Book of abstracts

Table of contents

D1S1-1 ..... **5**

From Stress Chains to Acoustic Emission

Ke Gao[1], R A Guyer[1,2], Esteban Rougier[1], P A Johnson[1]

D1S1-2 ..... **6**

Stress and fractures - how do they influence seismic wave velocity?

Jerzy Gieras

D1S3-1 ..... **7**

Modeling in nonlinear acoustic NDT: from contact models to diagnostics-prognostics

Vladislav Aleshin[a], Kevin Truyaert[b], Steven Delrue[b], Anton Pylypenko[a,b], Koen Van Den Abeele[b], and Olivier Bou Matar[a]

D1S3-2 ..... **8**

A 2D multiphysics model for vibration induced heating at closed defects: a qualitative analysis

Kevin Truyaert[1], Koen Van Den Abeele[1], Vladislav Aleshin[2], Anton Pylypenko[1,2], Marina Terzi[2] & Steven Delrue[1]

D1S3-3 ..... **9**

Analytical and numerical modelling of nonlinear ultrasonic wave propagation due to higher-order elastic material definition and defect interaction

Rafal Radecki, Andrzej Klepka, Pawel Packo

D1S4-1 ..... **10**

Investigation of thermal effects in contact-type damage

Andrzej Klepka, Kajetan Dziedziech, Łukasz Pieczonka, Jakub Roemer

D1S4-2 ..... **11**

Evaluation of physical aging in polymers using nonlinear ultrasonic wave mixing

P. Yambagyang[a], J. Reboud[a], A. Demčenko[a], J. M. Cooper[a]

D1S4-3 ..... **12**

Elastic nonlinear swelling of aluminum alloys under influence of neutron radiation

F.R. Akhmedzhanov[1], A.F. Boltabaev[2]

D2S1-1 ..... **13**

Dynamic characterization of smart concrete: observation of slow dynamics through electrical measurements

Jesús N. Eiras[1], F. Ouvrier-Buffet[1], François Duplan[2], Cédric Payan[1]

D2S1-2 ..... **14**

Slow dynamics in buildings as a proxy of structural damage

Ariana Lucia Astorga[a], Philippe Guéguen[a], Jacques Rivière[a,b], Toshihide Kashima[c], Paul Allan Johnson[d]

D2S1-3 ..... **15**

Asymptotic Approach to Nonlinear Waves in Elastic Solids with Slow Dynamics

Włodzimierz Domański[1], Stanisław Jemioło[2], Aleksander Franus[2]

D2S3-1 ..... **16**

Study of the relaxation time on fast dynamics tests on mortar samples: NIRAS and FANSIRAS techniques.

Vicente Genovés Gómez[1], Alicia Carrión García[2], Jorge Gosálbez Castillo[2], Jordi Payá Bernabeu[1]

D2S3-2 ..... **17**

Influence of moisture on nonlinear properties of mortar in different damage conditions

C. Payan[1], V. Genovés Gómez[2], M. Griffa[3], J. Bittner[4], M. Remillieux[5], R. Guyer[5], J. S. Popovics[4]

D2S3-3 ..... **18**

Nonlinear nondestructive evaluation of concrete affected by swelling pathologies

Florian Ouvrier-Buffet[1,2], Vincent Garnier[2], Cédric Payan[2], Jesús Nuño Eiras[2], Narintsoa Ranaivomanana[3], Benoît Durville[1], Christophe Marquié[1]

D3S1-1 ..... **19**

Handling nonlinearities in metallic materials and structures using nonlocal elasticity

Adam Martowicz[1], Łukasz Pieczonka[1], Jakub Bryła[1], Jakub Roemer[1]

D3S1-2 ..... **20**

Ultrafast imaging with pump excitation for closed crack characterization

Yoshikazu Ohara[1], Sylvain Haupert[2], Sinan Li[3]

D3S1-3 21

Evolution of damping and velocity during conditioning and relaxation in diverse media

Marco Scalerandi[1], Angelo Di Bella[1], Antonio Gliozzi[1], Charfeddine Mechri[2,3], Mourad Bentahar[2,4], Mauro Tortello[1]

D3S2 22

Contact-based theory of hysteresis and relaxation in geomaterials

L. Ostrovsky[1,2], A. Lebedev[2], J. Riviere[3], P. Shokouhi[3], C. Donahue[4], E-R. Dauson[4], S. Manakov[2], P. Johnson[4]

D3S3-1 23

Shear shock wave generation and focusing in the human head

Sandhya Chandrasekaran, Bharat Tripathi, David Espindola, Gianmarco Pinton

D3S3-2 25

Anisotropic muscle shear moduli measured by the Doppler method

Timofey Krit, Shamil Asfandiyarov, Valery Andreev

D3S3-3 26

Evaluation of soft layered materials using air-coupled acoustic radiation force excitation of guided wave and spatial multiple signal classification

Patrycja Pyzik, Lukasz Ambrozinski

D4S1-1 27

Enhancement of nonlinear response via mode match of local defect resonance

Igor Solodov

D4S1-2 28

Fixed-voltage fundamental wave difference (FAD) for high-selectivity imaging of closed cracks

Yoshikazu Ohara[1], Hiromichi Namajima[1], Sylvain Haupert[2], Toshihiro Tsuji[1], Tsuyoshi Mihara[1]

D4S1-3 29

Nonlinear Elasticity of 3D Printed Ti6Al4V with Porosity

Jan KOBER[a], Alexander KIRCHNER[b], Zdenek PREVOROVSKY[a]

D4S2 30

High-resolution mechanical spectroscopy, HRMS: Status and Perspectives

Leszek B. Magalas[1]

D4S3-1 ..... **31**

How is slip nucleated at a frictional interface?

Tom de Geus[1], Marko Popović[1], Wencheng Ji[1], Alberto Rosso[2], Matthieu Wyart[1]

D4S3-2 ..... **32**

Dynamic elastic-plastic contact model of rough surfaces in the presence of adhesion

A. Di Bella, M. Scalerandi, A.S. Gliozzi, M. Tortello

D4S3-3 ..... **33**

Rayleigh wave harmonic generation in materials with depth-dependent non-linear properties: theoretical results

P. Mora[12], M. Spies[2]

D5S1-1 ..... **34**

Low cost integrity inspection in wellbores: challenges in nonlinear measurements using time reversal

E. Dauson, C. Donahue, P. Johnson

D5S1-2 ..... **35**

The influence of plate thickness on guided waves self-focusing through the time-reversal process

Jakub Spytek, Łukasz Pieczonka, Łukasz Ambroziński

D5S1-3 ..... **36**

Probing defects at different depths using time-reversal acoustics

Lukasz Pieczonka[1], Jakub Spytek[1], Patrycja Pyzik[1], Jakub Mrówka[1], Jakub Benduch[1], Jan Fabianski[1]

D5S2-1 ..... **37**

Investigation of modulation transfer effect for elastic waves.

Jakub Górski[1], Andrzej Klepka[1], Kajetan Dziedziech[1], Jakub Mrówka[1]

D5S2-2 ..... **38**

Acousto-optical studies of acoustical activity in lanthanum hallosilicate crystals

F.R. Akhmedzhanov[1], S.Z. Mirzaev[1], J.T. Nazarov[2], J. O. Kurbanov[1]

D1S1-1

From Stress Chains to Acoustic Emission

Ke Gao[1], R A Guyer[1,2], Esteban Rougier[1], P A Johnson[1]
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The Ecke apparatus, a D=2 laboratory simulation of a sheared fault apparatus (ICNEM 2014), and recent numerical simulation of this apparatus, using combined finite element and discrete element methods (FEMDEM), will be discussed. Analysis of the FEMDEM results allow a reasonably complete picture of the elastic response of the model earthquake system. This picture will be described in a presentation heavy on pedagogy.

D1S1-2

Stress and fractures - how do they influence seismic wave velocity?

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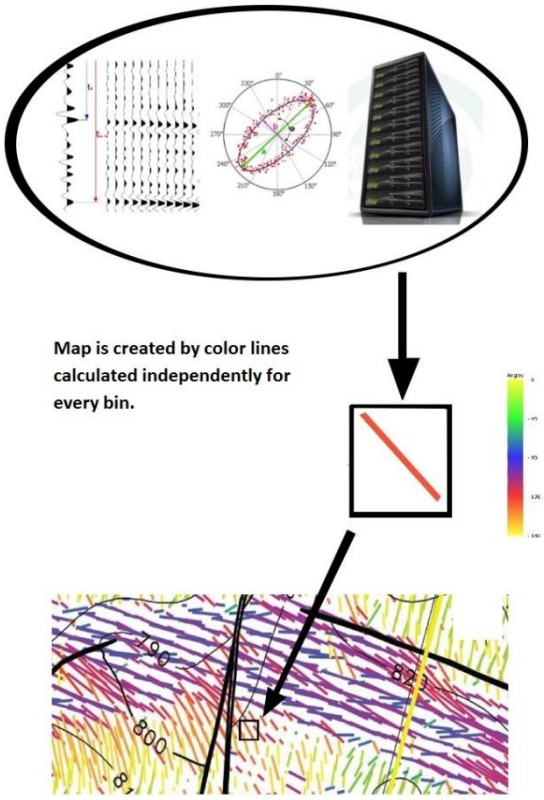
One of the main methods of exploration of earth crust are seismic methods. Geophysicists gather seismic data from interesting regions then process it to get image of subsurface. Thanks to the evolution of processing methods nowadays more and more precise geological model can be made. Some rock features like fracture orientation and intensity require even more dedicated approach. By precise seismic velocity estimation for different azimuths, anisotropy maps of velocities can be constructed . It is recognized that seismic waves are influenced by fractures. But what about stress, can we find places of increased stress, and can we measure its change in time using seismic methods?



D1S3-1

Modeling in nonlinear acoustic NDT: from contact models to diagnostics-prognostics

Vladislav Aleshin[a], Kevin Truyaert[b], Steven Delrue[b], Anton Pylypenko[a,b], Koen Van Den Abeele[b], and Olivier Bou Matar[a]

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We present a numerical method capable of describing elastic waves and thermal effects in materials with frictional defects, and discuss related opportunities for NDT. Planar defects (cracks, delaminations, loose joints) in solids represent additional boundaries at which proper boundary conditions, i.e. a relationship between contact loads and displacements, should be defined. However, the account for friction makes this task difficult since the most common friction model, the Amontons-Coulomb law, never provides contact displacements but only determines the link between contact loads of the kind $T=\mu N$ when the contact faces slip. As a result, the displacements are to be implicitly obtained from an elastic reaction of the entire material, calculated in a way that satisfies the slip conditions at all points where slip takes place. To overcome this difficulty and get local load-displacement relationships, we consider displacements as arguments and allow for irregular contact faces (roughness). In this situation, it is possible to use a previously developed semi-analytical method of contact mechanics (Method of Memory Diagrams, MMD) that provides loads for all possible displacement histories (example in Fig. 1).

Next, we incorporate these explicit boundary conditions into a finite element environment. This yields a flexible numerical method that allows one to calculate all elastic fields in a sample of arbitrary geometry excited by an arbitrary waveform (Fig. 2). In addition, the friction-induced energy loss can be analytically calculated allowing to determine local heat sources which can be coupled to a heat transport finite element module in order to account for thermal effects.

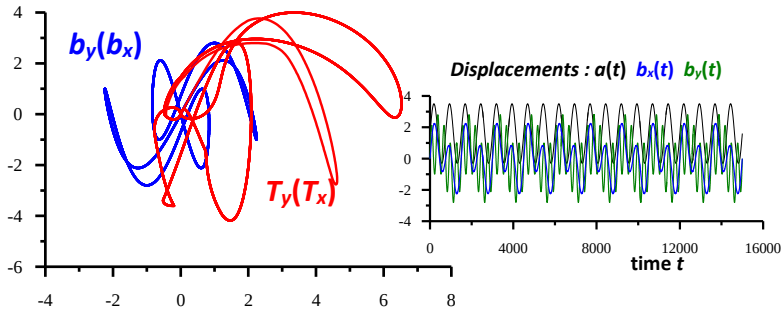

Fig. 1. Contact model: loads T_x and T_y calculated for a certain loading history in terms of displacements b_x and b_y.

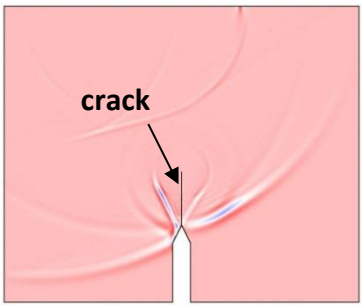

Fig. 2. Snapshots of a typical displacement wave pattern.

The numerical method called MMD-FEM is currently being validated in a series of experiments in which nonlinear signatures of a calibrated (engineered) defect are measured. Once the theory and experiment agreement is achieved, the code becomes a powerful NDT tool that can be used for a detailed reconstruction of damage parameters. Indeed, it would be possible to compare a response measured on a sample with unknown damage and the modeling results for a guessed damage configuration. To facilitate a fitting procedure, recognition by neural networks can be used.

As a result, geometric defect parameters could be potentially retrieved in a much finer way than most of the modern imaging techniques which provide only an approximate sizing of the damage. Finally, by adding a description of evolving damage via existing numerical methods of damage mechanics, we can proceed to the prognostics state, at which conclusions on the lifetime and serviceability of a structure or material can be drawn.

D1S3-2

A 2D multiphysics model for vibration induced heating at closed defects: a qualitative analysis

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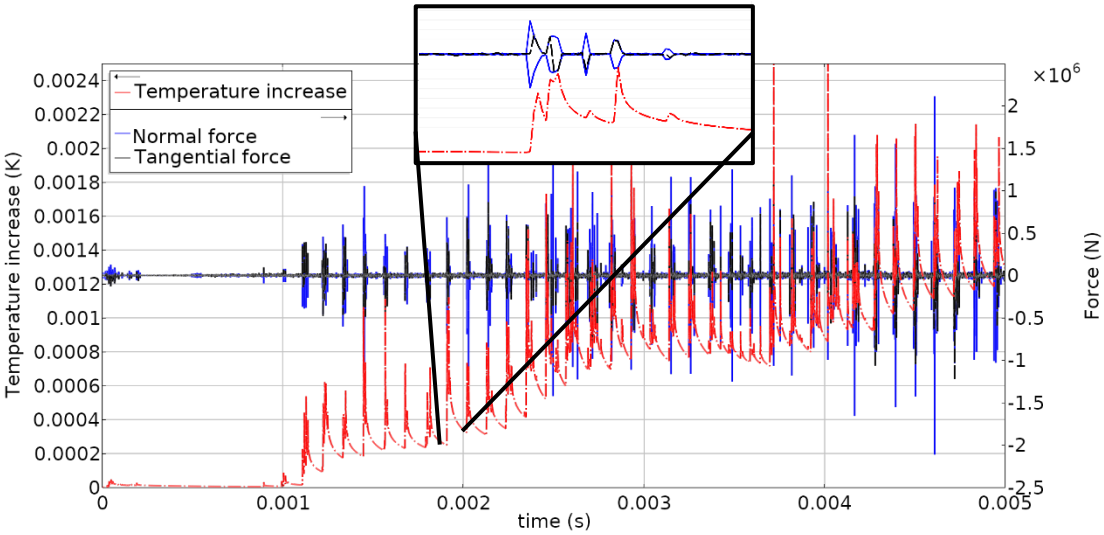
Ultrasonic vibrothermography is known as a promising Non-Destructive Testing (NDT) technique for the detection of closed defects. The technique uses ultrasonic wave excitation to induce frictional behavior at the defect's interfaces. As a result, the vibrational energy of the elastic wave will be locally converted into thermal energy and heat will be generated around the defect, which subsequently dissipates through the medium by way of thermal diffusion. In practice, the generated heat can then be recorded by an infrared camera, creating thermograms that allow to detect the defect.

Apart from defect detection, defect characterization has become one of the major research interests in NDT, e.g. to anticipate the severity of the defect. To obtain reliable and high quality defect classification by ultrasonic thermography, theoretical models capable of interpreting the obtained thermograms are necessary.

In this study, a previously developed two dimensional model, consisting of a mechanics/dynamics module to describe the (nonlinear) interaction between elastic waves and a closed defect with rough surfaces, is extended with the calculation of the instantaneous friction-induced energy loss at the contact interface. The model allows to monitor the evolution of both the normal and tangential contact stresses and the temperature at each point on the defect interface. Figure 1 shows an example of the stresses and the temperature increase for a particular location on a surface breaking crack, simulated during 5 ms, after being periodically excited at 100 kHz. The simulated data clearly illustrates periodic temperature increases that are directly linked to the dynamic frictional contact behavior of the defect interfaces. This locally generated heat subsequently propagates through the sample, allowing for thermographic measurements to be performed on the surface of the sample.

In order to confirm the reliability and accuracy of the model, a qualitative analysis will be performed by comparing the simulated data with numerical and experimental results described in literature.



D1S3-3

Analytical and numerical modelling of nonlinear ultrasonic wave propagation due to higher-order elastic material definition and defect interaction

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Abstract:

The nonlinear features of the propagating ultrasonic waves are extensively investigated in order to quantify and qualify the condition of the material degradation. These features will be exhibited in the spectral domain of the responses from the examined plate-like structure, if, for instance, the higher-order material characteristic or the breathing/shearing motion between the surfaces of generated micro-cracks are present.

This work focuses on the numerical and analytical solutions of the nonlinear ultrasonic wave propagation. First, the numerical approach based on the Local Interaction Simulation Approach (LISA) is used to solve the guided ultrasonic wave propagation problem, where Landau's higher-order elastic material definition is considered. Moreover, the numerical analysis is extended by introducing the possibility of modelling a contact nonlinearity, namely, the breathing crack motion. The cumulative synchronism between the first and second harmonic is investigated with the consideration of two nonlinear sources being present. Two Lamb wave mode pairs are considered (S0-s0 and S1-s2).

Second, the analytical approach based on the Harmonic Balance method is shown to solve the equilibrium state of the bulk shear wave interacting with contacting crack surfaces, which exhibit a shear hysteretic motion. This approach allows to predict in qualitative and quantitative manner of the response of the examined system. Results from the analytical approximation are compared with the experimental responses.

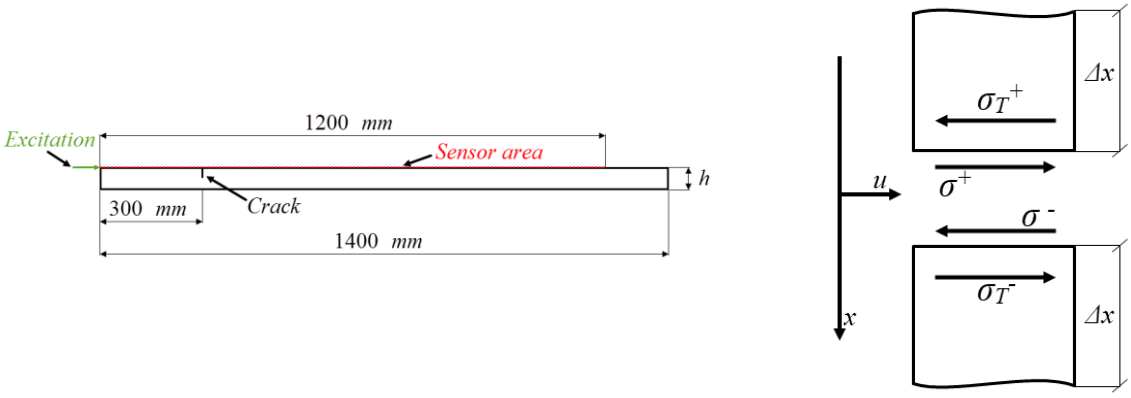

Figure 1. Considered models of two cases investigated in the presented work: a) two-dimensional plate-like structure used for numerical modelling of the propagation of the synchronous Lamb wave pairs S0-s0 and S1-s2; b) one-dimensional model used for analytical solution of the propagating bulk shear wave interacting with the contact surfaces, which exhibit hysteretic shear motion.

D1S4-1

Investigation of thermal effects in contact-type damage

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Abstract:
The contact type damages are one of the most common types of damage in structures. Due to the multiplicity of physical phenomena occurring during relative movement of the damage surfaces, there are very difficult to analyze. Nevertheless, damage detection and localization methods based on phenomena resulting from interaction of the damage interface with acoustic waves have been developed for many years. One of the phenomena occurring due to contact is generation of a local, variable temperature field. The article focuses on the analysis of non-linear effects, in particular modulation of the response signal, activated as a result of the introduction of a variable temperature field into the vicinity of contact damage. It has been shown that the heat generated as a result of surface friction can contribute to the appearance of sidebands in the signal spectrum. For cracked aluminum plate the vibro-acoustic modulation test with thermal low frequency excitation has been performed. The variable thermal field together with high frequency acoustic wave have been introduced to the structure using laser and piezoelectric transducer respectively. The response has been measured by Polytec laser vibrometer. The results show that variable thermal field can be one of the reason for signal modulation.

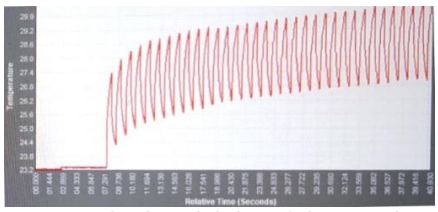

Fig. 1. Measured changes in temperature in the vicinity of the crack under thermal excitation

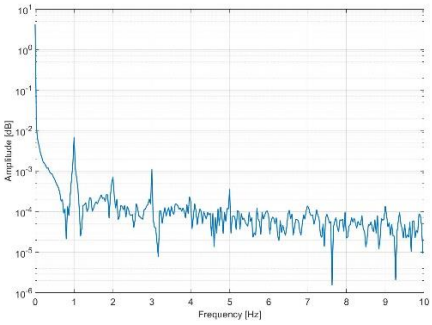

Fig. 2. Spectrum of demodulated response signal.

D1S4-2

Evaluation of physical aging in polymers using nonlinear ultrasonic wave mixing

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Amorphous thermoplastic polymers such as polyvinylchloride (PVC) and polymethylmethacrylate (PMMA) are widely used in engineering and healthcare technologies, due to their competitive costs, simple processing, biocompatibility and good mechanical properties. However, physical ageing, a structural relaxation process observed below the glass transition temperature Tg, significantly affects the polymers mechanical properties (e.g. rigidity, brittleness and density) and is challenging to control. These changes can be very small, so conventional non-destructive measurement techniques cannot detect them early enough to provide mitigation measures (such as maintenance or replacement). In this study, we demonstrate the detection of physical ageing in polyvinyl chloride (PVC) as an example amorphous thermoplastic polymer widely used in industry, using nonlinear wave mixing. We show that the physical ageing is more pronounced after rejuvenation and quenching processes, and that the nonlinear energy increased dramatically during annealing processes.

We used a submersion pulse-echo ultrasonic measurement setup, (Fig. 1(a)). First, a specimen was heated in an oven above the glass transition temperature Tg for 60 min and immediately quenched in antifreeze liquid (at- 34 °C). The heating step erased the thermo-history of the polymer. The quenched specimen was then placed into a water bath, where two sources, at 2.5 and 3.75 MHz, generated initial waves. The response of the nonlinear sum-frequency interaction was captured with a 30 s sampling rate at 6.25 MHz (sum-frequency, Fig. 1.b). A magnetic stirrer was used to set a uniform temperature in the water chamber (Fig. 1c)

The system shows that nonlinear ultrasonics is suitable to detect the physical ageing of amorphous polymers at annealing temperature. When the polymer structure underwent structural relaxation, the nonlinear wave mixing energy gradually increased due to the non-equilibrium state and then continually developed due to physical aging. In addition, the gradient of the nonlinear wave mixing energy increased exponentially with annealing temperatures (Fig.1.c), showing the potential for high sensitivity. This method can be beneficially applied for the evaluation of physical ageing due its high sensitivity to changes in the structural relaxation in polymers and agrees with the physical ageing theory [J. M. Hutchinson, *Prog. Polym. Sci.,* 1995].

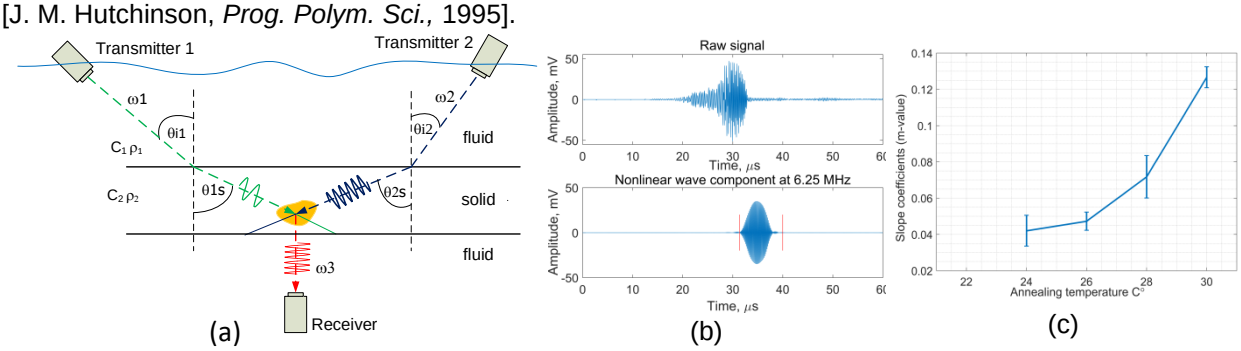

Figure 1. (**a**) Pulse-echo measurement set-up for non-collinear wave mixing. (**b**) Nonlinear wave component at 6.25MHz (bottom) after extraction from a raw signal (top). (**c**) Effect of annealing temperature on the physical aging rate (error bars are standard deviation of 5 measurements).

D1S4-3

Elastic nonlinear swelling of aluminum alloys under influence of neutron radiation

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The swelling of polycrystalline samples of aluminum alloys SAV-1 and AMG-2 at room temperature under the influence of the integral neutron flux has been investigated. The samples of alloys were prepared in the form cylinder about 2 cm height and of 1.2 cm diameter. The density of the alloy was determined by the mass and volume measurements of the samples with an accuracy of 0.2%. The linear dimensions of samples before and after irradiation were measured with a micrometer with an absolute accuracy of 1 μm. The change in the linear dimensions of the samples after irradiation was determined also by measuring the propagation time of ultrasonic waves with a frequency of 10 MHz by the pulse interference method. The samples were irradiated with fast neutrons in the vertical channels of the WWR-SM reactor. It has been found that neutron irradiation leads to a noticeable swelling at medium radiation doses.

The observed change in the volume of the alloys is apparently due to a change in the concentration of pores in the volume of the alloy under the influence of neutron radiation. An increase in the number of vacancies and their diffusion leads to the appearance of clusters of vacancies — pores, in the vicinity of which the concentration of vacancies is low. The resulting diffusion flow of vacancies into the pores leads to an increase in the pore volume and surface area. This, in turn, leads to an additional increase in the diffusion flow and a further increase in the pore volume. As a result, the alloys swell with increasing radiation dose to a fluence of about 10^{18} n/cm^2.

With a further increase in the dose of radiation up to 10^{20} n/cm^2, the dynamic equilibrium between the pressure of the atoms of the lattice and interstitial atoms and the pressure created by surface tension is disturbed. Large pores are broken into a number of smaller clusters, which leads to a decrease in swelling and, ultimately, to the return of the sample volume to its original state.

Based on these data, the change in the average lattice parameter of the alloys under the influence of neutron radiation was determined. In fig. 1 is shown the dependence of the lattice parameter of the AMG-2 alloy on the neutron fluence. It is established that the dependence of the lattice parameter of SAV-1 and AMG-2 alloys on the neutron dose correlates with similar data for other alloys. Nonlinear elastic properties of irradiated aluminum alloys are discussed.

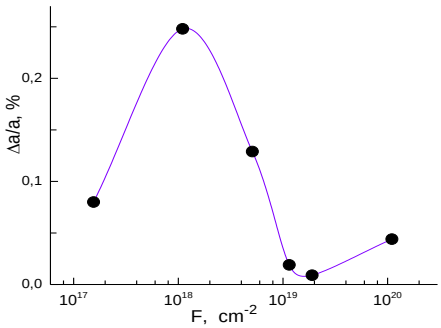

Fig. 1. The change in the lattice parameter of the alloy AMG-2 under the influence of neutron radiation

D2S1-1

Dynamic characterization of smart concrete: observation of slow dynamics through electrical measurements

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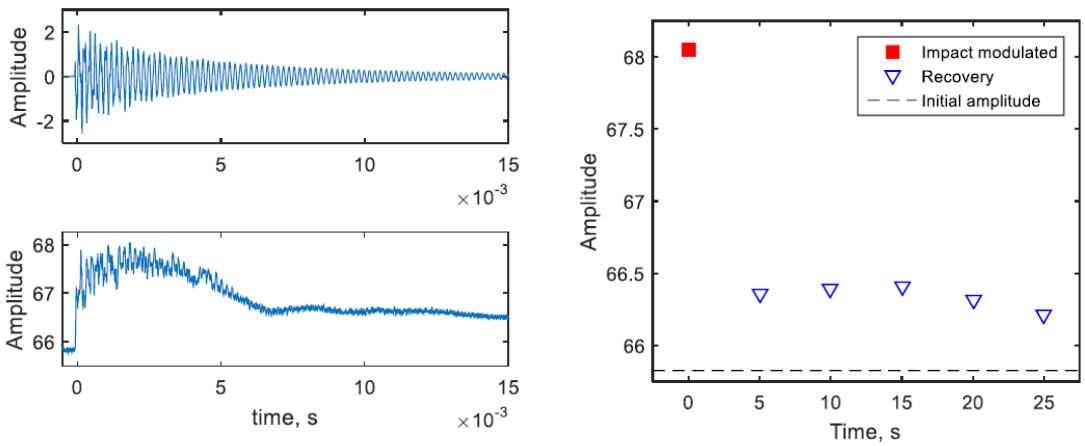
The development of self-sensing concrete has attracted keen interest in the scientific community since early developments in the 90's. Such type of concrete is produced by adding electrical conductive fillers into conventional concrete, which confer it enhanced piezoresistance (ability to sense carrying load). This characteristic opens the possibility for structural health monitoring of concrete structures, avoiding costly attached or embedded sensors which suffer from low durability. Despite the wealth of research studies reporting the piezoresistive properties under quasi-static loading, the studies informing on the dynamic sensing capacity on such materials is still scant. This study investigated the effect of dynamic loadings on the piezoresistive properties of electrical conductive fiber reinforced concrete. Different prismatic concrete samples (40x40x160 mm) were produced which incorporated different contents of electrically conductive fibers (length ~6 mm). The sensing capacity of the different concretes types, were monitored with an alternate current (AC) while compressive loading cycles are applied (at 0.1 MPa·s^{-1} and up to 5 MPa). Also, an AC is used to investigate the vibration sensing capacity under different dynamic excitations. For the most conductive concretes investigated herein, the results show that the variation of electrical resistance closely follows the vibrations sensed by an off-the-shelf accelerometer. Yet, the electrical resistance increases suddenly upon dynamic excitation and slowly recovers as the vibration amplitude decreases towards the initial electrical resistance (that before dynamic excitation). The recovery of the initial electrical properties is not achieved once the vibration amplitude vanished, but it continued at longer time scales. These effects were also evaluated after imparting gradual damage on the same set of concrete samples. Finally, conclusions are drawn about the sensitivity of the extracted features to detect damage.



D2S1-2

Slow dynamics in buildings as a proxy of structural damage

Ariana Lucia Astorga[a], Philippe Guéguen[a], Jacques Rivière[a,b], Toshihide Kashima[c], Paul Allan Johnson[d]

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Slow dynamics is the most fascinating signature of nonlinear elasticity. This relaxation process in which the elastic properties of a material recover after a transitory excitation might be closely linked to structural damage. We monitor variations of fundamental frequency in buildings during single earthquakes (short-term monitoring) and after a sequence of several earthquakes (long-term monitoring), observing slow dynamics in both cases, and confirming the multi-scale feature of this phenomenon. We apply relaxation models developed in laboratory to fit our building data and obtain some relaxation parameters that are able to characterize permanent variations of structural stiffness, and therefore, of structural state. For instance, evidence of damage after the Tohoku earthquake in 2011 is clearly manifested in the long-term behavior of the fundamental frequency recovery of Japanese buildings. Our results are compared with those observed in laboratory experiments of granular materials and at the crust of the Earth after strong earthquakes. Despite the difference between scales, conditions and level of complexity, the analogy between results allows us to confirm the universality of slow dynamics and its connection with the degree of fracturing and mechanical damage.

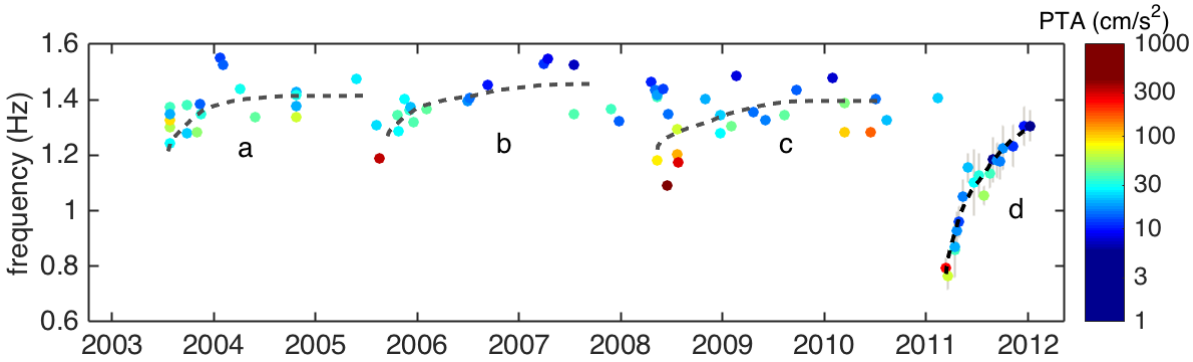

Figure 1. Slow dynamics observed after a sequence of earthquakes in a long-term monitored building. Each dot correspond to a seismic event. Colorscale indicates peak accelerations recorded at the top-floor of the building.

D2S1-3

Asymptotic Approach to Nonlinear Waves in Elastic Solids with Slow Dynamics

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Many elastic materials demonstrate nonclassical nonlinear features like a softening under a dynamic loading. This phenomenon which can be observed in dynamic acousto-elastic testing reveals a decrease of a sound speed over a long period of time and then a slow recovery to the initial state. The long-time relaxation process called a slow dynamics can be represented by the evolution of the internal variable in the continuum mechanics approach. We follow the model proposed by Berjamin et al. [1]. The governing equations in this model are written in Lagrangian coordinates. Apart from the evolution equations of the internal variable, they consist also of the equations of motion together with the compatibility relations between the material time derivative of the deformation gradient and the space derivative of the velocity field. We assume that the pure elastic part of the internal energy is described by the Murnaghan form (see Fig. 1). We study the propagation of plane waves. Applying the weakly nonlinear perturbation method [2], with the help of the multiple scale analysis, we derive evolution equations for waves' amplitudes. The coefficients in the obtained equations are expressed in terms of material parameters.

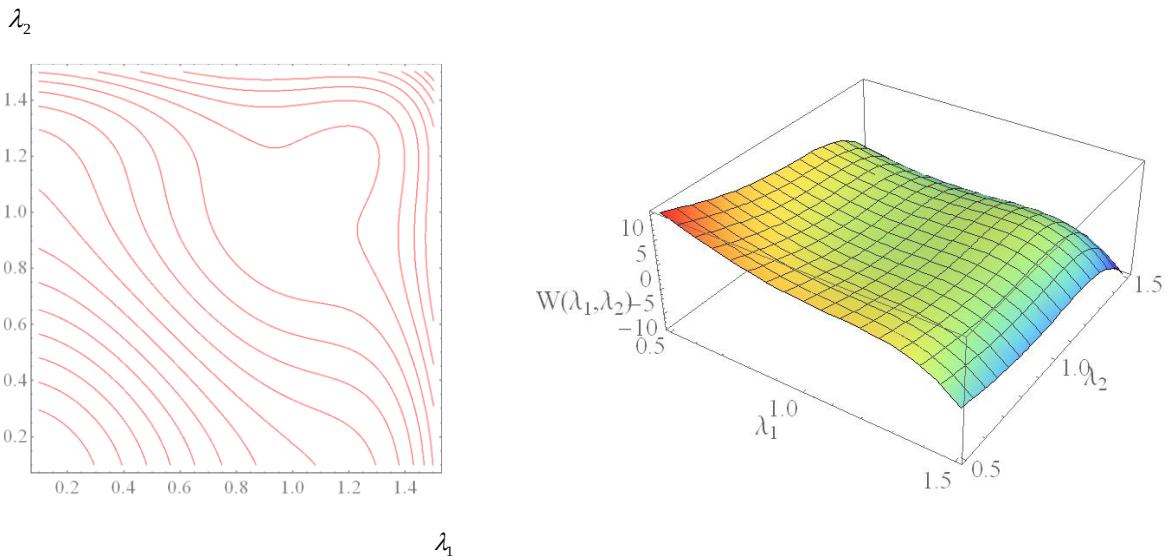

Fig. 1. Contour plot and 3D plot of the Murnaghan strain energy function $W(\lambda_1, \lambda_2)$ with respect to principal elongations.

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D2S3-1

Study of the relaxation time on fast dynamics tests on mortar samples: NIRAS and FANSIRAS techniques.

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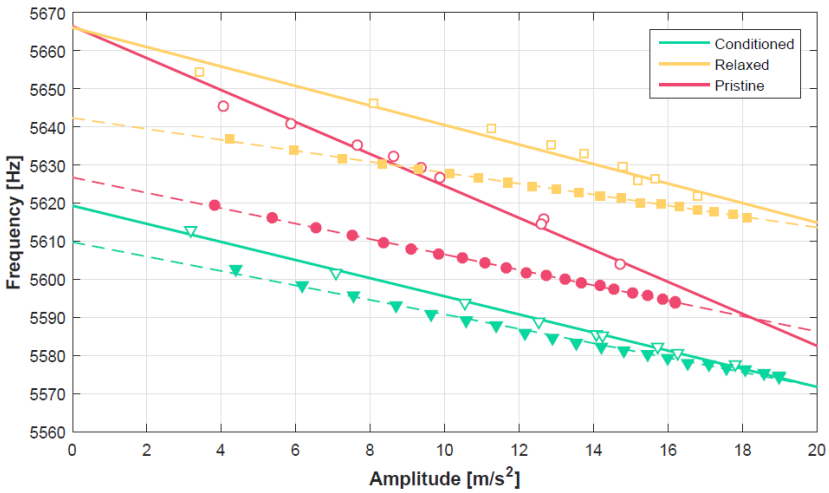
Nonlinear Elastic Wave Spectroscopy (NEWS) techniques allow extracting nonlinear information of materials with a mesoscopic structure. However, all these techniques are strongly affected by different variables, like atmospheric ones, but also by the history of previous dynamic events as well as its intensity, also known as conditioning. The aim of the present study is to analyze by means of two impact spectroscopy techniques, NIRAS (Nonlinear Impact Resonance Acoustic Spectroscopy) and FANSIRAS (Flipped Accumulative Nonlinear Single Impact Resonance Acoustic Spectroscopy) the relaxation time between the dynamic events (tests) as a preliminary study to explore the conditioning effect in different techniques and input energies during the fast dynamics tests.
Mortar samples, which represent most used materials in civil engineering, were manufactured. One sample was exposed to 400 ºC to create internal damage in the form of distributed cracks. Other mortar prism was dried at 40 ºC at a constant mass. After that, the samples were tested at room conditions and stored in a climate chamber between tests. Every time the samples were tested, 5 sequentially increasing amplitude NIRAS tests were performed, applying FANSIRAS algorithm to the last impact event. The samples were tested for different relaxation times up to 15 days, extracting nonlinear parameters for NIRAS (empty scatters, solid line) and FANSIRAS (filled scatters, dashed line) techniques. During the experiment, three different trends were observed and tagged as Conditioned, Relaxed and Pristine. The difference between NIRAS and FANSIRAS nonlinear parameters appeared to show interesting information about the conditioning state of the samples tested with these techniques.



D2S3-2

Influence of moisture on nonlinear properties of mortar in different damage conditions

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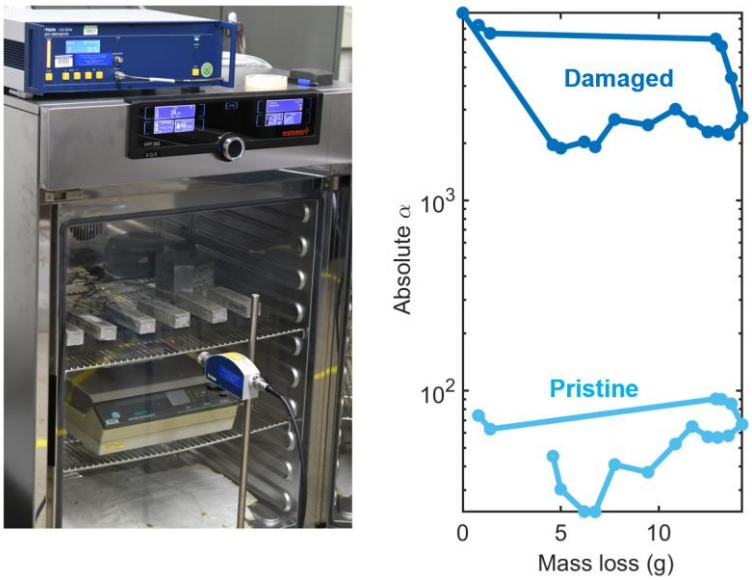
Abstract:
The effect of moisture on the nonlinear elastic behavior of micro-heterogeneous materials such as rocks and concrete has already been investigated and modeled. It is shown that depending on the microstructural features, these properties can be strongly influenced by small changes in a way or the opposite. This work aims to explore this influence and to characterize effect of environmental moisture nonlinearity measurements in cement-based materials in different damaged states. A set of mortar sample were fabricated, a subset was exposed to thermal shocks in order to provide a pure mechanical and distributed damage without any possible chemical influence. Nonlinear behavior of the samples was measured utilizing nonlinear resonant ultrasound spectroscopy (NRUS) tests inside an environmental chamber with controlled temperature and relative humidity, initially at high humidity and gradually drying over time before coming back to the fully saturated state. The results show that pristine samples behave as already reported in the literature, but the damaged one exhibit a strong variation at early drying states. Parallel measurements of the drying process under controlled environmental conditions were performed to see the differences of the mass loss between damaged and pristine samples. In order to understand the physical mechanism in play, ongoing experiments aim at imaging the water front inside both pristine and damaged samples during the drying process using X ray tomography.



Left: Experiments inside the environmental chamber. Right: Nonlinearity as a function of drying, monitored in mass loss of water.

D2S3-3

Nonlinear nondestructive evaluation of concrete affected by swelling pathologies

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In nuclear power plants, the reactor building made of reinforced concrete is the third containment barrier. Thus, concrete has to maintain low permeability and sufficient mechanical properties all along its service life. Early age detection of swelling pathologies in concrete by non-destructive testing (NDT) is a major concern, especially in the case of existing nuclear power plants where core drilling is not allowed.
The objective of this work is to detect and map the extent of swelling pathologies at early stages in massive concrete elements using ultrasonic nondestructive testing. It is well known that nonlinear acoustics allow an early detection of Alkali Silica Reaction (ASR) on small laboratory samples with a high variation of the non-classical nonlinear parameter. A similar study was recently conducted on mortar samples affected by Delayed Ettringite Formation (DEF) but not on realistic concrete (which may behave differently from mortar). That is why we propose to focus on this topic in the first part of this work. Nonlinear Resonant Ultrasonic Spectroscopy (NRUS) tests are carried out on concrete samples (7×7×28 cm^3) affected by DEF with a realistic grain size distribution and with a moderate kinetic expansion. In order to better understand results, microscopy and micro-cracking analyses were carried out on the samples at the end of the experiments. Results show a good correlation between NRUS results and microscopic observations during DEF at early stage (under 0.21% expansion). No significant evolutions of the nonlinear parameter are observed due to the filling of Interfacial Transition zone (ITZ) by ettringite crystals.
In the second part of this work, a new technique based on propagative wave interaction has been developed in order to perform tests on large dimensions concrete specimens. For that, a concrete block sizing 40x40x70 cm^3 containing a highly nonlinear object supposed to be representative of ASR pathology, was casted. The results show the possibility of our method to map the nonlinearity in the sample.

Picture of the experiment and results.

This work is a part of an international project named Observatoire de la Durabilité des Ouvrages en Béton Armé (ODOBA) led by the French Technical Safety Organization (Institut de Radioprotection et de Sureté Nucléaire – IRSN).

D3S1-1

Handling nonlinearities in metallic materials and structures using nonlocal elasticity

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The work is devoted to nonlocal elasticity applied to solve static and dynamic problems for models of metallic materials and structures with nonlinear parameters accounted for. As reported in the literature, nonlocality opens new perspectives regarding more physical modeling of complex behavior of the materials and structures exhibiting various types of nonlinearities. These nonlinearities may reflect nonlinear constitutive relations, geometric properties and boundary conditions. Originally introduced in the sixties of the previous century, nonlocality effectively handles experimental observations, not having any modeling counterparts before. It should be also noted that nonlocally formulated governing equations allow for a convenient control of the dispersion characteristics of the modeled solid.
Fig. 1 visualizes exemplary results of the authors' numerical studies performed for a metallic wire made of a shape memory alloy (SMA) and cracked aluminum plate.

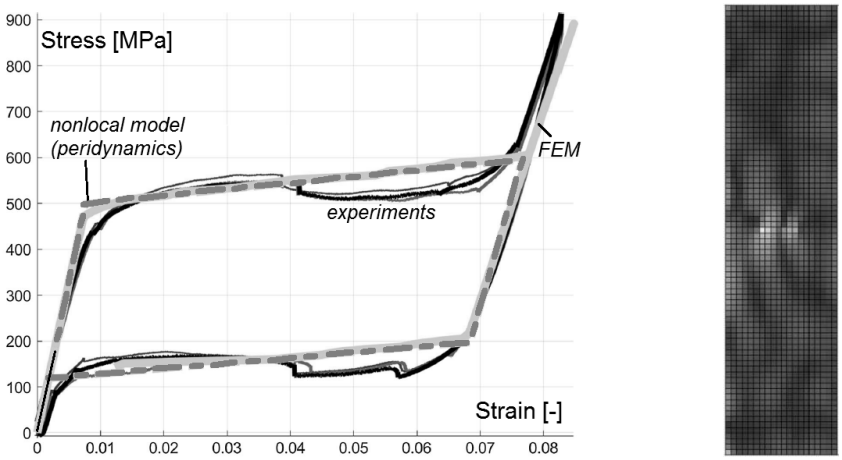

Fig. 1. Applications of peridynamics to modeling nonlinearities in metallic materials and structures: (on left) hysteretic stress-strain relation for an SMA Nitinol wire, (on right) superficially distributed wave modulation intensity for vibro-acoustic modulation in a centrally cracked aluminum plate.

In both studied cases a nonlocal modeling technique, i.e., the peridynamics, is considered to account for nonlocal elasticity. Quasi-statics and transient analysis are considered to respectively investigate the hysteretic behavior of the SMA wire while stretching and vibro-acoustic modulation revealed due to the presence of a damage.

The research was financed within the scope of the project no. OPUS 2017/27/B/ST8/01822 „Mechanisms of stability loss in high-speed foil bearings – modeling and experimental validation of thermomechanical couplings" financed by the National Science Center, Poland.

D3S1-2

Ultrafast imaging with pump excitation for closed crack characterization

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Nonlinear acoustic/ultrasonic methods have been studied not only for nondestructive evaluation (NDE)[1] of closed cracks and micro damage in engineering materials but also for characterization of granular or cracked geo-materials. Among them, dynamic acoustoelastic testing (DAET)[2] is one of the most powerful approaches to explore various kinds of dynamic elastic nonlinearity such as clapping, hysteresis, slow dynamics, etc., which are very important for both NDE and geoscience. The method relies on dynamically exciting a sample with a low frequency (LF) vibration (pump excitation), which applies a strong strain periodically. Simultaneously, a high frequency ultrasonic wave (probe wave) probes the changes in wave speed and in attenuation as a function of the strain induced by the pump excitation. Thus far, the probe wave is transmitted by a monolithic transducer, so even with an image reconstructed from a mechanical scanning, the spatial resolution is very much constrained because of the lack of focusing on signal receptions. In addition, the speed of measurement over a wide range is limited by the scanning. Recently, the ultrafast imaging, typically acquired with thousands of frames per second, has been developed and primarily applied in biomedical applications[3,4]. In this study, we combine the pump excitation with ultrafast phased array imaging (Fig. 1), to propose a new NDE method for closed crack imaging as well as a new tool for studying dynamic elastic nonlinearities. We applied the proposed technique to closed-crack specimen (A7075).The results show this method can image closed cracks rapidly with good sensitivity, contrast and resolution, which is practically useful for NDT. Furthermore, the hysteretic crack response was observed, suggesting the method could be a new tool to give physical insights for other fields such as geoscience.

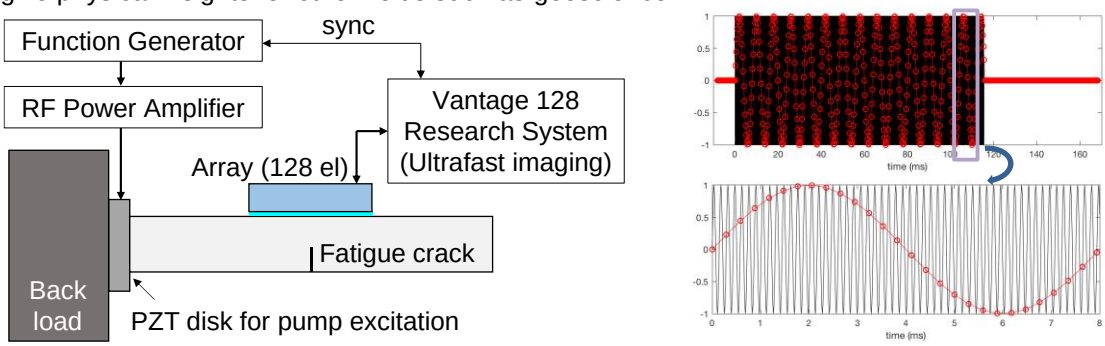

Fig. 1: Schematic experimental setup (left) and pump wave down-sampled by ultrafast imaging (right).

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D3S1-3

Evolution of damping and velocity during conditioning and relaxation in diverse media

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In nonlinear mesoscopic materials, fast and slow dynamics effects [1-3] are usually occurring simultaneously. The former is an instantaneous nonlinear phenomenon due to the explicit dependence of velocity and attenuation on strain. Slow dynamics is a non-equilibrium effect, governed by the dependence of the linear modulus and Q-factor on the dynamic strain level: when excited at constant strain, the sample properties vary in time ("conditioning") until they reach a new equilibrium state. When excitation is removed, the system recovers, again slowly in time, its original viscoelastic properties ("relaxation").

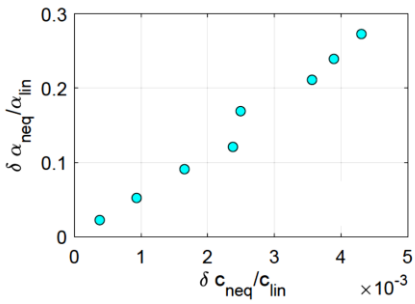

Figure 1: linear correlation between conditioning effects on velocity and damping

We used an approach [4,5] which allows us to quantify fast and slow dynamics (during both conditioning and relaxation) almost in real time, i.e. also close to the very beginning of the conditioning process (early stages). Nonlinear and non-equilibrium parameters were extracted from the temporal evolution of velocity and damping coefficient and studied as a function of conditioning amplitude. Results are presented for different materials (mortar and concrete, also affected by damage) and compared with each other, in view of supporting modelling efforts, focused on specific physical phenomena and with the aim of proposing Ultrasonic Nonlinear Nondestructive Techniques able to discriminate different damage sources.

Correlations between parameters linked to non-equilibrium and nonlinear effects, i.e. slow and fast dynamics, are studied in details. A quantitative analysis of the influence of conditioning on results obtained in fast dynamics experiments will also be discussed.

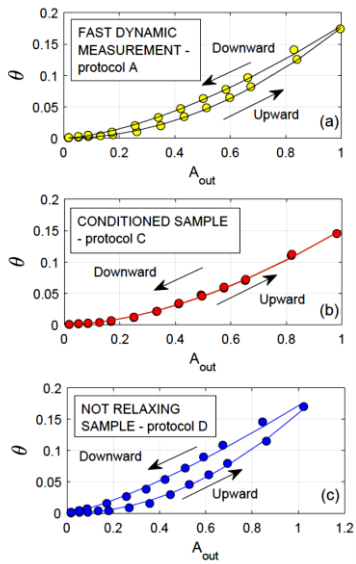

Figure 2: effects of slow dynamics on fas dynamics experiments

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D3S2

Contact-based theory of hysteresis and relaxation in geomaterials

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This presentation reviews the basics and the recent development of the physical model of slow time relaxation in structured materials and its application to numerous experimental results of recent years. The model (also covering the hysteretic fast-time behavior) is based on the theory of contact forces according to which after a strong impact, a small fraction of the contacts (possibly including those within the microcracks) does not immediately return to the initial state so that the full recovery occurs only due to the thermal fluctuations. This model explains most of the experimental data including the rather universal logarithmic recovery and deviation from the latter at the initial stage of the process, as well as the linear dependence of the elastic modulus (and sound velocity) on the excitation amplitude.

The recent development includes, in particular, the dependence of the recovery process on the impact duration, and the situations when excitation and relaxation processes occur simultaneously. For the latter, the model is modified to include both these factors in an Arrhenius-type recovery equation.

Some unsolved problems are also discussed. In particular, the dependence of the recovery process on the duration of excitation is not quantitatively described yet; the relevant experiments are being carried out. Another interesting problem is the relation between the slow material response to longitudinal and shear (torsion) excitation which have also been experimentally observed (Fig. 1).

The work is in progress.

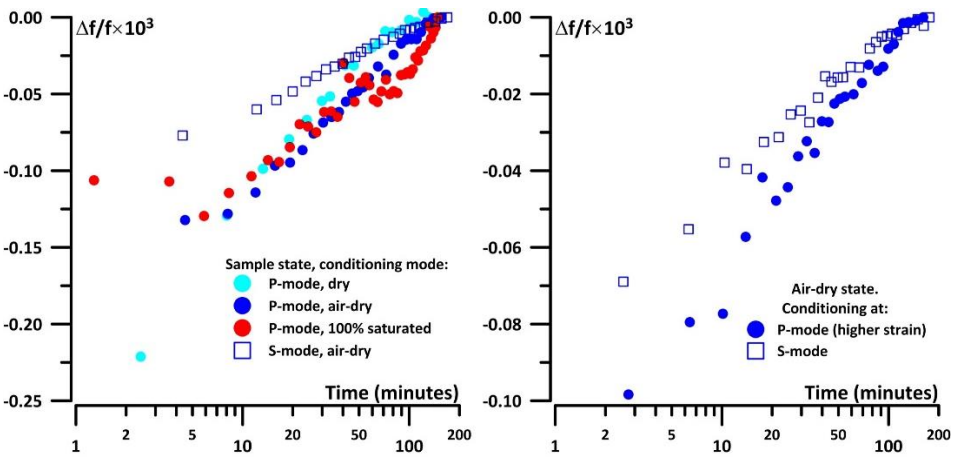

Fig. 1. Slow dynamics in a sample of carbonate excited by the P- mode (left) and the S-mode (right). Excitation strain amplitude was up to10^{-5}, with a duration of about 30 min. Both the P-mode and S-mode responses were measured for water-saturated and dry samples (see insets).

D3S3-1

Shear shock wave generation and focusing in the human head

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Joint Department of Biomedical Engineering, University of North Carolina at Chapel Hill and North Carolina State University

Background and objective: Soft solids, such as the brain or gelatin, have a shear wave speed that is smaller than the compressional wave speed. This allows the use of ultrasound to observe shear wave dynamics. Using high frame-rate ultrasound imaging (up to 12,000 images/second) in conjunction with high sensitivity motion tracking (<1 micron), we have recently shown that planar shear waves can develop into destructive shock waves in the brain. Due to the large Mach numbers in the brain, these shock waves were observed to readily occur at what would be considered low-grade impacts for traumatic brain injury. Since this physical phenomenon was only recently discovered there are no 2D simulation tools and no observations of shear shock wave formation arising from complex geometries such as the human skull. Here we present a high-order finite volume method that can simulate shear shock waves in a relaxing 2D medium. Experimentally, we show that shear shock waves can be focused due to the spherical human skull morphology. Finally, we show that shear shock wave focusing can be generated *in situ* in fresh porcine brain.

Contribution and methods: A skull was 3D printed based on a CT-scan of human skull. It was subsequently filled with a gelatin-graphite phantom that was calibrated to have the same elastic and acoustic properties as brain tissue. The phantom was attached to a shaker and vibrated using a Gaussian-enveloped 10 cycle pulse within a frequency range of 30 to 150 Hz, consistent with the range observed in traumatic brain injury impacts. The resulting shear wave was imaged volumetrically with a mechanically translatable 5.2 MHz ultrasound array using our custom ultrasound imaging sequences at 6200 images/second. The beamformed images were processed with adaptive motion estimation algorithms that we designed for shear shock wave tracking. An excellent match with custom piecewise parabolic finite volume simulations is demonstrated. In the second series of experiments a craniectomy was performed on porcine heads and a plate was attached to the brain which was vibrated between 30 to 150 Hz. It is shown that focused shear shock waves were also generated in fresh brain.

Results and discussion: Shear shock wave focusing was observed at the geometrical focus of the skull, amplifying the surface accelerations by factors between 10-20. For example, for a 20 G input at the brain surface, shear shock wave focusing was observed within the quasi-elliptical skull boundary with a highly destructive peak acceleration of 400 G occurring at the natural geometric focus of the skull. The experimental and numerical waveforms closely match, e.g. the RMS amplitude error is between 12.05% and 12.27%. These results demonstrate the importance of including shear shock wave physics which is absent from current models of traumatic brain injury.

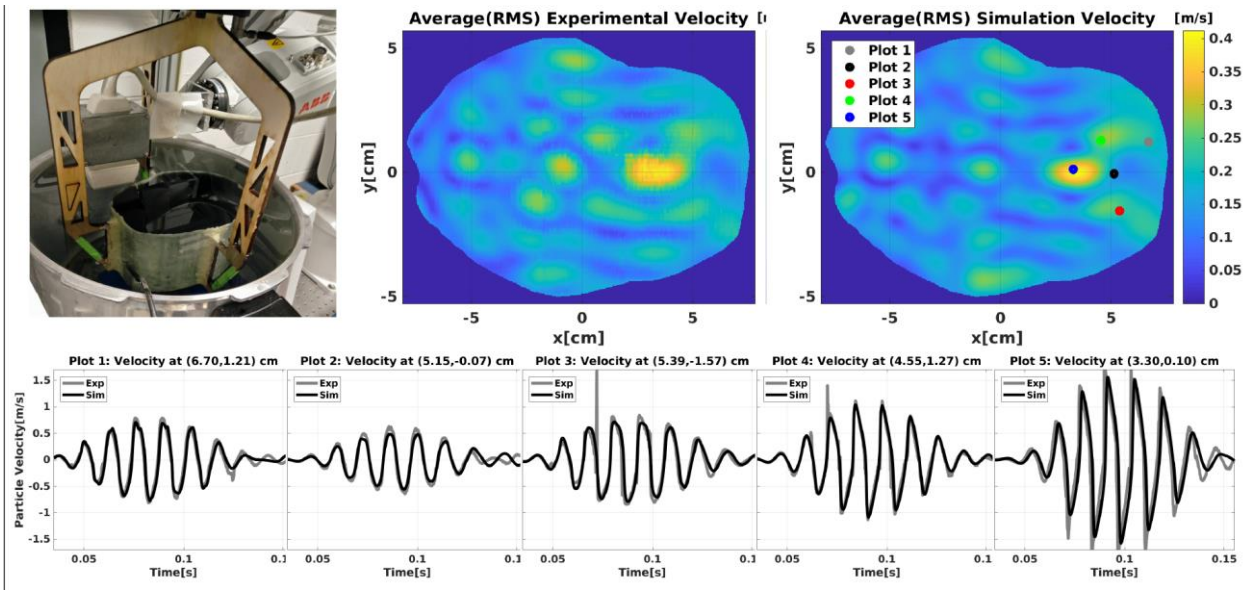

Figure: High frame-rate ultrasound experiments and piecewise parabolic simulations of shear waves in a human skull phantom demonstrating shock wave generation and focusing.

D3S3-2

Anisotropic muscle shear moduli measured by the Doppler method

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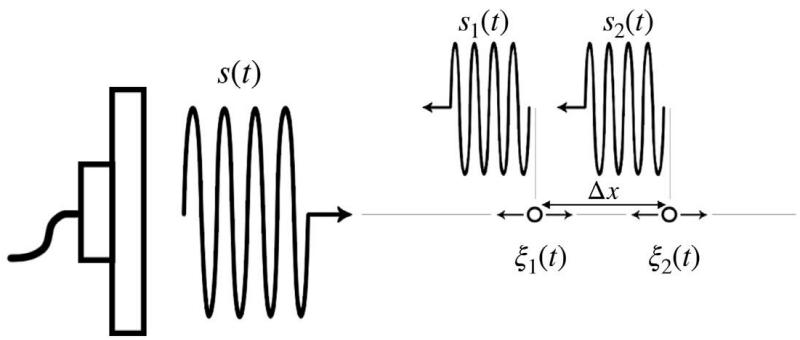
Our work deals with the modeling and processing of signals by the method of transient elastography [1] applied to muscles. Elastic shear moduli in the muscle can vary several times depending on the direction of shear wave propagation. Such a specific structure of muscles requires a preliminary check on model signals. The method has already been used to measure the elastic properties of tissues [2]. Our approach aims to measure the anisotropic properties of muscles. Shear displacements of the certain scattering particle in muscle $\xi(t) = \xi_0 \sin(\omega_b t + \varphi_b)$ are created with a shaker. An ultrasonic piezoelectric transducer mounted on the moving part of the shaker is the emitter and the receiver of ultrasonic pulses which creates the probe pulses $s(t) = s_0 \sin \omega_0 t$ with high-frequency filling. The reflected pulse has the frequency shifted according to the Doppler effect



$s_r(t) = s_{0r} \sin\left(\omega_0 t + m_j \sin(\omega_b t + \varphi_b) + \varphi\right)$, where m_j is the Doppler modulation index [2], *r* is the number of the scattering particle. The received signal passes quadrature processing, which is described in detail in [2]. With this processing, we get the time dependence of the speed of oscillations $\frac{\partial \xi(t)}{\partial t}$. Restoring the speeds of two closely lying scattering particles and determining the phase difference between the oscillations of these two particles we determined the speed of the shear wave c_t. The shear modulus is determined as $\mu = \rho c_t^2$. In the experiment we created the pulses with sinusoidal filling at a frequency of 2.5 MHz and a period of 8 periods with a repetition frequency of 10 kHz. At this frequency, the maximum depth of penetration for ultrasound is 7.5 cm, which was determined by the time of arrival of the reflected pulse. The pulses reflected from the scattering particles located in a medium with a shear modulus of 2.5 kPa and a density of 1.1 g/cm³. The velocities of longitudinal ultrasonic and shear waves were 1550 m/s and 1.5 m/s respectively. The received signal is a sequence of reflected pulses, which forms a one-dimensional A-scan. The time delay of the reflected pulse is determined by the distance from the emitter to the inhomogeneity of the medium. The received signal is divided into segments according to the duration of the probe pulse. For a probe pulse duration of 3.2 μs, the minimal distance between the scattering particles that can be resolved is 2.4 mm. The maximum distance between the scattering particles is determined by the shear wavelength of 15 mm. This work is supported by RSCF, project No. 19-72-00086.

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D3S3-3

Evaluation of soft layered materials using air-coupled acoustic radiation force excitation of guided wave and spatial multiple signal classification

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Abstract (Arial, 10pt): Precise knowledge of material elastic properties is important in various fields reaching from geophysics through engineering to medicine. Elastic waves are commonly used for estimation of these parameters. Shear waves elastography (SWE) has been developed as a tool permitting imaging of lesions stiffer than surrounding tissues. More recently adaptation of this technique for evaluation of eye cornea elasticity was proposed. The method, called acoustic micro tapping (AµT), uses a focused air-coupled transducer that creates acoustic-radiation force resulting from reflection of the ultrasonic beam. Because the thickness of eye cornea is much smaller than the wavelength of excited shear waves, boundary conditions at the tissue interfaces have to be considered.

In this paper we present experimental evaluation of guided waves propagation in thin soft materials mimicking soft-tissue. Two scenarios were considered: symmetric air-tissue-air and non-symmetric air-tissue-water interfaces. From experimental data obtained using AµT source and laser Doppler vibrometer as a detector appeared that high attenuation limits wave propagation distance and thus reduces wavenumber resolution obtained from 2D Fourier transform. To solve this problem, we use super-resolution multiple signals classification (MUSIC) to process data in spatial domain. Resulting dispersion curves from both boundary conditions will be compared to suitable analytical models.

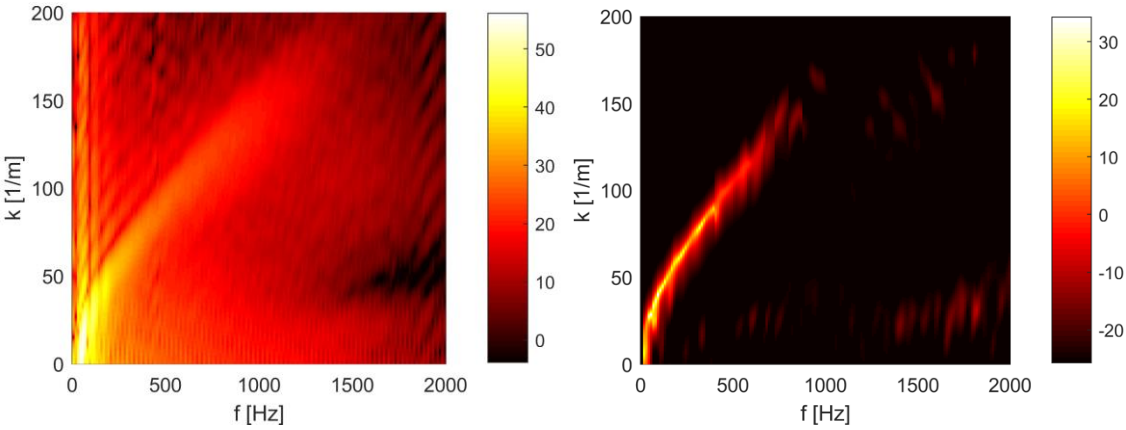

Fig. 1. Frequency-wavenumber spectrum obtained using 2D Fourier transform (a) and Multiple Signal Classification (b). Note the same dB scale for both images and super-resolution capability of the latter image.

D4S1-1

Enhancement of nonlinear response via mode match of local defect resonance

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Activation of mechanical resonance in localized inclusions and defects (LDR) enables to route the input acoustic energy directly to the defect that dramatically increases its vibration amplitude and shifts it into nonlinear regime. In planar defects, like delaminations, the LDR is an outcome of a standing wave formation due to constructive interference of flexural waves in a plate structure. Like in any distributed resonant system, the interference maxima occur at a set of particular frequencies that activate the fundamental and higher-order LDR modes. Due to plate wave dispersion, the various order LDR frequencies are usually not multiples of the fundamental LDR frequency. The higher harmonics generated in such a nonlinear resonator excited at a fundamental mode are, therefore, not matched to the higher-order resonances that prevents full development of the maximal higher harmonic response of the resonator (Fig. 1). In the experiments to be presented, the nonlinear LDR response is first studied for a simulated defect of a circular flat-bottomed hole (FBH) in PMMA. Conventional second and third higher harmonic responses for excitation at the fundamental LDR frequency are measured and used to evaluate background nonlinearity parameters of the resonator. An increase by orders of magnitude in these parameters is then obtained as the excitation frequencies are changed in the vicinity of the fundamental LDR in order the second and third harmonics match the higher-order FBH resonances. A similar result is also obtained for a subharmonic excitation: the second harmonic in this case always matches the fundamental LDR and manifests the maximum efficiency. The mode match approach is then applied to enhance resonant nonlinearity of realistic defects and used for efficient nonlinear imaging of impact damage in composites.

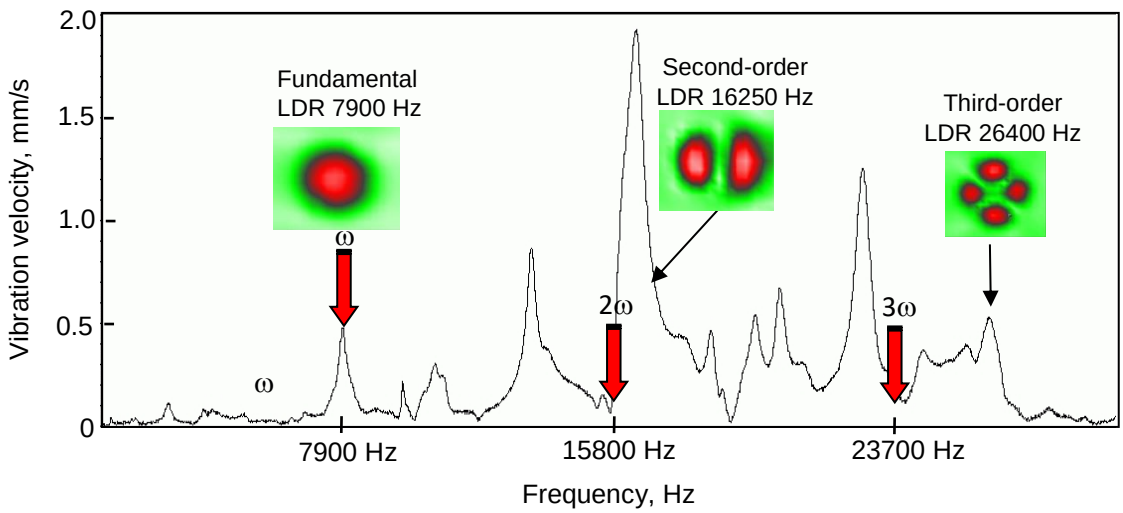

Fig. 1. Vibration spectrum and vibration fields of the fundamental and the higher-order LDR in FBH. Arrows indicate the higher harmonic positions for excitation at the fundamental LDR 7900 Hz.

D4S1-2

Fixed-voltage fundamental wave difference (FAD) for high-selectivity imaging of closed cracks

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Although ultrasonic testing (UT) has the highest sensitivity to fatigue cracks, on-site inspection of using UT has often encountered the problem of low signal-to-noise ratio (SNR) due to other linear scatterers (coarse grains, welds, geometric change, etc.). Furthermore, the crack closure due to compressive residuals stress or by oxide film generation between crack faces weakens crack response. To realize a high-selectivity imaging of fatigue cracks, various types of nonlinear ultrasonic phased array (PA) [1-4] of combining nonlinear ultrasonics with PA has been studied. Among them, a fixed-voltage fundamental wave amplitude difference (FAD) is a promising approach in terms of a high sensitivity and easy implementability. Fixed-voltage FAD is based on the measurement of the incident-wave-amplitude dependence of fundamental wave[5,6], because the energy of the nonlinear components generated at cracks is supplied from fundamental components. This enables us to measure all nonlinear components generated at closed cracks without directly measuring specific nonlinear components. Note that fixed-voltage FAD changes incident wave amplitude at a fixed excitation voltage by employing e.g. all-, odd-, and even-elements for transmission. Here, we investigated the maximum-incident-wave-amplitude dependence of fixed-voltage FAD in fatigue-crack specimens by varying the transmission aperture (32 to 128 elements). Consequently, high-selectivity imaging of a fatigue crack was achieved by increasing the maximum incident wave amplitude (Fig. 1). Moreover, we quantitatively examined the incident-wave-amplitude dependence of the closed crack responses in detail. It was found that different parts within a single fatigue crack showed different nonlinear behaviors.

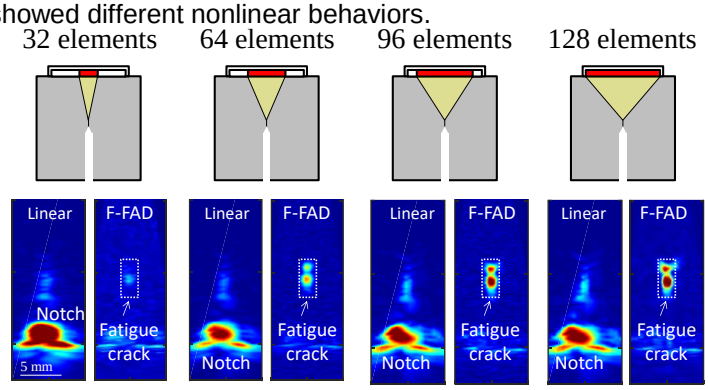

Figure 1: Imaging results of a fatigue crack (A7075) by linear PA and fixed-voltage FAD.

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D4S1-3

Nonlinear Elasticity of 3D Printed Ti6Al4V with Porosity

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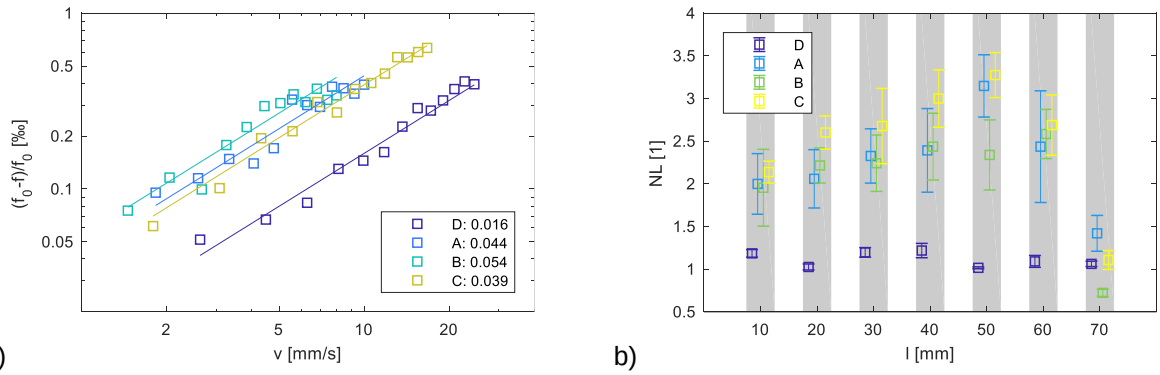
Additive manufacturing (AM) of metallic parts is a technology which needs to assure the highest output quality. There is a demand for methods that would monitor the manufacturing process and that would evaluate the quality of finished products. The aim of the study is to investigate whether nonlinear elasticity would be a useful indicator of damage in 3D printed material.

A common defect of metals prepared by AM is porosity. It can be caused by a wrong setup of manufacturing process when the powder bed is not thoroughly melted by the beam. In order to determine the effect of porosity, a set of prismatic samples was prepared by Electron Beam Melting from Ti6Al4V powder. One sample was manufactured with optimal parameters (D), while others included an internal volume with increasing levels of porosity (A, B, C).

Each sample was tested by Impact Modulation Spectroscopy method with setup similar to Dynamic Acousto-Elastic Testing. A highly repeatable 0.2J impact was exerted in the longitudinal axis of the sample. The impact response was measured by laser vibrometer on the opposite end. The impact excited predominantly longitudinal resonance modes starting at 25 kHz. Simultaneously a continuous ultrasonic excitation in transverse direction was performed at 4 MHz. Ultrasonic transducers were coupled with silicon grease and reattached for each impact test. Also their location was moved to perform a linear scan of the porous region.

The experiment produced two sets of data: vibrometric and ultrasonic. Each set was analyzed by linear and nonlinear methods. The vibrometric data were subjected to RUS and NRUS. The RUS showed decreasing resonance frequencies with increasing porosity, while their amplitudes were not indicative. The NRUS analysis of impact ringdowns demonstrated increased nonlinearity of porous samples (Fig. 1a). Ultrasonic data were used to analyze attenuation and nonlinear modulation. Using a measure of attenuation (pre-impact transmitted signal energy) is enough to determine the porous region of a sample. Evaluated nonlinear modulation (which was compensated with respect to changes of material attenuation) was also indicative of material porosity (Fig.1b).

The results show that both linear and nonlinear indicators were able to assess and localize porosity of 3D printed material.



a) b)

Fig. 1: a) Results of NRUS at first longitudinal mode show increased elastic nonlinearity of porous samples. b) Dependence of normalized sideband integral on location. The results reliably localize porous sections of samples which span from 8 – 67 mm. The overall nonlinear response is proportional to the level of material porosity.

D4S2

High-resolution mechanical spectroscopy, HRMS: Status and Perspectives

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The concept of anelasticity was defined by Clarence M. Zener in his classic book 'Elasticity and Anelasticity of Metals' published in 1948. Dissipation of mechanical energy in solids due to anelastic phenomena yields numerous relaxation effects induced by dislocations, point defects, phase transitions, etc. The field related to anelasticity evolved from internal friction and ultrasonic attenuation in solids to mechanical spectroscopy (1991). The high-resolution mechanical spectroscopy, HRMS, was developed for the resonant and subresonant mode in 2014. The multi-scale high-resolution characterization of dissipation of mechanical energy in solids for low-frequency mechanical spectroscopy is presented in this lecture.

It is demonstrated that devised interpolated discrete Fourier transform (IpDFT) methods provide precise characterization of exponentially damped sinusoidal signals embedded in additive white Gaussian noise and corrupted by time-dependent zero-point drift (ZPD). It is important to emphasize that, from the same input data, classical methods for determining the logarithmic decrement, δ , give incorrect results, and these inaccuracies are quantitatively assessed. The performance of novel interpolated DFT methods is also discussed, with emphasis on the reference-resolution (RR) and high-resolution (HR) methods. Hitherto unattainably high-resolution estimations of the logarithmic decrement and resonant frequency are successfully obtained. These are: (1) ZPD-free exponentially damped sinusoidal signals embedded in additive noise using the RR method and (2) exponentially damped sinusoidal signals embedded in additive noise and corrupted by ZPD using the HR method. The proposed methods can be successfully used in a wide range of damping conditions (δ from 1×10^{-9} to 0.5) and for frequencies from 10^{-3} Hz to kHz.

Measurement of the phase lag between the leading stress and lagging behind strain was a challenging task for decades; this experimental technique was considered to be one of the most difficult. Usually, the background level is high (e.g. $\tan\varphi = 5 \times 10^{-3}$ in DMA analyzers), which adversely affects resolution and practical applications to study different materials. Recent advances in measurements of mechanical loss tangent, tg φ, and shear modulus in low-frequency mechanical spectroscopy pave the way to measure very small mechanical losses with the same background level (or lower) as in free decaying oscillations. The high-resolution estimation of the loss tangent and modulus is obtained from Hilbert transform. It is emphasized that high-quality stress and strain signals must be carefully acquired from the high-resolution mechanical spectrometer, and the frequency of both signals must be strictly controlled. This approach includes the so-called Signal Quality Test, which involves complementary and supplementary analysis of stress and strain signals using IpDFT, Hilbert transform, and the 'true envelope' of signals. In addition, the stress and strain signals are controlled at each step of the experimental procedure: (1) simulations, (2) generation of the reference harmonic signal, (2) bipolar amplifier, (3) laser triangulation system used to detect strain, (4) noise, (5) ZPD, (6) signal analysis, and (7) computing methods and algorithms. Digitalized stress and strain signals are obtained using simultaneous and coherent sampling (20-bit DAC and 24-bit ADC). Recent experimental results indicate that the mean background level in the high-resolution mechanical spectrometer ranges from 1 to 2×10^{-5} in the frequency range from 10^{-3} to 5 Hz. Moreover, the dispersion of experimental points is extremely low, $\pm1\text{x}10^{-5}$.

The progress in development of high-resolution mechanical spectroscopy, HRMS, is reviewed and novel applications in materials science are advocated.

D4S3-1

How is slip nucleated at a frictional interface?

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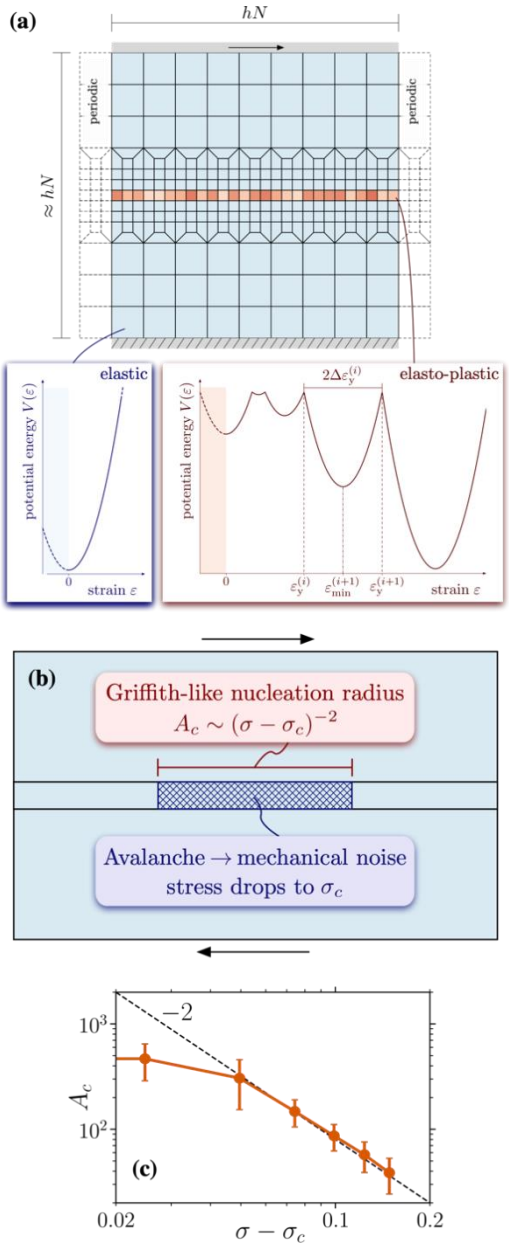
Quasi-statically sliding a solid block over a nominally flat surface proceeds by stick-slip: macroscopic slip events are punctuated by periods of loading. We identify how macroscopic slip is nucleated by collective asperity detachments. This insight allows us to make a prediction for the force at which macroscopic slip is nucleated [1].

We propose a model that includes asperity-level disorder, elastic interaction between local slip events, and inertia. Thereto we model the frictional interface as a continuum in which the asperity contacts are modelled using 'blocks' that represent one or several asperity contacts, see Fig. 1(a). Each block thereby responds elastically up to a yield stress, upon which it releases part of its built-up elastic energy. The disorder comes from randomly drawing the yield stresses from some distribution.

We argue that avalanches of local slips occur during the entire loading phase of the stick-slip cycle. We quantify the number of avalanches as a function of stress increase through the density of asperities at a local distance x to yielding. This distribution displays a pseudo-gap $P(x) \sim x^{\theta}$ with a non-trivial exponent: an intriguing observation that could be tested experimentally, for example using acoustic emission.

The avalanches themselves are power law distributed both in terms of size and radius: each avalanche can reach any radius with a certain probability. We, furthermore, find that avalanches are compact: asperities yield many times within an avalanche, causing the stress drop to a value σ_c (while outside the avalanche it remains $\sigma \geq \sigma_c$). We argue that through this mechanism, an avalanche nucleates fracture when it reaches a critical radius, governed by a Griffith criterion, see Fig. 1(b,c).

In our idealized setting (with disorder on short length-scales, but still being a perfectly flat interface at long length-scales), these properties allow us to predict that the stress at which avalanches typically nucleate fracture decreases with increasing system size such that stick-slip disappears in an infinitely large system.



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How collective asperity detachments nucleate slip at frictional interfaces. arXiv: 1904.07635.

Figure 1. (a) Novel model of solid-solid friction. (b) Sketch of nucleation of fracture-like macroscopic slip by an avalanche. (c) Scaling of A_c as predicted by the Griffith-like criterion for nucleation of macroscopic slip.

D4S3-2

Dynamic elastic-plastic contact model of rough surfaces in the presence of adhesion

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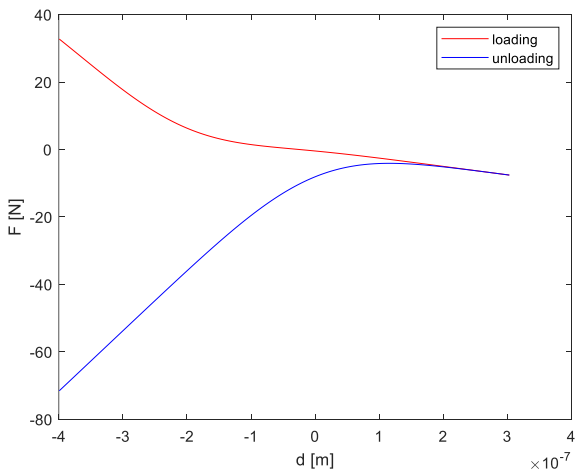
Interest in the study of adhesion between solids arises due to its significant influence on friction and wear of contacting surfaces. An important conclusion from the great many studies on adhesion and deformation is that the adhesion of clean surfaces could be greatly diminished due to surface roughness. The physical based model that we propose here is based on the model developed by Mukherjee and coworkers [1], which describes the adhesion at the contact of rough surfaces, revisioning the RG adhesion model [2]. In particular, the adhesion is considered at the contact between rough surfaces with small-scale surface asperities, using an elastic–plastic model of contact deformation that is based on accurate finite element analysis of an elastic–plastic single asperity contact. The model considers from fully elastic through elastic–plastic to fully plastic regimes of contacting asperities, in the presence of adhesional surface forces. The goal of our work is to simulate a dynamic experiment in which the behaviour of a crack is monitored in time, when it is perturbed by an applied external force (e.g. sinusoidal), starting from the knowledge of the force necessary to be applied at the equilibrium. The model is able to evaluate the displacement of the investigated crack (and probably of an elastic solid sample with microcracks, e.g. concrete, mortar) through the deformation of the internal asperities, whose heights are supposed to follow a normal distribution, monitoring the applied force both during the loading and the unloading. The difference in loading and unloading curves is a crucial point: the shape of the unloading curves strongly depends on the maximum force that we have applied during the loading, thus memory and hysteresis are intrinsic features of the model (as depicted in the below panel). Therefore, it is expected that dynamic solutions of the problem may be a good solution for the case of nonlinear mesoscopic elastic materials, and an equivalent Preisach-Mayergoytz (PM) space description of the interaction forces [3] (with physical based PM parameters) could be proposed. Physical parameters in numerical simulations are selected in order to avoid that asperities may undergo very large deformations, that may violate the basic assumption of no interaction between them.



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D4S3-3

Rayleigh wave harmonic generation in materials with depth-dependent non-linear properties: theoretical results

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This study is motivated by the perspective of characterizing gradients of non-linear mechanical properties caused by surface treatments involving the plastic deformation of the surface, such as shot-peening, and make a step further toward their non destructive evaluation. Such treatments are used to introduce compressive residual stresses near the surface to increase the lifetime of components. As a byproduct micro-cracks are also generated, affecting the sound velocities by some tens of percents and the non-linear properties up to hundred times higher. Characterizing the mechanical state of a treated sample non destructively – and especially its stress state – remains an open problem. Linear and nonlinear Rayleigh waves were shown in the past to be sensitive to the treatment. Because gradients are involved, all quantities are frequency-dependent. Studies first mainly focused on the anomalous dispersion, however the sources affecting the velocity are multiple and isolating the contribution of the acoustoelastic effect failed so far. More recently, the focus came onto nonlinear quantities. Up to now, the frequency dependence of the harmonic generation ratio remains little explored, but one study gave milestones [1]. This work aims at giving a theoretical background to quantitatively interpret this frequency dependence.

In this work [2], we theoretically study the nonlinear behavior of Rayleigh waves in materials having inhomogeneous third order and homogeneous second order properties. Compared to the complete homogeneous case, the constants coupling the harmonics turn out to depend on frequency. The sensitivity and selectivity to l, m, n – the three Murnaghan's constants – is discussed. Numerical examples are given for depth profiles characteristic of dislocation densities in shot-peened metals (see Figure). The predicted low-frequency scales are consistent with observations recently reported [1].

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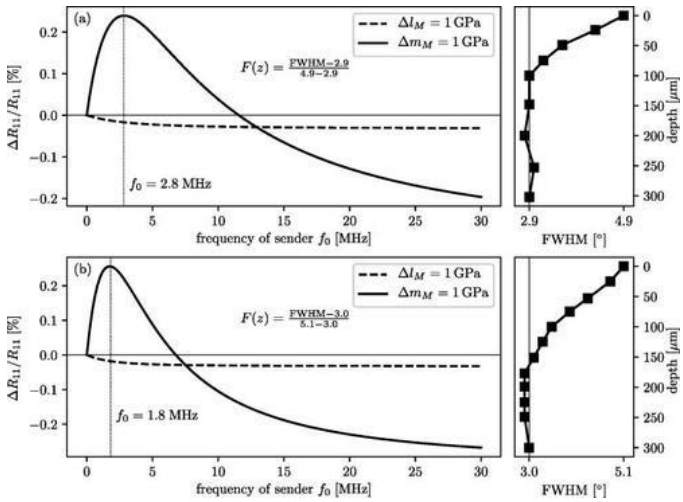

Predicted change on the nonlinear Rayleigh wave coefficient of a virtual mild steel sample for a profile proportional to the FWHM (dislocation density) measured in DA718 samples shot-peened at intensities: (a) 0.1 mmA and (b) 0.2 mmA.

D5S1-1

Low cost integrity inspection in wellbores: challenges in nonlinear measurements using time reversal

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Carbon dioxide sequestration in wellbores could benefit from a low cost method to inspect the wellbores for damage over many decades. Using time reversals methods to focus acoustic energy to points within the wellbore could allow us to measure nonlinearity at those specific points, and to detect changes in nonlinear parameters which may be correlated with damage.

Using time reversal methods in a low cost way in a wellbore presents certain challenges that are different from the application of time reversal methods for focusing on smaller systems. A borehole system is large, and connected to the earth, so a wave from an acoustic source may not encounter nearby scatters in all directions. Thus, some portion of the wave energy be lost to the system and will not help with focusing. Additionally, for a low cost system, it may not be possible to have an extensive distributed set of acoustic sources. Using a single large acoustic source, or a sparse system of acoustic sources makes it more challenging to excite high enough strains at the focus point to measure nonlinear parameters, without also exciting higher strains on the path between the acoustic sources and the focus point. A high strain on the acoustic path at locations other than the focus point will make it harder to confirm the location of changes in nonlinear behavior.

To examine the limitations and practical considerations of using time reversal to focus acoustic energy over the longer distances involved in a wellbore this project uses time reversal to focus acoustic energy in a large sample (~8000lbs) of Berea sandstone with a quarter sized borehole drilled into it. It is possible to use time reversal methods to focus acoustic energy in time both on the outer surface of the sample, and inside the borehole.

This work is in progress, and this presentation will discuss the ongoing challenges with applying time reversal in wellbore damage detection applications.

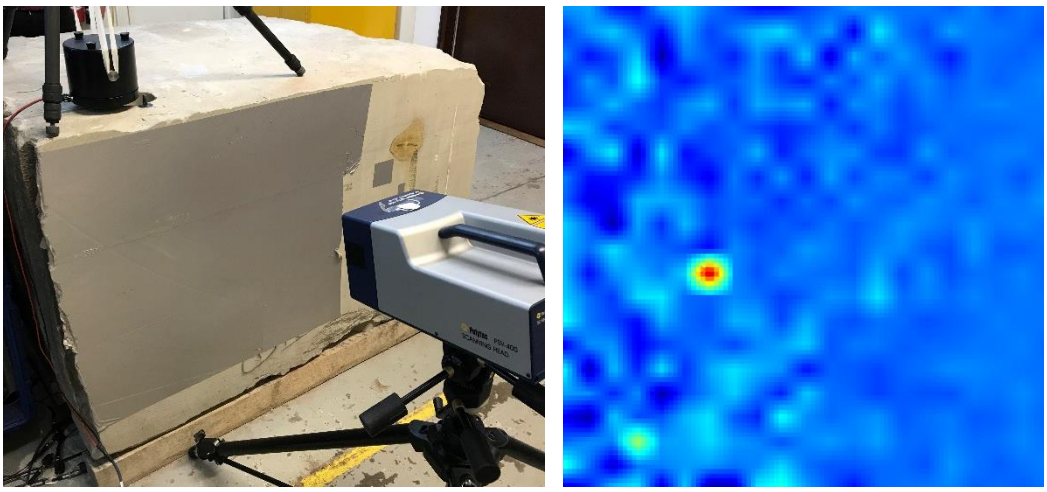

Figure 2: (left) Berea sandstone sample containing a quarter sized borehole. (right) Acoustic focus using time reversal with deconvolution at time of focus on the surface of the sample. This focus was creates using 8 acoustic sources of various excitation amplitude and frequency response and an input chirp with a frequency range of 1kHz to 50kHz.

D5S1-2

The influence of plate thickness on guided waves self-focusing through the time-reversal process

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Time reversal (TR) principle has been used in the numerous NDT applications to visualize defects of both linear and nonlinear character. One of the more interesting uses of TR is the ultrasonic wave focusing using multiple wave sources, which enables high local amplitudes to perturb the defect and make its response more detectable. However, similar effect can be achieved by processing diffuse wave field through an approach known as coda wave interferometry, without the direct TR data acquisition and backpropagation. Calculating the simple cross correlation function between the time histories of an arbitrary virtual source and the other remaining measurement points yields a high-amplitude focal spot at the chosen point. This operation follows law of diffraction limited focus and thus the average wavelength of the wavefield constitutes the size of the TR focal spot. Based on this property we present the application of the artificial guided wave focusing for defect imaging in the plate-like structures. The dispersive nature of the guided waves results in the dependence between the wavelength and the plate thickness. The analysis based on the width of the focal spot can be therefore used as an effective estimator for different types of plate defects. The potential of this method is evaluated based on the wavefield acquired from the surface of the CFRP plate using Scanning Laser Doppler Vibrometer (SLDV). The scanned field was saturated with broadband white noise signals using six piezoelectric transducer attached to the plate. Before performing the measurement the plate was damaged by impact, which resulted in the internal delamination that is invisible to the naked eye. As predicted, the synthetic focusing based on the acquired wavefield results in different focal spot sizes in damaged and undamaged areas.

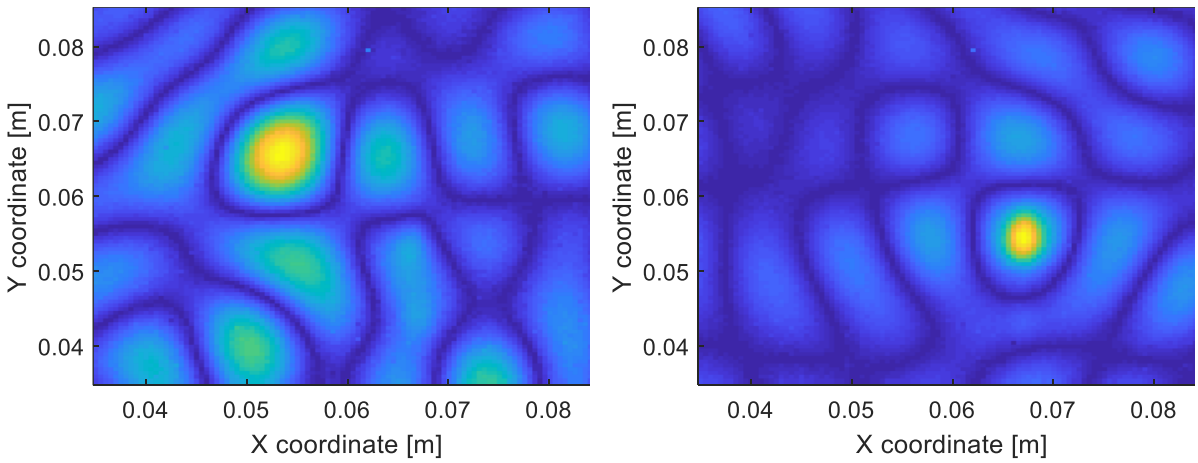

Fig. 1. Results of the synthetic focusing on the undamaged (left image) and the damaged (right) spot of the CFRP plate. The clear difference in focal spot thickness can be ascribed to local plate delamination which results in altered dispersion property and local change in wavelength.

D5S1-3

Probing defects at different depths using time-reversal acoustics

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It has been shown experimentally that it is feasible to use time-reversal elastic nonlinearity diagnostics (TREND) to estimate the penetration depth of cracks in steel samples. TREND is a method to focus elastic waves energy to a point in space in order to probe that point for damage. High frequencies are used to probe near the surface, while low frequencies are used to probe deeper into the material. Depth estimation of a material discontinuity is important to determine when a critical size of defect is reached. This paper aims at the analysis of the time reversal focusing process by means of numerical simulations. The influence of excitation frequency and waveform on the focal spot size and penetration depth are analyzed. An in-house simulation framework based on a commercial Finite Element (FE) solver is used to perform a series of numerical simulations of time-reversal focusing in a representative material volume with a curved surface-penetrating discontinuity.

The research was financed within the scope of the project no. SONATA 2015/19/D/ST8/01905 financed by the National Science Center of Poland.

D5S2-1

Investigation of modulation transfer effect for elastic waves.

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The paper presents investigation of modulation transfer effect. This effect - originally observed in the early nineteen thirties for radio waves propagation in ionosphere - was manifested by modulation transfer of a weaker wave in presence of a strong amplitude-modulated wave. The research are focused for both, application to damage detection and analysis of possible sources of modulation transfer.
The different nonlinear model are analyzed to find the potential source of non-linearities responsible for sidebands transfer form low to high frequency. The models include quadratic damping and hysteresis.
Two experiments were conducted. In both surface bonded piezoceramic transducer and electromagnetic shaker were used to excite structures. Laser vibrometry was used to acquire the response of the structure.
The first experimental subject was cracked beam. The structure was excited by modulated low-frequency signal and high frequency acoustic wave. This combination of excitations induced a modulation transfer from low-frequency to high-frequency wave in presence of structural damage. The experimental analysis of results was focusing on the damage-related nonlinearities.
In the second experiment presented method was tested on real-life structure. The cracked and uncracked rim were used as subject. As previously structures was excited by two sources of vibration. The experimental results confirmed operation of the method.

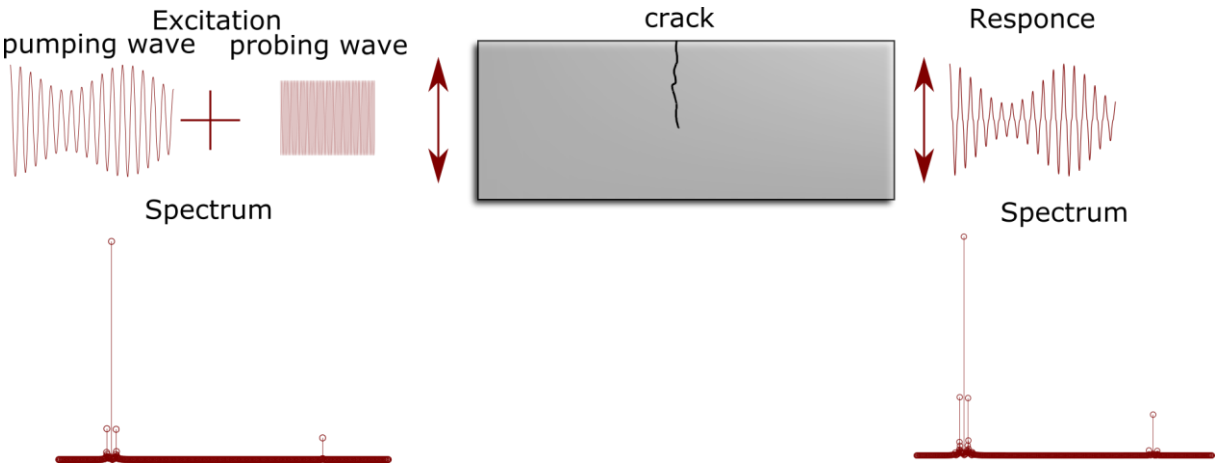

Fig. 1 Modulation transfer in presence of crack - illustration

D5S2-2

Acousto-optical studies of acoustical activity in lanthanum hallosilicate crystals

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Acoustic activity is manifested in the form of pure rotation of the plane of polarization of a transverse acoustic wave, when this wave propagates along a third or higher order symmetry axis. This is true for non-centrosymmetric crystals in which there are no mirror symmetry planes or inversion axes. Characteristic features of this phenomenon, were observed for the first time for quartz crystals by the method of inelastic neutron scattering. In the present work, the method of Bragg diffraction of light was used to observe the rotation of the polarization plane in lanthanum hallosilicate crystals. In such experiments, the intensity of the diffracted light, measured at different points in the sample, along the propagation of an acoustic wave, oscillates with a period that is determined by the specific rotational ability of the crystal.

Samples for research have been prepared from optically pure single crystals oriented with particular accuracy (about 10') along the [001] acoustic axis. For the excitation of plane-polarized transverse acoustic waves, in the frequency range 0.4–1.8 GHz, piezoelectric transducers of X-cut lithium niobate with an aperture of 3 × 4 mm were used. The linearly polarized light with a wavelength of 632.8 nm fell and diffracted in the ZX plane under angles that did not exceed ~ 5^0. Such diffraction and polarization geometry of the experiment ensured the minimal influence of the diffraction divergence of the acoustic wave.

The specific rotation of the plane of polarization of transverse acoustic wave propagating along the [001] axis was determined from the dependence of the intensity of diffracted light I_{comp} on the distance from the piezoelectric transducer z along the direction of propagation of the wave:

$$I_{comp} \sim p^2_{eff} \exp(-\alpha z)\cos^2(\beta z + \varphi). \quad (1)$$

Here p_{eff} is the effective photoelastic constant φ is the initial phase of the acoustic wave, determined by the orientation of the piezoelectric transducer relative to the axis [100] and α is the attenuation coefficient of the acoustic wave. On the basis of the experiments the specific rotation of the plane of polarization of transverse acoustic waves in lanthanum hallosilicate crystals has been determined at various wavelengths (Fig.1).

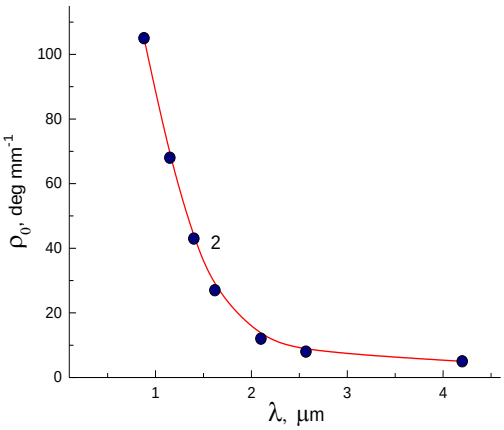

Fig. 1. Dispersion of the specific rotation of the polarization plane of transverse waves in lanthanum hallosilicate crystals