Listes des publications dans le cadre du projet SUPREME

1. Articles acceptés dans des revues à comité de lecture :

1. A.-C. Hladky-Hennion, J.O. Vasseur, B. Dubus, B. Djafari-Rouhani, D. Ekeom, B. Morvan,
"Numerical analysis of negative refraction of transverses waves in an elastic material”,
Journal of Applied Physics, 104, 064906, 6 pages (2008).

Abstract:
A numerical analysis of negative refraction process is reported using a phononic crystal with an elastic solid matrix. The phononic crystal considered in this study is made of a periodic arrangement of holes in aluminum. Dispersion curves are discussed and conditions for which negative refraction can appear are identified. These conditions are obtained for the transverse waves, whereas the longitudinal waves are evanescent. A calculation is performed with a prism shape phononic crystal and it clearly exhibits a negative refraction angle. Several analyses are provided with a view to characterizing the wave going out of the phononic crystal. Finally, improvements, with respect to the impedance matching and index tuning are discussed.

2. A. L. Shuvalov, A. A. Kutsenko, A. N. Norris
“Divergence of logarithm of a unimodular monodromy matrix near the edges of the Brillouin zone“,
Wave Motion,Volume 47, Issue 6, Pages 370-382 (2010).

Abstract:
A first-order ordinary differential system with a matrix of periodic coefficients $\mathbf{Q}(y)=\mathbf{Q}(y+T)$ is studied in the context of time-harmonic elastic waves travelling with frequency ω in a unidirectionally periodic medium, for which case the monodromy matrix $\mathbf{M}(\omega)$ implies a propagator of the wave field over a period. The main interest to the matrix logarithm $\ln\mathbf{M}(\omega)$ is owing to the fact that it yields the 'effective' matrix $\mathbf{Q}_{\text{eff}}(\omega)$ of the dynamic-homogenization method. For the typical case of a unimodular matrix $\mathbf{M}(\omega)$ ($\det\mathbf{M}=1$), it is established that the components of $\ln\mathbf{M}(\omega)$ diverge as $(\omega-\omega_0)^{-1/2}$ with $\omega\to\omega_0$, where ω_0 is the set of frequencies of the passband/stopband crossovers at the edges of the first Brillouin zone. The divergence disappears for a homogeneous medium. Mathematical and physical aspects of this observation are discussed. Explicit analytical examples of $\mathbf{Q}_{\text{eff}}(\omega)$ and of its diverging asymptotics at $\omega\to\omega_0$ are provided for a simple model of scalar waves in a two-component periodic structure consisting of identical bilayers or layers in spring-mass-spring contact. The case of high contrast due to stiff/soft layers or soft springs is elaborated. Special attention in this case is given to the asymptotics of $\mathbf{Q}_{\text{eff}}(\omega)$ near the first stopband that occurs at the Brillouin-zone edge at arbitrary low frequency. The link to the quasi-static asymptotics of the same $\mathbf{Q}_{\text{eff}}(\omega)$ near the point $\omega=0$ is also elucidated.

3. B. Morvan, A. Tinel, A.C Hladky-Hennion, J Vasseur, B Dubus,
"Experimental demonstration of the negative refraction of a transverse elastic wave in a phononic crystal",
Applied Physics Letters, **96**, 101905 (2010)

Abstract:
The negative refraction of transverse elastic waves is demonstrated experimentally in a two-dimensional phononic crystal _PC_ made of a square lattice of cylindrical air cavities in an aluminum matrix. Dispersion curves of elastic waves in this PC exhibit a unique branch with phase and group velocities of opposite signs in a broad frequency range. Measurement of refraction angles through prismatic PC included in an aluminum block demonstrates negative refraction of elastic transverse wave.

4. C. CROËNNE, B. MORVAN, J.O. VASSEUR, B. DUBUS, A.-C.HLADKY-HENNION,
"Analysis of elastic waves transmitted through a 2D phononic crystal exhibiting negative refraction",
IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol 58, n° 1, 178-186 (2011).

Abstract:
A two-dimensional phononic crystal (PC) made of a square lattice of air holes in an aluminum matrix is studied. The band structure calculated in the irreducible Brillouin zone of the PC exhibits a branch with a negative slope that allows negative refraction. This phenomenon has been numerically verified using a prism shaped PC, for plane waves entering the PC with two different incidences. A detailed study of the waves at the exit of the PC shows that the plane wave is reconstructed after several wavelengths. Finally, the description of the refracted waves is interpreted using a point source array, giving information about the angular spreading and the relative amplitude of each refracted beam

5. C. CROËNNE, D. MANGA, B. MORVAN, , A. TINEL, B. DUBUS, J.O. VASSEUR, A.-C.HLADKY-HENNION
"Negative refraction of longitudinal waves in a two-dimensional solid-solid phononic crystal", Phys. Rev. B **83**, 054301 (2011) – Published February 25, 2011

Abstract:
Negative refraction of longitudinal waves is evidenced experimentally in a two-dimensional phononic crystal (PC) with a solid matrix. The PC is made of a triangular arrangement of steel rods embedded in epoxy. The dispersion curves present a branch with a negative slope, corresponding to a mixed mode with a predominantly longitudinal behavior. Experiments are carried out on a prism shaped PC inserted inside an epoxy block, excited with a longitudinal transducer. Measurement of the refraction angle at the output side of the PC shows the negative refraction of longitudinal waves through a solid PC. Theoretical results agree quite well with the experimental results. Possibility to use the PC in a fluid background is verified numerically, with the simulation of a focusing flat lens.

6. J. Pierre, O. Boyko, L. Belliard, J. O. Vasseur
"Negative refraction of zero order flexural Lamb waves through a two-dimensional phononic crystal"
Appl. Phys. Lett. **97**, 121919, 2010

Abstract:
We investigate experimentally the refraction of antisymmetric Lamb waves at frequencies in the second band of a two-dimensional phononic crystal. The heterostructure is made of a square lattice of air inclusions in a Silicon plate. Our experimental scheme is based on the selective generation of narrow band elastic waves at a few MHz. Both positive and negative refractions are observed. The comparison of our data with computed dispersion curves shows very good agreement.

7. B. Bonello, L. Belliard, J. Pierre, O. Boyko, B. Perrin, J. O. Vasseur
"Negative refraction of surface acoustic waves in the subgigahertz range"
Phys. Rev. B **82**, 104109, 2010.

Abstract:
We used the picosecond ultrasonic technique to experimentally demonstrate the negative refraction of surface acoustic waves in a two-dimensional phononic crystal. The sample is made of a square lattice of circular voids drilled at the surface of a thick silica substrate. The lattice parameter is of a few micrometers. Broad band surface acoustic waves with Fourier components in the GHz range were excited. The negative refraction is observed for Rayleigh waves with frequencies in the second band and propagating along the direction ΓM in the reduced Brillouin zone. We then used a plane wave expansion method to calculate the dispersion of the waves in our sample and to analyze our experimental data.

8. A.L. SHUVALOV, A.A. KUTSENKO, A.N. NORRIS, O. PONCELET
"Effective Willis constitutive equations for periodically stratified anisotropic elastic media", en révision à Proc. Roy. Soc., le 31 oct. 2010.

Abstract:
A method to derive homogeneous effective constitutive equations for periodically layered elastic media is proposed. The crucial and novel idea underlying the procedure is that the coefficients of the dynamic effective medium can be associated with the matrix logarithm of the propagator over a unit period. This is motivated by the fact that the equivalence is precise for a homogeneous medium and its enforcement for the inhomogeneous medium guarantees that displacements and stresses are faithfully propagated over arbitrarily long distances. The effective homogeneous equations are shown to have the structure of a Willis material, characterized by anisotropic inertia and coupling between momentum and strain, in addition to effective elastic constants. Expressions are presented for the Willis material parameters which are formally valid at any frequency and horizontal wavenumber as long as the matrix logarithm is well defined. The general theory is demonstrated for scalar SH motion in two dimensions. Low frequency, long wavelength expansions of the general Willis parameters are also developed using a Magnus series and explicit conditions for convergence are derived.

2. Communications Internationales avec proceedings

1. A.-C. Hladky-Hennion, J. Vasseur, B. Dubus, B. Djafari-Rouhani, B. Morvan, A. Tinel, D. Ekeom,
"Negative refraction of transverse waves in an elastic phononic crystal",
Proceedings of the 2008 IEEE Ultrasonic Symposium, Pékin, 253-256, (2008).

Abstract:
This paper reports numerical and experimental analyses of negative refraction process using a phononic crystal, made of a periodic arrangement of holes in aluminium. Dispersion curves are discussed and conditions for which negative refraction can appear are identified. Negative refraction is clearly obtained for transverse waves. Experiments confirm numerical predictions.

2. B. Morvan, A. Tinel , A.-C.Hladky-Hennion, J. Vasseur, J.P. Groby, B. Dubus, B. Djafari-Rouhani, « Negatively refracted transverse waves : study of the ultrasonic field at the exit of an elastic phononic crystal",
Proceedings of the 2009 IEEE Ultrasonic Symposium, Rome, 1126-1129, (2009).

Abstract:
A two-dimensional phononic crystal (PC) with square lattices composed of air holes in aluminum matrix is studied. The band structure of the PC exhibits some properties which allow the negative refraction of transverse wave transmitted through the PC. The left-handed behaviour of the PC is verified numerically with an emphasis on the process of refracted beam construction near the exit surface of the PC.

3. J. Pierre, B. Bonello, O. Boyko, and L. Belliard
"Refraction of surface acoustic waves through 2D phononic crystals"
15th International Conference on Photoacoustic and Photothermal Phenomena (ICPPP15), Leuven, Belgium, 19-23 Juillet 2009,
J. Phys: Conf. series **214**, 012048 (2010)

Abstract:
As for the photonic crystals which are their optical counterpart, unusual effects related both to the opening of forbidden band gaps and to the subsequent folding of the dispersion curves, are expected to occur in the phononic crystals (PC's). Among these, the refraction of an elastic wave impinging on a PC is probably one of the most topical issues for the physicists studying the dynamic behavior of elastic periodic structures. Indeed, it is now well established that under certain conditions, the refracted beam propagates along a direction lying within the same half space as the incident acoustic beam, leading to negative refraction. This effect has recently been observed with longitudinal bulk acoustic waves but not yet with surface acoustic waves (SAW's). Our goal in this work was to experimentally investigate under which conditions Lamb waves or Rayleigh waves can also undergo negative refraction. To study the refraction of Lamb waves, we have elaborated samples consisting of a periodic lattice of holes drilled throughout silicon thin plates. The lattice of holes had either squared or hexagonal symmetries; the filling ratio was around 0.5. For each sample, the lattice parameter was

chosen to be about equal to the plate thickness, which was from a few micrometers to a few hundred micrometers.
Lattices of holes, a few micrometers deep, were also drilled at the surface of a semi-infinite sample in order to study the refraction of Rayleigh waves. The elastic waves were generated and detected using two different all-optical experimental techniques. The refraction at frequencies below 100 MHz was investigated using a conventional laser ultrasonic technique: the SAW was excited by illuminating the surface of the sample with a transient grating, issued from a frequency doubled YAG laser (532 nm, pulse duration 30 ps, repetition rate 20 Hz). A stabilized Michelson interferometer was used to detect the normal component of the deformation field in an area lying a few mm apart from the excitation area, after the waves have travelled through the PC. The samples with a spatial periodicity of a few micrometers, for which forbidden band gaps are expected to open at frequencies in the GHz range, were investigated using the picosecond ultrasonic technique. Whatever the lattice parameter and the experimental technique, we measured the refraction for different incident angles and different frequencies around the band gap. Our experimental findings are then compared to theoretical predictions.

4. J. Dubois, C. Aristégui, O. Poncelet, A. L. Shuvalov,
« Coherent acoustic response of a screen containing a random distribution of scatterers: comparison between different approaches", GDR + 9th Anglo-French Physical Acoustics Conference, Kendal, GB, janvier 2010

Abstract:
Theoretical models underlying the ultrasonic study of suspensions and bubble swarms in liquids often rely on the concept of a coherent wave response, within which the given medium is viewed as an effective homogeneous medium. More specifically, the coherent response can be formulated in a straightforward manner via the effective wave number and the effective impedance. These in turn can be expressed through the actual material properties of the given scattering medium. The derivation of the effective wave number and impedance is the issue of a number of different approaches existing in the multiple-scattering theory.
The present work deals with a coherent response of acoustic wave impinging on a screen of cylindrical inclusions randomly distributed in a fluid. The reflection and transmission coefficients have been expressed via the effective wave number and impedance that are provided by three different models due to Foldy, Waterman & Truell, and Linton & Martin. The obtained expressions have been analyzed with a view to illuminate what is the quantitative difference between those approaches as revealed in the coherent response, and how this difference depends on the basic parameters of the problem such as the frequency, the concentration of scatterers and their contrast relatively to the fluid matrix. Another aspect of this work is to compare the above analytical results with the numerical data. It has been obtained by means of a deterministic computational code which delivers the coherent wave field through averaging the outputs for various samplings of the positions of scatterers. Knowing this numerical benchmark allows us to specify the validity domains for each of the three analytical methods under study.

5. C. Croënne, A.-C. Hladky-Hennion, J. Vasseur, A. Tinel, B. Morvan, B. Dubus
" Negative refraction of elastic transverse and longitudinal waves in 2D phononic crystals made of a solid matrix”**,**
ICA (International Congress on Acoustics), Sydney, Août 2010. pp 633-637.
http://www.acoustics.asn.au/conference_proceedings/ICA2010/cdrom-ICA2010/papers/p633.pdf

Abstract:
Waves propagating in left-handed materials have unusual properties such as phase and group velocities of opposite signs and negative refraction index. Periodic lattices have been shown to exhibit such properties both for electromagnetic (photonic crystals) and in-fluid acoustic (phononic crystals) waves. This work addresses the question of negative refraction for elastic longitudinal and transverse waves.
Bidimensional phononic crystals made of a periodical lattice of cylindrical inclusions in a solid matrix are considered. Dispersion curves are computed using plane wave expansion or finite element methods. By choosing carefully constitutive materials, lattice geometry and inclusion volumic fraction, two phononic crystals, for transverse or longitudinal waves, are optimized in order to obtain: 1) left-handed behaviour for an isolated branch of dispersion curve; 2) circular equifrequency contours indicating isotropy of wave phase velocity. In both cases, finite element calculations of elastic wave transmission through prism shape phononic crystals predict negative refraction angle.
Prismatic phononic crystals are fabricated in massive block. Incident elastic ultrasonic waves are generated on one side of the block using transducers, and elastic waves transmitted through the phononic crystal are detected by laser vibrometry on the opposite side. Measured refraction angles are in agreement with calculations, demonstrating negative refraction index. This work was supported by the French "Agence Nationale pour la Recherche" (SUPREME project).

6. C. Croënne, A.-C. Hladky-Hennion, J. Vasseur, B. Dubus
"Effective parameter retrieval of phononic crystal slabs”,
Proceedings of the 2010 IEEE Ultrasonic Symposium, San Diego, 1861-1864, (2010)

Abstract:
Effective parameters (propagation constant and impedance) of finite slabs of 2D phononic crystals immersed in a fluid are extracted using two retrieval methods inspired from the study of electromagnetics. Difficulties in the homogenization are highlighted, coming from the presence of evanescent waves at the interfaces of the PC slabs. This is confirmed by the study of the field map inside the crystal.

7. C. Croënne, A.-C. Hladky-Hennion, J. Vasseur, B. Dubus, M. Bavencoffe, A. Tinel, B. Morvan, D. Manga

"Negative refraction of longitudinal waves in an elastic phononic crystal”,
Proceedings of the 2010 IEEE Ultrasonic Symposium, San Diego, 523-526, (2010)

Abstract:
Two-dimensional phononic crystals (PC) with square or triangular lattices composed of steel rods in a polymer matrix are studied. The band structure of the PC exhibits several negative branches. Among them, one allows the negative refraction of longitudinal waves transmitted through the PC. The left-handed behaviour of the PC is exhibited numerically as well as experimentally, by using a prism shaped PC. Finally, a numerical simulation is presented, with the PC immersed in a fluid, for focusing applications.

8. E.D. Manga, C. Croënne, A. Tinel, B. Morvan, E. Le Clezio, L. Haumesser, B. dubus, J. Vasseur, A.-C. Hladky-Hennion,

"Experimental demonstration of the negative refraction of a longitudinal elastic wave through a two dimensional solid phononic crystal",
Proceedings of the 1st Mediterranean Congress on Acoustics, Sale, Morocco, 28-30 October 2010. sous presse

Abstract:
We report the first experimental demonstration of the negative refraction of an elastic longitudinal wave in a two-dimensional solid Phononic Crystal (PC). This property is fundamental for the realization of a flat lens and leads to numerous researches in the fields of phononic crystals. A prism shaped PC made of stainless steel rods assembled in triangular lattice in an epoxy resin matrix is studied. Its band structure exhibits a branch where the phase velocity is opposite to the group velocity leading to negative refraction. The mode corresponding to this branch has a predominantly longitudinal behaviour and would be interesting for acoustic imaging because it is well coupled to a wave propagating in water. To characterize the crystal, the refraction angles are deduced from the measurement of the wave numbers of the refracted waves propagating in the surrounding medium after transmission through the PC. These experimental results lead to the determination of the dispersion curves that are in a very good agreement with the theoretical ones.

9. B. Dubus, C. Croënne, A.-C. Hladky-Hennion, J. Vasseur, A. Tinel, B. Morvan,

"Development of elastic super-lenses made of phononic crystals for ultrasonic imaging",
Forum Acusticum 2011 in Alborg, Denmark, June 27-July 1, 2011, pp 987-990

Abstract:
This paper describes the development of elastic super-lenses constituted by phononic crystals. Required left-handed properties (phase and group velocities of opposite signs, isotropy of wave phase velocity) are obtained by an adequate choice of constitutive materials, lattice geometry and inclusion volumic fraction. Numerical simulations of ideal and phononic crystal-based lenses are presented showing how index or impedance mismatches affect the building of image.

3. Communications Internationales sans proceedings

1. A.C. Hladky-Hennion, J. Vasseur, B. Dubus, B. Morvan,
"Analysis of the elastic waves at the exit of a phononic crystal in the case of negative refraction", GDR + 9th Anglo-French Physical Acoustics Conference, Kendal, GB, janvier 2010

Abstract: There is a growing interest in the study of phononic crystals (PC), and prospective applications concern superlensing effect, wave guiding, selective filtering and multiplexing devices. This work concerns the study of negative refraction of elastic transverse waves that can occur in simple prism shape PC with an elastic matrix (periodic arrangement of holes in an elastic matrix). In previous studies, the authors have shown, numerically as well as experimentally, the negative refraction of an incident ultrasonic beam at an interface between the considered PC and a homogeneous medium. In order to better understand the negative refraction phenomenon that takes place at the interface between PC and the homogeneous surrounding medium, FEM calculations are performed. The displacements are studied along a direction parallel to the exit surface of the PC, for variable directions of the incident elastic wave. It shows an intermediate region, at the interface of the PC, where the plane wave is rebuilt. Depending on the incident wave direction, some grazing waves can also take place. Their origin can be first explained by introducing a wavevector in the second Brillouin zone of the periodic structure. Another approach to explain this grazing wave is based on the diffraction effects associated with the interface. This approach is not contradictory with the first explanation but its advantage is to account for the limited width of the incident beam. In the future, the role of the evanescent waves has to be considered in particular near the interface of the phononic crystal structure to progress towards the development of ultrasonic super lens.

2. B. Bonello, L. Belliard, J. Pierre, O. Boyko

«Negative refraction of Rayleigh and Lamb waves through 2D phononic crystals**»,** IEEE Ultrasonic Symposium, San Diego, (2010)

Abstract: Negative refraction of elastic waves is likely to occur with two families of artificial structures: elastic metamaterials and phononic crystals (PC's). In the former case, the property is the consequence of effective mass density and compressibility both negative in some frequency range. However, although elastic metamaterials featuring the double negativity have already been elaborated, the conditions on the physical properties of the constituents are so hard to realize that this promising approach remains exploratory in a large extent. In the latter case, the effective index of the heterostructure is controlled through its band structure and negative refraction isn't related to the double negativity but rather to the bands folding and the negative slope of some dispersion branches. Several experimental evidences of the phenomenon have been given to date. However, most of these studies deal with the refraction of bulk waves, caused by 2D PC's immersed in a fluid or drilled into a solid matrix. In this work, we report on

experimental data showing that surface acoustic waves (SAW) propagating in PC's featuring a solid matrix, undergo negative refraction as well.

First, we have investigated the refraction of Rayleigh waves through a PC constituted by a lattice of voids into a silica substrate. The PC had the square symmetry and the lattice parameter was a=4 µm. We used the picosecond ultrasonic technique to excite broad band SAW with Fourier components extending up to 0.7 GHz. The negative refraction is observed for Rayleigh waves with frequencies above 400 MHz, in the second band and propagating along ΓM direction in the reduced Brillouin zone, as predicted by our calculations of the dispersion of Rayleigh waves in air holes/SiO_2 PC.

We then used the laser ultrasonic technique to investigate the refraction of narrow band flexural Lamb waves, through a lattice of air holes drilled throughout a silicon plate. The typical dimensions of the PC were a few hundred of µm, yielding a band gap and subsequent folding in the MHz range. We recorded the out of plane component of the displacements field on a large area on both sides of the normal to the interface between the PC and the Si plate. In order to further analyze our experimental data, we calculated the dispersion of Lamb waves in air/Si PC. The results, together with our experimental data, unambiguously show that antisymmetric Lamb waves undergo negative refraction in our sample.

3. O. Boyko, J. Pierre, L. Belliard, B. Bonello
"Negative refraction of Rayleigh waves"
Phonons2010 – Taïpei, Taïwan - avril 2010

Abstract: Novel phenomenon in two-dimensional phononic crystals was recently investigated using monochromatic Rayleigh wave. Using a prism with phononic crystal structure, we have observed a signal where it should not be propagated: that is a negatively refracted wave. It was now theoretically demonstrated that under certain conditions, the outgoing pulse is expected to refract on negative side of the normal to the interface. This behavior lies in the regular arrangement of the crystal's scattering units and subsequent Bragg scattering of the waves inside the crystal, both resulting in complex band structures of propagating modes and phononic stop bands. When the incident wave is coupled with negative slope dispersion curve and is transformed into a Bloch wave, wave propagation stops to be limited by simple Snell's law.

Negative refraction has recently been observed with longitudinal bulk acoustic waves but not yet for surface acoustic waves (SAW's). We present out study on samples with a spatial periodicity of a few micrometers consisting of a periodic lattice of holes drilled into silica substrates. The lattice of holes had the squared symmetry and the filling ratio was around 0.75. We use an amplitude grating and a YAG laser in order to excite selectively SAW's in the 5-20 MHz frequency range. The normal component of the deformation field was detected using a stabilized Michelson interferometer, in an area lying a few mm apart from the excitation area, after the waves have travelled through the PC. We have detected elastic energy in the negative refraction zone of the sample that we attribute to the refraction associated to the first folded branch of the dispersion curve. These experimental findings are then compared to theoretical predictions.

4. C. Croenne, A.C. Hladky-Hennion, J. Vasseur, B. Dubus, B. Morvan, D. Manga, A. Tinel

"Vibration Numerical and experimental negative refraction of longitudinal waves in an elastic phononic crystal materials"
10th Anglo-French Physical Acoustics Conference, Fréjus, 19-21 Janvier 2011

Abstract:
Phononic crystals (PC's) are usually defined as artificial materials made of periodic distributions of scatterers embedded in a matrix. By varying the geometry of the array of inclusions and the nature of the constitutive materials, the band structures of PC's may exhibit dispersion curves with a negative slope i.e. the wave vector and the group velocity vector associated with an acoustic wave point in opposite directions. This property is typical of a left handed material and implies a negative index of refraction in the Snell-Descartes law. The negative refraction phenomenon may allow realizing flat super-lens able to focus elastic waves with a resolution lower than the diffraction limit. Such super-lenses can have potential applications in the fields of medical imaging or ultrasonic beam based therapy.
In this talk, negative refraction of longitudinal waves is evidenced, numerically as well as experimentally, in a two-dimensional phononic crystal (PC) with a solid matrix. The PC is made of a triangular arrangement of steel rods embedded in epoxy. The dispersion curves present a branch with a negative slope, corresponding to a mixed mode with a predominantly longitudinal behaviour. Possibility to use the PC in a fluid environment is verified numerically, with the simulation of a focusing flat lens. Last results show that several conditions have to be fulfilled to obtain an image of a point source: circular equifrequency contours, index matching and impedance matching, among others.

5. K.J. Olympio, C. Croenne, J. Vasseur, B. Dubus, B. Morvan, A.C. Hladky-Hennion
"Application of phononic crystals to filtering and to the negative refraction of elastic waves",
2011 US Navy Workshop on Acoustic Transduction Materials and Devices, 10-12 mai 2011, State College, PA, USA

Abstract:
Phononic crystals (PC's) are usually defined as artificial materials made of a periodic distribution of scatterers embedded in a matrix. Their dispersion curves may present, under certain conditions, absolutely forbidden bands e.g. frequency domains where the propagation of elastic wave is prohibited whatever the direction of propagation of the incident wave: the presence of a band gap opens up potentialities for filtering applications. Moreover, it is possible to use unusual properties in the pass bands of the dispersion curves, such as branches with a negative slope (i.e. with wave vector and Poynting vector are in opposite directions). This property is typical of a left handed material and implies a negative index of refraction according to the Snell-Descartes law. The negative refraction phenomenon may allow realizing flat super-lens capable of focusing elastic waves with a resolution lower than the diffraction limit. Such super-lenses can have potential applications in the fields of medical imaging and ultrasonic beam based therapy. Moreover, by adjusting the phase velocities of the PC with respect to the external fluid medium, the propagation direction of the waves can be tailored to stealth applications.
In this talk, filtering applications of the PC are first presented in the case of PC made of holes in an elastic matrix. Then, negative refraction of longitudinal waves using PC is

presented, numerically as well as experimentally, in a two-dimensional PC with a solid matrix. In that case, the PC is made of a triangular arrangement of steel rods embedded in epoxy. The dispersion curves present a branch with a negative slope, corresponding to a mixed mode with a predominantly longitudinal behavior. Possibility to use the PC in a fluid environment is verified numerically, with the simulation of a focusing flat lens. Finally, multi-objective optimization using a genetic algorithm will show how the frequency of negative-slope branches varies with other physical parameters.

3. Communications nationales avec proceedings

1. E.D. Manga, L. Haumesser, F. Vander Meulen, A.C. Hladky-Hennion, J. Vasseur, B. Morvan, C. Croënne, E. Le Clezio,
«Application de la réfraction négative à l'imagerie ultrasonore de deux sources acoustiques »,
Actes du 10ème Congrès Français d'Acoustique, CFA 10, Lyon, France, 12-16 avril, 2010, 1-6

Résumé:
Le travail, réalisé dans le cadre du projet ANR SUPREME (SUPerlentille à REfraction négative à base de MEtamatériaux et de cristaux phononiques), consiste en l'étude numérique et expérimentale de champs de pression transmis à travers un cristal phononique 2D. Les courbes de dispersion du cristal, constitué d'un réseau triangulaire de tiges cylindriques solides (acier) dans une matrice fluide (eau), montrent l'existence d'une bande de fréquences à réfraction négative dans laquelle les surfaces équi-fréquences (EFS) sont parfaitement circulaires. La première caractéristique implique que des faisceaux divergents incidents sur le cristal se re-focalisent en sortie, les EFS circulaires permettant une re-focalisation optimale. Les résultats présentés concernent l'étude d'images formées à travers le cristal par deux points sources. Une attention particulière sera portée à l'influence sur l'image, de la position des sources par rapport au cristal,
ainsi que de leurs positions relatives.
L'étude expérimentale est réalisée sur un cristal de 10 mm d'épaisseur avec comme sources ponctuelles deux « pinducers » de diamètre 2,4 mm placés près du cristal. En réception, un hydrophone permet de mesurer le champ de pression en « chaque point » dans le plan des deux sources ponctuelles. D'un point de vue numérique, les simulations sont réalisées par Eléments Finis, à l'aide du code de calcul ATILA. Les résolutions axiales et latérales des images reconstruites sont discutées en présence d'une ou de deux sources acoustiques. Il est montré que, pour les grandes distances inter-sources (relativement à la longueur d'onde), le champ de pression à la sortie du cristal est tel que les points image issus des deux sources sont bien distincts. Pour de petites distances inter-sources, des interférences entre les champs générés donnent lieu des distorsions des points images qui sont discutées en terme de pertinence pour les dispositifs d'imagerie ultrasonore.

2. A-C. Hladky-Hennion, J. Vasseur, C. Croënne, J.-P. Groby, B. Dubus, B. Djafari-Rouhani, B. Morvan, A. Tinel

«Réfraction négative d'ondes transverses dans les cristaux phononiques»

Actes du 10ème Congrès Français d'Acoustique, CFA 10, Lyon, France, 12-16 avril, 2010, 1-4

Résumé:

Les travaux de recherche récents montrent un intérêt grandissant pour l'étude des cristaux phononiques et leurs applications potentielles pour l'effet superlentille, le filtrage sélectif ou les dispositifs de multiplexage. Le travail présenté concerne certaines études récentes réalisées dans le cadre du projet blanc SUPREME (SUPer lentille à REfraction négative à base de MEtamatériaux et cristaux phononiques ANR-08-BLAN-0101-01). Après une présentation générale du contexte du projet, les courbes de dispersion de cristaux phononiques sont analysées et montrent que, sous certaines conditions de géométrie et de matériaux constituants, des ondes élastiques transverses peuvent se réfracter négativement. C'est par exemple le cas pour un cristal phononique 2D constitué d'un réseau carré de cavités cylindriques dans une matrice aluminium. Après la présentation des courbes de dispersion mettant en évidence une branche négative isolée, les ondes sont caractérisées. Le dispositif expérimental est ensuite présenté. Les résultats de mesure sont en bon accord avec les résultats numériques et mettent bien en évidence une onde réfractée négativement. Enfin, le phénomène de reconstruction des ondes en sortie du cristal phononique est analysé, ainsi que l'étalement angulaire des faisceaux diffractés, en prenant en compte le caractère limité de l'excitation. Plusieurs pistes d'amélioration du dispositif sont proposées et en cours d'étude.

3. J. Dubois, C. Aristégui, O. Poncelet

« Réponse d'une structure chargée aléatoirement d'inclusions résonantes : application aux effets de type métamatériaux. »

10ème Congrès Français d'Acoustique, CFA 10, Lyon, France, 12-16 avril, 2010

Résumé:

La conception de métamatériaux acoustiques est actuellement sujette à de nombreux travaux. Outre les cristaux phononiques, les milieux aléatoires constituent une voie de développement possible. Ces milieux sont vus par les ondes cohérentes, comme des milieux homogènes équivalents, aux propriétés effectives appropriées. Dans le cadre de l'homogénéisation dynamique, les régimes de fonctionnement de type métamatériaux sont gouvernés par les résonances basse-fréquences des inclusions, se comportant dès lors comme des micro-résonateurs.

L'objectif de ce travail est d'étudier la validité des théories d'homogénéisation en présence des résonances de micro-résonateurs. Nous nous intéressons ainsi aux coefficients de réflexion et de transmission d'un écran d'inclusions cylindriques aléatoirement réparties dans une matrice fluide. Ces réponses cohérentes sont calculées à partir du nombre d'onde effectif et de l'impédance effective de l'écran, établis dans le contexte des travaux de Foldy, Waterman et Truell, Linton et Martin. Les prédictions obtenues sont finalement confrontées à des résultats issus d'un code de différences finies, pour des régimes harmoniques proches des fréquences de résonance et pour des concentrations d'inclusions relativement élevées.

4. Communications Nationales sans proceedings

1. E.D. Manga, L. Haumesser, F. Vander Meulen, G. Robin, M. Lethiecq et E. Le Clezio, « Focalisation des ondes ultrasonores à travers un réseau phononique », JAPSUS, Journées du GAPSUS, 3-5 juin 2009, Le Mans, France.

Résumé:

Les travaux présentés concerneront la réalisation expérimentale de l'image d'une source ponctuelle (type transducteur focalisé) à travers un cristal phononique 2D à maille triangulaire, constitué de tiges cylindriques d'acier et d'une matrice fluide. A moyen terme, il est envisagé d'effectuer la mesure de l'indice de réfraction effectif du réseau phononique.

2. J. Pierre, L. Belliard, O. Boyko and et B. Bonello

« Réfraction d'ondes élastiques de surface par un cristal phononique 2D à matrice solide »

10ème Congrès Français d'Acoustique, CFA 10, Lyon, France, 12-16 avril, 2010

Résumé:

Dans ce travail expérimental, nous avons étudié la réfraction d'ondes élastiques de surface par un cristal phononique 2D à matrice solide. Nous décrirons les deux techniques expérimentales qui ont été utilisées. Des ondes élastiques de surface dans la gamme du MHz sont engendrées et détectées par une technique de laser-ultrasons (acoustique nanoseconde), alors que l'acoustique picoseconde est utilisée pour les ondes au GHz. Les échantillons consistent en un arrangement périodique de trous dans un substrat solide (ondes de Rayleigh) ou dans une plaque d'épaisseur finie (ondes de Lamb). Nous avons mesuré des déplacements de surface dans la zone de réfraction négative pour différents paramètres géométriques du réseau phononique. Nous attribuons ces modes de vibration au repliement des courbes de dispersion induit par la périodicité du milieu. Ces résultats expérimentaux seront ensuite comparés aux prédictions théoriques.

3. J. Dubois, O. Poncelet, C. Aristégui

« Quelques considérations sur la réponse acoustique cohérente de métamatériaux à structure aléatoire. » Poster. 10ème Congrès Français d'Acoustique, CFA 10, Lyon, France, 12-16 avril, 2010

Résumé:

Depuis quelques années, une attention particulière est portée sur les métamatériaux. Ils présentent la particularité d'avoir un indice de réfraction négatif, les célérités de phase et de groupe étant opposées, ou encore de présenter des propriétés absorbantes étonnantes. Ces comportements peuvent être en particulier obtenus à l'aide de structures comportant des distributions aléatoires d'inclusions résonantes, le contraste des propriétés acoustiques inclusions/matrice étant marqué.

La transposition industrielle de ces matériaux nécessite d'une part de considérer des échantillons de tailles finies (écran par exemple), et d'autre part d'accéder « directement » au champ cohérent, ceci pouvant être atteint par une forte concentration d'inclusions ou une épaisseur d'écran adaptée.
Dans ce contexte, des expériences « numériques » sont réalisées à l'aide d'un code de différences finies. La réponse acoustique d'un écran d'inclusions cylindriques immergées dans un fluide est alors déduite. Le caractère cohérent de la réponse est évalué, pour des épaisseurs et concentrations variables, à partir de confrontations avec des résultats issus de modèles de diffusion multiple. Par ailleurs, les conséquences de la compétition entre les résonances d'écran et d'inclusion sont soulignées, la dimension finie de l'écran annihilant l'effet « métamatériaux » escompté originellement.

4. J. Vasseur, A-C. Hladky-Hennion, C. Croënne, J.-P. Groby, B. Dubus, B. Djafari-Rouhani, B. Morvan, A. Tinel,
«Réfraction négative d'ondes transverses dans les cristaux phononiques»
12èmes journées de la matière condensée, Troyes; 23-27 août 2010

Résumé:
Les travaux de recherche récents montrent un intérêt grandissant pour l'étude des cristaux phononiques et leurs applications potentielles pour l'effet superlentille, le filtrage sélectif ou les dispositifs de multiplexage. Le travail présenté concerne certaines études récentes réalisées dans le cadre du projet blanc SUPREME (SUPer lentille à REfraction négative à base de MEtamatériaux et cristaux phononiques ANR-08-BLAN-0101-01). Après une présentation générale du contexte du projet, les courbes de dispersion de cristaux phononiques sont analysées et montrent que, sous certaines conditions de géométrie et de matériaux constituants, des ondes élastiques transverses peuvent se réfracter négativement. C'est par exemple le cas pour un cristal phononique 2D constitué d'un réseau carré de cavités cylindriques dans une matrice aluminium. Après la présentation des courbes de dispersion mettant en évidence une branche négative isolée, les ondes sont caractérisées. Le dispositif expérimental est ensuite présenté. Les résultats de mesure sont en bon accord avec les résultats numériques et mettent bien en évidence une onde réfractée négativement. Enfin, le phénomène de reconstruction des ondes en sortie du cristal phononique est analysé, ainsi que l'étalement angulaire des faisceaux diffractés, en prenant en compte le caractère limité de l'excitation. Plusieurs pistes d'amélioration du dispositif sont proposées et en cours d'étude.

5. J. Pierre, O. Boyko, L. Belliard, B. Bonello
«Réfraction négative du mode de Lamb antisymétrique A0 par un Cristal Phononique 2D à matrice solide»
12èmes journées de la matière condensée, Troyes; 23-27 août 2010

Résumé:
Dans ce travail expérimental, nous avons étudié la réfraction d'ondes de Lamb par un cristal phononique 2D à matrice silicium. Pour cette étude, nous avons utilisé une technique de laser-ultrasons. Cette technique nous permet de générer et de détecter des ondes élastiques de surface quasi-monochromatiques au MHz. L'échantillon étudié

consiste en un arrangement périodique de trous dans une plaque mince (e=160µm) de silicium. Une onde de Lamb antisymétrique A_0 est émise, dans le silicium non structuré, en amont du cristal phononique. Les déplacements de surface dans la zone de réfraction négative ont été mesurés, et ces modes de vibration ont été attribués au repliement des courbes de dispersion induit par la périodicité du milieu. Ces résultats expérimentaux sont en bon accord avec les prédictions théoriques.

6. Anne-Christine Hladky-Hennion, Charles Croënne, Jérôme Vasseur, Bertrand Dubus, Bruno Morvan
« Réfraction négative des ondes longitudinales dans un cristal phononique élastique»
Poster. Colloque National Métamatériaux 2011, Orsay, 14-15 mars 2011.

Résumé:
A l'image de la réfraction négative des ondes électromagnétiques dans les cristaux photoniques, les travaux présentés portent sur la réfraction négative des ondes acoustiques et élastiques à l'aide de cristaux phononiques. Ils bénéficient d'un soutien de l'ANR (projet blanc SUPREME ANR-08-BLAN-0101-01).
Les cristaux phononiques (CP) sont habituellement définis comme des matériaux artificiels faits d'une distribution périodique de diffuseurs dans une matrice. En faisant varier la géométrie du réseau d'inclusions et la nature des matériaux constitutifs, la structure de bande du CP peut présenter des courbes de dispersion avec une pente négative, c'est-à-dire que le vecteur d'onde et la vitesse de groupe, associés à une onde acoustique, sont de direction opposée. Cette propriété est typique d'un matériau main gauche et implique un indice de réfraction négatif dans la loi de Snell Descartes. Le phénomène de réfraction négatif autorise la réalisation de superlentilles plates capables de focaliser les ondes élastiques sous la limite de diffraction. De telles lentilles ont des applications potentielles dans le domaine de l'imagerie médicale ou de la thérapie.
Sur ce poster, la réfraction négative d'ondes longitudinales est mise en évidence, aussi bien numériquement qu'expérimentalement, pour un CP bi-dimensionnel à matrice solide, les études précédentes portant sur des CP à matrice fluide. Le CP est composé d'un arrangement triangulaire de tiges d'acier dans une matrice époxy. Les courbes de dispersion présentent bien une branche négative, qui correspond à un mode à comportement longitudinal prédominant. La possibilité d'utiliser le CP dans un environnement fluide est vérifiée numériquement par l'intermédiaire de la simulation d'une lentille plate. La démonstration de la réfraction négative des ondes élastiques rend possible la réalisation de superlentilles acoustiques solides et, à terme, le développement de dispositifs d'imagerie acoustique reconstituant une image réelle.

7. E.D. Manga , L. Haumesser, B. Morvan, C. Croenne, A. Tinel, E. Le Clezio, A.C Hladky-Hennion
« Réfraction d'une onde longitudinale à travers un cristal phononique solide immergé »
XIIèmes Journées d'Acoustique Physique Sous-Marine et Ultrasonore, JAPSUS 2011, Lille, France, 8-10 juin, 2011

Résumé:
Ce travail s'inscrit dans le projet ANR blanc SUPREME ANR-08-BLAN-0101-01, dont l'un des objectifs est d'exploiter les propriétés main gauche des cristaux phononiques

(CP) pour réaliser un système d'imagerie permettant de s'affranchir des limites de résolution liées à la diffraction. L'une des conséquences de ce caractère main gauche est d'entrainer la réfraction négative d'une onde à l'interface entre un milieu élastique homogène et le CP dans certaines bandes de fréquences. Dans ce cadre nous avons développé un CP constitué d'inclusions cylindriques d'acier inoxydable de diamètre 2mm dans une matrice de résine époxy. L'arrangement périodique des cylindres a un motif triangulaire avec un pas de 2,84mm. Ce CP a été caractérisé dans un milieu environnant solide [1], nous nous proposons ici d'étudier ce CP immergé dans de l'eau. Nous nous intéressons à la déviation d'une onde plane longitudinale à travers un CP de forme prismatique dans la bande de fréquences 0,749-0,860MHz pour laquelle il existe de la réfraction négative. Cette étude s'appuie sur des relevés expérimentaux du champ de pression transmis à travers le CP. Deux angles d'incidence sont étudiés: 30 et 60° qui correspondent aux angles aux sommets du prisme. Pour chaque incidence, plusieurs angles de réfraction possibles sont déterminés. Ces derniers correspondent aux différents couplages de l'onde longitudinale incidente avec les modes de Bloch dans le CP.

[1] Phys. Rev. B 83, 054301 (2011)

8. J. Pierre, M. Renier, O. Boyko-Kazymyrenko et B. Bonello
« Dispersion élastique en milieu périodique et réfraction négative»
XIIèmes Journées d'Acoustique Physique Sous-Marine et Ultrasonore, JAPSUS 2011, Lille, France, 8-10 juin, 2011

5. Papiers invités

1. B. Dubus, A.-C. Hladky-Hennion, J. Vasseur, B. Djafari-Rouhani, B. Morvan, A. Tinel, "Méta-matériaux acoustiques gauchers et imagerie ultrasonore”,
JAPSUS, Journées du GAPSUS, 3-5 juin 2009, Le Mans, France.

Résumé:
La notion de matériau ”gaucher” (ou ”main gauche”) a été introduite initialement en électromagnétisme par Veselago [1]. Elle définit une classe de matériaux dans lesquels le champ électrique, le champ magnétique et le vecteur d’onde associés à une onde plane constituent un trièdre tri-rectangle indirect. Les ondes se propageant dans des matériaux gauchers possèdent des propriétés inhabituelles : vitesse de phase et vitesse de groupe de signes opposés, indice de réfraction négatif, amplification des ondes évanescentes, effet doppler inversé... Ces matériaux sont généralement réalisés artificiellement, soit sous la forme d’un réseau périodique où la superposition des effets de diffraction est exploitée, soit par l’inclusion d’une distribution de micro-résonateurs qui modifient les propriétés de l’onde au voisinage des résonances locales. Sur le plan applicatif, ces méta-matériaux ouvrent de nouvelles perspectives en imagerie pour la réalisation de super-lentilles plates ayant une résolution meilleure que la limite de diffraction [2] et capables de reconstituer une image réelle. Cette présentation aborde le développement, pour les ondes acoustiques et élastiques de méta-matériaux gauchers. La démarche générale de conception d’un cristal phononique présentant les propriétés recherchées, les méthodes de caractérisation expérimentale et les principaux problèmes à résoudre pour la réalisation d’une super-lentille acoustique sont discutés. Les résultats présentés sont issus du projet ANR SUPREME. [1] V.G. Veselago, The electrodynamics of substances with simultaneously negative values of ε and μ, Sov. Phys. Usp. 10-4, (1968). [2] J.B. Pendry, Negative refraction makes a perfect lens, Phys. Rev. Lett. 85-18, (2000).

2. A.-C. Hladky-Hennion, J. Vasseur, B. Dubus,
"Theoretical and experimental emphasis of potential applications of phononic crystals: filtering capabilities and negative refraction”,
1rst International Workshop on Phononic Crystals, 24-26 june 2009, Nice, France.

Abstract:
The acoustic group of IEMN, today composed of 6 researchers and 4 PhD students and post-doc, has been created in 1978 by J.-N. DECARPIGNY et J.C. DEBUS. At the beginning, it was essentially concerned by the design of transducers, in the low and middle frequency ranges (1 kHz - 20 kHz). Therefore, it has developed theoretical activities (finite element code ATILA and boundary element method) as well as experimental studies (acoustic and electric measurements, material characterization). Studies on periodic structures have begun at the end of the 80’s. The goal was to develop a general modelling tool for the description of periodic structures, for underwater applications, such as reflecting or absorbing panels. Then the method has been extended to the studies of active periodic structures, such as 13 piezocomposites for medical applications, as well as for the calculation of dispersion curves in materials. Today, the activities on phononic structures are a central topic in the group. The existence of an absolute band gap in these structures confers to these materials potential

applications such as filtering of elastic waves. Moreover, in some cases, the band structure exhibits some properties which allow negative refraction. The goal of this talk is to present the main activities on this topic.
The first part of the talk concerns the propagation of elastic waves through a one dimensional chain of beads, where band gaps and localization are underlined. Particular results on chains with grafted stubs allow potential applications for the filtering and the multiplexing of elastic waves.
Then, the propagation of Lamb waves in a plate with an engraved periodic grating is addressed. Mode conversions and reflections are analyzed. Attenuation of the Lamb waves in the vicinity of a forbidden band is studied and it is related to the forbidden bands inside the Brillouin zone, where the wavenumber becomes complex.
The third part presents the frequency filtering capabilities of a PZT layer on silicon substrate phononic crystals. This structure presents a practical interest for possible co-integration on silicon chip. Complete structure is modelled, with appropriate interdigited electrodes to propagate a guided mode in the piezoelectric layer, and the scattering matrix of the filter is evaluated.
The last part of this talk is devoted to recent results on negative refraction of ultrasonic transverse waves in a phononic crystal, made of holes in a solid matrix. The band structure of the device exhibits some properties which allow the negative refraction of a transverse wave transmitted through the phononic crystal. Theoretical and experimental results are compared. It allows some attractive applications for ultrasonic imaging. This work has received a support of the French ANR (National Agency for Research, ref ANR-08-BLAN-0101-01).
These works are performed in collaboration with the EPHONI team in IEMN (Bahram Djafari-Rouhani), with University of Paris 6 (Michel de Billy), with LOMC in University of Le Havre (Maxime Bavencoffe, Bruno Morvan) – France, with the University of Tucson - USA (Pierre Deymier) and with the University of Oujda – Morocco (E.H El Boudouti).

3. B. Bonello,
“Measuring the dispersion an imaging surface acoustic waves on two-dimensional phononic crystals”,
1st International Workshop on Phononic Crystals, June 24-26, 2009 – Nice, France.

Abstract:
In this communication, I will give an overview of recent experimental results we have obtained on two-dimensional solid/solid or solid/air phononic crystals (PC’s), emphasizing on the achievements of our experimental setups.
First, we have experimentally studied the dispersion of Lamb waves propagating on two-dimensional PC’s. The periodic structures consisted of air filled inclusions in a silicon plate. The samples had spatial periodicities from a few micrometers to one millimeter, well adapted to probing at elastic frequencies in the GHz and the MHz range respectively. Both square and centered rectangular symmetries were examined. We have also investigated samples made of a thin solid/solid PC deposited onto a homogeneous plate. In each case, the dispersion is obtained through spatiotemporal Fourier transforms of the surface displacements. We discuss the opening of stop bands at the zone boundaries and we compare our data to theoretical calculations.

The samples with a spatial periodicity of a few micrometers, for which forbidden band gaps are expected to open at frequencies in the GHz range, were investigated using the picosecond ultrasonic technique which main features will be recalled. In the second part of my talk, I will present a dynamic visualization of Rayleigh waves propagating at the free surface of a semi infinite PC, recorded with this technique.
Introducing a defect into an otherwise perfect PC generally leads to elastic mode(s) localized inside the phononic band gap. We have studied how the antisymmetric Lamb mode A_0, behaves in a 2D PC with a vacancy. I will present our preliminary results in the last part of this communication.

4. B. Dubus, C. Croënne, A.-C. Hladky-Hennion, J. Vasseur, A. Tinel, B. Morvan,
"Left-handed media and acoustic super-lenses made of phononic crystals: current status and main challenges", **conférence plénière**
1st Mediterranean congress on Acoustics, sale, Morocco, 28-30 octobre 2010

Abstract:
Left-handed acoustic media have both negative negative density and negative compressibility. Acoustic waves propagating in left-handed media exhibit unusual properties such as phase and group velocities of opposite signs, negative refraction index or inverse Doppler effect. The concept of left-handiness has been extended recently to elastic media having therefore negative density and negative longitudinal or/and shear moduli. Left-handed media are usually artificially fabricated materials. Doubly negative physical properties are obtained in steady-state by using multiple diffractions or reflections in a periodic lattice (so-called phononic crystals) or by exploiting resonance effect of resonators included in the medium (locally resonant materials or metamaterials). These materials open up many perspectives in imaging: acoustic flat lenses made of left-handed media could provide a resolution better than diffraction limit and copy an existing field by producing a real image.
This paper describes theoretical and experimental results on the development of elastic left-handed materials by using phononic crystals. By choosing carefully constitutive materials, lattice geometry and inclusion volumic fraction, phononic crystals are optimized in order to obtain left-handed behaviour for an isolated branch of dispersion curve as well as circular equifrequency contours indicating isotropy of wave phase velocity. Experiments are performed on ultrasonic longitudinal waves transmitted through a prismatic phononic crystal and detected by laser vibrometry. Negative refraction angles are measured, demonstrating that the phononic crystal behaves as a left-handed elastic material. Main challenges to take up in order to develop flat acoustic super-lenses and to produce real acoustic images are discussed. This work was supported by the French "Agence Nationale pour la Recherche" (SUPREME project).

5. A.-C.Hladky-Hennion, C. Croenne, B. Dubus, J. Vasseur, N. Swinteck, P.A. Deymier, B. Morvan,

"Negative refraction of elastic waves in 2D phononic crystals",
1rst International conference on Phononic Crystals, Metamaterials & Optomechanics, **keynote lecture**, May 29-June 2nd 2011, Santa Fe, NM, USA.

Abstract:

Negative refraction of elastic waves is evidenced in a two-dimensional phononic crystal (PC), made of a triangular lattice of steel rods embedded in epoxy. Experiments are carried out on a prism shaped PC inserted inside an epoxy block. The influence of different parameters is discussed in terms of image reconstruction.

6. B. Bonello, L. Belliard, J. Pierre, M. Rénier, O. Boyko,

"Phononic crystals to control the propagation of elastic waves : recent advances”,
1rst International conference on Phononic Crystals, Metamaterials & Optomechanics, **keynote lecture**, May 29-June 2nd 2011, Santa Fe, NM, USA.

Abstract:
XXX

7. B. Dubus, C. Croënne, A.-C. Hladky-Hennion, J. Vasseur, A. Tinel, B. Morvan

"Recent advances in the development of elastic super-lenses made of phononic crystals”,
International Congress on Ultrasonics, September 5-8, Gdansk, Poland, (2011).

Abstract:
New perspectives are offered in ultrasonic imaging by left-handed media which could provide a resolution better than diffraction limit and produce real image with a simple flat lens (also called superlens). Left-handed elastic media are artificial media have both negative density and negative longitudinal or/and shear moduli. Elastic waves propagating in such media exhibit unusual properties: phase and group velocities of opposite signs, negative refraction index, inverse Doppler effect. Doubly negative physical properties can be obtained in phononic crystals, in steady state, by using multiple diffractions or reflections in a periodic lattice. This paper describes theoretical and experimental results on the development of elastic left-handed materials and supelenses.
Numerical simulations are conducted to design the elastic phononic crystal in term of constitutive materials, lattice geometry and inclusion volumic fraction. Several properties are required in dispersion curves: phase and group velocities of opposite signs for an isolated branch exhibiting quasi-longitudinal behaviour, circular equifrequency contours indicating isotropy of phase velocity, matching of phase velocities in the phononic cristal and in the external medium. Experiments are performed on ultrasonic longitudinal waves transmitted through a prismatic phononic crystal and detected by laser vibrometry. Negative refraction angles are measured, demonstrating that the phononic crystal behaves as a left-handed elastic material. Finally, results on the development of a flat elastic super-lens and the production of real acoustic images from a point source are given. This work was supported by the French "Agence Nationale pour la Recherche" (SUPREME project).

6. Séminaires

B. Dubus, "Méta-matériaux gauchers et imagerie acoustique" Université de Bordeaux le 18/02/2009

Résumé:

La notion de matériau "gaucher" (ou "main gauche") a été introduite initialement en électromagnétisme par Veselago[1]. Elle définit une classe de matériaux dans lesquels le champ électrique, le champ magnétique et le vecteur d'onde associés à une onde plane constituent un trièdre tri-rectangle indirect. Les ondes se propageant dans des matériaux gauchers possèdent des propriétés inhabituelles : vitesse de phase et vitesse de groupe de signes opposés, indice de réfraction négatif, amplification des ondes évanescentes, effet doppler inversé… Ces matériaux sont généralement réalisés artificiellement, soit sous la forme d'un réseau périodique où la superposition des effets de diffraction est exploitée, soit par l'inclusion d'une distribution de micro-résonateurs qui modifient les propriétés de l'onde au voisinage des résonances locales. Sur le plan applicatif, ces méta-matériaux ouvrent de nouvelles perspectives en imagerie pour la réalisation de super-lentilles plates ayant une résolution meilleure que la limite de diffraction[2] et capables de reconstituer une image réelle. Cette présentation aborde le développement, pour les ondes acoustiques et élastiques, de méta-matériaux gauchers. La démarche générale de conception d'un cristal phononique présentant les propriétés recherchées, les méthodes de caractérisation expérimentale et les principaux problèmes à résoudre pour la réalisation d'une super-lentille acoustique sont discutés. Les résultats présentés sont issus du projet ANR SUPREME.

1. V.G. Veselago, The electrodynamics of substances with simultaneously negative values of ε and μ, Sov. Phys. Usp., 10-4 (1968).
2. J.B. Pendry, Negative refraction makes a perfect lens, Phys. Rev. Lett. 85-18, (2000).