a material is subject to an external perturbation (strain ranges in the order of 10^{-6} or even lower), immediately after its removal a wave velocity drop is observed, with a variation of the order of up to a few percent. Slowly in time, velocity relaxes back to its original unperturbed value.
As we show here, relaxation can be described as a multi-relaxation process, i.e. as the superposition of infinite relaxation processes with a distribution of relaxation times, which can be inferred by inversion of experimental data. The main properties of the distribution are experiment independent and can be linked to spatial features at the material microscale. In particular, the most relevant relaxation time correlates well with the grain size, as shown considering materials with grains spanning more than two decades in size, from metals to civil engineering concrete.



CAPTION: Most relevant relaxation time vs. grain size for metal alloys (Titanium-Aluminum alloy and intact Aluminum alloy), sandstones (Berea), mortar and concrete (with different sand and gravel size).

Numerical simulation of a heat flow due to thermoacoustic oscillations in a looped tube

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[2]Department of Mechanical Engineering, Graduate School of Engineering, Osaka University, Suita, Osaka, Japan
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ABSTRACT
Numerical simulation is performed to examine a heat flow due to thermoacoustic oscillations in a looped tube with a stack subjected to a temperature gradient. Heat exchangers with hot and cold (ambient) heat baths are installed in contact with the stack at both ends. Use is made of the one-dimensional wave equations derived previously by assuming a thin and thick diffusion layers, which are applicable, respectively, to a flow passage in the outside of the pore in the stack and in the inside of it. At the ends of the stack and the heat exchangers where an abrupt change in the cross-section occurs, influences of flow separation and vortex shedding occurring in the vicinity of the ends is taken into account in a one-dimensional hydraulic model. Such a domain that these influences are dominant is confined in a narrow axial interval comparable with the diameter of the flow passage. Therefore it is taken into account through the matching conditions at the ends of the heat exchangers where the continuity of mass, momentum and energy fluxes is required. It is found that the onset of instability is well simulated up to saturation of the pressure, and that the heat flow to and from the heat baths is also obtained. It is then revealed that the heat flow steps up with a delay over hundreds of periods behind that of the excess pressure, although the growth rate is higher than that of the excess pressure, and that a thermoacoustic streaming is available.

ACKNOWLEDGEMENTS
This work was supported by the Japan Society for the Promotion of Science (JSPS KAKENHI Grant Nos. 21K03863 and 18H01375).

Intricate coupling between Rayleigh streaming and heat transfer: a theoretical and numerical study

V. Daru[1], C. Weisman[2], D. Baltean-Carlès[2] and H. Bailliet[3]
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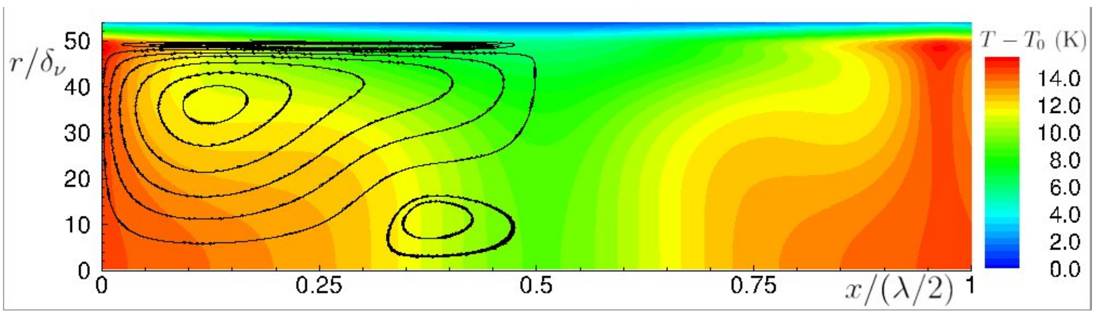
ABSTRACT
Coupling between acoustically induced thermal effects and Rayleigh streaming in a standing wave guide is investigated analytically and numerically. Firstly, analytical expressions for acoustic and streaming flows are developed showing the influence of a transverse temperature gradient. The latter modifies the Rayleigh streaming pattern and may generate reverse streaming cells. Secondly, the longitudinal temperature gradient due to thermoacoustic heat transfer in the fluid is calculated depending on the properties of the solid wall. At high acoustic levels, the average temperature field is reorganized due to convective transport by the streaming flow, which produces a transverse temperature gradient. All these combined result in the establishment of an analytical criterion for the transition in streaming patterns at high acoustic levels. A numerical configuration is then introduced to assess the validity of this criterion. The resonator is designed to be inharmonic, as in experiments, to inhibit the development of shock waves that have important effects on the thermal field. The heat conduction is accounted for in the wall. As the acoustic level is increased, the average temperature field becomes stratified transversely and reverse streaming cells appear near the acoustic velocity antinodes, as predicted with the analytical criterion. For higher acoustic levels, these different cells evolve into increasingly large stagnant zones, where the mean temperature is stratified longitudinally. The numerical results confirm the analytical prediction and previous experimental observations, showing that the intrinsic coupling between the thermal effects and acoustic streaming at high levels is very well described.



CAPTION: Contours of the average temperature difference $T-T_0$ (K) at steady state, with the heat conduction solved in the wall, in an axisymmetric representation (λ = wavelength, δ_ν= viscous boundary layer thickness). Streamlines of the streaming flow are represented in the left part of the figure. Computations are performed at high acoustic level, Re_{NL} = 66.5.

GHz acoustic streaming for the synthesis of ultra-thin high speed streaming jets: a numerical study

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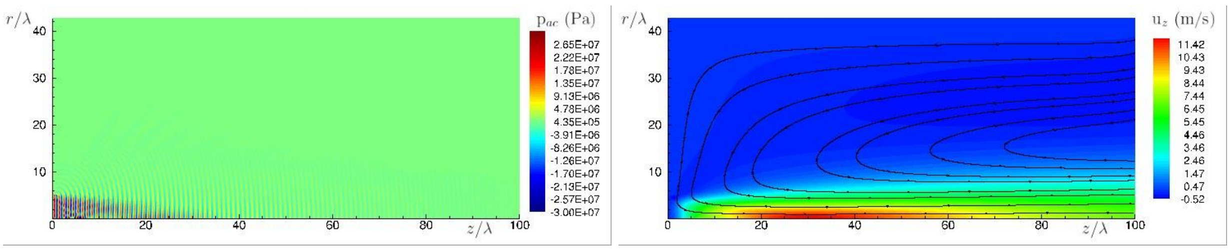
ABSTRACT
GHz acoustics has a great potential for particles manipulation at microscales [1] and nanoscales [2], cells permeabilization [3], and biosensing [2]. Indeed, GHz acoustics enables to generate high speed ultra-thin streaming jets that can be used to trap objects by using hydrodynamics forces or exert a localized controlled force on an interface. Yet the theoretical and numerical study of acoustic streaming at these frequencies is still at its infancy. In particular unsteady effects occurring when the source is turned on have not been explored in the litterature. In this presentation, direct numerical simulations of acoustic streaming are conducted with high order explicit numerical schemes for frequency ranging from 100 MHz to a few GHz. These simulations are used to show (i) how the physics and in particular the source terms are modified when the attenuation length becomes close to the wavelength, (ii) how the steady regime is reached at the different frequencies, and (iii) how the width of the streaming jet evolve with the lateral extent of the transducer and the driving frequency. We conclude that ultra-localized streaming jets can only be obtained at very high frequency.

ACKNOWLEDGEMENTS
This work is supported by Institut Universitaire de France.



CAPTION: Numerical simulation of the acoustic field radiated by a piston of lateral extent $\mathrm{r} = 5\,\lambda$ at 1GHz. Left: Contours of the instantaneous pressure field. Right: Contours of the axial velocity component and streamlines of the average flow (streaming) produced by this acoustic field.

[1] X. Guo et al., IEEE Int. Conf. Rob. Autom., 11392 (2020)

[2] W. Cui, L. Mu, X. Duan, W. Pang and M. A. Reed, Nanoscale 11: 14625 (2019)

[3] X. Guo et al., Adv. Sci., 8 :2002489 (2021)

Numerical study of the acoustic streaming induced by a high frequency, focused vortex single beam, acoustic tweezers

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ABSTRACT
Acoustic vortices are three-dimensional wave beams with a helical phase. Their study has recently led to the development of a new contactless manipulation method: single-beam acoustic tweezers, based on high-amplitude focused vortices that generate three-dimensional and selective restoring forces by the mean of acoustic radiation pressure.

Acoustic tweezers offer promising possibilities for biological applications, such as the direct manipulation of cells, or the study of their mechanical properties. For this purpose, the frequency of the existing systems must be increased significantly. Another non-linear phenomenon is then amplified: the flow induced by the viscous attenuation of waves in the bulk, Eckart streaming. This flow, which can disrupt the acoustic manipulation, must be characterized. Due to the complex geometry of focused vortices, the prediction of streaming from acoustic quantities is poorly understood and is the subject of this study.

Numerical simulations based on a decomposition of the time scales are proposed. First, the 3D acoustic field is computed and then used as a source term in CFD simulations.

This allows to predict the structure of the flow and quantify its velocity from the amplitude of the acoustic vortex and its topological charge. Finally, these results are used to study the high-frequency behavior of an acoustic tweezers operating in water at 50 MHz on glass beads of about ten micrometers, close to a cell size.

Dependence of the acoustic radiation force and microstreaming on the material and shape of a particle in an ultrasonic standing wave

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ABSTRACT
We investigate the microstreaming around a small solid elastic particle in an ultrasonic standing wave, and its influence on the acoustic radiation force, in dependence of material properties and shape of the particle. The considered configuration is limited to axisymmetric particle shape and orientation, and therefore accessible to numerical methods. The results of a finite element method study reveal a transition from viscous scattering- to microstreaming-dominated regime of the acoustic radiation force that depends on the particle density. Furthermore, as a deviation of the particle shape from a sphere becomes smaller than the viscous boundary layer thickness, we show that the influence of the shape on the viscous contributions to the acoustic radiation force diminishes, allowing the use of analytical viscous models for a spherical particle. However, extreme asymmetric shape perturbations, such as crowns with sharp edges, can give rise to noticeable viscous contributions for a dense particle larger than the viscous boundary layer thickness. We also introduce a hybrid analytical model for the acoustic radiation force on a spherical particle that accounts for the microstreaming and particle compressibility, and shows a good agreement with numerical simulations for an arbitrary particle size and density.

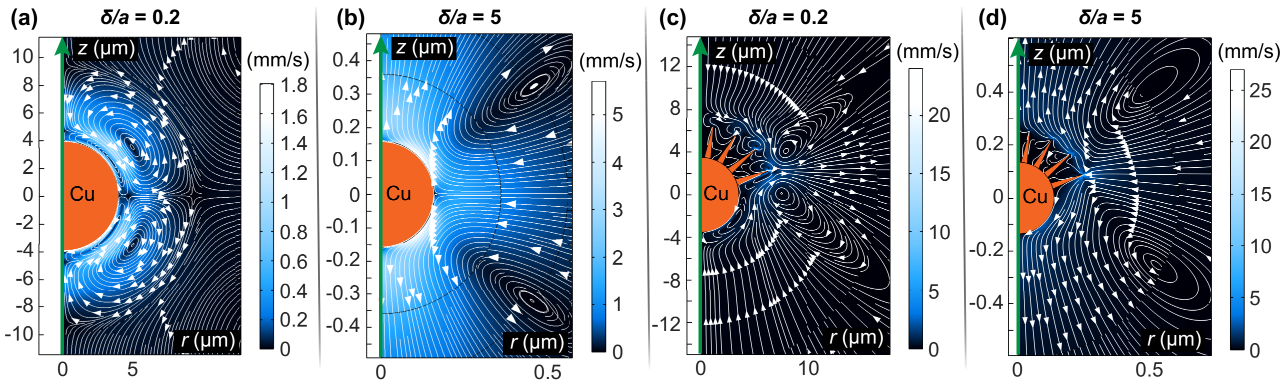

Figure 1: Influence of the size and shape of a particle on the Eulerian microstreaming patterns. The copper (Cu) particle of radius a is submerged in water, positioned in the middle between the pressure node and antinode of a standing wave with an amplitude of 500 kPa and a frequency of 500 kHz, yielding $\delta = 0.74$ μm. The configuration is axisymmetric, with the pressure gradient of the standing wave oriented parallel to the z-axis, axis of symmetry. (a), (c) and (b), (d) show the microstreaming around a larger ($\delta/a = 0.2$) and a smaller particle ($\delta/a = 5$), respectively. A comparison of particles of spherical shape in (a), (b) with the particles of equivalent volume with protruding crowns with sharp edges in (c), (d) reveals that the magnitude and the directionality of the microstreaming around the larger particle ($\delta/a = 0.2$) are heavily influenced by the particle shape, whereas they are largely unaffected by the particle shape near the smaller particle ($\delta/a = 5$).

A model of array-based ultrasonic mid-air haptics

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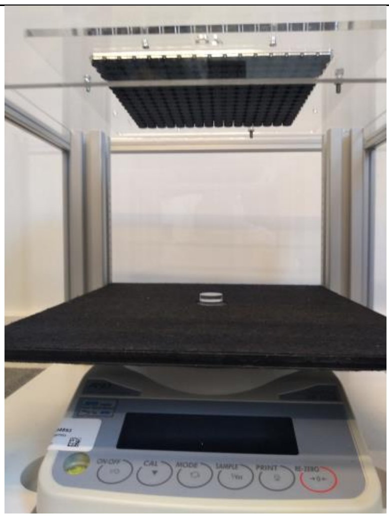
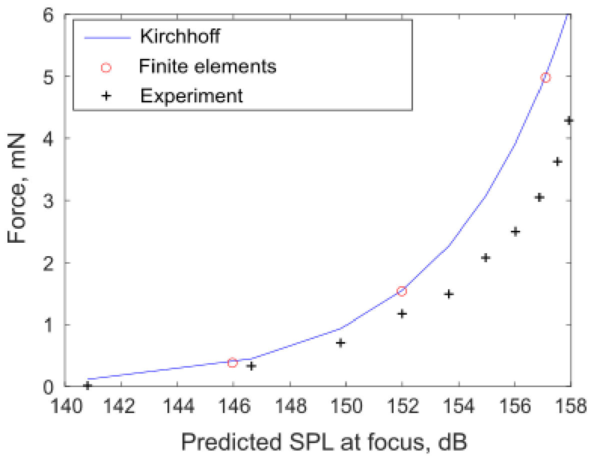
ABSTRACT

Mid-air ultrasonic haptics typically uses a phased array of ultrasound emitters to apply a force to a human hand and thereby create a haptic effect leading to the illusion of the presence of a physical object. It is used for human-computer interaction applications such as virtual reality. Here, the forces due to an array of 40kHz emitters is explored. The haptic effect is achieved by focusing the ultrasound beam to a point to create a high intensity local region. A force then occurs when an object, such as a human hand, is positioned at the focus of the ultrasound beam. In this scenario, the momentum of the sound wave is transferred directly to the object and the haptic force is governed by the ultrasonic intensity. The illusion of extended objects can be created by scanning the focal point over the hand. The high intensities at the focus also create flows in the form of acoustic streaming where some of the wave momentum is absorbed by the air leading to a forcing and hence a flow. This paper describes a model of these processes based on linear acoustics models, followed by application of the momentum flux integral to predict the forces and numerical fluid mechanics models to predict the flows. This modelling approach is shown to be in good agreement with measured forces suggesting that it captures the governing physics.

ACKNOWLEDGEMENTS

Supported financially by the Royal Society and the Wolfson Foundation. Thanks go to Drs Rob Malkin and William Frier of Ultraleap ltd, Bristol, UK, for useful discussions, supply of the experimental equipment and help with the experiments.





CAPTION: The left panel shows a phot of the experimental set up with array mounted at the top and a force balance at the bottom. The right panel shows a comparison between the model and the experiment.

Born approximation of acoustic radiation force and torque

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ABSTRACT
The Born approximation provides a simple method for calculating acoustic radiation force and torque on compressible objects of arbitrary shape and including material inhomogeneity. This approximation was introduced at the 2018 ISNA in Santa Fe, and the current presentation will review subsequent developments and applications of this approach. The Born approximation avoids solving for the total scattered field, and instead expresses the radiation force and torque as integrals of the monopole and dipole scattering forces throughout the volume of the object. A requirement is that the specific acoustic impedance throughout the object does not differ significantly from that of the background fluid. Also, the incident field must not be too similar to a progressive plane wave, because the approximation is associated with the radiation forces due to energy density gradients in the incident field. Comparisons with a complete theory for radiation force and torque on compressible spheroids, based on expansions of the incident and scattered fields in spheroidal wave functions, indicate that the Born approximation is accurate for impedance contrasts up to at least 30%. Comparisons also reveal that the size of the spheroid may be on the order of a wavelength. The derivation, validation, and applications of the Born approximation are reviewed. Closed-form solutions for spheres and finite cylinders are presented, and for selected distributions of material inhomogeneity. Applications include acoustofluidic separation of biological entities, and acoustic forces on irregularly shaped objects near interfaces. The approximation also serves as a useful benchmark for other methods of calculation.

ACKNOWLEDGEMENTS
TSJ was supported by the Applied Research Laboratories Chester M. McKinney Graduate Fellowship in Acoustics.

Born approximation of acoustic radiation force used for acoustofluidic separation

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ABSTRACT
Acoustofluidic separation often involves biological targets with specific acoustic impedance similar to that of the host fluid, and with dimensions on the order of the acoustic wavelength. This parameter range, combined with the use of standing waves to separate the targets, lends itself to use of the Born approximation for calculating the acoustic radiation force. Considered here is the configuration analyzed by Peng et al. [J. Mech. Phys. Solids **145**, 104134 (2020)], in which two intersecting plane waves radiated into the fluid by a standing surface acoustic wave exert a force on a eukaryotic cell modeled as a sphere surrounded by two concentric spherical layers. The angle at which the two plane waves intersect is determined by the surface wave velocity in the substrate and the sound speed in the fluid. The acoustic field in this case is a standing wave parallel to the substrate and a traveling wave perpendicular to the substrate. For all parameter values considered by Peng et al., including spheres several wavelengths in diameter, the Born approximation of the acoustic radiation force parallel to the substrate is in good agreement with a full theory based on spherical wave expansions of the incident and scattered fields.

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Acoustic radiation force equations for broadband applications in frequency power law media

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ABSTRACT

Two widely acoustic radiation force relationships: one for radiation force balances, (F=W/c, W= transmitted power and c, the speed of sound) and another for radiation forces in tissues, frequently employed for shear wave elastography,($F= (\alpha/c)\ [I_0 \exp(-2\alpha\ z)]$, where α is absorption per distance, z is propagation distance and I_0 is initial intensity), appear to be in conflict and came from continuous plane wave assumptions decades ago. New equations are derived from the nonlinear radiation stress tensor for materials with their absorption obeying frequency power law and for the general case of pulses. The first case for force balances represents forces incident on a plane while the second is a force at a location in a lossy medium such as tissue. The second case can be represented as omnidirectional forces impinging on an enclosing spherical surface. By shrinking the spherical surface down to a point and using Gauss's theorem, the two cases are shown to be equivalent. Both new equations are in integral forms in the frequency domain and they reduce to the well known expressions above for the continuous plane wave case. Validation for the new results are drawn from acoustic output measurements. These expressions have wide applicability for describing acoustic radiation forces in shear wave elastography (SWE), acoustic output measurement, diagnostic imaging, drug delivery, HIFU, lithotripsy, sonochemistry, levitation, and microfluidics.

ACKNOWLEDGEMENTS

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Calibration of the axial restoring force produced by a single-beam acoustic tweezers

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ABSTRACT

Acoustic tweezers are ultrasonic devices based on radiation pressure, allowing a contactless mean force to be exerted on objects interacting with the acoustic field. The trapping ability of the single-beam acoustic tweezers and its use for three-dimensional selective manipulation of elastic spheres has recently been demonstrated. However, the experimental calibration of the axial restoring force is still missing.

The presented study aims to calibrate a single-beam ultrasonic tweezers operating at 40 kHz in air on spherical elastic beads of diameter 2 mm to 4.76 mm. For this purpose, trapping experiments are carried out in microgravity. This environment allows for fine characterization by removing the beads' weight acting against the radiation force.

The existence and stability of the trap is observed for each bead tested. The stiffness of the trap is then obtained by analyzing the axial oscillations of the beads when they are moved from their equilibrium position. It is then possible to link the amplitude of the acoustic emission to the stiffness of the acoustic trap. In addition, these results validate a recent theory for calculating the radiation pressure on an elastic sphere.

This calibration work paves the way for the use of acoustic tweezers for non-contact manipulation in microgravity.

Acoustic radiation force on objects near boundaries

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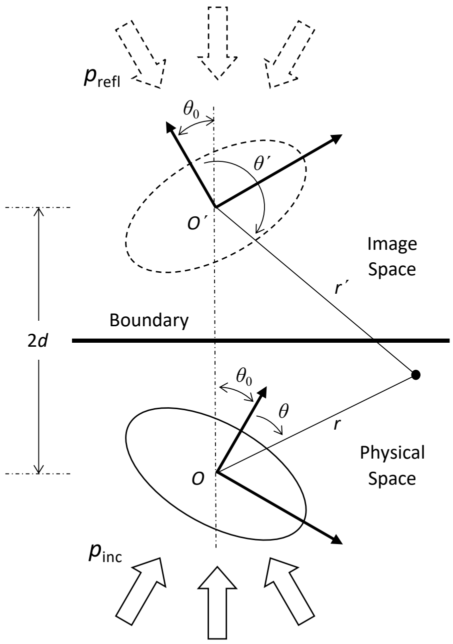
ABSTRACT
Acoustic radiation force and torque on objects near pressure release or rigid boundaries are calculated using expansions of the pressure field in terms of both spherical and spheroidal wave functions. The present formulation of the theory thus applies to spheres and spheroids, both prolate and oblate. There is no restriction on the size or aspect ratio of the object. In each case, the boundary condition at the interface is satisfied through the use of a virtual (image) object that is a mirror reflection of the physical object with respect to the boundary. The boundary condition at the object surface is satisfied after expressing the expansions of each component of the total field in a common coordinate frame using addition theorems for spherical harmonics. The radiation force and torque are expressed as a summation of terms involving products of the coefficients in spherical wave expansions of the incident and scattered fields. Results from the present analytical model are compared with those from a finite-element model. The importance of object-boundary interaction effects is assessed by comparing the radiation force predicted by the proposed theory with that obtained by modeling the same object in a free field with a standing wave. Potential experimental validation is discussed as well.

ACKNOWLEDGEMENTS
BES is supported by the Applied Research Laboratories Chester M. McKinney Graduate Fellowship in Acoustics.



CAPTION: Geometry used to obtain expansions of the total pressure field that satisfy conditions at the boundary and the surface of the physical object. The physical object is centered at a distance d below the boundary in "physical space." The virtual (image) object is centered above the boundary in "image space." There is no limitation on the orientation θ_0, size, or aspect ratio of the spheroid, which can be oblate or prolate. The incident wave p_{inc} and the reflected wave p_{refl}, which are indicated with the arrays of solid and dashed arrows, respectively, can be any arbitrary field, such as a plane wave at oblique incidence.

Direct measurement of the radiation force of a focused acoustic beam on a spherical solid particle in water

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ABSTRACT

The acoustic radiation force (ARF) is a nonlinear phenomenon resulting from a change in the wave momentum due to absorption or scattering. The purpose of this paper is to present a method for direct measurement of ARF exerted by an ultrasonic beam on a millimeter-sized spherical particle in a liquid and to compare the measurements with theoretical predictions. A focused ultrasonic beam was generated by a concave piezoceramic transducer with a center frequency of 1.072 MHz, a focal length of 70 mm, and an aperture of 100 mm. The transducer was placed face down in a water tank. A spherical bead was fixed under the source in the center of a large-diameter plastic ring with the help of stretched fishing lines. The ring was attached to a specially shaped rigid frame, which rested on an electronic balance without touching the tank walls. This made it possible to directly measure the vertical component of ARF acting on the bead with an accuracy of 30-40 µN. A thin membrane was placed above the bead to dampen the effect of acoustic streaming. A positioning system was used to place the bead at different points on the transducer axis. The radiation force measurements were in good agreement with theoretical predictions. Some discrepancy occurred when the bead was close to the focal point, which was caused by the appearance of standing waves. Proper selection of the electrical impedance of the transducer helped reduce this artifact and thus measure ARF with high accuracy.

ACKNOWLEDGEMENTS

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Sonofragmentation and Sonocrystallization: How Cavitating Liquids Make and Break Solids

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ABSTRACT

We do not yet understand, at a molecular level, how things break. What happens to macroscopic solids (crystalline or not) as stresses are applied and how those stresses create breakage of chemical bond breakage and weaker inter-molecular interactions remain remarkably mysterious. The application of ultrasound to crystallization (i.e., sonocrystallization) can dramatically affect the properties of the crystalline products [1]. Sonocrystallization induces rapid nucleation, generally yields smaller crystals of a more narrow size distribution compared to quiescent crystallizations [2], and has become increasingly important in the pharmaceutical industry for the preparation of APIs (active pharmaceutical ingredients). The control of morphology of the crystallization process is critical to reproducible dose response for APIs and is under increasing scrutiny in pharmaceutical manufacturing. Ultrasound can induce significant improvement in the uniformity of crystallite size and rates of crystallization. We have developed a mechanistic understanding of the origin of these phenomena and begun to separate the details of the effects of ultrasound on nucleation, mass transport, shockwave fragmentation of crystallites, and inter-particulate collision. Decoupling experiments were performed to confirm that interactions between shockwaves and crystals are the main contributors to crystal breakage. We have discovered a mechanochemical extension the Bell–Evans–Polanyi principle: activation energies for solid fracture correlate with the binding energies of the solids [3].

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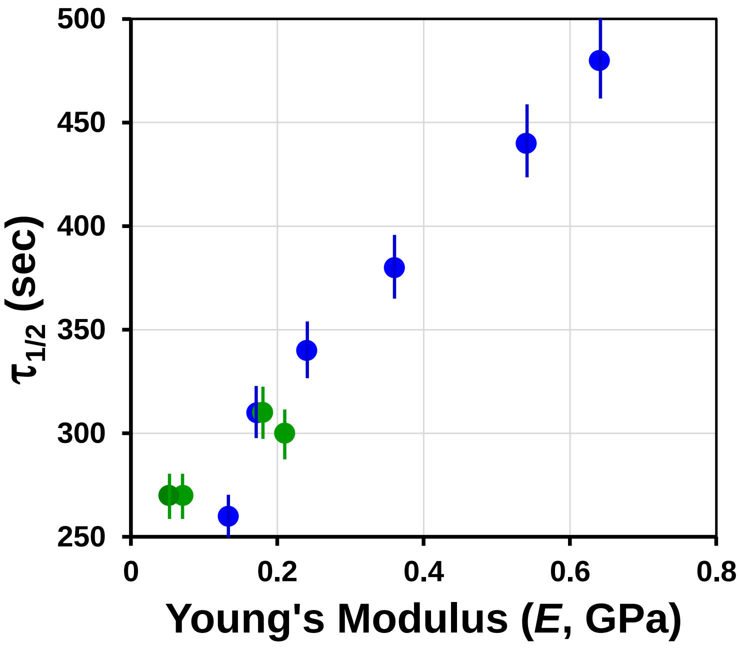

CAPTION: Sonofragmentation of molecular crystals are controlled by the strength of the crystalline materials (e.g., the Young's modulus). For crystals suspended in cavitating liquids, there is a linear decrease in the rate of fragmentation with increasing strength of the crystals.

The interacting acoustic bubble pair: coupled oscillation, radiation force and streaming

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OBJECTIVES
The acousto-fluidics of a unique couple of interacting gas bubbles is experimentally investigated as an elementary substructure of a bubble cloud. The influence of the inter-bubble distance on the bubble oscillations, the secondary radiation force they are submitted to and the surrounding flow they induce, is quantified.

METHODS
The main drawback in the investigation of bubble pair interaction is to maintain their spatial stability. To overcome this problem, a dual-frequency levitating chamber is proposed in order to trap two micrometric bubbles (~100µm radii) at two successive nodes of a high frequency (1 MHz) field with a separation distance of 750µm [1]. Due to the large contrast between the bubble size and the bubble resonant radius corresponding to the trapping acoustic frequency, they do not experience oscillations. Therefore, a low frequency field (30kHz) is then superimposed to the trapping frequency in order to trigger oscillations of the bubble walls. The experimental setup allows capturing both the bubble time-resolved oscillations and the microstreaming they produced using a PIV (Particle Imaging Velocimetry) technique.

RESULTS
For moderate driving pressure amplitudes, the two bubbles oscillate spherically in a coupled way with the inter-bubble distance. Depending on the bubble sizes in comparison to the resonant radius, constructive or destructive behavior of their oscillation amplitudes occur. When the two bubbles are smaller or greater than the resonant radius of the low-frequency field, they are attracted due to the presence of the secondary radiation force. The proposed setup allows the measurement of this force between two bubbles oscillating at an equilibrium inter-bubble distance and its comparison to a commonly-used modelling of the attracting force (the Crum's model [2]).
For sufficiently high driving pressures, the Crum's model is no longer available as bubbles may exhibit nonspherical oscillations: the flow they induce in the vicinity of the bubbles pair modify the balance of applied forces the attraction law between the two bubbles. In the range of investigated inter-bubble distances (around three times the mean bubble radius), no acoustic coupling is observed between nonspherically oscillating microbubbles. However, at the fluid timescale, the expansion of the microstreaming pattern induced by a single bubble can be large enough to interact with the one produced by the second bubble (see Figure 1).
Finally, we describe the case of two interacting bubbles whose radii are larger than the resonant radius. When increasing the driving pressure amplitude, they approach slowly until they jump to a quasi-contacting equilibrium state where the two bubbles are separated by a distance of only a few micrometers (see Figure 2). This effect is the consequence of the sign reversal of the secondary radiation force, responsible of a new inter-bubble equilibrium distance when nonlinear effects are considered for sufficiently small separation distance.

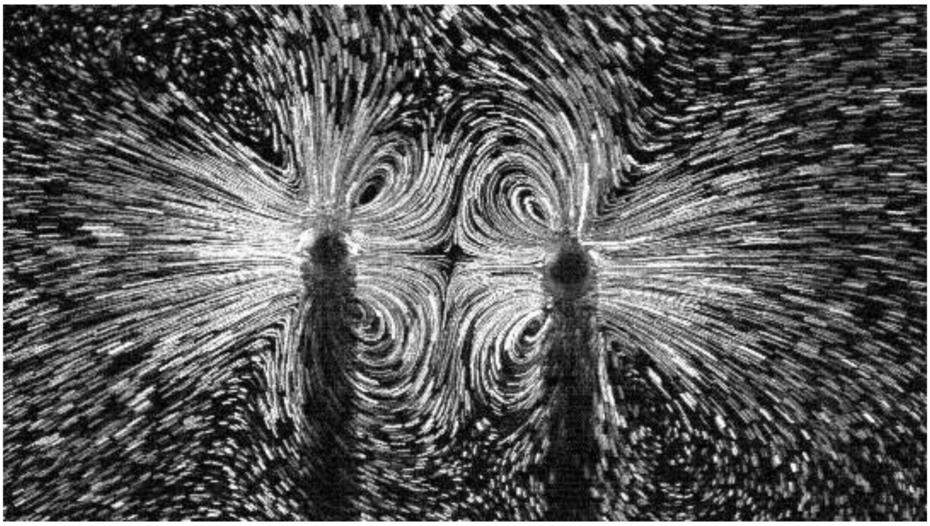

FIGURE 1: Microstreaming pattern produced by two non-spherically oscillating bubbles.

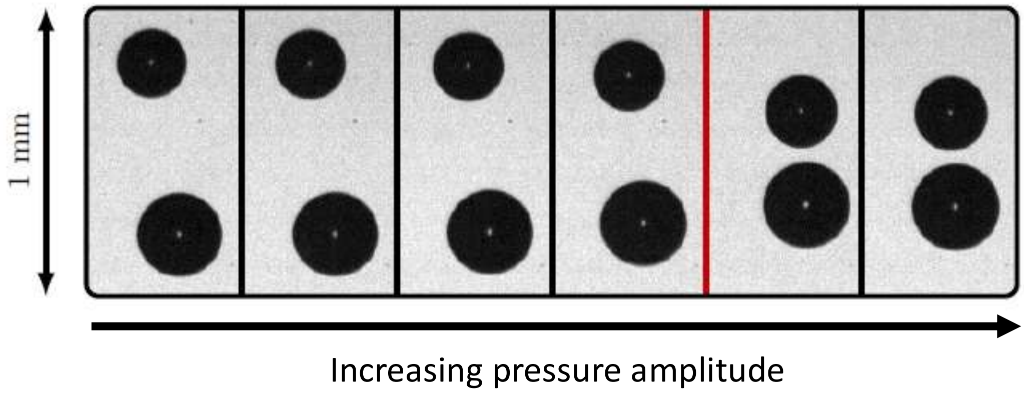

FIGURE 2: A sequence of bubble attraction due to the increase of driving pressure amplitude. Above a certain threshold, the bubble pair suddenly jump until a quasi-contacting equilibrium separation distance.

CONCLUSIONS

Acoustic and fluid couplings between two interacting acoustic bubbles are evidenced at the acoustic and fluid timescale using a dual-frequency levitation chamber. The sign reversal of the secondary radiation force leads to a quasi-contacting state where bubbles could further exhibit intense interactions. We believe that capturing bubble pair interactions may lead to a better understanding of the multi-bubble physics that occur in dense bubble clouds.

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ACKNOWLEDGEMENTS

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Toward material characterization using multibubble sonoluminescence

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ABSTRACT

Sonoluminescence (SL) is a unique acoustical phenomenon in which violent collapse of a bubble in a liquid subject to acoustic excitation leads to the production of light. While it is known that the composition of the liquid in which SL is performed has various effects on the light produced, there remains a large parameter space to explore. One such example is the effect of biological materials and the potential to use SL emissions as a diagnostic tool. We present an apparatus to produce multibubble sonoluminescence (MBSL) and subsequent measurements of those emissions. Specifically, we report MBSL intensity as a function of time in the presence of dimethyl sulfoxide and argon in aqueous solutions. This system utilizes a commercially available sonicator as the source of acoustic excitation, and it will enable further characterization of the effects of biological fluid content on SL emission and exploration of the possibility of using SL emissions as a probe. In addition, we are exploring the potential for MBSL emissions to be used to measure gas content in liquids, providing an alternative to traditional gas chromatography methods.

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Ultrasonic degassing and cavitation

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OBJECTIVES
The degassing process of liquids by ultrasound [1] is not sufficiently understood yet. There are unclear aspects with respect to the microscopic action of cavitation bubbles, and as well with respect to macroscopic phenomena like the acoustic emission spectrum and the visual appearance of bubbles and bubble structures. In this joined work, we try to highlight some aspects connected with rectified diffusion and coalescence of very small, acoustically driven bubbles, and to correlate acoustic spectra, bubble field dynamics, and dissolved gas content in a laboratory scale experiment.

METHODS
To describe the behavior of driven bubbles in the size range of 100 nm, we use analytic approximations and simulations based on spherical single bubble models. For multi-bubble fields, the single bubble equations are coupled by pressure and pressure gradient (secondary Bjerknes force) terms. In the experiment, an 80 l ultrasonic cleaning bath is equipped with side windows and a fixed hydrophone for simultaneous observations of bubble fields and acoustic emissions. The emission spectrum is analyzed in terms of fundamental (f0=25 kHz), subharmonic, and cavitation noise levels. Cavitation noise is determined in a window around 2.25xf0.

RESULTS
The microscopic considerations remain with the paradoxical situation that just for the very small bubbles, which are expected in early degassing stages, the “standard” mechanisms of ultrasonic degassing do not work well: Due to the high Laplace pressure, the volume oscillations are very weak, and dynamic diffusion effects cannot overcome gas outflow from the bubbles (compare [2]). For the same reason of weak oscillations, mutual attraction of bubbles is weak, and collision times of neighboring bubbles become exceedingly long [3]. In the experiment, we see an upward progression of spectral components over about 15 minutes, until a stationary, partly degassed state is reached. This state is characterized by few visible bubbles that are concentrated in localized structures (streamers, double layers). Before, extended veils of large upwards running bubbles and large streamer structures occur, populating a large part of the bath volume. Our preliminary data of acoustic spectra indicate a kind of period doubling transition during degassing (compare Lauterborn & Cramer [4]), which proceeds over many minutes (see Fig. 1).

CONCLUSIONS
The microscopic processes during the initial stages of ultrasonic degassing remain puzzling. Potentially, nano-bubble stabilization mechanisms that lower the Laplace pressure might help for an explanation. One candidate is electrostatic stabilization [5]. On the macroscopic scale, more involved dynamics including the interaction of bubble populations, bubble structures, and gas diffusion appear in evidence. Further experiments with simultaneous recordings of dissolved gas content, acoustic emission spectra, and bubble dynamics are necessary for a deeper understanding.

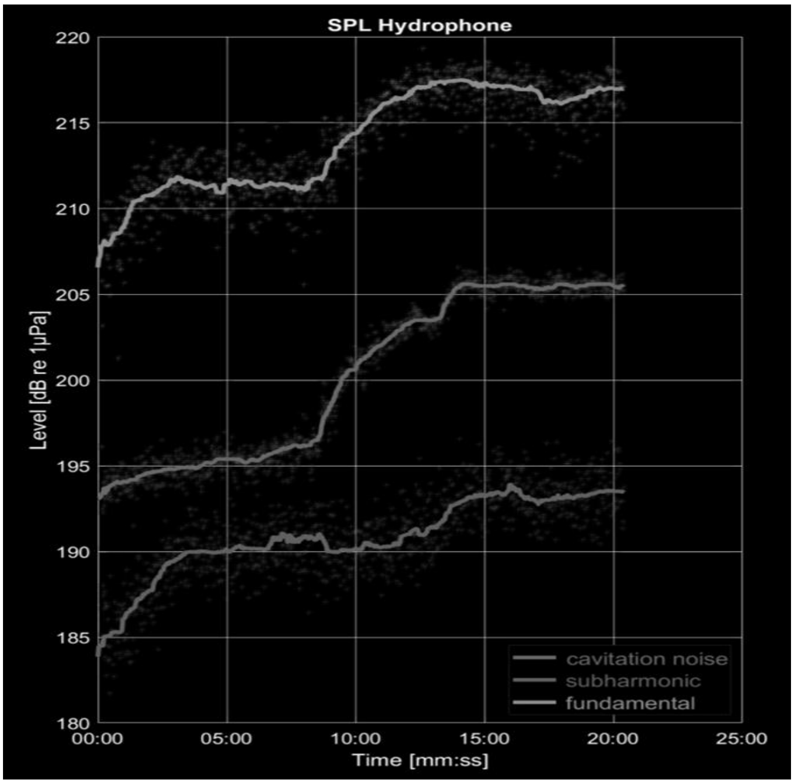

FIGURE 1: Progression of the spectral components vs. time: fundamental (top), noise (middle), subharmonic (bottom). Until about 9 minutes, the fundamental runs in parallel to the subharmonic. Later, it runs in parallel to the noise. This appears reminiscent to a period-doubling route to chaos.

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Design and characterization of a novel sonochemical reactor design

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ABSTRACT

Ultrasound-induced inertial cavitation (the violent collapse of bubbles within an acoustic field) has for decades been explored to facilitate chemistry (sonochemistry). Historically, sonochemistry is conducted with little concern of the acoustic field or required power to nucleate cavitation. As such, sonochemical reactions and their industrial application are often limited by the intense energy required to nucleate, and the subsequent stochasticity of, inertial cavitation. In this work, we present an improved sonochemical reactor design that guides and focuses the acoustic wave to a reactor vessel, ensuring the reaction volume undergoes vigorous cavitation. In addition, we have shown that the incorporation of nanoparticles, which act as an agent for entrapping nanobubbles, in the reaction solution substantially increases the cavitation activity. The increase in cavitation activity was verified by two experimental methods: 1) a terephthalic acid assay and 2) passive cavitation detection (PCD) of the reaction volume. The terephthalic acid assay detects the production of OH radicals due to the sonolysis of water. It is an indirect measure for cavitation activity and a metric for sonochemical efficacy of the reactor design. By using PCD, we measured the cavitation noise from the reaction volume, which we then correlated to the sonochemical efficacy from the terephthalic acid assay. These findings are helpful for experimentalists that intend to use power ultrasound in various applications. In the future, our group intends to further explore the use of acoustic cavitation for hydrogen production and other chemical processes that are related to green energy storage and energy conversion.

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Bubble collapse directly at an object: fast jet and shock wave

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ABSTRACT

Cavitation bubbles close to solid surfaces have been studied intensively in the last decades. Nevertheless, the issue is still good for surprises. A striking example is the formation of very fast, thin jets from bubbles oscillating in very close proximity to a flat solid surface [2].

These jets result from self-impact of annular inflow at the axis of symmetry and can reach a speed of the order of 1000 m/s. The annular inflow and thereby fast jet formation, paradoxically, is viscosity induced, since the boundary layer at the solid surface plays a distinctive role. In this presentation, we describe details of the mechanism leading to fast jet formation and present numerical and experimental results on the phenomenon.

The numerical model consists of a bubble filled with a small amount of non-condensable gas in a compressible liquid. We use the volume of fluid method to capture the interface between liquid and gas. The Navier Stokes equations are discretized with the finite volume method. The model is implemented in the open source software package OpenFOAM [1]. From the computations, one can derive the pressure load on the object from jet impact and bubble collapse shock wave.

Capturing the phenomenon experimentally is a notoriously difficult task, since the short time window of ~100 ns and small spatial region of ~50 µm where the jet occurs are demanding. Our first photographic evidence of this phenomenon is given, using high-speed imaging of laser-generated bubbles under normal ambient conditions, enhanced to subpixel resolution via raytracing of a fitting CFD simulation [3, 4].

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Inertial and Stable Cavitation Noise Characterization in a Sonochemical Reactor using SVD and Machine-Learning Techniques

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ABSTRACT
The ability to detect, characterize, and control inertial and stable cavitation has tremendous promise in the fields of biomedicine, chemistry, and rheology. Two notable application areas are biomedicine and chemistry in which the ability to control cavitation can be used to enhance the permeation of cell membranes for drug delivery and facilitate chemical reactions critical for carbon sequestration, chemical valorisation, and hydrogen production. Typically, spectral features of cavitation noise signals obtained through Fourier analysis are analyzed resulting in a qualitative categorization of the signal. In addition, quantitation of cavitation noise emissions is challenging, and there is little research accounting for calibration differences of various passive cavitation detectors (PCDs). This presentation will explore the use of singular value decomposition (SVD), machine-learning techniques, and precise hydrophone calibration to improve the analysis of the cavitation noise data. Here, we will use a sonochemical reactor as the source of cavitation. We will show that these techniques better characterize the bubbles and pressures produced in the reactor. Further research will be done in controlling cavitation by altering pulse repetition frequency (PRF), pulse length (PL), and duty cycle (DC) in order to optimize the efficiency in various sonochemical reactions.

Nonlinear acoustic and elastic metamaterials

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ABSTRACT
Metamaterials have become a very active topic for research in numerous domains of engineering and science because of their promise to create materials, structures, and devices that can control wave propagation in ways that exceed the capabilities of conventional homogeneous and composite materials. Most acoustic and elastic metamaterials research has focused on linear behavior. However, linear metamaterials suffer from a few notable drawbacks, primarily *i*) the effective material properties of interest tend to be limited to narrow frequency bands that cannot be changed by external stimuli, and *ii*) they have very limited utility for applications where nonlinearity is unavoidable or essential, e.g., shock testing or impact mitigation. Nonlinearity has therefore been explored as a means to expand the palette of accessible dynamic response of synthetic materials to external stimuli. Examples of desirable behavior include increased bandwidth of specific performance criteria by creating tunable band gaps via material configurability, enhanced harmonic generation and capacity to absorb mechanical energy, and improved control over the magnitude and shape of propagating waves. We will provide an overview of linear and nonlinear acoustic and elastic metamaterials, including historical context of relevant metamaterial and composite material research and present results from recent research on nonlinear metamaterials to improve energy absorption, enable nonreciprocal wave propagation, shape propagating waveforms, and design materials that support two-dimensional solitary waves. We will conclude with a discussion on promising avenues of future research for nonlinear metamaterials.

ACKNOWLEDGEMENTS
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An approach to compute the propagation of ultrasonic waves in underwater rocks.

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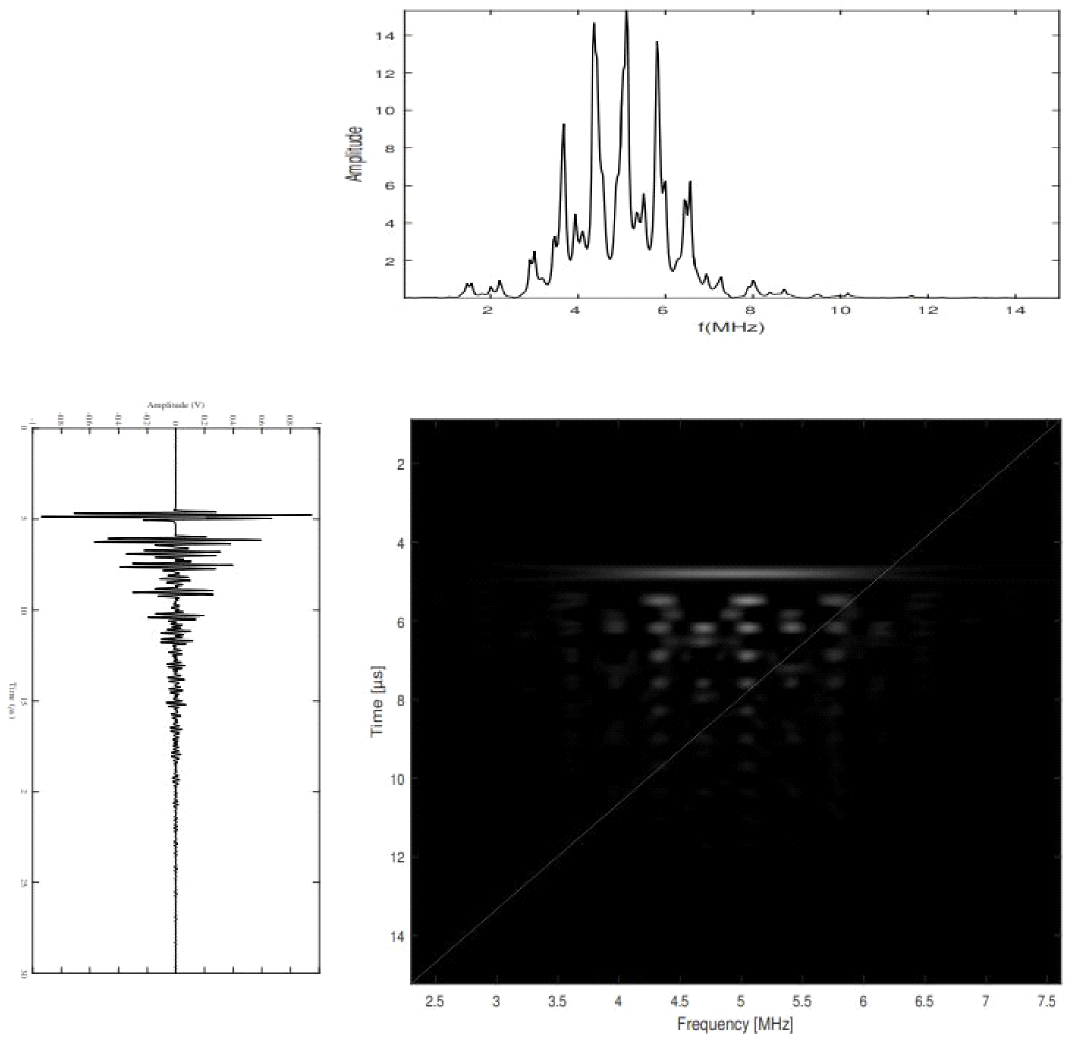
ABSTRACT

In the present work, our objective is to characterize the rocks by ultrasonic pulse echo calculation. Nowadays, the calculation of ultrasonic waves has received a great scientific and practical importance, it requires the development of a more efficient control technique in order to meet the desired quality and safety rules. Indeed, a matrix transfer approach has been introduced to model the signal propagation in a layer immersed in a fluid. This approach is mainly based on the calculation of the transmitted signal in the time domain of a layered material immersed in water to verify the ability of calculating the ultrasound parameters. We then deduce the ultrasonic wave response of the rocks and compare it to literature data. This approach has also been suggested as a new alternative to exploit for rock characterization.



CAPTION: the transmitted signal of layer structure rocks, time domain, frequency domaine, time-frequency representations

Analysis of the nonlinear local interaction between two noncolinear plane waves

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ABSTRACT

In contrast-enhanced echography, an improved image quality is reached through a high contrast-to-tissue ratio. To exploit this, a new imaging modality called cross-amplitude modulation (xAM) is used. By transmitting finite cross-propagating plane-waves, the medium cumulative nonlinearities are suppressed, and the amplitude modulation enhances the nonlinear behavior of the contrast agents. Although the propagation of progressing plane-waves is fully known, the theory of noncollinear nonlinear interacting plane waves has still some unanswered questions. One of them is the generation of local nonlinearities at the intersection of the plane-waves. To mathematically describe this phenomenon, the Westervelt equation is extended by the non-zero d'Alembertian operator of the Lagrangian density. Therefore, it is possible to quantify the difference between global medium nonlinearities and local nonlinearities due to the interaction of both plane-waves. For infinite plane-waves with a single frequency, is possible to make a 2D analytical study for the effect of the cross term. But to imitate an in vivo study, this research should be expanded in a 3D case with finite size, pulsed sources. This can be achieved by using the Iterative Nonlinear Contrast Source (INCS) method, a solver of the Westervelt equation in a 4D spatiotemporal domain. Based on a Neumann scheme, the pressure is iteratively updated after the convolution of each nonlinear contrast source term with the Green's function. Finally, this study can provide some insight in the nature of local nonlinearities and its relation to cumulative nonlinearities based on the pressure amplitude and the angle used for the incident field.

Nonlinear broadband admittance boundary condition for time -domain simulation of sound propagation

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ABSTRACT
Cavitation has played an active and important role in the development of therapeutic ultrasound. From its vital role in the effectiveness of lithotripsy to its essential role in the application of histotripsy, the awareness of cavitation must be considered in practically every clinical implementation of High Intensity Focused Ultrasound. This lecture will present several examples of how cavitation has been an essential ingredient of many current and promising therapeutic ultrasound methodologies and technologies.

Using ray tracing approximation to reduce acoustic propagation in weakly nonlinear regime to the Burgers' equation

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ABSTRACT
High Intensity Focused Ultrasound (HIFU) is a therapy that uses ultrasound waves to non-invasively destroy malignant cells inside the human body. The technique works by sending a high-energy beam of ultrasound into the tissue using a focused transducer. Numerically modelling HIFU presents a problem due to nonlinear effects leading to the formation of harmonics of the source frequency. Each significant harmonic requires a finer grid to resolve, rapidly increasing computational complexity. We look to use the weakly non-linear ray theory framework to reduce the nonlinear PDE in Rd to a set of one dimensional PDEs. We construct rays emanating from the transducer on which we calculate the phase of the waves via the Eikonal equation. In ray coordinates the amplitude can be found by solving the nonlinear transport equation along the ray. This equation can be transformed into the Burger's equation which we then solve and transform back to obtain the amplitude along each ray.

"HIFU Beam" software for modeling nonlinear axially symmetric focused ultrasound fields in layered media

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ABSTRACT
High Intensity Focused Ultrasound (HIFU) beams used for noninvasive therapeutic applications are often strongly affected by nonlinear propagation effects including formation of high-amplitude shock fronts at the focus. The software termed "HIFU beam" has been developed for simulating axially-symmetric nonlinear fields, including high-amplitude shock fronts, generated by single-element ultrasound transducers and annular arrays in flat-layered media that mimic biological tissues. Numerical models include the Khokhlov–Zabolotskaya–Kuznetsov (KZK) and one-way Westervelt equations with thermoviscous absorption as well as power-law absorption to capture frequency-dependent effects. Equivalent source model is included in the KZK-based algorithm to increase the accuracy of simulations for strongly focused beams. Wide-angle parabolic approximation is employed in the algorithm for solving the Westervelt equation. Combinations of time- and frequency-domain finite-difference numerical schemes are used to simulate formation of high-amplitude shocks in the focal region of the beam. The software comprises a MATLAB toolbox combined with a user-friendly graphical interface and binary executable compiled from FORTRAN source code; it is available for Windows operating systems only and can be freely downloaded from the website http://limu.msu.ru. Simulation examples representing typical cases of ultrasound transducers, focusing conditions, and propagation in layered media are presented to illustrate software features and capabilities for HIFU applications. The developed software tool can be used for predicting the pressure levels in nonlinear HIFU fields generated by the existing transducers and help in designing new transducers capable for reaching desirable parameters of such fields.

ACKNOWLEDGEMENTS
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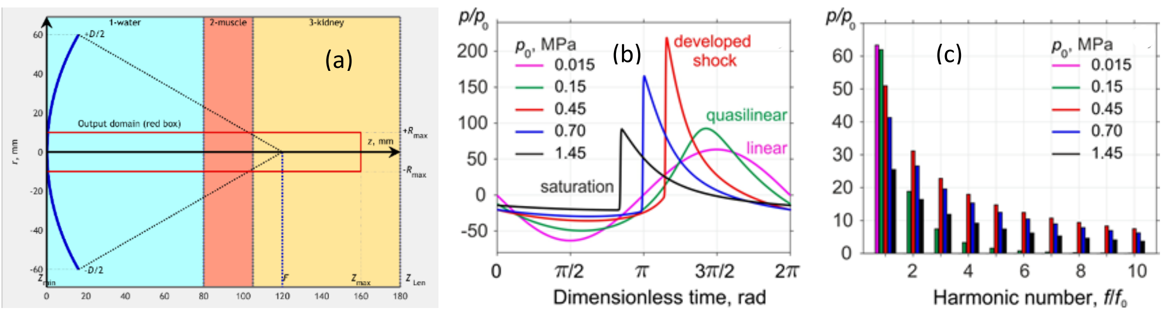

CAPTION: Diagram of the simulation window (a) and representative output results for the focal pressure waveforms (b) and corresponding spectra (c) in water generated by a single-element 1 MHz source (100 mm diameter, 90 mm radius of curvature) at increasing initial pressure levels.

Simulations of Ultrasound Treatment of the Intervertebral Disc

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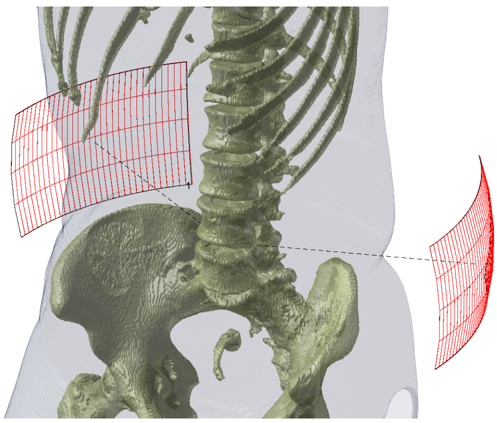
ABSTRACT
We aim to assist patients suffering from lower back pain with a motion-restoring treatment to reinstate the function of degenerated intervertebral discs (IVD). The first step to achieving this is the fractionation of the dehydrated nucleus pulposus whilst sparing the annulus fibrosis, via ultrasound-mediated inertial cavitation of sonosensitive particles injected directly into the central part of the IVD. This requires the creation of a well-formed acoustic focus in the central part of the IVD, with peak rarefactional pressures in excess of 7 MPa at a propagation distance of up to 20 cm from the skin.

K-wave acoustic simulations were run on 100 patient CT scans and helped establish the feasibility of treatment of the L4L5 IVD using a 0.5 MHz ultrasound array. The simulations were further used to optimize the acoustic window and bilateral therapeutic array configuration, and to determine the resulting focal pressure and dimensions created when targeting the L4L5 IVD nucleus.

Given the presence of bone, all k-wave simulations were conducted using the elastic wave equation mode, which is limited to linear simulations. However, the assumed array surface pressure of 2MPa and the target fractionation peak rarefactional pressure threshold of 7MPa over a 20 cm propagation distance make it necessary to consider the potential effect of non-linearity, which are expected to be significant based on independent simulations using the KZK equation. This was initially addressed through the application of an empirically derived correction factor dependent upon propagation depth. Further potential approaches to capture non-linear effects in prohibitively large computational domains will be discussed.



CAPTION: Illustration showing the positioning of the therapeutic ultrasound array required to treat L4L5 IVD.

Acoustical transmission through a weak shock wave

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ABSTRACT

Recent experiments (Ducousso et al., Phys. Rev. Appl., 15, L051002, 2021) demonstrated the possibility to image weak shock propagation in solids by an ultrasonic probe wave. Wave interaction with a steady, ideal step shock in air has been previously described (Burgers, Selected Papers, Springer, 478–486, 1995 - Brillouin, Acustica, 5, 149, 1955 - McKenzie and Westphal, Phys. Fluids, 11, 2350, 1968), without consideration for the particular case of a weak shock nor for the influence of the medium. The present paper considers an unsteady weak shock interacting in any inviscid fluid with an incident probe wave. No reflected wave, slower than the shock, arises. The transmitted wave, two vortex and entropy modes behind the shock, and the shock front disturbance, are determined by the linearisation of the Rankine-Hugoniot relations. For a weak shock, entropy mode and energy jump relation can be omitted. Generalized transmission laws are obtained. The shock motion induces a Doppler effect, whose sign is dependant on the nonlinear parameter of the fluid, air and water giving opposite trends. The transmitted wave amplitude is either increased or reduced through energy exchanges with the shock. For an incidence angle beyond the critical angle, instead of a total reflexion with an evanescent wave, we observe an inversion of the direction of the transmitted wave, propagating in the same direction but slower than the shock. This phenomenon seems specific to weak shocks. Numerical simulations indicate the previously described scheme keeps unchanged in case of a non-uniform flow behind the shock.

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Interferometric measurements of laser-induced shockwaves in air

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ABSTRACT

Laser-induced shockwaves in air are ideal for model studies of blast waves and nonlinear propagation effects. Focusing a sufficiently energetic laser pulse to a small spot size causes the surrounding air to form into a rapidly expanding plasma. After a finite time a shockwave detaches from the plasma boundary and adiabatically propagates. For propagation times exceeding tens of microseconds, past studies generally measure characteristics of the shockwave with condenser microphones. General features of the shockwaves can be deduced from these measurements; however, the presence of the microphone introduces a number of measurement artifacts. Distortion of the time-domain signal is caused by the sensor acting as a diffracting boundary. Furthermore, the limited bandwidth does not allow the rise time to be correctly quantified. In contrast, optical interferometry is a nonintrusive diagnostic for quantifying shockwave characteristics. In this study a Nd:YAG laser (1064 nm, 5.5 ns pulse duration, 850 mJ) is focused through a converging lens, with f-number 5.56, in order to generate laser-induced shockwaves. Mach-Zhender interferometer measurements are made from 10 mm to 200 mm from the focal point of the lens. Optical phase differences are used to estimate density and pressure time-histories, along with peak pressure as a function of distance. These estimates can serve as initial conditions for numerical simulations and source characterization.

Use of simplified bowed string model in physics education: A laboratory experiment

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ABSTRACT
This paper proposes an educational science experiment on elastic string vibration where the string is excited by bowing. A custom-built monochord is used to study the resulting vibration experimentally. The monochord employs the Faraday's law of induction to measure the string displacement. The proposed experiment is accompanied by numerical simulations based on the integration of a nonlinear 1D damped wave equation with an external forcing term. The simulations give students the ability to compare the theory with practice. The study of bowed string dynamics aims to make the proposed science experiment more meaningful and engaging to students, since many string instrument, such as violin, cello, and other viol family instruments, are played in such a manner. The proposed experiment can be used by teachers teaching BSc and MSc level students in acoustics, physics, applied mechanics, applied mathematics, and other related fields of science.

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Nonlinear mechanisms of generation of vorticity at the open end of acoustic waveguides

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ABSTRACT
For high enough levels of acoustic pressure inside a cylindrical tube, a nonlinear mechanism is responsible for the generation of vorticity at the open end of the tube, which results in energy loss. It has been observed [Buick et al, JASA, 2011] that, provided the magnitude of the acoustic velocity is large enough, two nonlinear regimes are possible. In the first regime, vorticity appears only in the immediate vicinity of the tube. For higher acoustic velocities, vortex rings are formed at the open end of the tube and are advected outwards. This behaviour changes according to the values of a Reynolds number Re_δ associated with the width of the acoustic boundary layer inside the duct. We use a three-dimensional Lattice Boltzmann Method (LBM) to simulate the velocity and the pressure fields at the exit of the tube, for different values of Re_δ. We also conduct experiments with 2D phase-locked particle image velocimetry (PL-PIV) within a similar range of values of Re_δ. The expected behaviour is observed in both experimental and numerical results, and the numerical scheme is correctly validated by the PIV measurements. Rounding-off the inner edge of the tube leads to a supression of the mechanism responsible for the generation of vorticity, and this is also observed both numerically and experimentally.

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3D-printed acoustic holograms to generate thermal holographic patterns

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OBJECTIVES

In this work we present the use of 3D-printed acoustic holograms coupled to a low-cost MRI compatible transducer to create controlled thermal patterns in absorbing media.

METHODS

Acoustic holograms are created with time-reversal methods, setting virtual sources along the desired shape emitting with the same amplitude and phase in a homogeneous liver-like medium. The phase-conjugated back-propagated field is recorded in a parallel surface to the transducer and the acoustic holographic lens is designed assuming each pixel vibrates as a Fabry-Perot resonator, so at the exit plane of the lens the phase of the field will be same as the recorded. Both acoustic and thermal simulations were performed with a k-space pseudo-spectral method considering absorbing media. Experiments were done to characterize acoustic fields in water with a hydrophone and thermal holographic patterns in liver with Infra-red camera and MR-thermometry and compared with numerical results. Two holographic thermal patterns were created: one with the shape of the number '2' generated with a flat transducer and other that enlarges the natural focus of a focused transducer, turning it into an ellipse, both performed at 1.1 MHz.

RESULTS

Good agreement was found between acoustic simulations and experimental measurements, with an average relative error of 31% at the target region. Thermal holographic patterns measured with both techniques were similar and matched with thermal simulations. For the '2'-shaped hologram, peak temperature increases 4.5 °C after 12 s heating at 20 W. For the ellipse-like hologram temperature raised to 6 °C in both simulation and MRI thermal measurement after 30 seconds heating, while for the natural focus of the transducer the same sonication time led to a temperature increase of 15 °C. Regions inside which simulated temperature elevation was greater than 4 °C were 17 × 16 mm^2 and 7 × 25 mm^2 without and with the lens, while the same experimental measurements resulted in region sizes of 11 × 16 mm^2 and 7 × 30 mm^2, respectively.

CONCLUSIONS

3D-printed acoustic holograms can create controlled thermal holographic patterns inside absorbing media. This shows the capabilities of this technology to be used as a low-cost alternative to phased-array systems to perform thermal treatments such as hyperthermia as the heating region can be adapted to therapeutical targets of arbitrary shape and location.

ACKNOWLEDGEMENTS

This research has been supported by the Spanish Ministry of Science, Innovation, and Universities (MICINN) through Grant Nos. IJC2018-037897-I, FPU19/00601, and PID2019-111436RBC22, by the Agència Valenciana de la Innovació through Grant Nos. INNCON/2021/8 and INNVA1/2020/92, and by Generalitat Valenciana through Grant No. AICO/2020/268. Action co-financed by the European Union through the Programa Operativo del Fondo Europeo de Desarrollo Regional (FEDER) of the Comunitat Valenciana 2014–2020 (Nos. IDIFEDER/2018/022 and IDIFEDER/2021/004). Action co-financed by BPI France, Région Grand Est and FEDER (UFOGUIDE project).

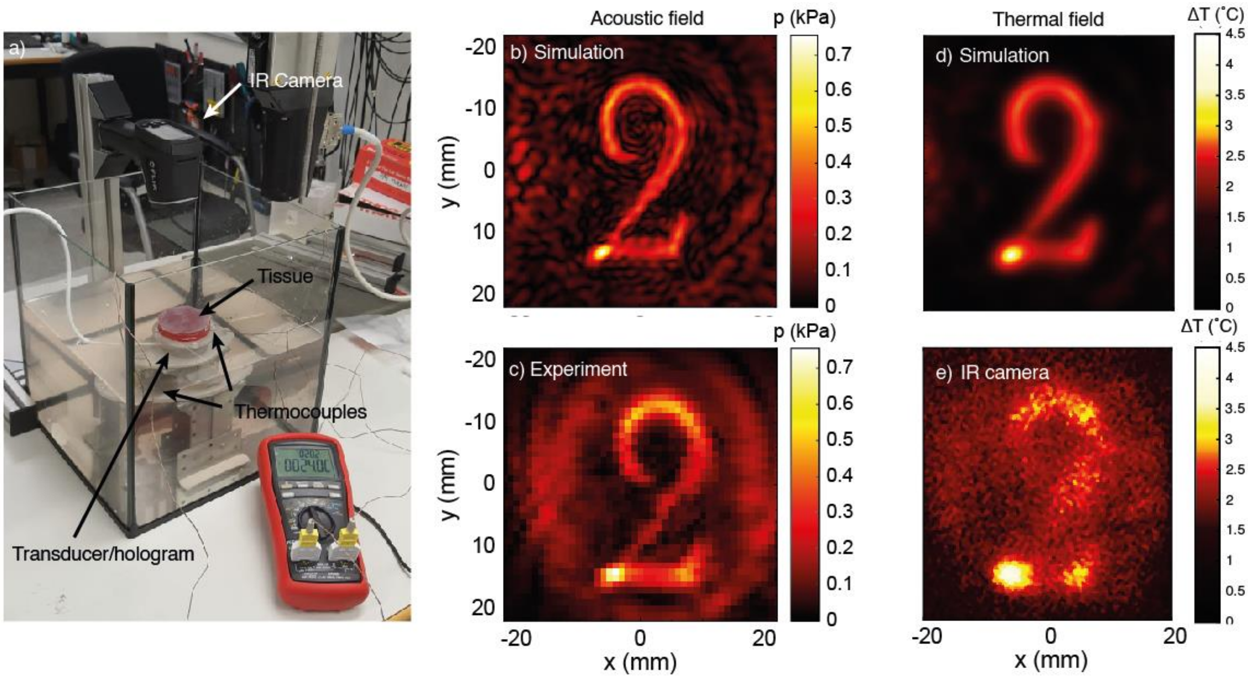

FIGURE 1: a) Experimental setup for thermal measurements. b) Simulated and c) measured acoustic field. d) Simulated and e) measured thermal field.

Advancements in Nonlinear Acoustics for Underwater Sensing Applications

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ABSTRACT
The purpose of this research is to demonstrate potential enhancements in performance capabilities of undersea environmental sensing utilizing a nonlinear acoustics approach. This nonlinear approach includes kernel estimation using a least-squares approach for obtaining measured system response. There are several mathematical methods, including: maximally-sparse sampling of the kernels (for first-, second- and third-order); combatting ill-conditioning on its own terms by realizing an exponential decrease of the growth of the number of kernel coefficients; capturing frequency content beyond input excitation (transmit) band; and estimating the effects of noise on the kernel responses – to summarize the background techniques involved. The current objective is achieved by combining theory and rigorous experimentation. In the analysis, we employ the most recent scientific advances in underwater acoustic signal processing and analysis methods developed by Dr. Albert H. Nuttall and co-authors in order to evaluate and quantify in-water test measurements and performance results obtained from a rigorous and highly controlled test design. Overall findings demonstrate promise for providing enhancements to undersea sensors and dual-use applications. Current findings reveal newly developed system responses unseen elsewhere from this unique research. Dual-use commercial applications include medical imaging and diagnosis of disorders, among many others.

ACKNOWLEDGEMENTS

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Dynamics of particles and bubbles in standing acoustic waves

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ABSTRACT
This is a brief review of recent studies of complex dynamics of microparticles and gaseous bubbles in an acoustic field due to the period-averaged radiation force. It is known that a standing wave affects the particle motion much stronger than the traveling wave, and ultrasonic standing waves are used for concentrating particles and biological cells into separated clusters or, on the contrary, for mixing them in small volumes. Acoustic fields are also used for manipulating particles. Recent results concerning the effects of particles' concentration and mixing in planar and cylindrical resonators are discussed; the theory is compared with available experimental data. The biomedical and other applications are briefly outlined.

The importance of acoustic cavitation in the evolving technologies of therapeutic ultrasound

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ABSTRACT
Cavitation has played an active and important role in the development of therapeutic ultrasound. From its vital role in the effectiveness of lithotripsy to its essential role in the application of histotripsy, the awareness of cavitation must be considered in practically every clinical implementation of High Intensity Focused Ultrasound. This lecture will present several examples of how cavitation has been an essential ingredient of many current and promising therapeutic ultrasound methodologies and technologies.

CONTRAST DETECTION SCHEME FOR SIGNAL CORRUPTED BY NONLINEAR PROPAGATION OF ULTRASOUND THROUGH MICROBUBBLES CLOUD

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OBJECTIVES

Medical contrast-agent enhanced ultrasound (CEUS) enables blood flow and perfusion imaging, which provides useful diagnostic information of an organ's condition. The agent consists of encapsulated microbubbles (1-5 µm diameter) that generate nonlinear echoes, which in combination with contrast-specific imaging techniques, improves the sensitivity and specificity of ultrasound flow and perfusion imaging. These techniques generally work by sequentially transmitting complementary pulses to suppress the linear tissue clutter signal when the echoes of the pulses are combined linearly. However, ultrasound also propagates nonlinearly when it travels through tissue and microbubble clouds, which reduces the contrast to tissue ratio (CTR) [1]. In this study, we propose to improve the power modulation (PM) pulsing scheme by implementing higher-order singular value decomposition (HOSVD) to combine the received echoes instead of conventional linear processing.

METHODS

An in-vitro experiment was performed on a tissue-mimicking material (TMM) flow phantom, made with polyvinyl alcohol and background scattering particles. It consists of a compartment on top and a 1 mm diameter channel within the phantom. To obtain ultrasound images in the presence of nonlinear propagation through a microbubble cloud, diluted phospholipid-coated microbubbles were put into the phantom's top compartment. The microbubbles of interest were infused with a perfusion pump through the channel below the compartment. The pump was turned off just before the acquisition to have very low flow. An ultrasound probe (Philips/ATL P7-4) was partly submerged in the microbubbles-filled chamber. A research ultrasound machine (Verasonics Vantage 256) performed the 'checkerboard apertures' PM pulsing scheme [2], which consist of transmitting with even-numbered elements, all elements, and odd-numbered elements. We implemented HOSVD on the received echoes with spatial, temporal, and transmit aperture as the input dimensions. Contrast-to-tissue ratios (CTR) were derived from the image intensity in the channel region versus that of a neighboring tissue region.

RESULTS

The representative microbubble contrast images with nonlinear propagation through microbubbles cloud after different processing are shown in Figure 1. HOSVD on PM achieved 6 dB and 15 dB CTR improvement, compared to conventionally processed PM and unfiltered images, respectively.

CONCLUSIONS

We demonstrated that compared to conventionally subtracting the pulses, processing the PM echoes with HOSVD can improve contrast detection.The CTR improvement could be significant for myocardial perfusion imaging, where slow microbubble flow, and nonlinear propagation through clouds of microbubbles present in the cardiac chambers are expected.

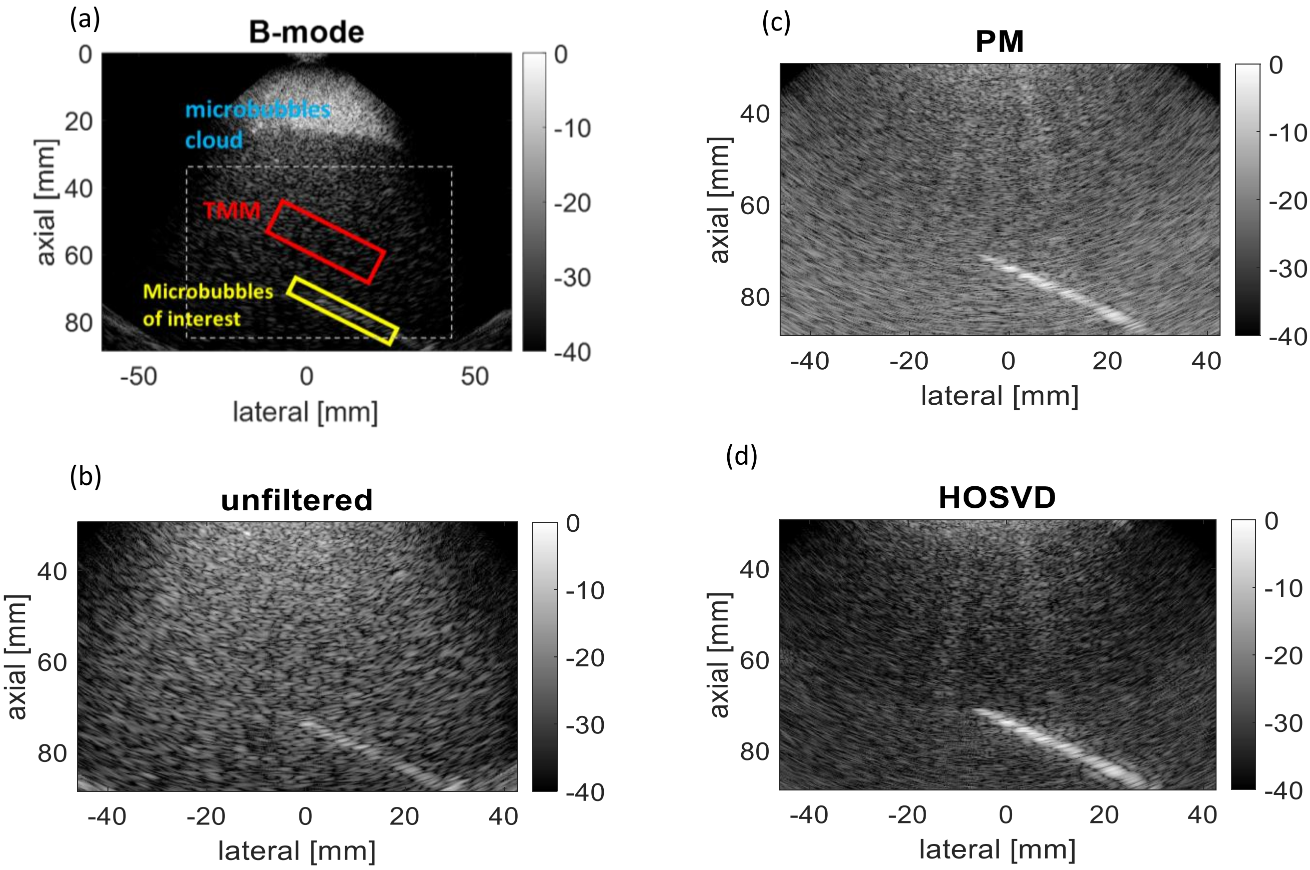

FIGURE 1: (a) B-mode image of the flow phantom with regions-of-interest for CTR calculation indicated by the rectangles (yellow = microbubbles, red = TMM). The channel goes out of plane and could not be entirely visualized in the images. (b), (c), (d) Representative contrast images of different processing.

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Nonlinear dilatational viscosity and shear-thinning in lipid-encapsulated microbubbles

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ABSTRACT

Several characterization studies of lipid-encapsulated microbubbles have reported observations in which the measured shell dilatational viscosity exhibited an apparent increase with the microbubble initial radius, which is inconsistent *ex facie* with a zero-thickness lipid monolayer encapsulation model. Incorporation of a nonlinear viscous term which is dependent on the dilatation rate (Cross Law shear-thinning) has been proposed to partly address this problem [1]. However, little experimental evidence has been presented to resolve if the model accurately describes the dynamic behavior of lipid microbubbles over a broad range of initial size and acoustic excitation regimes. In this presentation, we consider three models (constant, radius-dependent, and shear-rate dependent) for the interfacial viscosity which are consistent with previously reported dilatational viscosity measurements of a lipid-encapsulated microbubble formulation using different approaches. Numerical simulations using various excitation waveforms over a large parameter space reveals that there are regimes where measurable parameters of the microbubble response are expected to be dramatically different amongst the models. Examples from a collection of optically-measured microbubble responses in these regimes will be presented to illustrate differences between the models. Analysis over a large parameter space was possible due to the large number of experimentally observed radius-time curves that were obtained from previous studies [2,3]. Incorporating nonlinear shear-thinning with the Marmottant model of lipid microbubble dynamics may be a straightforward approach to more accurately model some of the observed behavior. Implications of the shear-thinning model on predictions of the bubble wall velocity and cavitation noise emissions from individual bubbles will be discussed.

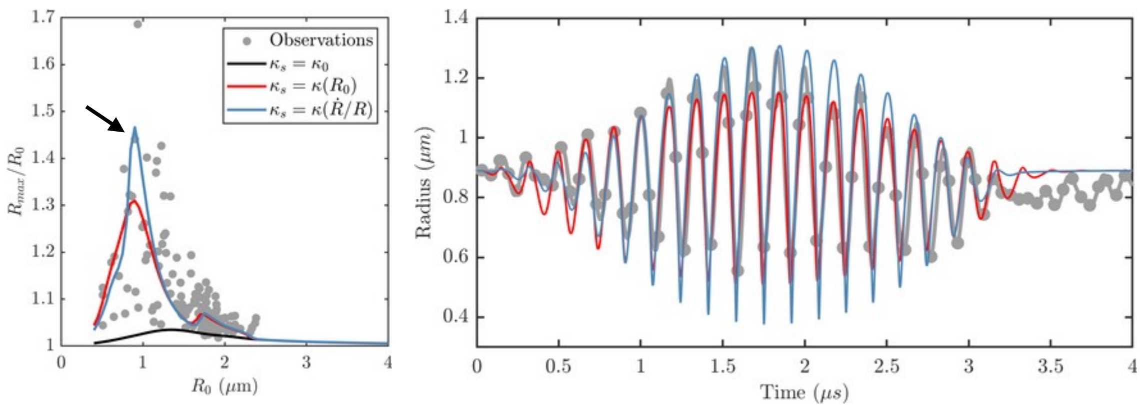

FIGURE: (Left) Summary of maximum radial expansion (R_{max}/R_0) for (n=125) optically-measured microbubble responses using a 6-MHz 20-cycle cosine-weighted burst and (right) example of radius-time response for individual microbubble (indicated by the arrow). Results of numerical simulations using constant (black), radius-dependent (red) and shear-rate dependent (blue) models are shown.

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Momentum Conservation and the Second law in Biological Communication

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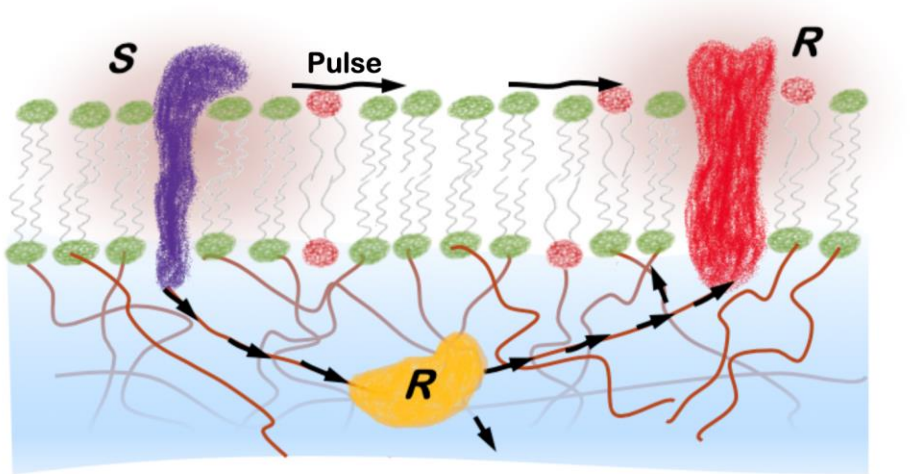
ABSTRACT
An approach is presented in which physical properties of the interface - not individual molecules - are identified as the potential origin of biological function.

Three key ideas are discussed: i) How physical state determines function (state-to-function approach). ii) The violation of momentum conservation in biology and how it is resolved in biological communication and finally iii) How thermodynamics allows to explain specificity in biology.

One advanced application of these three ideas is the problem of nerve pulse propagation, where momentum conservation and phase transitions lead to the propagation of non-linear solitary like pulses. We further discuss the problem of cell signaling and finally take a leap into the future to discuss the role of physics in order to address the question of "What is health?"



CAPTION: Communication by pulses which changes state, which changes enzymatic activity (specifically), which excites new pules and/or changes state… a feedback loop is created, which can be understood by biochemistry, momentum conservation and thermodynamics.

Model of electromechanical sound waves in lipid membranes near melting transition

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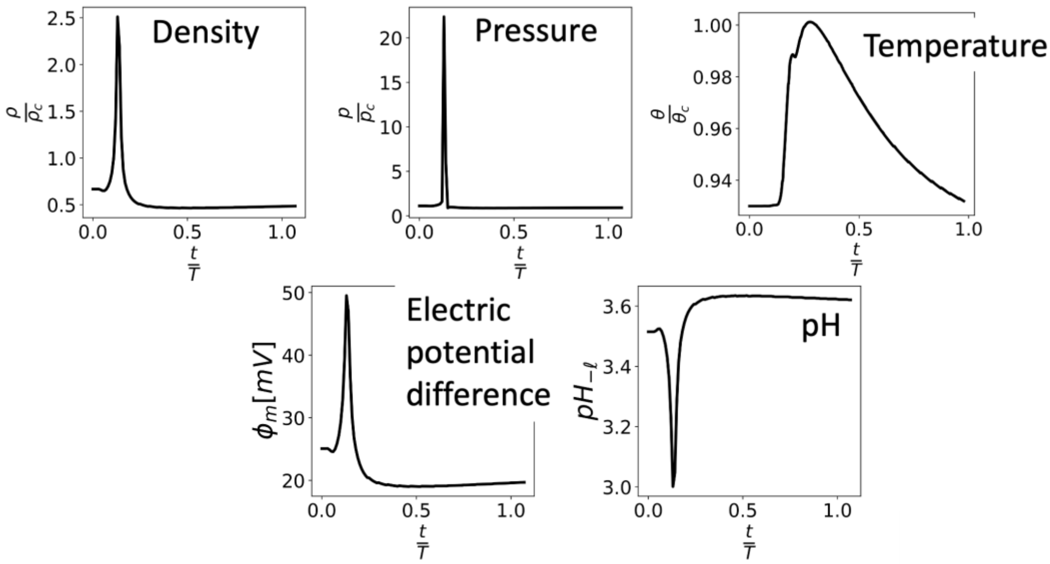
ABSTRACT
We describe a theoretical model of nonlinear sound waves in lipid membranes near phase transition. The calculated solutions correspond to observations of nonlinear compression waves in lipid monolayers as well as to action potentials in living cells. Key properties are a sigmoidal response to stimulation amplitude and annihilation upon collision. We explain the role of the phase diagram in producing the nonlinear characteristics and how sound in lipid membranes propagates thermal, electrical, and chemical variations in addition to the well-known mechanical changes. While the electrical aspect of the signal carries digital information about the stimulus (an all-or-none behavior), nonelectrical aspects are predicted to propagate analogue information.



CAPTION: Model calculation of multiple aspects of a nonlinear sound wave as a function of time, as appear at a distance x/L = 1 from the excitation point. The plotted aspects include the variation in density, lateral pressure, temperature, electric potential difference across the membrane, and pH at the membrane surface (bulk pH is 7).

Soliton Propagation in Shallow Water Enables a New Neuromorphic Computing Machine

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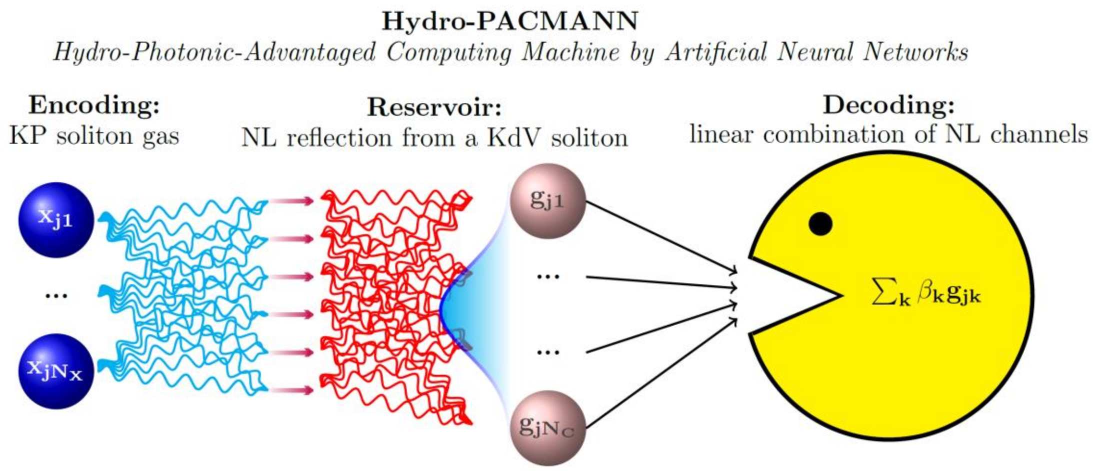
ABSTRACT
Nonlinear waves (NLWs) have played a historical role in establishing the science of complexity foundations. While NLWs are widespread in acoustics, fluid dynamics, and optics, they have also been the protagonists of the recent development of new machine learning paradigms, as reservoir computing (RC), where the information transmission acts as the excitation of a dynamic system which, as a black box that mimics the human brain, processes information to perform complex tasks at low energy consumption [Marcucci *et al.*, Phys. Rev. Lett. **125** (2020)]. With an incredibly fast adoption in the scientific community, NLWs ubiquitous nature has been establishing a bridge between two fundamental fields: nonlinear physics and computational science.
To enable NLWs to do computation, that is, to constitute the whole core of a neuromorphic computer, we designed the hydro-photonic-advantaged computing machine by artificial neural networks (Hydro-PACMANN), a RC system where light-water interactions are the leading physical phenomena, and the electronics is limited to a CCD camera in detection.

Conflict of Interest
The Authors are employed by Apoha Ltd., a company dedicated to the development of biophotonic computational devices.



Schematic representation of our artificial neural network. The input data determine the amplitudes of Kadomtsev–Petviashvili (KP) solitons, forming a soliton gas in shallow water. The reflection from the water, imprints a phase-structure on a CW-laser beam, which carries information to another water tank. Here, by nonlinear reflection on a single KdV soliton, we design a nonlinear activation function acting on the light beam. Finally, we divide the output intensity distribution in channels, that we linearly combine to complete the training and allow our machine to learn a given dataset.

Linear Waves at Viscoelastic Interfaces Between Viscoelastic Media

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ABSTRACT
We derive the general dispersion relation for interfacial waves along a planar viscoelastic boundary that separates two viscoelastic bulk media, including the effect of gravity. Our unified theory contains Rayleigh waves, capillary-gravity-flexural waves, Lucassen waves, bending waves in elastic plates, and the standard dispersion-free sound waves, as limiting cases. To illustrate our results, we consider waves at a viscoelastic interface immersed in water, and also at an air-water interface. We furthermore investigate pressure waves at a viscoelastic interface separating two identical viscoelastic bulk media, for which we consider both Kelvin-Voigt and Maxwell materials, as applicable to polymer gels and solutions. For all cases, we study how material properties determine the crossovers, scaling, and existence regimes, of the various interfacial waves. Since we include viscoelastic effects for all media involved, our theory allows to model waveguiding phenomena in biology, such as pressure pulses in axon membranes, which are possibly relevant for acoustic nerve pulse propagation phenomena.

ACKNOWLEDGEMENTS
This research has been partially funded by Deutsche Forschungsgemeinschaft (DFG) through grant CRC 1114 “Scaling Cascades in Complex Systems”, Project Number 235221301, Project C02 “Interface dynamics: Bridging stochastic and hydrodynamic descriptions”. Work was funded in part by the European Research Council under the EU’s Horizon 2020 Program, Grant No. 740269.

Implications of the detonation theory for travelling phase transitions at interfaces

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ABSTRACT
A growing body of evidence is suggesting that nonlinear acoustics plays a fundamental role in biological communication. Nerve impulses are highly nonlinear electro-mechanical waves that are known to travel along the surface or the membrane interface that surrounds a neuron. Researchers have previously shown, both experimentally and theoretically, that the nonlinear characteristics typical of a nerve impulse can be derived from the material properties of the membrane interface. For example, by applying the nonlinear acoustics framework to the longitudinal waves that travel in a membrane, characteristics like threshold for excitation and solitary propagation were shown to result from nonlinear compressibility associated with a phase change in the material. Nonlinear acoustics provide a substantially thermodynamically reversible description of nerve impulse propagation, which is consistent with the remarkable energy efficiency of real neurons, and is in contrast with the largely irreversible conventional description of the phenomenon.

Despite tremendous progress, fundamental questions related to the generation and then sustenance of these impulses over long distances, mechanism of annihilation of colliding impulses, and the coupling of these impulses to local biochemistry remain open. We propose that the well-established ZND detonation model can provide key new insights by applying it to two different interfacial acoustic phenomenon (1) compression waves in a lipid monolayer at the air-water interface (2) the expansion and collapse of a lipid coated vapor cavity.

ACKNOWLEDGEMENT
Some of the work referenced in here was supported by Engineering and Physical Sciences Research Council (EPSRC) under Programme Grant EP/L024012/1 (OxCD3: Oxford Centre for Drug Delivery Devices) and was performed together with Prof. Robin Cleveland at the University of Oxford.

Time and length scale of solitons in nerves

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ABSTRACT

The soliton theory for nerve pulse propagation makes many useful predictions about the properties of nerve pulses that can be verified in experiments. This includes mechanical changes and reversible heat release. It also provides an explanation for all kinds of medical phenomena including anesthesia, the action of lithium and the treatment of essential tremor. The soliton theory is based on the 1D wave equation in nerve axons in situations where the sound velocity is a nonlinear function of density (Fig.1).

The theory only contains four parameters. Three of them directly originate from the density dependence of the sound velocity close to a melting transition that was found in nerve membranes. The fourth parameter is associated with dispersion, i.e., the frequency dependence of the sound velocity. The dispersion parameter determines the width of the solitons, but in the absence of independent experimental evidence remains a free fitting parameter.

We show here that the dispersion parameter is a function of density related to the relaxation time scales of the nerve membrane. The relaxation time scales can directly be obtained from the heat capacity of the membrane. As a consequence, solitons display a width and a time scale that is fully determined by the thermodynamic properties of the nerve membrane such that no free parameters remain. We obtain a time scale of the soliton in the millisecond range and a pulse length between cm and a meter. This is of the right order for describing biological systems.

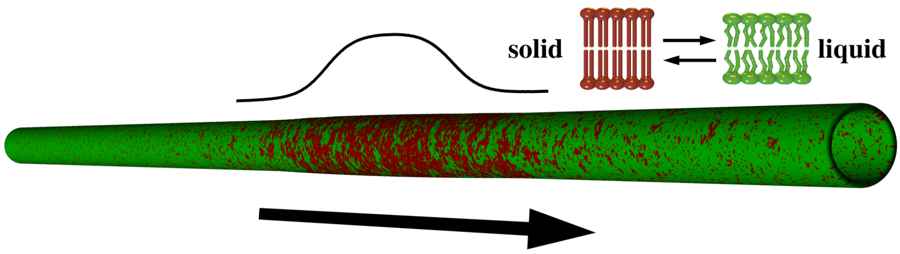

FIGURE 1: Schematic representation of a soliton in nerve axons involving a change in the physical state of the membrane from liquid (green) to solid (red). From Gonzalez-Perez et al. 2016. Biophys. Chem. 216:51-59. The width and timescale of the soliton is the topic of this presentation.

Nonlinear resonant ultrasound spectroscopy using white-noise excitation

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ABSTRACT

Nonlinear resonant ultrasound spectroscopy (NRUS) is a technique for non-destructive sample evaluation by which a strain-dependent nonlinear parameter is quantified that exhibits heightened sensitivity to defects as compared to monitoring of linear resonance attributes. As NRUS measurements have traditionally used a controlled sweep of sinusoidal inputs, applications of the method have been largely limited to laboratory experiments. Here we present NRUS results which utilized a white noise signal as input, in order to better approximate ambient excitation and facilitate efficient validation using time-domain models. Studied samples were chosen to reflect a range of nonlinear responses and underlying mechanisms (acrylic, sandstone, fractured steel). We excited the studied samples using bonded piezoelectric transducers which delivered white-noise inputs at increasing amplitudes, with the nonlinear response measured with a laser doppler vibrometer. By comparing results against those obtained from traditional NRUS, we find comparable trends in the nonlinear parameter under white-noise excitation, including similar relative differences in magnitude across the samples and consistent values across similar mode shapes. While we note that white-noise strain estimation is complicated by simultaneous excitation of multiple resonant modes, NRUS results from white-noise excitation demonstrate promising viability of the technique for (1) ambient in-situ inspection, and (2) a more-tractable approach to model the physics of various NRUS signals.

Measurement of the nonlinear shear modulus in a gel-like medium applying the acoustical resonator method with an additional static stress

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ABSTRACT

Measurements of the nonlinear parameter of a gel-like medium were carried out in an acoustical resonator in the form of a rectangular parallelepiped fixed without slipping between two solid-state boundaries. A sample of thickness L (Fig.1, left) is fixed on an oscillating plate (x = 0). The other plate of finite mass on the free surface of the sample (x = L) moves together with this surface. Metal weights are attached to the oscillating plate. By changing the number of weights, it is possible to achieve additional static deformation of the resonator up to 65%. A one-dimensional model can be applied to a resonator beginning from the thickness four times smaller than its length in the direction of oscillations. The resonator is made of plastisol. Layer is solidified between two parallel wooden plates. The dynamic method assumes measuring resonance curves at various static deformations. Dots (Fig.1, right) represent the measured shear stress (τ) on the relative deformation (ε) created by the static load. Nonlinear properties appear at strains of more than 20%. The nonlinear parameter β = 0.53 ± 0.06 was determined by the polynomial approximation (solid curve). Shear modulus measured dynamically: μ = 15.4 ± 1.1 kPa. The results were compared to static measurements where the dependence becomes nonlinear at strains greater than 30%. The static values of the shear modulus μ = 13.46 ± 0.13 kPa and the nonlinear parameter β = 0.60 ± 0.07 correspond to the values obtained in the dynamic method within an error.

ACKNOWLEDGEMENTS

This work is supported by RSCF, project No. 22-22-00751.

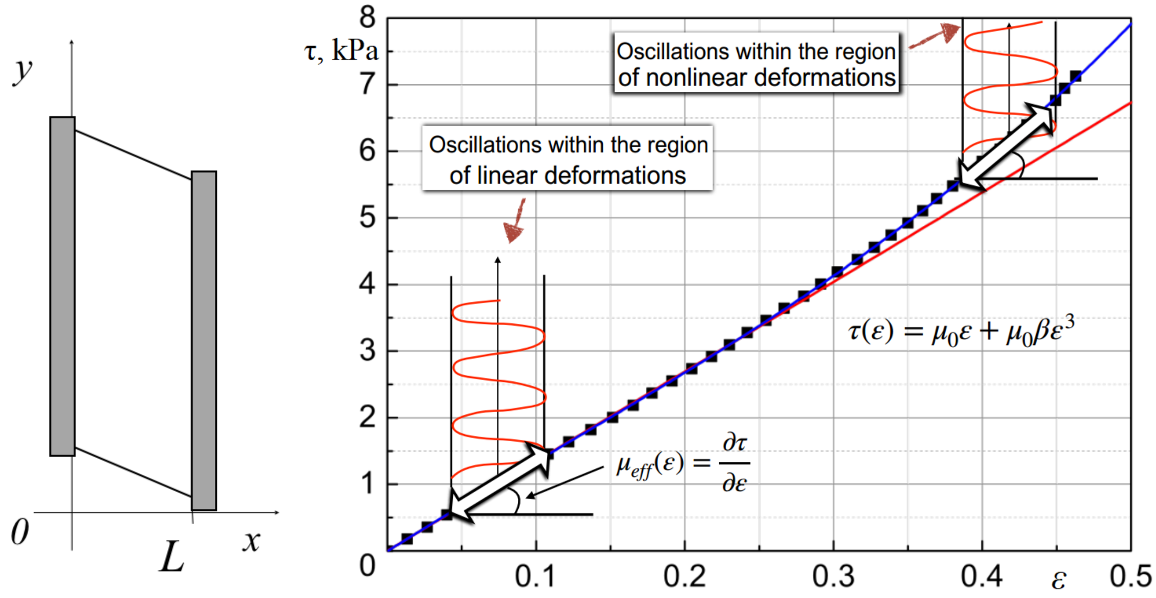

FIGURE 1. Left: the standing shear wave excitation method. Right: measured shear stress (dots) on the relative deformation created by the static load and its approximation (solid curve).

Improving the sensitivity of nonlinear array imaging for non-destructive applications

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ABSTRACT
Nonlinear ultrasound has shown its sensitivity to early formation of defects such as micro-cracking and material ageing. This is because the formation of micro-defects is typically associated with an increase in material nonlinearity. When an ultrasonic wave propagates in a nonlinear material, there is transfer of energy from the fundamental frequency to its harmonics. This exchange in energy depends on the nonlinearity level within the material and the amplitude of the wave at that location. Spatial mapping of nonlinearity within a sample can be performed with the use of arrays with appropriate delay laws. To this end, a two-dimensional finite difference numerical simulation has been created to model nonlinear elastic wave propagation. Array modelling was implemented by exciting a set of surface nodes with the same delay law where an element within the array is located, whilst a free surface boundary condition is applied everywhere else. This model was then used to investigate, from a sensitivity to damage perspective, the difference between focused transmission and sequential firing of elements while focusing is performed in post processing. The model allows energy from the coherent scattered field within the material to be monitored, which is not possible in real experiments. The result shows the influence of the type of array and the amplitude of excitation used. This model was then used to optimize an experiment and thereby increase the sensitivity of nonlinear array imaging to damage.

ACKNOWLEDGEMENTS
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Experimental investigation of the crack closure by applying Dynamic Acousto-Elastic Testing on a steel sample

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ABSTRACT

Ultrasonic measurements are commonly used for defect sizing, but because of potential partial crack closure, the ultrasonic signal can behave differently, and as a result, the crack depth can be underestimated. In the literature on metal samples with long cracks, a connection is made between crack closure and the nonlinear ultrasonic response, and among crack non-linearity quantification methods, DAET seems to be a good candidate. In this paper, the relation between the crack closure pressure and the curve from the DAET test is studied. An industrial steel component with several partially closed fatigue cracks is driven in its compressional mode while a standard 45° shear wave transducer probes the crack state. A three-point bending test is simultaneously performed with ultrasonic measurements to obtain reliable indications about the crack closure state. Repeatable measurements are obtained, and clearly measurable nonlinearities are recorded. A correlation between the variation of the echo amplitude and the closure pressure is found, while the total crack depth does not seem to influence the echo variations. The recorded non-linear phenomena and experimental results are then discussed by comparing them with theoretical considerations. The DAET reliable information provided in this paper about the crack closure state could be of importance with a view to predicting the remaining useful life of industrial components.

Phase-space domain: a path to the next generation of nonlinear ultrasound

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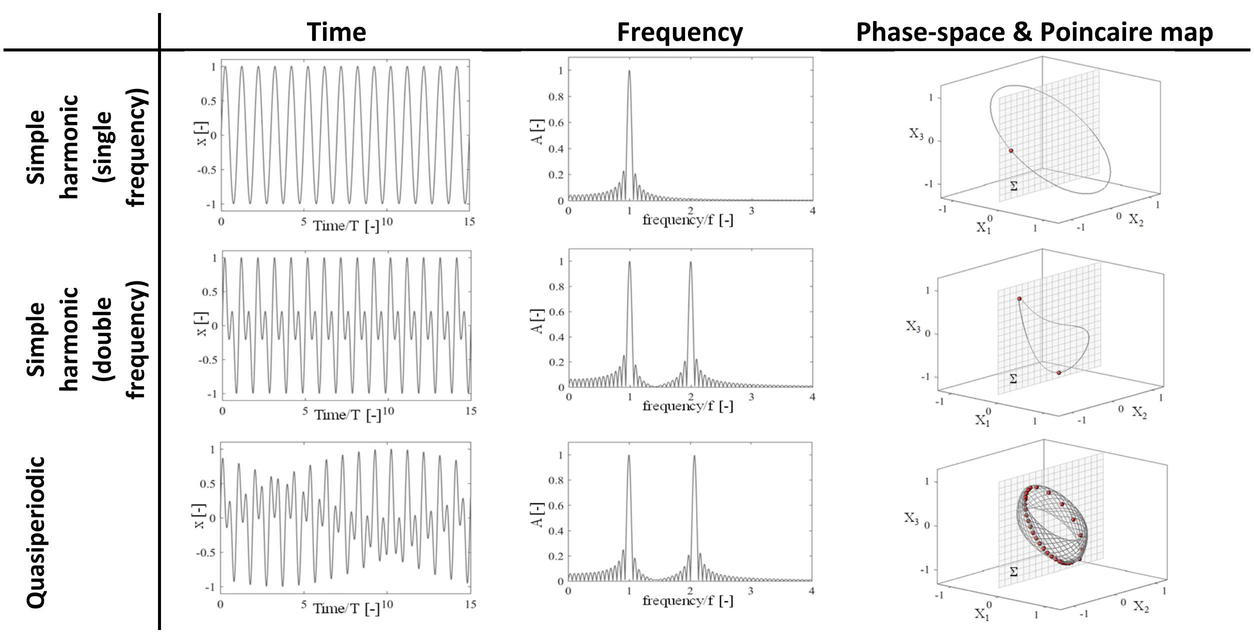
ABSTRACT

This paper summarizes the new findings and results of several studies in which the phase-space domain was successfully used to analyze complex ultrasound nonlinearities. Linear ultrasound testing (UT) in the "***time domain***" was introduced around 1930, nonlinear UT in the "***frequency domain***" was introduced around 1960, and now the "***phase-space***" domain is expected to fundamentally revolutionize UT for decades to come in many different industrial and medical applications. UT techniques based on acoustic nonlinearity have shown promising results in evaluating discontinuities in materials. These techniques have been successfully used in applications where traditional linear ultrasound was incapable of detecting defects. However, current nonlinear ultrasound techniques use frequency domain analyses that make them incapable of classifying different physical phenomena that cause similar spectral effects. Additionally, the time and frequency domains are incapable of revealing complex physical phenomena, such as chaos, because analyzing chaotic behavior is not a task for which time and Fourier analyses are well suited. In several applications, it is shown that phase-space analysis of nonlinear ultrasound waveforms can reveal fundamental nonlinear characteristics of the acoustic field not seen in time or frequency domain analyses. It also shown that the unique information gained from phase-space analysis such as dimensions, maximum Lyapunov exponent, and other topological characteristics in a map (i.e. Poincaré map) can be used to identify and classify complex nonlinear acoustic behavior, as well as damage-sensitive feature to detect and evaluate defects.



CAPTION: Simulated simple harmonic with one center frequency, simple harmonic signal with two center frequencies, and quasiperiodic signal. Time delay and embedding dimension p to construct phase-space are set to 0.25T and 3 respectively.

Tracking of Ga penetration into Al alloy via fast Nonlinear Resonant Ultrasound Spectroscopy measurements

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ABSTRACT

Gallium is a metal with a low melting temperature, which, when liquid, can rapidly penetrate into the microstructure of Al alloys. Gallium uses predominantly grain boundaries in the polycrystalline alloy as channels to spread into the volume of the material. It also enters into crystal dislocations and crystal lattice in form of interstitial atoms. The effect on material properties, called Liquid Metal Embrittlement, is severe. As a consequence of weakened grain boundaries, the fracture process changes from ductile transgranular into brittle intergranular, the material strength is significantly reduced.

The process allows us to observe, within a reasonable time scale, a transition from intact polycrystalline microstructure into a “brick-and-mortar” system and partially back. We chose the Nonlinear Resonant Ultrasound Spectroscopy (NRUS) as a method of monitoring. The NRUS was modified by using a relatively short chirp excitation, in order to allow the single NRUS run to be completed within 12 s. The amplitude sequence of the NRUS includes a stepwise upward and downward branch with interleaved low amplitude baseline probing. Such sequence allows us to assess multiple linear and nonlinear indicators of the material state, including fast and slow dynamics effects. The obtained time evolution curves are in a good agreement with previous studies. The behavior displayed by the classical nonlinear parameters seems to suggest that nonlinear elasticity in polycrystalline metals is to some extent associated with the grain boundaries. Furthermore, we show that the chirp probing can be used as an efficient tool for monitoring of slow dynamics relaxation.

ACKNOWLEDGEMENTS

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Nonlinear ultrasonic phased array for closed-crack imaging

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ABSTRACT

Closed cracks are challenging defects for ultrasonic testing since they are transparent to conventional ultrasound techniques. This can cause the underestimation or overlook of closed cracks, resulting in potential catastrophic accidents. To solve this problem, we have developed new nonlinear ultrasonic methods that are able to image nonlinear signatures using phased array (PA) probes. In this study, we introduce two types of nonlinear ultrasonic methods working with arrays. The first one is called fundamental wave amplitude difference (FAD),[1] that is based on the nonlinear incident-wave-amplitude dependence of fundamental responses [Fig. 1(i)]. The key of success of FAD is how high incident wave amplitude can be generated in samples to cause the contact vibration of crack faces. However, it is not easy to increase the incident wave amplitude at MHz frequencies. To enhance the applicability of nonlinear ultrasonic methods with PA , we have developed ultrafast imaging (MHz range) with pump excitation (kHz range) [Fig. 1(ii)].[2] We have successfully captured high-speed crack dynamics using plane wave imaging (PWI) during the pump excitation that can generate a large displacement of more than 1000 nm. Furthermore, we will talk about ongoing work toward 3D crack imaging.[3]

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ACKNOWLEDGEMENTS

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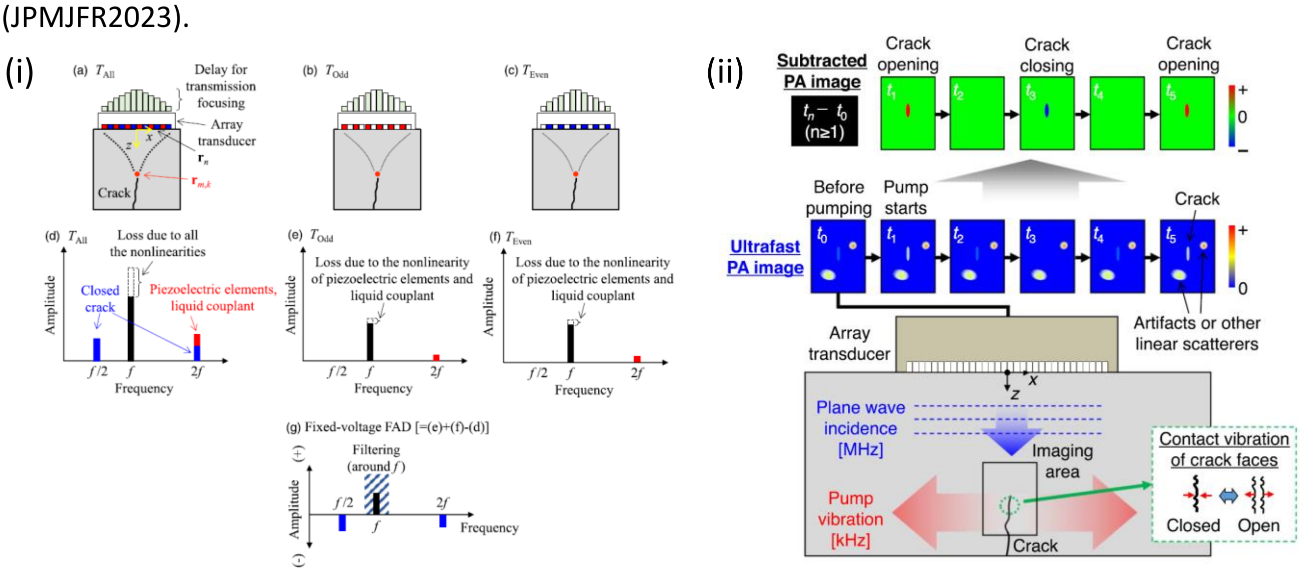

Fig. 1: Nonlinear ultrasonic phased array for closed-crack imaging. (i) Fundamental wave amplitude difference (FAD).[1] (ii) Ultrafast imaging with pump excitation.[2]

Role of Force Chains in Nonclassical Nonlinear Dynamics in Cemented Granular Materials

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ABSTRACT

Nonclassical nonlinear dynamics are commonly observed in cemented granular materials under elastic wave excitation. Here, we present evidence for a mechanism responsible for the nonclassical nonlinear dynamics observed in many cemented granular materials that are generally classified as mesoscopic nonlinear elastic materials. We demonstrate numerically that force chains are created within the complex grain-pore network of these materials when subjected to dynamic loading. The interface properties between grains along with the sharp and localized increase of the stress occurring at the grain-grain contacts leads to a reversible decrease of the elastic properties at macroscopic scale and peculiar effects on the propagation of elastic waves when grain boundary properties are appropriately considered. These effects are observed for relatively small amplitudes of the elastic waves, i.e., within tens of microstrain, and relatively large wavelengths, i.e., orders of magnitude larger than the material constituents. The mechanics are investigated numerically using the hybrid finite-discrete element method and match those observed experimentally using nonlinear resonant ultrasound spectroscopy as well as harmonic generation.

Nonlinear ultrasonic measurements of the damage evolution of concrete samples during fatigue under different cyclic loading rates

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ABSTRACT

Concrete bridges are subjected to a large number of cyclic loads by cars, trucks or trains during their service life. As a result, the concrete fatigues at the areas subjected to high stresses. In recent years, knowledge gaps as well as discrepancies between the fatigue behavior observed in the laboratory and the actual fatigue behavior of concrete structures have been discovered. For example, fatigue strengths calculated based on laboratory tests have a lower value than the actual fatigue strengths estimated in real structures. The high cyclic loading frequency and the resulting internal temperature increase during the laboratory tests apparently cause additional damage in the concrete specimens.

In the present investigation nonlinear ultrasonic methods were used to detect and quantify the development of the damage in concrete during fatigue tests under different cyclic loading rates. The aim of this investigation was to relate the resulting fatigue strength of concrete to the damage development and to the cyclic loading rate of the experiments. A better understanding of the relationship between these parameters will improve the previously insufficient applicability of laboratory results from fatigue tests to the damage development in real structures.

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Nonlinear vs linear ultrasound for detectability of kissing bonds

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ABSTRACT

Kissing bonds in adhesive joints are precursors to damage and failure in materials and components used in safety-critical industries. They are zero-volume, low-contrast contact defects widely regarded as “invisible“ in conventional ultrasonic testing. In this study, the recognition of the kissing bonds is studied in aviation-relevant aluminum lap-joints with standard bonding procedures using epoxy- and silicone-based adhesives. The protocol to simulate kissing bonds comprised customary surface contaminants PTFE (Teflon) oil and PTFE spray. Preliminary destructive tests revealed brittle fracture of the bonds with typical single-peak stress-strain curves indicating ultimate tensile strength (UTS) reduction due to adding contaminants. The curves are analyzed by using nonlinear stress-strain relation with the higher-order terms containing the second- and third-order nonlinearity parameters. It is shown that the lower-UTS bonds manifest a high nonlinearity while the high-strength contacts are candidates for a low nonlinearity. Based on that, the nonlinear approach (higher-harmonic mode) is set side by side with linear ultrasonic testing (high-frequency reflection) for experimental locating the kissing bonds fabricated in the adhesive lap-joints. The sensitivity of the linear ultrasound is shown to be adequate to detect only a substantial bonding force reduction between the epoxy and the silicone intact adhesives, while the impact of contamination remains undistinguishable. On the contrary, the probing of the kissing bonds vibration with laser vibrometry reveals dramatic growth of the higher harmonic amplitudes (Fig. 1) and thus validates highly-sensitive detectabilty of these troublesome defects.

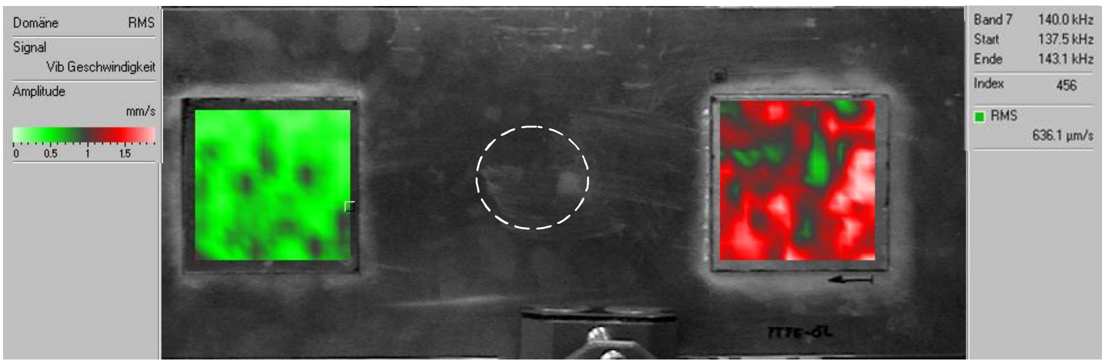

Fig. 1. Higher harmonic (7th) fields generated in adhesive bonds: pure epoxy adhesive (left square) and kissing bond (epoxy plus Teflon oil) (right square). Dashed circle indicates position of the excitation transducer (20 kHz) on reverse side of the specimen.

Nonlinear Elastic Properties of Granular Media: The Effect of Water Adsorption and Grain Shape

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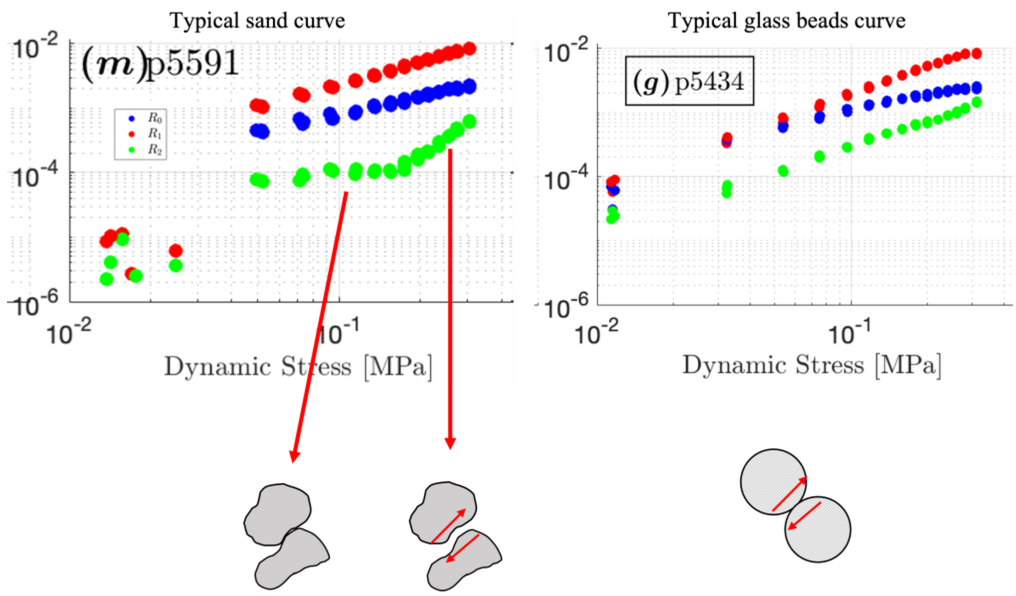
ABSTRACT
Our study focuses on unraveling the microphysical origins of the nonlinear elastic properties of granular media. Previous work has shown that the nonlinear elastic response of consolidated granular media like rocks likely arises from two distinct mechanisms, one that might be related to the opening/closing of grain contacts, and the other one related to shearing. We utilize a pump-probe approach called Dynamic Acousto-Elastic Testing (DAET) that tracks the nonlinear elastic response at each phase of a dynamic cycle, thereby providing direct observations of transient softening/weakening and hysteresis phenomena. To gain further insights on the mechanisms taking place at the microscopic scale, we investigate how relative humidity (RH) and grain angularity affect the nonlinear elastic response of (1) spherical glass beads and (2) angular sand particles. We find that the elastic nonlinearity increases greatly with RH in glass beads, while little to no dependence with RH is found in sand particles. The increase in nonlinearity with RH observed in glass beads is consistent with the idea that water adsorption on the grains makes the contact junctions weaker and prone to greater disturbances when subjected to dynamic loading. Conversely, the lack of RH dependence in sand particles is likely due to the inability of adsorbed water to weaken the locked grain junctions. Finally, for angular particles, and irrespective of RH level, we observe a stress threshold below which the R_2 parameter (related to the third harmonic) is amplitude independent (figure below). No such threshold is observed for spherical beads.



CAPTION: Nonlinear elastic response of angular (left) and spherical (right) granular media. For angular sand particles, the parameter R_2 (related to third harmonic and shearing of the grain junctions) remains small and amplitude-independent at low dynamic excitation and increases sharply when dynamic stress exceeds a particular threshold. In comparison, results in spherical glass beads show a steady increase over the entire dynamic stress range.

Stiffness anisotropy induced by static and dynamic loading in sandstone

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ABSTRACT
Nonlinear behaviour of consolidated granular materials is investigated by means of acoustoelastic and dynamic acoustoelastic testing methods. In case of dynamic loading, slow dynamic response including conditioning and relaxation phases is observed. The experiment consists of pump and probe scheme, where external strain is induced using low-frequency monochromatic continuous wave excitation at the first longitudinal mode and short probing pulses are used to monitor the evolution of wave velocities and damping. Both longitudinal and shear wave transducers are used for probing and two different shear wave polarizations with respect to the conditioning strain are compared. The variations on the sandstone bar (120 x 30 x 30 mm^3) are rather small, thus precise experimental and data processing techniques are crucial. It is shown that conditioning effects on longitudinal and shear wave velocities are correlated. However; the correlation factor is anisotropic, i.e., dependent on the polarization of the shear wave. Similar behaviour is observed on the evolution of damping. Results are compared to conventional acoustoelastic testing experiment with strain induced by sample compression. Although the extent of velocity variations is much larger, the correlation factors are comparable to the ones measured in dynamic loading.

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Stress equations of motion and compliances for nonlinear ultrasonics in incompressible solids

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ABSTRACT
Until recently, theories of nonlinear ultrasound in solids have exclusively been approached from formulating displacement-based equations of motion, i.e., Navier's form. The resulting models often contain second-, third-, and higher-order elastic stiffness constants arising from nonlinear constitutive relationships. Conversely, it is possible to formulate stress-based equations of motion in which stress is the dependent variable and second-, and higher-order compliance constants become the primary material parameters. This presentation is focused on the stress-based formulation applied to elastic waves in solids and extensions to nonlinear ultrasonics. The situation involving the interaction of a dynamic stress wave with a solid containing an initial static stress (acoustoelasticity) is highlighted. While the stress-based approach is non-conventional, it offers the benefit that the compliance constants remain finite when including kinematic constraints of incompressibility, which is needed for applications involving some soft solids. Results including the consideration of incompressibility on the second-, third-, and fourth-order compliance constants are given.

Nonlinear wave mixing in compressible and incompressible elastic solids containing cubic nonlinearity

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ABSTRACT
Wave mixing or the scattering of sound from sound is one of the canonical phenomena seen in nonlinear acoustics. For mixing nonlinear elastic waves, much of the attention has focused on first-order nonlinear effects leading to the usual sum and difference frequencies. This presentation highlights a recent extension to the mixing of waves in a solid medium containing second-order or cubic nonlinear effects. In these cases, the sum and difference frequencies mix to produce generated waves with frequencies $\omega_p \pm 2\omega_q$ in addition to contributions back to the fundamental waves ω_p and ω_q. The model is developed for resonance and non-resonance mixing in generally anisotropic solids. After the model is provided, specific results for isotropic solids will be highlighted. For this case, resonance conditions for the mixed waves are given followed by analysis of the geometry of the mixing zone. It is observed that some mixing configurations have sharp resonances whereas others have broad regions of high amplitudes near resonance. Lastly, the results are extended to include incompressible materials appropriate to some soft solids.

Nonlinear propagation of shear wave beams in soft elastic media with transverse isotropy

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ABSTRACT

Transversely isotropic (TI) soft solids are approximately incompressible and possess a single preferred material direction, referred to here as the fiber direction to reflect the origins of anisotropy in many soft tissues. The theory for plane nonlinear shear wave propagation in a TI soft solid [Cormack, JASA **150**, 2566 (2021)] is extended here to include leading order effects of wavefront curvature. The material is modeled using a general expansion of the strain energy density that comprises thirteen terms that define the elastic moduli. Coupled equations of motion for shear horizontal (SH) and shear vertical (SV) displacement fields, which are polarized perpendicular to and in the plane of the fiber direction, respectively, are derived using energy considerations. Terms in the equations of motion that are linear in strain account for diffraction and anisotropy of the wave speeds. Nonlinear terms include those from quadratic and cubic plane wave interactions, as well as additional quadratic nonlinear contributions that arise from wavefront curvature. Two special cases are investigated that illustrate the effects of anisotropy and diffraction on nonlinear shear wave propagation. Spatially varying SV source motion in the fiber direction exploits a quadratic nonlinear interaction unique to TI soft solids that results in an axial second harmonic with longitudinal polarization. Diffraction of SH waves in the fiber plane reveals anisotropic effects such as steering of the propagation direction and an increase or decrease in the extent of the near field, the effects of which on the cubic propagation nonlinearity are investigated analytically and numerically.

Weakly nonlinear plane waves in transversely isotropic elastic materials

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ABSTRACT
We present recent results on the propagation and interaction of weakly nonlinear plane waves in transversely isotropic elastic materials [1]. We aim to reveal the difference in the shear waves' behaviour in anisotropic versus isotropic materials. We are interested in weakly nonlinear effects. It is known that a quadratic nonlinearity cannot show up in shear waves when we restrict ourselves to isotropic materials. The "weakest" type of nonlinearity which is manifested by shear waves propagation is cubic in isotropic materials. We demonstrate that the quadratic nonlinearity may appear even for a single shear wave propagation due to the presence of fibres. To show the appearance of the quadratic nonlinearity for shear waves propagating in anisotropic materials, we use a weakly nonlinear asymptotics method. We analyze particularly simple models of transversely isotropic materials. We study fibre reinforced materials in which the strain energy function decouples into the part representing a matrix material and the other part which represents the properties of reinforcing fibres that are embedded in the matrix. For simplicity, we choose the model in which the anisotropic part of the energy function depends on only one strain invariant. This is the so-called standard reinforcing model [2]. Applying the weakly nonlinear asymptotics method, it is shown that the inviscid Burgers equation describes an evolution of a single quasi shear wave for this model. The result contradicts the case of isotropy, where the evolution equation with quadratic nonlinearity cannot describe any shear wave propagation.

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Modeling of nonlinear torsional wave propagation in a thin circular rod with Lagrangian mechanics

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ABSTRACT
Coupled nonlinear wave equations are derived and analyzed for the special case of finite-amplitude torsional wave propagation in a thin rod with circular cross section. Finite-amplitude shear deformation from a torsional source produces longitudinal motion in the rod due to the normal stress effect. The derivation procedure begins by expanding the displacement field in powers of the radial coordinate, and then expressing the displacement field in terms of wave functions for the twist and longitudinal displacement by applying the stress-free nonlinear boundary conditions at the rod surface. The hypothesis of plane cross sections is found to be insufficient for satisfying the boundary conditions at the required order. Lagrangian mechanics are employed to obtain coupled wave equations based on the resulting expressions for the kinetic and strain energy densities. The approach thus differs from a previous derivation of the same problem by Sugimoto et al. [Wave Motion **6**, 247 (1984)], who did not assume the existence of a strain energy function (hypoelasticity) and employed nonlinear dynamical equations to obtain the coupled wave equations. Similarities and differences between the wave equations determined using the present approach and those obtained by Sugimoto et al. will be discussed.

An exact solution of an augmented Burgers equation and amplitude-dependent acoustic propagation speed for strong nonlinearity

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ABSTRACT

Nonlinear sound propagation in the atmosphere is usually modeled using an augmented Burgers equation accounting for a weak nonlinearity and atmospheric absorption. Because the absorption includes the molecular vibrational relaxation, such a Burgers equation is more complex than the regular Burgers equation that only accounts for the thermoviscous dissipation in the absorption. Although an exact solution of the regular Burgers equation has long been derived using the Cole-Hopf transform, an exact solution of the augmented Burgers equation has not been derived previously. Thus, this paper presents an exact solution of the augmented Burgers equation. This novel solution is shown to be equivalent to the solution using the Cole-Hopf transform when the absorption only involves thermoviscous dissipation. It can also be reduced to the known solution of an N-wave when the absorption is ignored.

The augmented Burgers equation is an approximation valid for weak nonlinearity. However, this assumption may not be accurate for acoustic signals propagating from the lower atmosphere and which are subsequently refracted downward from the upper atmosphere (e.g., stratosphere and thermosphere) due to the decreasing air density with increasing altitude [Lonzaga, et al., Geophysical Journal International, 200(3), pp.1347-1361]. Consequently, the current paper also discusses the effects of a strong nonlinearity that lead to an amplitude-dependent increase in signal propagation speed. For an impulsive signal such as a sonic boom, these effects cause a dispersion of the signal similar to the observed dispersion of acoustic signals from supersonic Concorde as well as from large explosions.

Laboratory-scale characterization of lightning strikes: acoustical and electrical measurements synchronized with optical visualizations

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ABSTRACT
Thunder initiated from lightnings can be heard up to tens of kilometers, with an acoustic pressure up to several Pascals. In real atmospheric conditions, the generation of acoustic waves is conditioned by the electric energy of the discharge, which is not measurable. The geometry of the lightning, for example their lengths and curvatures, also has a great influence on the acoustic waveform. Furthermore, the real atmospheric conditions, such as the temperature, the wind direction and its intensity, cannot be controlled nor measured extensively. In this communication, a laboratory-scale acoustical characterization of thunder is performed on a 1 m long lightning strike. Every strike is characterized using a microphone array, and a synchronized optical visualization to obtain the shape of the discharge channel. A synchronized measurement of electrical parameters (discharge current and instantaneous voltage) is also performed to obtain the energy of the discharge. The measured waveforms are similar to those measured on smaller spark discharges, with an "N" shape exhibiting a two-shock structure. However the electric parameters are well controlled and stable, a large variability of the waveforms is observed 6 meters away from the source, with acoustic peak pressure between 200 and 400 Pascals, and arrival times between 16.5 and 17 micro seconds. This variability is linked to the observed variability of the discharge channel geometry. Future collaborative work will focus on comparisons with numerical reconstruction of the discharge channel using the microphone array data.

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Measurement and visualization of coalescence resulting from two nonlinear spherical wavefronts intersecting in air

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ABSTRACT
Coalescence of intersecting Mach waves, which are generated by turbulent structures in supersonic jet flow, has been proposed as a significant contributor to acoustic waveform steepening in the near field of a jet and produces the noise referred to as crackle [Baars et al., AIAA (2013); Fiévet et al., AIAA (2016)]. Recently, numerical simulations of intersecting waveforms based on the KZK equation have demonstrated that the coalescence process can lead to increased steepening, with the degree of steepening dependent on parameters including intersection angle, waveform duration, and geometrical spreading [Willis et al., AIAA (2022)]. Schlieren imaging was used to visualize intersecting Mach waves in a laboratory-scale Mach 3 jet flow. Subsequently, a simplified experiment was desired that does not depend on turbulence for wave generation while still exhibiting behavior seen in Mach waves. To achieve this, a spark source was used to generate repeatable waveforms in air as part of two experiments modeling coalescence. The first employs reflection from a rigid plane to model symmetric intersection corresponding to different angles of incidence. The second employs intersecting waveforms emanating from different openings in a 3D-printed enclosure. Along with visual observation, schlieren images of the coalescing waves allow for precise positioning of microphones along the axis of intersection. Measurements of nonlinear evolution were made for the intersecting waveforms produced with both experimental setups and compared with measurements made for one waveform alone. The measurements permit assessment of the extent to which coalescence enhances waveform steepening.

ACKNOWLEDGEMENTS
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Nonlinear scattering of crossed ultrasonic beams in the presence of turbulent jet flow in water: Experiments and theory

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OBJECTIVES

The nonlinear interaction between mutually perpendicular crossed CW ultrasonic beams - interacting in the presence of turbulence in water – generates a radiated sum frequency component that propagates outside the overlap region. In past experiments the primary components were modeled as locally plane traveling wave fields with primary frequencies labeled as f_1 and f_2; while the sum frequency component $f_+ = f_1 + f_2$ in the far-field is an outgoing spherical "scattered" wave. A cubic nonlinear term in the Reynolds Stress Tensor $\rho u_i u_j$ predicts the nonlinear scattering using this term as a virtual source (using the Born approximation) in the full Lighthill nonlinear wave equation for aerodynamic sound generated. In this paper the nonlinear crossed beam experiment in the presence of turbulence was performed in a relatively small open acrylic water tank (10 cm cube) such that both the incident primary components are standing wave fields interacting nonlinearly in the presence of turbulence. Experiments for scattering at the sum frequency f_+ are presented along with a theoretical model using standing waves primaries in an effort to understand the results.

METHODS

Experiments on the nonlinear scattering of sound by sound (in the presence of turbulence) were performed in an open 10 cm cubic acrylic water tank of wall thickness 3.2 mm. This demonstration apparatus allows for the nonlinear scattering of mutually perpendicular crossed CW ultrasonic standing wave fields of primary frequency components: $f_1 = 2.240$ MHz, $f_2 = 2.293$ MHz; which interact nonlinearly (in a localized region) with turbulence. Turbulent shear flow was generated by a submerged circular water jet with nozzle exit diameter d=3.2 mm with a 60 cm^3/s volume flow rate (with average exit velocity ~ 800 cm/s and Reynold's number Re ~ 25000). In the presence of turbulence, nonlinear scattering (~10 d from the nozzle) was measured outside the interaction region at the combination frequency $f_+ = 4.533$ MHz. Identical 1.27 cm diameter quartz circular plane array transducer units (T_1 and T_2) epoxied at the center of two adjacent vertical tank sidewalls generated primary ultrasonic fields. Two 4.5 MHz receiving transducer units (6.35 mm diam PZT-4) labeled R_f and R_b measured the nonlinear scattering in the forward or backward directions $\mathbf{n} = \mp (\mathbf{i} \cos(45) + \mathbf{j} \sin(45))$. In the absence of turbulence there was virtually no radiated sum frequency component. The jet flow is downward aligning the axis with the overlap region. The suction side of the water pump was connected under the bottom center of the tank. Doppler shift, frequency broadening and intensity measurements are also compared at other scattering angles.

RESULTS

Figure 1. shows the experimental setup of the nonlinear crossed beam experiment in the presence of turbulence using standing wave fields. Results are shown in Figure 2. If the fields were locally plane traveling waves then the forward scattering results would show a much narrower power spectrum due to the sum frequency broadening which involves the 2nd moment of random Doppler shifts when compared to the backscattering.

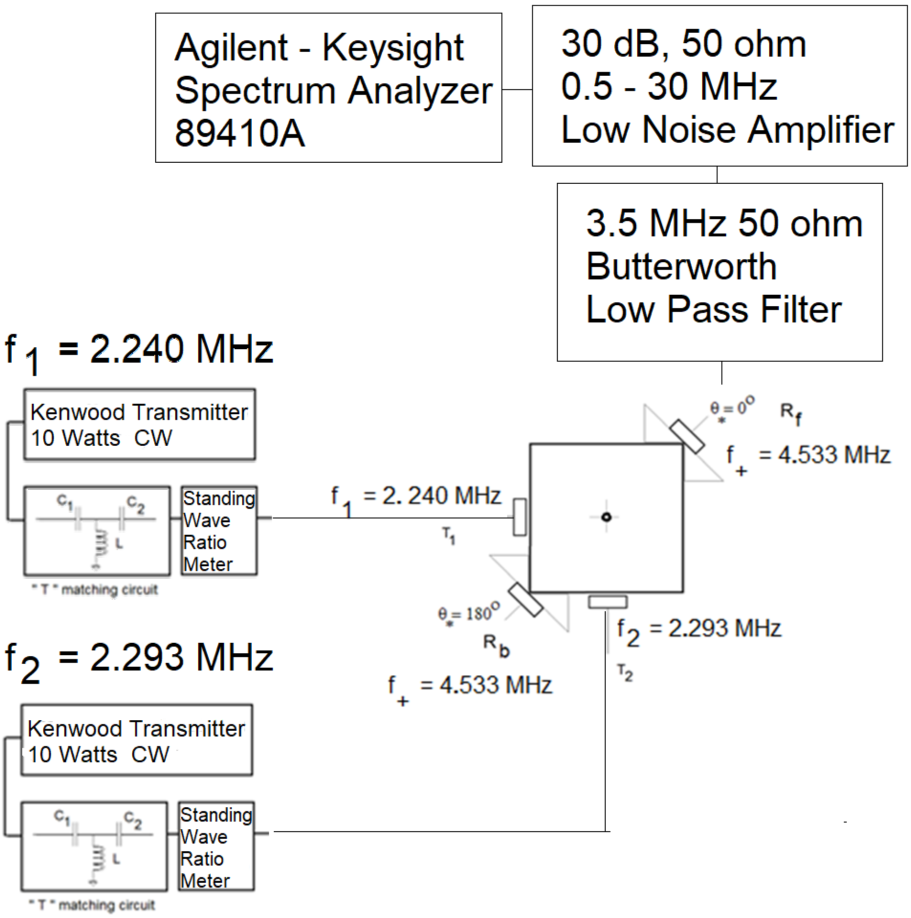

FIGURE 1: Experimental setup of the nonlinear scattering of crossed standing wave fields in the presence of turbulence.

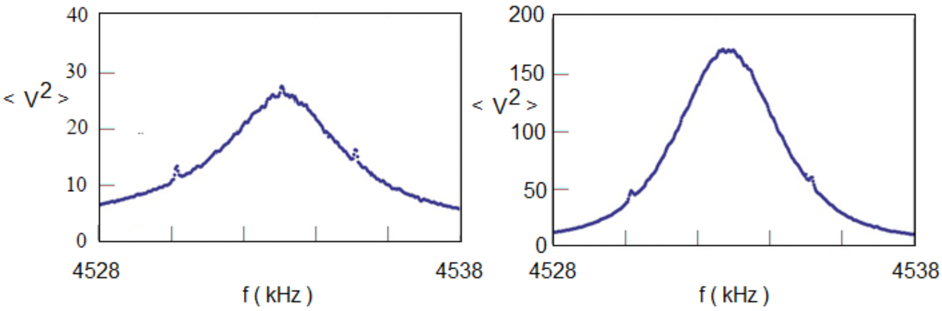

FIGURE 2: Nonlinear sum frequency power spectrum (average of 10,000 spectra). The vertical scale is multiplied by $(1\ \mu\text{Vrms})^2$. LHS: (a) Forward scattering at $\theta_* = 0^o$, rms frequency broadening = 2313 Hz, skewness factor S = - 0.025, kurtosis factor K = 2.44; RHS: (b) Back scattering $\theta_* = 180^o$, broadening = 1780 Hz, S = 0.059, K = 3.20 .

CONCLUSIONS

There is some experimental evidence that one needs to use a standing wave field for each of the primary components. Then from a theoretical development, the nonlinearly scattered wavenumber $\mathbf{K}_+$ of four crossed-beam interactions must be considered: $\mathbf{K}_+ = k_1 (\mathbf{n} - \mathbf{n}_1) + k_2 (\mathbf{n} - \mathbf{n}_2)$, where $\mathbf{n}_1 = \mp \mathbf{i}$, $\mathbf{n}_2 = \mp \mathbf{j}$, $\mathbf{n} = \mathbf{i} \cos\theta + \mathbf{j} \sin\theta$ (the unit vector in the scattering direction) and $k_1 = 2\pi f_1/c$, $k_2 = 2\pi f_2/c$. Here, c is the infinitesimal speed of sound in water ~ 1482 m/s at 20° C .

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