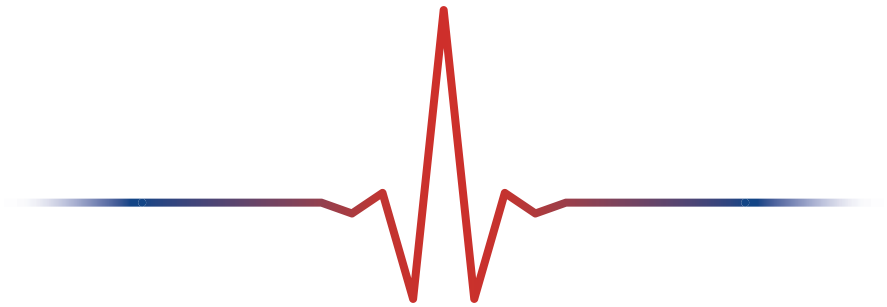
International Symposium on Intrinsic Localized Modes: 30th Anniversary of Discovery



January 25-27, 2018
Kyoto Prefectural General Social Welfare Hall, Kyoto, Japan

Organized by

Albert J. Sievers, Cornell University, USA
Masayuki Sato, Kanazawa University, Japan

Supported by

Toyota Physical and Chemical Research Institute
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Book of Abstracts

International Symposium on Intrinsic Localized Modes: 30th Anniversary of Discovery

January 25-27, 2018

Kyoto Prefectural General Social Welfare Hall

Kyoto, JAPAN

Scope

The international symposium on intrinsic localized modes: 30th anniversary of discovery commemorates the 30th anniversary of the first paper on intrinsic localized mode (ILM) by Prof. A.J. Sievers and Prof. S. Takeno. In this symposium, various studies on theoretical and experimental problems on ILMs/discrete breathers (DBs) are presented. The organizing committee is excited with the opportunity to discuss recent progress of ILM in different fields such as physics, mathematics, mechanical engineering, electrical engineering and material science and engineering in Kyoto, in which Prof. Takeno worked for a long time. The organizing committee welcomes the participation of various researchers not only on ILM but also on various field of nonlinear dynamics at the symposium.

Organizing Committee

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Venue

Kyoto Prefectural General Social Welfare Hall

South of Horikawa-Marutamachi, Kamikyo-ku, Kyoto 602-8143 JAPAN

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Session Schedule

2018.1.25 (Thu.)

9:00-9:10 Opening

9:10-10:10 **The Legacy of Discrete Breathers**
Sergej Flach (Institute for Basic Science, Korea)

10:10-10:20 Short Break

10:20-11:00 **Localized excitations in 2d lattices and transport of charged particles**
Alexander Chetverikov (Saratov State University, Russia)

11:00-11:40 **Discrete breathers in arrays of magnetic dots**
Yaroslav Zolotaryuk (Bogolyubov Institute for Theoretical Physics, Ukraine)

11:40-12:20 **Phase Dynamics of Tunneling Intrinsic Localized Modes in Weakly Coupled Nonlinear Chains**
Yury A Kosevich (Semenov Institute of Chemical Physics, Russia)

12:20-13:50 Lunch break

13:50-14:30 **Delocalized nonlinear vibrational modes: relation to discrete breathers**
Sergey Dmitriev (Institute for Metals Superplasticity Problems of Russian Academy of Sciences, Russia)

14:30-15:10 **Modeling of Discrete Breathers in Crystals from ab initio and in Classical Approach: Pros and Cons**
Ivan Lobzenko (Toyota Technological Institute, Japan)

15:10-15:50 **Surface discrete breathers in Pt3Al**
Elena Korznikova (Institute for Metals Superplasticity Problems of Russian Academy of Sciences, Russia)

15:50-16:10 Coffee Break

16:10-16:50 **Nonlinear atomic vibrations and structural phase transitions in strained carbon chains**
George Chechin (Southern Federal University, Russia)

16:50-17:30 **Nonlinear atomic vibrations in strained graphene monolayer: bushes of nonlinear normal modes**
Denis Ryabov (Southern Federal University, Russia)

17:30-18:10 **Experiments and theory on solitary waves in muscovite mica**
Juan F.R. Archilla (Universidad de Sevilla, Spain)

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9:40-10:20	**Experiments and simulations of stationary and traveling Intrinsic localized modes** Masayuki Sato (Kanazawa University, Japan)
10:20-10:30	Short Break
10:30-11:10	**Time-periodic Driving of Nuclear Reactions by Intrinsic Localized Modes Arising in Hydrogenated Metals** Volodymyr Dubinko (NSC Kharkov Institute of Physics & Technology, Ukraine)
11:10-11:50	**Nonlinear compact periodic solutions in flat band networks** Carlo Danieli (Institute for Basic Science, Korea)
11:50-13:20	Lunch break
13:20-14:00	**Topological Protection of Mechanical Wave Modes in Tunable 1D and 2D Lattices** Jinkyu "JK" Yang (University of Washington, USA)
14:00-14:40	**Nonlinear Wave Propagation in Origami-based Mechanical Metamaterials** Hiromi Yasuda (University of Washington, USA)
14:40-15:20	**Discrete breathers in granular chains** Guillaume James (Université Grenoble Alpes, France)
15:20-15:40	Coffee Break
15:40-16:20	**Energy localization in ring coupled boost converters using passivity based control** Rutvika Manohar (Kyoto University, Japan)
16:20-17:00	**Chameleon's behavior of the discrete nonlinear electrical transmission lattice** Alain Bertrand Togueu Motcheyo (University of Yaoundé 1, Cameroon)
17:00-18:10	**Poster Session**
19:30-21:30	**Banquet**

2018.1.27 (Sat.)

9:00-9:40 **Using Hilbert transform and classical chains to simulate quantum walks**
Daxing Xiong (Fuzhou University, China)

9:40-10:20 **Ergodicity-breaking in Discrete Nonlinear Schrodinger Equation**
Mithun Thudiyangal (Institute for Basic Science, Korea)

10:20-11:00 **Geometric formulation of a class of natural Hamiltonian systems - in search for an extension of Toda's dual transform -**
Shin-itiro Goto (Kyoto University, Japan)

11:00-11:10 **Closing**

13:00-15:30 **Excursion**

Poster Presentation

P1 **Ergodic to Nonergodic Transition in DNLS Lattice**
Yagmur Kati (Institute for Basic Science, Korea)

P2 **Investigation of Spatially Localized Oscillations in the Two-dimensional Hexagonal Lattice of Fermi-Pasta-Ulam beta Type**
Shun Izumi (Osaka University, Japan)

P3 **Lattice spatial modes and switching to ILMs in an electric transmission line**
K. Miyasaka (Kanazawa University, Japan)

P4 **Driving condition for generating train of moving ILMs in one-dimensional FPU chain**
Soichiro Tanaka (Kyoto University, Japan)

P5 **Thermal conduction in symmetric potential lattices**
Kazuyuki Yoshimura (Tottori University, Japan)

P6 **Dynamics of Moving Intrinsic Localized Modes in Pairwise Interaction Symmetric Potential Lattices**
Yusuke Doi (Osaka University, Japan)

P7 **A Numerical Study on Localized Modes in Resonant Circuit Array for Application to Wireless Power Transfer**
Masayuki Kimura (Kyoto University, Japan)

Abstract

The Legacy of Discrete Breathers

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Discrete breathers (DB) and intrinsic localized modes (ILM) are synonymic dynamical states for nonlinear lattice wave equations - periodic in time and localized in space, and widely observed in many applications. I will start to review the main theoretical and experimental results on DB/ILM properties. I will highlight several hard problems – quantization, and impact on (non)equilibrium dynamics – which still await detailed analysis.

I will then discuss the DB/ILM legacy and impact on understanding a number of related phenomena. The Fermi-Pasta-Ulam model, which is the base of the famous FPU paradox, allows for exact qBreather solutions, which are periodic in time and localized in momentum space. Compact DB/ILM solutions exist for classes of lattice equations with global gauge symmetry and additional constraints based on destructive interference, e.g. for flat band lattices which admit compact states even at the linear limit. Such finetuned lattices with all bands flat at the linear limit may also admit exact traveling DB/ILM solutions.

DB/ILM solutions are integrable limit solutions for a class of nonlinear lattice wave equations, where they turn into single site excitations of uncoupled oscillator sets. The corresponding preserved actions lead to a set of observables off the integrable limit. They define equilibrium Poincare manifolds which account for the time an initial wave configuration needs to reach equipartition. The manifolds further account for the statistics of nonergodic fluctuations at equilibrium – a long-sought technique to quantitatively measure the impact of DB/ILM solutions on (non)equilibrium fluctuations by correlating individual microscopic dynamical space-time events with statistical properties of nonergodic fluctuations.

Localized excitations in 2d lattices and transport of charged particles

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Localized long-living nonlinear mobile modes [1-3] excited in a lattice of point particles interacting via potential Morse forces are studied first in a frame of a model with appropriately chosen bonds [4-5]. Numerical simulations on a base of classical motion equations are performed to define configurations of meta-stable modes and their characteristics including in particular excitations being horseshoe like. It is shown that tracks of mobile localized waves may be long enough. Then interaction of two such intrinsic localized waves propagating along different crystallographic axes is considered to investigate behavior of the waves under collisions [6-7]. We observe that both of soliton-like modes destroy as a rule if they do not collide head on. However one of them or even both of them survive at special conditions. Transport of charged particle trapped by the localized wave is studied in a frame of the quantum-classical tight-binding model [8-9]. It is shown that localized intrinsic waves are able to carry a charged particle for a long distance and transport may be controlled due to interaction of the localized modes.

This work was supported by the grant of the Russian Scientific Foundation 16-12-10175 (Chetverikov A.P.).

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Discrete breathers in arrays of magnetic dots

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The dynamics of ferromagnetic arrays of magnetic particles (dots) with the easy-plane anisotropy is investigated. The particles interact with each other via the magnetic dipole interaction and the whole system is governed by the system of Landau–Lifshitz equations. We demonstrate existence of spatially localized and time-periodic solutions known as discrete breathers (or intrinsic localized modes) that have no analogue in the continuum limit and are reminiscent to the discrete breathers in Heisenberg ferromegnets, studied previously [1]. These solutions consist of the core where the magnetization vectors precess around the hard axis and the tails where the magnetization vectors oscillate around the equilibrium position. Existence diagram on the parameter plane “frequnency-discreteness constant” and breather asymptotic properties are discussed as well.

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Phase Dynamics of Tunneling Intrinsic Localized Modes in Weakly Coupled Nonlinear Chains

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We present a brief survey of the phase-coherent dynamics of intrinsic localized modes (discrete breathers) in a system of two weakly coupled nonlinear chains and its comparison with periodic tunneling dynamics of a quantum particle in a double-well potential and with macroscopic quantum tunneling. We consider the dynamics of relative phase of two classical tunneling intrinsic localized modes in weakly coupled nonlinear chains and show that the dynamics of the relative phase in the $\pi/2$ tunneling mode coincides exactly with the experimentally observed dynamics of the relative phase of a quantum particle, periodically tunneling in a double-well potential. The observed coincidence demonstrates the correspondence between the dynamics of classical localized excitations in two weakly coupled nonlinear chains and tunneling dynamics of quantum particles in a double-well potential. The connection of the observed phase dynamics with the uncertainty principle is discussed.

Delocalized nonlinear vibrational modes: relation to discrete breathers

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Delocalized nonlinear vibrational modes in lattices have been analyzed in [1]. Such modes are exact, symmetry dictated solutions to the equations of motion of lattice particles that exist regardless the amplitude of the mode and potentials used to describe the interaction between particles. Recently such modes have been constructed for two-dimensional hexagonal lattice (e.g., graphene has such lattice) [2]. It was shown later that delocalized nonlinear vibrational modes can be used for setting initial conditions to excite discrete breathers in graphene [3] and other crystals. Delocalized nonlinear vibrational modes demonstrate the effect of modulational instability when their amplitude exceeds a threshold value. In some cases, the modulational instability can result in spontaneous energy localization in the form of discrete breathers. These phenomena will be discussed for graphene and other two-dimensional crystal models.

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Modeling of Discrete Breathers in Crystals from *ab initio* and in Classical Approach: Pros and Cons

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Intrinsic localized modes (ILM), which discovery is conventionally associated with the paper by A.J. Sievers and S. Takeno [1], gain a significant attention during last two decades. Despite successful observation of ILMs (also referred to as discrete breathers, or just breathers) in macroscopic and mesoscopic systems, it is still very challenging task to reveal their presence in crystals, where main obstacle is highly delocalized phonon oscillations. That makes computer modeling a main instrument for studying breathers in crystals. There are two main approaches for such modeling: quantum mechanical (so-called *ab initio*) and classical dynamics.

Ab initio modeling allows one to investigate electron shell change induced by discrete breather (see Fig. 1). Nevertheless, quantum mechanical approach is very demanding for computational resources and allows treatment of relatively small systems (first time such approach was used for breathers in graphane [2], studied system consisted of 16 atoms).

Classical molecular dynamics is very powerful tool for treatment relatively big systems of atoms (see Fig. 2) for rather long evolution time, although results depend heavily on the choice of interatomic potential. Such potentials often designed to represent linear properties of materials, such as phonon frequencies and Young modulus, and that might be inappropriate for highly nonlinear intrinsic localized modes.

Current work compares the use of two approaches for discrete breathers. We point out special cases where classical approach is not reliable, and show how *ab initio* modeling can be used to correct results. Advantages of classical molecular dynamics are also addressed in presenting the modeling of three-dimensional ILMs in BCC crystal of V.

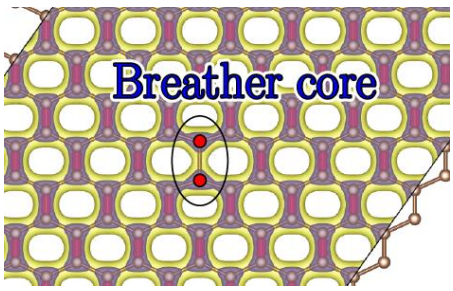

Fig. 1 Electron distribution in graphene in the vicinity of ILM.

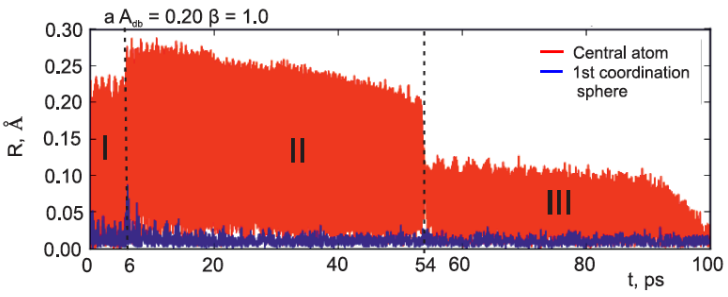

Fig. 2 ILM phases in BCC crystal of V. System consists of more than 5000 atoms.

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Surface discrete breathers in Pt_3Al

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A lot of intermetallic materials having a wide gap in the phonon spectrum can support existence of intrinsic localized modes – discrete breathers (DB). Pt_3Al is an example of the material having a wide gap in the phonon spectrum due to a big mass difference of the components. Different types of DB in Pt_3Al have been exited and analyzed [1]. All these modes were investigated for the case of bulk material. However, consideration of surface effects in nonlinear dynamics is of particular importance due to the fact that any external impact inducing DB excitation in case of real materials starts from the surface. It was earlier shown for the case of graphene [2] that structure and properties of bulk and surface DBs differ significantly.

In present work the analysis of surface effect and orientation on the DB dynamics and properties has been performed. A considerable effect of the surface termination layer has been demonstrated. The properties of DBs differ substantially in the case of a surface terminating with Pt atoms and Pt and Al atoms in equal proportions. The energy of the DB on the PtAl surface is substantially (three to four times) smaller than the energy in the bulk DB or the energy of the DB located near the Pt surface.

Reasons for variability of surface DB behavior are discussed.

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Nonlinear atomic vibrations and structural phase transitions in strained carbon chains

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Monoatomic carbon chains can exist in two different modifications. The first one is polyyne, representing the chain with alternating single and triple bonds [chemical structure (-C=C-)n]. The second modification is cumulene, representing the chain with double bonds [chemical structure (=C=C=)n]. Because of many unique mechanical, physical, and chemical properties, which were experimentally studied or theoretically predicted, carbyne is considered as perspective material for various nanodevices, for hydrogen storage, etc.

Chemical synthesis of pure carbyne chains and their experimental study are very difficult and, therefore, theoretical investigations play important role in prediction of its properties and in description of different physical phenomena, which are possible in this material. Many interesting results on strained carbyne chains were obtained with the aid of density functional theory

(DFT) computer simulations.

In the paper [1], structural transformation of cumulene under certain strain was revealed. This is the Peierls phase transition, which leads to the radical change of carbyne electron spectrum. As a result of this transition, an energy gap in the electron spectrum appears and the conductive cumulene transforms into polyyne which is semiconductor or insulator. This phenomenon opens perspectives to control electrical behavior of carbyne by mechanical strain.

The aforementioned paper, devoted to DFT-studying of properties of strained carbyne, deal actually with a static structure of this material, or with linear vibrations (phonon spectrum) of strained carbyne. In contrast, the problem of nonlinear atomic vibrations in strained carbon chains was studied for the first time in our paper [2]. During this study we revealed an unexpected phenomenon of softening of the longitudinal π-mode vibrations above a certain critical value of the strain. We found that for strains lower than $\eta = 11\%$ cumulene demonstrates monotonic hard type of nonlinearity (the frequency grows with increase of the π-mode amplitude a). However, for $\eta > 11\%$ there is a certain range of amplitudes a in which soft nonlinearity occurs, namely, the frequency of the π-mode abruptly decreases and then again begins to increase.

The phenomenon of vibrational modes softening is well known in the theory of structural phase transitions where by condensation (“freezing”) of such modes one tries to explain the nature of the

displacement-type phase transitions. This is the so-called concept of soft modes. In the majority of the papers on this subject, soft modes are treated in purely phenomenological manner with some vague arguments about the change of electron-phonon interactions in crystal under change of such external parameters as temperature and pressure. In contrast, in our study a soft vibrational mode in cumulene appears as a direct result of the ab initio simulation without any additional assumptions.

In [2], the phenomenon of the π-mode softening has been explained by the fact that above the critical value of the strain the old atomic equilibrium positions become unstable and two new equilibrium positions appear near each of them. Vibrations in the vicinity of these new equilibrium positions correspond to the softening of the π-mode. In turn, condensation of the π-mode leads to a new atomic equilibrium configuration that corresponds to the Peierls phase transition. After this transition, the unit cell turns out to be twice as large than that of cumulene, and the carbon chain transforms into another carbyne form, polyyne, with bond lengths alternation.

In [3] and in the present report, we discuss not only the condensation of the π-mode, but also condensation of two other symmetry-determined nonlinear normal modes, which are possible in cumulene chains. With the aid of DFT and molecule-dynamics simulations combined with some group-theoretical methods [4], we predict the possibility of existence of two new types of carbon chains, besides cumulene and polyyne. They both possess alternation of bond lengths, but with different alternating schemes compared to that of the polyyne.

We think that the obtained results may be used in construction of new nanotechnology devices, in which electrical properties of carbyne can be controlled by mechanical strain. The presented results can also be useful for searching new forms of carbyne, which are predicted in this work.

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Nonlinear atomic vibrations in strained graphene monolayer: bushes of nonlinear normal modes

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The last decades were marked by intensive studies of nonlinear atomic vibrations in periodic structures. One well-known type of such vibrations represents discrete breathers. In the present work, we discuss another type of nonlinear vibrations, which represent *delocalized* dynamical objects in crystal lattices.

Traditionally, harmonic approximation is used as a first step in the studying of nonlinear dynamics of classical N-particle Hamiltonian systems. In this way, one can introduce linear normal modes which, being exact solutions in the framework of this approximation, are independent from each other. If small anharmonic terms in the Hamiltonian are taken into account, normal modes turn out to be only approximate solutions. Therefore, the following natural question arises: "Do there exist any *exact* solutions in nonlinear dynamical systems *beyond* the harmonic approximation?"

Since any crystal can be characterized by some space group, we are interested in exact vibrational solutions dictated by this symmetry. It occurs that such "symmetry-determined" solutions do exist and we call them *bushes of nonlinear normal modes* (NNMs). The general theory of bushes of NNMs in systems with discrete symmetries was developed in [1-3]. Bushes of vibrational modes in different physical systems with different point and space symmetries were studied in the series of our previous works.

Every bush is characterized by some *subgroup* $G_j \subset G_0$ of the symmetry group G_0 of dynamical system in its equilibrium state (or a subgroup of its Hamiltonian). The possibility of a bush to exist as exact dynamical regime is provided by some symmetry-related selection rules for excitation transfer between modes of different symmetry [1]. In particular, a vibrational mode with higher symmetry cannot excite any mode with lower symmetry: excitation transfers from a given mode to the modes with higher symmetry group, *independently* of the specific type of interparticle interactions in the considered physical system.

Construction of the bushes of NNMs can be performed with the aid of the group-theoretical methods based on the apparatus of irreducible representations of the symmetry groups.

Each bush represents a full collection of nonlinear normal modes, which are connected by "force"

interactions, and the number of these modes (m) is the dimension of the given bush. It is essential that bushes with small dimensions (for example, with m = 1, 2, 3, 4,…) can be excited in many physical systems with discrete symmetry. One-dimensional bushes (m = 1) describe time-periodical motion while bushes whose dimension $m > 1$ describe quasi-periodical motion with m basis frequencies in the Fourier spectrum.

Every bush represents a dynamical object since amplitudes of these modes change during the time evolution. It can be considered as an individual Hamiltonian system, whose dimension is less than the whole dimension of the considered system. The energy of the initial excitation turns out to be trapped in the given bush.

We speak about *stability* of the given bush, if the collection of its modes is conserved in time. If the bush with the symmetry group G_j loses its stability, when we increase the energy of initial excitation, it transforms into another bush with larger dimension and with lower symmetry group $\tilde{G}_j \subset G_j$ [4].

In the present report, we discuss group-theoretical results on the small-dimensional vibrational bushes in graphene (some previous results were published in our papers [5,6]). All low-dimensional bushes in graphene have been found. In particular, it occurs that there are 4, 14, 1 and 6 one-, two-, three- and four-dimensional bushes, respectively. Here we present displacement patterns of the modes entering above bushes and the behavior of their modes in time by *ab initio* simulations based on the density functional theory. In particular, we discuss the transfer of excitation from the initially excited mode to the other modes of the bush.

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Experiments and theory in solitary waves in muscovite mica.

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It has been shown from fossil tracks and experiments with alpha particles that nonlinear excitations, travel across the closest packed of K+ planes in mica muscovite, a layered silicate [1]. Recently it has been deduced that those excitations transport also electric charge [2,3]. It has been confirmed experimentally that nonlinear excitations produced by alpha particles transport charge in muscovite [4]. Exploration of the nonlinear excitations spectrum of the K^+ layer shows the existence of nanopterons [5], that is, kinks coupled to a plane wave with finite amplitude. For some values of the velocity nanopterons transform in kinks with no radiation. Among them only the kinks with velocity larger than phonons in the first Brillouin zone are stable. There exist only a crowdion [6] and bi-crowdion [5] that have the right energy range and are natural carriers of electric charge. There exist also breathers with low energy that travel long distances. Exact breathers are also coupled to plane waves [7] and for some values of the velocity the amplitude the plane wave may vanish. The existence of different nonlinear charge excitations is necessary to interpret fossil tracks in which a primary quodon scatters many secondary quodons that should be much less energetic [3].

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How Intrinsic Localized Modes were Produced

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I have visited Prof. Takeno's office in 1 March1986 and asked him to start theoretical research about solid-state physics as a master's program in electronics under the supervision of Prof. Takeno. That visit was the beginning of two-years collaboration between Prof. Takeno and myself. During this period, the theme of this symposium, intrinsic localized modes (ILMs) [1- 3], was born. Prior to the publications of [1-3], first presentation of ILMs was done at the autumn meeting of Japan Physical Society in 1986. The response from audiences was quite negative. After participation of Prof. Sievers in this research in the end of the year, the concept of ILMs materialized and developed. The situation of ILMs has changed since then. In this symposium, I try to present how ILMs started including the motivation I was taught from Prof. Takeno.

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Experiments and simulations of stationary and traveling Intrinsic localized modes

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Intrinsic localized modes (ILMs), or discrete breathers are studied theoretically and experimentally by many people after its finding by Sievers and Takeno at 1988. We have explored nature of ILMs experimentally and compared observations with simulations. Stationary ILMs are generated and their positions can be controlled by applying perturbations from outside of the lattice. At a certain condition, traveling ILMs at a constant velocity can be generated. These nonlinear localized modes are made from degrees of freedoms of the lattice. Lattice phonon modes are such degrees of freedom when the system is at rest. When the number of ILMs is small and the lattice is large compared to the ILM, those phonon modes can be measured by a linear resonance technique. In addition, there are other linear modes associated with the ILM, such as natural frequency of the driven-damped system and linear localized modes. Those are not excited and hard to see without other perturbations, however, play important roles at stability of the ILM and transitions related to the ILM states.

Time-periodic Driving of Nuclear Reactions by Intrinsic Localized Modes Arising in Hydrogenated Metals

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We present atomistic simulations of the ILM formation in the hydrogen sub-lattice of Ni and Pd hydrides. Large amplitude atomic motion in ILMs may result in time-periodic driving of adjacent potential wells occupied by hydrogen ions (protons or deuterons). This driving is shown to result in the increase of amplitude and energy of zero-point vibrations (ZPV). Based on that, we demonstrate a drastic increase of the D-D or D-H fusion rate with increasing number of modulation periods evaluated in the framework of Schwinger model [1], which takes into account suppression of the Coulomb barrier due to lattice vibrations. In this context, we present numerical solution of Schrodinger equation for a particle in a non-stationary double well potential, which is driven time-periodically imitating the action of an ILM [2]. We show that the rate of tunneling of the particle through the potential barrier separating the wells can be enhanced enormously by the driving with increasing amplitude of the driving. Presented results may explain the experimental observations of large excess heat and nuclear products in hydrogenated Ni and Pd [3].

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Nonlinear compact periodic solutions in flat band networks

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(Dated: September 25, 2017)

Linear wave equations on translationally invariant flatband (FB) networks exhibit one or more dispersionless bands in their Bloch spectrum. These macroscopically degenerate bands exist due to local symmetries and destructive interference on the lattice. Short-range hopping FB networks host compact localized (eigen)states (CLS) with nonzero amplitudes restricted to a finite volume. We consider the presence of local nonlinear terms in the wave equations. We study the continuation of CLS into the nonlinear domain while keeping their compactness and renormalizing their frequency. We then study the stability of these nonlinear CLS in terms of resonances with extended and compact localized states.

Topological Protection of Mechanical Wave Modes in Tunable 1D and 2D Lattices

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Study of topology in engineering has traditionally been associated with geometrical shapes of structures. Inspired by the recent discovery of topological insulators, topology is now being associated with structures at a more subtle level. This sort of topology characterizes the intrinsic dispersive behavior rather than geometry, and it is quantified in terms of topological invariants. At a physical level, topological difference may result in the presence/absence of robust vibration modes on the boundaries of finite structures. Therefore, topological systems can potentially offer novel ways to robustly manipulating mechanical waves for applications in energy harvesting, vibration isolation, and structure heath monitoring.

In this presentation, we summarize our research directed towards gaining the fundamental understanding of this new design paradigm and building novel topological metamaterials. First, we propose a 1D tunable mechanical system, in which we experimentally demonstrate the localization of stress waves – one of the most fundamental topological phenomena. The system is composed of a granular chain of cylinders interacting as per Hertz's contact law. We show numerically and experimentally that *in situ* tuning of contact angles leads to a topological transition in the system, and that is quantified by the jump in a topological invariant [1]. This is accompanied by the emergence of a boundary mode in the system. Also, we show the scheme of creating a *topological defect* by placing two topologically distinct lattices adjacently and detect a robust localized vibration mode at the interface.

Owing to the aforementioned tunability, we also propose a slight variant of this design, in which a torsional wave excitation is enforced to *dynamically* change the contact angles [2]. Consequently, inter-particle stiffness is both space- and time-dependent. We numerically demonstrate that such a system shows a non-reciprocal wave propagation behavior. In addition, we show its remarkable connection with the topological transport of the Thouless pump in quantum mechanics, where a time-dependent one dimensional system is characterized by the topological invariant of two dimensions, i.e., Chern number. Extending these ideas to 2D structures, we propose a topological plate structure, which consists of a systematically arranged local resonators on top of a thin plate. Inspired by the spin Hall Effect in physics, we judiciously create a *subwavelength* scale topological waveguide in the system [3]. We analytically and numerically show that this waveguide can guide flexural waves robustly in the presence of bends, and also imparts a one-way propagation characteristic to them, thereby surpassing the capability of traditional waveguides. Finally, we show the ability to *in situ* tune wave path in one single topological structure made of Stewart platforms [4]. We numerically show that by a simple dial-in action, the bistable nature of designed Stewart platform can be harnessed to manipulate the path of a robust waveguide. We also demonstrate the sharp contrast of wave propagation efficiency between the conventional waveguides and the topological waveguides by using this platform.

In conclusion, we have designed and analyzed topological mechanical lattices in 1D and 2D mechanical settings. The preliminary results show that the introduction of the *topology* concept to mechanical realms – inspired by topological insulators in electronic and optical systems – can open a new way to manipulating stress waves, such as directional propagation, filtering, and localization of wave modes.

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Nonlinear Wave Propagation in Origami-based Mechanical Metamaterials

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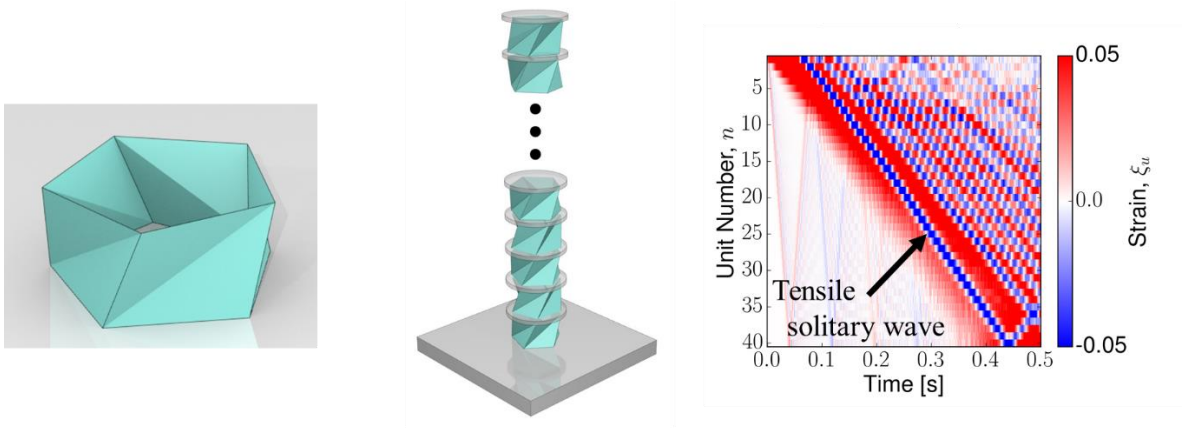
We study nonlinear wave dynamics in mechanical metamaterials composed of origami-based unit cells, specifically the Triangulated Cylindrical Origami (TCO) as shown in Fig.1(a). Previous study has shown that these TCO cells can exhibit highly tunable characteristics in their static behavior, such as strain-softening/hardening and mono-/bistable behaviors [1]. Based on this versatile mechanism of the TCO unit cell, we assemble a one-dimensional chain of TCO cells, so called origami-based mechanical metamaterials, in this study (Fig. 1(b)). For experimental studies, we fabricate physical prototypes of the TCO system by using paper sheets cut by a laser cutting machine. The tunable mechanical properties of these prototypes are verified experimentally, which corroborate our analytical and numerical predictions. Then, we analyze wave propagation in this origami-based system by considering the case where compressive impact is applied to the end of the chain. If the strain softening configuration is selected for all of the unit cells, our analysis shows that an application of compressive impact creates a tensile solitary wave (Fig. 1(c)), propagating ahead of the initial compressive wave. This tensile solitary wave – despite the application of the compressive impact – is called rarefaction waves. By using the non-contact digital image correlation technique based on three inexpensive cameras, we verify the existence of such rarefaction waves in this TCO platform. It should be noted that the experimental observation of the rarefaction waves has not been previously reported in mechanical discrete systems, though this interesting overtaking behavior has been predicted by our numerical study [2]. In addition to the compression-to-tension conversion, this origami-based system exhibits the tunable wave speed of the tensile solitary wave due to the tailorable stiffness of the TCO unit cells. In conclusion, the origami-based mechanical metamaterial in this presentation can serve as a fertile testbed for realizing unique tunable static/dynamic mechanisms. This can lead to the development of novel engineering devices for efficient impact mitigation and vibration filtering.



(a) (b) (c)

Fig. 1. (a) Schematic illustration of the Triangulated Cylindrical Origami (TCO) unit cell, and (b) TCO-based mechanical metamaterial. (c) Tensile solitary wave propagating in the origami-based mechanical metamaterials.

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Discrete breathers in granular chains

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Chains of beads interacting by contact are widely studied in the context of impact dynamics and acoustic metamaterials. While much effort has been devoted to solitary waves in granular chains, there is now an increasing interest for breathers (spatially localized oscillations). Due to their oscillatory nature and associated resonance phenomena, breathers exhibit complex dynamical properties which have strong potential applications for the design of acoustic metamaterials allowing to efficiently damp or deviate shocks and vibrations. In this talk, we review recent results and open problems concerning the dynamics of breathers in granular systems and their approximation through modulation equations.

Keywords: nonlinear waves, modulation equations, bifurcations, nonsmooth systems, impact mechanics, nonlinear metamaterials

Energy localization in ring coupled boost converters using passivity based control

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Abstract This paper discusses the behaviour of a ring coupled boost converter system from the view point of energy exchange. The boost converters are coupled in a ring with 'dissipation' in the form of inductance and resistance between them. Energy transfer and localisation of energy in such a system is observed and the possible reasons for the occurance of such localization are discussed.

1 Introduction

Dispersed generation is a widely discussed topic for non-conventional sources like photo voltaic and fuel cells. In this paper we focus on DC power system with five converters coupled in a ring formation, from the point of view of passivity based control (PBC). PBC is a control method which brings the system to the desired equilibrium by shaping energy characteristics of the system. As a result it is shown that the properties of PBC govern the exchange of energy between the converters. This gives rise to the flow of energy which is localized under the excitation by external input.

2 System Modelling and Control

The system under consideration consists of five boost converters (#0 to #4) with five different sources, connceted in a ring. By using boost converters it is ensured that the output in the loop is higher than the input sources. The system configuration is shown in Fig.1. The circuit equations are given in Eq.(1).

$$\begin{aligned} L_{\mathrm{n}}\dot{i}_{Ln} &= (1-\mu_{\mathrm{n}})v_{c\mathrm{n}} + E_{\mathrm{n}} \\ C_{\mathrm{n}}\dot{v}_{C\mathrm{n}} &= (1-\mu_{\mathrm{n}})i_{L\mathrm{n}} - i_{T\mathrm{n}} + i_{T(\mathrm{n}-1)} - \frac{v_{c\mathrm{n}}}{R_{2T(\mathrm{n}-1)}} \\ L_{T\mathrm{n}}\dot{i}_{T\mathrm{n}} &= v_{c\mathrm{n}} - v_{c(\mathrm{n}+1)} - R_{1T\mathrm{n}}i_{T\mathrm{n}} \end{aligned} \tag{1}$$

Here n denotes the index of the converters from 0 to 4.

PBC is applied to shape the energy function as a quadratic function of errors derived from the directed values. PBC aims to minimize this function by changing the duty cycle of the converters [1]. Thus the duty cycle becomes a function of the state of the system [2]. This system is, thus, nonlinear with respect to the duty cycle.

3 Localisation of Energy

For any initial localised excitation of energy in a coupled system, it is expected that this energy is distributed throughout the entire system in due course of time.

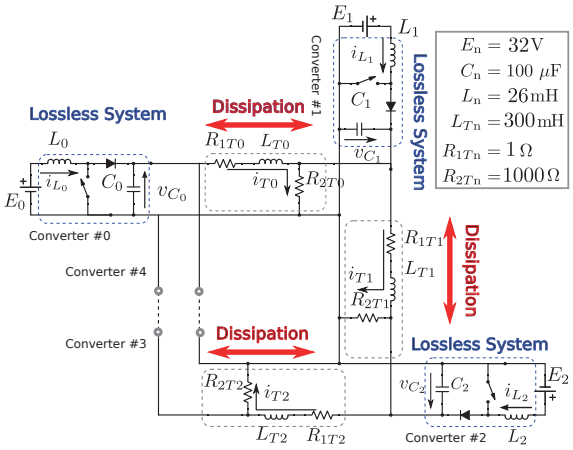

Figure 1: Schematic configuration of ring coupled converters.

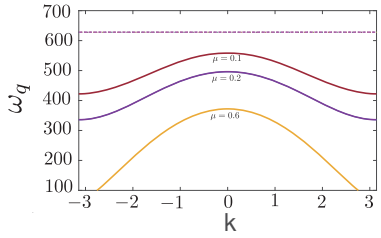

Figure 2: Dispersion Relation dependence on duty cycle μ_{n}. Here μ_n is kept at a constant value.

In the ring coupled converter system, each converter can be considered as a separate discrete entity with inductive coupling. As a boost converter is inherently an LC oscillator circuit, the coupled system exhibits similar equations to the 1D chain of interacting oscillators described in [3, 4]. The only difference is the dissipation present in the form of resistance in the circuit. For this system, the equations can be formulated as a second order of the term $v_{c\mathrm{n}}$ given by Eq.(2).

$$\begin{aligned} \ddot{v}_{C\mathrm{n}} = {} & \frac{(1-\mu_{\mathrm{n}})E_{\mathrm{n}}}{L_{\mathrm{n}}C_{\mathrm{n}}} - \frac{(1-\mu_{\mathrm{n}})^2}{L_{\mathrm{n}}C_{\mathrm{n}}}v_{C\mathrm{n}} - \frac{\dot{v_{C\mathrm{n}}}}{R_{2T\mathrm{n}-1}C_{\mathrm{n}}} \\ & - \frac{1}{L_{T\mathrm{n}}C_{\mathrm{n}}}\left[2v_{C\mathrm{n}} - v_{C\mathrm{n}-1} - v_{C\mathrm{n}+1} - R_{1T\mathrm{n}}(i_{T\mathrm{n}} - i_{T\mathrm{n}-1})\right] \end{aligned} \tag{2}$$

After linearising the equations of the system, the solutions obtained are small amplitude plane waves characterized by wave number k and angular frequency ω_k. Dispersion relation describes the effect of dispersion in the ring depending on the wave number. Setting the parameters appropriately as given in Fig.1, the dispersion relation is estimated as is given in Fig.2 [4]. Fig.2 shows that the angular frequency is a function of the duty ratio, as the expression for the onsite potential is nonlinear with respect to the duty ratio.

4 Results and Simulations

Here we discuss simulation results. When the input is sufficiently close to the desired output voltage, the duty ratio retains a small value. All inputs to the converters were set at 32 V with the desired output voltage of 35 V. Thus the duty ratio ($\mu_{\rm n}$) remains between 0.1 to 0.20. Converter #1 was driven with a sinusoidal input in addition to the original DC input.

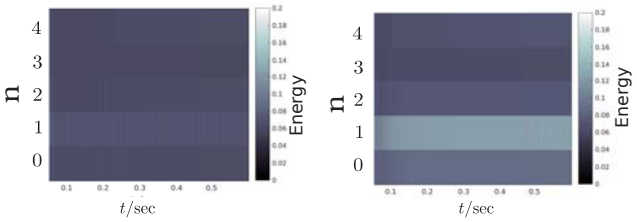

Figure 3: Energy plot when the frequency of the driving input is changed. The inputs are set to be $E_0, E_2, E_3, E_4 =$ 32 V and $E_1 = 32 + 6sin(\omega t)$ V (a) When $\omega = 350$ rad. (b) When $\omega = 620$ rad.

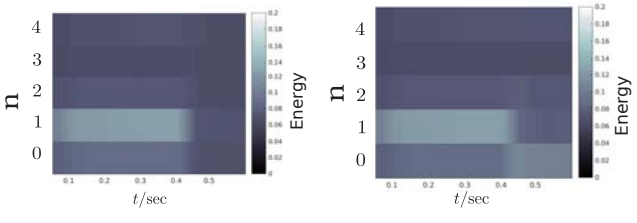

Figure 4: Changing the localised energy by introduction of 'impurity' with a switch. At $t = 0.4$ sec,The inputs are set to be $E_0, E_2, E_3, E_4 = 32$ V and $E_1 = 32 + 6sin(\omega t)$ V (a) When the impurity is subtractive, i.e $L_{T1}, L_{T2} = 70$ mH (b) When the impurity is additive i.e $L_{T1} = 70$ mH and $L_{T1} = 400$ mH.

Inspite of the control applied, and the natural characteristic of the energy to dissipate, converter #1 retains the energy when driven at the resonant frequency.

Figure 3(a) shows the energy plot when the applied frequency is in the linear range i.e 350 rad. All the localised energy is quickly dispersed, and just the constant supplied sinusoidal input is reflected in the output energy charactersitic. On the other hand, when the frequency is increased to 680 rad, the oscillator resonates, and the energy is not dispersed but retained at the same position as shown in Fig.3(b).

Figure 4(a) shows the annihilation of the localised energy with addition of an 'impurity' in the coupling between converter#1 and converter#0. Fig.4(b) shows that it is possible to move the localised energy to the neighbouring converter #0 by switching ON and OFF an inductive impurity in the circuit. While doing this, some energy is lost in dissipation.

5 Discussion

When a system exhibits the properties of discreteness and has nonlinear equations describing it, then these equations have solutions in which are time periodic and localised in space. In physical systems it has been observed in chemical structures like antiferromagnets, cantilever arrays and relevant to this research, in nonlinear transmission line model [5]. Correspondingly, in this paper energy localisation in ring coupled converter systems was obtained. The dispersion relation for the converter was calculated for the system, and the effect of the driving frequency on the localisation of energy was studied. It was shown that this localised energy can be moved within the converters in the system or can be annihilated. Annihilation of localised system returns the system to the state where all converters converge to an equilibrium at the lowest energy state.

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Chameleon's behavior of discrete nonlinear electrical transmission lattice

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Generally, in function of the disposition of capacitor and inductor, the electrical lattice can adopts right (R), left (L) or composite LR-handed media. Following Togueu Motcheyo et al.[1], We show that modulable [2] discrete nonlinear transmission line can adopt *Chameleon's* behavior due to the fact that, without changing its appearance structure, it can become alternatively purely right or left handed line which is different to the composite one.

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Using Hilbert transform and classical chains to simulate quantum walks

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In this work we report a classical simulation strategy that we have proposed recently used to simulate quantum dynamics, in particular quantum walks. This strategy is based on a classical device of linearly coupled chain of springs together with the technique of Hilbert transform. Through this strategy, we obtain the quantum wave function from the classical evolution. Specially, this goal is achieved with the classical momenta of the particles on the chain and their Hilbert transform, from which we construct the many-body momentum and Hilbert transformed momentum pair correlation functions yielding the real and imaginary parts of the wave function, respectively. With such a wave function, we show that the classical chain's energy and heat spreading densities can be related to the wave function's modulus square. This relation provides a particular perspective from quantum aspects to understand ballistic energy and heat transport.

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Ergodicity-breaking in Discrete Nonlinear Schrödinger Equation

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Statistical mechanics of the discrete nonlinear Schrödinger equation shows a phase transition in the energy and norm density parameter space and the phase transition is characterized by the formation of long-lived excitations in the non-Gibbsian regime. It is believed that this phase transition line is connected with the non-ergodicity. In order to elucidate this connection we consdered the general character of non-ergodicity, the power law probability distribution (PDF). We recordered the excursion times of an observable and measured the exponent of the power law to explore the non-ergodicity. In my talk, I will present the rescently obstained results of the ergodicity breaking in this system.

Geometric formulation of a class of natural Hamiltonian systems - in search for an extension of Toda's dual transform -

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In Prof Toda's paper published in 1967[1], his famous integrable lattice model was introduced. As is commonly well known, his lattice model has been used and studied well in various research areas, such as pure and applied mathematics and theoretical physics. His way to find his lattice model is to use a transform of variables, called the dual transform. This transform makes nonlinear force terms linear ones, and a key to successful application is the existence of the inverse transform. Despite this transform is successful, mathematical sophistication and generalizations are not well developed.

There exists another transform with which nonlinear force terms in a class of Hamiltonian systems are changed to linear ones. That is the Legendre transform for potential energy functions. Since the linearized process is common, the dual transform may be related to the Legendre transform. On the other hand, the Legendre transform is used in Hessian geometry, where Hessian geometry is a class of Riemannian geometry being equipped with strictly convex functions. It should be noted that Hessian geometry is applied in information geometry that is a geometrization of mathematical statistics, and information geometry has been developed in recent years. Thus it is expected that there are some overlap between information geometry and theory for a class of Hamiltonian systems if there exists a link between the dual transform and the Legendre transform. Also, exploring the Legendre transform applied to a class of potential energy functions of Hamiltonian systems, we expect to develop a new avenue in dynamical systems theory and other neighboring disciplines.

In this talk classical Hamiltonian systems are considered, where a Hamiltonian function can be written as the sum of a kinetic and the potential energy functions. In addition, those energy functions are assumed strictly convex so that Legendre transform can be successfully applied. It is then shown how the Legendre transform is applied to such Hamiltonian systems, how the canonical equations of motion are written with transformed coordinates, and how to generalize Toda's dual transform. Also with convex analysis, it is shown some inequalities for this class of Hamiltonian systems.

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Ergodic to Nonergodic Transition in DNLS Lattice

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We study discrete nonlinear Schrodinger equation as a mean-field approximation to interacting many-body systems, and as a proper tool for the description of photonic networks. We analyze the impact of the existence of coherent states on the statistics of so-called extreme events, i.e. long time fluctuations off equilibrium, and characterize its dynamics where the Gibbs distribution fails to provide statistical grounds for computing averages. A systematic way is used to characterize the equilibrium fluctuations, as well as the relaxation dynamics from extreme non-equilibrium states via using the probability distribution of the excursion times of an observable. The calculated exponent from the power law shows that the ergodic to non-ergodic transition line is not matching the Gibbs/Non-Gibbs crossover, yet non-ergodicity always occurs in the non-Gibbs regime.

Investigation of Spatially Localized Oscillations in the Two-dimensional Hexagonal Lattice of Fermi-Pasta-Ulam β Type

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Recently energy-localization phenomena in high dimensional lattices attract attention and have been studied theoretically and numerically, for example, by using of asymptotic analysis, nonlinear normal modes, group-theory or molecular dynamical methods [1-7].

In this paper, to obtain strongly localized oscillations and understand their configurations and properties, we investigate the nonlinear modes in the two-dimensional hexagonal lattice of Fermi-Pasta-Ulam β type by numerical simulation (Fig. 1.) and iteration method.

The localized modes will be expected to be long life and, if so, to play an important role in mechanical or engineering applications.

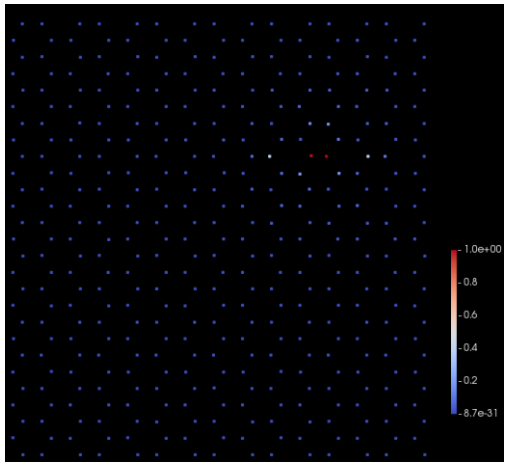

Fig. 1. A snapshot of Energy Distribution

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Lattice spatial modes and switching to ILMs in an electric transmission line

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We observed experimentally lattice special modes (LSMs) in a nonlinear lattice at a driven-damped condition. LSM is studied by Burlakov (1996), but it has not studied experimentally so far. It is generated in a nonlinear lattice at a large damping condition, which suppresses multiple modulational instabilities which lead often nonlinear lattices into chaotic states at a driving condition. LSM is composed from a uniform excitation with a standing wave excited by four-wave scattering process. By changing the driver frequency, the LSM-pattern changes their number of peaks because of different wave-number of the generated standing wave. At a sufficiently large frequency difference of the driver, LSMs are continuously changed into ILMs.

Driving condition for generating train of moving ILMs in one-dimensional FPU chain

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Intrinsic localized modes (ILMs) are known as energy localized vibrations in nonlinear coupled oscillators [1]. In particular, in the flexible Fermi-Pasta-Ulam (FPU) chain [2], the existence of various ILMs such as longitudinal, transverse, and rotating ILMs has been numerically shown[3], and the mobility of the ILMs has also been investigated[4]. We have focused on moving ILM and have been studying a method for generating moving ILMs in the FPU chain for applications in phonon engineering.
In the one-dimensional FPU chain, moving ILMs can be excited by driving an edge of the chain [5,6]. However, amplitude and frequency of the excitation for generating a train of moving ILMs without exciting non-localized waves have not been clarified yet. In this study we introduce the variance of peak values and peak intervals of energy distribution at a certain time for identifying a parameter region in which moving ILMs are generated without exciting non-localize/traveling waves. As a result, the parameter region can be clearly distinguished from the other regions by the smallness of the variance.

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Thermal Conduction in Symmetric Potential Lattices

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It is well known that one-dimensional lattices often exhibit anomalous thermal conduction while some lattice models are known to exhibit a normal conduction i.e., the Fourier law. Thermal conduction of one-dimensional lattices has been extensively studied so far [1]. However, it is not still fully clarified which property of the lattice potential dominates its thermal conduction property. In this study, we focus on a particular symmetry of the potential function and its influence on the thermal conduction.

We consider the one-dimensional lattice described by the Hamiltonian

$$H = \sum_n \frac{1}{2} p_n^2 + \sum_n \frac{1}{2}(q_{n+1} - q_n)^2 + \sum_n \sum_{r=1}^{M} \frac{b_r}{4}(q_{n+r} - q_n)^4 , \quad \text{- (1)}$$

where b_r are constants and M is the truncation order of the long range anharmonic interaction. When M=1, this model reduces to the Fermi-Pasta-Ulam β lattice. The potential of this lattice has been shown to have a particular symmetry in a good approximation when M is large enough and each b_r is given by $b_r = b_1/r^2$ [2]. The lattice is called the pairwise interaction symmetric lattice (PISL). It has been shown that in the PISL moving intrinsic localized modes (ILMs) have no spatially-extended tail and propagate smoothly without noticeable velocity loss for a long time. Such high mobility of ILMs may pose the conjecture that the PISL has an anomalous high thermal conductivity.

We carried out non-equilibrium molecular dynamics simulations for lattice (1) interacting with high and low temperature heat baths. It has been found that lattice (1) does not support any temperature gradient and exhibits ballistic transport up to a certain system size N_c. This threshold size N_c increases as the potential symmetry becomes more accurate with increasing M. The ballistic transport can still be observed even when a harmonic on-site potential, which preserves the symmetry, is added to H. We will show numerical results for the heat transport property of the PISL including these results.

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Dynamics of Moving Intrinsic Localized Modes in Pairwise Interaction Symmetric Potential Lattices

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It has been well known that traveling intrinsic localized mode (ILM) [1-2] can be produced by perturbation to stationary ILMs. Although traveling ILMs are observed in various lattice systems and physical models, its dynamics has not been fully understood yet. In this study, relation between shapes of interaction potential and dynamics of the traveling ILM is investigated. It is shown that a symmetry of pairwise interaction potential plays important roles in smooth mobility of ILM in lattices. Moreover, this symmetry for the smooth mobility of traveling ILM is realized by introducing long-range interaction to Fermi-Pasta-Ulam β lattices (the pairwise interaction symmetric lattice (PISL) [3]).

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A Numerical Study on Localized Modes in Resonant Circuit Array for Application to Wireless Power Transfer

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Localized mode in a resonant circuit array consisting of overlapped plane coils and capacitors is numerically investigated in this study for application to wireless power transfer. The resonant circuit array can be modeled as a linearly coupled oscillator array. When another single coil approaches to the array, an impurity is induced to the array because of mutual magnetic flux between the array and the coil. As a result, a localized mode emerges around the impurity. The frequency and the localization strength of the localized mode is numerically investigated with respect to the position of the coil and the overlapping of plane coils.

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