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Editorial

Special issue on current trends in computational and experimental techniques in nonlinear dynamics

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Abstract We present an introduction and review for the EPJ ST Special Issue on Current Trends in Computational and Experimental Techniques in nonlinear dynamics. This volume consists of 39 articles which consider topics of interest that arise in current research in nonlinear dynamics: complex systems, fluid flow problems, conservative systems, statistical fluctuations in non-equilibrium systems, networks of coupled oscillators, and numerical analysis of nonlinear oscillations. It covers theory, experimental studies, and applications.

1 Introduction

The present issue on Special Topics of the European Physical Journal is a selection of articles that focus on nonlinear dynamics. It covers theory, experimental studies, and applications in engineering. These articles deal with topics of interest that arise in current research in nonlinear dynamics: complex systems, fluid flow problems, conservative systems, statistical fluctuations in non-equilibrium systems, networks of coupled oscillators, and numerical analysis of nonlinear oscillations. This multidisciplinary field is covered in this volume by invited and contributed articles written by physicists, computational scientists, applied mathematicians, and engineers with expertise in computational and experimental techniques.

We took advantage of the opportunity to select several contributions to this Special Issue from the presentations at the virtual conference, “Advanced Computational and Experimental Techniques in Nonlinear Dynamics,” organized in Puebla, Mexico, from October 26 to 30, 2020. However, this volume in no way reflects the conference program. It aims at addressing recent developments in this multidisciplinary field. The interdisciplinary approach exhibited in these contributions illustrates the benefits of applying diverse perspectives on a physical problem. These different perspectives may come from applied mathematics, theoretical physics, or neuroscience, along with the application of their respective tools such as numerical continuation, graph theory, and models in statistical physics, to name just a few. A clear example is the rich phenomenology of the Kuramoto and related models, which may provide a pragmatic approach to deal with the complex dynamics of interacting flame oscillations arising from different sources in spatial configurations which can induce new phenomena [2].

Our selection consists of 39 invited and contributed articles from an inherently international scientific community. This Special Issue is organized in six necessarily overlapping categories due to the multidisciplinary nature of this field. More precisely, they include the following:

I Dynamics of complex systems.
II Nonlinear systems with conservation laws.
III Multistability and instabilities in reduced phase space dimensions.
IV Bifurcations and numerical analysis of nonlinear oscillations.
V Multidisciplinary applications in engineering and control.
VI Fluid Flows: complex geometries and instabilities.

To gain further insight into the topics covered in this Special Issue, we briefly describe these categories. In the first category, *Dynamics of Complex Systems*, we consider studies which incorporate several features of complex systems such as nonlinearity, emergence, spontaneous order, network signatures, delay, and noise. In the second category, *Nonlinear Systems with Conservation Laws*, the authors consider conservative systems as diverse as Bose–Einstein condensates, nematic liquid crystals, and magnetized spinning tops. In the next category, *Multistability and Instabilities in Reduced Phase Space Dimensions*, dissipative systems such as mechanical and optoelectronic models are investigated, along with models for hidden attractors and scroll attractors. Dissipative maps with several control parameters are

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also considered. In the fourth category, *Bifurcations and Numerical Analysis of Nonlinear Oscillations*, within the framework of bifurcation theory and numerical analysis, models for Bose–Hubbard dimers and nematic superconductors are studied. Along the same lines, a noninvertible Lorentz-like map and a class of systems with a three-dimensional vector field are investigated. Within the next category, *Multidisciplinary Applications in Engineering and Control*, interesting practical applications are considered ranging from optical chaos in LiDAR systems for 3D imaging to memristor-based circuits which are used for encryption and logic gates. Control and characterization of chaotic systems are also both included in this category. Finally, in the last category, *Fluid Flows: complex geometries and instabilities,* a reaction-diffusion system with two chemicals and a linearized Boussinesq equation are investigated. A few other fluid flow models are taken into account in the articles in this category, such as those for describing nanofluids and the effects of magnetic fields.

In the next sections we present a brief description of each article in this Special Issue within its category. We begin our volume with a short review by Miranda et al. [1], who report on the dynamics of two-degrees-of-freedom Hamiltonian systems; in particular, the corresponding Hamiltonian maps are considered. The authors describe a dynamical phase transition observed in Hamiltonian systems, which is precisely a transition from integrability to non-integrability. The behavior of chaotic diffusion in the chaotic sea is considered using two methods, one of which is a numerical description to obtain the critical exponents, while the other is an analytical result obtained from a diffusion equation.

2 Dynamics of complex systems

In the first article in the category *Dynamics of Complex Systems*, by Aravind et al. [2], the authors consider a rich physical system to study the dynamics of flame oscillations and explore emergent behavior of coupled nonlinear oscillators in their experiments. A high-speed camera is used to image the flames generated by a lamp in a set of different configurations. Image characterization allows the authors to find dependence between the volume of fuel in the lamp and the behavior of the flame, particularly the flame area and frequency of oscillation. The authors also explore experiments consisting of two lamps and find interactions between the two flames.

The second article, by Bistel et al. [3], presents a set of algorithms aimed at locating and identifying individual birds. This workflow is formed by two different multilayer neural networks: one locates a given subject as being the source of a birdsong, and the other classifies the song theme among a set of six possible themes. Both neural networks are trained with synthetic data. This system constitutes an interesting tool for the automatic monitoring of small bird populations.

The next article, by Faci-Lázaro et al. [4], analyzes networks composed of two layers of interacting neuronal networks and explores their robustness when these are subjected to damage in the form of either targeted attack or failure. More precisely, they observe how the dynamics of this spatial network of Izhikevich neurons respond to targeted and random removal of neurons, observing an emergence of boosts of activity, whose mechanisms are explored. Their results show that the functionality of these networks does not decrease with damage, but on the contrary, they are able to increase their level of activity when the damage experienced is sufficiently strong.

The fourth article, by Ramírez-Ávila et al. [5], considers a game to study the synchronization phenomena of integrate-and-fire oscillators. The authors focus on finding the basins of attraction for synchronization in this discrete model as a function of the game setup: number of players, number of sides in the game, number of boxes in the board, and four different rules to be updated, where the latter strongly affects complete synchronization. Statistical analyses are carried out on the simulations to find differences and similarities between the setups and the time they take to reach synchronization.

The next article, by Sosa et al. [6], presents results for the rates of energy exchange between oscillators in a heterogeneous ensemble of globally coupled mechanical phase oscillators. More precisely, the article focuses on the stationary collective dynamics of an ensemble of coupled mechanical phase oscillators subjected to an external harmonic excitation applied to one of the oscillators, and to friction forces. Heterogeneity in the system is given by different individual moments of inertia and friction coefficients.

The sixth article, by Bountis et al. [7], investigates forced nonlinear chains. Their main interest is in studying phenomena of supratransmission such as the propagation of signals at forcing frequencies outside linear frequency band in chains with hysteretic damping. The authors consider different types of hysteretic damping and see considerable differences in their supratransmission properties such as forcing threshold and wave shapes.

The next article, by Nguefoue et al. [8], considers a network of mobile systems whose nodes are constituted by moving agents. The agents have internal states whose dynamics are ruled by coupled Rössler equations. This coupling depends on the distance between the agents, which also affects their displacements relative to each other. The vision range, i.e. the agent interaction cutoff, strongly affects the system dynamics. Synchronization in this system is possible for suitable coupling strengths.

The eighth article, by Peters et al. [9], investigates the effects of varying the memory time on the dynamics of both optical and mechanical resonators in the presence of noise. For a memory time that is commensurate with the inverse dissipation rate, both optical and mechanical resonators show stable limit cycles, where a cascade of period-doubling bifurcations occurs as the memory time increases. For longer memory times, the mechanical resonator displays a regime of chaotic dynamics associated with a double scroll attractor, in contrast to those for the optical resonator.

The next article, by Jaimes-Reátegui et al. [10], is devoted to the problem of synaptic plasticity in neural dynamics. Using the FitzHugh–Nagumo model, the authors show that neurotransmission between linearly and nonlinearly coupled neurons can induce multistability. They also study switching between the coexisting states under multiplicative noise and analyze the probability distribution of the resting and spiking states.

The tenth article, by Alvarez-Llamoza, et al. [11], investigates a model that couples several identical local maps with both a global mean field and an external field described by a suitable map. The authors determine the conditions for generalized and complete synchronization to occur. As for the local map dynamics, the cases of a tent map and a logarithmic map are considered. The authors explore the emergence of the state of generalized synchronization of chaos.

Finally, the last article in this category, by Tarigo et al. [12], considers the Mackey–Glass delay differential equation. One of its main contributions is the investigation of the gamma-a-parameter plane by means of simulations over a grid, for fixed initial conditions of different kinds. The results are presented in terms of the number of spikes of a solution, as isospike diagrams. Different initial conditions reveal differences in isospike diagrams and, hence, reveal regions of multistability.

3 Nonlinear systems with conservation laws

In the first article in the category *Nonlinear Systems with Conservation Laws*, by dos Santos et al. [13], the authors consider an effective quasi-one-dimensional funnel-shaped Bose–Einstein condensate with embedded vorticity. More precisely, by means of a variational method, the underlying Gross–Pitaevskii equation is reduced to a 1D nonpolynomial Schroedinger equation (NPSE) for modes with zero or nonzero embedded vorticity, which are tightly confined by the funnel potential in the transverse plane. Numerical results demonstrate high accuracy of the NPSE reduction for both signs of the nonlinearity. By means of simulations of NPSE with the self-attraction, collisions between solitons are studied as well.

The next article, by Panayotaros [14], focuses on continuation of static solutions of discretized Landau–de Gennes theory for nematic liquid crystals in lattices and graphs under variations of an intersite coupling parameter in two dimensions. The paper shows that solutions that can be continued from the zero coupling limit are equilibria of an Oseen–Frank theory. An analogous connection between the two theories is also shown for dynamics of the gradient flow of the two-dimensional Oseen–Frank and Landau–de Gennes energy functionals.

The third article, by Giordano et al. [15], considers a Hamiltonian model of the Levitron, a magnetized spinning top that can be suspended in the air by an external magnetic field. The authors use analytical and numerical methods to study the dynamics near an equilibrium that describes levitation and to find regions of stability. Asymptotic analysis is also used to study the nutation of the Levitron, where controlling the nutation can limit losses and enhance flying time.

4 Multistability and instabilities in reduced phase space dimensions

The first article in the category *Multistability and Instabilities in Reduced Phase Space Dimensions*, by Ramírez-Ávila et al. [16], deals with the spiking and spiking-bursting behavior in the two-dimensional Rulkov mapping. The model consists of two variables, slow and fast, and three parameters. The authors use scaling arguments to split the parameters and show that one of them can be kept fixed and the dynamics can be studied as a function of the other two. The periodicity and Lyapunov exponents are calculated and remarkable nested sequences of periodicities in the oscillations are found. These sequences can be expressed as linear combinations of integer numbers and appear in several regions of the control space.

The second article by, Giordano et al. [17], considers the Levitron with added dissipative effects. These lead to modifications of the dynamics studied by the authors in a Hamiltonian model of the system (see EPJS-D-21-00154R1). The authors use quantitative indicators of chaotic trajectories to distinguish between stable and unstable flight trajectories.

The third article, by Jaimes-Reátegui et al. [18], studies the dynamics of two neurons described by Hind–Marsh–Rose models. These are optically and unidirectionally connected by an erbium-doped fiber laser (EDFL), which accounts for the neuronal synapse. Depending on the EDFL parameters, the postsynaptic neuron can have different dynamical regimes including silence, tonic spikes, bursts with different number of spikes, and chaos.

In the next article, by Escalante-González et al. [19], the authors propose a method allowing for the construction of multistable systems with different numbers of self-excited and hidden attractors. The idea behind the construction is to use a nonlinear function to produce coexisting self-excited attractors at specific locations. Thus, hidden nested attractors appear depending on the number of self-excited attractors.

The fifth article, by Wang et al. [20], reports on a new 3D sub-quadratic Lorenz-like system possessing rich dynamics. The proposed system gives birth to Lorenz-like chaotic attractors coexisting with an unstable origin and two stable node-foci in a broad range of parameters. This suggests that the decrease in the powers of some variables may widen the ranges of some parameters for which hidden attractors may exist. This not only may provide a new method to detect hidden Lorenz-like attractors, but also poses an interesting problem that the existence of hidden attractors can be determined by the degrees of the polynomials of the studied systems.

The next article, by Ruiz-Silva et al. [21], reports on synchronization states for a specific pair of mutually coupled multistable scroll systems. The authors show that the nature of the coupling scheme determines the obtained synchronization type, while the coupling strength allows for the various synchronized state attractors that differ from the initial attractors.

The last article in this category, by de Oliveira et al. [22], reports on boundary crises in a one-dimensional nonlinear Gauss map with two bifurcation parameters. The authors found that the probability for the characteristic lifetimes follows a power law whose exponent is $\frac{1}{2}$. The chaotic transients for the Gauss map are found to exhibit the same universal behavior as those for the quadratic map.

5 Bifurcations and numerical analysis of nonlinear oscillations

In the first article in the category *Bifurcations and Numerical Analysis of Nonlinear Oscillations*, by Giraldo et al. [23], the authors report results for an open two-site Bose–Hubbard dimer. They investigate, within the framework of a semiclassical model with symmetric pumping, a transition that involves symmetry breaking and the creation of periodic oscillations and multistability as the pump strength is increased. They show that the associated one-parameter bifurcation diagram of the semiclassical model captures the essence of the statistical properties of computed quantum trajectories as the pump strength is increased.

The next article, by Jelleyman and Osinga [24], examines a phenomenon known as wild chaos in a noninvertible Lorentz-like map. Wild chaos is characterized by more than one positive Lyapunov exponent. The authors numerically detect the presence of wild chaos by comparing geometric criteria such as homoclinic and heteroclinic tangencies, and Lyapunov exponents in a range of parameters that goes beyond theoretical studies.

In the third article of this category, by Bengochea et al. [25], the authors study the existence of a family of periodic orbits in a three-dimensional vector field, which generalizes a model introduced by Yu and Wang in 2013. Such vector fields have a zero-Hopf singularity at a non-isolated equilibrium. The class of systems is formulated in the most general setting with a single parameter describing the family.

The next article, by de Leo et al. [26], studies static solutions of nematic superconductors in annular domains using Ginzburg–Landau equations. The authors present new numerical and analytical results on solutions that exhibit saturation of the order parameter in the interior of the domain. The main interest is in the dependence of the saturation region on the parameters, especially the radii. The numerical study combines a shooting method with asymptotic analysis near the boundary. The theory includes results on thresholds for nontrivial solutions and the behavior of these solutions near the critical points.

6 Multidisciplinary applications in engineering and control

In the first article in the category *Multidisciplinary Applications in Engineering and Control*, by Ho et al. [27], the authors report high-quality experimental results on high-speed 3D imaging using laser chaos. They characterize a new chaos LiDAR system configuration and demonstrate its capability for high-speed 3D imaging. Compared with previous schemes, the proposed scheme substantially increases the system technical capacities, such as frame rate and field of view. By quantitatively analyzing technical characteristics, such as the signal-to-noise ratio, the authors show that the proposed scheme has better detection performance suitable for practical applications.

The next article, by Takhi et al. [28], considers a controller that is used to synchronize a master–slave system. The systems present chaotic behavior, where the slave system displays disturbances and uncertainties to be investigated. A microcontroller implementation for the problem is presented.

The third article, by Chaudhary et al. [29], investigates a control technique wherein adaptation in conjunction with synchronization is employed to control chaos in a nonlinear chemical system both analytically and numerically. A Lyapunov function is used as a diagnostic for the suppression of complexity.

In the next article, by Shi et al. [30], a novel chaos-based encryption algorithm is studied. This algorithm assumes a 4D chaotic system based on a memristor model. There are two important steps in this algorithm: a Hash process to disturb the initial values of the chaotic system, followed by an S-box substitution and bit-XOR operation to change the pixel values. The results show the effectiveness of the proposed encryption algorithm.

In the fifth article, by Jiang et al. [31], a model for a memristor is considered, where the main goal is to propose a new XOR logic circuit. The nonlinear circuit model is one-dimensional, where in addition an external periodic driving signal is applied. Experiments are carried out that confirm the numerical simulations of the model.

The last article, by Uzun [32], presents a comparative analysis of the accuracy of several machine learning methods to reproduce the time series of different chaotic dynamical systems. These methods are known as support vector machines (SVM), naïve Bayes (NB), Knearest neighbor (KNN), and tree algorithms. Although all methods perform well, the fine KNN method yields the highest accuracy.

7 Fluid Flows: complex geometries and instabilities

In the first article in the category *Fluid Flows: complex geometries and instabilities*, by Llamoca et al. [33], the authors study reaction fronts inside a two-dimensional domain subject to a Poiseuille flow and focus on a cubic reaction-diffusion system with two chemicals. Both supportive and adverse Poiseuille flow with the flow velocity are addressed, where the width of the system is also a bifurcation parameter. The authors find that supportive flow favors stable symmetric fronts, while adverse flow can result in both symmetric and asymmetric fronts. For suitable bifurcation parameters, the fronts become oscillatory or may result in intermittent bursts in the front profile.

The second article, by Cáceres [34], studies the 1D linearized Boussinesq equation for the evolution of a surface gravity wave propagating in a random bottom. It addresses the correspondence between the solution of the linearized Boussinesq equation with the telegrapher's equation. It extends a previous analysis by the author to the weak and very weak regimes. It finds that the telegrapher's equation correspondence can be applied beyond the strong disorder limit as an approximation.

The next article, by Zhang et al. [35], investigates static solutions of a flow system coupled to thermal and magnetic fields. The equations model a nanofluid under the influence of an induced magnetic field and are reduced to a boundary value problem for an ordinary differential equation system solved by a shooting method. The results indicate conditions for faster flow and for thinner thermal boundary layer.

The fourth article, by Akram et al. [36], studies a hydromagnetic peristaltic flow system. The authors reduce the problem to a boundary value problem that they solve numerically. They discuss the influence of the different parameters of nanoparticle diffusivity.

The next article, by Qian et al. [37], considers peristaltic flow in a curved channel with sinusoidal boundary in a magnetic pseudoplastic fluid. The authors construct traveling wave solutions using an expansion method and investigate the flow and pressure as a function of the parameters.

The the sixth article in this category, by Mallikarjuna et al. [38], investigates heat transmission enhancement by nanoparticles in a fluid bounded by divergent walls. The fluid equations are reduced to an ODE boundary value problem for static solutions that is solved numerically. The authors display the dependence of the flow parameters as a function of nanoparticle concentration.

Finally, in the last article, by Nadeem et al. [39], the authors consider a model for a one-dimensional bubbly cavitating flow of elastic fluids. The effects of several parameters such as the velocity profile and bubble pressure are discussed in some detail.

8 Concluding remarks

This volume brings together topics from a wide spectrum of current research in nonlinear dynamics and its applications. We hope that this volume will be valuable to scientists, in particular in physics, engineering, and applied mathematics, who are interested in nonlinear phenomena and complex systems. We would like to thank all the authors of this special issue for their valuable contributions. We also wish to express our gratitude to the referees of the articles, for their helpful and thoughtful reviews. We thank the managing editor Sabine Lehr, team manager Sandrine Karpe, and the entire EPJ ST editorial staff for their kind assistance in preparing this issue. Special thanks are due to the Editor of EPJ ST, Professor Jürgen Kurths, for his support and for the opportunity to work on this special issue.

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