

非线性摩擦纳米发电俘能技术的若干进展

谭栋国, 池实民, 欧旭, 周加喜, 王凯

SOME ADVANCES IN ENERGY HARVESTING TECHNOLOGY OF NONLINEAR TRIBOELECTRIC NANOGENERATOR

Tan Dongguo, Chi Shimin, Ou Xu, Zhou Jiayi, and Wang Kai

在线阅读 View online: <https://doi.org/10.6052/0459-1879-24-158>

您可能感兴趣的其他文章

Articles you may be interested in

利用摩擦纳米发电机的流体能量俘获研究新进展

PROGRESSION ON FLUID ENERGY HARVESTING BASED ON TRIBOELECTRIC NANOGENERATORS

力学学报. 2021, 53(11): 2910-2927

非线性振动能量俘获技术的若干进展

SOME ADVANCES IN NONLINEAR VIBRATION ENERGY HARVESTING TECHNOLOGY

力学学报. 2021, 53(11): 2894-2909

柱体流激振动能量俘获理论与技术研究若干进展

SOME ADVANCES IN ENERGY HARVESTING THEORY AND TECHNOLOGY BASED ON FLOW-INDUCED VIBRATION OF CYLINDRICAL STRUCTURES

力学学报. 2024, 56(3): 524-539

摆式摩擦发电机非线性机电耦合建模研究

NONLINEAR ELECTROMECHANICAL MODELING OF PENDULUM-TYPE TRIBOELECTRIC NANOGENERATORS

力学学报. 2023, 55(10): 2178-2188

压电与摩擦电复合型旋转能量采集动力学协同调控机制研究

HYBRID PIEZOELECTRIC-TRIBOELECTRIC ROTATIONAL ENERGY HARVESTER USING DYNAMIC COORDINATED MODULATION MECHANISM

力学学报. 2021, 53(11): 2961-2971

一种磁力滑动式翼型颤振能量俘获器

A MAGNETIC SLIDING AIRFOIL FLUTTER ENERGY HARVESTER

力学学报. 2023, 55(10): 2146-2155



关注微信公众号, 获得更多资讯信息

研究综述

非线性摩擦纳米发电俘能技术的若干进展¹⁾谭栋国^{*,†} 池实民^{*} 欧旭^{*} 周加喜^{†,2)} 王凯[†]^{*}(湖南科技大学土木工程学院, 湖南湘潭 411201)[†](湖南大学机械与运载工程学院, 长沙 410082)

摘要 摩擦纳米发电技术是一种基于电负性不同的材料, 通过静电感应和摩擦起电的耦合作用实现材料间电荷转移, 从而将环境能量转化为电能的能量俘获技术. 因在物联网及其相关智慧产业以及新能源等领域的巨大应用潜力, 摩擦纳米发电俘能技术自被提出后便受到极大地关注并成为国内外的研究热点. 将非线性力学机制拓展至摩擦纳米发电俘能技术构造的非线性摩擦纳米发电机在低频环境激励下具有复杂的非线性动力学行为, 可以产生大幅值动力学响应, 进而高效地将低频环境能量转化为电能. 文章首先简要介绍了摩擦纳米发电俘能原理与非线性摩擦纳米发电机的基本工作原理, 然后从双稳态摩擦纳米发电俘能、多稳态摩擦纳米发电俘能和准零刚度摩擦纳米发电俘能等 3 个方面详细总结了非线性摩擦纳米发电俘能方法的研究工作. 此外, 从碰撞式摩擦纳米发电俘能、混合机制摩擦纳米发电俘能等两个方面详细阐述了非线性摩擦纳米发电俘能系统的性能提升策略. 最后, 通过总结非线性摩擦纳米发电俘能技术的研究进展, 分析了目前研究中的不足, 并对未来非线性摩擦纳米发电俘能技术的研究方向进行了展望.

关键词 能量俘获, 非线性系统, 摩擦纳米发电, 低频区域, 环境能量

中图分类号: O322 文献标识码: A doi: 10.6052/0459-1879-24-158

SOME ADVANCES IN ENERGY HARVESTING TECHNOLOGY OF NONLINEAR TRIBOELECTRIC NANOGENERATOR¹⁾Tan Dongguo^{*,†} Chi Shimin^{*} Ou Xu^{*} Zhou Jiaxi^{†,2)} Wang Kai[†]^{*}(School of Civil Engineering, Hunan University of Science and Technology, Xiangtan 411201, Hunan, China)[†](College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China)

Abstract Triboelectric nanogenerator (TENG) technology is a kind of energy harvesting technology based on materials with different electronegativity, which realizes charge transfer between materials through the coupling effect of electrostatic induction and triboelectric, so as to convert environmental energy into electric energy. Due to its huge application potential in the fields of the Internet of Things and its related smart industries and new energy, the TENG technology has received great attention and become a research hotspot at home and abroad since it was proposed. The nonlinear mechanical mechanism is extended to the TENG, which has complex nonlinear dynamic behavior under the excitation of low frequency environment and can generate large dynamic response, and then efficiently convert the low frequency environmental energy into electric energy. In this paper, the principle of energy harvesting by TENG (e.g., the sliding-mode TENG and the contact-separation mode TENG) and the basic working principle of nonlinear TENG are

2024-04-07 收稿, 2024-05-27 录用, 2024-05-28 网络版发表.

1) 国家自然科学基金 (12302011, 12122206, 12272129) 和中国博士后科学基金 (2023M731062) 资助项目.

2) 通讯作者: 周加喜, 教授, 主要研究方向为特种装备低频减振隔振、振动能量俘获等. E-mail: jxizhou@hnu.edu.cn

引用格式: 谭栋国, 池实民, 欧旭, 周加喜, 王凯. 非线性摩擦纳米发电俘能技术的若干进展. 力学学报, 2024, 56(9): 2495-2510

Tan Dongguo, Chi Shimin, Ou Xu, Zhou Jiaxi, Wang Kai. Some advances in energy harvesting technology of nonlinear triboelectric nanogenerator. *Chinese Journal of Theoretical and Applied Mechanics*, 2024, 56(9): 2495-2510

briefly introduced. Then, the research work of energy harvesting by nonlinear TENG is summarized in detail from three aspects: bistable TENG, multistable TENG and quasi-zero-stiffness TENG, etc., that are employed to harvest low-frequency ambient energy. Moreover, the fundamental principle of these nonlinear TENGs and the typical researches are reviewed as well. Meanwhile, it can be clearly seen that the frequency band of the energy harvesting of the nonlinear TENG is narrow, and the electrical output of the nonlinear TENG should be further improved. To address these issues, the researchers have proposed a lot of methods to improve the electrical performance of the nonlinear TENG. The performance improvement strategy of the nonlinear TENG is described in detail from two aspects, such as impact-mode TENG and hybrid TENG. Finally, this paper summarizes the research progress of nonlinear TENG, analyzes the shortcomings of current research, and prospects the future research direction of nonlinear TENG technology.

Key words energy harvesting, nonlinear systems, triboelectric nanogenerator, low-frequency region, environmental energy

引言

近年来,随着无线通讯技术的进步,物联网信息技术得到了突飞猛进的发展,其在智慧城市、智慧交通、智慧医疗和智慧物流等领域得到了广泛应用并受到了国内外学者的高度关注^[1-3].物联网及其相关智慧产业的发展离不开庞大的传感器网络节点,其将万物与互联网相连,以进行信息交换,从而实现物品的智能化感知和管理^[4].因此,庞大的传感器网络节点是物联网技术广泛应用的关键所在,如何稳定、持久且低成本地为数以万计的传感器网络节点供能,是制约物联网技术进一步发展的瓶颈问题.

传统供能方式因成本较高以及后期维护困难等缺陷难以为物联网中庞大的传感器网络节点供能^[5].因此,发展新型供能方式为物联网传感器网络节点供能,对推动物联网进一步发展具有重要意义.物联网传感器网络节点周围环境中存在各种各样的可再生能源,譬如风能^[6-7]、波浪能^[8-9]和振动能^[10-11]等.将这些环境可再生能源转化为电能为物联网传感器网络节点供能,是解决物联网传感器网络节点供能问题的潜在方案之一^[12-15].

到目前为止,已经有诸多能量俘获技术相继被提出,譬如:电磁感应式俘能技术^[16-18]、压电式俘能技术^[19-21]、热释电式俘能技术^[22-23]和静电感应式俘能技术^[24-26]等.摩擦纳米发电俘能技术是一种基于电负性不同的材料,通过静电感应和摩擦起电的耦合作用实现材料间电荷转移,从而将环境能量转化为电能的能量俘获技术.王中林院士团队^[27]于2012年设计了首个摩擦纳米发电机,提出了摩擦纳米发电俘能方法,见图1.摩擦纳米发电俘能方法一经提出,就以输出电压高、材料选择广、俘能装置

易于制造和成本低等优点^[28-30]迅速成为能量俘获领域的研究热点.随着摩擦纳米发电俘能技术的发展,研究人员发现摩擦纳米发电机的输出功率与材料本身的性质、介电质薄膜的相对滑动距离(分离距离)及滑动速度(接触分离速度)等密切相关^[31-32].因此,提高摩擦纳米发电机摩擦层材料本身的电学性质,以及增强摩擦纳米发电机系统(摩擦层)运动响应是提升摩擦纳米发电机俘能效率的有效手段.

传统摩擦纳米发电机在低频激励下难以实现大幅动力学响应,而大部分环境能量具有宽频和低频特征,因此利用传统摩擦纳米发电机难以实现低频环境能量的高效俘获.将非线性力学机制拓展至摩擦纳米发电,构造的非线性摩擦纳米发电机,在低频环境激励下具有复杂的非线性动力学行为,可以产生大幅值动力学响应,且能够高效地将低频环境能量转化为电能^[33-35].目前,国内外学者基于双稳态^[36-38]、多稳态^[39-41]和准梁刚度^[42-44]等力学机制,构造了诸多不同类型的非线性摩擦纳米发电机,用来俘获低频环境能量.部分研究成果已经在新能源领域、自供电传感器领域和健康监测等领域成功应用^[45-47].然而,非线性摩擦纳米发电机还存在诸如尺寸大、结构不够紧凑、可靠性不足等缺陷,以及非线性力

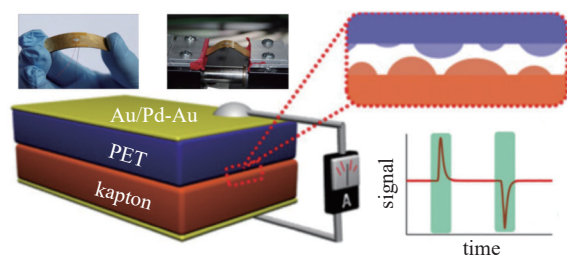


图1 首个摩擦纳米发电机^[27]

Fig. 1 The first triboelectric nanogenerator (TENG)^[27]

电耦合模型难以建立、低频俘能频带调控难等挑战, 限制了非线性摩擦纳米发电俘能技术的进一步发展.

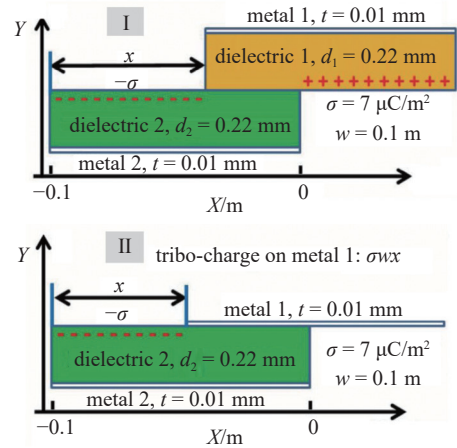
本文首先拟从摩擦纳米发电俘能理论出发, 简要总结滑动式摩擦纳米发电机和接触-分离式摩擦纳米发电机的俘能原理. 然后, 从非线性力学机制入手, 系统阐述双稳态摩擦纳米发电、多稳态摩擦纳米发电和准零刚度摩擦纳米发电 3 种非线性摩擦纳米发电俘能方法, 详细介绍 3 种方法中摩擦纳米发电系统的基本原理、建模方法以及发展现状. 此外, 从非线性摩擦纳米发电俘能系统性能提升策略出发, 详细介绍碰撞式摩擦纳米发电俘能方法和多机制摩擦纳米发电俘能方法两种性能提升策略. 最后, 总结非线性摩擦纳米发电俘能方法的潜在应用.

1 摩擦纳米发电俘能理论

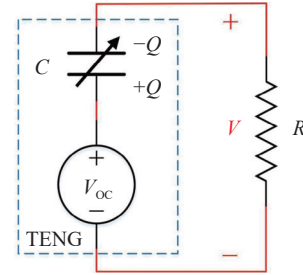
摩擦纳米发电机是基于静电感应和摩擦起电效应收集环境能量的俘能装置. 从工作模式来看, 摩擦纳米发电机可以分为以下 4 种: 水平面内滑动模式^[48-51]、垂直接触-分离模式^[52-55]、单电极模式^[56-59]和独立层模式^[60-63]. 实际上, 工程中常用的模式为水平面内滑动模式与垂直接触-分离模式. 因此, 本章简要总结了滑动式与接触-分离式摩擦纳米发电机俘能原理.

1.1 滑动式摩擦纳米发电机俘能原理

按照摩擦层的类型分类, 滑动式摩擦纳米发电机可以分为介电质-介电质型滑动式摩擦纳米发电机和电极-介电质型滑动式摩擦纳米发电机. 具体而言, 介电质-介电质型滑动式摩擦纳米发电机主要由两片介电质薄膜与两片电极薄膜组成, 两片介电质薄膜构成摩擦层, 两片电极构成导电层, 如图 2(a-I) 所示^[31]. 电极-介电质型滑动式摩擦纳米发电机主要由一片介电质薄膜与两片电极薄膜组成, 介电质薄膜与其中一片电极薄膜构成摩擦层, 该电极薄膜与另一电极薄膜构成导电层, 如图 2(a-II) 所示^[31]. 图 2(b) 给出了摩擦纳米发电机的等效电路模型, 其中, V 表示摩擦纳米发电系统输出电压, R 代表外电路中的负载电阻. 从图中可以清晰地看出, 滑动式摩擦纳米发电系统由一个等效电容 C 和一个开路电压源 V_{OC} 串联而成^[64]. 基于此, 滑动式摩擦纳米发电机的电学控制方程为^[65]



(a) 滑动式摩擦纳米发电机^[31]
(a) Sliding-mode TENG^[31]



(b) 摩擦纳米发电机的等效电路模型^[64]
(b) Equivalent circuit model of TENG^[64]

图 2 滑动式摩擦纳米发电机理论模型

Fig. 2 Theory of sliding-mode TENG

$$V = -\frac{1}{C}Q + V_{OC} \quad (1)$$

式中, C 和 V_{OC} 分别代表滑动式摩擦纳米发电机的等效电容和开路电压, Q 表示外电路中的电荷转移量, V 表示滑动式摩擦纳米发电机的输出电压.

介电质-介电质型滑动式摩擦纳米发电机的电学控制方程为^[31]

$$V = -\frac{Q}{w\epsilon_0(l-x)}\left(\frac{d_1}{\epsilon_{r1}} + \frac{d_2}{\epsilon_{r2}}\right) + \frac{\sigma x}{\epsilon_0(l-x)}\left(\frac{d_1}{\epsilon_{r1}} + \frac{d_2}{\epsilon_{r2}}\right) \quad (2)$$

式中, l 和 w 分别代表介电质薄膜的长和宽, d_1 和 d_2 分别代表介电质 1 和介电质 2 的厚度, ϵ_0 表示真空介电常数, ϵ_{r1} 和 ϵ_{r2} 分别表示介电质 1 和介电质 2 的相对介电常数, σ 代表摩擦膜的表面电荷密度, x 代表介电质 1 和介电质 2 之间的相对滑动距离.

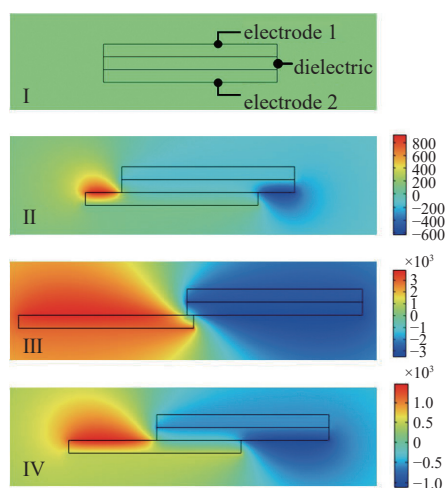
电极-介电质型滑动式摩擦纳米发电机的电学控制方程为^[31]

$$V = -\frac{Q}{w\epsilon_0(l-x)}\frac{d}{\epsilon_r} + \frac{\sigma x}{\epsilon_0(l-x)}\frac{d}{\epsilon_r} \quad (3)$$

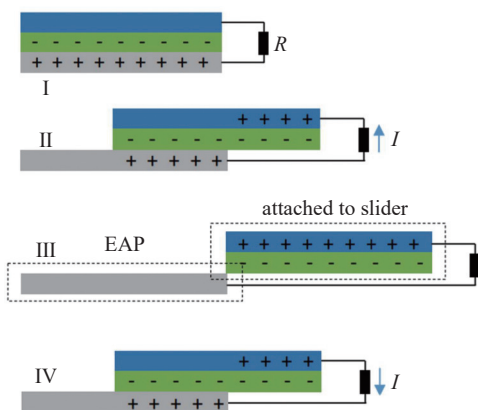
式中, d 代表介电质的厚度, ϵ_r 代表介电质的相对介

电常数.

为了进一步了解滑动式摩擦纳米发电机的俘能原理, 图 3 给出了电极-介电质型滑动式摩擦纳米发电机的工作原理^[65-66]. 在本例中, 介电质与电极 2 构成摩擦层. 当电极-介电质型滑动式摩擦纳米发电机处于工作状态时, 其电势分布云图与电荷转移示意图分别如图 3(a) 和图 3(b) 所示. 显然, 当介电质与电极 2 完全重合时, 由于其吸引电子的能力不同, 介电质带负电荷, 电极 2 带正电荷, 此时介电质与电极 2 之间的电势差为 0, 如图 3(a-I) 所示. 此时, 外电路中没有电荷转移, 如图 3(b-I) 所示. 随着介电质相对于电极 2 向右滑动, 其间的电势差逐渐增大, 如图 3(a-II) 所示. 正电荷从电极 2 (高电势) 通过外电路转移至电极 1 (低电势), 进而产生从电极 2 流向电极 1 的电流, 如图 3(b-II) 所示. 一旦介电质与电极 2



(a) 电势分布云图^[65]
(a) Electric potential distributions^[65]



(b) 电荷转移原理^[66]
(b) Electron transfer behaviors^[66]

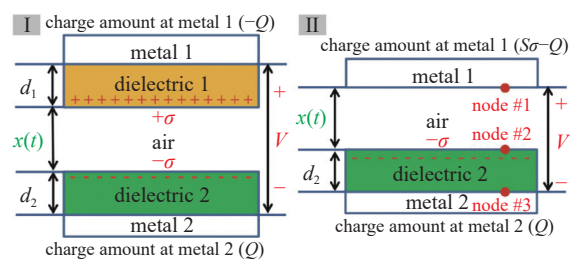
图 3 电极-介电质型滑动式摩擦纳米发电机工作原理

Fig. 3 Operating principle of conductor-to-dielectric sliding-mode TENG

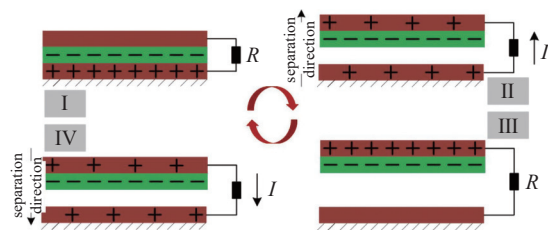
之间的相对滑动距离达到最大时, 其间电势差达到最大, 电极 2 的正电荷将全部转移至电极 1, 此刻外电路中没有电流产生, 如图 3(a-III) 和图 3(b-III) 所示. 随后, 介电质相对于电极 2 向左滑动, 其间电势差减小, 外电路中产生由电极 1 流向电极 2 的电流, 如图 3(a-IV) 和图 3(b-IV) 所示. 当滑动式摩擦纳米发电机处于工作状态时, 摩擦层之间将产生周期性滑动, 因此外电路中将产生交流电.

1.2 接触-分离式摩擦纳米发电机俘能原理

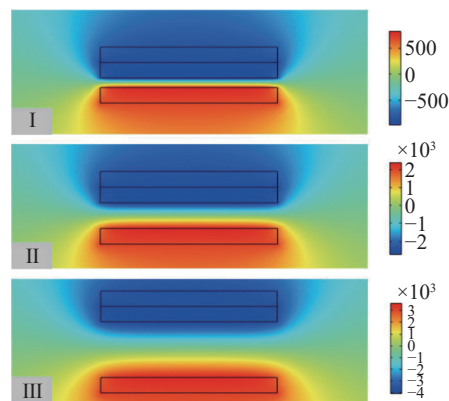
根据摩擦层类别, 接触-分离式摩擦纳米发电机与滑动式摩擦纳米发电机相同, 可以分为介电质-介电质型接触-分离式摩擦纳米发电机和电极-介电质型接触-分离式摩擦纳米发电机, 分别如图 4(a-I) 和 4(a-II) 所示^[32]. 接触-分离式摩擦纳米发电系统与滑



(a) 接触-分离式摩擦纳米发电机^[32]
(a) Contact-separation mode TENG^[32]



(b) 电荷转移原理^[65]
(b) Electron transfer behaviors^[65]



(c) 电势分布云图^[65]
(c) Electric potential distributions^[65]

图 4 接触-分离式摩擦纳米发电俘能原理

Fig. 4 Theory of contact-separation mode TENG

动式摩擦纳米发电机相同, 等效电路模型由一个等效电容和一个开路电压源串联而成. 电极-介电质型接触-分离式摩擦纳米发电机的电学控制方程为^[65]

$$V = -\frac{Q}{S\epsilon_0} \left(\frac{d}{\epsilon_r} + x \right) + \frac{\sigma x}{\epsilon_0} \quad (4)$$

式中, S 代表摩擦层之间接触的面积.

介电质-介电质型接触-分离式摩擦纳米发电机的电学控制方程为^[32]

$$V = -\frac{Q}{S\epsilon_0} \left(\frac{d_1}{\epsilon_{r1}} + \frac{d_2}{\epsilon_{r2}} + x \right) + \frac{\sigma x}{\epsilon_0} \quad (5)$$

电极-介电质型接触-分离式摩擦纳米发电机工作状态下的电荷转移示意图与电势分布云图分别如图 4(b) 和图 4(c) 所示^[65]. 由图 4(b-I) 可知, 当介电质与电极 2 完全重合时, 外电路中没有电流产生. 这是因为介电质与电极 2 之间的电势差为 0, 外电路中不发生电荷转移. 随着介电质与电极 2 分离, 其间产生电势差, 且随着分离距离增大, 电势差逐渐增大, 如图 4(c) 所示. 因此, 随着介电质与电极 2 分离距离增大, 正电荷从电极 2 经过外电路转移到电极 1, 电流方向与正电荷流动方向相同, 如图 4(b-II) 所示. 当分离距离达到最大, 正电荷全部转移至电极 1, 此时外电路中没有电流产生, 如图 4(b-III) 所示. 随后, 介电质与电极 2 之间的分离距离减小, 其间电势差减小, 正电荷从电极 1 流向电极 2, 外电路中产生与之相同流向的电流, 如图 4(b-IV) 所示. 直到介电质与电极 2 再次完全重合, 正电荷全部转移至电极 2. 因此, 当接触-分离式摩擦纳米发电机摩擦层周期性接触-分离时, 外电路中将产生交流电.

2 非线性摩擦纳米发电俘能方法

传统线性摩擦纳米发电俘能方法难以高效俘获低频环境能量. 将非线性力学机制拓展至摩擦纳米发电, 发展非线性摩擦纳米发电俘能方法, 可以利用复杂的非线性动力学行为诱发高效的电学输出. 本章简要总结了具有低频环境能量高效俘获能力的典型非线性摩擦纳米发电俘能方法^[67-70], 主要包括: 双稳态摩擦纳米发电俘能方法、多稳态摩擦纳米发电俘能方法和准零刚度摩擦纳米发电俘能方法.

需要注意的是, 非线性摩擦纳米发电机在工作状态下, 摩擦膜之间存在静电力. 然而, 根据文献^[66]

可知, 静电力对非线性摩擦纳米发电机的力学响应和电学性能的影响可以忽略不计. 因此, 本文所提及的非线性摩擦纳米发电机动力学控制方程中并没有体现力电耦合项 (静电力).

2.1 双稳态摩擦纳米发电俘能方法

将负刚度机构拓展至摩擦纳米发电, 构造具有双稳态力学机制的摩擦纳米发电俘能系统, 即可得到双稳态摩擦纳米发电机. 通常, 双稳态摩擦纳米发电机由双稳态结构与摩擦纳米发电俘能模块构成. 双稳态结构由负刚度机构构成, 摩擦纳米发电俘能模块由介电质薄膜和电极薄膜构成. 从能量角度分析, 双稳态摩擦纳米发电俘能系统具有两个稳定平衡点与一个不稳定平衡点, 当系统动能足以驱动其跨越不稳定平衡点时, 系统将在两个稳定平衡点之间作大幅值高速度阱间振荡, 此时双稳态摩擦纳米发电机可以高效地将低频环境能量转化为电能. 基于此原理, 国内外学者设计了各种各样的双稳态摩擦纳米发电机, 其可以高效俘获低频环境能量^[71-73].

基于双翅目昆虫飞行机制, Luo 等^[74] 提出了一款双稳态摩擦纳米发电机, 如图 5(a-I) 所示. 该双稳态摩擦纳米发电机可以模拟双翅目昆虫飞行过程中翅膀的运动形态. 其中, 当刚性梁长度较短时, 系统只有一个稳定平衡点, 是一个单稳态系统. 一旦刚性梁长度增大, 系统具有两个稳定平衡点, 此时系统表现出双稳性. 基于拉格朗日方程, 可以得到仿双翅目双稳态摩擦纳米发电机的动力学控制方程

$$M\ddot{X} + \xi\dot{X} + F = M\ddot{z} \quad (6)$$

式中, M 和 ξ 分别表示质量和阻尼矩阵, F 为系统所受力的矩阵形式, X 代表集中质量的相对位移, $\ddot{z}$ 是系统所受基础激励. 经过理论分析与实验研究, 可以发现仿双翅目双稳态摩擦纳米发电机在低频区域具有复杂的动力学行为, 当其运动形式为大幅值阱间运动时, 可以高效地将低频振动能量转化为电能.

受拉弓时动能势能转化原理启发, Tan 等^[75] 设计了悬臂梁-摆臂式负刚度机构, 进而提出了仿弓形双稳态摩擦纳米发电机, 其基本构型如图 5(a-II) 所示. 弓形双稳态摩擦纳米发电系统包含两个稳定平衡点和一个不稳定平衡点, 具有典型的双阱特征. 稳定平衡点和不稳定平衡点之前的势能差被称为势能壁垒, 当系统的动能足以克服势能壁垒时, 弓形双稳态摩擦纳米发电机的运动状态为大幅值阱间运动,

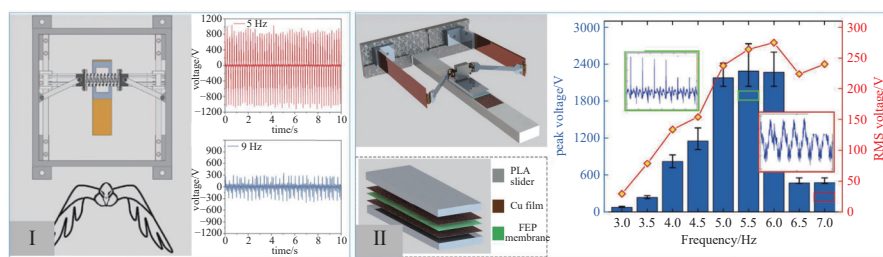
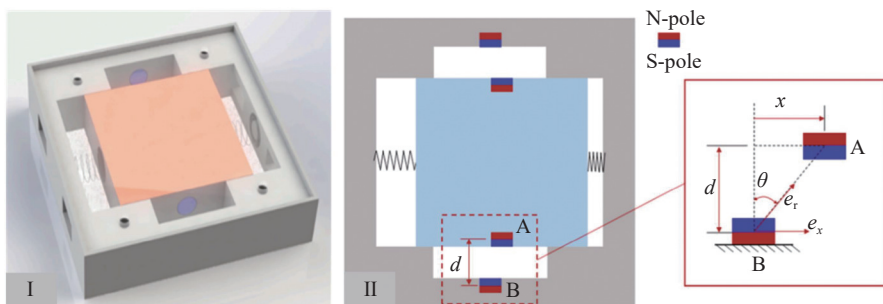
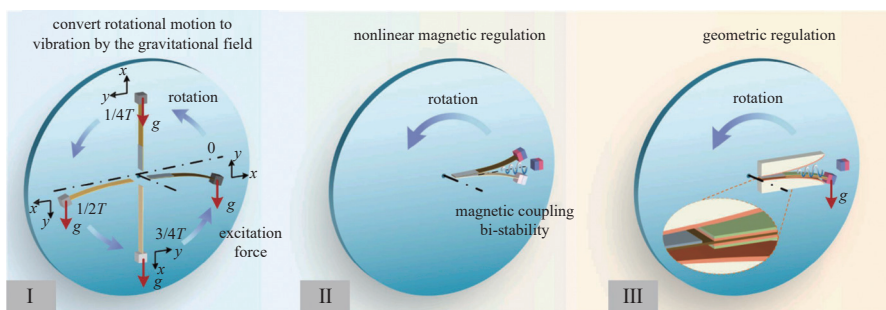
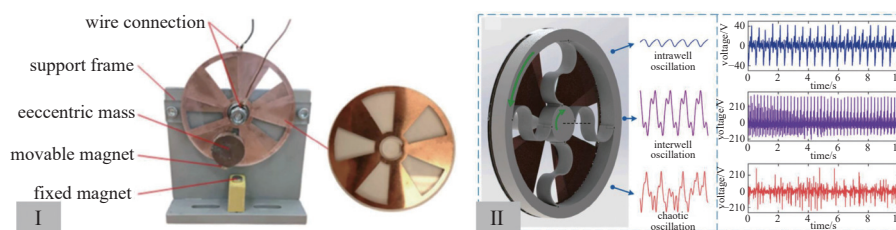
(a) 机械式双稳态摩擦纳米发电机^[74-75](a) Mechanical bistable TENG^[74-75](b) 磁致式双稳态摩擦纳米发电机^[76](b) Magnetic bistable TENG^[76](c) 基于动态协同调节机制的双稳态摩擦纳米发电机^[78](c) Bistable TENG with the dynamically synergistic regulation mechanism^[78](d) 圆盘形双稳态摩擦纳米发电机^[79-80](d) Disc-shaped bistable TENG^[79-80]

图 5 双稳态摩擦纳米发电机

Fig. 5 Bistable TENGs

此时可以产生高幅值输出电压,如图 5(a-II)所示。当系统难以跨越不稳定平衡点时,运动状态表现为小幅值阱内运动,此时输出电压幅值较小。这表明当双稳态摩擦纳米发电机的运动形式为阱间运动时,可以实现高效的低频振动能量俘获。

上述双稳态摩擦纳米发电机主要通过机械式负刚度机构实现双稳态力学机制,然而机械式双稳态

结构在实际工作环境下具有装配误差大以及稳定性差的缺陷。针对这些问题,研究人员将磁致式负刚度机构引入摩擦纳米发电系统,提出了多种磁致式双稳态摩擦纳米发电机^[76-77]。研究结果表明,磁致式双稳态摩擦纳米发电机不仅可以实现低频环境能量的高效俘获,还可以有效降低装配误差,并提高系统稳定性。利用磁致式负刚度机构,Zhao 等^[76]设计了一

款磁致式双稳态摩擦纳米发电机, 如图 5(b) 所示. 图 5(b-I) 给出了该摩擦纳米发电机的简化模型, 理论和实验结果均表明, 该磁致式双稳态摩擦纳米发电机可以在低频区域高效地将振动能量转化为电能, 且其俘能带宽约为传统摩擦纳米发电机 (不考虑双稳态力学机制) 的两倍.

旋转运动能量作为一种常见的环境能量, 广泛分布于旋转式机械装置周围. Zhao 等^[77] 提出了一款具有动态协同调节机制的圆盘形磁致式双稳态摩擦纳米发电机, 如图 5(c) 所示. 经过实验测试, 发现该摩擦纳米发电机在动态调节机制的引导下可以高效地将旋转能量转化为电能. 此外, Zhao 等^[78] 基于磁致式负刚度机构提出了另一种新型双稳态摩擦纳米发电机, 同样可以实现旋转运动能量的高效俘获. 将该摩擦纳米发电机安装至汽车轮胎上, 进行实际道路测试, 结果表明, 该摩擦纳米发电机能够为转子供电并实现其状态监测.

不同于旋转运动能量, 扭转振动能量存在于轴系以及人体关节处且具有低频特征. 利用两块相斥的磁块实现负刚度, Zhao 等^[79] 提出了一款圆盘形双稳态摩擦纳米发电机, 如图 5(d-I) 所示. 研究结果表明, 该摩擦纳米发电机可以高效地将低频扭转振动能量转化为电能. Tan 等^[80] 基于柔性机构设计理论设计了 S 形柔性梁, 进而构造了一款紧凑型柔性双稳态摩擦纳米发电机, 如图 5(d-II) 所示. 实验结果表明, 该摩擦纳米发电机不仅可以高效俘获低频扭转振动能量, 还能够将人体运动能量转化为电能, 并驱动低功率传感器.

综上所述, 双稳态摩擦纳米发电机在低频激励下具有复杂的动力学行为, 当系统可以跨越不稳定平衡点时, 其在两个稳定平衡点之间作大幅值阱间振荡. 此时, 双稳态摩擦纳米发电机可以高效地将低频环境能量转化为电能.

2.2 多稳态摩擦纳米发电俘能方法

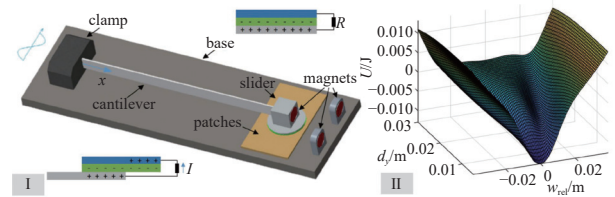
为了进一步提高低频环境能量的俘获效率, 研究人员将双稳态力学机制拓展至多稳态力学机制, 提出了多稳态摩擦纳米发电俘能方法. 与双稳态系统相比, 多稳态系统的稳定平衡点大于两个, 呈现多势能阱特性. 在同一工况下, 多稳态系统的势能壁垒低于双稳态系统. 因此, 多稳态系统比双稳态系统更容易克服势能壁垒, 跨越不稳定平衡点, 实现大幅值阱间运动, 进而高效地将低频环境能量转化为电能.

一般情况下, 多稳态系统分为: 三稳态系统^[81-83]、四稳态系统^[84-86] 以及五稳态系统^[87-89] 等.

基于磁致式负刚度力学机制, Fu 等^[66] 提出了悬臂梁式三稳态摩擦纳米发电机, 如图 6(a-I) 所示. 为了研究悬臂梁式三稳态摩擦纳米发电机的动力学特性, 基于哈密顿原理, 结合拉格朗日方程推导了该摩擦纳米发电机的动力学控制方程

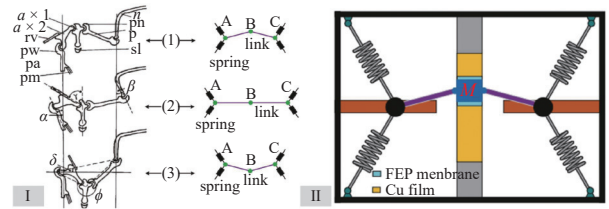
$$\ddot{q} + 2\xi\omega\dot{q} + \omega^2q + F_m = \alpha\ddot{g} + F_f\phi(L_b) \quad (7)$$

式中, ξ 代表系统阻尼比, ω 表示悬臂梁第一阶固有频率, $\ddot{g}$ 表示基础激励, F_m 和 F_f 分别表示悬臂梁端部磁块所受磁力和摩擦层薄膜之间的摩擦力, $\phi(L_b)$ 表示悬臂梁末端的模态变形. 图 6(a-II) 给出了悬臂



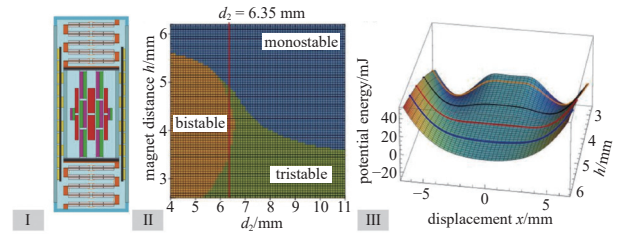
(a) 悬臂梁式三稳态摩擦纳米发电机^[66]

(a) Cantilever-type tristable TENG^[66]



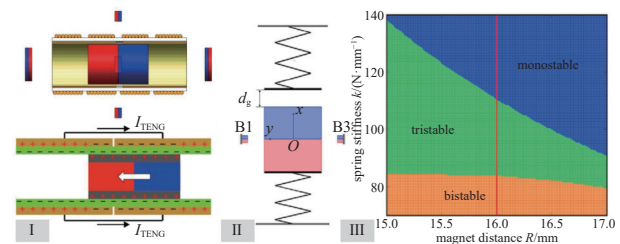
(b) 仿生多稳态摩擦纳米发电机^[90]

(b) Bionic multistable TENG^[90]



(c) 磁致式多稳态摩擦纳米发电机^[91]

(c) Magnetic multistable TENG^[91]



(d) 磁悬浮式/弹簧式多稳态摩擦纳米发电机^[92-93]

(d) Magnetic levitation-based/spring-assisted multistable TENG^[92-93]

图 6 多稳态摩擦纳米发电机

Fig. 6 Multistable TENGs

梁式三稳态摩擦纳米发电机的势能云图,从图中可以明显看出,该摩擦纳米发电机具有三稳态力学机制.理论分析结果表明,相较于双稳态摩擦纳米发电系统,三稳态摩擦纳米发电系统的势能壁垒更低,更容易实现大幅值阱间运动,从而可以高效地将低频振动能量转化为电能.

受仿生类4肢结构与双翅目飞行机制启发(图6(b-I)),Yang等^[90]提出了一种仿生多稳态摩擦纳米发电机,如图6(b-II)所示.由静力学分析结果可知,该摩擦纳米发电机具有四稳态力学机制.当该摩擦纳米发电机运动状态为大幅值阱间运动时,其具有高效的电学输出性能.Wang等^[91]利用磁致式负刚度机构,设计了一款磁致式多稳态摩擦纳米发电机,如图6(c-I)所示.从图6(c-II)可以看出,该摩擦纳米发电机在不同的系统参数下分别呈现出双稳态、三稳态和多稳态力学特性.由系统势能云图图6(c-III)可知,随着俘能系统从双稳态系统变为三稳态系统以及多稳态系统,势能壁垒将逐渐降低.研究结果表明,该磁致式多稳态摩擦纳米发电机可以在低频激励下产生大幅值动力学响应,高效地将低频振动能量转化为电能.

利用磁悬浮机制,Yang等^[92]设计了一款磁悬浮式三稳态摩擦纳米发电机,如图6(d-I)所示.研究结果表明,与传统摩擦纳米发电机相比,该摩擦纳米发电机在低频结构振动激励下可以产生大幅值动力学响应,具有更优异的电学输出性能.Yang等^[93]提出了一种弹簧式多稳态摩擦纳米发电机,如图6(d-II)所示.该多稳态摩擦纳米发电机在低频振动激励下具有复杂的动力学行为,可以高效地将低频振动能量转化为电能.

相比于双稳态摩擦纳米发电机,多稳态摩擦纳米发电机具有更低的势能壁垒,相同工况下多稳态摩擦纳米发电机更容易在低频区域产生大幅值动力学响应.因此,多稳态摩擦纳米发电机可以高效地将低频振动能量转化为电能,实现高效的电学输出性能.

2.3 准零刚度摩擦纳米发电俘能方法

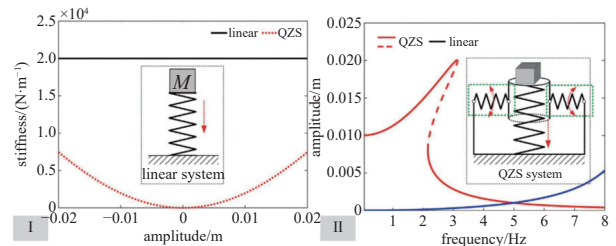
为了进一步提高低频甚至超低频区域振动能量的俘获效率,研究人员将准零刚度力学机制^[94-96]拓展至摩擦纳米发电,提出准零刚度摩擦纳米发电俘能方法,设计了多种准零刚度摩擦纳米发电机^[97-98].通常,准零刚度机构由一个垂直弹簧和两个水平弹

簧构成^[99].准零刚度系统的刚度远低于传统线性系统,如图7(a-I)所示.相比于传统线性系统,准零刚度系统在低频区域具有大幅值动力学响应,如图7(a-II)所示^[97].因此,通过引入准零刚度机构发展准零刚度摩擦纳米发电俘能方法是提高摩擦纳米发电机低频、超低频区域能量俘获性能的有效途径.

针对超低频振动能量难以俘获的问题,Wang等^[98]将准零刚度机制拓展至摩擦纳米发电,提出了一款准零刚度摩擦纳米发电机,其基本构型如图7(b-I)所示.该准零刚度摩擦纳米发电机的运动方程为

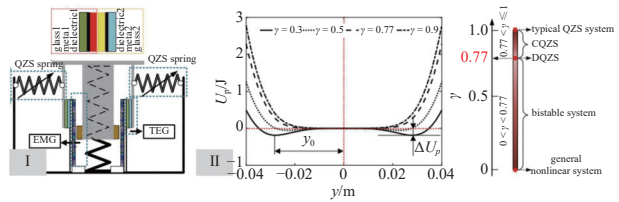
$$M\ddot{y} + c\dot{y} + F = -MA \sin(\omega t) \quad (8)$$

式中, M 代表准零刚度摩擦纳米发电机的集中质量, c 表示准零刚度摩擦纳米发电机的系统阻尼, F 代表



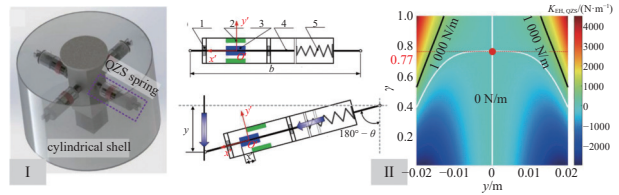
(a) 准零刚度系统与线性系统性能对比^[97]

(a) Performance comparison between QZS system and linear system^[97]



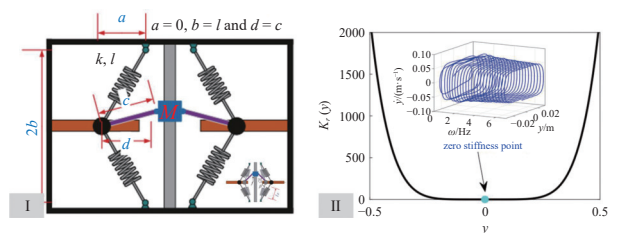
(b) 准零刚度摩擦纳米发电机^[98]

(b) QZS TENG^[98]



(c) 双极准零刚度摩擦纳米发电机^[97]

(c) Dual QZS TENG^[97]



(d) 仿生型准零刚度摩擦纳米发电机^[90]

(d) Bionic QZS TENG^[90]

图7 准零刚度摩擦纳米发电机

Fig. 7 Quasi-zero-stiffness (QZS) TENGs

准零刚度系统回复力, A 代表基础激励幅值, ω 代表激励频率.

图 7(b-II) 给出了该准零刚度摩擦纳米发电机的位移-势能曲线. 由图可知, 不同的系统刚度比下, 该摩擦纳米发电机呈现出不同的力学特性, 当刚度比大于 0.77 时, 该摩擦纳米发电机呈现出准零刚度特性, 此时系统在超低频区域可以产生大幅值动力学响应, 从而高效地将超低频振动能量转化为电能.

为了进一步深入研究准零刚度摩擦纳米发电机电力电耦合系统非线性动力学行为与电学输出之间的相互作用关系, Wang 等^[97] 提出了双极准零刚度摩擦纳米发电机, 如图 7(c-I) 所示, 其中负刚度机构由准零刚度弹簧构成. 图 7(c-II) 给出了双极准零刚度摩擦纳米发电机的刚度特性, 由图可知, 该摩擦纳米发电机具有准零刚度特性. 当该摩擦纳米发电机处于准零刚度区间时, 其可以产生大幅值动力学响应, 进而产生较高的电学输出. 基于双翅目昆虫飞行机制, Yang 等^[90] 设计了一款仿生型准零刚度摩擦纳米发电机, 如图 7(d-I) 所示. 从系统刚度曲线可以看出, 该仿生型准零刚度摩擦纳米发电机具有平坦且较宽的准零刚度区间. 当仿生型准零刚度摩擦纳米发电机在此区间内时, 其可以高效地俘获低频振动能量.

综上所述, 准零刚度摩擦纳米发电机具有高静刚度、低动刚度的准零刚度特性, 当准零刚度摩擦纳米发电系统处于准零刚度区间时, 可以高效地俘获低频甚至超低频振动能量.

3 非线性摩擦纳米发电俘能系统性能提升策略

到目前为止, 国内外学者已经提出了各种各样的非线性摩擦纳米发电俘能系统, 可以有效俘获低频环境能量. 然而, 传统的非线性摩擦纳米发电俘能系统在低频区域的俘能频带较窄, 俘能效率有待提升. 基于此, 本章总结了两种非线性摩擦纳米发电俘能系统性能提升策略, 分别为碰撞式摩擦纳米发电俘能方法与混合机制摩擦纳米发电俘能方法.

3.1 碰撞式摩擦纳米发电俘能方法

传统滑动式双稳态摩擦纳米发电机的俘能频带集中在狭窄的阱间运动频带, 严重限制了其低频俘能性能. 针对这一问题, Tan 等^[65] 将碰撞模式引入滑动式摩擦纳米发电机中, 提出了滑动-碰撞一体式双

稳态摩擦纳米发电机, 如图 8(a-I) 所示. 滑动-碰撞一体式双稳态摩擦纳米发电机的动力学控制方程为

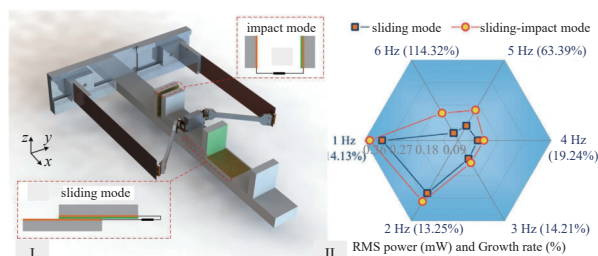
$$M\ddot{z} + F_1 + F_2 - F_3 = M_1\ddot{u} + F_f \quad (9)$$

式中, M 代表系统的等效质量, F_1 , F_2 和 F_3 分别代表不同分量的合力, $M_1\ddot{u}$ 代表基础激励, F_f 代表摩擦力. 当系统发生碰撞事件时, 用 t^- 和 t^+ 分别表示碰撞前的时刻和碰撞后的时刻, 有

$$\dot{z}(t^+) = -r\dot{z}(t^-) \quad (10)$$

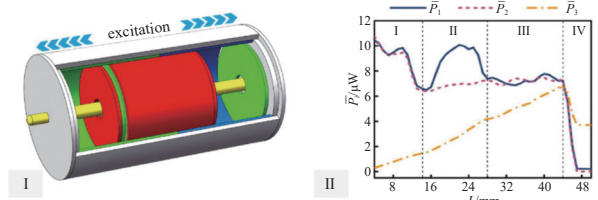
式中, $\dot{z}(t^-)$ 和 $\dot{z}(t^+)$ 分别代表滑块碰撞前后的相对速度, r 代表恢复系数.

图 8(a-II) 给出了滑动-碰撞一体式双稳态摩擦纳米发电机和滑动式双稳态摩擦纳米发电机在不同运动模式下的输出功率. 由图可知, 当俘能系统运动



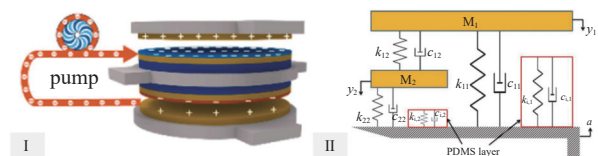
(a) 滑动-碰撞一体式摩擦纳米发电机^[65]

(a) Sliding-impact TENG^[65]



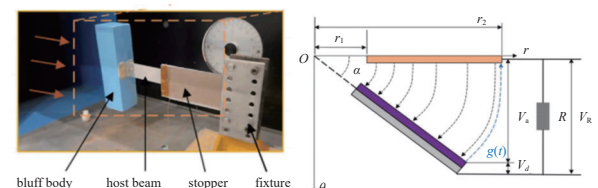
(b) 胶囊型摩擦纳米发电机^[100]

(b) Capsule-structured TENG^[100]



(c) 新型非线性摩擦纳米发电机^[101-102]

(c) Novel nonlinear TENG^[101-102]



(d) 悬臂梁式摩擦纳米发电机^[103]

(d) Cantilever-type TENG^[103]

图 8 碰撞式摩擦纳米发电机

Fig. 8 Impact-mode TENGs

明, 引入电磁俘能机制, 可以极大提升该非线性摩擦纳米发电机的电学输出性能. 此外, 任静等^[109]设计了一款新型电磁-摩擦电混合式纳米发电机, 如图 9(b-II) 所示, 可有效俘获人体低频运动能量. 实验结果表明, 将电磁俘能机制引入摩擦纳米发电机构造的电磁-摩擦电混合式纳米发电机, 不仅能够显著提高人体低频运动能量的俘获效率, 增强发电机的电学输出性能, 还可以有效拓宽其俘能频宽.

针对引入电磁俘能机制后构造的滑动式电磁-摩擦电混合式纳米发电机, 杨亚等^[110]详细地阐述了其工作原理, 如图 9(b-III) 所示. 研究结果表明, 与传统非线性摩擦纳米发电机相比, 电磁-摩擦电混合式纳米发电机具有更大的输出功率, 更高的机电转换效率. 此外, 电磁-摩擦电混合式纳米发电机在自驱动传感器、可穿戴设备的供电和物联网等方面具有重要的应用前景. Han 等^[111]设计了一款双面绒毛式电磁-摩擦电混合式纳米发电机, 如图 9(c) 所示. 该纳米发电机通过结合电磁俘能机制与摩擦电俘能机制, 显著提高了发电机空间利用率, 并极大提升了发电机超低频波浪能俘获效率. 实验结果表明, 该电磁-摩擦电混合式纳米发电机能够高效俘获超低频波浪能, 并为微小型电子设备和蓝牙系统供电, 可助力海洋环境状态实时监测. 总体而言, 通过引入电磁等俘能机制, 发展混合机制摩擦纳米发电俘能方法, 可有效提升非线性摩擦纳米发电机的电学性能.

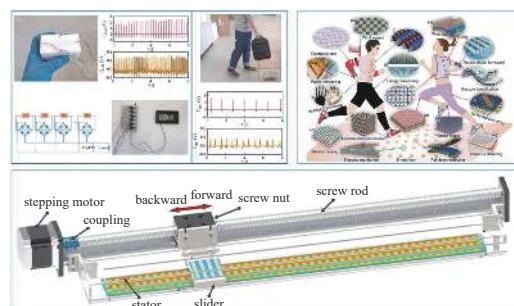
4 非线性摩擦纳米发电机的潜在应用

随着化石能源的日渐减少, 人类生活环境中存在的大量可再生能源, 譬如风能、水能、波浪能和振动能等, 逐渐进入人们的视野. 利用非线性摩擦纳米发电机从环境中俘获可再生能源, 将其转化为电能是解决化石能源日益减少的有效途径之一. 迄今为止, 国内外学者已经开发了不同的非线性摩擦纳米发电俘能系统, 用于俘获自然环境中存在的风能、波浪能和振动能等, 如图 10(a) 所示^[112-114]. 相关研究结果表明, 非线性摩擦纳米发电机可以在环境激励下产出复杂的非线性动力学行为, 高效地将低频环境能量转化为电能. 因此, 利用非线性摩擦纳米发电俘能方法俘获环境可再生能源, 发展新能源技术是非线性摩擦纳米发电俘能方法的潜在应用之一.

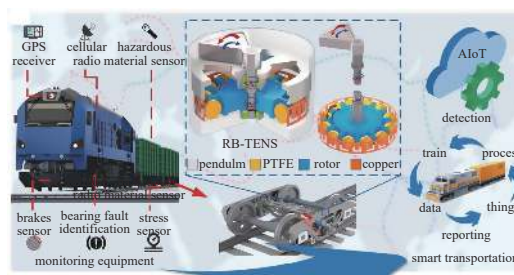
众所周知, 物联网的发展离不开数以万计的微型传感器, 传统供能方式难以为数量众多, 规模庞大



(a) 利用非线性摩擦纳米发电机俘获环境可再生能源^[112-114]
(a) Harvesting renewable energy from the ambient environment by the nonlinear TENG^[112-114]



(b) 通过非线性摩擦纳米发电机设计自供电传感器^[108,115-116]
(b) Designing self-powered sensors by the nonlinear TENG^[108,115-116]



(c) 基于非线性摩擦纳米发电机实现健康监测^[117]
(c) Health monitoring devices based on the nonlinear TENG^[117]

图 10 非线性摩擦纳米发电机的潜在应用

Fig. 10 Potential applications of the nonlinear TENG

的传感器网络节点供能. 非线性摩擦纳米发电机可以高效地将环境能量转化为电能, 因此, 国内外学者利用非线性摩擦纳米发电机俘获物联网传感器网络节点周围的环境能量, 开发了多种自供电传感器, 在电子皮肤^[118]、低功率传感器^[119]、可穿戴电子设备^[120]和物联网^[121]等领域得到了广泛的应用, 如图 10(b) 所示^[108,115-116]. 因此, 利用非线性摩擦纳米发电俘能方法开发自供电传感器, 以助力物联网及其相关领域的进一步发展也是非线性摩擦纳米发电俘能方法的潜在应用之一.

随着工程领域的发展和人类社会的进步, 信号监测技术在工程实际中以及人们生活中的应用越来越

越广泛,譬如机械结构健康监测、土木结构健康监测和人体健康监测等.信号监测技术的发展离不开微型无线传感器,利用非线性摩擦纳米发电机俘获机械结构振动能量、土木工程结构振动能量和人体运动能量等,来为这些微型无线传感器供电,进而实现信号监测以及健康监测,已经成为当前的研究热点之一^[117,122-125],如图 10(c)所示.因此,利用非线性摩擦纳米发电俘能方法助力结构健康监测同样是非线性摩擦纳米发电俘能方法的潜在应用之一.

5 总结与展望

摩擦纳米发电机的提出有望解决物联网传感器网络节点供电难的问题,进一步促进物联网及其相关智慧产业的发展.然而,由于物联网传感器网络节点周围的环境能量具有低频和宽频特征,传统摩擦纳米发电机难以俘获低频环境能量为传感器网络节点供电.非线性摩擦纳米发电机在低频环境激励下具有复杂的非线性动力学行为,可以产生大幅值动力学响应,并能够高效地将低频环境能量转化为电能.本文首先简要介绍了摩擦纳米发电俘能理论与非线性摩擦纳米发电机的基本工作原理.然后详细总结了 3 种用于俘获低频环境能量的典型非线性摩擦纳米发电俘能方法,厘清了非线性摩擦纳米发电机的非线性动力学行为与电学输出之间的相互作用机制.此外,详细总结了两种非线性摩擦纳米发电俘能系统性能提升策略.最后,从可再生新能源、自供电传感器以及健康监测技术等 3 个方面分析了非线性摩擦纳米发电俘能方法的潜在应用.

非线性摩擦纳米发电机是近年来新能源领域的研究热点之一,目前正在结构设计、材料制备、数学模型建立以及实践应用等方面取得了丰硕的研究成果.但是,非线性摩擦纳米发电机在工程实际中还存在诸如尺寸大、结构不够紧凑、可靠性低和非线性力电耦合模型难以建立与求解,低频俘能频带较窄等多方面的不足.因此,非线性摩擦纳米发电机的发展还面临如下挑战.

(1) 紧凑型非线性摩擦纳米发电机的创新设计.传统非线性摩擦纳米发电机多由机械结构组成,结构复杂、尺寸较大、自重较重且系统不紧凑.因此,基于柔性结构设计方法,结合优化设计方法,创新设计小尺寸、紧凑型非线性摩擦纳米发电机是非线性摩擦纳米发电俘能方法进一步发展的关键.

(2) 非线性摩擦纳米发电机的力电耦合模型建立与分析方法.非线性摩擦纳米发电机是复杂的力电耦合系统,其中包含诸如摩擦及碰撞等复杂的非线性因素.因此,基于哈密顿原理,结合摩擦纳米发电俘能理论,考虑摩擦力与静电力对力电耦合系统的影响,建立非线性力电耦合模型,并求解非线性力电耦合方程,是完善非线性摩擦纳米发电俘能方法理论部分的核心问题.

(3) 非线性摩擦纳米发电机的低频俘能频带调控方法.环境能量具有低频和宽频的特征,传统非线性摩擦纳米发电机的低频俘能频带较窄,且目前非线性摩擦纳米发电机的低频俘能频带调控方法较少.因此,如何拓宽非线性摩擦纳米发电机低频俘能频带,且对低频俘能频带实现自主调控是非线性摩擦纳米发电机在实际应用中的另一关键性问题.

参 考 文 献

- 王之晨,冯靖祎.我国基于物联网技术的智慧医疗系统及其发展应用. *中国医疗设备*, 2022, 37: 174-179 (Wang Zhichen, Feng Jingyi. Application of digital health system based on internet of things in China. *China Medical Devices*, 2022, 37: 174-179 (in Chinese))
- 杨建国,杨明,许诗语等.物联网技术在智慧交通系统中的应用. *黑龙江科学*, 2021, 12: 116-117 (Yang Jianguo, Yang Ming, Xu Shiyu, et al. Application of internet of things in intelligent traffic system. *Heilongjiang Science*, 2021, 12: 116-117 (in Chinese))
- 王玲.基于物联网的智慧物流实时数据平台设计. *现代工业经济和信息化*, 2022, 12: 45-47 (Wang Ling. Design of intelligent logistics real-time data platform based on internet of things. *Modern Industrial Economy and Informationization*, 2022, 12: 45-47 (in Chinese))
- Wang J, Lim M, Wang C, et al. The evolution of the internet of things (IoT) over the past 20 years. *Computers & Industrial Engineering*, 2021, 155: 107174
- 杨恩,王岩,王建业等.基于薄膜拍打型摩擦纳米发电机的风能收集研究. *中国科学:技术科学*, 2021, 51: 684-698 (Yang En, Wang Yan, Wang Jianye, et al. Research on a film-flapping triboelectric nanogenerator for wind energy harvesting. *Scientia Sinica Technologica*, 2021, 51: 684-698 (in Chinese))
- 房方,姚贵山,胡阳等.风力发电机组数字孪生系统. *中国科学:技术科学*, 2022, 52: 1582-1594 (Fang Fang, Yao Guishan, Hu Yang, et al. Digital twin system of a wind turbine. *Scientia Sinica Technologica*, 2022, 52: 1582-1594 (in Chinese))
- Bae J, Lee J, Kim S, et al. Flutter-driven triboelectrification for harvesting wind energy. *Nature Communications*, 2014, 5: 4929
- 王中林,蒋涛,许亮等.纳米发电机应用:海洋蓝色能源. *中国科学:技术科学*, 2023, 53: 989-1001 (Wang Zhonglin, Jiang Tao, Xu Liang, et al. Application of nanogenerator: Ocean blue energy. *Scientia Sinica Technologica*, 2023, 53: 989-1001 (in Chinese))
- Zhang Z, Li X, Yin J, et al. Emerging hydrovoltaic technology. *Nature Nanotechnology*, 2018, 13: 1109-1119

- 10 周生喜, 陶凯, 秦卫阳等. 振动能量俘获专题序. *力学学报*, 2021, 53: 2891-2893 (Zhou Shengxi, Tao Kai, Qin Weiyang, et al. Preface of theme articles on vibration energy harvesting. *Chinese Journal of Theoretical and Applied Mechanics*, 2021, 53: 2891-2893 (in Chinese))
- 11 Zhang H, Marty F, Xia X, et al. Employing a MEMS plasma switch for conditioning high-voltage kinetic energy harvesters. *Nature Communications*, 2020, 11: 3221
- 12 毛新辉, 张继元, 齐欢等. 利用斜齿离合升频机制实现瓦级输出的超低频电磁式振动能量收集器. *力学学报*, 2023, 55: 2168-2177 (Mao Xinhui, Zhang Jiyuan, Qi Huan, et al. An ultra-low frequency electromagnetic vibration energy harvester with watt-level output driven by the helical clutch frequency-upgrading mechanism. *Chinese Journal of Theoretical and Applied Mechanics*, 2023, 55: 2168-2177 (in Chinese))
- 13 潘侠圭, 余宁, 严博. 不倒翁式电磁俘能器的非线性动力学特性研究. *力学学报*, 2023, 55: 2217-2227 (Pan Xiagui, Yu Ning, Yan Bo. Nonlinear dynamics characteristics of tumbler-inspired electromagnetic energy harvesters. *Chinese Journal of Theoretical and Applied Mechanics*, 2023, 55: 2217-2227 (in Chinese))
- 14 Fang S, Du H, Yan T, et al. Theoretical and experimental investigation on the advantages of auxetic nonlinear vortex-induced vibration energy harvesting. *Applied Energy*, 2024, 356: 122395
- 15 Zhao L, Zou H, Wei K, et al. Mechanical intelligent energy harvesting: From methodology to applications. *Advanced Energy Materials*, 2023, 13: 2300557
- 16 黄曼娟, 冯孝为, 刘会聪等. 基于双稳态磁耦合效应的瓦级高功率电磁振动能量收集器. *机械工程学报*, 2022, 58: 92-100 (Huang Manjuan, Feng Xiaowei, Liu Huicong, et al. Bistable electromagnetic vibration energy harvester based on magnetic coupling effect realizing watt-level power output. *Journal of Mechanical Engineering*, 2022, 58: 92-100 (in Chinese))
- 17 孙洪鑫, 罗一帆, 杨国松等. 电磁集能式调谐质量阻尼器的结构减震及能量收集分析. *振动与冲击*, 2017, 36: 51-56 (Sun Hongxin, Luo Yifan, Yang Guoshong, et al. A RETMD with performances of structural aseismic control and energy harvesting for a single-DOF structure. *Journal of Vibration and Shock*, 2017, 36: 51-56 (in Chinese))
- 18 Yu N, Ma H, Wu C, et al. Modeling and experimental investigation of a novel bistable two-degree-of-freedom electromagnetic energy harvester. *Mechanical Systems and Signal Processing*, 2021, 156: 107608
- 19 Wang J, Zhou S, Zhang Z, et al. High-performance piezoelectric wind energy harvester with Y-shaped attachments. *Energy Conversion and Management*, 2019, 181: 645-652
- 20 于家豪, 陶凯. 振动俘能技术在可穿戴领域的应用. *机械工程学报*, 2022, 58: 46-71 (Yu Jiahao, Tao Kai. Applications of vibration energy harvesting technology in the field of wearable devices. *Journal of Mechanical Engineering*, 2022, 58: 46-71 (in Chinese))
- 21 刘琦, 秦卫阳, 邓王蒸等. 惯性固支梁双稳态振动俘能系统设计与实验验证. *振动工程学报*, 2022, 35: 1165-1173 (Liu Qi, Qin Weiyang, Deng Wangzheng, et al. Design and dynamical characteristics of bistable vibration energy harvester with amplified inertial forces acting on double-clamped beams. *Journal of Vibration Engineering*, 2022, 35: 1165-1173 (in Chinese))
- 22 赵宁, 乔双, 马雯等. 热释电材料性能及应用研究进展. *稀有金属*, 2022, 46: 1225-1334 (Zhao Ning, Qiao Shaung, Ma Wen, et al. Research progress on performance and application of pyroelectric materials. *Chinese Journal of Rare Metals*, 2022, 46: 1225-1334 (in Chinese))
- 23 Pandya S, Velarde G, Zhang L, et al. New approach to waste-heat energy harvesting: Pyroelectric energy conversion. *NPG Asia Materials*, 2019, 11: 26
- 24 董凯, 唐伟. 纳米发电机与微纳能源收集. *中国科学: 技术科学*, 2023, 53: 953-966 (Dong Kai, Tang Wei. Nanogenerators and micro/nano energy harvesting. *Scientia Sinica Technologica*, 2023, 53: 953-966 (in Chinese))
- 25 Zhang Y, Wang T, Luo A, et al. Micro electrostatic energy harvester with both broad bandwidth and high normalized power density. *Applied Energy*, 2018, 212: 362-371
- 26 Han Q, Ding Z, Qin Z, et al. A triboelectric rolling ball bearing with self-powering and self-sensing capabilities. *Nano Energy*, 2020, 67: 104277
- 27 Fan F, Tian Z, Wang Z. Flexible triboelectric generator. *Nano Energy*, 2012, 1: 328-334
- 28 季喜军, 熊枫, 石树正等. 基于摩擦纳米发电机的自驱动自清洁雨量传感器. *微纳电子技术*, 2022, 59: 257-263 (Ji Xijun, Xiong Feng, Shi Shuzheng, et al. Self-driving and self-cleaning rainfall sensor based on triboelectric nanogenerator. *Micronanoelectronic Technology*, 2022, 59: 257-263 (in Chinese))
- 29 Xu W, Zheng H, Liu Y, et al. A droplet-based electricity generator with high instantaneous power density. *Nature*, 2020, 578: 392-396
- 30 Wang Z, Chen J, Lin L. Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors. *Energy & Environmental Science*, 2015, 8: 2250-2282
- 31 Niu S, Liu Y, Wang S, et al. Theory of sliding-mode triboelectric nanogenerators. *Advanced Materials*, 2013, 25: 6184-6193
- 32 Niu S, Wang S, Lin L, et al. Theoretical study of contact-mode triboelectric nanogenerators as an effective power source. *Energy & Environmental Science*, 2013, 6: 3576-3583
- 33 Ko H, Kwon D, Bae K, et al. Self-suspended shell-based triboelectric nanogenerator for omnidirectional wind-energy harvesting. *Nano Energy*, 2022, 96: 107062
- 34 Xu L, Pang Y, Zhang C, et al. Integrated triboelectric nanogenerator array based on air-driven membrane structures for water wave energy harvesting. *Nano Energy*, 2017, 31: 351-358
- 35 Yang J, Chen J, Yang Y, et al. Broadband vibrational energy harvesting based on a triboelectric nanogenerator. *Advanced Energy Materials*, 2014, 4: 1301322
- 36 李魁, 杨智春, 谷迎松等. 变势能阱双稳态气动弹性能量收集的性能增强研究. *航空学报*, 2020, 41: 223710 (Li Kui, Yang Zhichun, Gu Yingsong, et al. Performance enhancement of variable-potential-well bi-stable aeroelasticity energy harvesting. *Acta Aeronautica et Astronautica Sinica*, 2020, 41: 223710 (in Chinese))
- 37 钱有华, 陈娅妮. 双稳态压电俘能器的簇发振荡与俘能效率分析. *力学学报*, 2022, 54: 3157-3168 (Qian Youhua, Chen Yani. Bursting oscillations and energy harvesting efficiency analysis of bistable piezoelectric energy harvester. *Chinese Journal of Theoretical and Applied Mechanics*, 2022, 54: 3157-3168 (in Chinese))
- 38 Huang X, Yang B. Improving energy harvesting from impulsive excitations by a nonlinear tunable bistable energy harvester. *Mechanical Systems and Signal Processing*, 2021, 158: 107797
- 39 李海涛, 丁虎, 陈立群等. 三稳态能量收集系统的同宿分岔及混沌动力学分析. *应用数学和力学*, 2020, 41: 1311-1322 (Li Haitao,

- Ding Hu, Chen Liqun, et al. Homoclinic bifurcations and chaos thresholds of tristable piezoelectric vibration energy harvesting systems. *Applied Mathematics and Mechanics*, 2020, 41: 1311-1322 (in Chinese))
- 40 Zou D, Liu G, Rao Z, et al. Design of a multi-stable piezoelectric energy harvester with programmable equilibrium point configurations. *Applied Energy*, 2021, 302: 117585
- 41 张颖, 王伟, 曹军义等. 多稳态俘能系统的准确磁力建模方法. *力学学报*, 2021, 53: 2984-2995 (Zhang Ying, Wang Wei, Cao Junyi, et al. An accurate modelling method of magnetic force in multi-stable energy harvesting system. *Chinese Journal of Theoretical and Applied Mechanics*, 2021, 53: 2984-2995 (in Chinese))
- 42 王凯, 周加喜, 蔡昌琦等. 低频弹性波超材料的若干进展. *力学学报*, 2022, 54: 2678-2694 (Wang Kai, Zhou Jiaxi, Cai Changqi, et al. Review of low-frequency elastic wave metamaterials. *Chinese Journal of Theoretical and Applied Mechanics*, 2022, 54: 2678-2694 (in Chinese))
- 43 孙秀婷, 钱佳伟, 齐志凤等. 非线性隔振及时滞消振方法研究进展. *力学进展*, 2023, 53: 308-356 (Sun Xiuting, Qian Jiawei, Qi Zhifeng, et al. Review on research progress of nonlinear vibration isolation and time-delayed suppression method. *Advances in Mechanics*, 2023, 53: 308-356 (in Chinese))
- 44 Wang Q, Zhou J, Wang K, et al. Dual-function quasi-zero-stiffness dynamic vibration absorber: Low-frequency vibration mitigation and energy harvesting. *Applied Mathematical Modelling*, 2023, 116: 636-654
- 45 李申芳, 王军雷, 王中林等. 利用摩擦纳米发电机的流体能量俘获研究新进展. *力学学报*, 2021, 53: 2910-2927 (Li Shenfang, Wang Junlei, Wang Zhonglin, et al. Progression on fluid energy harvesting based on triboelectric nanogenerators. *Chinese Journal of Theoretical and Applied Mechanics*, 2021, 53: 2910-2927 (in Chinese))
- 46 李虎, 赵璐明, 李喆等. 自驱动健康监测及生理功能调节器件的研究进展. *生物工程学报*, 2019, 35: 2367-2385 (Li Hu, Zhao Luming, Li Zhe, et al. Progress in self-powered health monitoring and physiological function regulation devices. *Chinese Journal of Biotechnology*, 2019, 35: 2367-2385 (in Chinese))
- 47 禹健, 郭艳婕, 杨雷等. 固-液摩擦纳米发电机. *机械工程学报*, 2021, 57: 160-181 (Yu Jiang, Guo Yanjie, Yang Lei, et al. Solid-liquid triboelectric nanogenerator. *Journal of Mechanical Engineering*, 2021, 57: 160-181 (in Chinese))
- 48 丁亚飞, 陈翔宇. 基于摩擦纳米发电机的可穿戴能源器件. *物理学报*, 2020, 69: 170202 (Ding Yafei, Chen Xiangyu. Triboelectric nanogenerator based wearable energy harvesting devices. *Acta Physica Sinica*, 2020, 69: 170202 (in Chinese))
- 49 Shao J, Jiang T, Tang W, et al. Studying about applied force and the output performance of sliding-mode triboelectric nanogenerators. *Nano Energy*, 2018, 48: 292-300
- 50 Zhou L, Liu D, Zhao Z, et al. Simultaneously enhancing power density and durability of sliding-mode triboelectric nanogenerator via interface liquid lubrication. *Advanced Energy Materials*, 2020, 10: 2002920
- 51 He W, Liu W, Chen J, et al. Boosting output performance of sliding mode triboelectric nanogenerator by charge space-accumulation effect. *Nature Communications*, 2020, 11: 4277
- 52 张皓钧, 郭永亮, 崔锦峰等. 摩擦纳米发电机输出性能提升及自驱动防腐系统. *微纳电子技术*, 2021, 58: 715-722 (Zhang Haojun, Guo Yongliang, Cui Jinfeng, et al. Enhanced output performance of the triboelectric nanogenerator and self-powered anticorrosion system. *Micronanoelectronic Technology*, 2021, 58: 715-722 (in Chinese))
- 53 Zi Y, Wu C, Ding W, et al. Maximized effective energy output of contact-separation-triggered triboelectric nanogenerators as limited by air breakdown. *Advanced Functional Materials*, 2017, 27: 1700049
- 54 Han K, Tang W, Chen J, et al. Effects of environmental atmosphere on the performance of contact-separation mode TENG. *Advanced Materials Technologies*, 2019, 4: 1800569
- 55 刘卓, 欧阳涵, 邹洋等. 基于摩擦纳米发电机的自驱动植入式电子医疗器件的研究. *中国科学: 技术科学*, 2017, 47: 1075-1080 (Liu Zhuo, Ouyang Han, Zou Yang, et al. Self-powered implantable electronic medical devices research based on triboelectric nanogenerator. *Scientia Sinica Technologica*, 2017, 47: 1075-1080 (in Chinese))
- 56 唐炬, 吴豪颖, 李祎等. 基于管状结构的液-固接触摩擦纳米发电机. *中国电机工程学报*, 2022, 42: 6094-6103 (Tang Ju, Wu Haoying, Li Yi, et al. Liquid-solid contact triboelectric nanogenerator based on tubular structure. *Proceedings of the CSEE*, 2022, 42: 6094-6103 (in Chinese))
- 57 Mule A, Dudem B, Patnam H, et al. Wearable single-electrode-mode triboelectric nanogenerator via conductive polymer-coated textiles for self-power electronics. *ACS Sustainable Chemistry & Engineering*, 2019, 7: 16450-16458
- 58 Gogurla N, Roy B, Park J, et al. Skin-contact actuated single-electrode protein triboelectric nanogenerator and strain sensor for biomechanical energy harvesting and motion sensing. *Nano Energy*, 2019, 62: 674-681
- 59 Zheng Z, Yu D, Guo Y. Dielectric modulated glass fiber fabric-based single electrode triboelectric nanogenerator for efficient biomechanical energy harvesting. *Advanced Functional Materials*, 2021, 31: 2102431
- 60 陈力, 李招招, 夏远辰等. 基于兔毛的软接触摩擦纳米发电机. *微纳电子技术*, 2023, 60: 265-271 (Chen Li, Li Zhaozhao, Xia Yuanchen, et al. Soft contact triboelectric nano-generator based on rabbit hair. *Micronanoelectronic Technology*, 2023, 60: 265-271 (in Chinese))
- 61 武世豪, 李程龙, 李刚等. 基于纤维素纳米纤维的摩擦纳米发电机. *中国造纸学报*, 2021, 36: 105-110 (Wu Shihao, Li Chenglong, Li Gang, et al. Triboelectric nanogenerators based on cellulose nanofibers. *Transactions of China Pulp and Paper*, 2021, 36: 105-110 (in Chinese))
- 62 Li Z, Zhang S, Guo H, et al. On the performance of freestanding rolling mode triboelectric nanogenerators from rotational excitations for smart tires. *Nano Energy*, 2023, 113: 108595
- 63 Sun W, Jiang Z, Xu X, et al. Harmonic balance analysis of output characteristics of free-standing mode triboelectric nanogenerators. *International Journal of Mechanical Sciences*, 2021, 207: 106668
- 64 Tan D, Zhou J, Wang K, et al. Design and theoretical investigation of a torsional bistable triboelectric nanogenerator. *International Journal of Mechanical Sciences*, 2022, 236: 107760
- 65 Tan D, Zhou J, Wang K, et al. Sliding-impact bistable triboelectric nanogenerator for enhancing energy harvesting from low-frequency intrawell oscillation. *Mechanical Systems and Signal Processing*, 2023, 184: 109731

- 66 Fu Y, Ouyang H, Benjamin D. Nonlinear structural dynamics of a new sliding-mode triboelectric energy harvester with multistability. *Nonlinear Dynamics*, 2020, 100: 1941-1962
- 67 Cao B, Wang P, Rui P, et al. Broadband and output-controllable triboelectric nanogenerator enabled by coupling swing-rotation switching mechanism with potential energy storage/release strategy for low-frequency mechanical energy harvesting. *Advanced Energy Materials*, 2022, 12: 2202627
- 68 Yuan Z, Jin X, Li R, et al. Hybrid triboelectric-electromagnetic magnetic energy harvester-based sensing for wireless monitoring of transmission lines. *Small*, 2022, 18: 2107221
- 69 Guan D, Xu G, Xia X, et al. Boosting the output performance of the triboelectric nanogenerator through the nonlinear oscillator. *ACS Applied Materials & Interfaces*, 2021, 13: 6331-6338
- 70 Tan D, Zhou J, Wang K, et al. Modeling and analysis of the friction in a non-linear sliding-mode triboelectric energy harvester. *Acta Mechanica Sinica*, 2022, 38: 521330
- 71 Zhao H, Ouyang H. Structural and electrical dynamics of a grating-patterned triboelectric energy harvester with stick-slip oscillation and magnetic bistability. *Nonlinear Dynamics*, 2022, 109: 479-506
- 72 Bai Q, Liao X, Chen Z, et al. Snap-through triboelectric nanogenerator with magnetic coupling buckled bistable mechanism for harvesting rotational energy. *Nano Energy*, 2022, 96: 107118
- 73 Deng H, Ye J, Du Y, et al. Bistable broadband hybrid generator for ultralow-frequency rectilinear motion. *Nano Energy*, 2019, 65: 103973
- 74 Luo H, Liu J, Yang T, et al. Dipteran flight-inspired bistable triboelectric nanogenerator for harvesting low frequency vibration. *Nano Energy*, 2022, 103: 107755
- 75 Tan D, Zhou J, Wang K, et al. Bow-type bistable triboelectric nanogenerator for harvesting energy from low-frequency vibration. *Nano Energy*, 2022, 92: 106746
- 76 Zhao H, Ouyang H. A vibro-impact triboelectric energy harvester with a magnetic bistable mechanism and grating-patterned films for dual power enhancement. *Mechanical Systems and Signal Processing*, 2022, 178: 109318
- 77 Zhao L, Zou H, Wu Z, et al. Dynamically synergistic regulation mechanism for rotation energy harvesting. *Mechanical Systems and Signal Processing*, 2022, 169: 108637
- 78 Zhao L, Zou H, Zhao Y, et al. Hybrid energy harvesting for self-powered rotor condition monitoring using maximal utilization strategy in structural space and operation process. *Applied Energy*, 2022, 314: 118983
- 79 Zhao H, Ouyang H. Theoretical investigation and experiment of a disc-shaped triboelectric energy harvester with a magnetic bistable mechanism. *Smart Materials and Structures*, 2021, 30: 095026
- 80 Tan D, Zhou J, Wang K, et al. Wearable bistable triboelectric nanogenerator for harvesting torsional vibration energy from human motion. *Nano Energy*, 2023, 109: 108315
- 81 吴志强, 王耀光, 张祥云等. 一类三稳态系统确定性及随机分岔现象分析. 天津大学学报 (自然科学与工程技术版), 2018, 51: 895-902 (Wu Zhiqiang, Wang Yaoguang, Zhang Xiangyun, et al. Deterministic and stochastic bifurcations of a tri-stable system. *Journal of Tianjin University (Science and Technology)*, 2018, 51: 895-902 (in Chinese))
- 82 Mei X, Zhou S, Yang Z, et al. A tri-stable energy harvester in rotational motion: Modeling, theoretical analyses and experiments. *Journal of Sound and Vibration*, 2020, 469: 115142
- 83 Zhou S, Zuo L. Nonlinear dynamic analysis of asymmetric tristable energy harvesters for enhanced energy harvesting. *Communications in Nonlinear Science and Numerical Simulation*, 2018, 61: 271-284
- 84 颜粟, 徐鉴. 振动驱动三连杆的多稳态分岔和实验. 力学季刊, 2014, 35: 541-547 (Yan Su, Xu Jian. Multistable bifurcation and experiment for a three-link mass rod with vibration driving. *Chinese Quarterly of Mechanics*, 2014, 35: 541-547 (in Chinese))
- 85 Yang T, Cao Q. Dynamics and high-efficiency of a novel multi-stable energy harvesting system. *Chaos, Solitons & Fractals*, 2020, 131: 109516
- 86 Mei X, Zhou S, Yang Z, et al. Enhancing energy harvesting in low-frequency rotational motion by a quad-stable energy harvester with time-varying potential wells. *Mechanical Systems and Signal Processing*, 2021, 148: 107167
- 87 Zhou Z, Qin W, Yang Y, et al. Improving efficiency of energy harvesting by a novel penta-stable configuration. *Sensors and Actuators A: Physical*, 2017, 265: 297-305
- 88 Qian Y, Chen Y. Research on multi-valued response and bursting oscillation of series multi-stable piezoelectric energy harvester. *The European Physical Journal Plus*, 2022, 137: 588
- 89 Zhang Y, Duan J, Jin Y, et al. Discovering governing equation from data for multi-stable energy harvester under white noise. *Nonlinear Dynamics*, 2021, 106: 2829-2840
- 90 Yang T, Xu H, Tang J, et al. Exploring nonlinear degradation benefit of bio-inspired oscillator for engineering applications. *Applied Mathematical Modelling*, 2023, 119: 736-762
- 91 Wang C, Lai S, Wang J, et al. An ultra-low-frequency, broadband and multi-stable tri-hybrid energy harvester for enabling the next-generation sustainable power. *Applied Energy*, 2021, 291: 116825
- 92 Yang X, Wang C, Lai S. A magnetic levitation-based tristable hybrid energy harvester for scavenging energy from low-frequency structural vibration. *Engineering Structures*, 2020, 221: 110789
- 93 Yang X, Lai S, Wang C, et al. On a spring-assisted multi-stable hybrid-integrated vibration energy harvester for ultra-low-frequency excitations. *Energy*, 2022, 252: 124028
- 94 周佳豪, 潘洪斌, 蔡昌琦等. 准零刚度柔性隔振超结构设计及仿真分析. 哈尔滨工程大学学报, 2022, 43: 1258-1264 (Zhou Jiahao, Pan Hongbin, Cai Chanqi, et al. Design and simulation analysis of a quasi-zero stiffness flexible vibration isolation metastructure. *Journal of Harbin Engineering University*, 2022, 43: 1258-1264 (in Chinese))
- 95 Zhang C, He J, Zhou G, et al. Compliant quasi-zero-stiffness isolator for low-frequency torsional vibration isolation. *Mechanism and Machine Theory*, 2023, 181: 105213
- 96 胥强荣, 沈承, 韩峰等. 一种准零刚度声学超材料板的低频宽频带隔声行为. 物理学报, 2021, 70: 244302 (Xu Qiangrong, Shen Cheng, Han Feng, et al. Broadband low-frequency sound insulation performance of quasi-zero stiffness local resonant acoustic metamaterial plate. *Acta Physica Sinica*, 2021, 70: 244302 (in Chinese))
- 97 Wang K, Zhou J, Ouyang H, et al. A dual quasi-zero-stiffness sliding-mode triboelectric nanogenerator for harvesting ultra-low frequency vibration energy. *Mechanical Systems and Signal Processing*, 2021, 151: 107368
- 98 Wang K, Ouyang H, Zhou J, et al. A nonlinear hybrid energy har-

- vester with high ultralow-frequency energy harvesting performance. *Meccanica*, 2021, 56: 461-480
- 99 Zhou J, Wang K, Xu D, et al. Multi-low-frequency flexural wave attenuation in Euler-Bernoulli beams using local resonators containing negative-stiffness mechanisms. *Physics Letters A*, 2017, 381: 3141-3148
 - 100 Zhao H, Ouyang H. A capsule-structured triboelectric energy harvester with stick-slip vibration and vibro-impact. *Energy*, 2021, 235: 121393
 - 101 Qi Y, Liu G, Kuang Y, et al. Frequency band broadening and charge density enhancement of a vibrational triboelectric nanogenerator with two stoppers. *Nano Energy*, 2022, 99: 107427
 - 102 Ibrahim A, Hassan M. Extended bandwidth of 2DOF double impact triboelectric energy harvesting : Theoretical and experimental verification. *Applied Energy*, 2023, 333: 120593
 - 103 Zhao C, Hu G, Yang Y. A cantilever-type vibro-impact triboelectric energy harvester for wind energy harvesting. *Mechanical Systems and Signal Processing*, 2022, 177: 109185
 - 104 陈延辉, 谢伟博, 代克杰等. 非谐振式低频电磁-摩擦电复合振动能收集器. *物理学报*, 2020, 69: 208402 (Chen Yanhui, Xie Weibo, Dai Kejie, et al. Non-resonant and low-frequency triboelectric-electromagnetic hybridized nanogenerator for vibration energy. *Acta Physica Sinica*, 2020, 69: 208402 (in Chinese))
 - 105 Vidal J, Slabov V, Kholkin A, et al. Hybrid triboelectric-electromagnetic nanogenerators for mechanical energy harvesting: A review. *Nano-Micro Letters*, 2021, 13: 199
 - 106 Egbe K, Nazar A, Jiao P. Piezoelectric-triboelectric-electromagnetic hybrid rotational energy harvesters (H-REH). *International Journal of Mechanical Sciences*, 2022, 235: 107722
 - 107 Pang Y, Cao Y, Derakhshani M, et al. Hybrid energy-harvesting systems based on triboelectric nanogenerators. *Matter*, 2021, 4: 116-143
 - 108 Zhao H, Ouyang H, Zhang H. A nonresonant triboelectric-electromagnetic energy harvester via a vibro-impact mechanism for low-frequency multi-directional excitations. *Nano Energy*, 2023, 107: 108123
 - 109 任静, 何剑. 非谐振式的电磁-摩擦复合式纳米发电机. *中北大学学报 (自然科学版)*, 2023, 44: 455-464 (Ren Jing, He Jian. An electromagnetic-triboelectric hybrid nanogenerator based on non-resonant mechanism. *Journal of North University of China (Natural Science Edition)*, 2023, 44: 455-464 (in Chinese))
 - 110 杨亚, 杨婉璐. 复合型电磁-摩擦纳米发电机. *科学通报*, 2016, 61: 1268-1275 (Yang Ya, Yang Wanlu. Hybridized electromagnetic-triboelectric nanogenerator. *Chinese Science Bulletin*, 2016, 61: 1268-1275 (in Chinese))
 - 111 Han C, Cao Z, Yuan Z, et al. Hybrid triboelectric-electromagnetic nanogenerator with a double-sided fluff and double halbach array for wave energy harvesting. *Advanced Functional Materials*, 2022, 32: 2205011
 - 112 Zhang L, Meng B, Xia Y, et al. Galloping triboelectric nanogenerator for energy harvesting under low wind speed. *Nano Energy*, 2020, 70: 104477
 - 113 Gao Q, Xu Y, Yu X, et al. Gyroscope-structured triboelectric nanogenerator for harvesting multidirectional ocean wave energy. *ACS Nano*, 2022, 16: 6781-6788
 - 114 Wei X, Zhao Z, Zhang C, et al. All-weather droplet-based triboelectric nanogenerator for wave energy harvesting. *ACS Nano*, 2021, 15: 13200-13208
 - 115 Gao Q, Cheng T, Wang Z. Triboelectric mechanical sensors-progress and prospects. *Extreme Mechanics Letters*, 2021, 42: 101100
 - 116 Dong K, Peng X, Wang Z. Fiber/fabric-based piezoelectric and triboelectric nanogenerators for flexible/stretchable and wearable electronics and artificial intelligence. *Advanced Materials*, 2020, 32: 1902549
 - 117 Fang Z, Zhou Z, Yi M, et al. A roller-bearing-based triboelectric nanosensor for freight train synergistic maintenance in smart transportation. *Nano Energy*, 2023, 106: 108089
 - 118 Yu J, Hou X, He J, et al. Ultra-flexible and high-sensitive triboelectric nanogenerator as electronic skin for self-powered human physiological signal monitoring. *Nano Energy*, 2020, 69: 104437
 - 119 Yang Y, Wen J, Chen F, et al. Barycenter self-adapting triboelectric nanogenerator for sea water wave high-entropy energy harvesting and self-powered forecasting in marine meteorology. *Advanced Energy Materials*, 2022, 32: 2200521
 - 120 Zhu P, Zhang B, Wang H, et al. 3D printed triboelectric nanogenerator as self-powered human-machine interactive sensor for breathing-based language expression. *Nano Research*, 2022, 15: 7460-7467
 - 121 Zhou H, Huang W, Xiao Z, et al. Deep-learning-assisted noncontact gesture-recognition system for touchless human-machine interfaces. *Advanced Function Materials*, 2022, 32: 2208271
 - 122 Zhang Q, Barri K, Kari S, et al. Multifunctional triboelectric nanogenerator-enabled structural elements for next generation civil infrastructure monitoring systems. *Advanced Function Materials*, 2021, 31: 2105825
 - 123 Yang D, Ni Y, Kong X, et al. Self-healing and elastic triboelectric nanogenerators for muscle motion monitoring and photothermal treatment. *ACS Nano*, 2021, 15: 14653-14661
 - 124 Tan D, Wang K, Zhou J, et al. A brief review of nonlinear triboelectric nanogenerator. *International Journal of Dynamics and Control*, 2024, 12: 2072-2092
 - 125 Gao J, Zhou J, Wang Q, et al. Design and optimization of quasi-zero-stiffness dual harvester-absorber system. *International Journal of Mechanical Sciences*, 2024, 273: 109227