Perspectives in flow-induced vibration energy harvesting

Wang, Junlei; Yurchenko, Daniil; Hu, Guobiao; Zhao, Liya; Tang, Lihua; Yang, Yaowen

2021

Wang, J., Yurchenko, D., Hu, G., Zhao, L., Tang, L. & Yang, Y. (2021). Perspectives in flow-induced vibration energy harvesting. Applied Physics Letters, 119(10), 100502-. https://dx.doi.org/10.1063/5.0063488

https://hdl.handle.net/10356/161206

https://doi.org/10.1063/5.0063488

Applied Physics Letters

Perspectives in flow-induced vibration energy harvesting

Cite as: Appl. Phys. Lett. **119**, 100502 (2021); https://doi.org/10.1063/5.0063488
Submitted: 15 July 2021 • Accepted: 24 August 2021 • Published Online: 09 September 2021

Junlei Wang, Daniil Yurchenko, Guobiao Hu, et al.

AIP Publishing

Applied Physics Letters PERSPECTIVE scitation.org/journal/apl

Perspectives in flow-induced vibration energy harvesting

Cite as: Appl. Phys. Lett. **119**, 100502 (2021); doi: 10.1063/5.0063488
Submitted: 15 July 2021 · Accepted: 24 August 2021 ·
Published Online: 9 September 2021

View Online Export Citation CrossMark

Junlei Wang,[1] Daniil Yurchenko,[2] Guobiao Hu,[3,a)] Liya Zhao,[4] Lihua Tang,[5] and Yaowen Yang[3]

AFFILIATIONS

[1]School of Mechanical and Power Engineering, Zhengzhou University, Zhengzhou 450000, China
[2]Institute of Mechanical, Process and Energy Engineering, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom
[3]School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore
[4]School of Mechanical and Mechatronic Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney, NSW, Australia
[5]Department of Mechanical Engineering, University of Auckland, Auckland, Auckland 1010, New Zealand

[a)]Author to whom correspondence should be addressed: guobiao.hu@ntu.edu.sg

ABSTRACT

Flow-induced vibration (FIV) energy harvesting has attracted extensive research interest in the past two decades. Remarkable research achievements and contributions from different aspects are briefly overviewed. Example applications of FIV energy harvesting techniques in the development of Internet of Things are mentioned. The challenges and difficulties in this field are summarized from two sides. First, the multi-physics coupling problem in FIV energy harvesting still cannot be well handled. There is a lack of system-level theoretical modeling that can accurately account for fluid–structure interaction, the electromechanical coupling, and complicated interface circuits. Second, the robustness of FIV energy harvesters needs to be further improved to adapt to the uncertainties in practical scenarios. To be more specific, the cut-in wind speed is expected to be further reduced and the power output to be increased. Finally, Perspectives on the future development in this direction are discussed. Machine-learning approaches, the versatility of metamaterials, and more advanced interface circuits should receive more attention from researchers, since these cutting-edge techniques may have the potential to address the multi-physics modeling problem of FIV energy harvesters and significantly improve the operation performance. In addition, in-depth collaborations between researchers from different disciplines are anticipated to promote the FIV energy harvesting technology to step out of the lab and into real applications.

I. INTRODUCTION

In the context of the rapid development of Internet of Things (IoTs) [including Industrial Internet of Things (IIoTs)], providing power supply for billions of network devices to guarantee their perpetual operation in heterogeneous environments has been recognized as one of the biggest challenges. Energy harvesting technology has been widely deemed as a promising way to enable low-power consumption IoT devices to be self-sustained.[1] Over the past two decades, harnessing energy from ambient vibration has been extensively explored. Wind induced by atmospheric motion is one of the most ubiquitous natural energy sources on Earth, and water covers 71% of the Earth's surface. Both wind and water circulation have inspired the exploration of flow-induced vibrations (FIVs) phenomena, which facilitate the hydrokinetic energy conversion based on the readily available knowledge of vibration energy harvesting. It is worth mentioning that various rotational devices have also been proposed by researchers for wind energy harvesting.[2–5] Rotational energy harvesters, especially electromagnetic ones, can usually produce larger power outputs. However, vibration-based energy harvesters are often more compact. The main structure of many vibration-based energy harvesters is only a thin beam. Therefore, vibration-based energy harvesters are more suitable for miniaturization.[6] Figure 1 illustrates several scenarios where abundant wind/water sources can be found, including: (a) high-rise buildings under wind loading; (b) remote areas with streaming rivers; (c) metro stations and tunnels with blasts of wind generating by passing trains; (d) tall bridges with accessible wind and water flow sources; and (e) oceans waves and currents. Due to the universality Perspective of the energy source, FIV energy harvesting appears to be more promising compared to ambient vibration energy harvesting. On the other hand, the underlying mechanism of flow-induced

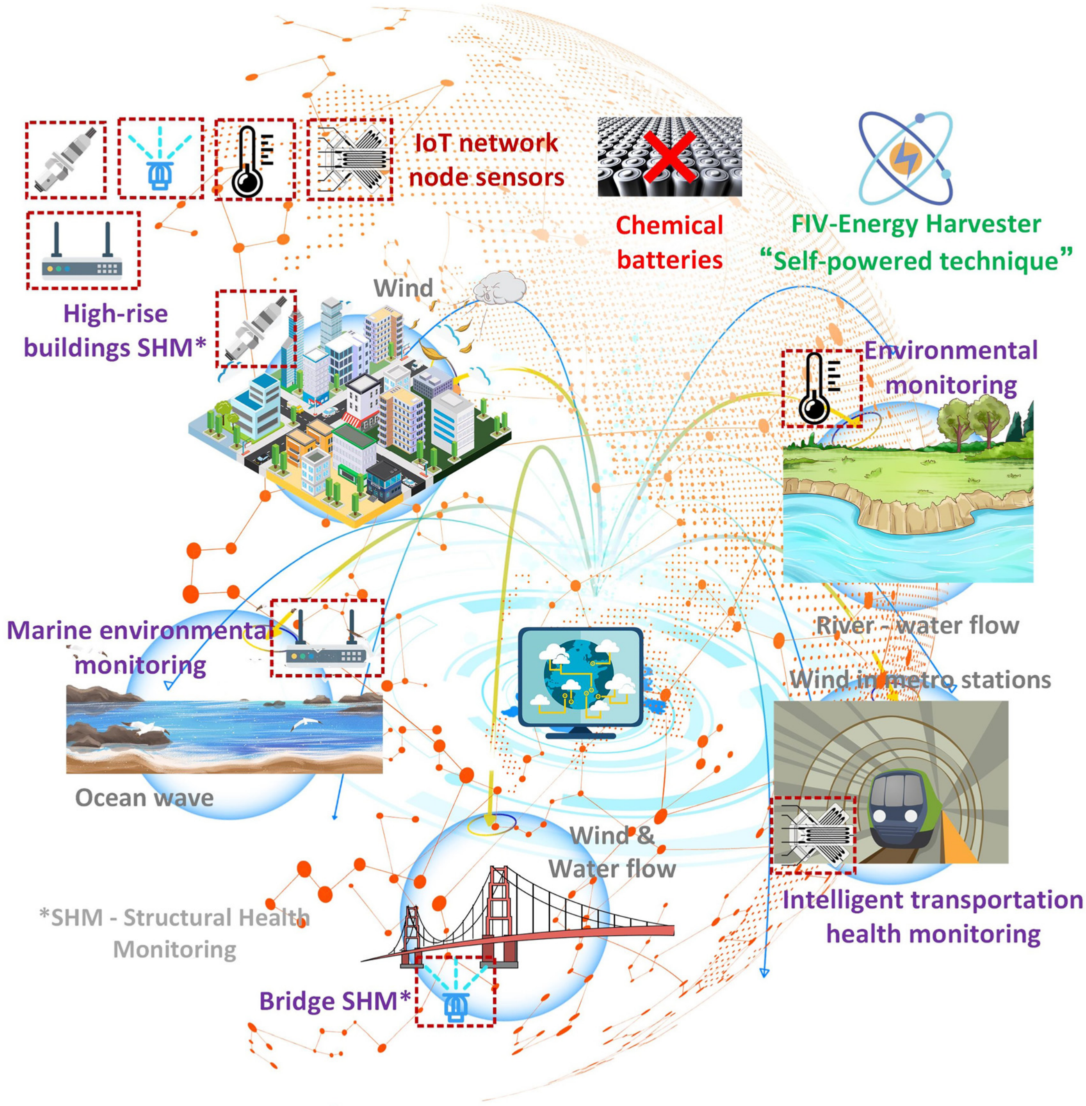


FIG. 1. Potential application scenarios of flow-induced vibration energy harvesters to realize self-powered IoT network nodes, including high-rise buildings under great wind effects, remote areas with streaming rivers, metro stations and tunnels with blasts of wind, tall bridges with accessible wind and water flow sources, and oceans with ceaseless waves and currents.

vibration is the occurrence of limit-cycle oscillations in the system. A flow-induced vibration usually takes place around the resonant frequency of a system and undergoes large-amplitude motion. Thus, the small-amplitude and low-frequency issues in ambient vibrations never exist in flow-induced vibration. Therefore, from the Perspective of the underlying mechanism behind the physical phenomenon, flow-induced vibration is intrinsically easier to be harnessed and more efficient than harvesting ambient vibrations, which often have very little energy available for scavenging. For the above reasons, FIV energy harvesting has been massively researched in recent years. It is envisioned that the successful applications of FIV energy harvesters in various scenarios will enable the IoT network node sensors to be self-sustained by extending the operating lifetime and finally promoting the development of IoT networks.

II. MULTI-PHYSICS PROBLEMS IN FIV ENERGY HARVESTING

FIV energy harvesting is multidisciplinary research that involves a number of problems, including fluid-structure interaction, vibrations, stability and bifurcation, electromechanical coupling, interface circuit design, and power management. Figure 2 presents and summarizes the relationships between the multi-physics problems in designing a general flow-induced vibration energy harvester. A brief survey will be provided on the state of the art in this field from the

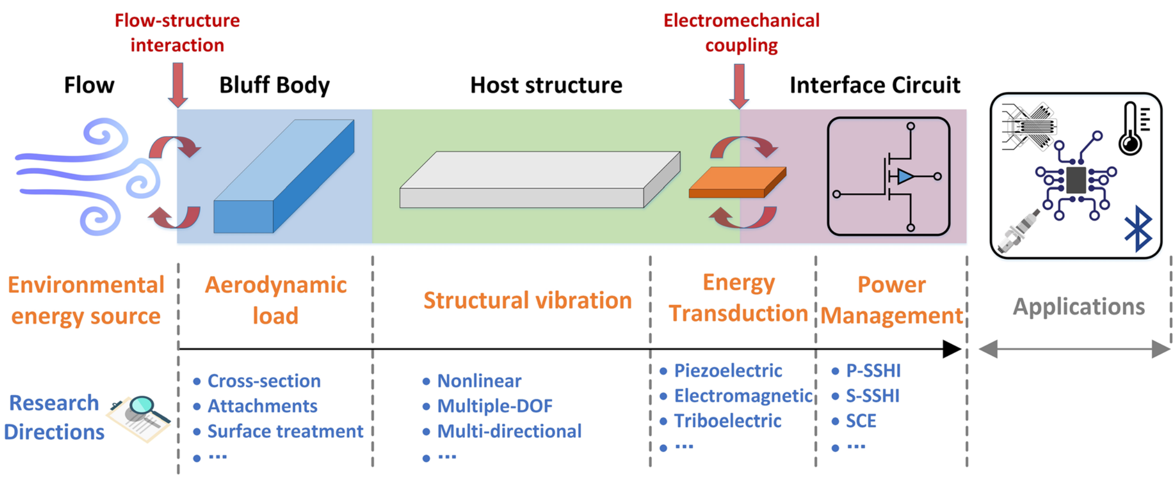


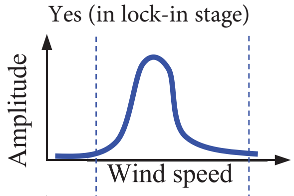
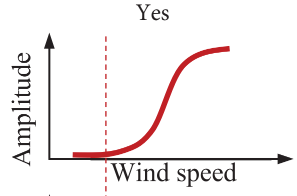
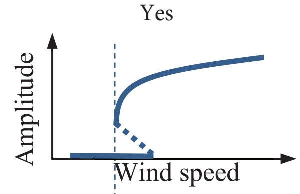
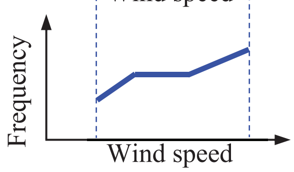
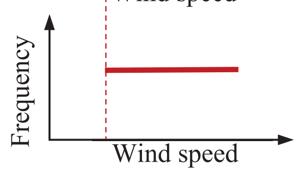
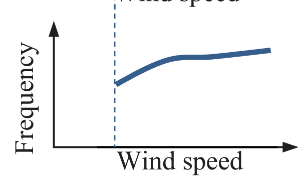
FIG. 2. Multi-physics problems in flow-induced vibration energy harvesting.

Perspectives of different disciplines. Several comprehensive review papers on this topic can be found in Refs. 7–10.

A. Fluid–structure interaction

The flow-induced vibration constitutes the first step toward converting the hydrokinetic energy into mechanical energy. According to the underlying mechanisms, common FIV phenomena can be classified into galloping,[11,12] vortex-induced vibration (VIV),[13,14] flutter,[15,16] and buffeting.[17] According to the literature, galloping and vortex-induced vibration are the most comprehensively explored phenomena for energy harvesting. Different flow-induced vibration phenomena are the consequences of different types of aerodynamic instabilities. Their corresponding aeroelastic responses are, thus, different. Table I summarizes and compares the aerodynamic response characteristics of VIV, galloping, and flutter in detail. The fluid-structure interaction (FSI) refers to the bidirectional coupling between the physic laws that describe fluid dynamics and structural mechanics. The computation of FSI problem remains a challenge due to the strong inherent nonlinearity. In the field of FIV energy harvesting, since the FSI problem just constitutes one of the multi-physics problems, the quasi-steady hypothesis (QSH) is often adopted to simplify the problem.[18] The QSH assumes that the aerodynamic force applied on the oscillating solid body equals when the solid body is at a steady state. This hypothesis is valid under the condition that the characteristic timescale of the flow is much smaller than that of the imposed oscillations. Based on the QSH, one can perform CFD simulations[19] or experimental tests[20] to figure out the relationship between the flow speed and the aerodynamic force, depending on the shape and roughness of the structure. A data fitting technique is often used to interpret the obtained

TABLE I. Comparison of the aerodynamic response characteristics, i.e., velocity-amplitude and velocity-frequency relationships, of vortex-induced vibration and galloping.

	Vortex-induced vibration	Galloping	Flutter
Threshold flow-speed	Yes	Yes	Yes
Lock-in	Yes	No	No
Limit-cycle oscillation	Yes (in lock-in stage)	Yes	Yes
Amplitude			
Vibration frequency			

relationship into an explicit mathematical expression in the form of, such as, polynomial functions.[21] In this way, the FSI problem is basically addressed to pave the way for the theoretical systematic level modeling of the whole multi-physics system.

In a given flow field, the aerodynamic force acting on the solid bluff body depends on the geometry. The cross-sectional profiles of commonly used bluff bodies include square, rectangle, triangle, D-shape, etc. Among these traditional bluff bodies, an experimental study indicated that a square-sectioned bluff body usually demonstrates a better aerodynamic performance for benefiting galloping energy harvesting.[22] Since the bluff body plays a dominant role, enormous efforts have been devoted to exploring innovative bluff bodies to improve the FIV energy harvesting performance. For example, experimental results showed that using a fork-shaped bluff body could increase the generated energy output and reduce the onset/cut-in wind speed.[23] Another study also pointed out that a fork-shaped bluff body could strengthen the vorticity to obtain a high air lift force.[24] Compared with triangular and square-sectioned bluff bodies, using a fork-shaped bluff body increased the power output of the wind energy harvester by up to 5 times.[24] Rather than redesigning the bluff body, attaching ornaments to traditional bluff bodies is another way to alter the fluid-structure interaction and the aerodynamic behavior. A study showed that adding Y-shaped attachments on a cylinder bluff body could lead to the transition from VIV to galloping.[25] Due to the aerodynamic phenomenon transition, the introduction of Y-shaped attachments significantly enlarged the bandwidth of operating wind speeds. Other similar studies include adding ornaments/attachments on the bluff body[13,26,27] and decorating the bluff body by metasurface treatment[19] for improving the efficiency of a wind energy harvester.

In recent years, efforts have also been devoted to achieving coupled VIV and galloping phenomena for wind energy harvesting. A coupled VIV-galloping region is expected to have a lower cut-in wind speed, inherited from VIV, and a broad operation wind speed region, inherited from galloping. Therefore, coupled VIV-galloping energy harvesters are supposed to exhibit better performance. Both experimental investigations[28,29] and theoretical studies[30,31] have been carried out. In addition, energy harvesting systems using multiple bluff bodies have been investigated. Due to the existence of multiple bluff bodies, the wake galloping effect should be considered. Such problems could be generally divided into two kinds: whether the main structure vibrates, while the interacting structure stays stable or vibrates together, which is nearly impossible to accurately develop a theoretical model to describe the aerodynamic force.

B. Structural vibration

Besides the aerodynamic load determined by the bluff body, the flow-induced vibration also depends on the dynamics of the elastic structure attached to the bluff body. Therefore, various innovative structures have been proposed for FIV energy harvesting. A cantilevered beam is the most typical structure that has been widely used to constitute the host structure of an FIV energy harvester. Inspired by the successful applications of nonlinearities in energy harvesting from a base excitation, multi-stable systems with a number of potential wells have been utilized to increase the power output of FIV.[8,32] For instance, experimental studies have shown that the cut-in wind speed of a bistable galloping energy harvester can be reduced up to 41.9%.[33,34] For the coupled VIV and galloping energy harvester, introducing a magnet-induced monostable nonlinearity was proved to increase the voltage amplitude and reduce the cut-in wind speed.[30] Lately, the studies of linear FIV energy harvesters are extended to nonlinear ones. From another aspect of the literature review, one can find that the development of FIV energy harvesters evolves from single-degree-of-freedom to multiple-degree-of-freedom.[35] An experimental study first disclosed that the dynamic response of a two-degree-of-freedom Galloping Piezoelectric Energy Harvester (GPEH) is more complex: different modes can be activated under different conditions.[36] A theoretical study provided a foundation to explain the mode activation phenomenon in a 2DOF GPEH reported.[37] Recently, in view of the successful applications of metamaterials in various disciplines, an original study showed that introducing the metamaterial concept in the design of a multiple-degree-of-freedom GPEH could increase the power output by about 171.2%.[38]

C. Energy transduction

Several energy transduction mechanisms, such as piezoelectric,[39] electromagnetic,[40] triboelectric,[41] and electrostatic,[42] can be employed to convert vibration energy into electrical energy. Piezoelectric transducers in the form of thin patches are the most widely used by appropriately bonding them onto an elastic structure, resulting in a considerable voltage output. Lots of designs using piezoelectric and electromagnetic transductions are summarized in the literature review papers.[7,8] In recent years, triboelectric materials have been extensively researched and utilized in the design of energy harvesters. The triboelectric effect refers to the phenomenon that two originally uncharged bodies become charged when brought into contact and then separated.[41] The triboelectric effect universally occurs between materials with different charge affinities, and the biggest merit of triboelectric materials is their low cost.[43] The utilization of triboelectric materials has greatly diversified the design of wind energy harvesters. Unlike traditional structures, like beams, plates, etc., triboelectric energy harvesters can be designed in the form of a shoe-pad,[44] a morphing wing skin of an unmanned aerial vehicle (UAV),[45] and using various materials, such as leaf powder.[46]

D. Interface circuits and power management

The interface circuit is also an important component to constitute a whole energy harvesting system. Parallel/series synchronized switching harvesting on inductor (P/S-SSHI)[47,48] and synchronized charge extraction (SCE)[49] are typical interface circuits designed to boost the efficiency of a piezoelectric energy harvester from FIV.[50] A study comprehensively compared the performance of four typical interface circuits for galloping energy harvesting can be found in Ref. 51. Overall speaking, though more advanced interface circuits have emerged in the field of piezoelectric energy harvesting from base excitations,[52,53] using advanced interface circuits for wind energy harvesters has received far less attention to date. The reason is that the complexity of the multi-physics coupling problems in wind energy harvesting prevents further in-depth considerations of complicated interface circuits. To partly address the complex multi-physics coupling problem, the equivalent circuit representation method[54] brings the opportunity to establish a system-level model of the whole energy harvesting device that contains aerodynamics, elastic vibrations, piezoelectric materials, and interface circuits. Examples of establishing the equivalent circuit models of a galloping energy harvester[55] and a VIV-based energy harvester[20] can be found in the literature.

E. IoT applications

With the fast development of IoT technology, there will be an urgent need to address the power supply requirements of the widespread IoT sensor networks. The ultimate goal of developing a reliable and efficient wind energy harvester is to provide the power supply for low-power consumption devices in IoT applications. Existing examples of using wind energy harvesters in real circumstances include smart building sensing application,[56] tunnel lighting application,[57] self-powered wind barrier monitoring application,[58] etc. From the ViPSN prototype developed as a programmable IoT platform by Li *et al.*,[59] it can be found that to serve a relatively real application, the demo prototype consists of many modules to improve the system's extensibility. In another work by Liu *et al.*,[60] wireless energy harvesting technology was proposed to be adopted in constituting an IIoT to achieve a larger transmission rate. In general, according to the literature review, one can find that researchers have placed lots of hopes on the energy harvesting technology for IoT applications.[61,62]

III. CHALLENGES AND DIFFICULTIES

Though wind energy harvesting technology has been developing for the last two decades, successful applications and mature commercial products are still relatively rare. The real ambient environment and external excitations are ever-changing, featuring uncertainties and poor predictability. To further mature and promote the wind energy harvesting technology enabling its commercialization for various practical applications, it is essential to address the difficulties and challenges this field currently faces.

- Multi-physics coupling analysis
  From the fundamental Perspective, the development of theoretical methods of modeling and predicting the dynamics of the wind energy harvesters is essential for their superior design and the system-level optimization. Despite a variety of available theoretical methods in each physical domain, there is a lack of comprehensive system-level modeling methods that can simultaneously taking into account of the FSI effect, the elastic vibration behavior, the bidirectional electromechanical coupling, and the complicated interface circuits.
- Robustness improvement
  As aforementioned, the random feature of the energy source in the ambient environment poses a great difficulty on the energy harvesting technology. How to improve the robustness of an energy harvester, i.e., widen its operation bandwidth and increase its power output, is of great importance from the application Perspective. However, various conventional ways to achieve system robustness improvement, including modifying the bluff body, introducing nonlinearities, extending the design to a multiple-degree-of-freedom system, etc., have been explored. Novel concepts from other fields may be introduced to reinvigorate the research of wind energy harvesters.

IV. PROSPECTIVE DIRECTIONS

After two decades' development, what are the wind energy harvesters of the future, and what research directions and efforts the scientific society should undertake to achieve this remarkable future? This section discusses several prospective directions.

A. Machine-learning approaches for addressing the FSI problem

The nonlinear aerodynamics of the FSI problem is literally the biggest stumbling block on the way to accurately model wind energy harvesters. The conventional method of representing the nonlinear aerodynamic force is by data curve fitting using polynomial functions. However, the results in the literature showed that none of the polynomial functions could accurately represent the aerodynamic force relationship, and a different choice of polynomial functions might result in a different prediction result.[21] For example, the results in Ref. 21 showed that there could be a more than 150% discrepancy between the predictions of the power output from a GPEH when using fifth and seventh polynomial functions to fit the same experimental data for representing the aerodynamic force.

In recent years, with the wide implementation of machine learning approaches in various disciplines, researchers have attempted to employ them for addressing the FSI problem as well. A recent study treated the whole wind energy harvester as a black box with specified input (wind speed and cross section type) and output (voltage output and maximum displacement) parameters. Their technique roadmap is demonstrated in Fig. 3(a). The authors explored the feasibility of training a machine learning model based on a series of experimental results for predicting the root mean square (RMS) voltage output from the wind energy harvester.[63] The major advantage of this scheme is that without knowing the underlying physics behind the multi-physics problem, the complicated effects of various factors on the energy harvesting performance of the wind energy harvester can be revealed by a well-trained machine learning model. However, from another Perspective, a well-trained machine learning model cannot provide any in-depth insight into the fundamental physics and mechanisms. Therefore, it could also appear to be the disadvantage of this scheme. Another preliminary study was proposed to use the machine learning approach to represent the nonlinear aerodynamic force relationship first and then integrate with the finite element model of the wind energy harvester for predicting its dynamic response.[64] The technical procedures are elaborated in Fig. 3(b). In this scheme, the machine learning technique is used to only cope with the most challenging part, i.e., FSI problem, while the other discipline-related parts are still dealt with by the existing mature approaches. The advantages of this scheme are twofold. First, fewer training samples, i.e., less experimental data, are required, since the problem in the black box is much simpler. Second, the obtained model is partly supported by solid theories, thus can help understand the mechanisms behind the whole system. Despite these works, the research of the application of machine learning approaches for modeling wind energy harvesters is still in its infancy stage. It is envisioned that future studies may promote the application of machine learning approaches in addressing the FSI problem using regression analysis and various global optimization techniques.

B. Metamaterial-based design for improving the performance

Various innovative structures for wind energy harvesting have been proposed in the last two decades. In recent years, enormous efforts have also been dedicated to employing metamaterials for

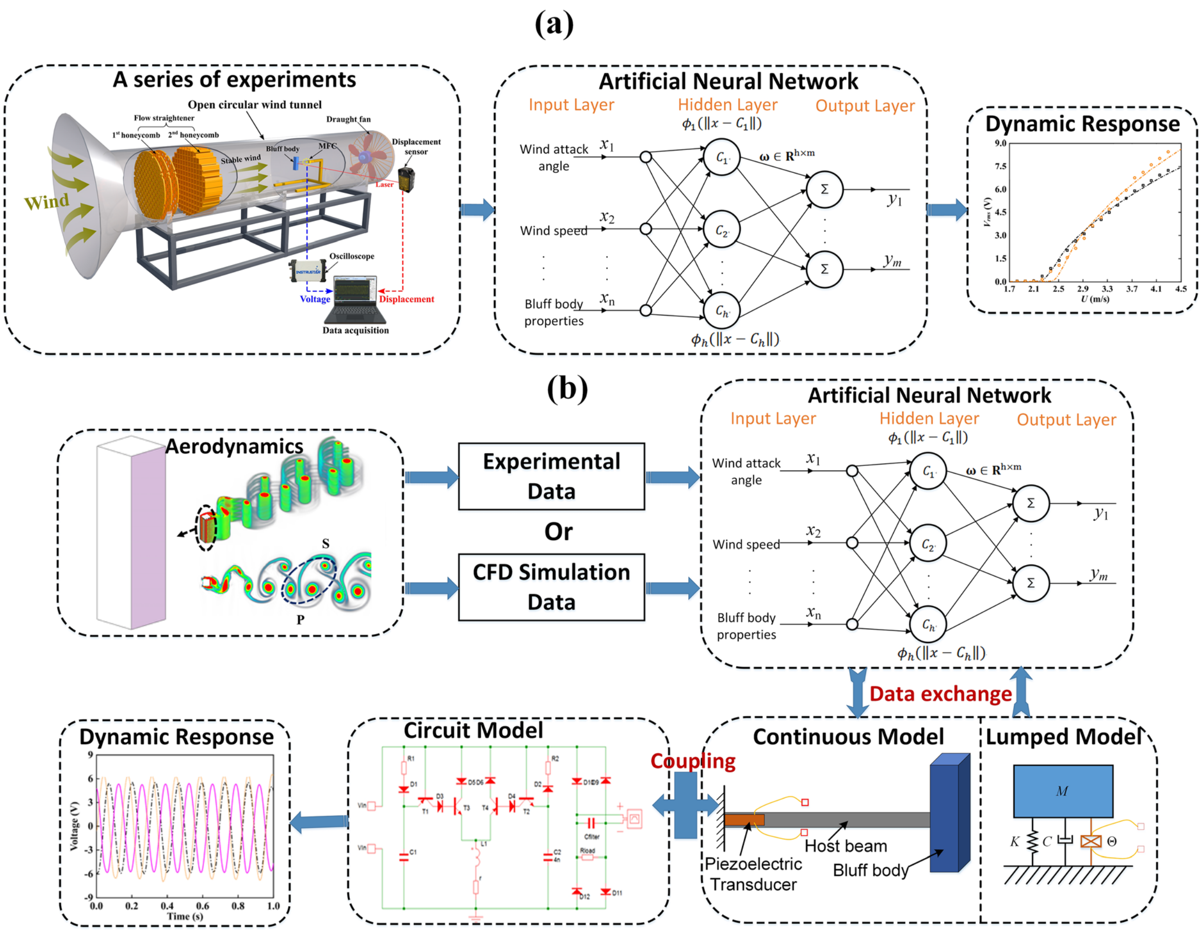


FIG. 3. Two general schemes for the application of the machine-learning technique in modeling an FIV energy harvester. (a) Scheme A[63] and (b) Scheme B.[64]

harvesting energy from base excitations. The extraordinary phenomena in metamaterials, such as negative refraction induced wave focusing,[65] the defect state mode,[66] and the topological interface mode,[67] have been successfully employed for improving energy harvesting efficiency.[68] In view of the prosperous examples in the base excitation energy harvesting, it is naturally wondered that could the metamaterial concept be adopted in the design of wind energy harvesters as well. Two recent studies attempted to explore the feasibility of the above idea. Their results showed that on the one hand, the metamaterial concept could be borrowed in the design of the bluff body to alter its aerodynamics for improving the energy harvesting efficiency.[19] On the other hand, the host structure of a wind energy harvester could be designed following a metamaterial manner to enhance the energy harvesting performance,[38] i.e., reduce the cut-in wind speed and increase the power output. These are the two research studies on this topic that can be found for the current. Considering the versatility of metamaterials, there are still a lot of new directions to be explored.

C. Advanced interface circuits for efficiency boosting

According to the experience of base excitation energy harvesting, it is learned that using an advanced interface circuit can boost the efficiency by 900%.[47] Though more advanced interface circuits have kept emerging in recent years,[52,53] less attention has been paid by the colleagues who are working on wind energy harvesting. In most advanced interface circuits, how to efficiently and robustly realize the synchronized switching operation is the key to achieve efficiency boosting.[69] Unlike base excitation, wind energy harvesters carry out limited-cycle oscillations under negative damping-induced self-excitation. The vibration frequency of a VIV or galloping energy harvester is near its own natural frequency. Due to this fact, the synchronized switching operation may be easier to implement for wind energy harvesters. Therefore, novel advanced interface circuits with simpler and subtler synchronized switching operation mechanisms may be customized for wind energy harvesters in the future. In addition, most advanced interface circuits were proposed, especially for piezoelectric energy harvesters. With the mushroom growth of triboelectric energy harvesters, the development of their complementing interface circuits is relatively delayed. From the Perspective of promoting the whole system toward practical applications, more attention should be paid to the research of the complementing interface circuits. In addition, the electrical domain theories for wind energy harvesting need to be further enriched by keeping pace with base excitation energy harvesting, such as the energy flow analysis[70] and the power limit theory.[71]

D. From lab research toward real applications

According to the existing proposed technologies, the practical applications of wind energy harvesters in addressing real engineering problems are still immature. Currently, the wind energy harvesting technology is still mostly limited to the lab research. As aforementioned that the challenges that limit the application of wind energy harvesting are its robustness, power density and power output, reliability, and others. The wind characteristics in the ambient environment are often uncertain, i.e., its speed frequently varies, which greatly influences the power output of the wind energy harvesters.

Since the power supply supported by the energy harvesting technology is not as stable as the power supply of chemical batteries, there arise some technical demands on adjusting conventional processing algorithms. Edge computing is an emerging paradigm to adapt to the above scenarios where the energy could suddenly run out, and the computation may be interrupted before one execution being successfully completed.[72,73] Therefore, to help the energy harvesting technology step out of the lab, on the one side, scientists need to be dedicated to improving the robustness of energy harvesting systems. Conversely, FIV energy harvesting community relies on the contributions of the colleagues from other disciplines to reduce the power consumption requirement, enhance the edge computing algorithms, etc. Unfortunately, the collaborations between researchers from the fields of energy harvesting and IoT technology are still very limited. It is expected to see prospect in-depth collaborations between multidisciplinary researchers to make a significant contribution to achieve the grand goal of establishing ubiquitous and perpetual IoT networks.

Though the power output of a single FIV energy harvester is limited, in the future, its low cost enables us to fabricate millions of them. One million FIV energy harvesters with an independent capacity of 10 mW can lead to a considerable power output of 10 kW. Therefore, with millions of FIV energy harvesters, in addition to the point-to-point operation mode, i.e., a single FIV energy harvester working as an independent power supply for a single electronic device, they will establish a power grid to serve for large-scale power supply. Figure 4 shows several conceived scenarios where FIV-EH power grids can be

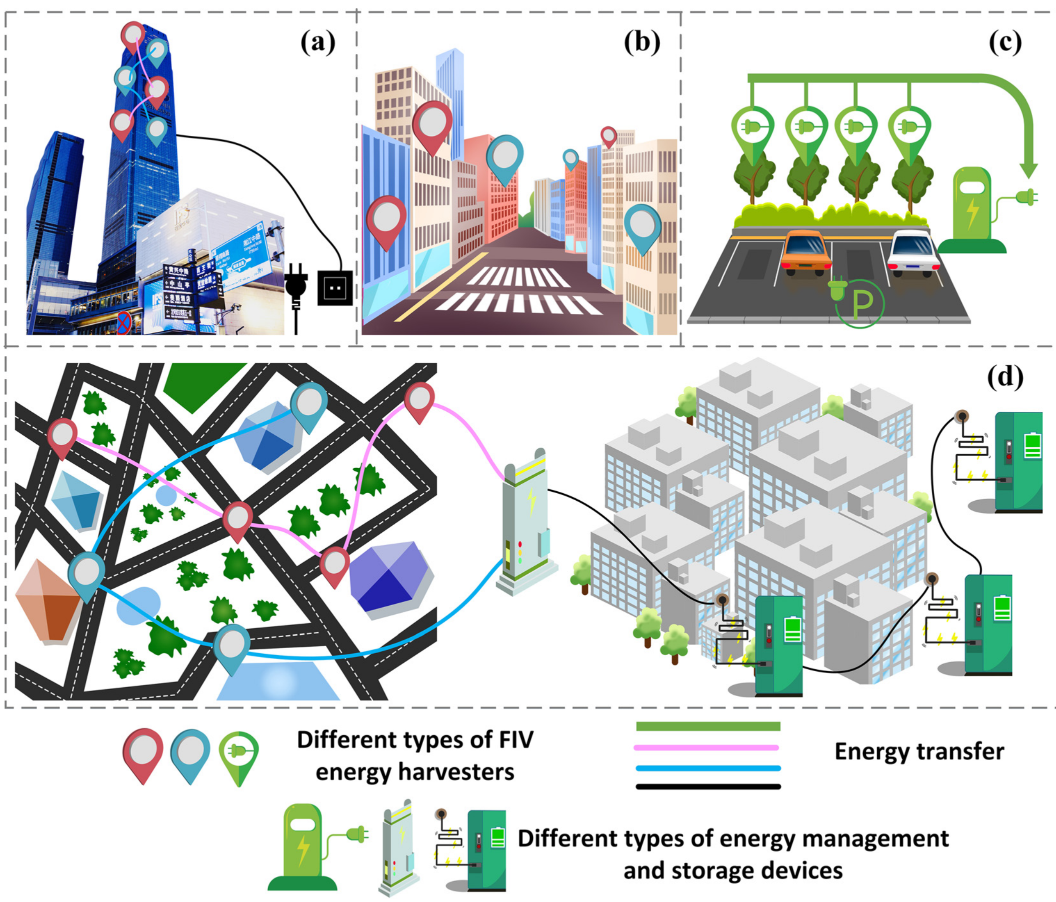


FIG. 4. (a) FIV energy harvesters (EHs) attached on a high-rise building to power electronic devices on the ground; (b) a straight street plays the role of a wind tunnel, and FIV-EHs are installed at both sides of the street for harnessing energy; (c) thousands of FIV-EHs implemented in a suburb to constitute a charging station; (d) millions of FIV-EHs distributed in the city at the places where wind resources are abundant, a power grid is established to transfer the harvested energy for community use.

potentially implemented. In the first scenario [Fig. 4(a)], thousands of FIV energy harvesters are attached to the exterior sides of a high-rise building. The winds are often faster and more consistent at higher altitudes. Thus, the thousands of FIV energy harvesters are supposed to produce cumulative large power outputs. The harvested energy can then be collected and managed to power electronic devices, such as street and traffic lights, on the ground where the wind is less consistent. The second scenario [Fig. 4(b)] notes that some streets are often similar to a wind tunnel, where the wind is guided along the street direction. Hence, at both sides of the street, we can install thousands of FIV energy harvesters. The power outputs from the thousands of FIV energy harvesters can be stored and managed to power some public facilities. The third scenario [Fig. 4(c)] happens in a remote suburb that is often under the impact of power shortage. To address this issue, thousands of FIV energy harvesters can be deployed in the suburban district to constitute several charging piles for electric vehicles. The reason for not deploying a wind turbine might be that a wind turbine is costly and visually appalling, noisy structures that require a high-standard working condition and high cut-in wind speed. In the last scenario [Fig. 4(d)], it is conceived that millions of FIV energy harvesters are distributed throughout a city at the places where wind/water resources are abundant. However, those places, e.g., lakesides and open grounds, may not have a huge power demand. Thus, a power grid can be established to connect all the FIV energy harvesters. The energy from the millions of FIV energy harvesters can then be transferred to the places where there is a higher power demand, such as residential and office areas.

V. CONCLUSIONS

In this Perspective, the multi-physics problems in flow-induced vibration energy harvesting are summarized and classified into fluid–structure interaction, bidirectional electromechanical coupling (transduction mechanism), and interface circuit coupling. The remarkable works in each direction are briefly reviewed to depict the state-of-the-art. Remaining challenges and difficulties in FIV energy harvesting are discussed. From the fundamental theory aspect, a universal solution to address the multi-physics coupling problem in modeling FIV energy harvesters is still lacking. From the practical application aspect, the robustness of FIV energy harvesters needs to be further improved to adapt to heterogeneous environments. In view of the successful applications in various disciplines, the machine-learning technique may be a suitable tool for addressing the highly nonlinear FSI problem as well. In the future, researchers may devote more efforts to integrating machine-learning approaches with conventional dynamic methods to improve the mathematical models of FIV energy harvesters. Moreover, metamaterials boosted the development of many disciplines in the past two decades. However, there have been limited studies of adopting metamaterial concepts in the design of FIV for performance improvement. Exploring the versatility of metamaterials for benefiting FIV energy harvesting should receive more research attention. In addition, interface circuits are important in real applications. More advanced interface circuits customized for FIV energy harvesters are anticipated from our colleagues from the electricity community. Finally, promoting energy harvesting from lab research toward practical applications is not the responsibility of one person. Researchers from different disciplines should establish in-depth collaborations to coordinate technical requirements in each other's area.

This work was supported by the National Natural Science Foundation of China (Grant No. 51977196).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

REFERENCES

[1] C.-W. Yau, T. T.-O. Kwok, C.-U. Lei, and Y.-K. Kwok, "*Energy harvesting in internet of things*," in *Internet of Everything* (Springer, 2018), pp. 35–79.

[2] Y. Yang, Q. Shen, J. Jin, Y. Wang, W. Qian, and D. Yuan, "Rotational piezoelectric wind energy harvesting using impact-induced resonance," Appl. Phys. Lett. **105**(5), 053901 (2014).

[3] J. Zhang, Z. Fang, C. Shu, J. Zhang, Q. Zhang, and C. Li, "A rotational piezoelectric energy harvester for efficient wind energy harvesting," Sens. Actuators, A **262**, 123–129 (2017).

[4] S. Fang, S. Wang, S. Zhou, Z. Yang, and W.-H. Liao, "Exploiting the advantages of the centrifugal softening effect in rotational impact energy harvesting," Appl. Phys. Lett. **116**(6), 063903 (2020).

[5] S. Fang, S. Wang, G. Miao, S. Zhou, Z. Yang, X. Mei, and W.-H. Liao, "Comprehensive theoretical and experimental investigation of the rotational impact energy harvester with the centrifugal softening effect," Nonlinear Dyn. **101**(1), 123–152 (2020).

[6] D. Shen, J.-H. Park, J. Ajitsaria, S.-Y. Choe, H. C. Wikle, and D.-J. Kim, "The design, fabrication and evaluation of a MEMS PZT cantilever with an integrated Si proof mass for vibration energy harvesting," J. Micromech. Microeng. **18**(5), 055017 (2008).

[7] A. Abdelkefi, "Aeroelastic energy harvesting: A review," Int. J. Eng. Sci. **100**, 112–135 (2016).

[8] J. Wang, L. Geng, L. Ding, H. Zhu, and D. Yurchenko, "The state-of-the-art review on energy harvesting from flow-induced vibrations," Appl. Energy **267**, 114902 (2020).

[9] M. Hamlehdar, A. Kasaeian, and M. R. Safaei, "Energy harvesting from fluid flow using piezoelectrics: A critical review," Renewable Energy **143**, 1826–1838 (2019).

[10] H. Zhu, T. Tang, H. Yang, J. Wang, J. Song, and G. Peng, "The state-of-the-art brief review on piezoelectric energy harvesting from flow-induced vibration," Shock Vib. **2021**, 1.

[11] J. Wang, L. Tang, L. Zhao, and Z. Zhang, "Efficiency investigation on energy harvesting from airflows in HVAC system based on galloping of isosceles triangle sectioned bluff bodies," Energy **172**, 1066–1078 (2019).

[12] L. Ding, X. Mao, L. Yang, B. Yan, J. Wang, and L. Zhang, "Effects of installation position of fin-shaped rods on wind-induced vibration and energy harvesting of aeroelastic energy converter," Smart Mater. Struct. **30**(2), 025026 (2021).

[13] J. Wang, W. Zhao, Z. Su, G. Zhang, P. Li, and D. Yurchenko, "Enhancing vortex-induced vibrations of a cylinder with rod attachments for hydrokinetic power generation," Mech. Syst. Signal Process. **145**, 106912 (2020).

[14] Q. Zou, L. Ding, H. Wang, J. Wang, and L. Zhang, "Two-degree-of-freedom flow-induced vibration of a rotating circular cylinder," Ocean Eng. **191**, 106505 (2019).

[15] M. Bryant and E. Garcia, "Modeling and testing of a novel aeroelastic flutter energy harvester," J. Vib. Acoust. **133**(1), 011010 (2011).

[16] K. Li, Z. Yang, and S. Zhou, "Performance enhancement for a magnetic-coupled bi-stable flutter-based energy harvester," Smart Mater. Struct. **29**(8), 085045 (2020).

[17] M. Usman, A. Hanif, I.-H. Kim, and H.-J. Jung, "Experimental validation of a novel piezoelectric energy harvesting system employing wake galloping phenomenon for a broad wind spectrum," Energy **153**, 882–889 (2018).

[18] A. Barrero-Gil, G. Alonso, and A. Sanz-Andres, "Energy harvesting from transverse galloping," J. Sound Vib. **329**(14), 2873–2883 (2010).

[19] J. Wang, S. Sun, L. Tang, G. Hu, and J. Liang, "On the use of metasurface for Vortex-Induced vibration suppression or energy harvesting," Energy Convers. Manage. **235**, 113991 (2021).

[20]J. Wang, L. Tang, L. Zhao, G. Hu, R. Song, and K. Xu, "Equivalent circuit representation of a vortex-induced vibration-based energy harvester using a semi-empirical lumped parameter approach," Int. J. Energy Res. **44**(6), 4516–4528 (2020).
[21]U. Javed and A. Abdelkefi, "Impacts of the aerodynamic force representation on the stability and performance of a galloping-based energy harvester," J. Sound Vib. **400**, 213–226 (2017).
[22]Y. Yang, L. Zhao, and L. Tang, "Comparative study of tip cross-sections for efficient galloping energy harvesting," Appl. Phys. Lett. **102**(6), 064105 (2013).
[23]F.-R. Liu, H.-X. Zou, W.-M. Zhang, Z.-K. Peng, and G. Meng, "Y-type three-blade bluff body for wind energy harvesting," Appl. Phys. Lett. **112**(23), 233903 (2018).
[24]F.-R. Liu, W.-M. Zhang, Z.-K. Peng, and G. Meng, "Fork-shaped bluff body for enhancing the performance of galloping-based wind energy harvester," Energy **183**, 92–105 (2019).
[25]J. Wang, S. Zhou, Z. Zhang, and D. Yurchenko, "High-performance piezoelectric wind energy harvester with Y-shaped attachments," Energy Convers. Manage. **181**, 645–652 (2019).
[26]G. Hu, K. T. Tse, K. C. S. Kwok, J. Song, and Y. Lyu, "Aerodynamic modification to a circular cylinder to enhance the piezoelectric wind energy harvesting," Appl. Phys. Lett. **109**(19), 193902 (2016).
[27]Q. Zou, L. Ding, T. Song, L. Yang, and L. Zhang, "Influence of coverage of fin-shaped rods on flow-induced vibration and power extraction of cylinder-based wind energy harvester," Smart Mater. Struct. **30**(6), 065004 (2021).
[28]J. Wang, S. Gu, C. Zhang, G. Hu, G. Chen, K. Yang, H. Li, Y. Lai, G. Litak, and D. Yurchenko, "Hybrid wind energy scavenging by coupling vortex-induced vibrations and galloping," Energy Convers. Manage. **213**, 112835 (2020).
[29]J. Wang, C. Zhang, S. Gu, K. Yang, H. Li, Y. Lai, and D. Yurchenko, "Enhancement of low-speed piezoelectric wind energy harvesting by bluff body shapes: Spindle-like and butterfly-like cross-sections," Aerosp. Sci. Technol. **103**, 105898 (2020).
[30]K. Yang, T. Qiu, J. Wang, and L. Tang, "Magnet-induced monostable nonlinearity for improving the VIV-galloping-coupled wind energy harvesting using combined cross-sectioned bluff body," Smart Mater. Struct. **29**(7), 07LT01 (2020).
[31]K. Yang, K. Su, J. Wang, J. Wang, K. Yin, and G. Litak, "Piezoelectric wind energy harvesting subjected to the conjunction of vortex-induced vibration and galloping: Comprehensive parametric study and optimization," Smart Mater. Struct. **29**, 075035 (2020).
[32]A. Bibo, A. H. Alhadidi, and M. F. Daqaq, "Exploiting a nonlinear restoring force to improve the performance of flow energy harvesters," J. Appl. Phys. **117**(4), 045103 (2015).
[33]K. Yang, J. Wang, and D. Yurchenko, "A double-beam piezo-magneto-elastic wind energy harvester for improving the galloping-based energy harvesting," Appl. Phys. Lett. **115**(19), 193901 (2019).
[34]J. Wang, L. Geng, K. Yang, L. Zhao, F. Wang, and D. Yurchenko, "Dynamics of the double-beam piezo-magneto-elastic nonlinear wind energy harvester exhibiting galloping-based vibration," Nonlinear Dyn. **100**, 1963 (2020).
[35]L. Zhao, L. Tang, and Y. Yang, "Enhanced piezoelectric galloping energy harvesting using 2 degree-of-freedom cut-out cantilever with magnetic interaction," Jpn. J. Appl. Phys., Part 1 **53**(6), 060302 (2014).
[36]G. Hu, J. Wang, H. Qiao, L. Zhao, Z. Li, and L. Tang, "An experimental study of a two-degree-of-freedom galloping energy harvester," Int. J. Energy Res. **45**(2), 3365–3374 (2021).
[37]G. Hu, J. Liang, L. Tang, and J. Wang, "Improved theoretical analysis and design guidelines of a two-degree-of-freedom galloping piezoelectric energy harvester," J. Intell. Mater. Syst. Struct. (published online, 2021).
[38]G. Hu, J. Wang, and L. Tang, "A comb-like beam based piezoelectric system for galloping energy harvesting," Mech. Syst. Signal Process. **150**, 107301 (2021).
[39]S. Fang, X. Fu, X. Du, and W.-H. Liao, "A music-box-like extended rotational plucking energy harvester with multiple piezoelectric cantilevers," Appl. Phys. Lett. **114**(23), 233902 (2019).
[40]Z. Li, Z. Yan, J. Luo, and Z. Yang, "Performance comparison of electromagnetic energy harvesters based on magnet arrays of alternating polarity and configuration," Energy Convers. Manage. **179**, 132–140 (2019).
[41]F.-R. Fan, Z.-Q. Tian, and Z. L. Wang, "Flexible triboelectric generator," Nano Energy **1**(2), 328–334 (2012).
[42]Z. Lai, J. Wang, C. Zhang, G. Zhang, and D. Yurchenko, "Harvest wind energy from a vibro-impact DEG embedded into a bluff body," Energy Convers. Manage. **199**, 111993 (2019).
[43]J. Chen and Z. L. Wang, "Reviving vibration energy harvesting and self-powered sensing by a triboelectric nanogenerator," Joule **1**(3), 480–521 (2017).
[44]P. Bai, G. Zhu, Z.-H. Lin, Q. Jing, J. Chen, G. Zhang, J. Ma, and Z. L. Wang, "Integrated multilayered triboelectric nanogenerator for harvesting biomechanical energy from human motions," ACS Nano **7**(4), 3713–3719 (2013).
[45]K. Tao, Z. Chen, H. Yi, R. Zhang, Q. Shen, J. Wu, L. Tang, K. Fan, Y. Fu, and J. Miao, "Hierarchical honeycomb-structured electret/triboelectric nanogenerator for biomechanical and morphing wing energy harvesting," Nano-Micro Lett. **13**(1), 1–16 (2021).
[46]Y. Feng, L. Zhang, Y. Zheng, D. Wang, F. Zhou, and W. Liu, "Leaves based triboelectric nanogenerator (TENG) and TENG tree for wind energy harvesting," Nano Energy **55**, 260–268 (2019).
[47]D. Guyomar, A. Badel, E. Lefeuvre, and C. Richard, "Toward energy harvesting using active materials and conversion improvement by nonlinear processing," IEEE Trans. Ultrason., Ferroelectr., Frequency Control **52**(4), 584–595 (2005).
[48]J. Liang and W. Liao, "On the influence of transducer internal loss in piezoelectric energy harvesting with SSHI interface," J. Intell. Mater. Syst. Struct. **22**(5), 503–512 (2011).
[49]E. Lefeuvre, A. Badel, C. Richard, and D. Guyomar, "Piezoelectric energy harvesting device optimization by synchronous electric charge extraction," J. Intell. Mater. Syst. Struct. **16**(10), 865–876 (2005).
[50]L. Zhao, L. Tang, and Y. Yang, "Synchronized charge extraction in galloping piezoelectric energy harvesting," J. Intell. Mater. Syst. Struct. **27**(4), 453–468 (2016).
[51]L. Zhao and Y. Yang, "Comparison of four electrical interfacing circuits in wind energy harvesting," Sens. Actuators, A **261**, 117–129 (2017).
[52]B. Zhao, K. Zhao, X. Wang, J. Liang, and Z. Chen, "Series synchronized triple bias-flip circuit: maximizing the usage of single storage capacitor for piezoelectric energy harvesting enhancement," IEEE Trans. Power Electron. **36**, 6787 (2021).
[53]A. Morel, A. Quelen, C. Berlitz, D. Gibus, P. Gasnier, A. Badel, and G. Pillonnet, "Fast-convergence self-adjusting SECE circuit with tunable short-circuit duration exhibiting 368% bandwidth improvement," IEEE Solid-State Circuits Lett. **3**, 222–225 (2020).
[54]Y. Yang and L. Tang, "Equivalent circuit modeling of piezoelectric energy harvesters," J. Intell. Mater. Syst. Struct. **20**(18), 2223–2235 (2009).
[55]L. Tang, L. Zhao, Y. Yang, and E. Lefeuvre, "Equivalent circuit representation and analysis of galloping-based wind energy harvesting," IEEE/ASME Trans. Mechatronics **20**(2), 834–844 (2015).
[56]Y. Fang, T. Tang, Y. Li, C. Hou, F. Wen, Z. Yang, T. Chen, L. Sun, H. Liu, and C. Lee, "A high-performance triboelectric-electromagnetic hybrid wind energy harvester based on rotational tapered rollers aiming at outdoor IoT applications," iScience **24**(4), 102300 (2021).
[57]R. V. Bethi, P. Laws, P. Kumar, and S. Mitra, "Modified Savonius wind turbine for harvesting wind energy from trains moving in tunnels," Renewable Energy **135**, 1056–1063 (2019).
[58]Y. Wang, J. Wang, X. Xiao, S. Wang, P. T. Kien, J. Dong, J. Mi, X. Pan, H. Wang, and M. Xu, "Multi-functional wind barrier based on triboelectric nanogenerator for power generation, self-powered wind speed sensing and highly efficient windshield," Nano Energy **73**, 104736 (2020).
[59]X. Li, L. Teng, H. Tang, J. Chen, H. Wang, Y. Liu, M. Fu, and J. Liang, "ViPSN: A vibration-powered IoT platform," IEEE Internet Things J. **8**, 1728 (2021).
[60]X. Liu, S. Hu, M. Li, and B. Lai, "Energy-efficient resource allocation for cognitive industrial Internet of Things with wireless energy harvesting," IEEE Trans. Ind. Inf. **17**, 5668 (2021).
[61]S. Muzafar, "Energy harvesting models and techniques for green IoT: A review," in *Role of IoT in Green Energy Systems* (IGI Global, 2021), pp. 117–143.
[62]M. K. Mishu, M. Rokonuzzaman, J. Pasupuleti, M. Shakeri, K. S. Rahman, F. A. Hamid, S. K. Tiong, and N. Amin, "Prospective efficient ambient energy

harvesting sources for IoT-equipped sensor applications," Electronics **9**(9), 1345 (2020).
[63]C. Zhang, G. Hu, D. Yurchenko, P. Lin, S. Gu, D. Song, H. Peng, and J. Wang, "Machine learning based prediction of piezoelectric energy harvesting from wake galloping," Mech. Syst. Signal Process. **160**, 107876 (2021).
[64]G. Hu, J. Wang, C. Lan, L. Tang, and J. Liang, "Deep-learning assisted finite element model of a galloping piezoelectric energy harvester," Proc. SPIE **11588**, 115880H (2021).
[65]S. Tol, F. Degertekin, and A. Erturk, "Gradient-index phononic crystal lens-based enhancement of elastic wave energy harvesting," Appl. Phys. Lett. **109**(6), 063902 (2016).
[66]L. Y. Wu, L. W. Chen, and C. M. Liu, "Acoustic energy harvesting using resonant cavity of a sonic crystal," Appl. Phys. Lett. **95**(1), 013506 (2009).
[67]C. Lan, G. Hu, L. Tang, and Y. Yang, "Energy localization and topological protection of a locally resonant topological metamaterial for robust vibration energy harvesting," J. Appl. Phys. **129**(18), 184502 (2021).
[68]G. Hu, L. Tang, J. Liang, C. Lan, and R. Das, "Acoustic-elastic metamaterials and phononic crystals for energy harvesting: A review," Smart Mater. Struct. **30**(8), 085025 (2021).
[69]W. Liu, G. Qin, Q. Zhu, and G. Hu, "Synchronous extraction circuit with self-adaptive peak-detection mechanical switches design for piezoelectric energy harvesting," Appl. Energy **230**, 1292–1303 (2018).
[70]J. Liang and W.-H. Liao, "Energy flow in piezoelectric energy harvesting systems," Smart Mater. Struct. **20**(1), 015005 (2011).
[71]C. Lan, Y. Liao, G. Hu, and L. Tang, "Equivalent impedance and power analysis of monostable piezoelectric energy harvesters," J. Intell. Mater. Syst. Struct. **31**(14), 1697–1715 (2020).
[72]Y. Mao, J. Zhang, and K. B. Letaief, "Dynamic computation offloading for mobile-edge computing with energy harvesting devices," IEEE J. Sel. Areas Commun. **34**(12), 3590–3605 (2016).
[73]J. Xu, L. Chen, and S. Ren, "Online learning for offloading and autoscaling in energy harvesting mobile edge computing," IEEE Trans. Cognit. Commun. Networking **3**(3), 361–373 (2017).