Metamaterials beyond photonics

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Abstracts

Barnwell, Ellis

Elastic wave propagation in pre-stressed periodic structures; tuning, band-gap switching and invariance

The effect of nonlinear elastic pre-stress on linear elastic wave propagation in a two-dimensional periodic structure is investigated. The medium consists of cylindrical annuli embedded on a periodic square lattice in a uniform host material. An identical inhomogeneous deformation is imposed in each annulus and the theory of small-on-large is used to find the incremental wave equation governing subsequent small-amplitude linear elastic waves in the context of both antiplane (SH) and in-plane (P-SV) waves. A modified plane-wave-expansion method is employed in order to determine permissible eigenfrequencies. It is found that pre-stress significantly affects the band gap structure for Mooney-Rivlin and Fung type materials, allowing stop bands to be switched on and off. However, it is shown that for specific classes of materials, phononic properties remain invariant under nonlinear deformation, permitting some rather interesting behaviour and leading to the possibility of what we shall term phononic cloaks.

Bigoni, Davide

Experiments on the dynamics of self-oscillating elastic structures

The experimental setting developed for dynamical analysis of flutter instability by Bigoni and Noselli ["Experimental evidence of flutter and divergence instabilities induced by dry friction", J. Mech. Phys. Solids, 59, 2208 - 2226 (2011)] was limited to the Ziegler's double pendulum. Their setup is extended through a complete re-design of the mechanical device to allow investigation of flutter and divergence instabilities in elastic structures. Results of systematic investigations are presented and discussed in the light of the theory of self-oscillating systems.

Caleap, Mihai

Engineering three-dimensional ultrasonic colloidal meta-systems with tuneable anisotropy

We explore the use of acoustically assembled colloidal metamaterials to create reconfigurable meta-devices. This idea is demonstrated experimentally by real-time control of the characteristics of a metamaterial-based acoustic filter. We describe how acoustic radiation forces can be used to assemble particles into colloidal structures that serve as microscopic elements in acoustic meta-devices [M. Caleap and B.W. Drinkwater, Proc. Natl. Acad. Sci. 111, 6226 (2014)]. The method uses high pressure three-dimensional acoustic standing waves to trap a suspension of micro-particles in patterns resembling crystal or quasi-crystal lattices. The lattice constants can then be adjusted in real-time by changing the wavelength of the standing wave. Technological applications, ranging from tuneable filters to acousto-optical devices, are anticipated. Both crystalline and quasi-crystalline structures are likely to be well suited to many metamaterial applications and the ability to actively control their properties could further open up the design space (i.e. for engineering reconfigurable waveguides and hence controlling the propagation of waves).

Carta, Giorgio

Multi-scale high-contrast resonators for the reduction of earthquake-induced vibrations of fluid-solid systems

New concepts based on the use of metamaterials have been recently proposed for the design of seismic isolation systems. The main drawback of the majority of the existing systems is that they are efficient only in a narrow high-frequency range. We present an innovative design of a "seismic metamaterial", consisting of multi-scale high-contrast resonators in a fluid-solid system, which is

capable of mitigating the vibrations of the structure in a wide low-frequency interval. In particular we apply this novel design to a cluster of three-dimensional fuel storage tanks, commonly found in an industrial petroleum plant. By means of numerical simulations in the transient regime, we demonstrate that the vibrations of the fluid-filled tanks induced by the excitations of real earthquakes are significantly reduced by the system of resonators, for any fluid level in the containers. Furthermore, a large cluster of storage tanks is modelled as a periodic structure by imposing Floquet-Bloch conditions at the boundaries of a repetitive cell. The results of our computations, performed for an actual industrial problem and realistic earthquake load profiles, prove that metamaterial systems can be effectively employed for the seismic protection of real structures.

Colquitt, Daniel
The foundations of seismic metamaterials: Plates and Half-spaces
Metamaterials barely existed fifteen years ago, but now forms a major research area. Although initially developed for optics, the field of metamaterial research has expanded rapidly and now includes the development of novel materials for applications in acoustics and elasticity. More recently, the applicability of metamaterials to seismology has sparked the interest of geophysicists in the development of novel methods to control surface waves. Given the interest in this emerging area, there is a need to study the properties of the solutions to fundamental canonical problems. We will present some recent results for two relevant problems and develop the theoretical framework for these seismic metamaterials. We will initially consider a periodic array of resonators on an elastic plate providing explicit expressions for the dispersion equation and solutions. This then motivates the more complicated problem of periodic arrays of resonators on elastic half-spaces. We will analyse the dispersive properties of these structures and present explicit solutions in the metamaterial regime. We will also examine the transmission problem for surface waves and present a novel method for the control of surface waves on elastic solids.

Cotterill, Phil
Acoustic material technologies in sonar applications
We provide a brief overview of Thales's technology sectors and the materials technologies of interest for sonar applications. In particular we focus on two specific media: micro-voided and macro-voided composites, the modelling of which is important for the understanding of sound propagation in these materials.

Craster, Richard
Modelling of waves through structured media primarily in elasticity
The full elasticity equations are a vector system that connect stresses and displacements. For structured media, composites or materials that have resonators or inclusions embedded within them or upon them, it is natural to try and obtain effective media equations. Unfortunately in several applications one is not in a regime where quasi-static homogenisation is valid and so we consider dynamic homogenisation. A range of different problems are discussed and treated and analogies drawn, where possible, with electromagnetism. There are, for instance, analogous waves to spoof surface plasmons, that is, waves created purely by periodic geometric variation and these are discussed and used to illustrate the methodology of dynamic homogenisation.

Cummer, Steve
Applied Acoustic Metamaterials
While acoustic wave propagation in periodic structures is an old topic, modern research in acoustic metamaterials began with efforts to mimic progress in electromagnetic metamaterials with a focus on exotic material parameters, such as negative modulus and negative effective mass. The field has since branched into a wide range of topics including phononic bandgap materials, transformation acoustics, active materials, and thin metasurfaces. This presentation will focus on recent results from acoustic metamaterials research in my group, following several different directions. These include transformation acoustics, focusing on the design and experimental demonstration of structures based on fluid-based anistropic acoustic metamaterials; labyrinthine metamaterials and metasurfaces, a concept first described by Jensen Li in which the intra-cell coiling of propagation distance enables the control of transmission phase to create a wide range of properties and effects;

and active acoustic metamaterials, in which electronic control of the acoustic response of an active structure can create a very wide range of behaviours.

Drinkwater, Bruce
Building acoustic landscapes with meta-bricks
The ability to control acoustic fields is crucial in diverse applications such as loudspeaker design, ultrasound imaging and acoustic particle manipulation. The current approaches use fixed lenses or expensive and bulky phased arrays. Here we describe a new approach in which a particular acoustic field is created by transmission through a quantised meta-layer. The quanta here are small bricks, each of which encodes a specific function, for example the addition of a phase delay. An algorithm is developed which allows the optimal quantisation of the meta-layer to generate a given acoustic field to a required accuracy. This operation is similar to analogue-to-digital conversion and seeks to minimise the number of different bricks required. With this assembled meta-layer an incident coherent ultrasonic wave can be transformed into almost any diffraction-limited field. We show examples of focusing, steering and the more complex bottle-shaped fields required for the creation of a sonic tractor beam.

Groby, Jean-Philippe
Perfect sub-wavelength absorption in reflection and transmission problems
The ability to perfectly absorb sound with sub-wavelength structures is of great scientific and engineering interest. Solving this challenge requires us to reduce the structure dimensions while increasing the energy density at low frequencies and finding conditions for impedance matching. By using the concepts of slow wave propagation to increase the energy density with small dimensions and of critical coupling to match the impedances, we discuss perfect absorption for both reflection and transmission problems. The system analyzed here is a rigid panel comprising a periodic distribution of thin closed (opened) slits for the reflection (transmission) problem. The slit upper walls are loaded by resonators, producing the slow wave propagation that shifts the slit resonances to the deep sub-wavelength regime. By compensating the intrinsic losses of the system with the energy leakage, the critical coupling condition can be achieved. For the reflection problem, sub-wavelength perfect absorption is possible with identical loading resonators because one type of symmetry is involved. For the transmission problem, perfect absorption is not possible in such a system as long as both symmetric and anti-symmetric resonances are staggered in frequency. An alternative consists of using asymmetric distribution of resonators.

Guenneau, Sebastien
From models of platonics to seismic metamaterials
Control of Lamb waves propagating in thin elastic plates with sub-wavelength inclusions provides a nice playground for investigation of control of similar types of waves propagating at the interface between structured soil and air: So-called Rayleigh waves share some of the features of flexural waves and two large scale field experiments conducted by the team of Stephane Brule at the civil engineering company Menard in 2012 confirm one can use simple plate models to grasp (some of) the physics of surface seismic waves in sedimentary basins. The first experiment shows one can shield Rayleigh waves around the frequency 50 Hz that neatly falls within a stop band of an approximate plate model. The second experiment is a proof of concept of a flat seismic lens via negative refraction in the frequency range 5 to 10 Hz. More experiments are underway with various types of sub-wavelength inclusions (boreholes, columns of concrete etc.), with notably a large scale experiment on a seismic cloak that will be designed and tested in collaboration with Institut Fresnel in Marseille, Imperial College in London, ISTerre in Grenoble and the Menard Company.

Haberman, Michael
Physical origins of Willis coupling in acoustic metamaterials
It is convenient to study and describe bulk inhomogeneous media in the long wavelength regime with dynamic effective material properties. Analytically, these constitutive properties are determined by averaging fields at the microscale over a representative unit cell to provide a local description of the inhomogeneous media. Considering these effective properties as local descriptors implies certain constraints on their values if the media behaves according to the restrictions associated with passivity, reciprocity, and causality. In addition to the traditional properties

(effective wavenumber, impedance, density, and compressibility), recent research has shown that inhomogeneous media with asymmetric unit cells and/or composed of a periodic lattice require effective properties that couple the average volume-strain and momentum fields. This type of coupling is known as Willis coupling in elasticity and is analogous to bianisotropy in electromagnetism. This work shows that multiscale models of acoustic metamaterials that neglect Willis coupling predict effective properties that do not satisfy passivity, reciprocity, and causality. The microscale and mesoscale origins of macroscopic coupling will be determined using a self-consistent multiple scattering homogenization scheme for periodic media. Examples of one-dimensional periodic fluid media displaying coupling will be presented together with a discussion on the determination of these properties.

Haslinger, Stewart
Controlling flexural waves with structured Kirchhoff-Love plates
The design of metamaterials, photonic crystals and micro-structured systems that are able to generate effects unattainable with natural media, is an important and rapidly-growing area of research. Many ideas originate in electromagnetism and optics, and are now being applied to other wave-related branches of physics such as elasticity and acoustics. The analogue of photonics known as platonics uses the Kirchhoff-Love plate equations to model the flexural vibrations of a thin elastic plate, which is patterned with a structured array of scatterers/inclusions. By varying the structure, we can demonstrate a multitude of wave phenomena including negative and ultra-refraction, blocking, enhancement and cloaking. The main topic of this talk is the filtering and localisation of flexural waves in an elastic plate constrained by a semi-infinite two-dimensional cluster of point scatterers. We give special attention to waves localised close to the front grating. A discrete Wiener-Hopf technique is employed and a formal connection between the dispersion properties of flexural Floquet-Bloch waves and the semi-infinite platonic crystal is demonstrated. We shall also discuss the connection with previous results for both finite stacks of gratings embedded within the plate, and the doubly periodic two-dimensional array of scatterers.

Hladky, Anne-Christine
Tunable Bragg band gaps in phononic crystals
Phononic crystals are the subject of numerous theoretical and experimental works thanks to their peculiar spectral properties (stop bands, pass bands with negative dispersion …). Recent studies have introduced significant breakthroughs with the goal of tuning these frequency ranges via the application of an external stimulus in order to achieve flexibility and reconfigurability for the device. In this presentation, we first present Phononic Crystals made of piezoelectric materials. It shows that the pass bands and stop-bands of the device under study are easily tunable by only changing the electrical boundary conditions applied on each electrode of the device. Experimental results are compared with success to theoretical predictions. Further studies are also presented on one-dimensional piezoelectric phononic crystals whose constituent materials or geometry are time-varying functions. Temporal dependency is demonstrated to drastically affect the transmission of acoustic waves through these time-varying phononic crystals. Nonlinear phenomena such as non-reciprocal wave propagation and parametric amplification are observed.

Hopper, Hugh
Acoustic metamaterials at Dyson: current work and future challenges
The noise generated by domestic products has a major impact on the end user and noise is a key priority for many manufacturers. Traditional acoustic treatments such as foams are bulky and perform poorly at low frequencies. Metamaterials show the potential to improve on both of these aspects which could enable a step change in the acoustic performance of products. At Dyson, we have been investigating various configurations of metamaterial including arrays of resonators, metaporous materials with solid inclusions embedded in foams and a superabsorber concept which uses metamaterials to guide sound waves into porous media where it is absorbed. Key challenges for the current investigations are packaging constraints and achieving the desired acoustic performance over a broad frequency range. During the course of our investigations, several roadblocks have been identified for implementing metamaterials which could be considered in future projects. Firstly, airflow may alter the performance of the metamaterial. Secondly, the design and optimisation of the material's configuration should be streamlined as much as possible by

reducing the design space. Finally, using commonly available "base" materials in the construction of the metamaterials will ensure that manufacturing is safe and affordable. Collaborations between industry and academia will help to solve these problems and identify any further issues to enable a widespread adoption of the technology.

Hussein, Mahmoud

Nanophononic metamaterial: Locally resonant metamaterial that does not depend on subwavelength effective properties

The concept of a metamaterial has been introduced in electromagnetics and acoustics as an artificially structured locally resonant material that exhibits unique, and often extreme, effective properties in the subwavelength regime. Here we introduce the notion of a metamaterial to the area of heat transfer at the nanoscale. While our concept also uses local resonances to induce unique and extreme properties - in this case pertaining to nanoscale phonon transport and thermal conductivity - the underlying phenomenon is not limited to the subwavelength regime and does not depend on an effective properties characterization. One possible configuration for this new type of metamaterial, termed nanophononic metamaterial (NPM), is based on a silicon membrane with a periodic array, or a forest, of nanoscale pillars erected on a free surface. The numerous resonances of the nanopillars hybridize with the heat-carrying phonon modes of the base membrane. This reduces the phonon group velocities near each coupling point in the band structure and as a result the overall in-plane lattice thermal conductivity of the membrane drops significantly. This effect is counterintuitive because the nanopillars add modes to, rather than take modes away from, the system. This concept provides a new paradigm for metamaterials and an unprecedented opportunity for boosting the performance of thermoelectric devices.

Johnson, Steven

Limits (or targets) of metamaterials: bounds on light-matter interactions

When designing metamaterials, meta-atoms, and other complex electromagnetic materials (whether subwavelength or not), it is useful to have shape-independent limits on the attainable performance. Such limits are not necessarily "negative" constraints, but can often provide "positive" targets for future research to approach (or even exceed, if the assumptions underlying the limits can be circumvented). Many famous such results include the Yablonovitch limit for solar cells, the Manley-Rowe limits to nonlinear frequency conversion, and the Wiener bounds on homogenized material properties. In this talk, I will review some newer bounds derived more recently in our group: scaling limitations on cloaking, upper bounds on scattering/absorption, upper bounds on the local density of states and radiation, and limits on the performance of "exceptional" resonances. Several of the bounds are derived surprisingly simply from fundamental energy considerations: the absorbed power (a quadratic function of the fields) is bounded above by the total absorbed+scattered power (the real part of a linear function of the fields via the optical theorem), and the resulting quadratic < linear constraint implies an upper bound on the material polarization. For a material with a (local, linear) susceptibility χ at a frequency ω, the resulting upper bounds on light-matter interaction depend on $|\chi| / \omega \operatorname{Im} \chi$ and the source/matter separation distance d, but are independent of shape or periodicity and apply equally well to complex subwavelength structures such as metamaterials (with the bounds depending only on the constituent materials).

Maling, Ben

Whispering Bloch Modes

The properties of Rayleigh-Bloch waves along linear arrays in acoustics, elasticity, and photonics, are well documented. In this talk, we consider the effect of curvature on such systems, and in particular its contribution to radiative energy loss. To demonstrate the relevant physics, we consider continuously deforming such an array into a circular ring, resulting in spatially-confined eigenstates that we refer to as whispering Bloch modes. Using asymptotic analysis and arguments based on symmetry we show that for a given array there is a critical radius of curvature that results in the radiation loss switching formally from exponentially small to algebraic, and discuss the implication of this result in the broader context of a design problem.

Maurel, Agnes

Homogenization of thin interfaces, effective jump conditions

We present a method of homogenization adapted for thin micro-structured interfaces, with thickness smaller than the typical wavelength. The approach is based on a two scale expansion of the solution in an inner region and an asymptotic matching of this solution with the outer solution. We show that the structuration can be replaced by effective jump conditions across a vanishing equivalent interface. Validations of the method are presented in the frequency regime and in the temporal regime.

McPhedran, Ross

Controlling Waves: 500 Million Years Ago to Tomorrow

This public lecture will describe two topics. The first of these is the impact of the evolution of image-forming eyes on the diversity of marine species around 500 million years ago, relying on what we can learn from comparison of the fossil records and existing species. The second concerns cloaking, the hiding of objects from detection by waves-i.e. the attainment of sorts of invisibility.

Milton, Graeme

On the elasticity tensors of 2d and 3d printed materials

Back in 1995 Andrej Cherkaev and myself showed that every positive definite 4th-order tensor satisfying the symmetries of elasticity tensors can in fact be realized as the effective tensor of an appropriate microstructured material built from two materials, one sufficiently compliant, and the other sufficiently stiff. The building blocks for achieving this are pentamode materials, elastic structures that are stiff to one loading (they support any desired applied stress) but at the same time have five easy modes of deformations (they are easily compliant to five independent strains, hence the name pentamode). Thus there are no hidden restrictions on elasticity tensors beyond the positive-definiteness, needed for thermodynamic stability in an unconstrained material. In 2d or 3d printed materials made from one phase plus void, the situation is a little different. The moduli of the elastic phase are fixed, and assumed known, and one seeks the set of all possible effective tensors that can (theoretically) be made by mixing the elastic phase with void in prescribed proportions f and 1-f. (Knowing how the proportions affect the elasticity tensor is important if weight is a consideration). This set is known as the G-closure at constant volume fraction. Here we find that many "sides" of the G-closure can be completely characterized. Associated with each "side" are families of microstructures comprised of "Avellaneda material" minimizing a sum of complementary energies, embedded in a thin walled structure, where the walls contain the appropriate m-mode material. Under certain strains the material "slips" along the walls with very little energetic cost, while the structure supports applied stresses in the orthogonal space, and the associated response to them is the same as the "Avellaneda material" and hence is optimal. The analysis also extends to mixtures of an elastic phase and an almost rigid phase. This is joint work with Marc Briane and Davit Harutyunyan.

Movchan, Alexander

Flexural waves in structured plates - singular perturbations and localisation

The talk presents an analytical model of waves in Kirchhoff elastic plates. Dispersion relations are analysed and discussed to emphasise the phenomena of dynamic anisotropy, localisation and neutrality. Approximate cloaking for flexural plates is presented in the context of a singular perturbation approach, which also provides counter examples, where cloaking of a defect in a Kirchhoff plate is not possible. The models are accompanied by numerical simulations and examples.

Movchan, Natalia

Structured waveguides: controlling vibrations of elongated systems

The talk presents an analytical approach to analysis of the challenging problem of controlling vibrations of multi-scale systems such as elongated multiply supported bridges or tall multi-storey buildings. The spectral analysis of such sophisticated finite systems becomes more transparent with the approximations based on the dispersion properties of Bloch waves existing in the corresponding periodic structures of infinite extent. These waveguide approximations provide insights into the wave spectrum of finite multi-structures and enable a simple isolation of frequency ranges in which

troublesome resonance modes may occur. The approach opens a new way of optimal design of elongated systems by adding substructures that act as wave by-pass systems, preventing catastrophic vibrational damage due to resonance from occurring.

Norris, Andrew
Low frequency transparency and implications in acoustics and elasticity
A first step towards acoustic transparency is to reduce low frequency scattering. The first part of the talk will discuss methods for achieving this in practice using either elastic shells in a fluid matrix or by a purely solid phononic crystal. Applications to finite frequency wave control in water based on these metamaterial elements will be presented, including a cylindrical-to-plane wave lens, gradient index and negative refraction lenses, supported by experimental results showing broadband response and positive gain. The second part of the talk will explore theoretical implications of low frequency transparency for acoustic and elastic waves. Remarkably, realization of low frequency transparency under plane wave incidence requires the strictly infinite frequency effect that the scattered wave in the forward direction precedes the incident wavefront. That is, the scatterer must "boost" the wavefront forward in time. This result is a consequence of a new formula for the acoustic integrated extinction (IE), which is the integral of the total scattering cross-section over all wavelengths. Perfect invisibility, i.e. transparency for all frequencies, requires that the IE vanish, which makes it a useful metric for broadband cloaking. Connections to multiple scattering and static elastic cloaking will be discussed.

Pagneux, Vincent
PT symmetric scattering in flow duct acoustics
We show both theoretically and experimentally that an acoustical wave in an air flow duct going through a pair of diaphragms, one with amplification and another with an equivalent amount of attenuation, displays all the features of a parity-time (PT) symmetric system. Using a scattering matrix formalism, we show the novel features which reflect the PT-symmetry of the scattering acoustical system. We report experimentally the existence of a transition between PT-symmetric scattering eigenstates, which are norm preserving, and symmetry-broken pairs of eigenstates exhibiting net amplification and loss. Some extensions to periodic systems will be also presented.

Parnell, William
Wave speed invariance to tension - stretching the truth?
The concept of hyperelastic invariance has been employed recently in various contexts associated with metamaterials and in particular in association with elastodynamic cloaking, elastic wave disentanglement and so-called phononic cloaks. Here, the concept of total hyperelastic invariance is investigated and it is shown that strain energy functions governing the constitutive behaviour of the soft medium in question, can be theoretically devised to ensure that certain linear elastic waves are unaffected by the presence of nonlinear pre-stress. We describe a number of potential applications and also discuss the relation of these results to experimental results from the early 20th century regarding the invariance of the pitch of a plucked stretched string to tension at large deformation.

Pendry, John
Controlling nanoscale light
Our intuitive understanding of light has its foundation in the ray approximation and is intimately connected with our vision: as far as our eyes are concerned light behaves like a stream of particles. Here we look inside the wavelength and study the properties of plasmonic structures with dimensions of just a few nanometres: a tenth or even a hundredth of the wavelength of visible light, where the ray picture fails utterly. In this talk we show how the new concept of transformation optics that manipulates electric and magnetic field lines rather than rays can provide an equally intuitive understanding of sub wavelength phenomena and at the same time be an exact description at the level of Maxwell’s equations. The concepts are applied to a number of plasmonic structures.

Poncelet, Olivier

Mie-type locally resonant random metamaterials through a microfluidic, bottom-up approach

Mie-type sub-wavelength resonators (low frequency resonant cavities) are a promising conceptual and technical approach in designing and fabricating dense bulk acoustic/elastic metamaterials covering large, small, zero and negative index regimes. Reaching such extreme effective properties for the macroscopic wave-propagation necessitates high wave-speed contrasts in between the inclusions and the matrix: typically a ratio of about 1/10. For dense surrounding matrices with sound speeds in the order of 1 000 m/s, the main challenge is to achieve the production of local resonators supporting waves travelling at speeds less than 100 m/s. The strategy used by our group and some physico-chemist partners is the synthesis of (macro- or micro-) porous micro-beads by means of soft matter techniques, enabling the production of large amounts of soft 100-μm scaled resonators with wave-speeds ranging from 300 m/s down to 80 m/s for L-waves and from 150 m/s down to 40 m/s for T-waves. It is experimentally shown that random fluid-based dispersions of such strong Mie-resonators exhibit zero and negative acoustic index in the ultrasonic frequency range, along with single or/and double negativity of their acoustic properties. The latter will be exemplified within a generalized diagram of complex-valued acoustic parameters.

Rowley, William

Theoretical design of an acoustic beam shifter in air

An acoustic beam shifter is a device that displaces incident sound waves by a fixed amount over all frequencies [1]. Here we illustrate the design process based on transformation acoustics and attempt to theoretically realise the device in air using inhomogeneous media. Transformation acoustics gives rise to a set of required anisotropic material properties for the device; if these properties can be achieved, the beam shifter can be realised over all frequencies with a perfect impedance match to its surroundings. Here the aim is to construct the beam shifter using strategically arranged isotropic media; however, it is shown that apparently non-physical properties are required for the constituent phases, and in particular a negative mass density is necessary for perfect shifting. The possibility of sacrificing ideal properties (associated with invariance and perfect transformation acoustics) is described, in order to improve the feasibility of realization of the device based on [2]. This is achieved by introducing an impedance mismatch and constructing a device from physical media (i.e. phases having positive mass density) but where the shifter has effective properties that are as close as possible to the ideal. This gives broadband beam shifting with non-perfect transmission. Of course negative density has been shown to be a realizable property over specific frequency ranges of inhomogeneous resonant media [3] and therefore we also discuss mechanisms for realising the beam shifter by employing an appropriately chosen inhomogeneous resonant medium for one of the constituent phases.

[1] S.A. Cummer. Transformation Acoustics. In Acoustic Metamaterials, Ch 8, Editors: R.V. Craster and S. Guenneau, 197-216, 2013.

[2] B.I. Popa, L. Zigoneanu and S.A. Cummer. Experimental Acoustic Ground Cloak in Air, Phys. Rev. Lett., 106, 25, 253901, 2011.

[3] Z. Liu et al. Locally resonant sonic materials. Science 289, 1734-1736. 2000

Sambles, Roy

Acoustic metasurfaces

Acoustic Surface Waves may be supported at frequencies below the resonance frequencies associated with holes drilled into or through a solid. By arranging a series of such cavities or holes in lines, pairs of lines or even honeycomb arrangements novel dispersion behaviour of the supported Acoustic Surface Waves may be found. Original data on samples which display negative dispersion and Dirac points will be presented.

Selsil, Ozgur

Active cloaking of finite clusters in a Kirchhoff plate

Following our recent work on active cloaking of inclusions in thin plates, we now consider active cloaking of finite clusters in a Kirchhoff plate. Cloaking is achieved via active sources, which are represented by the non-singular Green's function for the biharmonic operator; we find complex amplitudes of these active sources to cancel out selected multipole orders of the scattered field. We demonstrate the efficiency of our method with several numerical illustrations.

Sheng, PIng

Absorption of sound using subwavelength structures

Traditional means of acoustic absorption generally make use of porous and fibrous materials, gradient index structures, or perforated panels with tuned cavity depth behind the panels. They result in either imperfect impedance matching to the incoming wave, or very bulky structures with dimensions comparable to the wavelength. This state of affairs is dictated by the intrinsic low absorption coefficient of almost all the materials in the acoustic frequency range. In this talk I will first introduce the decorated membrane resonator (DMR) [1], comprising a 200 micron thick latex rubber membrane decorated by small platelet(s). In the simplest case of one circular button at the centre of a circular membrane, the DMR has multiple resonances, the first two usually below 1 kHz. Between the two eigenmodes there is an anti-resonance at which the dynamic effective mass displays a resonant dispersion and the DMR can totally reflect the incoming wave [1]. These DMRs can be turned into very effective sound absorbers, but there is always an upper bound of 50% absorption. To understand the 50% upper bound for the absorption of a single DMR, we have derived a conservation law for the thin membrane DMR, involving the sum of the complex pressure amplitudes for the incoming and outgoing waves [2]. From this conservation law it becomes easy to see that with one-sided illumination, 50% absorption is the upper bound. However, with a reflecting back surface to a single DMR so as to introduce multiple reflections, then total absorption becomes possible. In the above context, the emergence of hybrid resonances [3] is a logical outcome. It will be shown that by placing a DMR with deep-subwavelength transverse dimensions close to a hard reflecting surface, separated by a thin cell of sealed gas, the two lowest resonances are hybridized to create a new resonance at a frequency close to the anti-resonant frequency. The hybridized resonance can have two degrees of freedom, as its vibrational profile must be a linear combination of the eigenfunctions from the two original resonances. These two degrees of freedom are manifest as the average and variance of its (spatially varying) displacement normal to the membrane. Whereas the variance component is decoupled from the radiation modes, and serves the absorption functionality, the average displacement component can be tuned to impedance-match with the background medium. The net result is a perfect acoustic absorber at a frequency that is tunable by varying either the weight of the button or the thickness of the gas cell. By utilizing the very large displacement of the membrane, we have also realized the acoustic-electrical power conversion with a high efficiency of 23%. (Collaborators: G. Ma, M, Yang, S. Xiao, and Z. Yang.)

[1] Physical Review Letters 101, 204301 (2008).

[2] Comptes Rendus Mecanique, 343, 635 (2015).

[3] Nature Materials 13, 873 (2014).

Smith, John

Defence and security research drivers for advanced materials

This talk will provide an introduction to DSTL and its role ensuring that innovative science and technology contribute to the defence and security of the UK. Some technical challenges for advanced materials will be presented and the possible role of metamaterials discussed. The remainder of the talk will then focus on some examples of research into acoustic metamaterials showing the interplay of modelling with experimental verification. The slit-width dependence of the resonant transmission of sound in air through both a slit array and a single open-ended slit cavity will be presented: the experimental results accord well with the theory of Lord Rayleigh. Modelling and experimental results for an acoustic metamaterial comprising a rigid perforated plate closely spaced from a rigid boundary by a channel of air will also be presented. This system gives rise to near unity absorption of airborne sound on resonance.

Smith, Michael

Where acoustics and optics meet: metamaterial acousto-optics

Photoelasticity is an opto-acoustic material response which describes how the permittivity of a material changes in response to an induced mechanical strain. Similarly, electrostriction describes how the material deforms in response to an applied electric field. All materials exhibit some degree of photoelasticity and electrostriction, however the strength varies from one material to the next. Despite the fact that numerous homogenisation procedures exist to characterise the linear acoustic

and electromagnetic properties of materials, there are no known procedures for obtaining the effective photoelastic and electrostriction tensors for composite media. In this talk I will outline, for the first time, a theoretical method for determining the effective photoelastic and electrostrictive tensors of a composite material, based on a mixture of conventional perturbation theory and energy density methods.

Tallarico, Domenico
An elastic lattice containing tilted resonators: chirality, dynamic anisotropy and negative refraction
We consider a vibrating mass-truss lattice whose unit cell contains a resonator of triangular shape. The resonator is linked by trusses to the triangular lattice. We assume that the inertial resonator is "tilted", i.e. it is rotated with respect to the triangular lattice unit cell by an angle Ï‘0. A non-zero value for Ï‘0, breaks the reflectional symmetry around any axis, resulting in a chiral structure. In this talk, we discuss the implications of chirality on the dispersion diagram for Bloch waves. Using the chiral properties of the system, we design and implement a flat lens capable of focussing elastic waves by negative refraction.

Thompson, Ian
Scattering by objects in close proximity
The remarkable properties exhibited by metamaterials would be impossible without the complex scattering effects that occur as waves pass through the material and interact with its internal microstructure. For this reason, multiple scattering theory is crucial to our understanding of metamaterials. In this presentation, we will show how multiple scattering theory can break down in cases where the length scale of the internal microstructure is comparable to (or smaller than) the wavelength. This is not a flaw in any particular mathematical modelling technique; rather it is a fundamental property of solutions to partial differential equations. We will also sketch out some possible avenues for research into overcoming the problem.

Torrent, Daniel
Resonant and nonlocal properties of metamaterials
A great effort has been made toward describing metamaterials by means of frequency-dependent constitutive parameters, however, it is well known that this is not always possible given the so-called "non-local" effects. In this talk, we will present several examples of how non-local properties emerge in the form of new constitutive parameters that makes the traditional description of metamaterials more difficult. Finally, an alternative form of the wave equations and of the boundary conditions for the proper description of metamaterials will be discussed.

Umnova, Olga
Absorption of low-frequency sound by a resonant metasurface
The work is devoted to theoretical and experimental investigation of a resonant acoustic metasurface for total sound absorption at low frequencies. An equivalent admittance model is developed using the two-scale asymptotic homogenization method. Based on the model, the metasurface is built and tested in both impedance tube and anechoic chamber. The metasurface is composed of a regular array of spherical Helmholtz resonators with internal neck and its thickness is more than 25 times less than the wavelength of the absorbed sound. It is shown that:

a) the total absorption of a plane wave normally or obliquely incident on the surface can be achieved by tuning the design of the resonators and their arrangement on the backing and
b) the design is robust enough to achieve high absorption levels even when the incident wave is not plane and the metasurface has dimensions of the order of the wavelength.

Other applications, such as enclosure mode control and sound absorption by curved arrays, are also discussed.

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Wu, Ying

Effective medium theory for acoustic and elastic metamaterials

In this talk, I will review our work on the homogenization schemes for acoustic and elastic metamaterials. I will focus on the coherent potential approximation and show how it can lead to a formula that can predict the effective medium parameters for metamaterials beyond the long wavelength limit, where resonance occurs. The applications of the effective medium theory on the design of emerging materials with intriguing properties, like negative refraction, zero-index and linear dispersion, will be demonstrated. Then I will talk about the limitations on the coherent potential approximation based effective medium theory and discuss how other schemes, such as multiple-scattering, field-averaging and Green's function methods, can overcome those limits and give proper effective medium parameters. This talk will involve joint work with Ms. Xiujuan Zhang from KAUST, Prof. Zhaoqing Zhang, Prof. C. T. Chan and Prof. Ping Sheng from Hong Kong University of Technology, Prof. Yun Lai from Soochow University, Prof. Jensen Li from Birmingham University and Prof. Jun Mei from South China University of Technology.

Zhang, Pu

Soft phononic crystals with deformation-independent band gaps

Soft phononic crystals have advantages over rigid phononic crystals since they are flexible and reconfigurable. Normally the band gaps of soft phononic crystals will be modified after deformation. Indeed this is often an important property that can be exploited. However in some instances it may be that one wishes to deform the medium whilst retaining the band gap structure. We describe a special class of soft phononic crystals with band gaps that are independent of the imposed mechanical deformation, which enables us to design phononic crystals with robust performance. This remarkable behaviour is achieved when the constituent nonlinear elastic material belongs to the class of semilinear hyperelastic family, in which case all band gaps are independent of the imposed deformation. In addition, the incompressible neo-Hookean material can achieve similar deformation-independence for horizontally polared shear waves. This phenomenon is verified with both theoretical analysis and numerical simulation.