AIP | Chaos
An Interdisciplinary Journal of Nonlinear Science

Introduction: Collective dynamics of mechanical oscillators and beyond

Igor V. Belykh and Maurizio Porfiri

Citation: Chaos **26**, 116101 (2016); doi: 10.1063/1.4967727
View online: http://dx.doi.org/10.1063/1.4967727
View Table of Contents: http://scitation.aip.org/content/aip/journal/chaos/26/11?ver=pdfcov
Published by the AIP Publishing

CHAOS **26**, 116101 (2016)

Introduction: Collective dynamics of mechanical oscillators and beyond

Igor V. Belykh[1] and Maurizio Porfiri[2]
[1]*Department of Mathematics and Statistics and Neuroscience Institute, Georgia State University, 30 Pryor Street, Atlanta, Georgia 30303, USA*
[2]*Department of Mechanical and Aerospace Engineering, New York University Tandon School of Engineering, Brooklyn, New York 11201, USA*

(Received 30 October 2016; accepted 1 November 2016; published online 30 November 2016)

This focus issue presents a collection of research papers from a broad spectrum of topics related to the modeling, analysis, and control of mechanical oscillators and beyond. Examples covered in this focus issue range from bridges and mechanical pendula to self-organizing networks of dynamic agents, with application to robotics and animal grouping. This focus issue brings together applied mathematicians, physicists, and engineers to address open questions on various theoretical and experimental aspects of collective dynamics phenomena and their control. *Published by AIP Publishing.*
[http://dx.doi.org/10.1063/1.4967727]

Collective behavior in mechanical systems was discovered by the Dutch scientist Christiaan Huygens around 1665.[1] In the Huygens' setup, two pendulum clocks, hanging from a wooden beam, showed an "odd" symmetry and ended up oscillating in perfect anti-phase.[2–4] In recent years, collective dynamics has become an important topic with applications in a wide spectrum of biological and technological networks, including multi-robot teams, complex mechanical structures, and pedestrian bridges. This focus issue aims at the largely unexplored area of mathematical analysis and modeling of cooperative networks arising from different applications in mechanics and beyond. This highly interdisciplinary issue presents new research contributions which integrate knowledge from different disciplinary areas in applied mathematics and engineering, including stability theory, information theory, piecewise smooth and stochastic dynamical systems and networks, graph theory, classical mechanics, and bio-mechanics. We hope that this collection will contribute to further igniting interest in collective dynamics of mechanical oscillators and promoting interdisciplinary collaborations.

I. INTRODUCTION

The idea of organizing this focus issue was inspired by a successful two-part special session at the last 2015 SIAM Conference on Applications of Dynamical Systems that saw the participation of a large number of attendees and attracted significant interest during the conference.

This focus issue presents analytical, computational, and experimental studies toward an improved understanding of collective dynamics. The theoretical questions addressed here seek to clarify the relation between the dynamics of single units, composing a complex system, and the overall collective behavior. Such a collective response includes consensus in networks of mobile multi-agent systems, global chaotic synchronization of nonlinear oscillators, and the formation of chimera states. Stochastic communication, time-delays, limited bandwidth, dynamic and structural heterogeneities, and attacks on communication links are all investigated towards realistic, practical descriptions of collective mechanical systems.

Some of these theoretical constructs are demonstrated through careful modeling of complex mechanical systems, including metronomes, vibration machines, and bridges. Across a range of physical scales from a small metronome to a large bridge structure, a number of dynamical similarities are observed in their emergent response. For example, revisiting the classical experiment of Huygens through modern dynamical systems theory sheds light on the critical role of coupling in the stability of various synchronous states. Further insight into the striking complexity of collective dynamics in mechanical systems is garnered through experimental studies presented in this focus issue. Inverted bottle oscillators, metronomes on a lightweight platform, two-rotor vibration machines, and wobbling and aging bridges offer powerful experimental settings to demonstrate collective dynamics and unravel its physical underpinnings.

II. CONTRIBUTIONS TO THE FOCUS ISSUE

Jia *et al.*[5] analyze the dynamics of single and coupled inverted bottle oscillators, where each bottle oscillator is an oscillating flow of water in an inverted bottle. A number of novel phenomena are observed theoretically and experimentally. In a laboratory setup, the authors demonstrate the asymmetry and inhomogeneity of the single inverted bottle oscillator, along with in-phase and anti-phase synchronization and double frequency synchronization in the coupled system of two non-identical oscillators.

Buscarino *et al.*[6] study the interplay between synchronization and motion in a system of mobile agents. Motion is described according to the Vicsek model, a widely known model for self-propelled particles, and the dynamics is given by chaotic oscillators which become coupled when the positions of the corresponding agents are at a distance less than the interaction radius. The peculiar feature of this model is the presence of a transition from disordered to ordered motion as a function of its parameters. The authors exploit this characteristic to investigate how motion influences synchronization in the population of mobile chaotic oscillators. It is shown that that the effect of motion depends on the coupling strength; for some values of the coupling strength, the authors observe that all the oscillators converge towards the same trajectory when the motion is ordered. For other values of the coupling strength, the opposite may occur, whereby synchronization is promoted by disorder and inhibited by ordered motion.

Liu *et al.*[7] investigate a consensus problem for multi-agent systems. Considering the limited bandwidth of a real communication network, it is not practical to ensure the continuity of information transmission among neighboring agents in a multi-agent system. The authors propose new sampled-data-based algorithms for multi-agent systems with a directed communication topology. Consensus without a leader and containment with multiple leaders are studied, respectively, for a group of harmonic oscillators. Differing from existing algorithms, a remarkable advantage of the proposed sampled-data-based algorithms is that the sampling periods, communication topologies, and control gains are all decoupled and can be separately designed, relaxing restrictions in controllers' design.

Hoogeboom *et al.*[8] examine synchronization of a set of metronomes placed on a lightweight foam platform. While synchronization of pendulum clocks was observed by Christiaan Huygens in 1665, the phenomenon is still not entirely understood. It is known that there exist multiple types of limit behavior which are influenced by the coupling between the clocks or metronomes; however, it is unclear what determines the stability of these regimes. This paper contributes to the understanding of Huygens' synchronization by performing numerical modeling and experiments with two configurations of a set of metronomes. The configurations are a row setup containing one-dimensional coupling and a cross setup containing two-dimensional coupling. Depending on the configuration and coupling between the metronomes, that is, the platform parameters, in- and/or anti-phase synchronized behavior is observed in the experiments. It is numerically and experimentally demonstrated that varying the coupling parameters for both configurations has a significant influence on the stability of the synchronized solutions.

Dong *et al.*[9] study the vulnerability of a distributed consensus seeking multi-agent system. Due to the open nature of communication channels in networked multi-agent systems, the network is vulnerable to various malicious cyber attacks. The authors design a specific edge-bound content modification cyber attack which compromises the least number of communication links and renders the consensus dynamics of multi-agent systems unstable. The paper presents fast, distributed, model-free, and computationally light attack detection schemes and proposes an attack mitigation scheme.

Roy and Abaid[10] address the problem of coordinating multiple agents that interact and negotiate to reach an agreement, over a dynamic, random communication network. An important and interesting feature in this coordination problem is the existence of leadership by an individual or subset of the group. The agents representing the followers can communicate with any other agent, whereas agents serving as leaders are restricted to interact only with other leaders. The model incorporates the phenomenon of numerosity, which limits the perceptual capacity of the agents while allowing for shuffling with whom each individual interacts at each time step. The authors show that agents' traits can be chosen for an engineered system to maximize the convergence speed and that protocol speed is enhanced as the proportion of the leaders increases in certain cases.

Blaha *et al.*[11] put forward an experimental setup with three platforms containing a fixed number of metronomes to study the effects of network symmetries on the emergence of chimera states. In particular, the authors consider 15 metronomes per platform and observe that chimera states emerge for a broad range of parameters, namely, the metronomes' nominal frequency and the coupling strength between the platforms. The study shows that populations with few oscillators still exhibit chimera behavior although there is a minimum size under which chimeras no longer emerge. Many chimera states are also seen in the system when the coupling between platforms is asymmetric.

Dudkowski *et al.*[12] address the emergence of chimeras in coupled externally excited bistable oscillators, including mechanical oscillators. In particular, the authors analyze the influence of failure of external excitations due the fatigue of motors in physical mechanical oscillators on the stability of chimera states. Transitions between various types of chimeras as a function of the number of oscillators whose excitation is switched off are also reported in this study.

Chicoli and Paley[13] present a probabilistic information transmission model for individuals within a group. There are a variety of benefits to living in groups, many of which are conferred through information sharing between individuals. Useful information may include the location of a food source or the presence of a predator. One striking example of this benefit is the escape of a shoal of fish away from a potential threat. Fish that are unable to detect a threat directly may still respond rapidly by observing the movements of their neighbors. While differences in shoaling behavior have been observed in fish, it is unclear how the degree of alignment between individuals affects the response to predation. The authors model information spreading and the resulting escape response, demonstrating that the alignment of the group does affect the escape response. The model may be of general use in studying emergency planning, where panic spreads through a group.

Koh and Sipahi[14] investigate a multi-robot coordination problem which is influenced by communication/activation delays. In the presence of delays, there exists a certain delay margin which destabilizes the system. This margin depends strongly on agents' dynamics and the agent network. The authors study the role of three key elements, namely, the delay margin, network graph, and a distance threshold conditioning two agents' connectivity. They show that when the collective dynamics is unstable under this delay, its states can be naturally bounded, even for arbitrarily large threshold values, preventing agents to disperse indefinitely. This mechanism can push the system to recover stability in a self-regulating manner, mainly induced by network separation and enhanced delay margin.

Fradkov *et al*.[15] address the classical control problem of how to move a mechanical system from any initial state to any final state by means of controlling a force of small intensity. The authors study the control problem of start-up and passage through resonance in a two-rotor vibration machine. In this setup, the main practical problem is the generation of useful oscillations and the suppression of harmful ones. They show that the application of a feedback control makes passage through lower resonance feasible, with smaller control intensity compared with passage through resonance under a constant control torque. Particular attention is paid to the case where constant control torques do not allow the rotors to even start their rotation, such that the applied feedback control helps the rotors overcome gravity and initiate rotation.

Lombana and di Bernardo[16] study the problem of achieving synchronization in networks of nonlinear units coupled by dynamic diffusive terms. The authors consider two types of coupling consisting of a static linear term and a dynamic term, which can be either the integral or derivative of the sum of the mismatches between the states of neighbouring agents. The resulting dynamic coupling strategy is a distributed proportional-integral or proportional-derivative law that is shown to be effective in improving network synchronization, for example, when the dynamics at the nodes are nonidentical. The approach is verified via a set of representative examples including networks of nonlinear mechanical systems.

Ambegedara *et al*.[17] study noninvasive damage detection of highway bridges. The authors consider information-theoretic measures, including entropy and mutual information which require minimal assumptions regarding the specific location, material, and age of the bridge. The data used in this study are time series collected on spatially distributed sensors from a controlled damage experiment performed on a local bridge in upstate New York. In particular, the authors demonstrate that the spatial nearest-neighbor interactions as measured by mutual information tend to become weaker as more damage is present. This is consistent with the intuition that less force and energy pass between adjacent sites as the bridge is "loosened" due to the removal of bolts.

Belykh *et al*.[18] investigate the dynamics of pedestrian lateral locomotion and its interaction with a bridge, demonstrating that this bi-directional interaction enables two distinct lateral gaits. Both gaits can stably co-exist such that a misstep can cause the pedestrian to switch gait, potentially causing wilder bridge oscillations. The authors show that this bistability is controlled by the pedestrian mass, where heavier pedestrians are more prone to switching to the gait with stronger bridge wobbling. These observations may offer guidance for choosing the best strategy for a hiker with a heavy backpack to traverse light rope hanging bridges in the Himalayas, where a heavier hiker might want to send the backpack over the ropes separately to reduce the risk of the abrupt onset of large bridge swaying.

III. OPEN QUESTIONS AND FUTURE CHALLENGES

The area of collective behavior in mechanical systems is rich with open problems and challenges. We hope that this focus issue will encourage and motivate junior readers to approach this exciting field of research. We believe that the contributions collected here, together with other recent special issues on evolving networks[19] and patterns of network synchronization,[20] address some of the existing critical questions. However, many more questions remain open across theoretical and experimental research. For example, models of communication networks should address spatio-temporal correlation between the states and activation of network links, toward an improved understanding of data drop-out and agents' mobility. With respect to multi-robot teams, these models are critical for predicting the performance of the system in structured and unstructured environments, where communication is influenced by both the configuration of the team and presence of obstructions. Just as noise and uncertainty may influence communication, they may affect individual dynamics, resulting in unpredicted heterogeneities. Whether these heterogeneities strengthen or weaken the collective dynamics of the system remains an elusive question.

Beyond modeling, another theoretical aspect that is fertile with important problems is the control of collective dynamics to engineer coordinated motions via localized control actions. Coordinated motions may include global synchronization patterns and chimera states, generated by tailored control actions on network connections and individual units' dynamics. For mechanical systems, there may be a non-trivial trade-off between performance and energy expenditure, which is further exacerbated by partial observability and under-actuation. This is particularly relevant to multi-robot teams where limited battery life, sensory payload, and mechanical design may challenge the synthesis of decentralized control algorithms.

One of the application domains for modeling and control of networked mechanical systems is at the interface between engineering and biology. Therein, intensive research is being pursued to investigate hybrid systems consisting of human-made engineering artifacts that interact with natural, living organisms. For example, recent efforts have indicated the possibility of influencing collective behavior of animal groups through biologically inspired robots.[21–23] The potential integration of biologically inspired robots in laboratory and field experiments has been demonstrated in a number of species, spanning from insects to mammals. The design of control strategies is, however, in its infancy, due to the complexity of animal response which strains the use of existing strategies that are often grounded by accurate knowledge of the networked units. New data-driven strategies are likely needed to address this issue, perhaps tapping into different research fields, such as machine learning and behavioral control. Another relevant example of a hybrid system, presented in this focus issue, is constituted by bi-directional interactions of walkers with a pedestrian bridge.[18] Similar to animal grouping, understanding the response of the pedestrian bridge will require new insight into the mathematical analysis of human collective behavior.

While experimental research is rapidly progressing, a number of practical challenges are responsible for the considerable gap between theory and experiments. On a computer, one can simulate arbitrarily large coupled systems with identical properties and a precise communication network. However, practicality dictates the size of the system and its tolerance, limiting the validation of theoretical results to relatively small-scale systems with constrained interactions. For example, it may be difficult to systematically and experimentally study the role of the network topology in the collective dynamics of mechanical systems, including metronomes and inverted bottle oscillators discussed in this focus issue. Perhaps, another interesting area of research could entail the design of new small-scale, customizable mechanical oscillators for performing controlled laboratory experiments. While the work presented in this focus issue[11] addresses some of these elements, more investigations are needed. Another challenge is the measurement of large scale dynamics and subsequent identification of model parameters from noisy data of the collective response. This problem is touched upon in this focus issue in regard to damage identification in highway bridges.[17]

ACKNOWLEDGMENTS

We are thankful to the Editor-in-Chief, Jürgen Kurths, for encouraging the preparation of this focus issue and the Chaos editorial staff, Kristen Overstreet, Deborah Doherty, Melissa Guasch, and Ying Liu, for the guidance and assistance. We are grateful to the organizers of the 2015 SIAM Conference on Applications of Dynamical Systems, who provided a forum that inspired this issue. Finally, we are indebted to the authors and reviewers for their invaluable contributions. This editorial work was supported by the National Science Foundation under Grant Nos. DMS 1616345, CMMI 1561134, CMMI 1505832, CMMI 1433670, and the U.S. Army Research Office Network Science Division under Grant No. W911NF-15-1-0267.

[1] C. Huygens, "Letter to de Sluse," in *Oeuveres Completes de Christian Huygens (Letters; No. 1333 of 24 February 1665, No. 1335 of 26 February 1665, No. 1345 of 6 March 1665)* (Societe Hollandaise Des Sciences, Martinus Nijho, La Haye, 1665).
[2] M. Bennett, M. F. Schatz, H. Rockwood, and K. Wiesenfeld, "Huygens's clocks," Proc. R. Soc. London, Ser. A **458**, 563 (2002).
[3] A. Pikovsky, M. Rosenblum, and J. Kurths, *Synchronization: A Universal Concept in Nonlinear Sciences* (Cambridge University Press, Cambridge, 2001).
[4] J. P. Ramirez, L. A. Olvera, H. Nijmeijer, and J. Alvarez, "The sympathy of two pendulum clocks: Beyond Huygens' observations," Sci. Rep. **6**, 23580 (2016).
[5] J. Jia, Z. Shangguan, H. Li, Y. Wu, W. Liu, J. Xiao, and J. Kurths, "Experimental and modeling analysis of asymmetrical on-off oscillation in coupled non-identical inverted bottle oscillators," Chaos **26**, 116301 (2016).
[6] A. Buscarino, L. Fortuna, M. Frasca, and S. Frisenna, "Interaction between synchronization and motion in a system of mobile agents," Chaos **26**, 116302 (2016).
[7] Y. Liu, Y. Zhao, and G. Chen, "Sampled-data-based consensus and containment control of multiple harmonic oscillators: A motion-planning approach," Chaos **26**, 116303 (2016).
[8] F. N. Hoogeboom, A. Y. Pogromsky, and H. Nijmeijer, "Huygens' inspired multi-pendulum setups: Experiments and stability analysis," Chaos **26**, 116304 (2016).
[9] Y. Dong, N. Gupta, and N. Chopra, "Malignant content modification attacks on consensus seeking multi-agent system with double-integrator dynamics," Chaos **26**, 116305 (2016).
[10] S. Roy and N. Abaid, "Leader-follower consensus and synchronization in numerosity-constrained networks with dynamic leadership," Chaos **26**, 116309 (2016).
[11] K. Blaha, R. J. Burrus, J. L. Orozco-Mora, E. Ruiz-Beltrán, A. B. Siddique, V. D. Hatamipour, and F. Sorrentino, "Symmetry effects on naturally arising chimera states in mechanical oscillator network," Chaos **26**, 116307 (2016).
[12] D. Dudkowski, Y. Maistrenko, and T. Kapitaniak, "Occurrence and stability of chimera states in coupled externally excited oscillators," Chaos **26**, 116306 (2016).
[13] A. Chicoli and D. A. Paley, "Probabilistic information transmission in a network of coupled oscillators reveals speed-accuracy trade-off in responding to threats," Chaos **26**, 116311 (2016).
[14] M. H. Koh and R. Sipahi, "A consensus dynamics with delay-induced instability can self-regulate for stability via agent regrouping," Chaos **26**, 116313 (2016).
[15] A. Fradkov, D. Gorlatov, O. Tomchina, and D. Tomchin, "Control of oscillations in vibration machines: Start up and passage through resonance," Chaos **26**, 116310 (2016).
[16] D. A. B. B. Lombana and M. di Bernardo, "Synchronization and local convergence analysis of networks with dynamic diffusive coupling," Chaos **26**, 116308 (2016).
[17] A. S. Ambegedara, J. Sun, K. Janoyan, and E. Bollt, "Information theoretical noninvasive damage detection in bridge structures," Chaos **26**, 116312 (2016).
[18] I. V. Belykh, R. Jeter, and V. N. Belykh, "Bistable gaits and wobbling induced by pedestrian-bridge interactions," Chaos **26**, 116314 (2016).
[19] I. Belykh, M. di Bernardo, J. Kurths, and M. Porfiri, "Evolving dynamical networks," Physica D **267**, 1 (2014).
[20] D. Abrams, L. M. Pecora, and A. Motter, "Introduction to focus issue: Patterns of network synchronization," Chaos **26**, 094601 (2016).
[21] S. Butail, N. Abaid, S. Macri, and M. Porfiri, "Fish-robot interactions: Robot fish in animal behavioral studies," in *Robot Fish, Part IV* (Springer, 2015), pp. 221–240.
[22] A. Frohnwieser, J. C. Murray, T. W. Pike, and A. Wilkinson, "Using robots to understand animal cognition," J. Exp. Anal. Behav. **105**, 14 (2016).
[23] J. Krause, A. F. T. Winfield, and J. L. Deneubourg, "Interactive robots in experimental biology," Trends Ecol. Evol. **26**, 369 (2011).